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APPLICATION OF A CONCENTRIC VORTEX-CELL BIOMASS FURNACE TO GRAIN DRYING presented by

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APPLICATION OF A CONCENTRIC VORTEX-CELL BIOMASS FURNACE TO GRAIN DRYING

By

Eliud Ng'ang'a Mwaura

A DISSERTATION

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

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ABSTRACT

APPLICATION OF A CONCENTRIC VORTEX-CELL BIOMASS FURNACE TO GRAIN DRYING

By

Eliud Ng'ang'a Mwaura

Artificial crop drying is relatively energy intensive and uses about 60% of the energy required to produce corn, exclusive of irrigation. Biomass fuels, such as wood chips and corncobs, are potential alternatives to fossil fuels for crop drying.

A concentric vortex-cell furnace (CVCF) with a maximum heat output of 690 kW was built and incorporated in an in-bin counterflow (IBCF) corn dryer with an hourly capacity of 3 m³ at an initial grain temperature of 10°C, a drying temperature of 71°C, and corn dried from 25% to 15.5% moisture content (wet basis). The system was tested using wood chips and corncobs. Experimental tests included: (1) fuel consumption and drying capacity, and (2) corn contamination with polycyclic aromatic hydrocarbons (PAHs) and heavy metals. The results were compared with the performance of a propane (LP) fueled system.

The results demonstrate that the CVCF biomass furnace is a technically viable alternative to conventional fossil fuel burners. The drying capacity of the CVCF/IBCF system is approximately 90% of the LP fueled system. The reduction in the drying capacity is a result of the reduction in the flow rate of the drying air mass due to the heating of the air before the fan entrance.

The CVCF/IBCF system operates at about 70% efficiency in converting biomass fuels into energy for grain drying. The average specific energy consumption (kJ/kg of water removed) of the system is about 6,100 kJ/kg compared with 4,600 kJ/kg for the LP fueled system.

There is no objectionable discoloration or objectionable odor in the corn dried with the CVCF/IBCF system. The grain contains no dangerous concentration levels of PAH or heavy metals.

The operating costs (exclusive of labor and fixed costs) of the CVCF/IBCF system are 30 to 40% of the energy costs of the LP fueled system. The total break-even costs of the CVCF/IBCF system are about 20% higher than the total costs of the LP system (at 1983 prices) due to the high capital investment required to convert the LP system into a biomass system.

The CVCF furnace does not have immediate economic feasibility in the USA at the 1983 fossil fuel prices and interest rates. To Kimathi and his colleagues

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A

LIST OF SYMBOLS

A	Area, m ²
As	Ash content, percent
В	Inert heat absorbing compound
с	Concentration kg/m ³
Cf	Convective thermal resistance °C/W
с	Specific heat kJ/kg °C
D	Diameter m
D	Diffusivity constant m ² /hr
d	Diameter m
E	Activation energy kJ
Eb	Radiated thermal energy kJ/h
F _{m-n}	View factor for radiation from surface m to surface n
f	Friction factor
Fvv	Fractional void volume
G	Mass of wet grain kg
Gr	Grashoff number
g _c	Gravitational constant 9.8 kg _m m/kg _f s ²
h	Enthalpy kJ/kg
Н	Absolute humidity kg/kg
HHV	Higher heating value kJ/kg
∆H _R	Heat of combustion kJ
J	Radiocity w/m ²

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k	Thermal conductivity
LHV	Low heating value kJ/kg
L	Length m
М	Moisture content percent wet basis
м	Mass flow rate kg/h
m	Moisture content decimal dry basis
m	Mass fraction
Р	Pressure kPa
Pr	Prandtl number
Q	Rate of heat transfer kJ/h
R	Gas constant
R	Radius m
Ra	Rayleigh number
RH	Relative humidity percent
rh	Relative humidity decimal
Sg	Specific gravity
St	Stanton number
SECO	Specific energy consumption kJ/kg of water
Т	Temperature °C
t	Time h man man attention to be the
U	Velocity m/s
۷	Volume m ³
W	Weight of water removed kg
X	Mole fraction
Z	Excess air percent

xv

- ε Emissivity
- n Efficiency percent
- θ Grain temperature °C
- ρ Density kg/m³
- σ Stefan-Boltzmann constant 5.669 x 10⁻⁸W/m²k

Subscripts

- a Air
- B Bin
- c Combustion products
- c Convective
- D Dried grain
- e Eductor nozzle exit
- e Equilibrium
- F Furnace combustion chamber
- fg Evaporation
- i Increment
- j Increment
- m Moisture
- n Increment
- o Induced mass flow at initial conditions
- p Products of combustion
- p Dried product, i.e., grain
- r Reactants in a combustion process
- r Radiation heat loss
- s Motive fluid at initial supply conditions
- s Sky

t	Тор
v	Vapor
w	Wall
W	water

CHAPTER 1

INTRODUCTION

Cereal and pulse grains are a major source of food for human and animal consumption. In terms of world production in 1982, wheat ranks first, followed by corn, rice, and barley (Table 1.1). As a source of human food, rice has no equal among the grains, especially in the Orient where the major (91%) of the world's supply of rice is produced (FAO, 1982). Corn, millet, and sorghum are the main cereal grains for human consumption in Africa. According to USDA (1982), the USA produced in 1981 about 46% and 20% of the total world production of corn and all the cereals, respectively. Other important cereal grains are barley, oats, and rye.

Pulse grains, such as beans and peas, are a significant source of protein for human consumption, especially in Third World countries where meat consumption is comparatively low. Pulse grains are produced mainly in Asia (52% of world production), Africa, and South America (see Table 1.2). Soybeans are an important source of oil and protein for both human and animal consumption. The USA is the major producer of soybeans and produces more than 60% of the total world production (see Table 1.2).

Table 1.1.--Morld production (1981) of main cereal grains, 1,000 metric tons.

Region	Wheat	Corn	Rice	Barley	Sorghum	Millet	Total Cereals
Africa	8,594	32,860	8,562	3,197	11,174	10,282	76,329
Kenya	212	2,250	41	100	220	130	2,939
Asia	137,371	86,570	376,232	17,216	20,566	17,588	661,439
Europe	91,942	53,627	1,808	66,275	727	32	245,356
S. America	11,743	38,406	13,258	806	9,146	238	74,725
U.S.A.	76,025	208,314	8,408	10,414	22,360	1	333,748
World	458,195	451,704	413,785	158,488	71,984	29,653	1,663,328

Sources: FAO (1982), and USDA (1982).

colitie.	Region	Soybeans	Pulses
	Africa	319	5,076 900100100
	Asia	10,320	22,241
	Europe	552	2,401
	S. America	19,575	3,294
	U.S.A.	55,260	1,673
	World	87,941	42,403

Table 1.2.--World production of soybeans and pulses (1981), 1,000 metric tons.

Sources: FAO (1982), USDA (1982).

1.1 Michigan Grain Production

Michigan is a major grain producing state. Among the major grain producing states in the USA, Michigan, in 1982, ranked first in production of dry beans (30.0%), 6th in oats (4.6%), 8th in corn (3.7%), 7th in rye (3.1%), 22nd in wheat (1.2%), and 18th in soybeans (1.4%) (MDA, 1983). The shelled corn annual production in Michigan increased from 4.94 in 1978 to 7.81 million tons in 1981. This represents an increase of 58%. During the same period, annual soybean production increased from 0.55 to 0.82 million tons, an increase of 49%. Annual wheat production showed the highest increase from 0.42 million tons in 1978 to 1.13 million tons in 1981, an increase of 153%. Other grains showed production increases of 20% (dry beans) to 31% (barley); the oats production decreased by 10% (MDA, 1983).

1.2 Grain Preservation

Grains are stored either on the farm or in commercial storage facilities. Storage structures should provide suitable conditions for maintaining the grain quality. The stored grain should be protected from insects, rodents, molds, and the weather elements. Before storage, it should be properly conditioned.

Grain drying is the most widely used method of preserving grain (Brooker et al., 1974). Moisture is removed to prevent the development of a favorable environment for the growth of molds and insects. Grain drying may be either natural or artificial. Natural drying occurs in the field before harvest, in an ear corn crib, or when on the ground during solar drying.

Artificial drying is an energy intensive system. According to Brooker et al. (1974), about 60% of the energy required to produce corn exclusive of irrigation is used for artificial drying. In spite of the high energy demand for grain drying, more than 80% of the corn produced in the USA is artificially dried (ASAE, 1978). Artificial drying has the following advantages:

- a. allows early harvest which, in turn, reduces storm and shattering field-losses, and permits early land preparation for the next crop;
 - b. allows planning of the harvest season to make better use of the labor;
 - allows long-time storage without deterioration;
 - enables farmers to take advantage of higher prices at some time after harvest;

- e. maintains grain viability and quality;
- f. allows the use of full season hybrids (longer maturing varieties) that yield more grain per hectare.

Considering the above advantages, it is obvious that grain drying cannot be omitted without undue loss of grain quantity and quality at the farm level.

The current artificial grain dryers use convection-type heaters that burn fossil fuels, usually liquefied petroleum (LP) gas or natural gas. According to Friedrich (1978), high-temperature dryers operate at about 50% efficiency in utilizing fuel to evaporate moisture from grains. It takes from 4650 to 8140 kJ to remove one kilogram of water from grains such as corn, depending on the initial and final moisture content, the amount of fines, the dryer design, and the weather conditions (Brooker et al., 1978).

It is obvious that the current high-temperature dryers require large amounts of energy. Also, the fossil fuels compete with domestic and industrial uses. It is, therefore, desirable to develop drying systems which can reduce fossil fuel requirements for grain drying.

There are four principle possibilities of reducing fossil fuel usage (ASAE, 1978):

- increased use of high moisture corn storage to feed animals at farms close to where corn is grown;
- 2. use of natural air or low temperature drying;

- use of combination drying systems employing the advantages of high-speed, high-temperature drying and low-speed, low-temperature (or natural air) drying;
 - use of solar heated drying systems;
- 6 5. application of crop residues as a crop drying the formation of the state of th

The last item is the subject of the research in this dissertation.

1.3 Biomass Fuels for Grain Drying

Biomass energy is a form of solar energy stored by plants in the form of hydrocarbons. Many researchers have investigated utilization of this energy (Steffgen, 1974; Shrader, 1977; Hall, 1979; Stout, 1979; Claar et al., 1980a and 1980b; Claar, 1981; Anderson et al., 1981; Sukup et al., 1982; Morey et al., 1980 and 1982; Richey et al., 1980). Steffgen (1974) observed that the 540 million tons of agricultural wastes produced in 1970 in the USA, if converted to fuel oil, could have replaced more than half the fossil fuels needed to generate electricity, or could have replaced all the natural gas and fuel oil used that year for generating electricity. Burwell (1978) noted that 303 million tons of cereal straw and corn stalks/cobs could have supplied about 5.5% of the 71.x10⁹ GJ of energy used by the USA in 1975.

In making these estimates, Steffgen (1974) and Burwell (1978) did not account for the residues that are needed to conserve soil fertility. If this factor is accounted for, the total energy available is much less than the above estimates. Agricultural biomass can be converted to oil by liquefaction, to gas by hydrogasification or pyrolysis, and to alcohol by fermantation. It can also be directly converted to thermal energy by combustion. The combustible energy value of biomass is relatively high and has, therefore, been a subject of considerable research (Pimentel et al., 1981; Helsel and Wedin, 1983).

Before discovery of fossil fuels, wood was the principal fuel for mankind. As recently as 1900, wood accounted for 25% of the total US energy supply; by 1976 it provided less than 1.5% (Fisher, 1976). By comparison, 8% of Sweden's and 15% of Finland's energy needs were met by wood in 1977 (Merril and Gage, 1978). Biomass is still the major source of energy in Third World countries, especially in rural areas.

One ton of shelled corn produces about 0.25 tons of corncobs. Depending on the efficiency of combustion and the design of the drying system, corncobs from 0.25 ton of shelled corn can dry one ton of corn from 26 to 15.5% wet basis* (Richey et al., 1980). Thus, if all the corncobs are collected, they can be converted to enough energy to dry the entire US corn crop and also provide thermal energy for other farm applications such as heating of buildings and processing of other crops.

During periods of low grain prices, the grain may have a greater value as a fuel than as a feed or food. Of the corn crop, 3 to 5%

*All moisture in this thesis are stated on a wet basis unless otherwise indicated.

can provide enough energy to dry the remainder of the crop with an efficiently designed combustion system (Morey and Thimsen, 1980).

The forest products industry derives 45% of its total energy need from burning bark and mill wastes. Much of the wood waste is not utilized and is thus available to nearby farms. It may be also practical to set aside some land for biomass fuel production. Commercial forests for fuel is another possibility (Stobaugh and Yergin, 1980).

Incineration of biomass for crop drying requires a well designed furnace to ensure complete combustion. Incomplete combustion may cause undesirable odors', discoloration and contamination of grain (Anderson et al., 1981; Hütt and Winkler, 1978; Jacko et al., 1982; Joe et al., 1982). Thus, development of efficient and clean burning solid fuel combustion systems is an important step in increasing the utilization of crop and residue materials for heat energy.

1.4 Grain Production and Storage in Kenya

Cereal grains, in particular corn and legumes, constitute the staple food for most Africans, including Kenyans. Cereals are grown by "small scale" (under 20 hectares) and "large scale" (over 20 ha) farmers under different ecological, social-economic, environmental and technological conditions. The production problems are many and varied.

Large scale farmers produce grains almost entirely as cash crops and usually have the equipment and the know-how to handle the crops more efficiently than the small scale farmers. The latter, depending on how "small" they are, produce grains for home consumption and for cash if they have a surplus. Some grain is consumed fresh

before it matures and the rest is stored for seed and for future consumption. Small scale farmers face major problems in drying, cleaning, and storage of grains.

Handling practices vary from place to place within Kenya. Some farmers, especially the small scale ones, harvest unhusked ear corn and suspend it from trees or place it over fires in their homes or on special platforms. The latter method is an example of utilization of biomass energy for crop drying, especially along the coastal region of Kenya. In other regions traditional granaries are found in which unhusked or dehusked ear corn is kept for natural drying. The granaries vary in size, in accessability for inspection, in cleaning and removal facilities, and in the degree of protection they offer from insects, rodents, and the weather. Some corn is sun-dried (either as ear-corn or shelled grain) by spreading it on mats, or on the ground.

Solar drying may be economical, but is risky due to uncertainties in the weather, and in the labor availability for handling. Therefore, most farmers leave the crops in the field to dry naturally, and harvest when the grain is sufficiently dry (16 to 18%) for solar drying. This results in field infestation by insects and molds, and consumption by birds and rodents. Also, the land preparation for the next crop is delayed. To avoid the delay, some farmers cut the corn stalks and stack them in 2 to 4 meter diameter conical stacks and leave them in the field to dry for up to four months.

Long-term storage of grain is undertaken by the Kenya Cerals Board (a Kenya government agency). The Board is in charge of drying

and storage of cereal grains for the purpose of price stabilization and for emergency needs (such as occur during a drought). In 1981 the Board handled about 20% of the total Kenyan corn production of 500,000 metric tons. The remainder is handled by individual farmers or cooperatives. The Board buys grain from farmers at a specified standard quality and government price.

For long-term strategic storage (up to 3 years), the Board uses Cyprus bins. A Cyprus bin is an oval-shaped concrete structure which is constructed halfway underground. Corn is dried to 12% before it is placed in a Cyprus bin. The capacity of a typical Cyprus bin is about 250 tons. For short-term storage, corn is stored at 13% moisture in 90 kg bags in masonry sheds.

According to FAO (1982), the Kenyan corn production was 1.45 million metric tons in 1979; in 1980 it was 1.75 million tons and in 1981 2.20 million tons. The average annual grain losses on smallscale farms were estimated at 16%. This amounts to a monetary loss in Kenya of approximately \$42 million annually (MAO, 1981). There are also health hazards caused by aflatoxin contained in moldy grain (Anderson and Pfost, 1978).

Most of the grain losses in Kenya occur during storage. Insect damage is the most severe problem. Artificial drying is essential in the surplus-producing areas with high rainfall. Long-term storage conditions are most favorable at the higher altitudes due to the low temperatures and low relative humidities. Judging from the available literature on grain drying and storage in Kenya, it appears that the

current storage facilities and practices do not provide the necessary grain protection from insects and molds. Since the most severe insect and mold infestation occurs in the field, it is reasonable to assume that earlier harvesting and artificial drying can contribute substantially in minimizing the losses.

Kenya has no fossil fuel or mineral resources. It is, therefore, necessary to design grain drying systems that are effective, inexpensive, energy (fossil fuel) efficient and made of locally available materials. Such systems must utilize renewable biomass energy sources, such as crop residues and wood. Since biomass waste and wood are also used for domestic energy needs, there is a special need in Kenya to design efficient biomass combustion furnaces for grain drying.

1.5 Objectives

The general objective of this research is to design a direct fired vortex-cell biomass furnace and incorporate the unit in an existing on-farm grain drying system. The specific objectives are:

- To develop, build, and test a prototype of a directfired combustion, concentric vortex-cell biomass furnace for on-farm grain drying.
- To demonstrate the feasibility of the furnace as a technical alternative to LP gas and natural gas burners for on-farm grain drying.
- To integrate the furnace into a commercial in-bin counterflow drying system.

- To test commonly available (in Michigan) renewable biomass fuel sources such as wood chips and corncobs.
- To determine the safety aspects of the biomass furnace with respect to chemical absorption of smoke constituents by the grain.
- To determine the economics of drying with biomass energy.
- 7. To model semicontinuous in-bin counterflow grain
- 8. To model a concentric vortex-cell biomass furnace.

CHAPTER 2

LITERATURE REVIEW

2.1 Biomass Furnaces for On-Farm Grain Drying

Since the early 70's many investigations have been conducted on the use of biomass energy for grain drying and other farmstead operations. Most research has been directed towards the study of direct combustion systems for converting crop residues and processing wastes into thermal energy. Two main categories of combustion systems are found in the literature: direct-combusion systems, and gasification-combustion systems.

Studies on collection and direct-combustion of cobs and corn stover have been conducted at Iowa State University since 1975 (Kajewski et al., 1977; Claar et al., 1980b; Anderson et al., 1981; Wahby et al., 1981; Sukup et al., 1982; Anderson et al., 1983). A direct-combustion incinerator-type furnace burning cobs was developed by Pioneer Hi-Bred for drying ear seed-corn (Dahlberg, 1977). Seed Grains, Inc., also developed a corncob-fired furance (Claar et al., 1980b).

Crop residue burners have been marketed by several companies in the USA (Moraczewski, 1980), in Germany (Strehler, 1976), and Canada (Peill, 1980).

In all the furnaces referred to above, biomass is converted into thermal energy by direct-combustion. In direct-combustion

furnaces there is no distinct separation of the pyrolysis and combustion processes. Both processes occur in the same physical combustion chamber.

Gasification of biomass to produce producer gas, which is subsequently burned to provide energy for crop drying, has been studied at the University of Minnesota (Morey et al., 1980; Morey et al., 1982); at Purdue University (Foster et al., 1982); at Clemson University (Payne et al., 1981); at the University of Florida (Shaw et al., 1982); and at the University of Kentucky (Payne et al., 1980). No commercial units are, as yet, being marketed in the USA.

2.1.1 Major Products of Combustion

The major products of combustion of biomass fuels are heat, exhaust gases, and ash; the products of incomplete combustion of the fuels are tar and char.

The amount of heat released in combustion depends upon the heating value of the fuel. The heating value is determined by measuring the enthalpy change between reactants (fuel and oxygen in air) and products at 25°C in an adiabatic bomb calorimeter. The heating value is reported as the higher (gross) heating value (HHV), or the lower (net) heating value (LHV). The HHV represents the heat of combustion if the water vapor produced is condensed to a liquid at 25°C. The LHV is the heat of combustion when the water remains as vapor. The LHV is lower than the HHV because the latent heat of vaporization is not recovered. Heating values are reported in both wet and dry fuel basis. The unit of the heating values is kJ/kg of fuel.
The gaseous products of biomass combustion include CO_2 , H_2O , CO, N_2 , and traces of NO and SO_2 . If the oxygen level is low, the gases may contain tar. (Tar is a mixture of volatile hydrocarbon liquids (or vapors at elevated temperatures) produced by destructive distillation of biomass.) The gases appear as smoke if soot is present. <u>Soot</u> consists of a fine dispersion of black particles, chiefly carbon, produced by the incomplete combustion of hydrocarbon fuels. Thus, smoke is a vaporous mixture containing soot (and other unburned particles), water and tar vapors, and the other gases resulting from incomplete combustion.

<u>Char</u> (charcoal) is a black carbonaceous solid residue left after most of the volatile compounds, such as tar and water vapor, have been distilled from biomass fuels as a result of incomplete combustion or anaerobic heating. The char can be burned in oxygen releasing heat, CO₂, and ash.

<u>Ash</u> is the uncombustible residue (after complete combustion) consisting of a mixture of inorganic compounds. At high temperatures (above 750°C) the ash melts into a liquid, which, upon cooling solidifies into a glassy solid called <u>slag</u> (or clinker). Slag is undesirable in furnaces because it may clog grates and air supply openings.

2.1.2 Design Criteria for Biomass Furnaces

Claar et al. (1981) considered the following factors to be of significance in the design of a biomass furnace:

 The furnace should be able to supply heat for several farmstead applications.

- The furnace should be capable of handling several biomass fuel types.
- 3. The furnace system should be of simple construction.
- 4. The furance should require minimum labor
- 5. The furnace should be easy to control and maintain.
- The furnace should provide favorable combustion characteristics.

The last requirement (6) is the most difficult to achieve and the most critical. Incomplete combustion may cause contamination (with hazardous compounds) and discoloration of the grain when flue gases are used directly for drying the grain. If a heat exchanger is . used, it can become clogged by products of incomplete combustion.

2.1.3 Direct-Combustion Biomass Furnaces

There are four main types of direct-combustion furnaces employed in grain drying systems: (1) the cell furnace, (2) the vortex furnace, (3) the sloping grate furnace, and (4) the cyclone furnace. The design features and performance characteristics of these furnaces are discussed in the following sections.

2.1.3.1 The Cell Furnace

The cell furnace was originally developed to burn sugarcane bagasse, and later modified to burn wood. The furnace consists of a firebrick-lined cylinder with primary and secondary air supplied through tangential ports in the wall (see Figure 2.1). Buchele et al. (1981) have described the principle of operation of the cell furnace.



Figure 2.1. The Cell Furnace.

The distinguishing feature of the cell furnace is that fuel enters the furnace at the point of the greatest turbulence, usually near the top of the furnace. Fine fuel particles are separated from the heavier ones and are burned in suspension. The heavier particles fall onto the fuel pipe on the hearth at the bottom of the cell. Primary air is introduced to the pile of fuel in the hearth through many small ports in the refractory wall. The air and heat rapidly penetrate the pile (since there are no fine particles), and rapid drying and combustion takes place. The middle of the furnace consists of a restricted throat around which secondary combustion air is introduced through tangential ports producing a swirling turbulent action that intimately mixes the fuel and the air.

The cell furnace is suitable for burning chopped fuels such as wood chips and corncobs. The heat release is about 5 GJ/h-m² of grate area (Claar et al., 1981).

2.1.3.2 The Vortex Furnace

The vortex-type furnace has been a subject of considerable research at Iowa State University (Buchele et al., 1981; Wahby et al., 1981; Claar et al., 1981; Anderson et al., 1983). The vortex-type furnace consists of two chambers, one above the other. The lower chamber dehydrates and gasifies the pile of biomass which may be placed on a solid hearth or on a grate (see Figure 2.2). The char remaining after gasification is burned in the lower chamber. The volatile gases are completely burned in the upper chamber.



Figure 2.2. Vortex Furnace (from Claar et al., 1981).

To enhance complete combustion, air is introduced in the combustion chamber through tuyeres located tangentially in the wall of the furance. This creates a vortex spiral which causes the flame to have a turbulent and tight spiral. Thus, any unburned material or fly ash is centrifugally separated from the flame spiral, and thrown back onto the burning pile.

The wall of the furnace is lined with firebricks for insulation. The fuel is fed onto the hearth (or grate) by a side-mounted feed auger. The heat output and the flue gas temperature are controlled by regulating the fuel feed rate and the combustion air flow rate.

The Iowa State University (Claar et al., 1981) furnace is fabricated from two concentric steel cylinders. The inner cylinder is lined with firebricks. Combustion air is blown into the space between the two cylinders, and thus, preheated before entering the combustion chambers.

The heat release capacity of vortex furnaces is $5-9 \text{ GJ/h-m}^2$ of grate area depending on the overall combustion efficiency, the fuel type, the feed rate, the condition of the fuel, and the insulation of the furnace (Claar et al., 1981; Kenzler et al., 1982).

2.1.3.3 The Sloping Grate Furnace

The sloping grate furnace consists of a firebrick-lined combustion chamber (see Figure 2-3). The fire hearth is made of an inclined grate which supports the fuel during drying and combustion. The fuel is continuously introduced into the furnace at the top part



Figure 2.3. European Sloping Grate Principle (MacCallum, 1979).

of the grate. The fuel is dehydrated as it passes over the upper section. It then descends into the lower burning section. The ash is continuously removed from the lowest part of the grate. About 75-80% of combustion air is intrdouced under the grate (MacCallum, 1979); the 20-25% is introduced through tuyeres located at the burnout arch.

The sloping grate furnace is only suitable for boilers with heat exchangers (due to a fly ash problem). It has been modified for crop drying by introducing extra secondary combustion air above the grate (as in a vortex furnace) and by minimizing the undergrate primary combustion air (Buchele et al., 1981). The furnace can burn relatively high density wet (55-70% wb) fuels such as wood chips and corncobs. Straw and husks are not suitable since they are blown off the grate before complete combustion

Heat release of large sloping grate furnaces used in boilers is about 8-10 GJ/h-m² depending on the fuel used and its moisture content (MacCallum, 1979).

2.1.3.4 The Cyclone Furnace

A cyclone-type furnace has been developed in India (Singh et al., 1980). The furnace was designed to burn rice husks and generates heat for heating grain drying air, or for generating steam (in a boiler for parboiling paddy in the rice mill).

The cyclone furnace consists of a combustion chamber and a cyclone chamber (see Figure 2.4). The combustion chamber is fabricated from an oil barrel (55x140 cm) with a 40 degree conical bottom. An



Figure 2.4. Schematic Diagram of a Husk Fired Cyclone Furnace (Singh et al., 1980).

exit pipe at the cone bottom provides the outlet for the flue gases. The ashes are trapped at the bottom of the cone and are continuously removed.

The cyclone chamber consists of a cylinder (40 cm diameter and 70 cm long) mounted on the side of the combustion chamber and inclined at an angle of 30°. The rice husks are blown tangentially into the cyclone chamber by an air blower. The husks are thus kept rotating throughout the combustion chamber. The husk-air mixture is ignited by an oil burner.

The cyclone furnace is suitable for burning rice husks, chopped straw and other finely ground materials. The heat release is similar to that of the vortex furance $(5-9 \text{ GJ/h-m}^2)$.

2.1.4 Gasification-Combustion Furnaces

The direct heating of dryers with the exhaust flue gases from biomass combustion requires clean and complete burning to avoid contamination of the grain. Direct-combustion of biomass materials may result in smoke and fly ash. Gasification of the biomass to producer gas is a viable alternative to direct burning.

Richey et al. (1980) listed four advantages of gasification compared to direct-combustion furnaces:

- Minimum pollution of air without the use of heat exchangers.
- More efficient conversion of biomass to heat energy (80-90% of the energy is recovered).

- Low combustion temperatures (650-850°C) compared to direct-combustion (1000-1100°C), thus reducing the cost of construction materials and also reducing the formation of slag.
- Easier control of the combustion rate (by regulating primary airflow).

Biomass is gasified by burning the material with limited air to produce "producer" gas consisting of CO, H_2 , and some CH₄. The gas contains impurities such as CO₂, water vapor, and nitrogen. The heating value is 37,452 kJ/m³ compared to 37,260 kJ/m³ for natural gas (Richey et al., 1980).

The major experience with biomass gasification has been gained during World War II when West European countries could not obtain petroleum products. Portable gasifiers using charcoal and wood chips were used to power motor vehicles and tractors. These units had power output equal to approximately 75% of their gasoline rating (SERI, 1979).

It is possible to burn producer gas in a conventional dryer burner without visible smoke or particulates. However, it is difficult to avoid condensation of tar as the gas cools (Payne et al., 1980). Therefore, most investigators report that the gas should be burned in a combustion chamber attached to the gasifier unit (Richey et al., 1980; Payne et al., 1980, 1981; McCoy et al., 1981; Morey et al., 1980, 1981; Richey et al., 1981).

Gasifiers are either of the updraft or downdraft type. In the updraft design (Figure 2.5), solid fuel is intrdouced at the top of





the gasifier and is supported on a grate at the bottom. The fuel is ignited at the bottom of the pile on the grate. Air is forced upward through the grate, supporting partial combustion on the grate. The producer gas is collected at the top. The unburned fuel acts as a filter for particulates entrained within the gas. Updraft gasifiers of up to 9.5 MJ/h have been developed by seed companies to utilize corncobs as a fuel for drying the corn (Zink et al., 1982).

In downdraft gasifier systems, the air is blown from the top (or the sides) of the fuel chamber as shown in Figure 2.6. Combustion takes place in the funnel shaped bottom with the pyrolysis gases passing down and out through the high-temperature char. The high temperature cracks the tars into stable gases. The system is more suitable for internal combustion engines (Richey et al., 1981) and for grain drying systems in which the producer gas is burned in a gas burner (similar to a propane gas burner).

In cross-draft gasifier systems, the air intake is through a horizontal nozzle in one side near the bottom of the chamber. The gas exists through a vertical grate in the opposite side. The burning zone is adjacent to the air nozzle (Richey, 1980).

Srivastava and Posselius (1981) applied dimensional and similitude modeling to develop scaling laws for biomass gasifiers. Their techniques can be applied to direct combustion furnaces.

2.1.5 Direct-combustion Versus Gasification-Combustion Systems

Judging from the literature available, no comparative study has been conducted on the engineering performance and/or the economic



feasibility of direct-combustion and gasification-combustion systems for grain drying. It has been postulated that gasification systems have several advantages over direct-combustion. The advantages include (1) minimum air pollution due to low particulate emissions and complete combustion, (2) more efficient conversion of biomass to heat, (3) lower combustion temperature and thus, lower construction cost, and (4) more effective control of combustion rate. According to a study by Barrett et al. (1981), there is no significant difference between heat recovery efficiency and particulate emission from a direct-combustion (concentrix vortex-cell) furnace and two types of gasification-combustion furnaces (a down- and an up-draft furnaces).

Gasification is not absolutely essential for crop drying installations when the heat is required in situ. The difference between the direct-combustion and the close-coupled gasificationcombustion furnaces is the physical distance between the gasification and combustion chambers. In the direct-combustion furnace, biomass is dehydrated and gasified at the bottom of the furnace; secondary combustion of the gases starts immediately above the gasification section and continues throughout the secondary chamber. In the close-coupled gasification-combustion process the gases are burned in a second combustion chamber attached to the gasification chamber.

A well designed concentric vortex-cell furnace is more efficient than a gasification system since there is less heat loss between the gasification and combustion sections. For internal combustion engines and for replacing natural or LP gas systems for domestic or other similar uses, gasification systems are superior.

2.1.6 Emissions from Biomass Furnaces and Grain Contamination

During the drying process the products of combustion are usually introduced directly into the grain. Some compounds may be retained by the grain through condensation or absorption.

The relevant combustion products are CO_2 , CO, H_2O , aldehydes, ketones, polycyclic (or polynuclear) aromatic hydrocarbons (PAH), SO_2 , SO_3 , NO, N₂, soot and suspensions of heavy metals. The soot and other particulates absorb high quantities of the other combustion compounds including PAH (Winkler, 1977, cited by Hütt et al., 1978). The quantity and specific types of combustion compounds depend on the fuel used, and on the completeness of the combustion process. Solid fuels, which have not undergone a coking process, have long carbon chains and thus, produce more hydrocarbons than gaseous fuels (Hütt et al., 1978).

The PAH are the most critical compounds. Souci (1968) and Hangebrauck et al. (1964) reported that benzo [a] pyrene, benz [a] anthracene, dibenzo [a,h] anthracene, benzo [a] anthracene and benzo [a] pyrene have shown some carcinogenic activity in test animals. Hutt et al. (1978) identified 15 PAH compounds on corn dried with direct heaters using different commercial fuels. Contamination levels were on the order of 0 to 3 parts per billion (ppb) for well operating fuel burners. Maladjusted burners resulted in considerably higher concentrations. More recently, Joe et al. (1982) detected 11 PAH compounds in artificially dried barley malt. The PAH concentrations in the malt varied from 0.1 to 1.5 ppb (except for phenanthrene which showed a concentration of 2.1 ppb). Hutt and Winkler (1978) detected a benzo [a] pyrene (BaP) concentration of 0 to 0.61 ppb in 21 samples

of freshly harvested corn; they concluded that corn may contain trace PAHs prior to drying when grown near major highways or industrial plants.

Most of the grain dried in the USA is used for livestock feed. Thus, the risks to human beings is minimal. According to the Deutsche Forschungsgemeinschaft (1976), the extent to which PAHs from contaminated animal feeds are transferred into meat for human consumption is not clear.

According to Lijinsky and Ross (1967), a charcoal broiled steak may contain 50 ppb BaP, depending on the temperature and the type of fuel used in the broiler. Smoked foods contain from trace up to 6.6 ppb of BaP (Santodonato et al., 1980). Thus, it can be concluded that smoked and charcoal broiled foods may contain higher levels of carcinogenic and other PAH compounds than grain dried with well-designed and well-operated direct-heated biomass fueled grain dryers.

Jacko and Barrett (1981) described the equipment and procedures for determining particulate concentrations and size distributions in the exhaust gas streams of biomass furnaces. Barrett et al. (1981) compared the particulate emissions in biomass furnaces with those in LP gas burners; average emission was 0.19 kg/h from biomass furnaces, and 0.00028 kg/h from LP gas burners.

2.2 Biomass Combustion Theory

Biomass is any material derived from growing organisms. The energy contained in the biomass is stored in plants by the photosynthesis process. Combustion of biomass materials is one of the

bioconversion processes whereby the biomass energy is transformed into usable energy. All biomass materials found on farms such as wood, grain, straw, corncobs, etc., are potential sources of energy. Wood and corncobs are the most commonly used biomass fuels due to their favorable combustion and transportation characteristics (Buchele et al., 1981).

The theory on biomass combustion is related to the theory of combustion of coal and wood. It should be noted that the coal combustion mechanism is different from that of wood due to the different aging processes and high volatile component contents of wood and coal.

2.2.1 The Properties of Biomass Relevant to Combustion

The structure, physical and thermal properties, and chemical composition of biomass materials influence their utility as a fuel feedstock. The literature on the properties of wood and corncobs will be reviewed since these materials are the principle fuels used as energy sources for on-farm crop drying.

2.2.1.1 Chemical Properties

Combustion is an oxidation process by which carbon is oxidized to carbon dioxide, and hydrogen is oxidized to water. Combustion of biomass materials consists of a series of chain reactions. The exact pathways of the reactions are determined by the structure of the combustible molecules. The structure determines the location and accessability of the carbon and the hydrogen by the oxygen. Also, the

higher fuel heating value is affected by the carbon content of the fuel (Graboski and Bain, 1979).

The major chemical constituents of wood and corncobs are cellulose, hemicellulose and lignin (Tillman et al., 1981). The proportions of the constituents depend upon the species of the wood. Generally, softwoods have 40-45, 24-37, and 25-30% (dry basis) cellulose, hemicellulose and lignin, respectively. Hardwoods contain 40-50, 22-40, and 10-38 percent of these compounds, respectively (Shafizadeh and DeGroot, 1976). Thus, hardwoods generally have a higher hemicellulose and a lower lignin content and sometimes a slightly higher cellulose content; the cellulose percentage in both types of wood is similar.

Foley and Hooven (1981) determined the proportions of cellulose, hemicellulose, and lignin in corncobs. Their analysis included other compounds such as xylan, pectins, and hexogan, and also the distribution of these compounds in the woody and pith/chaff portions of the corncobs. Corncobs contain (on the average) 40, 36, and 6 percent cellulose, hemicellulose and lignin, respectively, on a dry basis. The exact proportions of these compounds differ among the different varieties of corn.

In addition to the cellulose, hemicellulose and lignin, wood and corncobs contain extractable compounds such as volatile oils (terpenes and sesquiterpenes), resins and fatty acids, pigments, and water soluble carbohydrates (starch, simple sugars, and organic acids). Wood and corncobs with a high extractive content have higher heating values (see Table 2-1) (Tillman et al., 1981). The nature and quantity

Fuel	Volatile matter	Fixed carbon	Ash	Source
Wood				
Cedar	77.0	21.0	2.0	a, b
Douglas Fir	86.2	13.7	0.1	a, b
Hemlock	84.8	15.0	0.2	a, b
<u>Bark</u>				
Cedar	86.7	13.1	0.2	a, b
Douglas Fir	73.0	25.8	1.2	a, b
Hemlock	74.3	24.0	1.7	a, b
Husklage	59.4	37.8	2.9	с
Corncobs	80.1	18.3	1.6	d
	80.3	18.1	1.6	е
Coal	6.4	81.4	12.2	f

Table 2.1.--Proximate analysis of selected biomass fuels (weight, percent, dry basis).

- a = Howlett and Gamache (1977).
- b = Mingle and Boubel (1968).
- c = Sukup (1982).
- d = Ebeling and Jenkins (1983).
- e = Payne et al. (1980)
- f = Babcock and Wilcox (1978).

of extractables determine the products after pyrolysis and gasification (Graboski and Bain, 1979).

2.2.1.1.1 Proximate and Ultimate Analysis

The proximate and ultimate analysis are terms expressing the chemical-physical characteristics and the chemical composition of a fuel without reference to the physical form in which the compounds appear. The <u>proximate analysis</u> classifies the fuel in terms of its moisture, volatile matter, ash, and fixed carbon contents. Thus, the proximate analysis provides information on the volatility of the fuel. Compared to coal, wood has a larger percentage of volatile matter and a smaller percentage of ash (Tillman, 1980). The proximate analysis of wood and corncobs has been published by several authors (Babcock and Wilcox, 1978; Hewlett and Gamache, 1977; Thimsen and Morey, 1981; Claar et al., 1978; Ebeling and Jenkins, 1983). Table 2.1 presents the proximate analysis for selected biomass fuels.

The <u>ultimate analysis</u> contains the elemental analysis of a fuel. Generally, the percentages of carbon, hydrogen, nitrogen, sulfur, oxygen, ash, and heating values are reported. The composition of wood and corncob fuels is fairly constant. These fuels do not contain sulfur and have very little nitrogen (Claar et al., 1978). Table 2.2 presents the ultimate analysis for selected biomass fuels. The free moisture (above the chemically bound water) in solid fuels results in erroneously high values of hydrogen and oxygen in the ultimate analysis because moisture is detected as additional hydrogen

Fuel	С	Н	0	N	S	Ash	HHV	Source
Wood								
Cedar	48.8	6.4	44.5			0.37	18.0	a
Douglas Fir	52.3	6.3	40.5	0.1		0.08	21.1	à
Hemlock	50.4	5.8	41.4	0.1	0.1	2.20	20.1	a
Average	50.5	6.2	42.1	0.1		0.88	19.7	-
<u>Bark</u>								
Douglas Fir	56.2	5.9	36.7			1.20	22.1	a
Corncobs	46.7	5.8	44.8	0.5	0.2	1.60	18.7	b
	47.6	6.0	44.2	0.5	0.1	1.63	18.6	с
	46.4	6.1	44.0	0.3	0.1	2.85	18.6	d
	46.6	5.9	47.1	0.4		1.60		f
Average	46.8	6.0	45.0	0.4	0.1	1.92	18.7	-
Coal	82.1	2.3	2.0	0.8	0.6	12.20	30.8	е

Table 2.2.--Ultimate analysis (percent dry basis) and higher heating values (MJ/kg) of selected fuels.

a = Tillman (1978).

- b = Ebeling and Jenkins (1983).
- c = Payne et al. (1980).
- d = Sukup (1982).
- e = Babcock and Wilcox (1978).
- f = Thimsen and Morey (1981).

and oxygen. Thus, the ultimate analysis is performed on dehydrated fuel and reported on a dry basis.

The carbon content of biomass materials is lower than of coal while the atomic carbon to hydrogen ratio is much higher in coals than in biomass materials (Graboski and Bain, 1979). The bound oxygen content of biomass materials is considerably higher due to alcohol groups in the cellulose, hemicellulose, and lignin fractions of the biomass (Kirk and Othmer, 1963). Thus, biomass materials have lower heating values than coal. The heating values of most biomass materials is in the range of 15-25 MJ/kg of biomass dry matter.

As stated previously, the nitrogen and sulfur contents of biomass are considerably lower than of coal. Therefore, sulfur and nitrogen pollutants resulting from direct-combustion of biomass are small enough to meet EPA standards (Graboski and Bain, 1979).

The ultimate analysis can be used to calculate the empirical chemical formula of a fuel. The formula is useful in developing combustion equations, calculating the stoichiometric air required for combustion, and predicting the airborne emissions. The fuel higher heating value can also be predicted using the ultimate analysis. Several authors have proposed empirical equations for predicting the higher heating value of biomass fuels using the ultimate analysis:

Tillman (1980):

$$HHV = 0.475C - 2.38$$
 (2.1)

Dulong-Bertholot (Spiers, 1962):

$$HHV = 0.475C + 1.44H - 2.9 * 10^{-4}(N + 0) + 0.0935$$
 (2.2)

Institute of Gas Technology (1978):

$$HHV = 0.34C + 1.32H + 0.069 - 0.12(N + 0) - 0.015As \quad (2.3)$$

Where HHV is the higher heating value in MJ/kg dry matter, and C, H, N, O, and As are the percentages (dry basis) of carbon, hydrogen, nitrogen, oxygen, and ash as given by the ultimate analysis of the fuel.

According to Graboski and Bain (1979), equation (2.3) is preferred for estimating higher heating values.

The proximate and ultimate analyses are determined using the American Society for Testing Materials (ASTM) Standard numbers D-3175-73, D-3175-77, and D-3174-73 for the proximate analysis; and numbers D-3178-73, D-3177-75, and D-2361-66 for the ultimate analysis; number D-3286-77 for the higher heating value; and number D-3683-78 for the ash analysis (Institute of Gas Technology, 1978).

2.2.1.2 Biomass Physical and Thermal Properties

The combustion mechanisms (the chemical reaction process as determined by the reactants, their kinetics, chain reactions, and equilibrium) of biomass materials depend upon their physical and thermal properties and in addition upon their composition and heating values. The relevant properties are: moisture content, thermal conductivity, specific heat, heat capacity, density (as related to void volume), and particle size distribution. The moisture content of a biomass fuel is a most important property because it affects the net heating value of the fuel, the heat recovery, the combustion efficiency, and the quality of the flue gases. The other physical and thermal properties, and to some extent the chemical properties, are also influenced by the moisture content (MC). Table 2.3 shows the effect of wood MC on the heat recovery and combustion efficiency.

Moisture content (%)	Recoverable heat ^b (MJ/kg)	Combustion efficiency (%)
0.0	16.51	82.5
4.8	16.37	81.8
13.0	16.08	80.4
20.0	15.80	78.9
28.6	15.36	76.8
42.9	14.37	71.8
50.0	13.65	68.2
60.0	12.22	61.1
71.4	9.35	46.7

Table 2.3.--The effect of moisture content on heat recovery and combustion efficiency of wood.^a

^aFrom Bliss and Black (1977).

^bTheoretical values based on a maximum heating value of 20 MJ/kg, an initial wood and air temperature of 17.0°C, and 50% excess air.

Wood, corncobs, and other biomass materials are hygroscopic. They absorb and desorb water depending upon the moisture content, the relative humidity and the temperature of the surrounding air, and the

inherent moisture retention capacity. Skaar (1972) and the USDA Forest Products Laboratory (1974) reported the maximum moisture contents of different wood species in the heartwood and sapwood parts of a tree. Softwoods contain 23% to 46% and 52 to 71% maximum moisture in the heartwood and sapwood, respectively. The maximum moisture contents in the hardwoods are 31 to 62% in the heartwood, and 30 to 59% in the sapwood. The data of Skaar (1972) indicate that the difference in moisture content between heartwood and sapwood is quite pronounced in the case of softwoods, but is less significant in hardwoods. The moisture content is higher in the sapwood than in the heartwood in the case of softwoods. For hardwood the MC of the heartwood can be higher than that of the sapwood in some trees. The moisture content of sapwood varies depending on the region and site of the tree, while that of the heartwood is fairly constant throughout the year due to the restricted movement of water. After a tree is harvested and chipped, its moisture content is in equilibirum with the environmental conditions.

According to the data of Foley and Hooven (1981), the MC of the woody portion of corncobs is higher than the pith/chaff portion. The moisture content of corncobs varies among varieties and the harvest corn kernal moisture content.

Tillman et al. (1981) proposed the following equations for predicting the energy required for drying wood:

$$q_{1} = (1-M)(100-T_{f})(C_{d})(W_{f})$$
(2.4)

$$q_{2} = M(100-T_{f})(C_{W})(W_{f})$$
 (2.5)

$$q_{3} = M(H_{fg})(W_{f})$$
 (2.6)

$$q_{\mu} = M(H_{W})(W_{f})$$
(2.7)

$$C_d = [1.11 + 4.82 \times 10^{-3} (T_{ave} - 273)]$$
 (2.8)

$$Q_{\text{total}} = q_1 + q_2 + q_3 + q_4$$
 (2.9)

Where M is the moisture content of the wood (decimal); T_f the temperature of the fuel (K); C_d the specific heat of dry wood (kJ/kg°C); C_w the specific heat of water (4.174 kJ/kg°C); W_f the weight of wet wood (kg); H_{fg} the heat of evaporization ow water (kJ/kg°C); H_w the heat of wetting (kJ/kg H_2^0); T_{ave} the average between the initial and the final wood temperature (K) and Q_{total} the total energy needed to evaporate water from wood (kJ/kg).

The total energy for evaporating water from maple wood at 50% MC and initially at 25° C is 1.36 MJ/kg if the wood is heated to a final temperature of 100° C.

Stamm and Loughborough (1935) determined the heat of wetting of wood (35.8-14.3 kJ/kg at a MC of 4-12 percent and 9.5-2.4 kJ/kg at a MC of 12-30 percent).

Knowledge of the thermal conductivity of wood, corncobs, and other biomass materials is necessary for modeling pyrolysis, gasification, and combustion. The thermal conductivity is a function of temperature, spatial direction, and the major constituents including moisture, cellulose, hemicellulose, and lignin. The available thermal conductivity data for wood are given in Table 2.4.

Wood type	Temperature °C	Conductivity W/m°C
Cypress, across grain		0.097
Pine, with grain	21.1	0.346
Oak, across grain	15.0	0.208
Fir, with grain	23.9	0.109
Maple, across grain	50.0	0.190
Pine board	43.3	0.102

Table 2.4.--Thermal conductivity of selected wood species.

Sources: cypress: Handbook of Chemistry and Physics (1966). pine, oak, and maple: McAdams (1954); Gray et al. (1960). fir: Chapman (1974).

As can be seen in Table 2.4, the available thermal conductivity data are limited to the 15 to 50°C range. Thermal conductivity data at higher temperatures at which pyrolysis and gasification occur are lacking in the literature. Moreover, the available data do not include the moisture ranges for which the thermal conductivity values were measured. Thus, if thermal conductivity values are to be used in modeling pyrolysis or gasification during combustion, reliable data over the actual range of combustion conditions must be developed. Several specific heat equations for wood at temperatures up to 100°C have been proposed. Beall (1968), Wenzel (1970), and Skaar (1972) developed the following equations:

Beall (1968): (2.10)

$$C_f = 1.085 + 0.409*M + 2.535*10^{-3}*T + 5.45*10^{-4}*M*T$$
 (2.10)
Wenzel (1970):
 $C_d = 1.11 + 4.82*10^{-3}*T$ (2.11)
Skaar (1972):
 $C_f = C_d (1.-M) + 4.19*M$ (2.12)

Where C_f is the specific heat of wet wood (kJ/kg°C); C_d is the specific heat of dry fuel (kJ/kg°C); M is the moisture content (decimal); and T is the wood temperature (°C).

As with the thermal conductivity, no references were found for the specific heat and heat capacity of biomass materials for the temperature range needed for pyrolysis and combustion. Hearmon and Burcham (1955), cited by Mohsenin (1980), suggested that the specific heat of wood, with or without moisture, does not depend greatly on species.

Equations (2.10) and (2.12) do not give the same values of the specific heat of wood, given the same temperature and moisture. For wood at 50°C and 20% moisture, equation (2.10) gives the specific

value of 1.3 kJ/kg°C; equation (2.12) gives a specific value of 1.9 kJ/kg°C at the same condition.

The density of biomass fuels is required for determining the energy content of the fuels on a volume basis. There are three ways of defining the density of biomass. Bulk density refers to the weight of a mass of material packed in a given container divided by the container volume. Apparent (or unit) density is the weight of each unit of the material divided by the volume of the unit; the pore space within each of the unit is included. True (or solid) density refers to the weight per unit volume of the solids within each unit of the material. All three are used to report the density of biomass materials. The density of biomass depends upon the nature of the material, its moisture content and degree of compaction. Unprocessed oven-dry wood, with 7 to 8 percent moisture, has an apparent density of 641 kg/m³ (hardwoods) and 449 kg/m³ (softwoods). High moisture content wood can have an apparent density as high as 961 kg/m³ (Graboski and Bain, 1979).

According to Tillman et al. (1981), the density of wood varies among different trees of the same species and also within the same tree. It increases from the pith to the bark, decreases with increasing height, and varies within the same growth ring.

The apparent density of wood, corncobs, and other biomass materials varies with moisture content. Graboski and Bain (1979) proposed the following relationship between the moisture content M (decimal wet basis, as given by the biomass proximate analysis), and

the dry and the wet biomass apparent densities, ρ_{ad} and ρ_{ar} respectively:

$$\rho_{ad} = (1.-11)\rho_{ar}$$
 (2.13)

The thermal and the physical properties of most farm wastes including corncobs, corn husks, and wood chips are unavailable in the literature. Due to the inherent nature of biomass, their properties are characterized by a wide variability.

2.2.2 The Process of Biomass Combustion

Biomass materials contain a variety of chemical constituents, some of which are not combustible (inert), such as water and inorganic ash. The combustible constituents include volatile hydrocarbons and nonvolatile carbonaceous and polymeric compounds. The combustion mechanism and the heat and emissions generated in a biomass furnace, depend upon the nature and the proportions of the chemical constituents of the fuel.

The range of combustible biomass materials is very diverse with respect to fuel composition and the state of aggregation. Not only is the chemical composition of biomass fuels variable, but large heterogeneities are usually encountered within the same type of fuel. The particle size and the thermophysical properties also vary between different materials and within samples from the same material. The wide range of chemical composition and physical properties complicates the theoretical analysis of the combustion process of biomass fuels (Edwards, 1974). The combustion process of wood has been studied more extensively than of any other biomass fuel (Junge, 1975; Tillman, 1980; Shafizadeh and Chin, 1977; Tuttle, 1978; Browne, 1958). It will be reviewed to illustrate the combustion processes for biomass materials.

Wood combustion involves the oxidation of the carbon and hydrogen to carbon dioxide (CO_2) and water (H_2O), as shown by the following equations:

$$C + O_2 \rightarrow CO_2 + 32.8 \text{ MJ/kg of C}$$
 (2.14)

$$H_2 + 1/20_2 \rightarrow H_20 + 141.9 \text{ MJ/kg of } H_2$$
 (2.15)

Equations (2.14) and (2.15) are simplifications of a complex series of pathways (involving free radical reactions) in which solids are converted to gases and other solids through solid-phase pyrolysis. Also, the gaseous compounds are converted into radicals by decomposition. The radicals react with each other and with the oxygen in the combustion air (Browne, 1958). While the CO_2 and H_2O are the major final products, there are numerous intermediate radicals and compounds such as OH, CH_2 , C_2H_5 , HOO, CO, etc.

Edwards (1974), and Shafizardeh and DeGroot (1977) simplified wood combustion assuming that the process is characterized by a series of distinct events (or reaction phases): (1) solid phase precombustion reactions, (2) gas-phase reactions, and (3) char oxidation.

The above events and the chemical pathways occurring within them, determine the rate and degree of completion of reactions (2.14) and 2.15), and also the formation of pollutants such as the oxides of nitrogen and polycylic aromatic hydrocarbons (USDA Forest Service, 1982; Chakraborty and Long, 1968).

2.2.2.1 Solid-phase Precombustion Reactions

The precombustion reactions for wood (and for most biomass solid fuels) are the initial processes occurring on the grate of a biomass furnace. The precombustion reactions are heating, evaporation of moisture, and pyrolysis of the dehydrated solid.

2.2.2.1.1 Heating and Drying

Before initiation of the pyrolysis reactions, the water in the solid fuel must be evaporated and the solids heated to the pyrolysis temperature (500-625°C) (Edwards, 1974; Browne, 1958). The heating and drying are endothermic processes. The specific heat of wet fuel is a function of the moisture content and may be estimated by equation (2.12) (Skaar, 1972). Thus, some of the heat of combustion is used to heat and dry the fuel.

The water in the fuel may limit the maximum temperature of the core of individual fuel particles. The heat transfer rate from the surface to the center of the particle depends upon the thermal conductivity of the fuel particles. The thermal conductivity of wood and other biomass products increases with moisture content as indicated by the following equation proposed by the US Forest Products Laboratory (1974):

$$k = [(5.18 + .096*1)S_{a} + .57*F_{vv}] \times 4.18 *10^{-4}$$
(2.16)

where: k = thermal conductivity, W/cm-K
M = mositure content, decimal
Sg = specific gravity
F_{vv} = the fractional void volume, decimal

Thus, moisture increases the rate of heat transfer from the surface to the center of a fuel particle. However, no overall drying or heating rate can be given for wood (and other biomass fuels) since particle sizes and individual particle moisture contents vary dramatically during high-temperature heating (USDA Forest Service, 1982). Also, drying occurs in a very short time, possibly in seconds due to the high combustion temperatures (Tillman et al., 1981).

2.2.2.1.2 Solid-phase Pyrolysis

Pyrolysis is an essential reaction in the solid fuel combustion of basic biomass. Pyrolysis of carbonaceous materials is defined as an incomplete thermal degradation, generally in the absence of oxygen resulting in char, condensable liquids or tars and gaseous products (Milne, 1979). Thus, pyrolysis involves the conversion of basic biomass structures such as cellulose and lignin into more readily oxidizable compounds. Slow pyrolysis occurs when materials are heated in the absence of oxygen at temperatures above 200°C. In biomass furnaces, rapid pyrolysis takes place in the presence of limited oxygen (air) at about 1100°C. Browne (1958) discussed the theoretical course of events in wood combustion preceding pyrolsis. Pyrolysis with and

without oxygen (air) can be presented by the following expression (USDA Forest Service, 1982):

DRY WOOD
$$\rightarrow$$
 CO₂ + CH₄ + C₂H₆ + C₃H₆ + CH₃COOH
+ CH₃CHO + TARS + CHAR (2.17)

Equation (2.17) is a simplification of the complex endothermic and exothermic chemical chain reactions whose pathways and rates depend upon the wood components, the particle size and geometry, the pyrolysis temperature and the heating rate, and the available amount of oxygen. Browne (1958) reported pyrolysis temperatures of 200 to 500°C, and 150 to 400°C in anaerobic and aerobic wood heating, respectively.

The pyrolysis of wood (and other biomass materials) is closely related to the three major components of biomass, namely, the hemicellulose, cellulose, and lignin (Milne, 1979; Antal et al., 1979; Shafizadeh and Chin, 1977). The pyrolysis of biomass has been studied by experimental investigations using each of the three components separately. Shafizadeh and Chin (1977) reported the following pyrolysis temperatures: hemicellulose 220-500°C, cellulose 320-380°C, and lignin 220-500°C. Thus, in pyrolysis the hemicellulose, cellulose, and the lignin fractions react differently.

<u>Holocellulose</u> is the total carbohydrate of wood, which is represented by cellulose and hemicellulose fractions. According to several studies on pyrolysis of pure holocellulose and lignin (Shafizadeh and Chin, 1977; Connors et al., 1980; Shafizadeh and Lai, 1972; Liu et al., 1977; Brink, 1976; Goheen et al., 1976; Prahacs et al., 1971), char,

tar, water, CO_2 , CH_4 , and C_2H_6 are the main products of pyrolysis. The proportions of these products are different for each major component. Lignin yields more char than holocellulose; the latter yields more tar than the former. Examples of the exact products of pyrolysis can be found in the previously cited literature (Fletcher and Harris, 1952; Brink et al., 1973; Fang and McGinnis, 1976; Shafizadeh, 1968).

Milne (1979) suggested that it is reasonable to assume that the pyrolysis of wood is closely related to the three major components of biomass. Several other investigators reached this conclusion although there has not been a quantitative demonstration of the relationship (Antal et al., 1979).

The products from wood pyrolysis are more complex than those from the three major components of wood when pyrolyzed separately. According to Milne (1979), no study has demonstrated that the products of wood are the sum of the products of its components under comparable conditions. Moreover, most pyrolysis studies are conducted in nearly complete exclusion of oxygen. In biomass furnaces, a limited supply of oxygen is furnished to sustain primary combustion. The behavior and the products of pyrolysis under these conditions are not well documented.

The kinetics of wood pyrolysis has been studied by several researchers such as Kanury (1972), Kung (1972), Roberts (1970), and Antal et al. (1979). Most kinetic analyses of pyrolysis are based on heating samples at low temperatures (200-400°C) without oxygen. Thermal decomposition curves are fit using a general equation of the form (Roberts, 1970; Milne, 1979):
$$\frac{\mathrm{d}V}{\mathrm{d}t} = kV^{\mathrm{n}} \tag{2.18}$$

where: $k = Ae^{(-E/RT)}$ (2.19)

$$\frac{\partial \rho}{\partial t} = (\rho - \rho_f) K$$
 (2.20)

where:
$$K = k_{\rho}e^{(-E/RT)}$$
 (2.21)

V and ρ are the fractions of total volatiles and the local density of pyrolysing material, respectively; ρ_{f} is the final density of the pyrolysing material. In the above equations, the activation energy E, and the product factors A, k, and n are not known with adequate precision to predict aerobic pyrolysis at high temperatures in biomass furnaces.

2.2.2.1.3 Influence of Moisture on Wood Pyrolysis

The moisture content of biomass fuel reduces the pyrolysis rate and influences the amount of char and volatiles produced (Shafizadeh and Lai, 1972). Wiggins and Krieger (1980) showed that there exists a sharp physical separation between the solid-phase heating/drying zone and the pyrolysis zone. This separation results from the temperature gradient within the pyrolysing solid. Moisture reduces the flame temperature in the furnace, thus, reducing the amount of volatiles and increasing the amount of char produced. This results in a reduction of the rate of pyrolysis (Tillman et al., 1981).

The influences of moisture on the flame temperature can be quantified by the relationship between moisture content, excess air and the adiabatic flame temperature (Tillman et al., 1981):

$$T_{ad} = 1920 - 151*M_d - 5.15*Z$$
 (2.22)

where T_{ad} is the adiabatic flame temperature (K); M_d is the moisture (decimal dry basis); and Z is the excess air (percent).

2.2.2.2 Gas-Phase Oxidation

The volatiles formed in solid pyrolysis are oxidized via a series of free radical pathways. Edwards (1974) discussed three zones of gas-phase reactions:

- The precombustion zone where chain initiation is dominant;
- The primary combustion zone where chain branching is most prominent;
- 3. The post-combustion zone where chain termination reactions occur.

2.2.2.2.1 Precombustion Reactions

Edwards (1974) showed the details of the pathways of the precombustion reactions:

$$C_2H_6 + B \rightarrow 2CH_3 + B$$
 (2.23)

$$CH_3 + C_2H_6 + CH_4 + C_2H_5$$
 (2.24)

 $C_2H_5 + B \rightarrow H + C_2H_4 + B$ (2.25)

$$H + C_2 H_6 + H_2 + C_2 H_5$$
 (2.26)

The compound B is any heat-removing molecule or particle such as ash which is catalyst to the chemical reactions.

Precombustion gas-phase reactions are also considered pyrolysis reactions. The acetic acid and acetaldehyde may be degraded by decarboxylation and decarbonylation as illustrated in equations (2.27) and (2.28) (USDA Forest Service, 1982):

$$CH_{3}COOH \rightarrow CH_{4} + CO_{2}$$
(2.27)

$$CH_{3}CHO + CH_{1} + CO \qquad (2.28)$$

The above anaerobic reactions are predominant if the precombustion zone is spatially increased by use of substoichiometric quantities of undergrate air and high placement of overfire tuyeres as is the case in a concentric vortex-cell furance.

2.2.2.3 Primary Combustion Reactions

When the gaseous products of pyrolysis are mixed with oxygen in the primary combustion zone, they undergo a series of radical reactions ultimately producing CO_2 and H_2O . The main reaction compounds form chain branches (Hay, 1974):

$$CH_3 + O_2 + B + CH_3O_2 + B$$
 (2.29)

$$CH_2O_2 \rightarrow CH_2O + OH \tag{2.30}$$

The above sequence of reactions generates the hydroxyl radical as well as the main combustion intermediate CH_2O . The latter reacts

with OH to form HCO and CO. CH_2O is the key intermediate resulting from oxidation via the OH and oxygen attack (Tillman et al., 1981). The concentration of CH_2O reaches its maximum in flames at 1320 K (which is within the range of wood and corncob combustion (Palmer, 1974).

2.2.2.3.1 Postcombustion Reactions

Chain termination reactions can be depicted by the following representative sequence of reactions (Palmer, 1974):

$$HCO + OH \rightarrow CO + H_2O$$
 (2.31)

$$CO + OH + CO_2 + H$$
 (2.32)

$$C0 + 0_2 + C0_2 + 0$$
 (2.33)

$$OH + H + B \rightarrow H_2 O + B$$
 (2.34)

$$CO + O + B \rightarrow CO_2 + B$$
 (2.35)

The equilibrium and rate constants for these individual reactions have been published (Jensen and Jones, 1978). However, no overall expressions are available due to the many variables and complexities associated with the oxidation of wood volatiles (Tillman, 1980).

2.2.2.4 Char Combustion

Bradbury and Shafizadeh (1980) described the empirical formula for cellulose char as $C_{6.7}H_{3.3}O$. The combustion of char is similar to the combustion of carbon described by Kanury (1975):

- 1. Diffusion of oxygen to the fuel surface;
- 2. Absorption of the oxygen on the surface;
- Reaction of oxygen within the solid to form absorbed products;
- Desorption of the absorbed products from the surface;
- 5. Diffusion of desorbed products away from the surface.

The slowest of the above steps determines the burning rate. In the case of carbon and char, combustion steps (2) and (4) are extremely fast. According to Glassman (1977), char oxidation is considered to be mass transport limited. This is due to the large particles and relatively high temperatures associated with char combustion. Thus, step (3) is much faster than steps (1) and (5). The burning rate is, therefore, controlled by the diffusion rate of oxygen to the char particles.

Several simultaneous char combustion mechanisms have been suggested. Mulcahy and Young (1957) proposed the following mechanisms based on hydroxy radicals:

$$20H + C + CO + H_2O$$
 (2.36)

$$OH + C \rightarrow CO + H \tag{2.37}$$

The classic Boudouard reaction was proposed by Glassman (1977):

$$C + CO_2 \rightarrow 2CO \tag{2.38}$$

Bradbury and Shafizadeh (1980) proposed:

$$C^* + 0_2 \rightarrow C(0)_m \rightarrow C0 + C0_2$$
 (2.39)

$$C^* + 0_2 \rightarrow C(0)_s \rightarrow C0 + C0_2$$
 (2.40)

The asterick designates an active reaction site, the subscript m is a mobile species and the subscript s is a stable species.

All the solid carbon, including the remains on the grate and in the fly ash, must be oxidized via the above reactions to form CO₂. The reactions must have sufficient residence time, high temperature, and turbulance (the tree Ts) to complete the reactions in order to eliminate particulate emissions from the furnace.

2.2.2.5 Concentric Vortex-Cell Furnace Combustion Theory

The design and the operating principles of the concentric vortex-cell biomass furnace are discussed in section 2.1.3.2 The CVCF is similar to the spreader-stoker furnace if primary combustion air is introduced into the fuel bed through the grate supporting the fuel. The difference between a spreader-stoker and CVCF is that in the former furnace, most of the combustion air is introduced into the furnace through the grate. In the CVCF, secondary combustion air is supplied tangentially through a set of tuyeres located above the fuel bed. In some CVCF designs, the hearth is solid and no undergrate air is supplied (Claar et al., 1980; Wahby et al., 1981).

Adams (1979, 1980) has developed a theoretical model for a spreader-stoker wood-waste-fired boiler that predicts the flight times

and mass reduction of combustible particles entrained in the furnace exhaust gases. The model also predicts the influence of fuel and operating parameters on particulate emissions. The spreader-stoker furnace employs the underfeed and overfeed principles described by Nicholls and Eilers (1934). Thus, the analyzed furnace is similar to the CVCF with undergrate air. Claar et al. (1981) suggested that this model can be modified to analytically model the CVCF combustion mechanism. However, the Adams (1979, 1980) models have not been validated.

Several authors (Claar et al., 1980; Tuttle, 1977; Sukup, 1982) stressed the need to maintain high combustion temperatures and turbulence, and to provide sufficient time for complete combustion. The CVCF design provides suitable conditions for fuel combustion (Claar et al., 1980). However, there has not been a study correlating the combustion rate and the amount of particulate emissions from the CVCF to the temperature, turbulence, and time aspects of the CVCF. Thus, concentric vortex-cell furnaces have been designed and built by trial and error, rather than by optimization of the three Ts for a given furnace size and capacity (Claar et al., 1980 and 1981; and Wahby et al., 1981).

2.2.2.6 Heat Transfer in Furnaces

Heat losses from a furnace determine the efficiency of fuel conversion into useful energy. The net energy loss from a furnace at steady-state conditions may be determined by the application of the first law of thermodynamics. The conservation of energy equation for

a steady state flow, open system with one inlet and one outlet is (Holman, 1980):

$$Q_{out} = W_{in} + H_1 - H_2 + (U_2^2 - U_1^2)/2g_c$$
 (2.41)

$$H_{1} - H_{2} = \sum_{i=1}^{n} M_{ri} \Delta h_{ri} - \Delta H_{R} - \sum_{i=1}^{n} M_{pi} \Delta h_{pi}$$
(2.42)

where:
$$\Delta h = h_T - h_0$$

 $Q_{out} = net heat loss (kJ/h)$
 $W_{in} = net work done on the system (kJ/h)$
 $H = enthalpy of products entering (1),$
or leaving (2) the system
 $h_T = enthalpy at temperature T(K) (kJ/kg)$
 $h_0 = enthalpy at 298 K (standard reference temperature)$
 $M = mass flow rate (kg/h)$
ri = reactant i (i = air, fuel dry matter,
 H_20 in fuel, etc.)
pi = product i of combustion (i = CO₂, H₂O, etc.)
 ΔH_R = heat of combustion at a reference temperature
of 298 K (kJ/kg)
 g_c = gravitational constant (9.81 kg-m/kg s²).
 U = velocity (m/s)

The heat loss determination using equations (2.41) and (2.42) requires that the temperature and the composition of the flue gases are known. The heat losses in the different components of the furnace cannot be determined from equation (2.41).

Heat transfer in furnaces occurs in a combination of the three modes of heat transfer, namely: radiation, convection, and conduction. Heat transfer by convection, radiation, and conduction can be analyzed using standard techniques available in numerous heat transfer books such as Holman (1981) and Siegel and Howell (1981). However, heat transfer by radiation and convection in flames within the combustion chamber requires special treatment due to the thermal properties of flames. Also, the combined radiation-convection heat transfer should be studied since it occurs in a furnace.

2.2.2.6.1 Convective Heat Transfer from Flames

Calculation of heat transfer in flames involves the determination of the convective heat transfer coefficient for the products of combustion. The thermal properties of flue gases and particulates entrained therein are quite different from those of air. Moreover, the use of the arithmetic mean of the surface and gas temperatures as the film temperature is inadequate due to the large variation in the physical and thermal properties with temperature. Also, chemical recombination reactions occur when the hot gases are cooled; consequently there may be some heat release within the boundary layer (Gray et al., 1976).

The thermal and transport properties of flue gas can be calculated if the composition of the gas is known. The properties are determined as follows:

1. specific heat (Holman, 1980): $c_m = m_1 C_1 + m_2 C_2 + m_3 C_3 + ... + m_n C_n$

2. viscosity (Brokaw, 1958):

(2.43)

where μ_{i} an μ_{j} are the viscosities of pure components i and j (N s/m^2),

$$\phi_{ij} = \frac{\left[1 + \left(\frac{\mu_{i}}{\mu_{j}}\right)^{\frac{1}{2}} \left(\frac{M_{j}}{M_{i}}\right)^{\frac{1}{2}}\right]^{2}}{2 \times 2^{\frac{1}{2}} \left[1 + \frac{M_{i}}{M_{j}}\right]^{\frac{1}{2}}}$$
(2.45)

where: x_i = the mole fraction of component i. x_j = the mole fraction of component j. M_i = the molecular weight of component i. M_j = the molecular weight of component j. 3. thermal conductivity (Mason and Saxena, 1958):

$$k_{\min} = \sum_{i=1}^{n} \frac{x_{i} k_{i}}{\sum_{\substack{j=1\\j \neq 1}}^{n} x_{j} \phi_{ij}}$$
(2.46)

 $\boldsymbol{\varphi}_{i,j}$ has the same value as that given by equation (2.45)

$$\rho_i = P/(R_i T)$$
 (2.47)

$$1/\rho = m_1/\rho_1 + m_2/\rho_2 + \dots + m_n/\rho_n$$
 (2.48)

where P is the total pressure (bars); R_i the gas constant of component i (J/kg K); ρ is the density of a mixture (kg/m³); ρ_i is the density of component i; m_i is the mass fraction of component i; and T is the temperature of the mixture (K).

5. Prandtl number:

(4) density:

$$\Pr = C\mu/k \tag{2.49}$$

Due to the large variation of temperature and, therefore, the thermophysical properties, weighted averages of the above properties are used. The following equation was suggested by Gray et al. (1976):

$$\mu_{ave} = \int_{T_w}^{f_e} \mu dT / (T_e^{-T_w})$$
(2.50)

where T_e and T_w are the flame and the furnace wall temperature (K).

Weighted averages for thermal conductivities, specific heats, densities, and Prandtl numbers are defined in a similar way as the dynamic viscosity (equation 2.50).

Adams (1979) developed empirical equations for determining the thermophysical properties of combustion gases, assuming that the combustion products behave as air at the same temperature:

$$\rho_{\rm m} = M_{\rm g}/R_{\rm u}T_{\rm e} \tag{2.51}$$

$$M_{a} = 30.5 - 12.5 X_{w}$$
 (2.52)

$$\mu_{\rm m} = (182 + .245) \times 10^{-7}$$
 (2.53)

where M_g is the molecular weight of flue gas; R_u is the universal gas constant (8.2*10⁻³ atm per kg-mole per K; X_w is the mole fraction of water (steam) in the flue gas; and T_e is the flue gas temperature (K).

The validity of the above equations is uncertain since the products of combustion do not behave as air.

Empirical heat transfer correlations have been developed by several researchers and are generally accepted for estimating convective heat transfer in tubes, plates and other geometrical shapes (Holman, 1981). The equations are of the form:

$$Nu = c Pr^{m}Re^{n}$$
 (2.54)

$$Nu = h_{c}L/k$$
 (2.55)

The heat transfer is then given by:

$$Q = Ah_{c}(T_{e}-T_{w})$$
(2.56)

The following is the defining equation for the Reynolds number:

$$Re = U\rho L/\mu$$
 (2.57)

The magnitude of the Reynolds number determines whether the flow is laminar (Re < 2,300) or turbulent (Re > 10,000). Transition from laminar to turbulent flow takes place in the range of Reynolds numbers between 2,300 and 10,000 (Holman, 1981).

2.2.2.6.2 Radiative Heat Transfer from Flames

The flame and the combustion products absorb and emit thermal radiation. Both gases and particulate materials present in the flame contribute to the absorbing/emitting potential of the flame.

The gases present in flames from biomass fuels include CO_2 , H₂O, CO, H₂, O₂, H, O, OH, N₂, N and NO. The atomic and the homonuclear diatomic molecules (H,O,N and H₂, O₂) are the only nonabsorbing constituents (Gray et al., 1976). The rest absorb and emit radiation over a specific wavelength range or band within the thermal spectrum. Carbon dioxide and water vapour are the most important absorbing/emitting gases in combustion products. They are the only two gases considered in engineering calculations; for more precise calculations other gases should be included (Hottel and Sarofim, 1967).

The range of wavelengths over which absorption occurs in carbon dioxide and water vapor gases have been given by (Gray et al., 1976) as 2.4-3, 4-4.8, and 12.5 to 16.5 μ m for CO₂, and 2.2-3.3, 4.8-8.5, and 12-25 μ m for H₂O. The absorptivities and emissivities of combustion gases vary considerably with wavelength. For engineering calculations, it is assumed that the gases are grey; thus, average values of absorptivities and emissivities for the whole of the wavelength range under consideration are used.

The absorptivity and emissivity of CO_2 and water vapour in a furnace depend upon the flame temperature, the mean beam length of the gas to the furnace walls, the partial pressure of the gases, the total pressure, the composition and the amount of the other gases in the combustion products, and the wall temperature.

Adams (1979) suggested the following equation for calculating the emissivity of CO_2 and H_2O in wood-fired boilers:

$$\epsilon_{cw} = 493[0.6/A_g(X_w + X_{co})]^{.45}/T_e$$
 (2.58)

where ε_{CW} is the combined emissivity of carbon dioxide and water vapor; A_g is the grate area (m²); X_W and X_{CO} are the mole fractions of the water vapor and carbon dioxide, respectively; and T_e is the flame temperature (K). Soot, fly ash, and particulates in the flame emit and absorb radiant thermal energy. The emissivity and absorptivity of particulates depend upon their size, shape, concentration, composition, and the temperature. Also, the wavelength of the radiant energy affects the emissivity/absorptivity of the flue gases. Adams (1979) suggested the following empirical equation for the emissivity of soot in a wood fired boiler:

$$\epsilon_{s} = 1 - \exp(-0.12\sqrt{A_{g}})$$
(2.59)

Adams (1979) also suggested an equation for calculating the flame emissivity from the values of gas and particulate emissivities:

$$\varepsilon = \varepsilon_{s} + \varepsilon_{sw} - (\varepsilon_{s})(\varepsilon_{sw})$$
(2.60)

Having determined the emissivity of the flame, the heat radiated to the wall is given by:

$$Q_r = A_W \varepsilon \alpha (T_e^4 - T_w^4)$$
(2.61)

2.3 Grain Drying

In this study a concentric vortex-cell biomass furnace (CVCF) is used to provide heat energy for an in-bin counterflow grain dryer (IBCF). The dryer was experimentally tested by Silva (1980) using liquid propane gas. The IBCF drying temperature is between 50 and 100°C depending upon the type of grain dried and the intended use of the grain (Silva, 1980; Kalchik et al., 1979). When feed corn is dried with air at 65 to 100°C, the IBCF dryer is a high-temperature, high-capacity dryer. High-temperature drying may affect grain quality in different ways depending upon the initial grain quality and moisture content, and the drying/cooling rate.

Grain and seeds are highly perishable if poorly handled. If well harvested, and stored at a low moisture content and low temperature, grain will retain the original germinability and other desirable qualities for a long period of time. In the following sections, grain drying is reviewed.

2.3.1 Importance of Grain Drying

The importance of grain drying has been discussed by Brooker et al. (1974). Drying facilitates early harvest, thus, reducing field losses from storm, insect damage, and natural shattering. Field conditions are often better for harvesting early in the season. Early harvest permits early and timely seedbed preparation for the next crop; this is particularly important in some tropical areas where two or more crops are raised in one year.

Grain drying permits farmers to better plan the harvest season, and to make better use of labor and machinery since harvesting is not dependent on fluctuations of the grain moisture content in the field. Finally, the early harvest enables farmers to take advantage of higher prices early in the harvest season.

The most important advantage of grain drying is that it permits long-time storage without deterioration in quality. By removing excess moisture from the grain, the possibility of natural heating of the grain due to molding and respiration is reduced. Thus, grain viability is maintained during storage. Dried grain (at moisture content below 13%) is less prone to insect, mites, and fungal damage than wet grain.

2.3.2 Corn Quality as Affected by Drying Methods

The desirable corn properties are dependent upon the intended use of the corn. In the US corn is mainly used as animal feed, with smaller usage as human food, seed and industrial starch manufacturing. Corn quality is dependent upon several factors: (1) the variety characteristics, (2) the environmental conditions during growth, (3) the time and the harvesting procedure, (4) the drying method, and (5) the storage practice (Brooker et al., 1974). During the drying process, corn quality is affected by the grain temperature and the drying rate.

Corn in the US is officially graded for quality under the Grain Standards Act. The grades and grade requirements are listed in Table 2.5. There are other properties which are of importance to specific corn users that are excluded from the standard, such as nutritional value, millability, viability, and susceptibility to breakage.

2.3.2.1 Effect of Drying on Nutritional Feed Value

The most important quality factor of corn for animal feed is the nutritional value. The effect of drying temperature on the nutritional value of corn for animal feed has received considerable research attention. Hathaway et al. (1952) found that corn dried at temperature

Grade	Minimum testweight LB/bu	Maximum Limits			
		Moisture %	BCFM %	Damaged kernels, %	
				heat damaged	Total
1	56	14.0	2.0	0.1	3.0
2	54	15.5	3.0	0.2	5.0
3	52	17.5	4.0	0.5	7.0
4	49	20.0	5.0	1.0	10.0
5	46	23.0	7.0	3.0	15.0

Table 2.5.--Numerical grades and sample grade requirements for US corn.

Sample grade shall be corn which does not meet the requirements for any of the grades numbers 1 to 5; or which contains stones; or which is musty, sour, or burned; or which has any commercially objectionable foreign odor; or which is otherwise of distinctly low quality.

Source: Brooker et al. (1974).

above 60°C significantly decreased its energy content and palatability. Sullivan et al. (1975) reported that heat has a definite effect on the nutritional value of corn; also, that the decrease in commercial quality due to drying at high temperatures may not necessarily result in a decreased value of corn as animal feed.

Jensen et al. (1960) reported that drying temperatures of 60° C, 82.2°C, and 104°C, have no deleterious effect on the nutritive value of corn for swine as measured by growth rate and feed use. Jensen (1978) showed that roasting corn at 15% and 23% moisture at 127°C and 150°C reduced the availability of lysine; he found that niacín is unaffected by roasting temperature, but pyridoxine (vitamin B6) availability is significantly reduced in 14% moisture corn when it is heated at 160°C.

From the above review it appears that corn which reaches temperatures above 60°C undergoes some minor nutritional changes. Nutritionists do not agree on the effects of drying temperature on the feed value of corn (Brooker et al., 1974). It is generally recognized that physical and chemical properties such as consistency, energy content, palatability, hardness, color, moisture, vitamins, protein and amino acid profile are affected by high drying temperature (Williamson, 1975).

2.3.2.2 Effect of Drying on Corn Milling Quality

Farmers and elevator operators who dry corn often consider only its feed value. Corn millers are concerned about the increasing volume of artificially dried corn being marketed (Freeman, 1978; Rutledge, 1978).

High starch yield (millability), maximum yield of selected fractions and prime products mix, and low fat content are the most important desirable characteristics of corn for milling. Brekke et al. (1973) compared the corn milling response of in-bin natural air drying with artificial drying in a small experimental fluidized dryer at air temperatures from 32 to 143°C (maximum corn temperatures were 32 to 104°C, respectively). The yield of total grits recovered by sieving, aspiration, and flotation decreased with increasing drying air temperature; also, the fat content of the grits increased with increasing air temperatures. Prime products recovered by rolling and

grading followed similar patterns; however, sometimes yields and fat contents were less satisfactory. The results also showed that the cold paste viscosity of selected products increased if corn dried at elevated temperatures. The corn dried with natural air had the best dry-milling quality; drying at 60°C yielded corn of acceptable dryingmilling quality except for a high percentage of stress cracks.

Freeman (1978) discussed the quality factors affecting the value of corn for wet milling. Drying at high temperatures causes "case hardening" of proteins. Case-hardened protein affects the millability by impairing separation and purification of starch. The result is starch with a high protein content and reduced viscosity. The drying temperature, drying rate, and the initial corn moisture content determine the degree of case hardening. High drying temperatures may also destroy some amino acids, especially lysine.

Watson and Mirata (1962) concluded that since kernel viability is evidently more easily altered by drying conditions than the other properties examined, corn dried to preserve viability should invariably be suited for starch manufacture. The drying temperature should not exceed 71°C.

2.3.2.3 Drying Corn for Seed

Generally the techniques used to dry seeds do not differ greatly from those used to dry grain for other purposes. However, extra dryer control and management must be practiced in order to ensure a high degree of germination (Copeland, 1976). The drying air temperature, the drying rate, and the initial moisture content are

the most critical factors affecting the germinating quality. Copeland stated that the product temperature limit varies with the type of seed, but should not exceed 38°C; the highest safe temperature also depends on the initial moisture content. Ulileman and Ullstrup (cited in Hukill, 1954) showed that seed corn can be dried safely at 49°C, if the moisture content is less than 25%; for moisture above 25%, 38°C, is the upper limit.

An excessive drying rate may cause stress cracks. Over-dried seeds are susceptible to mechanical damage, which is detrimental to seed quality.

2.3.2.4 The Effect of Drying on Commercial Grade

The effects of artificial corn drying on its composition, nutritional value, viability as seed, and industrial processing have been discussed in the previous sections of this review. These factors are not included in the determination of commercial grade. As shown in Table 2.5, the only factors considered in the grain standard code for corn are: (1) the testweight, (2) the moisture content, (3) the broken corn and heat damaged corn, and (4) the presence of foreign materials. Artificial drying has a direct effect on the testweight, the moisture content, and on the percentage of heat damaged corn, and has an indirect effect on broken corn. These factors will be reviewed in the following sections.

2.3.2.5 Testweight

The corn testweight is its bulk density and is influenced by grain shape, grain surface texture, moisture content, type and amount of impurities, size and uniformity, temperature, and other factors that affect the packing characteristics. According to Freeman (1978), testweight may indirectly indicate the wet milling quality of corn. High-temperature drying may reduce the extent of kernal shrinkage resulting from moisture removal and, hence, result in low testweight.

Hill (1975) studied the effect of drying temperature on testweight of shelled corn. According to his observations, the testweight increases during drying. The increase is due to shrinkage with a loss of moisture and decrease of the coefficient of friction on the surface, thus permitting closer packing of the kernals. The testweight increase is less at higher drying temperatures, possibly due to case hardening. The testweight reaches a maximum and declines with further drying. The maximum testweight is reached at 14 to 16% moisture (Brooker et al., 1974).

The amount of testweight increase with drying depends upon: (1) the degree of kernal damage, (2) the initial moisture content, (3) the temperature reached by the grain during the drying process, (4) the final moisture content, and (5) the grain variety. Early harvested, high moisture grain is not exposed to much weathering and shows a higher testweight after drying than the same grain harvested later at a lower moisture content (Brooker et al., 1974).

A higher testweight corn offers some saving in storage since less storage volume is required to store the same amount of dry matter.

2.3.2.6 Stress Cracks and Broken Corn

Although drying per se does not directly affect the number of broken kernals, it is well known that grain is physically and physiologically damaged when dried at excessively high temperatures. The degree of damage depends upon the maximum temperature reached by the grain and the length of the period during which the high temperature is sustained. The drying and cooling processes directly affect the degree of stress cracking, and thus determine the susceptibility of corn to breakage during subsequent handling.

Thompson and Foster (1963) defined stress cracks as the fissures in the endosperm, or starch inside the kernel, in which the seed coat is not ruptured. Ross and White (1972) studied the effect of overdrying in stress cracking in white corn. Their results show a general decrease in stress cracking as the white corn dried to lower moisture content, and as drying started at lower moisture contents. These phenomena are difficult to explain. There may be some physical and chemical changes such as gelatinization during over-drying which make the grain kernel more resistant to cracking during the cooling period. Generally, stress cracking decreases with decreasing drying air temperature. Slow cooling of both the white and yellow corn after drying results in a dramatic reduction in the number of checked kernels, particularly after subjecting the corn at drying air temperatures above 71°C.

Gustafson et al. (1978) concluded that there is no significant increase in breakage susceptibility when corn is dried to 18% moisture (or above) in a high-temperature dryer; the product of the heating time and the change of moisture content (under 18%) appears to be the best predictor of the change in breakage.

Freeman (1973) indicated that broken kernels too large to be removed by screening for wet milling may release starch granules during steeping. Free starch in the steeping water causes fouling of evaporator surfaces during steep water concentration.

2.3.2.7 Corn Color

Artificial drying affects other grain characteristics including color. Ross and White (1972) concluded that darkening and yellowing of white corn was apparent when it was dried with air at 88°C and 104°C, and when drying started at an initial moisture content above 25%. Discoloration was only slight in samples dried at 71°C from any initial moisture content, and for samples dried from 25% initial moisture content (mc) to 14% final mc with drying air at 104°C.

2.3.3 Drying Systems

There are three basic methods of grain drying: (1) hightemperature drying, (2) low-temperature drying, and (3) combination drying. In the US, high-temperature drying has been the primary technique for more than 25 years. This method is fast, but has a high fossil-fuel requirement, and can result in a low grain quality. Lowtemperature grain drying (energy may be obtained from electricity, liquid propane, solar energy, or any other heat source) is an energy efficient process and often results in high-quality grain, if properly managed. Mold spoilage risk is the main problem encountered in warm and humid areas. Natural drying is a low-temperature drying method and takes place when grain is either left standing (or stacked) in the field, or harvested and dried in a crib. The latter method is often practiced in the Third World and is the most risky since it exposes grain to the weather, insects, rodents, birds, and other destructive elements.

Combination drying processes for drying shelled corn started in the US in the late 1970's (Brooker et al., 1978). In these processes high-speed batch or continuous flow drying is combined with low heat or natural air in-bin drying. The high-speed, high-temperature dryers dry the corn to a moisture range of 18-23%. The corn is then transferred to storage where it is slowly dried to a safe storage moisture content. Combination drying offers a number of advantages, including: (1) increased output, (2) increased fuel efficiency, (3) improved product quality (compared to corn dried by high-speed, high-temperature processes). Brooker et al. (1978) subdivided the on-the-farm high- and low-temperature drying methods into the following categories: (1) highspeed, high-temperature batch and continuous dryers; (2) continuous in-bin drying systems; (3) batch-in-bin drying systems with and without stirring; (4) low-heat and no-heat in-bin drying systems with and without stirring; and (5) combination systems, in which high-speed batch or continuous flow systems are combined with low-heat in-bin drying systems.

2.3.3.1 Column Batch Dryers

Column batch dryers are stationary bed dryers, in which the air moves across a stationary grain column (see Figure 2.7). The dryer is often portable so that it can be moved from location to location when not filled with grain. According to Brooker et al. (1974), column batch dryers have the following characteristics: (1) column thickness is usually from 30 to 46 cm; (2) column batch dryers operate at high airflow rates (over 40 $m^3/min/m^3$); (3) drying air temperatures vary from 82 to 116°C; (4) due to the high flow rate coupled with a narrow column, the moisture gradient across the column is less than with batch in-bin systems; and (5) drying is completed in a 1 to 3 hour period, depending on the initial grain moisture content and the need for cooling.

Column dryers are popular because of their simple construction and operation, and because the initial cost is generally lower than of continuous flow types (Sutherland, 1975). They are suitable for moderate grain volumes (250-650 tons annually) with high initial moisture contents. Because the dryer has no storage function, it requires well planned and coordinated handling and storage systems.

The fuel consumption and, therefore, the operating costs depend upon the moisture removal range. The fuel efficiency decreases with decreasing moisture removal range. It requires (at 30% initial mc) about 5,800 kJ/kg of water removed when the final moisture is 25%, and 6,970 to 8,140 kJ/kg of water when the final moisture content is 15%.



Figure 2.7. Batch Column Dryer. (from Brooker et al., 1974).

The thicker the grain column is in a column dryer, the lower is the specific fuel consumption. However, thicker grain columns result in an increase in the moisture content gradient across the column.

Kirk (1959) investigated column thicknesses of 10.2, 20.3, 30.5, and 40.6 cm and concluded that: (1) the 20.3, 30.5, and 40.6 cm columns are similar in drying air requirements; (2) the operating costs do not significantly increase with an increase of static pressure of up to 0.5 kPa for a grain column thickness of 20.3 to 40.6 cm; (3) in the static pressure range of 0.06 to 0.5 kPa, the drying capacity increases linearly with static pressure; and (4) there is no significant difference in drying capacity with drying column thickness between 20.3 and 40.6 cm.

The moisture and the temperature gradients across the drying column in a column batch dryer along with the dryer operating costs can be reduced either by decreasing the drying airflow rate at a constant air temperature, or by decreasing the drying air temperature at a constant airflow rate (Morey et al., 1976).

2.3.3.2 In-Bin Dryers

In-bin drying systems dry and cool the grain in a bin designed either as a batch in-bin dryer or as a drying-storage bin. In the latter case the grain is left in the same bin for storage (see Figure 2.8).

In-bin drying may be categorized in different ways. Brooker et al. (1974) categorized in-bin drying as (1) full-bin drying, (2) layer-drying, and (3) batch in-bin drying.



Figure 2.8. Schematic of a Low-temperature In-bin Drying System.

In full-bin drying a single batch of grain (up to 5 m) is dried at relatively low airflow. To avoid grain deterioration during drying, the initial moisture content of the corn must not be above 21-23% (Brooker et al., 1974).

In the layer-drying process an initial shallow layer of grain is placed in the bin and drying is started. As the drying zone moves upwards, other layers of grain are added periodically, so that a layer of wet grain remains ahead of the drying zone. Eventually the bin is filled; drying continues until the entire grain mass is dried. This process allows the initial layers of grain to be relatively wet; they receive more drying air (and therefore dry faster) than the subsequent drier grain placed at the top of the bin.

Batch-in-bin drying is a process in which batches of grain are dried in a bin and transferred to a storage bin. This process utilizes large quantities of heated air which is forced through relatively shallow grain beds. Therefore, the drying rate is considerably higher than in the other in-bin drying systems.

In-bin dryers may be operated with high or low temperatures (heated air) or with natural air (unheated air). High-temperature in-bin drying is undesirable in full-bin and layer drying due to excessive overdrying at the bottom of the bin. However, stirring devices may be used to solve this problem.

Natural air and low-termperature drying are similar processes (Bakker-Arkema et al., 1978). The difference is that no heat is added in case of natural air drying. Low-temperature drying requires raising the drying air 3 to 6°C above the ambient temperature by either

electric heat, solar energy, or other heat sources (Zink et al., 1978). Liquid propane and electricity are the most common heat sources for low-temperature drying; both require low capital investment. Liquid propane gas is usually not used since it requires interval timers to limit the heating rate.

The airflow rate required for a drying system depends on the drying system, the harvest date, harvest moisture content, and the location.

Adding heat, even in small amounts, increases the drying capacity in a low-temperature drying system (by decreasing the drying air relative humidity). The temperature increase also results in faster mold development. To reduce mold growth, the average temperature in the bin should be below 10° C. With addition of low heat, the airflow can be limited to $2.4m^{3}/min-m^{3}$ for 24-26% mc corn, $1.6m^{3}/min-m^{3}$ for 22-24% mc, and $0.8 m^{3}/min-m^{3}$ for 20-22% mc corn (Brooker et al., 1978).

Although low-heat and natural air drying are slow, the quality of the finished grain is frequently high due to the low application of heat (Kalchik et al., 1979).

The main disadvantage of in-bin drying is that the grain at the bottom may be overdried and at the top underdried. Drying is stopped after the average moisture content in the bin reaches a desired value. Since unloading does not allow perfect mixing and blending to obtain a uniform moisture content, the corn may deteriorate during storage. Several improvements have been incorporated in in-bin drying to reduce the vertical moisture gradient. This includes grain recirculating, in-bin counterflow drying, grain stirring, and drying with alternating heated and unheated air (Browning et al., 1971).

According to Brooker et al. (1978), the specific fuel consumption of deep bin-in-storage drying is low (3,500 kJ/kg, or lower in some cases). Therefore, these systems are usually used in combination with other drying systems.

2.3.3.3 High-Speed Continuous Crossflow Dryers

Crossflow dryers have a wet grain holding bin at the top (see Figure 2.9). Grain flows by gravity from the top to the bottom through drying and cooling columns which are 20-45 cm wide. A column thickness of 28-36 cm is most common. Two fans, one for heating and one for cooling, are usually used. The drying rate and the final moisture content are mainly dependent upon the grain velocity, the air temperature, the airflow rate, and the initial moisture content. Moisture is usually controlled by regulating the grain flow rate by a metering auger at the bottom of the dryer, while maintaining a constant air temperature and airflow rate. The auger speed responds to a temperature sensor located in the grain column near the lower edge of the drying section.

The drying characteristics of crossflow dryers are similar to those of column batch dryers. The grain on the plenum side is overdried while that on the exhaust side is underdried.



Figure 2.9. Schematic of a Crossflow (Continuous Flow) Grain Dryer (From Brooker et al., 1974).

In some crossflow designs, the cooling air is reused. This allows recovery of heat from the cooled grain and also reduces the moisture content gradient across the grain column (Bakker-Arkema et al., 1980). Some designs incorporate a metering device that causes the grain on the plenum side to move faster than the grain on the outside (Rodriguez, 1982). Other designs use a "turnflow device" to interchange the grain on the plenum side with the grain on the exhaust side (Fontana, 1983). These improvements are intended to reduce the moisture content gradient across the grain columns.

2.3.2.4 Concurrentflow Dryers

Concurrent flow drying is a relatively new grain drying technique (Dalpasquale, 1981; Bakker-Arkema et al., 1983). In a concurrentflow dryer, high temperature (80-300°C) air flows in the same direction as the grain (see Figure 2.10). The hot air only encounters the cool and wet grain. Intense heat and mass transfer takes place at the grain/air inlet, causing rapid evaporative cooling of the air and heating of the grain. The latter is accompanied by rapid drying of the grain. The grain temperature remains considerably below the inlet air temperature. As the grain and the air flow through the drying bed, an equilibrium is reached (the equilibrium temperature is between the inlet air temperature and the initial grain temperature). The absolute and relative humidity of the air progressively increase as the grain dries.

The major advantage of concurrentflow drying is that all the grain kernels are subjected to the same thermal process. Thus, there



Figure 2.10. Schematic of a Concurrent Flow Dryer.

is no moisture difference among the kernels. This results in better grain quality.

Counterflow cooling has usually been combined with concurrentflow drying (Bakker-Arkema et al., 1982). Cold air first encounters the coldest grain, thus limiting thermal stresses.

Several authors have reported the advantages of concurrentflow drying including: (1) high capacity (in multi-stage concurrentflow dryers), (2) improved grain quality, (3) greater flexibility for adaptation to different crops, and (4) high termal effiency (Westelaken and Bakker-Arkema, 1978; Mühlbauer et al., 1978; Bakker-Arkema et al., 1982, 1983; Dalpasquale, 1982; Fontana, 1983).

2.3.3.5 In-Bin Counterflow Dryers

In-bin counterflow drying is an intermittent process in which the grain in a bin flows downwards, and the drying air flows in the opposite direction (see Figure 2.11). The drying process is the same as for the batch-in-bin dryer. Dried grain is removed from the bottom of the bin by the means of a tapered sweep auger which removes a thinlayer of grain from the bottom of the grain bed and delivers it to a vertical auger; the auger, in turn, discharges the hot dry grain into a cooling bin. The sweep auger is activated by a temperature sensing element placed about 46 cm above the false floor. As drying progresses, the temperature in the region of the sensor increases. When a preselected temperature is reached, the sweep auger is activated; it makes one complete turn around the bin removing a 7-9 cm thick layer of dry warm grain. As the auger completes the turn, damp grain


Figure 2.11. Schematic of the Internal View of an In-bin Counterflow Drying "Shivvers System."

moves into the sensor's region and the temperature at that point drops. The auger is turned off and waits for the next cycle. Thus, the mode of operation is intermittent. In a countinuous-flow, counterflow dryer, the sweep auger speed is set so that the grain receives sufficient residence time in the dryer such that the grain is dried to a desirable moisture content by the time it is discharged. The grain discharge rate is used to control the final moisture content.

In the counterflow drying process, the warm saturated air leaving the drying zone passes the cool and relatively wet incoming grain. Some energy is used to warm the cool grain, and condensation may occur on the cool grain especially if the bed is deep and the initial grain temperature is low (Brooker et al., 1974).

Silva (1980), Bakker-Arkema et al. (1980), and Kalchik et al. (1981) investigated the performance of the in-bin continuous flow counterflow dryer. The specific energy consumption decreases with increasing drying temperature (4,390 to 5,110 kJ/kg of water for drying air temperatures of 93 and 50°C, respectively); corn quality is not seriously affected by drying at high temperatures (82-93°C).

2.3.3.6 Combination Drying

In combination drying, wet grain is dried down to 18-24% mc (wb) in a high-temperature batch or continuous dryer. The grain is transferred to a bin in which drying is completed by a low-temperature in-bin drying process (Shove, 1978). Dryeration is a form of combination drying (Foster, 1964). In the dryeration process, grain is dried in three phases. The first phase consists of drying the grain down

to 2-3 percentage points above the desired final moisture in a hightemperature dryer. The partially dried grain is transferred to a tempering bin (second phase) and held hot for 6 to 10 hours. In the third phase the grain is finally cooled by aeration at low airflow $(.01-.03 \text{ m}^3/\text{min-m}^3)$ (Bakker-Arkema et al., 1978; McKenzie et al., 1972).

Gustafson et al. (1976) and Shove and White (1977) showed that the susceptibility to breakage in the 15-18% mc range is substantially reduced by eliminating immediate cooling after high-temperature drying. According to Kalchik et al. (1981), combination drying results in increased fuel efficiency and increased drying capacity. The average specific energy consumption for high-temperature drying is 5000 kJ/kg compared with 3800 kJ/kg for combination drying when corn is dried from 26 to 15.5% mc.

2.3.3.7 Drying Systems Suitable for Biomass Heating

The drying systems discussed previously have been designed for use with conventional fossil fuels as energy sources for heating the drying air. A batch dryer has distinct loading, heating (drying), cooling, and unloading phases during a drying cycle. Thus, the fuel burner is turned on during the heating phase and is turned off during the cooling, unloading, and the loading phases. In contrast, continuous flow dryers require a continuous supply of heated air for the drying sections.

The concentric vortex-cell furnace and other solid fuel burners require a continuous supply of fuel and combustion air to maintain

steady-state conditions. Sudden interruption of either fuel or air supply results in undesirable transient conditions characterized by the emission of products of incomplete combustion. Thus, a biomass furnace cannot be used for heating drying-air for a batch dryer without incorporation of a heated air diversion system to divert the heated air to some other use during the loading, cooling, and unloading phases. Unlike the batch dryers, continuous flow dryers are easily convertible to the use of biomass heated air.

2.4 Grain Drying Theory and Simulation

Much research has been conducted to study the processes by which water is removed from biological materials. The drying process consists of simultaneous heat and mass (moisture) transfer. Heat is required to provide the energy for evaporating moisture from the drying grain. The moisture is removed from the surface of the grain by an external drying medium, usually air.

Bakker-Arkema et al. (1974) listed six possible modes of moisture removal from cereal grains: (1) surface forces (capillary flow); (2) liquid movement due to moisture concentration differences (liquid diffusion); (3) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion); (4) vapor movement due to moisture concentration differences (vapor diffusion); (5) vapor movement due to temperature differences (thermal diffusion); and (6) water and vapor movement due to total pressure differences (hydrodynamic flow). The exact manner in which water leaves the grain is dependent upon drying air temperature, air velocity, moisture concentration, and product type and condition.

Two drying rate periods have been identified: (1) the constantrate period during the initial drying of extremely moist grain, and (2) the falling-rate period. Cereal grains dry during the fallingrate period (Bakshi and Singh, 1979). The drying rate decreases continuously as the moisture content decreases during the course of drying. The thermal and the physical properties of the grain which are moisture content dependent also change as drying progresses. Thus, the prediction of the drying rate during the falling-rate period is more complicated than during the constant-rate period.

The basic drying theory consists of a thin-layer drying equation (which is equivalent to drying a single grain kernel), coupled to a series of deep-bed drying equations.

2.4.1 Thin-Layer Drying Models

A "Thin-layer" of grain refers to a layer of grain that is approximately one kernel deep. A thin-layer drying equation predicts the drying rate of single kernels of grain as a function of the drying conditions.

Empirical, theoretical, and semi-theoretical thin-layer equations have been developed for different crops.

Empirical equations are developed by analyzing statistically the data obtained by drying thin layers of grain. Theoretical equations are based upon the diffusion theory (Crank, 1979). Thinlayer drying equations for several cereal grains have been reviewed and

published (Bakker-Arkema et al., 1983; Steffe, 1979; Dalpasquale, 1981; Bakshi and Singh, 1979).

First the thin-layer equations for corn will be reviewed. Thompson et al. (1968) developed an empirical thin-layer drying equation for corn in the range of 60 to 150°C.

 $t = A ln (MR) + B (ln(MR)]^2$ (2.62)

where: A = 0.004880 - 1.86178

 $B = 427.36 \exp(-0.033\theta)$

The most commonly used thin-layer equations are modified versions of the Thompson equation (Pfost et al., 1976).

Flood et al. (1969) developed an empirical drying equation for corn in the temperature range of 2 to 22°C:

MR = exp
$$(-kt^{0.663})$$
 (2.64)
where: MR = $(M-M_e)/(M_o-M_e)$
 $k = exp (-xt^y)$
 $x = [6.014 + 1.45*10^{-4}(rh)^2]^{.5}$
 $-(1.80 + 32)[0.334*10^{-3} + 3*10^{-8}(rh)^2]^{.5}$
 $y = 0.125 - 2.197*10^{-3} - [1.80 + 32][2.3*10^{-5}(rh) + 5.8*10^{-5}]$

Rugumayo (1979) developed an equation from mathematical diffusion theory similar to the model presented by Chu and Hustrulid (1968) for low temperature thin-layer drying of corn. The Troeger and Hukill (1970), the Muh (1974), and the Misra (1978) equations have been compared by Rugumayo (1979).

In the development of the above equations, it is assumed that moisture is uniformly distributed within the individual kernels of the grain. Therefore, the equations cannot be used to predict the moisture gradient within the kernels. The knowledge of the moisture content gradient within single kernels is needed in order to simulate the tempering process in grain-drying (Rodriguez, 1982; Fontana, 1983; Sabbah, 1971).

The Crank (1979) spherical diffusion equation can be used to calculate the moisture gradient in the grain kernels during the drying process:

$$\frac{\partial C}{\partial t} = D(\frac{\partial^2 C}{\partial r^2} + \frac{2\partial C}{r\partial r})$$
(2.64)

or:

$$\frac{\partial M}{\partial t} = D(\frac{\partial^2 M}{\partial r^2} + \frac{2\partial M}{r\partial r})$$
(2.65)

The following are the boundary conditions:

$$M_{(r,o)} = M_{initial}$$
$$M_{(o,t)} = M_{e}$$
$$C_{(r,o)} = C_{initial}$$
$$C_{(o,t)} = C_{e}$$

where C is moisture concentration (kg/m^3) and M is the moisture content (decimal). The analytical solution of equation (2.64) for the moisture

content distribution and the average moisture content of various regularly shaped bodies can be found in Crank (1979). For a sphere the average moisture content is (Sabbah, 1971):

$$MR = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp - \left[\frac{n^2 \Pi^2}{9} X^2\right]$$
(2.66)

where: $X = \frac{V}{A}(Dt)^2$

The diffusion coefficient (D) is a function of the moisture content, the grain temperature, and the type of grain. Sabbah (1971) using a spherical diffusion equation found for corn:

$$D_{\rm m} = 5.196 \times 10^{-3} M[\exp(-2673.33/\theta)]$$
 (2.67)

A diffusion constant equation should be used with the equation for which it was developed. The Chu and Hustrulid (1968) equation is a mass concentration-based diffusivity and is used to solve the equation:

$$\frac{M - M_{e}}{M^{*} - M_{e}} = \frac{6 \exp[-\pi/(R^{2}D_{c})]}{\pi^{2}}$$
(2.68)

The grain shape is not assumed spherical; the equivalent radius is defined as:

R - 3V/s

where: $V = kernel volume, m^3$

s = kernel surface area, m^2

The temperature and the moisture content T_a and M_e , respectively, are the drying air temperature and the corresponding equilibrium moisture content.

2.4.2 Equilibrium Moisture Content Models

The thin-layer equations discussed above require the grain equilibrium moisture content at the drying air conditions (temperature and relative humidity). The following are some of the equations used for predicting the equilibrium moisture contents of corn:

Thompson et al. (1968):

$$M_e = [ln(a - rh/{0.382(1.8T + 82)}]^{.5}$$
 (2.69)
Kalchick et al. (1979):
 $M_e = 0.062(RH)^{0.0274}/lnT$ O52 (2.70)

$$M_{2} = 0.396 \exp(.5*RH)/lnT$$
 5299.99 (2.71)

where M_e is the equilibrium moisture content (decimal); RH and rh are the percent and the decimal air relative humidity, respectively; and T is the air temperature (°C). Other equilibrium moisture content equations can be found in Bakker-Arkema et al. (1983). The equilibrium moisture content models should be used with the thin-layer equations for which they were validated.

2.4.3 Deep-bed Drying Models

For the research presented in this dissertation an in-bin semicontinuous flow dryer was used to dry corn. The in-bin drying process can be modeled using a deep-bed simulation model. Bakker-Arkema et al. (1974) developed a series of deep bed drying simulation models. The models are subject to the following assumptions:

- there is no shrinkage of the grain bed during the drying process;
- the temperature and the moisture content gradients within an individual particle are negligible;
- 3. particle to particle thermal conductivity is negligible;
- the airflow is plug type (no wall effects);
- 5. there is no heat loss through the dryer (or bin) walls and the walls have negligible heat capacity;
- the heat capacity of the moist air and of the grain is constant during short-time periods;
- accurate thin-layer, moisture equilibrium isotherms and latent heat of vaporization equations are known.

The models (Bakker-Arkema et al., 1974; Rugumayo, 1979) consider the basic laws of mass and heat transfer in the analysis of the drying process. Thin-layer equations developed by Rugumayo (1979), Thompson et al. (1968), and Misra (1978), are used to predict the drying rate of corn. Drying processes of other crops can be modeled if the appropriate auxiliary equations are included. The models solve for the grain and air temperature, the air absolute humidity and relative humidity, and the grain moisture content as a function of time and position in the drying or cooling bed.

The accuracy of the results depends upon the accuracy of the drying rate equations, and the equations used to predict the thermal and the physical properties of a given product.

2.4.3.1 Stationary Deep-bed Model

Brooker et al. (1974) analyzed stationary bed drying by making energy and mass balances on a differential volume located at an arbitrary position in the stationary bed. The following set of four differential equations was obtained:

$$\frac{\partial T}{\partial z} = \frac{-h a}{G_a c_a + G_a c_v H} (T - \theta)$$
(2.72)

$$\frac{\partial \theta}{\partial t} = \frac{h a}{\rho_p c_p + \rho_p c_w M} (T-\theta) - \frac{h_{fg} + c_v (T-\theta)}{\rho_p c_p + \rho_p c_w M} G_a \frac{\partial H}{\partial z}$$
(2.73)

$$\frac{\partial H}{\partial z} = -\frac{\rho_p}{G_a} \frac{\partial M}{\partial t}$$
(2.74)

$$\frac{\partial M}{\partial t}$$
 = an appropriate thin-layer drying equation (2.75)

The boundary and initial conditions are:

a.
$$T_{(0,t)} = T_{inlet}$$

b. $\theta_{(x,0)} = \theta_{initial}$

c.
$$H(o,t) = H$$
inlet

d.
$$M(x,o) = M$$
initial.

.

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CHAPTER 3

FURNACE DESIGN, CONSTRUCTION, AND OPERATION

3.1 Design and Construction

The concentric vortex-cell biomass furnace (CVCF) is a modification of a furnace developed at Iowa State University and described by Claar et al. (1981). The furnace consists of two concentric steel cylinders (see Figure 3.1). The outer cylinder is 1.22 m in diameter and 3.66 m high and is formed from 11 gage (GA) mild steel. The inner cylinder is 96.5 cm in diameter and 3.35 m high and made of 3 GA mild steel. The top 2.75 m of the inner cylinder is lined with 11.4 cm thick firebricks. The firebricks are supported by a round steel table with a hole in the middle. The outside and the inner diameters are 96 and 66 cm, respectively. The height of the table is 56 cm. The cylinders are covered with lids through which a chimney, 61 cm high and 36 cm in diameter, made of 3 GA mild steel is inserted. The inner lid is insulated (on the inside) with 2.5 cm thick blanket insulation with a thermal conductivity of 3.444 W/m-°C at 800°C. A 16 GA eductor is horizontally connected at the top of the chimney. The eductor consists of a 147 cm long diffuser with a throat diameter of 36 cm and a diffuser tail end diameter of 66 cm, and an 8-cm nozzle (see Figure 3.4). The increase in the air velocity at the nozzle tip and the expansion of the flue gases in the diffuser result in a





0.25-0.75 kPa pressure reduction at the top of the chimney inside the combustion chamber. The pressure reduction depends upon the air velocity at the nozzle tip.

A 76 cm diameter sloping (12 degree) grate with a cross sectional area of 0.43 m^2 is located 61 cm above the bottom of the inner cylinder to support the fuel pile.

An opening in the cylinder below the grate provides access to remove the undergrate ashes. The opening is controlled by means of two doors, the outside is hinged on the outer cylinder and the inside is bolted to the inner cylinder. A 15 cm diameter pipe is located in a hole cut on the inside door. A disc slides inside the pipe to regulate the undergrate airflow rate. The disc is adjusted manually by means of an axial bolt welded on the disc and rotating through a nut welded on the outside door (the disc-pipe mechanism acts as a gatevalve for regulating the undergrate airflow). Both doors can be opened to remove the ash below the grate.

A 25 cm^2 square opening is cut 90 cm above the furnace base in both cylinders to provide access to the combustion chamber for lighting and observation of the fire. The opening is covered with firebricks on the inside and a mild steel door on the outside.

The inner cylinder (lined with firebricks) has two rows of tuyeres, three tuyeres per row, positioned at an angle of 18 degrees with respect to the cylinder wall. The tuyeres are fabricated from 5 cm nominal diameter, schedule 40, seamed stainless-steel pipe. Each tuyere has a cross-sectional flow area of 22 cm².

The fuel is placed onto the sloping grate by an automatic auger feeder system. The system consists of an electric motor-driven feed wagon, a feed hopper and a stoker-auger driven by a 0.37 kW (1/2 Hp) motor. The rotational speed of the stoker-auger is controlled by a speed reduction system consisting of 4 to 1 variable speed belt drive, a 200 to 1 double reduction gearbox, and finally a 4 to 1 chain-drive reducer. The minimum rpm is 0.5; the maximum 2.

The combustion and the eductor air streams are supplied by a 0.74 kW (1Hp), 36 cm axial fan. The fan forces air into a 36x43x43 cm plenum from which the combustion and the eductor air streams are supplied.

The combustion air is forced into the furnace plenum (between the two cylinders) through a 20 cm diameter duct. The air is preheated to 93-205°C in the furnace plenum by convective and radiant heat transfer. The undergrate primary combustion air is introduced through the adjustable gatevalve previously described. Air for secondary combustion is introduced via the furnace plenum into the secondary combustion zone through the tuyeres. The combustion airflow is regulated by a butterfly valve.

The air for the venturi eductor nozzle is supplied by a 10 cm diameter duct connected to the fan plenum. The 10 cm duct is reduced to 8 cm diameter at the nozzle exit. The eductor airflow depends upon the combustion airflow rate. If the butterfly valve (regulating the combustion airflow) is fully open, less air is available for the eductor, and vice versa.

A 1.8 m diameter 24 GA sheet-metal shroud surrounds the top 1.3 m section of the furnace; it extends 1.2 m above the furnace to improve heat recovery and to facilitate coupling of the furnace to the in-bin counterflow drying bin.

3.2 Combustion Principle of the Concentric Vortex-Cell Furnace

In the concentric-vortex furnace, combustion air is preheated between the two steel cylinders. The primary air enters the fuel pile at the bottom of the grate where gasification and pyrolysis of the fuel takes place. The producer gases travel upwards into the secondary combustion zone of the furnace. Secondary air from the furnace plenum enters into the upper secondary combustion zone through the tuyeres. The tuyeres cause a vortex and mixing of the flue gases. Unburned material or fly ash is centrifugally separated from the flame spiral. The particulates fall onto the top of the burning pile and are reignited. There are no tuyeres located directly at the top of the burning pile. The high velocity air from such tuyeres would agitate the pile and cause excessive unburned particles to accelerate upwards and escape through the chimney.

The vacuum developed at the top of the chimney by the eductor ensures that smoke and other volatile gases do not escape through the feed auger and other leaks. Thus, the vacuum prevents backfiring through the feed system and accelerates the flue gases from the combustion chamber into the chimney.

The exhaust flue gases are blended with the ambient air in a 91.4×91.4 cm duct that connects the furnace shroud to the dryer fan

intake. The temperature of the blended air is between 100-150°C depending on the desired drying temperature.

The drying system consists of an in-bin counterflow unit built into a 5.50 m diameter, 3.70 m high bin. It is equipped with a 9 kW (12.5 Hp) centrifugal fan. The drying system is described in section 2.3.3.5.

3.3 Furnace Operation

The furnace is started by a propane torch and requires about 30 minutes before the desired operating temperature is reached. During the start-up period, a door in the heat duct between the furnace and the dryer fan intake is opened to allow the products of incomplete combustion to be discharged into the atmosphere. The dryer fan is turned on when the exit temperature of the furnace flue gas is about 540°C. The flue gases are blended directly with ambient air to obtain the desired drying air temperature. The fuel feed rate is regulated to maintain the proper drying temperature. The combustion air is kept at 120-170% of the stoichiometric air to avoid smoke and soot in the exhaust gas and to keep the exit temperature of the flue gas experience accelerated damage when the exhaust gas temperature exceeds 1095°C.

3.4 Concentric Vortex-Cell Furnace Design Theory

Concentric vortex-cell furnaces have been built by trial and error (Claar et al., 1981). The theoretical basis for the design of CVCF and other biomass furnaces is lacking in the literature. In the

following section the theoretical considerations are discussed that will contribute to the design of CVCF.

3.4.1 The Design Heat Output

The heat output of a furnace depends upon the environmental conditions, the furnace design, the grate area, the combustion chamber volume, and the efficiency of mixing the combustion air and the combustible materials in the furnace, and the inherent fuel characteristics (as defined by the particle size, the moisture content, and the fuel type). Claar et al. (1981) reported a heat output of 5.3 GJ/h per m² of grate area, of 1.9 GH/h per m³ of combustion chamber volume. The heat output of the MSU (Michigan State University) CVCF is 2.5 GJ/h (grate area = 0.43 m², combustion chamber volume = 1.3 m^3); with 20% moisture content of wood, the required maximum fuel feed rate is approximately 160 kg/h (assuming a net heating value of 15.63 MJ/kg).

3.4.2 Grate Design

The 1981 model of the MSU CVCF had a solid hearth similar to the hearth by Claar et al. (1980b). It was impossible to continuously separate the ash from the burning fuel on the solid hearth. The ash accumulated on the hearth, smothering the fire. Also, the increasing amount of the ash raised the bed-depth of the fuel pile, resulting in large amounts of fly ash in the flue gases. Complete combustion of char was impossible due to the inability of air to penetrate the mixture of unburned combustible materials and ash. This resulted in inefficiency due to unburned fuel and in a high resistance to the fresh fuel flow onto the hearth. To overcome the above limitations, the grate was redesigned in order to ensure complete char combustion and continuous separation of the ash from the combustible materials.

Junge (1979) suggested the following criteria for designing grate systems in spreader _stoker boilers:

- the system must provide uniform distribution of the undergrate air;
- the system must permit the removal of ash with minimum labor;
- the system must be able to withstand high temperatures;
- the system must be able to expand and contract with thermal cycling without buckling, warping, or opening large gaps;

5. the system must be designed for minimum maintenance.

To satisfy the above requirements, a slightly sloping grate (with 12-degree slope) was placed above a 0.25 m^3 ash receptacle. The grate was made of 16 GA, 4-mesh screen. Firebricks were randomly spaced on the screen to protect it from high temperatures. The screen (with 6.35 mm holes) was selected to facilitate combustion of wood chips and corncobs as well as large grains such as corn and soybeans.

During combustion the undergrate air cools the grate and provides oxygen required for complete char combustion. Combustible materials are held on the grate while the ashes fall through the grate. Combustion of char particles is completed under the grate. The 12-degree slope facilitates uniform fuel distribution on the grate. Also, a combustion front from the lower end of the grate (and advancing towards the feed) is established. Thus, three regimes are established in the furnace: (1) char combustion on and under the grate, (2) new fuel drying on the grate, and (3) fuel pyrolysing and burning between the char and the new fuel. The undergrate airflow is regulated to maintain char combustion (to provide pyrolysis heat) without fluidizing the fuel bed. Fluidization of the fuel bed results in excessive fly ash development and possibly undesirable combustion of fuel in the feed hopper.

3.5 Fuel Feed System

The designing of a fuel feed system consists of determining the feed auger size, maximum rpm and power requirement, and the feed auger speed control system.

The screw conveyer (auger) designed consists of a standard 25 cm diameter auger rotating in a semicircular trough. The auger is driven by an electric motor through the speed reduction system described in section 3.1.

The theoretical capacity of the auger was calculated using the following equation (Henderson and Perry, 1976):

m = 1.86 x
$$10^{-5} (D^2 - d^2)P\rho_b R$$
 (3.1)
where: m = capacity, kg/h
D = screw diameter, cm
d = shaft diameter, cm
p = pitch, cm
 ρ_b = material bulk density, kg/m³
R = auger speed, rpm

Equation (3.1) assumes that the auger is 100% full of the conveyed material. The volume of the auger occupied by the biomass material depends upon the particle size, flowability, abrasiveness, and packing characteristics of the fuel. The Link-Belt Company classified bulk solids (including wood chips) for auger conveyor design (Perry and Chilton, 1973). Wood chips are described as irregular in size with a sluggish flowability (angle of repose more than 45 degrees), nonabrasive, very light and fluffy, and interlocked to resist digging. The average bulk density of wood chips is 160-481 kg/m³. Given these characteristics, wood can occupy only 45% of the available screw conveyor volume. Thus, a 25 cm (diameter) screw has a maximum capacity of 0.227 m^3 /h per rpm using equation (3.1) with a factor of 0.45. This translates to 91 kg/h per rpm if an average bulk density of 400 kg/m³ is assumed.

The auger used on the MSU CVCF is designed for a minimum and maximum speed of 0.54 and 2.0 rpm, respectively. Thus, its minimum and maximum capacities are 49 and 181 kg/h, respectively. The maximum rate is slightly higer than the 160 kg/h required to give the maximum heat output of the furnace (section 3.3.1). The power requirement for screw conveyors is the sum of the power necessary to drive the screw empty and that necessary to move the material. The first component is a function of conveyor length, speed of rotation, and friction in the conveyor bearings. The second term is a function of the total weight of the conveyed material per unit time, the conveyed length, and the depth to which the trough is loaded.

In addition to the above components, extra power is required to overcome transient overloads due to extra friction on the system. The extra power is necessary when conveying irregularly sized materials such as wood chips and corncobs. The following equation was used to estimate the power required to convey the materials (Henderson and Perry, 1976):

$$Pk = M L \times 1.635 \times 10^{-4}$$
(3.2)

where PK is the conveying power, kW; M is the material flow rate kg/h; and L is the length, m.

According to equation (3.2), the power required to convey 181 kg/h for 1 m is less than 0.03 kW. The power required to drive the screw empty and to overcome transient resistances is considerable. A 0.37 kW (1/2 HP) motor was selected.

The fuel feed control system consists of two diaphragm switches (located at the top and bottom of the fuel hopper) and a magnetic relay switch (see Figure 3.2). The switches control the motor that drives the feed wagon discharge system. When the feed hopper is empty, the





contacts in the switches A and B (see Figure 3.2) are closed, and, therefore, the relay switch K is energized and closes contacts K1, K2, and K3 to energize the feed wagon motor M. Fuel is discharged into the fuel hopper. Upon reaching level 1 the fuel pushes against the diaphragm switch A and opens the contact. The current-flow through the relay is maintained through switch B at the top of the hopper and contact K1. Upon reaching level 2, the fuel pushes against switch B and opens its contact. Current-flow to the relay is interrupted and contacts K1, K2, and K3 are opened. The feed wagon motor stops. As the stoker-auger continues to move the fuel into the furnace, the fuel level falls below level 2, and contact B closes. Since contacts A and K remain open, the relay is not energized. When the fuel level falls below level 1, the pressure on switch A is released and contact A is closed. The relay is energized and the cycle is repeated. Thus, the intermittent action of the feed wagon motor maintains the fuel between levels 1 and 2 in the fuel hopper.

A vibrator (Model 20N manufactured by Eriez Magnetics) is attached to the side of the fuel hopper to prevent bridging of the fuel at the bottom of the hopper.

The stoker-auger speed (and therefore, the fuel feed rate) is manually set to maintain the desired drying air temperature by adjusting the variable speed belt drive. If the fuel conditions do not change drastically during the combustion process, the fluctuation in the drying air temperature is limited to $\pm 5^{\circ}$ C.

3.5.1 Furnace Air Supply System

The furnace air supply system in the MSU CVCF has three functions: (1) to supply oxygen for primary combustion (undergrate air) and secondary combustion (overfire air); (2) to provide high velocity air to the eductor for maintaining a vacuum in the combustion chamber for preventing backfiring (premature ignition of fuel) in the fuel hopper, especially during start-up; (3) to provide the vortex motion for centrifugal separation of fly ash and unburned particles from the flue gas.

The following equation can be used to estimate the stoichiometric combustion air (Perry and Chilton, 1973):

$$M_{a} = 1.38(C/12 + H/4 - 0_{2}/32 + S/32)$$
(3.3)

where M_a is the combustion air (kg/kg fuel dry matter); and C, H, O₂ and S are the percentages of carbon, hydrogen, oxygen, and sulfur, respectively.

The total amount of combustion air (for both the primary and the secondary combustion) is determined from equation (3.3) using an average ultimate analysis of wood, and the maximum fuel feed rate (160 kg/h) previously determined. The average ultimate analysis of wood (Table 2.2) is 50.5% carbon, 6.2% hydrogen, 46.1% oxygen, 0.88% ash, and 0.0% sulfur. Using these values in equation (3.3), the stoichiometric air required is 6.1 kg/kg of fuel dry matter. This is equivalent to 4.9 kg of air per kg of wood at 20% moisture. Thus, the stoichiometric air required in the MSU CVCF is 4.9x160 = 784 kg/h at

the maximum fuel (wood) feed rate. Excess air is required for complete combustion due to the poor mixing of air and combustible materials in the furnace. Also, wet fuels require more air than dry fuels. For design purposes, 50% excess air was assumed. This gives the maximum combustion airflow rate of 1180 kg per hour.

The minimum undergrate air may be determined if the ultimate analysis of char is known. (Table 2.2 contains the available ultimate analysis of char.) The stoichiometric air required for complete combustion of char is 10.5 kg/kg (using the average ultimate char analysis) or 2.1 kg/kg fuel dry matter since char constitutes about 20% of the products of pyrolysis (Admas, 1980). Thus, the undergrate airflow is approximately 4.2 kg/kg fuel dry matter with 50% excess air.

The eductor airflow requirement may be computed by applying the Bernoulli equation for adiabatic, nonviscous flow to the eductor nozzle. The assumption of adiabatic flow is justified by the fact that the heat transfer per unit mass is small compared to the kinetic energy changes. The velocity in the nozzle is too large to allow enough time for the air to come to thermal equilibrium with the walls of the short eductor nozzle. The Bernoulli equation for compressible flow is (assuming no elevation differences):

$$\frac{U_1^2}{2} + \frac{k(P_1/\rho_1)}{k-1} = \frac{U_2^2}{2} + \frac{k(p_2/\rho_2)}{k-1}$$
(3.4)

Where U is the gas velocity (m/s); P is the static pressure (kPa); ρ is the density (kg/m³); and k is the ratio of specific heat capacities $(k = C_p/C_v = 1.4 \text{ for air})$. The subscripts 1 and 2 denote the cross section at the nozzle entrance and exit. respectively.

The equation of mass continuity can be used to eliminate one of the unknown velocities, U_1 and U_2 :

$$A_{1}U_{1}\rho_{1} = A_{2}U_{2}\rho_{2}$$
(3.5)

Algebraic rearrangement of the above equations along with the isentropic relationship $P_1/\rho_1^k = P_2/\rho_2^k$ results in the following equation:

$$U_{2} = [2kRT_{1}C_{1}/C_{2}]^{1/2}$$
(3.6)

where: $C_1 = (P_2/P_1)^{(k-1)/k}$ $C_2 = [(A_2/A_1)^2 (P_2/P_1)^{2/k} - 1](k-1)$

Since k = 1.4 for air, equation (3.6) can be rewritten as:

$$U_{2} = 37.88[T_{1}C_{1}/C_{2}]^{1/2}$$
(3.7)

Equation (3.7) is suitable for adiabatic isentropic flow through converging/diverging nozzles. A similar equation for straight ducts can be developed from equation (3.4):

$$U_{2} = \left[2RT_{1}C_{1}k/(1-k)\right]^{1/2}$$
(3.8)

For air, k = 1.4 and R = 287, and

$$U_{2} = 44.82[T_{1}(-C_{1})]^{1/2}$$
(3.9)

Equations (3.6) and (3.9) were used to design the axial fan for both the eductor nozzle and the combustion airflows. For the eductor to maintain a sufficient vacuum in the combustion chamber, a pressure of 0.25 kPa below the atmospheric pressure is required. An axial fan operating at approximately 0.5 kPa above atmospheric pressure was selected.

The eductor nozzle is made of a 10 cm schedule No. 40 steel pipe connected to a 7.62 cm tapered reducer. The inside cross-sectional areas of the pipes are 0.0082 m^2 and 0.00477 m^2 , respectively. At an operating temperature of 50°C, the nozzle exit velocity and the mass flow rate are 38 m/s and 715 kg/h. A 14-inch diameter, 1 HP axial flow fan was available with a capacity of 2,100 kg air per hour at 10°C. With 715 kg/h flowing through the eductor, approximately 1385 kg/h is available for combustion (some of the eductor air is used to complete the combustion of unburned volatiles that may be contained in the flue gases).

Equation (3.9) was used to predict the airflow rate in the tuyeres. The tuyeres are constructed of schedule No. 40, 2 inch nominal diameter pipes with a flow area of 0.0022 m^2 . The pressure in the furnace plenum is between 0.125 and 0.25 kPa above the combustion chamber pressure (slightly below the atmospheric pressure) depending upon the undergrate airflow rate, the drying airflow and the combustion chamber temperature. The maximum furnace plenum temperature is about 100°C. Thus, the airflow velocity and the total airflow in the tuyeres are approximately 20 m/s and 879 kg/h (the undergrate airflow rate under these conditions is approximately 500 kg/h).

The above analysis is used for estimating the fan size for supplying the eductor and combustion air when the furnace is operated without the drying system. During drying the drying fan imposes an additional vacuum on the furnace resulting in additional airflow supplied to the furnace.

3.5.1.1 Eductor Design

The eductor consists of the eductor nozzle, a suction chamber, and a diffuser (see Figure 3.3). The eductor is a jet pump in which a high velocity fluid (the motive fluid) is forced through the nozzle. The momentum and the kinetic energy of the motive fluid are used to entrain and pump a second fluid stream, referred to as the induced fluid. At least three processes are involved (Davies et al., 1967):

- acceleration of the induced fluid by the impact of the particles of the motive fluid from the nozzle;
- entrainment of the induced fluid by viscous friction at the periphery of the nozzle jet;
- 3. overexpansion of the jet to a pressure below that of the induced fluid with consequent flow of the induced fluid towards the axis of the jet.

The design of an eductor requires consideration of the temperature and pressure of the motive and the induced fluids as well as the eductor size and geometry.

The diffuser is the most critical part of an inductor. The diffuser consists of the diffuser entrance, the diffuser throat, and the diffuser outlet or tail pipe (see Figure 3.3). According to Kroll



Figure 3.3. The Schematic Diagram of the Eductor.

C = Tail pipe			
<pre>B = Diffuser throat</pre>	T = Temperature (K)	Subscripts (s) Motive fluid	(o) Induced fluid
A = Diffuser entrance	P = Pressure (kPa)	M = Mass flow rate (kg/s)	

(1947), entrance to the diffuser throat should be rounded and bell-mouthed. The taper angle α should be larger than 20 degrees. This prevents shock and eddy losses at the inlet. The diffuser throat is the mixing zone of the eductor. Its length should be 4-14 diameters [the optimum length should be 7.5 diameters (Kroll, 1947)]. The throat cross-sectional area should allow the flow of both the motive and induced fluids without chocking or back flow.

Several methods for determining the optimum throat area have been suggested (Kastner and Spooner, 1950; Keenan et al., 1950; Davies et al., 1967). The procedures are especially suitable for eductors operating at relatively high nozzle pressures (over 34 kPa gauge). The diffuser tail pipe should have a divergence of 4 to 10 degrees after the throat for pressure recovery. The length of the tail pipe should be at least twice but not more than 12 times the throat diameter (Davies et al., 1967).

The distance of the nozzle exit to the diffuser throat affects the eductor performance (Kroll, 1947). The maximum distance increases with increased nozzle supply pressure, but should be 0.5 to 5 times the diffuser throat diameter. Kroll (1947) recommended that the nozzle position should be adjustable so that adjustment for best performance can be made during the eductor operation.

The MSU eductor system is designed to operate at a low nozzle supply pressure (0.5 to 0.75 kPa gauge). Also, the induced fluid (the flue gas) is energized by compressed air in the furnace and by the vacuum induced by the drying fan. Thus, the function of the eductor is to induce a slight vacuum in the furnace chimney and, therefore, to prevent backfiring in the fuel feed system. This means that the eductor design is not very critical. However, an eductor which induces a high vacuum in the furnace chimney is desirable since it allows more combustion air into the furnace and thus increases the furnace output.

Several investigators have developed a theory for constantpressure and constant-area mixing of the motive and induced air streams in eductors (Kastner and Spooner, 1950; Keenan et al., 1950; Davies et al., 1967). The theory is based upon equal temperatures of the streams. In the MSU CVCF, the motive air is only a few degrees above the ambient, the induced flue gas temperature is in the order of 700°C. Therefore, the motive and the induced fluids cannot be regarded as the same.

The following procedure is developed to calculate the theoretical eductor throat diameter for constant area mixing. The momentum equation is, referring to Figure 3.3:

$$A_1(P_1 - P_2) = (M_s + M_o)U_2 - M_s U_e - M_o U_i$$
 (3.10)

$$U_{i} = M_{o} / [\rho_{i} (A_{1} - A_{e})] = \{M_{o} / [\rho_{o} (A_{1} - A_{e})]\} (P_{o} / P_{1})^{1/k}$$
(3.11)

where A is area (m^2) ; P is pressure (kPa); M is mass flow rate (kg/s); U is velocity (m/s); k is the ratio of specific heat capacities, previously defined; and ρ is density (kg/m³). The subscripts 1, 2, e, i, o, and s denote the throat entrance, throat exist, nozzle exit, induced stream just before mixing, induced stream before mixing, and the motive stream, respectively. The nozzle exit velocity U_e is determined by equation (3.7). Substituting U_i in equation (3.11) and solving for P_2 .

$$P_{2} = P_{1} + \frac{M_{s}U_{e}}{A_{1}} + \frac{M_{0}^{2}}{\rho_{0}A_{1}(A_{1} - A_{e})} \left(\frac{P_{0}}{P_{1}}\right)^{1/k} - \frac{(M_{s} + M_{0})U_{2}}{A_{1}} (3.12)$$

The throat exit velocity, U_2 , depends upon the temperature, pressure, area, and the composition of the mixture at the diffuser throat exit. Assuming adiabatic mixing:

$$T_{2} = (M_{S}C_{S}T_{S} + M_{O}C_{O}T_{O})/M_{S}C_{S} + M_{O}C_{O})$$
(3.13)

Also:

$$1/\rho_{2} = \sum_{i=1}^{n} (Xi/\rho_{i})_{T_{2}}$$

Therefore,

$$U_{2} = (M_{S} + M_{O})/\rho_{2}A_{1}$$
(3.14)

Substituting equation (3.14) in (3.12):

$$P_{2} = P_{1} + \frac{M_{s}U_{e}}{A_{1}} + \frac{M_{0}^{2}}{\rho_{0}A_{1}(A_{1}-A_{e})} (P_{0}/P_{1})^{1/k} - \frac{(M_{s} + M_{0})^{2}}{A_{1}^{2}\rho_{2}}$$
(3.15)

The throat exit pressure P_2 must be at least equal to the atmospheric pressure on higher to force the mixture out of the eductor. Thus,

$$P_{1} + \frac{M_{s}^{U}e}{A_{1}} + \frac{M_{o}^{2}}{\rho_{o}A_{1}(A_{1}-A_{e})}(P_{o}/P_{1})^{1/k} - \frac{(M_{s}+M_{o})^{2}}{\rho_{2}A_{1}^{2}} = P_{a}$$

Rearranging:

$$A_{1}^{3}(P_{a}-P_{1}) - A_{1}^{2}(M_{s}U_{e} + A_{e}(P_{a}-P_{1})) - A_{1}\frac{M^{2}}{\rho_{o}}(P_{o}/P_{1})^{k} - \frac{M^{2}}{\rho_{2}} - M_{s}U_{e}A_{e} - \frac{M^{2}A_{e}}{\rho_{2}} = 0$$
(3.16)

Equation (3.16) can be solved for A_2 . Equations (3.9) to (3.16) can be used to find the theoretical optimum nozzle/throat area. The actual optimum area will vary slightly from the theoretical because of pressure losses due to eddy currents and nozzle/throat roughness.

3.5.1.2 Tuyere Design

The operating principles of tuyeres in concentric vortex-cell furnaces has been explained by Claar et al. (1980b). The main function of tuyeres in a concentric vortex-cell furnace is to direct the secondary combustion air into the combustion chamber in a downward vortex spiral. The downward vortex generated by the air from the tuyeres encloses an inner upward vortex consisting of a mixture of gaseous products of combustion, unburned particles, and fly ash. The solids are centrifugally separated from the inner flame spiral into the downward vortex airstream. The unburned particles are reignited on top of the fuel bed.

The concentric vortex action minimizes problems with clinkers, errosion of the firebricks, and corrosive deposits by condensing the

slagging fly ash when burning fuels with high fusible ash content (e.g., husklage).

The upward spiral of the flame increases the residence time for the entrained particles and combustion gases in the combustion chamber. This increases the combustion efficiency and minimizes the escape of unburned particles and fly ash through the chimney.

The design of tuyeres has been by trial and error. There has been no basic research effort to study the effect of tuyere design parameters on the reduction of fly ash from and combustion efficiency of concentric vortex-cell furnaces. The tuyere design parameters include the tuyere size and angle (the horizontal and the vertical angle with respect to the furnace wall), the number and the spacing of tuyeres and the exit air velocity.

As mentioned in section 3.1, six tuyeres are built into the MSU CVCF furnace. The tuyeres are in two rows, three tuyeres per row. The first row is located 1.52 m from the base of the furnace. The spacing between rows is 0.91 m, and the tuyeres are equally spaced around the furnace at an angle of 18° with respect to the furnace wall. The tuyeres are fabricated from 5-cm nominal diameter schedule 40 stainless-steel. The maximum exit air velocity from the tuyeres is estimated to be 20 m/s. This design is satisfactory for the MSU furnace.
CHAPTER 4

THEORY

4.1 Furnace Performance Simulation

The performance of a biomass furnace is measured in terms of the efficiency of converting the chemical energy stored in the mass into thermal energy. The major heat losses from a furnace are the radiation and the convectional heat losses to the environment and the incomplete combustion of fuel. Incomplete combustion is manifested by appearance of smoke in exhaust gases and/or carbonaceous material in ashes.

Biomass furnaces have different configurations of the combustion chamber, the grate, the exhaust system, and the combustion air supply system. They also differ in the design of the heat recovery systems. The sizes and the materials of construction are different. The radiation and convectional heat losses are affected by the configuration and the size of the furnace, as well as the temperature differential between the furnace and the environment. Thus, it is impossible to develop a universal simulation model applicable to all furnaces. The model of the MSU CVCF system developed in the following sections can be modified to simulate the heat losses and the performance of similar furnaces.

4.1.1 Preliminary Estimates

The conservation of energy equation (2.41) is used to analyze heat losses from the combustion chamber. If the work and the kinetic energy terms are assumed negligible, and if the enthalpy terms in equation (2.41) are replaced by the right hand side of equation (2.42), equation (4.1) is obtained:

$$Q = \Sigma M(h_o - h_{Tr})_{ri} + \Delta H_R + \Sigma M(h_{Te} - h_o)_{pi}$$
(4.1)

where M is the mass flow rate (kg/h); h_0 is the enthalpy of a compound at 298 K; h_{Tr} is the enthalpy of a reactant at temperature Tr (K); h_{Te} is the enthalpy of a product at temperature Te (K); ΔH_R is the heating value at 298 K; Tr is the initial temperature of the reactants (K); Te is the exit temperature of the products (K); the subscripts r, p, denote a reactant, and a product; and the subscript i denotes a compound. Equation 4.1 can be used to predict the adiabatic flame temperature (or the total heat losses if the final product temperature is known). In a biomass furnace the reactants are fuel dry matter, fuel free moisture, and air. The major products are carbon dioxide, water, nitrogen, and excess oxygen.

The MSU CVCF furnace is analyzed using Figure 4.1.

The energy balance on control volume 1 (CV1) results in equation (4.2):

$$\sum_{j=1}^{\Sigma} M (h_{T_{1}} - h_{T_{1}})_{i} = \sum_{j=1}^{\Sigma} M (H_{298} - h_{T_{3}})_{i}$$

$$+ \Delta H_{R} + \sum_{prod}^{\Sigma} M (h_{T_{4}} - h_{298})_{i} \qquad (4.2)$$



Figure 4.1. Schematic Flow Diagram of the MSU Concentric Vortexcell Furnace.

- 1, 2 = Ambient air
 - 3 = Preheated combustion air
- 1, 7 = Diluting air drawn around the furnace
- 2, 5 = Eductor air stream
 - 8 = Diluted flue pass to dryer

The adiabatic temperature T'_{4} is computed by equation (4.1) with zero heat losses:

$$\sum_{\text{reac}}^{\Sigma M} (h_{298} - h_{T_3})_{j} + \Delta H_{R} + \sum_{\text{prod}}^{\Sigma M} (h_{T_4} - h_{298})_{j} = 0 \quad (4.3)$$

The reactants in equations (4.2) and (4.3) are the air mass stream M_3 and the fuel. Similar equations are obtained for control volume 2 (CV2):

$$\sum_{prod}^{\Sigma} M (h_{T_{6}} - h_{T_{6}})_{i} = \sum_{react}^{\Sigma} M (h_{298} - h_{T_{2}})_{i} + \Delta H_{R_{0}}$$

$$+ \sum_{prod}^{\Sigma} M (h_{T_{6}} - h_{298})_{i} \qquad (4.4)$$

$$\sum_{reac}^{\Sigma} M (h - h_{T_2})_i + \Delta H_R + \sum_{o}^{\Sigma} M (h_{T_1} - h_{298})_i = 0 \quad (4.5)$$

The reactants in equations (4.4) and (4.5) are the air mass stream M_2 and the fuel.

The heat output from the combustion chamber is the sum of the energy required to preheat the combustion air and the fuel, the energy required for preheating the diluting air before mixing, and the heat lost to the environment. The heat input into the furnace is the product of the fuel dry matter feed rate (kg/h) and the fuel higher heating value (kJ/kg). Thus, for control volume CV1:

$$Q + M_{3}C (T_{3}-T_{2}) + M_{1}C (T_{7}-T_{1}) = -\Sigma M_{1}\Delta h_{i_{T_{3}}} + \Delta H_{R} + \Sigma M_{1}\Delta h_{i_{T_{3}}}$$
reac prod (4.6)

and for control volume CV2:

$$Q + M_{1}C (T_{7}-T_{1}) = - \sum_{reac} M_{1}\Delta h_{1} + \Delta H_{R} + \sum_{prod} M_{1}\Delta h_{1}$$
(4.7)

where $\Delta hi_T = hi_T - hi_{298}$ C = specific heat (kJ/kg°C).

The mass flow rates and the ambient temperature are known in equations (4.2) to (4.7). The equations are solved by an iterative procedure that starts with an estimated temperature of the preheated combustion air T_3 . Consequently, the adiabatic flame temperature can be computed from Equation (4.3). The corresponding furnace temperature ture T_{μ} is obtained from equation (4.2).

The eductor exit temperature is computed by applying mass and energy balances after mixing the flue gases and the eductor motive air at point 5. Thus,

$$T_{4} = \frac{(M_{4}CT_{4} + M_{2/3}CT_{2})}{(M_{4}C + M_{2/3}C)}$$
(4.8)

The temperature of T_6 obtained from equation (4.8) is compared with the solution for T_6 in equations (4.4) and (4.5). The iteration is repeated until a solution is obtained. This procedure results in approximate values for the combustion air preheated temperature T_3 , the furnace combustion chamber temperature T_4 , and the eductor exit temperature. The total heat loss cannot be predicted since equations 4.6 and 4.7 cannot be solved. The final combustion chamber temperature, the preheated combustion air temperature, preheated diluting air temperature, the furnace flue gas temperature before and after dilution, the drying air temperature and the total heat losses can be computed from a heat transfer analysis as will be shown in the next section.

4.1.2 Heat Transfer from Combustion Chamber

The heat losses from the combustion chamber occur in the form of radiative and convective heat transfer.

4.1.2.1 Radiative Heat Transfer

The flame in the combustion chamber looses heat to the chamber walls by radiation and convection. In the model the radiative heat transfer is predicted using the following equation:

$$Q_{R} = A_{w} \varepsilon F_{w-f} (T_{f}^{4} - T_{w}^{4})$$
(4.9)

The flame emissivity is computed using the Adams (1980) equations for soot, carbon dioxide, and water vapor (equations 2.58-2.60). Since the flame is entirely enclosed within the furnace chamber, the view factor F_{f-w} is equal to one.

4.1.2.2 Convective Heat Losses

The convective heat transfer from the flame to the combustion chamber walls is calculated by:

$$Q_e = A_w h_c (T_e - T_w)$$
(4.10)

The convective heat transfer coefficient h_c is estimated from the empirical correlation for rough pipes (Holman, 1981):

$$St_{b}Pr_{f}^{2/3} = f/8$$
 (4.11)

$$St_{b} = h_{c} / (\rho CU_{m})$$

$$(4.12)$$

Equations (4.11) and (4.12) are rearranged to solve for the convective heat transfer:

$$h_{c} = f_{\rho} C U_{m} / 8 \tag{4.13}$$

In equation (4.13) f is the friction factor. The friction factor depends upon the roughness of the surface and the Reynolds number, and varies between 0.008 and 0.1. In the MSU CVCF furnace the combustion chamber is lined with bricks and, therefore, it can be regarded as a rough pipe. The maximum value of 0.1 was selected for the friction factor of the chamber.

4.1.2.3 Total Heat Transfer from Combustion Chamber

The net energy out of the furnace is the sum of the enthalpy change of the reactants (fuel and air) from the initial temperature to the flame temperature, and the net heat transfer from and to the chamber walls. The next heat transfer is given by:

$$Q_{w} = A_{w} [(\epsilon_{f} F_{w-f} \sigma (T_{f}^{4} - T_{w}^{4}) + h_{c} (T_{f} - T_{w})]$$
(4.14)

4.1.3 Radiative Heat Transfer Between Cylinders

The furnace jacket consists of the annulus region (plenum) between the inner and the outer cylinders (marked D and E in Figure 4.2). Heat is transferred from the surfaces of the inner cylinder (6) to the outer surfaces of the cylinder (7) by radiation and convection. The surfaces (6) and (7) are considered concentric cylinders of infinite length. The radiation shape factors are (Howell, 1982):

$$F_{6-7} = 1$$
 (4.15)

$$F_{7-6} = r_6 / r_7 \tag{4.16}$$

$$F_{7-7} = 1 - F_{7-6}$$
(4.17)

The net radiative heat transfer from surface (6) to surface (7) is:

$$Q_{6-7} = \frac{\sigma (T_{6}^{4} - T_{7}^{4})}{\frac{1 - \varepsilon_{6}}{A_{6} \varepsilon_{6}} + \frac{1}{A_{6} F_{6-7}} + \frac{1 - \varepsilon_{7}}{A_{7} \varepsilon_{7}}}$$
(4.18)

The radiation thermal resistance between surfaces 6 and 7 is:

$$R_{16} = \frac{1 - \varepsilon_{6}}{A_{6}\varepsilon_{6}} + \frac{1}{A_{6}F_{6-7}} + \frac{1 - \varepsilon_{7}}{A_{7}\varepsilon_{7}}$$
(4.19)

Thus, equation (4.18) can be written as:

$$Q_{6-7} = \frac{\sigma \left(T_{6}^{4} - T_{7}^{4}\right)}{R_{16}}$$
(4.20)



Figure 4.2. Simplified Furnace Diagram. The letters refer to spaces and the numbers to surfaces.

Figure 4.3 represents the radiation, the conduction, and the convection heat transfer network for the plenum area between the inner and the outer cylinders, and the furnace combustion chamber. Heat balances on the network of Figure 4.3 result in the following set of simultaneous equations:

on surface 7:

$$\frac{E_{b_6}}{R_{16}} - E_{b_7} \left(\frac{1}{R_{16}} + \frac{1}{R_{17}}\right) - Q_{c_7-\infty} - Q_{c_71} - \frac{E_{b^{\infty}}}{R_{17}} = 0$$
(4.21)

On surface 6:

$$\frac{T_{w}^{-T_{c_{6}}}}{R_{18}} - \frac{E_{b_{6}}^{-} E_{b_{7}}}{R_{16}} - Q_{c_{6}} = 0$$
(4.22)

On the furnace wall W:

$$\frac{E_{bf} - E_{bw}}{R_{19}} + \frac{T_{f} - T_{w}}{C_{f}} - \frac{T_{w} - T_{b}}{R_{18}} = 0$$
(4.23)

The radiative heat transfer between the surfaces 1, 2, 3, and 4 is complex since all the surfaces radiate and absorb heat to and from each other. Surfaces 1, 2, 3, and 4 are formed by two coaxial cylinders (of inner and outer cylinders 2 and 4, respectively) and the two annular ends, 1 and 3. The radiation shape factors between various surfaces are calculated using the governing equations for the relevant shapes (C-86, C-87, and C-89) as presented by Howell (1982).



Radiation-convection Heat Transfer. Network from the furnace at temperature T_f to ambient at temperature T_∞ . R_1 , radiative resistance from outer furnace Figure 4.3.

wall(7) to the ambient; R_{16} radiative resistance from the inner cylinder wall (6) to the outer cylinder (7); R_{18} conduction resistance through the brick lining on the inside wall; R_{19} , radiative resistance from the flame to the combustion chamber wall; C_{∞} : Convective resistance from outer wall to the ambient; Q_{C6} ,

respectively, to the preheated air in the plenum; and $C_{f f}$: convective resistance q_{c7i} : Convective heat losses from the inner cylinder and the outer cylinder, from the flame to the furnace wall. The radiative heat transfer among the surfaces 1, 2, 3, and 4 can be simplified by analyzing the radiation network shown in Figure 4.4. The radiation resistance R_1 to R_{10} are defined in Figure 4.3. The network in Figure 4.4 is analyzed by the application of Kirchhoff's current law which states that the sum of the energy flows into a node is zero. The E_{bi} terms in Figure 4.3 represent the product σT_i^4 , the radiocity from a node i (the total radiation which leaves a surface per unit time and per unit area).

By applying the Kirchhoff law to the network in Figure 4.4, a set of four simultaneous equations is obtained:

$$\frac{E_{b_1}}{R_1} + \frac{J_2}{R_2} + \frac{J_4}{R_{10}} + \frac{J_3}{R_4} - J_1 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_4} + \frac{1}{R_{10}}\right) = 0$$
 (4.24)

$$\frac{E_{b_2}}{R_3} + \frac{J_1}{R_2} + \frac{J_3}{R_9} + \frac{J_4}{R_8} - J_2 \left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_8} + \frac{1}{R_9}\right) = 0$$
(4.25)

$$\frac{E_{b_4}}{R_7} + \frac{J_1}{R_{10}} + \frac{J_2}{R_8} + \frac{J_3}{R_6} - J_4 \left(\frac{1}{R_6} + \frac{1}{R_7} + \frac{1}{R_8} + \frac{1}{R_{10}}\right) = 0$$
 (4.26)

$$\frac{E_{b}}{R_{5}} + \frac{J_{1}}{R_{4}} + \frac{J_{2}}{R_{9}} + \frac{J_{4}}{R_{6}} - J_{3} \left(\frac{1}{R_{4}} + \frac{1}{R_{5}} + \frac{1}{R_{6}} + \frac{1}{R_{9}}\right) = 0 \quad (4.27)$$

A fifth equation is obtained by writing an energy balance for surface 4 that includes the convective heat loss from the surface:

$$\frac{J_{4} - E_{b_{4}}}{R_{7}} - Q_{C_{4}-1} - Q_{C_{4}-1}$$
(4-28)



Figure 4.4. Complete Radiation Network for the System 1, 2, 3, and 4 in Figure 4.2.

4.2 Heat Transfer Between the Furnace and the Hood

The surface marked 9 in Figure 4.2 is a reflective surface. Its emissivity and absorptivity are approximately zero. Thus, the thermal radiation resistance is high. Therefore, the four-surface system (3, 4, 8, and 9) reduces to a three-surface system consisting of surfaces 3, 5, and 8. The radiation network for the reduced system and radiation resistances R_{11} to R_{15} are presented in Figure 4.5.

The Kirchhoff analysis of the network in Figure 4.5 results in three simultaneous equations:

$$\frac{E_{b}}{R_{5}} + \frac{J_{7}}{R_{13}} + \frac{J_{6}}{R_{11}} - J_{5} \left(\frac{1}{R_{5}} + \frac{1}{R_{11}} + \frac{1}{R_{13}}\right) = 0$$
(4.29)

$$\frac{E_{b_5}}{R_{12}} + \frac{J_5}{R_{11}} + \frac{J_7}{R_{14}} - J_6 \left(\frac{1}{R_{11}} + \frac{1}{R_{12}} + \frac{1}{R_{14}}\right) = 0$$
(4.30)

$$\frac{E_{b_8}}{R_{15}} + \frac{J_5}{R_{13}} + \frac{J_6}{R_{14}} - J_7 \left(\frac{1}{R_{13}} + \frac{1}{R_{14}} + \frac{1}{R_{15}}\right) = 0$$
(4.31)

The energy balance on surface 3 (including radiation and convective heat gains and losses on both sides of the surface) gives:

$$\frac{J_3 - E_{b_5}}{R_5} - \frac{E_{b_3} - J_5}{R_5} - Q_{C_{3-0}} - Q_{C_{3-1}} = 0$$
(4.32)

Equation (4.33) is obtained from an energy balance on the top plate 5 (including convection from the top of the plate to the ambient and to the space between plate 5 and 3, and the radiation from the plate to the sky):



Figure 4.5. Radiation Network for the Surfaces 3, 5, and 8 in Figure 4.2.

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$$\frac{J_{6} - E_{b_{5}}}{R_{12}} - \frac{E_{b_{5}} - E_{b_{3}}}{R_{a}} - A_{5}[h_{\omega}(T_{5} - T_{\omega}) - h_{s_{1}}(T_{5} - T_{s_{1}})] = 0 \quad (4.33)$$

Equations (4.21) to (4.33) consist of a set of thirteen simultaneous equations with 13 unknowns. A computer program was written to solve the set of the equations after estimating initial values of T_2 , T_7 , and the temperature of the preheated combustion air T_d as functions of the combustion chamber temperature. The estimates are based on statistical analysis of the experimental temperature data. The following are the equations used for the initial guesses of the temperatures:

$$T_2 = 0.69T_f - 24.10 \tag{4.34}$$

$$T_7 = 0.24T_f - 139.80 \tag{4.35}$$

$$T_d = 9.18T_f - 83.00$$
 (4.36)

Equations 4.1 to 4.8 are used for the initial guesses of the preheated air temperature, the furnace adiabatic temperature, and the actual flame temperature.

The convective resistances and heat transfer rates are calculated using standard procedures for the relevant flow regimes, shapes, and temperatures as presented in the heat transfer literature (Holman, 1981; Gebhart, 1971). The convective heat transfer coefficient on the outer surfaces is a function of the ambient temperature. The influence of wind and precipitation are not included in this analysis.

A computer program was developed and used to analyze the furnace performance in terms of the heat losses and heat output at different fuel feed rates, and at different fuel and ambient conditions. The inputs to the model include:

- a. The fuel type.
- b. The fuel moisture content (% wet basis).
- c. The fuel feed rate (kg/h).
- d. The ambient temperature (°C) and the relative humidity (percent).
- e. The drying bin plenum pressure (kPa) (the pressure is employed to calculate the drying airflow rate).

The program solves for the maximum flame temperature and for the wall temperatures contained in equations (4.21) to (4.33). The output of the program includes (see Appendix A):

- 1. The temperatures in and around the furnace:
 - a. The preheated combustion air temperature.
 - b. The furnace combustion chamber (flame) temperature.
 - c. The exit flue gas temperature.
 - d. The diluted air temperature (immediately after mixing flue gases with ambient air).
 - e. The drying air temperature and absolute humidity.
- 2. The mass flow rates in the system (kg/h):
 - a. The fuel feed rate.
 - b. The combustion air.
 - c. The drying air.
 - d. The ash accumulation (and fuel accumulation if the combustion air is less than stoichiometric).

- 3. The total thermal energy input (MJ/h).
- 4. The total heat loss from the system (MJ/h).
- 5. The furnace and the system efficiencies (percent).

4.3 Grain Drying Simulation

The in-bin intermittent counterflow drying process is simulated using the MSU fixed bed simulation model (Bakker-Arkema et al., 1974), equations (2.72) to (2.75). The equations are solved by finite difference techniques. The Troeger and Hukill (1970) thin-layer equation is used for drying air temperatures less than 71°C, and the Thompson et al. (1968) equation (2.78) for grain temperature above 71°C. The DeBoer equations (Bakker-Arkema et al., 1974) are used to estimate the equilibrium moisture content required in the thin-layer equations.

The intermittent in-bin counterflow dryer is similar to a fixed bed in-bin dryer. The grain is held in the bin until the bottom layer (7.5-10 cm deep) has dried to a predetermined moisture content. The dry grain is then removed and the process continues until the bin is empty (if grain is not added to the bin). This process is simulated by an in-bin fixed bed drying model which reduces the bed depth instantaneously by the equivalent depth of the grain removed and increases the airflow rate accordingly. The grain conditions at various levels above the false floor are maintained and shifted downwards as drying progresses.

During intermittent counterflow drying, the drying airflow increases with a decrease in grain depth and decreases each time some

grain is added to the bin. To simulate these changes, the characteristic fan equation, which predicts the airflow delivered by the centrifugal dryer fan at a given static pressure, and the resistance of the grain to airflow should be known. The characteristic fan equation (4.37) was supplied by the manufacturer (Parkes, 1982):

$$Y = a - \beta P^C \tag{4.37}$$

where Y = volumetric airflow rate (m³/min)

P = pressure (kPa) a = constant (368.81 m³/min) β = 80.87 0 < P < 1.9 β = 56.23 1.9 \leq p \downarrow 2.4 c = 1.17 0 < P < 1.9 c = 1.95 1.9 \leq P < 2.4

The pressure drop due to the grain (corn) airflow resistance is predicted by equation (4.38) (Hukill and Shedd, 1955):

$$P = \frac{7 \times 10^{-3} d_{T}y}{\ln(1 - 0.512y)}$$
(4.38)

where y is the airflow rate $(m^3/min - m^2)$, and D is the corn depth (m). An additional constant τ was introduced in the original Hukill and Shedd equation to account for fines, corn kernel size, parking of the corn in the bin, and foreign materials. The value of the constant τ is found by solving equation (4.38) using experimental values of pressure (P) and grain depth (D). The value of τ for the corn at the Kalchik Farms was found to vary between 1.3 and 1.75. Equation (4.38) and (4.37) may be combined to a single equation (4.39):

$$\left(\frac{Ay - a}{\beta}\right)^{1/c} - \frac{7x10^{-3}Dry}{4n(1 - 0.512y)} = 0$$
 (4.39)

Thus, for a given grain depth there exists y > 0 which satisfies equation (4.39). The value of y is found by the secant iterative method for finding the roots of an equation (Conte and de Boor, 1980). The pressure drop is computed by equation (4.38), using the y value that satisfied equation (4.39).

The furnace thermal analysis model and the in-bin counterflow grain drying models are included in Appendices C and D, respectively.

CHAPTER 5

EXPERIMENTAL INVESTIGATIONS

5.1 Furnace/Dryer Performance

The MSU concentric vortex-cell furnace (CNCF) was tested in conjunction with an in-bin counterflow dryer. The fuels used were wood chips at 14, 19, and 45 percent moisture content, and corncobs at 10 and 12%. Shelled corn was dried from different initial moisture contents (22-27%) to approximately 17-18% and dumped hot in a cooling bin in which it was held for 6 to 12 hours before cooling at a low airflow rate (0.5-1.0 m³/min-m²). Moisture contents after cooling varied from 14 to 16%. The airflow in the drying bin varied from 11 to 13 min³/min- m²; the drying air temperature from 65 to 94°C. The airflow in the cooling bin varied from 0.5 to 1 m³/min-m²; the cooling air temperature from 0 to 13°C.

During each test the following temperatures were measured and recorded:

- The temperature in the furnace plenum and above the grate (after primary combustion).
- 2. The temperature between the two sets of tuyeres.
- 3. The temperature above the top set of tuyeres.
- 4. The temperature at the chimney exit.

5. The temperature at the dryer fan-intake after diluting the flue gases with ambient air.

6. The temperature in the dryer plenum.

In addition, wet and dry bulb temperatures of the exhaust air after drying were measured along with ambient wet and dry bulb temperatures.

The furnace temperatures were recorded using Type K (chromelalumel) thermocouples. All other temperatures were measured using Type T (copper-constantan) thermocouples. The limits of error are \pm 0.75% and \pm 0.83°C for Types K and T, respectively.

The temperatures were recorded on a Kaye Digistrip II recorder at one minute intervals during start-up, and every five minutes thereafter.

The furnace airflows were measured using Alnor-Velometer series 6000-P airflow meter (error limit \pm 0.5 m/min). The blended drying airflows were calculated from the characteristic fan curve after measuring the plenum pressure.

The fuel feed rate was determined by recording the time required to burn a known weight of fuel. The corn and the fuel moisture contents were determined using the standard oven method (ASAE 1982).

5.2 Chemical Analysis

The corn dried with the CVCF/IBCF system was analyzed for polycyclic aromatic hydrocarbon (PAH) and heavy metal contamination. The corn samples for the contamination analyses were taken at the dryer inlet and during each cycle as the grain was removed from the bottom of the IBCF dryer and discharged into the cooling bin. The cycle time was approximately one hour. The initial corn depth varied from 1.3 to 2 m. The residence time of the corn in the dryer varied from two to ten hours. The corn that was transferred to the cooling bin in the first cycle had the shortest residence time, the corn transferred in the last cycle had the longest.

A propane test was conducted in a batch column dryer for comparison.

5.2.1 Determination of Corn Contamination with PAH

The contamination of corn with PAHs was analyzed using a high performance liquid chromatography (HPLC). The chemicals and the reagents used for the analysis are described below.

Hexane and methylene chloride of analytical reagent grade were used along with acetonitrile distilled in glass of U.V. grade. Water was distilled, deionized, purified of organics, and filtered through a 0.22μ pore size membrane. Polynuclear aromatic hydrocarbon reference standards were obtained from Supelco, Inc. (Bellefonte, PA). Silica gel (SilicAR cc-7 special) was employed for the column chromatography.

5.2.1.1 Extraction and Purification of Samples

Samples were extracted with methylene chloride in a soxhlet extractor and purified by silica gel chromatography using procedures described by Jacko et al. (1982). Shelled corn (20 g) was extracted with 125 ml methylene chloride for six hours, with the temperature adjusted to give a cycle time of six minutes in the soxhlet. The methylene chloride was evaporated on a rotary evaporator, and the sample redissolved in $5m\ell$ of hexane. A 1.2 x 28 cm column containing 4 g silica gel was topped with 2 cm of anhydrous Na_2SO_4 and equilibrated with 25 m ℓ haxane. The corn sample was rinsed into the column with 5 m ℓ of hexane and the column eluted with 25 m ℓ of hexane which was discarded. Subsequently, the column was extracted with two 25 m ℓ fractions of CH_2Cl_2 and hexane (40:60) which were combined and evaporated to near dryness on a rotary evaporator. The sample was transferred to a test tube with CH_2Cl_2 and evaporated to dryness in a stream of N_2 . The samples were redissolved in 2 m ℓ of acetonitrile and filtered through a 0.4μ pore size membrane prior to analysis by high performance liquid chromatography (HPLC).

5.2.1.2 High Performance Liquid Chromatography

The HPLC analysis was carried out as suggested by Ogan et al. (1979). The HPLC equipment consisted of a Waters Associates (Waltham, MA) Model 680 automated gradient controller, a Waters M6000 and M45 solvent delivery system with U6K injector, a Perkin-Elmer LS-4 fluorescence detector and a Hewlett-Packard 3390-A integrator recorder. The column was a Beckman Ultrasphere 3μ -ODS (reverse phase), 4.6 mm I.D., and 7.5 cm long. The solvents employed were pure acetonitrile (Solvent A) and acetonitrile/water mixture at a 20:80 ratio (Solvent B). The chromatography was performed at a flow rate of 1.5 mg/min. The samples were eluted and the column re-equilibrated under the following program sequence:

0-20 min: 40% to 100% Solvent A
20-30 min: 100% Solvent A
30-35 min: 100% to 20% Solvent A
35-40 min: 20% to 40% Solvent A
40-55 min: 40% Solent A, isocratic

Polycyclic aromatic hydrocarbons were detected at excitation and emission wavelengths optimal for each compound as determined by preliminary scans of the reference materials on the LS-4 detector. The entrance and the exit slit widths were 10 nm each. Table 5.1 contains the wavelengths for the fluorescence detector used to determine the PAHs, along with the expected retention time and the detection limit of each compound. Actual elution times varied slightly from day to day, but were determined by establishing a reference mix before each unknown.

Table 5.1.--Excitation/emission wavelengths, retention times, and detection limits of different PAHs on the fluorescence detector.

Compound	Excitation/ emission wavelength (nm)	Retention time (min)	Detection limit (ppb)
Naphthalene (Nph)	261/328	4.4	1.25
Fluorine (F1)	257/305	8.6	0.12
Anthracene (An)	251/400	10.8	0.06
Fluoranthene (Ft)	235/388	13.6	0.06
Benz [a] anthracene (BaA)	281/386	17.6	0.06
Benzo [a] pyrene (BaP)	305/410	20.0	0.06

5.1.2 Determination of Corn Contamination with Heavy Metals

The concentration of heavy metal on the biomass and the propane dried corn was determined using inductively coupled argon plasma atomic emission spectroscopy (ICP-AES).

Intra-analyzed, concentrated nitric acid was employed along with yttrium of analytical grade. Water was the same as described in section 5.2.1

One-gram corn samples were wet-ashed with 5 ml of concentrated nitric acid in 30 ml containers and kept for 12 hours in a low temperature (75-80°C) oven. The samples were transferred to 25 ml volumetric bottles spiked with 10 ppm yttrium which acted as an internal standard. The samples were diluted to a volume of 25 ml with distilled water.

The plasma spectrometer (ICP-AES) employed for heavy metal analysis was a Model 955 Atom Comp manufactured by Jarrel-Ash Division (Waltham, MA). The results were printed directly in ppm. The following were the conditions during each analysis:

Coolant (Argon) flowrate	18.0 <i>l/</i> min
Sample carrier flowrate	0.5
Sample flowrate	1.0 <i>l/</i> min
Nebulizer pressure	1.8 bars
Forward power	1.1 kW
Refelected power	< 5 W

The detection limits for the heavy metals were the following: arsenic 3.0 ppm, cadmium 0.3 ppm, chromium 0.6 ppm, mercury 6.0 ppm, selenium 15.0 ppm, lead 3.0 ppm, and thallium 15.0 ppm.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Introduction

The primary objectives of this study were to develop and incorporate a concentric vortex-cell biomass furnace (CVCF) in an existing on-farm grain drying system, and to test and analyze the furnace/dryer system in order to determine its economic feasibility and safety aspects.

In this chapter the experimental and the simulated results will be compared. The simulation models are used to predict the fuel requirement and the corn drying rate using different fuels under different ambient conditions. An economic analysis is made for average conditions.

A corn contamination analysis is presented to assess the health hazards associated with biomass fuels.

6.2 Fuel Consumption

Table 6.1 contains the experimental and the simulated fuel consumption rates for different ambient and drying conditions. The table also contains the minimum theoretical fuel consumption rate required in the case of zero heat losses from the furnace/drying system.

Table 6.1.--The experimental and simulated fuel consumption rates of the CVCF biomass furnace at different ambient conditions and different drying air temperatures.

Test No.	Average condi	ambient itions	Exp aver c	perimental age drying conditions ^I		Fuel type*	Fue	:l feed rate kg/h	
	Temp °C	RH %	Temp °C	Airflow kg/h	Energy MJ/h	MC %	Experimental	Simulated	Minimum ²
н	12.4	64	77	18781	1213	W - 14.6	85	80	78
8	13.5	100	89	19450	1468	W - 14.6	110	98	82
n	2.0	76	78	18868	1434	C - 12.1	115	109	87
4	5.8	70	88	17639	1450	c - 12.1	100	114	88
2	- 0.9	87	82	18256	1513	W - 19.3	120	119	88
9	13.3	06	93	15828	1261	C - 10.1	100	66	75
7	0.6	63	82	16879	1374	W - 45.0	178	178	119

¹See Appendix B.

²Minimum = theoretical fuel consumption at zero heat loss.

*W = Wood chips

*C = Comcobs

The fuel consumption rate depends on the heat required to raise the drying air from ambient to the drying temperature, on the heat losses from the system, on the fuel heating value, and on the fuel moisture content. The fuel consumption varies slightly with the combustion air/fuel ratio (and therefore with the excess air).

An in-bin counterflow drying system (IBCF) was operated at a 2 m bed depth, an airflow rate of 300 kg/min, a drying temperature of 77°C, and at 12.4°C ambient temperature. This requires a minimum energy input of 1213 MJ/h (without considering heat losses). The energy input is equivalent to approximately 78 kg/h of wood chips or 74 kg/h of corncobs with 14.6 and 12.1 percent moisture (wet basis), respectively, if the average heat values of these fuels are used (20.97 and 18.65 MJ/kg, respectively). The minimum theoretical fuel feed rate for other tests is similarly computed and is presented in Table 6.1.

The actual fuel feed rate is the sum of the theoretical minimum feed rate and the feed rate required to offset the energy losses from the system. The experimental and the simulated fuel feed rates are included in Table 6.1.

Table 6.2 contains the experimental and the simulated heat losses from the furnace/dryer system for the tests and ambient conditions presented in Table 6.1.

The experimental heat losses are based upon the experimental furnace temperatures (of furnace surfaces and of the diluted air leaving the furnace), the drying air temperature in the drying bin plenum,

Table 6.2.--Experimental and simulated airflow, drying energy, total energy losses and furnace/ system efficiencies for Tests 1-7 given in Table 6.1.

Test	Average dryin kg/h	g airflow I	Drying e MJ/I	nergy h	Total energ MJ/h	y loss	Simulated e	ent ent
.0N	Experimental	Simulated	Experimental	Simulated	Experimental	Simulated	Furnace	System
	18781	17169	1213	1112	422	373	94	74
~	19450	18004	1468	1351	556	437	95	75
m	18868	17921	1434	1359	664	452	95	75
4	17639	16826	1450	1388	524	498	96	73
2	18256	17874	1513	1477	864	499	96	75
Q	15828	15427	1261	1229	540	476	95	71
7	16879	16892	1374	1376	810	467	67	77

¹See Appendix B.

the ambient temperature, and the drying air mass flow rate (kg/h). The average experimental heat losses are calculated as follows (using test No. 1 results for illustration):

Average experimental temperatu	res (Test 1):
Top of furnace shroud	39°C
Furnace side wall	91°C
Diluted air at furnace exit	99°C
Drying air (bin plenum)	77°C
Ambient	12°C
Sky temperature	-7°C

The sky temperature is estimated by an equation presented by Duffie and Beckman (1980):

$$T_{s} = 0.0552T_{a}^{1.5}$$
(6.1)

where T_s and T_a are the sky and the ambient temperatures (K), respectively.

1. Furnace radiation loss:

1 (a) From top of shroud (radiation):

$$Q_{rt} = \sigma A_{\epsilon} (T_{c}^{4} - T_{s}^{4})$$

$$= 5.66 \times 10^{-8} \times 2.6(312^{4} - 266^{4})$$

$$= 656 W (2,362 kJ/h)$$
(6.2)

1 (b) Wall radiation:

$$Q_{rw} = 0.5A_{w}[F_{w-g}\varepsilon_{w-g}(T_{w}^{4} - T_{a}^{4}) + F_{w-s}\varepsilon_{w-s}(T_{w}^{4} - T_{s}^{4})] (6.3)$$

= 3.3[(312⁴ - 285⁴) + (312⁴ - 266⁴)]
= 1,386 W (4,991 kJ/h)

Total radiation loss - $Q_{rt} + Q_{rw} = 7,353 \text{ kJ/h}$

2. <u>Furnace convective heat loss</u>: From top of shroud (convection): $T_{film} = (39 + 12.4)/2 = 25.7^{\circ}C (299K)$ $Gr = g\beta(T_w - T_a)L^3/v^2$ (6.4) $= 1.37 \times 10^{10}$ Ra - PrGr = 0.708 x 1.37 x 10¹⁰ = 9.7 x 10⁹ $h_t = (0.58k/D)Ra^{\cdot 2}$ (Eq. 7.25 Holman, 1981) (6.5) $= 0.026 \times 0.58 \times (9.7 \times 10^9)^{\cdot 2}/1.65$ $= 4.6 W/m^2 - {}^{\circ}C$

$$Q_{ct} = 4.6 \times 2.6 \times (39-12.4) = 318 \text{ W} (1,145 \text{ kJ/h})$$

The convective heat loss from the furnace wall is recovered through the shroud.

3. Duct/bin plenum heat loss:

The heat loss from the duct connecting the furnace to the bin plenum is computed by the product of the temperature difference between the diluted air temperature at the furnace exit and in the dryer plenum, the air mass flow rate (kg/h), and the specific heat of air. Thus:

$$Q_{duct} = M_a C_a \Delta T$$
 (6.6)
= 18,781 x (99 - 77)
= 413,182 kJ/h

where M_a is the drying air mass flow rate (kg/h); C_a is the specific heat of air (kJ/kg°C); and ΔT is the difference between the drying air temperature at the furnace (after the flue gases are diluted with the ambient air) and in the drying bin plenum (°C). The total system heat loss is equal to 421,680 kJ/h, the sum of the total loss from the furnace (8,498 kJ/h) and the combined loss from the duct and the bin plenum (413,182 kJ/h).

The total energy required is 1,635 MJ/h, being the sum of the energy required to raise the air from the ambient to the drying temperature (1,213 MJ/h) and the heat losses (421.68 MJ/h). The furnace/dryer system efficiency is therefore 74.2% (100 x 1213/1635) at these

conditions. Using an average heating value of 20,965 kJ/kg of wood, the required fuel feed rate is 78 kg/h of wood chips dry matter, which is equivalent to 92 kg/h of wet wood chips at 14.6% moisture (wet basis). The experimental and simulated fuel feed rates (at 14.6% moisture) are 85 and 80 kg/h, respectively (see Table 6.1).

In Table 6.2 the simulated and experimental heat loss values are compared. The simulated heat loss is computed using the procedure outlined in Chapter 4. The experimental and the simulated heat losses are similar. The experimental loss is greater than the simulated heat loss due to the following reasons:

1. The experimental flow rates of the air mass are higher than the simulated flow rates. The experimental volumetric airflow rates are determined from the characteristic fan curve using the experimental pressure data taken in the drying bin plenum. The volumetric flow rate is converted to mass flow rate by dividing the former by the specific volume of air as a function of the dry bulb temperature. However, the temperature in the bin plenum may not have been a true representative of the average temperature in the bin (Silva (1980). Empirical equations were developed to compute the total airflow through the furnace and into the dryer bin plenum as a function of the bin plenum pressure and the fuel feed rate. The equations are based on linear regression analysis of the experimental pressure and air flow data. The relation between P_f , the furnace fan pressure, and P_b , the pressure in the bin plenum in kPa is:

 $P_{f} = 0.3075P_{b} + 0.3058 \tag{6.7}$

The furnace volumetric air flow (m^3/min) was determined from the characteristic fan curve using the pressure P_f obtained from equation (6.7). The mass flow rate (kg/h) is determined by dividing the volumetric flow rate by the specific volume at ambient temperature. The equation for determinine the velocity of air blown around the furnace by the dryer fan is:

$$F_{f} = 146.28 - 13.08P_{b}$$
(6.8)

where F_f is the air flow velocity around the furnace (m/min). The mass flow rate of the air around the furnace is determined by multiplying the velocity by the cross-sectional area of the annular space between the shroud and the furnace, and dividing the product (m³/min) by the specific volume of air at ambient temperature.

The total gas flow out of the furnace is the sum of the mass flow rate of the air around the furnace and through the eductor, and the flue gas from the combustion process. The mass flow rate of the flue gas is the sum of the combustion air mass and the fuel rate, less the ash fraction in the fuel.

The predicted drying mass air flow is equal to the total gas flow out of the furnace calculated by the above procedure. The total air mass flow computed by the above method is slightly less than the experimental values (as shown in Table 6.2). This is due to leakage of air into the dryer fan through the duct section between the furnace and the dryer fan. The empirical equations do not account for the air leakage of the system. 2. The experimental temperature difference between the diluted air after the furnace and in the bin plenum may be in error due to the location of the thermocouples.

If the experimental mass airflow rate and heat losses for Test No. 1 are used, the expected fuel feed rate is 92 kg/h. The experimental fuel feed rate is 85 kg/h, compared to the simulated fuel feed rate of 80 kg/h. Thus, for Test No. 1, the experimental method of determining the heat loss overestimates the actual heat loss by about 8% and the simulation method underestimates the heat loss by approximately 6%.

6.2.1 Factors Affecting the Fuel Feed Rate

The fuel feed rate depends upon the following factors:

- Heat loss from the furnace/dryer system as affected by the ambient conditions (temperature, wind velocity, and precipitation);
- 2. the fuel moisture content;
- the required drying air temperature and air mass flow rate.

6.2.1.1 Effect of Ambient Temperature on Fuel Feed Rate

The simulated fuel feed rate, heat loss and the furnace/system efficiency at varying ambient temperature and at a constant drying air temperature of 80°C are presented in Table 6-3.

The <u>furnace efficiency</u> is defined as the ratio of the total useful energy out of the furnace to the total thermal energy input into the furnace. It is calculated by the equations:
Table 6.3Effect of ambient air conditions on fuel	consumption,
furnace and system efficiency, and total	heat loss
from CVCF/IBCF drying system; drying air	$tem = 80^{\circ}C$,
drying airflow = $12.3 \text{ m}^3/\text{m}^2$ -min.	

Ambient co	onditions	Fuel	Heat	Furnaça	System
Temperature °C	Absolute humidity* kg/kg	consumption kg/h	loss MJ/h	efficiency %	efficiency %
0	0.0029	115	482	95.9	75.0
2	0.0033	110	462	95.8	74.9
4	0.0038	106	447	95.6	74.9
6	0.0043	102	432	95.4	74.7
8	0.0050	98	417	95.3	74.6
10	0.0057	94	403	95.1	74.5
12	0.0065	90	388	94.9	74.3
14	0.0075	87	377	94.7	74.2

*Ambient air absolute humidity at 75% relative humidity.

$$Q_{in} = HM_f (1 - M_w) \tag{6.9}$$

$$n_{f} = (1 - Q_{L}/A_{in})100$$
 (6.10)

where Q_{in} is the thermal energy input to the furnace (kJ/h); Q_L is the heat loss from the furnace (kJ/h); H is the fuel higher heating value (kJ/kg dry matter); M_W is the fuel moisture content (decimal); and n_f is the efficiency (percent).

The <u>system efficiency</u> is defined as the ratio of the net energy available for drying divided by the total thermal energy input to the system:

$$n_s = (1 - Q_s/Q_{in})100$$
 (6.11)

where Q_s is the total heat loss from the system (kJ/h). The total heat loss includes the heat loss from the furnace, from the duct work linking the furnace to the bin, and from the wall of the drying plenum of the drying bin.

The heat loss from the furnace/dryer system increases linearly with a decrease of ambient temperature. A 1°C decrease in ambient temperature results in a 7.5 MJ/h increase in the heat loss. The fuel feed rate required to maintain the same drying air temperature increases by 2 kg/h (equivalent to 33.5 MJ/h) with the decrease of 1°C in ambient air temperature. Therefore, the increase in energy input (in the form of fuel) is higher than the increase in the heat loss.

The increase in the fuel consumption is mainly due to the energy required in heating the drying air from a lower ambient temperature. Additional energy is utilized in preheating the combustion air and the fuel. The energy required to counterbalance the heat loss is approximately 22% of the total fuel rate consumption increase.

According to the simulated results in Table 6.3, the heat loss varies from 377 MJ/h to 482 MJ/h when the ambient temperature decreases from 14 to 0°C. According to Silva (1980), the heat loss from the IBCF (when propane gas was employed) was 351 MJ/h at an ambient and a drying temperature of 10 and 71°C, respectively: the system efficiency at these conditions is 71%. The simulated heat loss from the entire CVCF/ IBCF system is 403 MJ/h at an ambient and a drying temperature of 10 and 80°C, respectively, with a system efficiency of 75% (Table 6.3).

The heat loss in a biomass fueled system is slightly higher than in a propane fueled system due to the extra duct linking the furnace to the fan. There is no data available to compare the heat loss from a propane fueled system with the biomass fueled system for the full range of ambient temperatures (0 to 14°C) included in Table 6.2.

According to Silva (1980), the heat loss from the propane fueled IBCF is equivalent to approximately 5.6 litres/h of liquid propane (at the ambient and drying temperatures of 10 and 71°C, respectively). The heat losses in Table 6.3 are equivalent to 22-25 kg kg of wood per hour and 30-32 kg of corncobs per hour at an ambient temperature of 14 and 0°C, respectively, when the fuel moisture content is 20%. In monetary terms the heat losses are equivalent to

approximately \$1.00/h and \$1.26/h when using biomass and liquid propane fuels, respectively.

The furnace and the system efficiencies are nearly constant for the 0 - 14° C temperature range presented in Table 6.3. The furnace efficiency is 95.9% at 0°C and 95.7% at 14°C. The system efficiency varies from 75% at 0°C to 74.2% at 14°C. These small changes are due to the fact that the drying temperature is constant, and therefore, the heat loss increase is compensated by an increase in fuel feed rate. The furnace efficiency is approximately 95% for the conditions in Table 6.3. Thus, the furnace heat loss is only 5% of the total heat loss.

6.2.2 Effect of Fuel Moisture on Fuel Consumption

The fuel moisture greatly influences the average performance of the CVCF and the required fuel consumption rate at a specific heat output. The moisture in the fuel reduces the net heating value of the fuel and the flame temperature, and therefore results in a high fuel consumption. Incomplete combustion is an additional undesirable effect of low flame temperature.

Table 6.4 lists the simulated heat loss, flame temperature, fuel consumption rate, and furnace/system efficiencies, when employing wood chips at different fuel moisture contents and different drying air temperatures. The simulations are based on an average airflow rate of 13 m³/min-m², and an ambient temperature of 4°C. The results are also plotted in Figure 6.1.

Table 6.4--Furnace/IBCF system performance using wood chips at different moisture contents (percent wet basis) for different drying air temperatures.

		· · · · · · · · · · · · · · · · · · ·	<u> </u>		L
ency	System	74 75 76 80	74 75 77 79	74 75 76 77	74 75 77 80
Effic1 %	Furnace	94 95 97	95 96 97 98 7	96 96 97 98	96 96 96
Heat 1oss M1/h		367 361 353 353 340 327	455 447 438 427 413	549 549 535 524 510	549 472 395 318 240
Furnace temperature	د	1272 1236 1191 1131 1051	1283 1246 1199 1138 1056	1291 1254 1205 1144 1060	1291 1248 1195 1129 1042
1 ption h	Corncobs	83 96 112 135 172	103 119 139 169 214	126 146 170 206 261	
Fue consum kg/	Wood chips	74 85 100 120 152	92 106 124 150 190	112 130 151 183 232	112 112 112 112
Moisture content %		10 20 20 20 20 20 20	10 20 20 20 20 20 20	10 20 40 50	10 20 50 50
Drying temperature	د	66.6 66.6 66.1 66.1 65.9	79.9 79.8 79.5 79.2	93.5 94.4 93.6 93.5	93.5 83.5 73.5 62.4 51.3





The three curves in Figure 6.1 fit an exponential curve:

$$Fr = ae^{bM}$$
(6.12)

where Fr is the fuel feed rate (kg/h) and M is the fuel moisture (percent). The regression coefficient b is 0.018 for the three curves. The coefficient a depends upon the higher heating value of the fuel and the required total heat output (as a function of the drying airflow rate and temperature as well as the ambient temperature). The values of the coefficient a for the conditions in Table 6.4 for wood chips are 60.18, 74.69, and 91.14; the values for corncobs are 67.45, 83.50, and 102.45 for average drying temperatures of 67, 80, and 94°C, respectively. The coefficients a for corncobs are higher than for wood chips (at the same drying air temperature) because corncobs have a lower heating value than wood chips. The coefficient of determination for all the curves is 0.989.

It can be concluded that the fuel feed rate required for a given drying condition increases exponentially with the fuel moisture content. The increase in fuel feed rate is attributed to the reduced dry matter of the fuel and the heat required to evaporate moisture from the fuel. The increase in the fuel dry matter feed rate at a constant drying air temperature is relatively small compared to the increase in the wet fuel feed rate. At a constant drying air temperature of 67°C, the wood chips dry matter consumption increases from 67 kg/h when the moisure content is 10% to 76 kg/h when it is 50%.

Table 6.4 also contains information on the furnace performance characteristics at varying fuel moisture contents at a constant fuel (wood chips) feed rate of 112 kg/h. The results indicate that for every 10 percent increase in the fuel moisture content, the furnace temperature decreases by an average of 62°C, and the drying air temperature by 10.6°C. This is due to the decrease in the fuel heating value since higher moisture fuel contains less dry matter and, therefore, less net energy than the same quantity of the lower moisture fuel.

At a constant feed rate (and constant ambient temperature), the heat losses decrease inversely with an increase in the fuel moisture content. A 10% increase in fuel moisture results in 77 MJ/h decrease in the heat losses. This can be attributed to the lower furnace temperature.

The furnace efficiency remains constant, but the system efficiency at constant fuel consumption increases with an increase in the moisture content due to a reduction of the duct heat losses. The duct heat losses decrease since the drying (and therefore the duct) temperature decreases. The increase in the system efficiency is 6% when the fuel moisture content increases from 10 to 50%.

6.2.3 Effect of Excess Air on Furnace Performance

Excess air is the quantity of the combustion air in excess of the stoichiometric air required for complete combustion. Some excess air is necessary in biomass furnaces to ensure complete fuel combustion (Babcock and Wilcox, 1978; Buchele et al., 1981). If combustion air is limited to the stoichiometric quantity, incomplete combustion may result due to a lack of thorough mixing of the fuel and the air. High

moisture fuels require high levels of excess air for drying the fuels prior to combustion (Tillman et al., 1981).

Too much excess air slows down the combustion reaction by excessive cooling of the furnace combustion chamber. More importantly, the excess air increases the pressure in and the mass flow rate from the combustion chamber. This results in backfiring (an explosion of prematurely ignited fuel) in the feed system and in an increase of the furnace gas velocities. Unburned entrained materials are carried out of the furnace and into the drying bin under such conditions.

In the MSU concentric vortex-cell furnace, the combustion and the eductor air are supplied by the same fan. Increasing the excess air reduces the eductor airflow. Consequently, the eductor develops less vacuum in the chamber causing backfiring and smoke-escape through the feed hopper.

Table 6.5 contains the simulated temperatures in the combustion chamber and of the drying air along with the furnace and the system efficiencies at different excess combustion air percentages. The data are based on an ambient temperature of 4°C and an air flow rate of $12.5 \text{ m}^3/\text{min-m}^2$ (17,600 kg/h).

The data in Table 6.5 are plotted in Figures 6.2 and 6.3. Figure 6.2 is a plot of the furnace combustion chamber and exhaust flue gas temperatures versus excess air (percent). The furnace and the system efficiencies as well as the drying air temperature are plotted against percent excess air in Figure 6.3. The furnace combustion chamber temperature decreases exponentially from 1,518 to

Excess air	Heat loss	Furnace and c air temperatu °C	lry ing Ires	Furr	ace and sys efficiency %	stem
%	MJ/h	Combustion	Exit	Drying	Furnace	System
0	591	1518	579	82.6	92.9	72.3
10	510	1457	590	82.9	93.6	72.9
20	499	1400	600	83.2	94.3	73.4
40	481	1300	615	83.5	95.4	74.4
50	472	1248	621	83.5	95.8	74.9
60	464	1203	626	83.4	96.2	75.3
80	446	1117	631	82.9	97.0	76.2
100	427	1038	632	82.0	97.7	77.3
140	379	896	622	79.0	99.2	79.8
180	345	763	594	74.5	99.4	81.6

Table 6.5.--The theoretical effect of excess combustion air (percent) on the CVCF furnace performance.

NOTE: Ambient temperature 4°C, relative humidity 75%, drying airflow 12.5 $m^3/min-m^2$ (292 kg/min)









763°C when the excess air is increased from zero to 180 percent. The furnace temperature versus percent excess air curve in Figure 6.2 fits the exponential equation:

$$F_{f} = ae^{bZ}$$
(6.13)

where T_f is the furnace (combustion chamber) temperature (°C) and Z is the excess air (percent). The constants a and b are regression coefficients which depend on the fuel feed rate, fuel moisture, fuel heating value, and the ambient temperature. The values of the coefficients a and b are 1,512.7 and 0.004 for the conditions presented in Table 6.5. The coefficient of determination is 0.9999.

The decrease in the furnace temperature (at constant fuel feed rate and ambient temperature) is due to the fact that the energy in the fuel is used to heat a larger air mass.

The exit flue gas temperature increases from 579 to 632°C when the excess air increases from 0 to 100%, and then decreases to 594°C at 180% excess air. The set of exit flue gas temperatures and the percent excess air data (also plotted in Figure 6.2) fits a cubic polynomial of the form:

$$T_e = a + bZ + cZ^2 + dZ^3$$
 (6.14)

The regression coefficients a, b, c, and d depend upon the fuel feed rate, moisture and heating value, and the ambient temperature. For the conditions presented in Table 6.5, least squares regression yields the following values of the coefficients (coefficient of determination equals 0.9998): a, 578.86; b, 1.17; c, -6.78 x 10^{-3} ; and d, 4.15 x 10^{-6} .

The variation of the drying temperature with an increase in excess air is similar to that of the exit flue gas temperature as shown in Figure 6.3. It can be expressed in the form of the cubic equation (6.14). The values of the coefficients (if T_e is replaced by T_d , the drying air temperature) are: a, 82.56; b, 0.04; c, -4.87E-4; and d, -8.58E-9. The r^2 for this fit is 1.00. This is evidenced in Table 6.5: the drying air temperature increases from 82.6 to 83.5°C when the excess air increases from zero to 50%, and then decreases to 74.5°C at 180% excess air.

The variation of the exit flue gas and the drying temperatures with an increase in excess air is attributed to the variation in the eductor air mass flow rate and temperature. The eductor and the combusion air are supplied by the same fan via a T junction. Excess combustion air is increased by opening a butterfly valve built into the line supplying the combustion air. An increase in the combustion air mass flow rate results in a decrease in the eductor flow rate and vice versa.

If the combustion airflow increases (with an increase in the excess air), the temperature of the flue gases leaving the combustion chamber decreases as previously explained. However, the mass flow rate of the flue gases increases. The temperature of the exit flue gases (the mixture of the products of combustion and the eductor air)

is calculated by the following equation:

$$T_{e} = (M_{f}C_{f}T_{f} + M_{n}C_{n}T_{n})/(M_{f}C_{f} + M_{n}C_{n})$$
(6.15)

where M is mass flow rate (kg/h); C is the specific heat (kJ/kg°C); T is the temperature (°C); the subscripts e, f, and n denote the eductor exit, the furnace, and the eductor-nozzle conditions, respectively. Equation (6.15) shows that if M_f increases, T_e and M_n decrease. This results in an increase or decrease of the exit flue gas temperature depending on the relative increase of M_f and decrease of T_f and M_n . When excess air increases from zero to 100%, the increase in M_f and the decrease in M_n offset the decrease in T_f , resulting in a slight increase in T_e . When excess air increases above 100%, the decrease in T_f is more dominant and therefore, the exit fue gas temperature (T_e) decreases (see Figure 6.2).

The drying air temperature varies directly with the exit flue gas temperature if the ambient temperature remains constant. Therefore, the drying air temperature versus excess air curve has a similar shape as the exit flue gas temperature curve. The drying air temperature decreases faster than the exit flue gas temperature (excess air greater than 100%) due to heat losses between the furnace and the drying bin.

The plots in Figure 6.2 and 6.3 indicate that the variations in the exit flue gas and the drying air temperature are small. A greater amount of excess air causes a greater mass flow rate of gases leaving the combustion chamber and less mass-flow through the eductor: the total mass-flow through and around the furnace remains the same. This is due to the fact that the combustion air and the eductor air are suppllied by the same fan, as mentioned earlier. Excess combustion air can only be increased by reducing the eductor flow rate. Since the total airflow through the furnace remains constant, at a constant fuel feed rate (constant energy input) and drying airflow rate, the drying air and the furnace exit flue gas temperatures remain nearly constant.

The data in Table 6.5 indicate that the system heat loss decreases from 591 to 345 MJ/h as the excess air is increased from zero to 180%. The decrease in heat loss is due to the decrease in the temperatrue of the furnace combustion chamber and the drying air. Since the furnace and the system efficiencies vary inversely with the heat loss, they increase with an increase in escess air. Furnace efficiency increases from 93 to 99% and the system efficiency increases from 72 to 82% with an increase in excess air from zero to 180%. Unlike many furnaces (used for generating steam), in which excess air results in additional heat loss through the stack, all the combustion products are passed through the grain in the MSU CVCF/IBCF system. Thus, the heat in the excess air is utilized. Moreover, higher excess air results in lower furnace temperatures, and subsequently in reduced radiation and convection heat losses from the furnace.

A 50% excess air was used in simulating the furnace performance except when excess air was varied to study its effect on the furnace performance. The 50% excess air is equivalent to an air/fuel ratio (dry basis) of 9.5 for wood chips and 8.3 for corncobs.

Excess air is difficult to measure without an exact knowledge of the fuel composition. Excess combustion air is expressed as:

$$Z = 100(A - S)/S$$
 (6.16)

where Z is the excess combustion air (percent), A is the actual combustion air mass flow rate (kg/h), and S is the stoichiometric combustion air required (kg/h).

Determination of the stoichiometric air requires an exact knowledge of the fuel composition (e.g., the fuel ultimate analysis). It is not possible to describe the fuels used on a farm at any given time in terms of the exact ultimate analysis without actual measurement. Corncobs may contain randomly varying amounts of husks, corn kernels, bees wings, and other foreign materials. Thus, the ultimate analysis of corncobs as found in the literature represents an average. The same argument holds for wood chips obtained from a sawmill; the sample may contain several tree species of wood and bark, each of which has a different chemical composition and heating value. Thus, the stoichiometric air for such heterogeneous fuels is difficult to determine.

If the stoichiometric air is unknown or difficult to quantify, the excess air cannot be measured.

A measurable unit in a biomass furnace is the air/fuel ratio. The optimum air/fuel ratio (and also the optimum excess air) varies between samples of the same biomass fuel depending upon the exact condition of the fuel in terms of moisture content, particle size distribution, and the foreign material fraction in the fuel. However, as long as sufficient combustion air is supplied to the furnace, small changes in the air supply do not have a significant effect on the combustion efficiency and the heat recovery of a biomass furnace (Sukup et al., 1983). This is evident from Table 6.5.

6.2.3.1 Fuel Higher Heating Value

The higher heating value of the two biomass fuels used in this study have been measured using a standard bomb-calorimeter method (ASTM Standard No. D3286-77, Institute of Gas Technology, 1978). The values are presented in Table 6.6. The average of the heating values found in the literature is also listed in the table. There is no significant difference between the two sets of values. The literature values are more suitable for simulation purposes since they represent measured values under a wide range of experimental and fuel conditions.

6.3 In-Bin Counterflow Corn Drying

The results of the corn drying tests are presented in Table 6.7. Included in the table are the average ambient and drying air temperatures (°C), the initial, intermediate, and final grain moisture contents, the electricity and the biomass fuel usage (electricity kW/h, fuel kg/h), the specific energy consumption (SECO, kJ/kg of water removed as defined in section 6.3.2), the corn drying capacity (wet ton/h), and the drying energy costs ($\frac{1}{2}$ wet ton).

The average ambient temperature varied from 2 to 13.5° C in the fall of 1983, and from -0.9 to 13.3° C in the fall of 1982. The average

	Moisture	Heat	ting values, MJ/kg
ruei	content %	as is	dry basis
Wood chips ^a	13.3	17.46	20.15
	14.4 ^b	17.57	20.51
	41.3 ^b	11.35	<u>19.35</u>
			20.13 (Average)
			20.97 (LA) ^C
Corncobs	13.05	16.56	19.05
	16.43 ^b	15.00	<u>17.95</u>
			18.50 (Average)
			18.65 (LA) ^C

Table 6.6.--Experimentally measured higher heating value (MJ/kg) of wood chips and corncobs at different moisture contents (percent wet basis).

 a Wood chips consisted of a mixture of soft maple (50%), aspen (40%) and 10% of other species such as hard maple and unidentified bark.

^bSamples artificially wetted.

 C LA = Average of values found in literature (see Table 2.2).

Table 6.7.--Actual drying rates, energy (fuel) consumption rates and operating costs (1983) prices) for seven drying tests at different ambient conditions at the Kalchik Farms, Bellaire, MI.

Test	Temperi °C	a ture	Moistu perc	re cont ent w.b	tent J.	Electricity	Fuel* feed	Spec	ific energ kJ/kg	ly consum H ₂ 0	ption	Capacity	Dry ing
2	ambient	drying	initial	hot	final		kg/h	Ne		Gro	SS	-11/51103	\$/ton ¹
								heating	after cooling	heating	after cooling		
1	12.4	11	26.2	18.8	16.0	12.0	85-W	5092	3821	6346	4763	2.7	1.69
2	13.5	68	23.5	17.0	14.1	12.0	N-011	7703	5461	10262	7344	2.5	2.27
m	2.0	78	22.6	16.5	14.4	12.0	115-C	9169	6992	11976	9133	2.2	2.18
4	5.6	88	22.2	14.2	14.2	11.0	100-C	6672	6672	8185	8185	2.4	1.78
S	6	82	26.4	16.7	15.9	12.0	120-W	6668	5422	1688	8289	2.0	3.07
9	13.3	63	25.8	14.7	13.1	11.0	100-C	5555	4946	7327	6524	1.8	2.37
7	0.6	82	27.4	14.6	14.6	11.0	178-W	6287	6287	9306	9306	1.5	5.82

*W = Wood chips

C = Corncobs

¹Wet ton

ambient relative humidity varied from 70% to 100% during the two test periods.

In Test No. 1 (Table 6.7) corn was dried from an initial moisture content of 26.2% to an intermediate moisture content of 18.8% in the high-temperature IBCF system and dumped hot (about 60°C) in the dryeration bin. The corn was held for approximately 6 hours after which it was cooled to the 16% final moisture content using ambient air at a low airflow rate (approximately $0.5 \text{ m}^3/\text{min-m}^2 \text{ per m}^3$ of corn). The corn was similarly dried in the Tests Nos. 2, 3, and 5. During the Test Nos. 4, 6, and 7 the corn was dried directly to a final moisture contents of 14.2%, 13.1%, and 14.6%, respectively, in the high-temperature system.

The electric power consumption was 10.7 kWh/h during the heating-drying phase. The difference between the 10.7 kWh/h and the rates in Table 6.7 are due to the electrical energy required to operate the cooling fan in the dyeration bin.

6.3.1 Biomass Fuel Feed Rate

The average fuel feed rates are included in Table 6.7. The fuel feed rate depends upon the total thermal energy required for the drying process as discussed in section 6.2 (see also Table 6.1 for the same information).

6.3.2 Experimental Specific Energy Consumption

The specific energy consumption (SECO, kg/kg of water removed) is presented in Table 6.7 under two categories, namely the net SECO

(for drying only) and the gross SECO (which includes the heat loss from the system). The net SECO is calculated by multiplying the temperature difference between the ambient and the drying air (°C) by the specific heat of air (kJ/kg) and the mass flow rate of the drying air (kg/h), adding the product to the electricity used (kJ/h), and dividing the sum by the water removed from the grain (kg/h). The gross SECO is calculated by multiplying the fuel dry matter consumption by the higher heating value and adding the electrical energy to the product; the sum is divided by the amount of water removed.

As can be seen in Table 6.7, the net and gross SECO depend upon the combined effects of the following factors:

- 1. The amount of water removed per ton of wet corn.
- 2. The moisture content percentage points removed after drying in the high-temperature phase.
- 3. The ambient temperature.
- 4. The drying temperature.
- 5. The airflow rate of the drying air.

The effects of the above factors on the drying capacity and the SECO are discussed in detail in section 6.5. It is obvious that when drying is completed in the high-temperature phase (i.e., corn dried to 15.5% or less), the process results in high SECO values. Thus, Tests 4, 5, and 7 resulted in high SECO values compared to Test No. 1.

The ambient and the drying air temperatures, as well as the drying airflow rates, have a direct effect on the SECO values. This effect is not obvious from Table 6.7 since some of the important parameters varied simultaneously.

6.3.3 Drying Capacity

The average drying capacity at an average drying temperature of 84°C for the seven tests shown in Table 6.7 is 2.2 wet tons per hour in drying from 25% to 15%. The drying capacities for Tests 6 and 7 are much lower than for the other tests (1.5 and 1.8 compared to 2.7 and 2.5 wet tons per hour for Tests 1 and 2, respectively). This is due to the fact that the corn was dried to a very low moisture content in the high-temperature phase (14.6% and 14.7% compared to 18.8% and 17.0% in Tests 1 and 2). If Tests 6 and 7 are excluded, the average capacity for the other tests is 2.4 wet tons per hour. This compares with a capacity of the IBCF fueled with propane of 2.6 wet tons per hour in drying from 26% to 17% at a drying air temperature of 71°C (Silva, 1980). Thus, there is a small loss in drying capacity when the IBCF is operated with biomass fuel. The slight decrease in capacity is due to the air flow reduction in heating the air before the fan entrance.

6.3.4 Standardized Dryer Performance

The standardized dryer performance data are presented in Table 6.8. The data include the value of the energy consumption (fuel hg/ha, electricity kWh/ha), capacity (wet ton/h), SECO (kJ/kg of water removed), and the drying costs (\$/wet ton). The standardized performance is based on drying corn from 26% to 18% moisture in the high-temperature phase and from 18% to 15.5% in the dryeration/cooling bin. The energy consumption per hectare is based upon a corn yield of 6.28 wet tons per hectare.

Table 6.8.--Standardized energy (fuel) consumption and operating costs (1983 prices) for different fuels (W = wood chips,C = corncobs) and fuel feed rates for the CVCF-IBCF drying system.*

Drying air Fuel consumptio	Drying air Fuel consumptio	Fuel consumptio	sumptio	na	r] ootutoittu	Capacity	Specific	Drying	costs ^b
t temperature c	temperature °C		kg/h	kg/ha	Electricity kWh/h	wet tons/h	energy use kJ/kg	\$/ton	\$/ton- point
M 77	77		85	246	35	2.17	5804	2.20	0.21
C 89	89		110	266	29	2.60	6230	2.29	0.22
C 78	78		115	331	35	2.18	7119	2.20	0.21
c 88	88		100	242	29	2.59	5228	1.68	0.16
W 82	82		120	298	30	2.53	6595	2.45	0.23
c 93	63		100	229	58	2.74	5051	1.58	0.15
W 82	82		178	442	30	2.53	6666	3.48	0.33
		_							

*Ambient temperatures can be found in Table 6.7.

^aBased on corn yield of 6.28 metric tons per hectare (100 bu/acre) dried from 26 to 18% MC w.b. in IBCF system and cooled to 15.5% in an in-bin dryeration system.

byood chips valued at 4.47\$/kg (wet), corncobs at 3.50\$/kg (wet), electricity 7\$/kWh.

The following is the standardization procedure:

 The corn drying constant k for each test is derived from the drying equation:

$$MR = \frac{M_{t} - M_{e}}{M_{o} - M_{e}} = exp(-kt)$$
(6.17)

Rearranging equation (6.17):

$$k = -ln(MR)/t \tag{6.18}$$

The theoretical time required to dry corn from
26 to 18% moisture is calculated as follows:

$$t_s = \ln[(0.18-M_e)/(0.26-M_e)]/k$$
 (6.19)

3. The standardized capacity (wet ton/h) is:

$$CP_{s} = CP_{e}/t_{s}$$
(6.20)

where CP_s and CP_e are the standardized and the experimental capacity (wet tons per hour). The other standardized data are based on the standardized capacity (CP_s) and time (t_s).

6.3.4.1 Standardized Drying Capacity

The standardized capacity is 2.2, 2.5, and 2.7 wet tons per hour for a drying air temperature of 78, 82, 89, and 93°C, respectively. The average standardized capacity is 2.5 wet tons per hour at an inlet air temperature of 84°C. 6.3.4.2 Standardized Specific Energy Consumption

The average standardized gross SECO for the CVCF/IBCF system is 6,099 kJ/kg of water, compared to 4,548 kJ/kg if propane is used (Silva, 1980). The difference is due to the extra heat loss through the additional duct work linking the furnace to the dryer (see section 6.2).

6.4 Corn Drying Simulation

The in-bin counterflow grain drying model discussed in section 4.2 was used to simulate the drying of corn in the CVCF-IBCF system. The simulated and experimental results are compared in Tables 6.9 and 6.10.

6.4.1 Cycle Times

The in-bin counterflow dryer (IBCF) is a semi-continuous counterflow dryer. Grain is dried in a stationary mode as in an in-bin batch drying system. When a thin layer (7.5-10 cm deep) of corn at the bottom of the bed is dried to a predetermined moisture content, it is transferred to a dryeration bin (see section 4.2). The transfer process takes approximately 25 minutes during which the drying proceeds. The time between two consecutive starts of the transfer process is defined as the cycle time. It is the time required to dry the 7.5 - 10 cm of grain that is transferred to the dryeration bin.

The experimental and simulated cycle times, moisture content at transfer, capacity (wet tons per hour), airflow rate and specific energy consumption rate are tabulated in Table 6.9 for Test No. 1. (See the tables in Appendix B for an explanation of other tests.)

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Cycle	Cycle	time, h	Moisture,	, % w.b.	Capacit	y, ton/h	Airflow	, cmm/m ²	SECO1
No.	exp	sim	exp	sim	exp	sim	exp	sim	simulated
1	1.80	1.43	18.9	18.7	1.3	1.7	12.0	12.0	7310
2	0.53	0.58	:	18.5	2.1	2.4	12.5	12.4	8837
ო	0.62	0.76	18.9	18.8	2.5	2.6	12.9	12.7	8873
4	0.77	0.93	18.6	18.6	2.6	2.6	:	12.9	7504
S	0.77	0.74	;	18.8	2.7	2.7	13.3	13.2	7068
9	0.85	0.73	;	18.8	2.7	2.8	3	13.5	6699
2	0.95	0.72	18.5	18.6	2.7	2.9	13.6	13.8	6455
ω	0.93	0.72	18.9	18.6	2.7	2.9	13.9	14.1	6362
6	0.80	0.71	1	18.5	2.7	3.0	14.2	14.4	6405
10	1.05	0.71	:	18.8	2.7	3.0	:	14.7	6583
11	0.93	0.71	18.9	18.8	2.7	3.0	l t	15.1	6831
	10.00 ²	8.7 ²	. 18 . 8 ³	18.7 ³	1	;	13.2	1	;
Cool ing	12.00	6.0	16.0	16.0	1	1	0.8	0.8	4610

ISECO: Net specific energy consumption

²Total time, h

³Average moisture contents

Operating conditions: average drying temperature 77°C, initial grain depth 2m average ambient temperature 12.4°C, initial grain moisture 26.2% average ambient relative humidity 84%

Cycle	Exhaust air	•	Bottom moisture %	layer content	Average moisture	Remaining bed
No.	Temperature °C	RH %	RH Before After i % Cycle cycle		in the bin %	depth m
1	26	100	26.2	18.7	26.2	1.85
2	38	100	19.9	18.5	26.8	1.69
3	43	100	20.7	18.8	27.0	1.53
4	44	100	20.9	18.6	26.5	1.37
5	45	100	20.6	18.8	26.0	1.21
6	47	92	20.5	18.8	25.4	1.05
7	48	65	20.3	18.6	24.7	0.09
8	54	42	20.2	18.6	23.8	0.74
9	59	27	20.1	18.5	23.0	0.58
10	64	18	20.0	18.8	22.5	0.42
11	70	10	20.0	18.8	21.5	0.26

Table 6.10.--Simulated operating conditions during Test 1.

The cycle times at different cycles are plotted in Figure 6.4. The first cycle requires the most time. The first cycle time is the time duration from the moment the drying fan is started until the start of the transfer of the first dried layer of corn to the dryeration bin. It requires more time to dry the first layer because of the following reasons:

- The grain is initially cold, and it requires time (and energy) to heat the grain (and the drying structure) before evaporation of moisture from the grain is initiated.
- All the grain in the bin is nearly at the same high initial moisture content and low temperature. More time is required to dry the initial bottom layer to a specified moisture content than is the case for subsequent layers.
- 3. The airflow increases as the bed depth decreases.

The length of the time interval between the start of the drying process and the first transfer depends upon the initial grain temperature and moisture content, the grain depth, the drying temperature, and the final (transfer) moisture content.

The cycle time of the second transfer is shorter than of the others. During the drying of the first cycle, the grain above the layer transferred is dried to a moisture close to the desired final moisture content. Thus, it takes a short time to dry the grain.

The simulated average moisture contents of the transferred corn before and after drying, the average moisture of the grain left in the





bin, and the exhaust drying air temperature and relative humidity are presented in Table 6.10. It can be seen that the initial moisture content for cycle 1 is 26.2%; for cycle 2, 19.9%; and for cycle 3 to 9 the initial moisture is about 20%.

As the drying continues, the following changes occur:

- 1. The average grain temperature is increased.
- The average moisture content of the grain remaining in the drying bin first has increased due to rewetting of the grain at the top, and then is decreased as the drying front moves upward (see Table 6.10).
- 3. The airflow rate is increased since the resistance to the airflow is decreased as the grain depth decreases.
- 4. The initial moisture content for each cycle (being the moisture content at the bottom layer after removal of dry grain in the previous cycle) is decreased gradually.
- The time between consecutive cycles decreases and therefore, the drying rate (capacity) is increased due to the combined effect of factors 1-4 above.

The experimental results in Tables 6.9 and 6.10 show some deviations from the expected trends, such as the experimental cycle time for cycle No. 10, which increased to 1.05 hrs compared to the previous and the following cycle times of 0.80 and 0.93 hrs, respectively. Also, the experimental cycle time increased from 0.77 hrs for the fifth cycle to 0.95 hrs in the 7th cycle. These irregularities are due to the falling drying air temperature, the difference in the original moisture content of grain in different layers, or a combination of the two.

6.4.2 Drying Capacity

The drying capacity (wet ton/h) is defined as

Capacity =
$$\sum_{i=1}^{N} G_i/t$$
 (6.21)

where N is the total number of cycles dried after time t (hours) and G_i is the weight of wet grain dried in cycle i (ton). The average capacity can also be defined as the product of the number of cycles and the average amount of grain dried per cycle, divided by the total drying time.

Both the simulated and the experimental capacities increase with time (and therefore with the number of cycles) as the cycle times decrease. The reasons for the reduced cycle time are discussed in section 6.4.1

There is close agreement between the simulated and the experimental capacities (3.0 and 2.7 wet ton/h, respectively).

6.4.3 Specific Energy Consumption

The simulated specific energy consumption (SECO) presented in Table 6.9 is the net energy required to remove one kilogram of water from the wet grain. The net SECO does not include heat losses from the system and is computed as follows:

$$SECO_{(N)} = \sum_{i=1}^{N} (G_{ai}C\Delta T\Delta t_{i} + E_{i})/W_{i}$$
(6.22)

where G_{ai} is the airflow during the drying of cycle i (kg/h); C is the specific heat of air (kJ/kg°C); ΔT is the temperature difference between the ambient and the drying air; Δt_i is the cycle time (h); E_i is the electrical energy used in drying cycle i (kJ); and W_i is the amount of water removed in cycle i (kg).

The total amount of water removed after a given cycle is calculated as follows:

$$W_{i} = (m_{oi} - m_{fi})G_{Di} + (m_{Bo} - m_{Bi})G_{Bi}$$
 (6.23)

where m_{oi} is the initial moisture content of the grain at the transfer layer dried in cycle i (decimal, dry basis); m_{fi} is the final moisture content of the grain transferred in cycle i; m_{Bo} is the initial average moisture content in the bin above the layer removed in cycle i; m_{Bi} is the average moisture content of the grain remaining in the bin after cycle i has been transferred; G_{Di} is the dry matter of the corn transferred in cycle i; and G_{Bi} is the dry matter of the corn remaining in the bin after cycle i.

The specific energy consumption at the end of each transfer as defined by equations (6.22) and (6.23) has not been determined experimentally. It requires the grain moisture content of the bottom layer before and after the layer has been dried as well as the average moisture of the grain remaining in the bin. These values cannot be obtained in a commercial operation.

The variation of the simulated specific energy consumption as drying progresses is illustrated in Table 6.9. The SECO is low during the first cycle, reaches a maximum during the second cycle, and decreases until the 8th cycle is reached.

After drying is started, 1.43 hours elapses (1.8 hours experimental) before the first layer of dried grain (26-18.7%) is discharged from the dryer. During this time the grain immediately above the bottom layer is dried to 19.9%. Thus, the initial moisture for the second cycle is only 19.9%, compared to 26.2% for the first cycle. Therefore, considerably more water is removed in the first cycle than in the second (224 kg in the first cycle compared to 86 kg for the second cycle). The shorter drying time for cycle No. 2 results in a higher specific energy consumption because there is little water removed in drying the corn from 19.9 to 18.5%. Due to the shorter drying time for the second cycle, the grain above the layer transferred is 20.7% (compared to 19.9% for the second cycle).

The third cycle requires 0.76 hours to dry. The fourth cycle time takes longer than the third cycle for the same reasons. However, after the fourth cycle, the cycle time progressively decreases because the grain is sufficiently heated to maintain a steady drying rate.

After the third cycle, the amount of water removed per cycle remains nearly constant (143 kg/cycle). However, the cycle time progressively decreases since the average temperature of the corn is also increasing as the drying continues. The decrease in the energy comsumption is shown in Figure 6.5.




As drying progresses, the grain depth also decreases. The decrease in depth results in an increase in airflow rate. After the 6th cycle the exhaust air leaving the drying bin is no longer saturated (see Table 6.10). The exhaust relative humidity decreases and the temperature increases. This is an indication of the start of inefficient use of energy. The specific energy consumption reaches a minimum after the 8th cycle and thereafter increases. The increase is a result of the decreasing amount of water removed per cycle. The depth at which the minimum specific energy consumption is reached depends upon the drying air temperature, the initial grain depth and moisture, and the degree of drying.

6.4.4 Airflow Rate

The simulated and the experimental airflow rates at the beginning of each cycle are tabulated in Table 6.9 and plotted in Figure 6.6. The experimental airflow rates were determined by measuring the static pressure (in the bin plenum) and the bed depth. The characteristic fan curve was also used to determine the airflow rate using the static pressure readings.

The simulated airflows were predicted employing the procedure discussed in section 4.2. There is a close agreement between the experimental and simulated airflow rates.

6.4.5 Comparison of Experimental and Simulated Grain Moisture Contents

Experimental and simulated moisture contents of each cycle are presented in Table 6.9.





The desired final moisture content is one of the inputs to the grain drying model. Whenever the average grain moisture content within the bottom layer (7.5-10 cm above the false floor) reaches the desired moisture, the layer is removed from the drying bin instantaneously and dumped in the cooling bin. Therefore, the simulated moisture content is always equal to or slightly less than the desired value.

The difference between the average experimental and simulated moisture contents is small (e.g., 18.8% experimental compared with 18.7% simulated for Test No. 1, Table 6.9).

6.4.6 Comparison of Experimental and Simulated Drying Data

Table 6.11 contains the experimental and simulated corn drying results for seven tests under different drying and ambient conditions. The average drying capacities and net specific energy consumption results are compared.

6.4.6.1 Capacity

The experimental capacity was determined by dividing the total amount of corn dried by the total drying time. The simulated capacity was determined by the procedure outlined in section 6.4.2. The data indicate close agreement between the experimental and simulated results.

The difference between the experimental and the simulated capacity is due to the following factors:

1. The sweep auger does not remove equal amounts of grain each time when grain is transferred to the

Table 6.11.--Comparison of CVCF-IBCF experimental and simulated results for seven tests under different drying conditions.

				_		_			
ption r	ing	sim ²	4610	4921	6433	5165	5856	4257	6234
y consum of wate	c001	exp ¹	3821	5461	6992	6672	5422	4946	6287
ic energ t) kJ/kg	ing	sim ²	6831	7924	8759	5165	6334	4867	6234
Specif. (ne	heat	exp ¹	5092	7703	9169	6672	6668	5555	6287
capacity n/h	sim ²		3.0	2.9	2.3	2.4	2.2	2.0	1.8
Average wet to	exp ¹	-	2.7	2.5	2.2	2.4	2.0	1.8	1.5
imental content %	final		18.8/16.0	17.0/14.0	16.5/14.4	14.2	16.7/15.9	14.7/13.1	14.6
Experimoisture	initial		26.2	23.5	22.6	22.2	26.4	25.8	27.4
Dry ing	cemperature °C		77	88	78	88	82	63	82
Ambient	cempera cure		12.4	13.5	2.0	5.6	-0.9	13.3	0.6
ł	No.			2	m	4	2	9	7

lexp: Experimental

²sim: Simulated

dryeration/cooling bin due to uneven grain flow characteristics such as density, broken kernels, foreign materials (BCFM), etc.

 The simulation model uses average ambient and drying temperatures, and an average initial grain moisture content; these parameters vary somewhat during a test.

6.4.6.2 Simulated Versus Experimental Specific Energy Consumption The experimental and simulated net specific energy consumption values for the heating and cooling phases are also presented in Table
6.10. The experimental SECO data are based upon the average airflow rate, the average moisture content, and the average drying capacity. The simulated SECO values are based on the integration of the SECO values for every cycle as discussed in section 6.4.3.

There are differences between the experimental and the specific energy consumption values due to the methods used to compute them. The integration method (used to calculate the simulated SECO) is more accurate but requires a knowledge of the average moisture content of the grain in the bin, as well as the moisture of the grain at the bottom of the bin before and after each transfer.

6.5 Predicted Drying Performance Parameters

The furnace and the drying models are used to predict the furnace/dryer performance under varying ambient conditions and dryer operating modes. The IBCF dryer is operated in four basic modes:

- <u>Mode 1</u>: The bin is filled to a depth of 1.8 m. Drying is started and continues until the bin is empty. A total of 30 wet tons are dried in 8 to 12 hours depending on the drying temperature, the initial moisture content, and on whether drying is completed in the high-temperature phase or in the cooling bin.
- <u>Mode 2</u>. The bin is initially filled to a depth of 1.8 m. Drying is started and the bin is refilled with 8 tons of wet grain every three hours. Drying continues until grain loading is stopped after 18 hours. A total of seven batches are added during the drying period. Approximately 57 wet tons are dried (21 cycles).
- <u>Mode 3</u>. As in Mode 2 except that 16 wet tons per batch are added. Drying continues in this mode until the bin is filled up to 3.7 m after 11 hours. Four batches (a total of 64 wet tons) are added to the bin. A total of 12 cycles (32 wet tons) are dried.
- <u>Mode 4</u>. As in Mode 2, but 4 wet tons are added per batch. The drying rate is greater than the refill rate. Drying continues until the bin is empty after 16 hours. A total of five batches (20 wet tons) are added to the initial 30 wet ton. Fifty wet tons (17 cycles) are dried during the 16-hour drying period.

In addition to the four modes discussed above, the IBCF dryer is used to partially dry grain to an intermediate moisture content and finally dry the grain in the dryeration bin (Method D). Alternatively, the grain can be dried directly to the final moisture in the IBCF dryer (Method ND).

Table 6.12 presents the predicted IBCF system performance parameters (simulated) in different drying modes and at different drying temperatures. The following parameters are studied: capacity, specific energy consumption, fuel feed rate, and drying costs.

6.5.1 Effect of Refill on Dryer Performance

The IBCF performance is better when operating in Modes 2 and 3, than in Modes 1 and 4. The capacity is 3.2 and 3.1 wet ton/h in Modes 2 and 3, respectively, compared with 3.0 and 2.9 wet ton/h in Modes 1 and 4. The net specific energy consumption is 4656 and 4792 kJ/kg of water removed in Modes 2 and 3 compared with 5010 and 5126 kJ/kg in Modes 1 and 4. The operating (energy) costs are also lower in Modes 2 and 3 than in Modes 1 and 4 (\$1.81, \$1.86, \$1.90, and \$1.91, in Modes 2, 3, 1 and 4, respectively).

The performance is superior in Modes 2 and 3 than in Modes 1 or 4 for the following reasons:

- Replenishing the bin with wet grain ensures complete saturation of the exhaust air. Thus, the air watercarrying capacity is fully utilized, resulting in better energy utilization.
- The wet grain is preheated by the exhaust air and therefore, dries faster upon reaching the bin bottom.

Table 6.12.--Simulated energy consumption, drying rate and operating costs for different dryer operation modes at average ambient conditions (4°C, 75% RH).

s _	propane	5.65	6.44	5.63	6.40	4.46	5.31	5.87	6.82	5.34	5.34	5.50	5.88
ing cost wet ton	corn- cobs	1.74	2.10	1.72	1.96	1.36	1.62	1.77	2.05	1.63	1.63	1.68	1.79
bryt s/	wood chips	1.94	2.33	1.90	2.16	1.51	1.80	1.96	2.28	1.81	1.81	1.86	1.99
rate % MC	propane &/h	63	63	72	72	72	72	81	81	72	72	72	72
el feed 1/h @ 20	corn- cobs	108	108	123	123	123	123	139	139	123	123	123	123
Fue kg	wood chips	86	96	109	109	109	109	123	123	109	109	109	109
Drytgg	SECO	5010	6035	5010	5573	6271	7474	5140	5972	4656	4656	4792	5126
Dry ing rate	wet ton/h	2.65	2.20	3.00	2.64	3.79	3.18	3.23	2.78	3.16	3.16	3.07	2.87
Dry ing,	Method ⁶	a	QN	۵	QN	٥	Q	٥	Q	۵	۵	٥	Q
Initial Mr	% w.b.	26	8	26	26	22	22	26	26	8	26	8	26
Drying	C. C.	67	67	80	80	80	80	2	ষ	80	80	80	80
Initial		1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	3.7	1.8	1.8	1.8
lara		1									2	e	4

¹Modes defined in Section 6.5.

D: corm dried to 18% MC in IBCF dryer followed by dryeration to 15.5%. ND: corm dried to 15.5% in IBCF (no dryeration) ²Drying method:

³SECO: Net specific energy consumption, kJ/kg of water removed.

3. There is no increase in the airflow rate since the depth either remains constant (Mode 2) or increases with time (Mode 3); the airflow rate increases in Modes 1 and 4 with a decrease in grain depth.

6.5.2 Effect of Dryeration on System Performance

The data in Table 6.12 indicate that the dryeration process results in a higher drying capacity, a lower specific energy consumption, and a lower drying energy cost compared to drying completely in the IBCF dryer. When the drying air temperature is 80°C, the simulated drying capacity is 3 and 2.6 wet ton/h with and without dryeration, respectively; the respective SECO values are 5,010 and 5,573 kJ/kg of water, and the energy cost per wet ton \$1.90 and \$2.16 (wood chip fuel).

The improvement of the system performance with dryeration is attributable to the following factors:

- Less moisture is removed by the IBCF dryer resulting in less drying time of each wet ton of grain in the counterflow dryer.
- 2. The last 2.5% moisture remaining in the corn after the high-temperature drying phase is the portion of the moisture most difficult to remove. This moisture is now removed slowly during the aeration process.
- 3. The aeration process uses a low airflow rate $(0.5 1 \text{ m}^3/\text{min}-\text{m}^2)$ and an insignificant amount of electrical energy to cool the grain and remove the last 2.5% of moisture.

6.5.3 Effect of Drying Air Temperature on System Performance

The drying air temperature has a direct effect on the grain drying capacity, the specific energy consumption, and the drying costs. The effect of the drying air temperature is shown in Table 6.12. The drying capacity increases substantially with an increase in the drying air temperature. The drying capacities are 2.7, 3.0, and 3.2 wet ton/h when corn is dried from 26 to 18% at the drying air temperatures of 67, 80, and 94°C, respectively. The higher temperature air increases the drying rate of the corn and has more watercarrying capacity since the saturation absolute humidity is higher.

The effect of drying air temperature on the specific energy consumption depends upon the moisture percentage points removed in the high-temperature phase. If corn is dried from 26 to 18% the SECO is 5,010 kJ/kg at 67 and 80°C drying air temperatures, and 5,140 kJ/h at 94°C. However, if corn is dried from 26 to 15.5% in the high temperature phase, the SECO is 6,035, 5,573, and 5,972 at air temperatures of 67,80, and 94°C, respectively. Thus, if drying is completed in the high-temperature phase (i.e., corn dried down to 16% moisture content or less), the SECO decreases with increasing drying air temperature up to a point after which the SECO increases with the temperature increase. The inflection point depends upon the ambient temperature, the amount of water removed, and the rate of increase in drying capacity with the temperature increase.

In the example given above, the drying capacity is 2.2 wet ton/h at 67° C and 2.6 wet ton/h at 80° C. Thus, the capacity increases

by 20%; the energy required to heat the drying air increases by 19% resulting in an 8% reduction in the specific energy consumption. When the drying air temperature is raised to 94°C, the capacity increases by 26% while the energy increases by 40%. Thus, raising the drying temperature from 67 to 94°C results in a 1% reduction in the SECO when corn is dried from 26 to 15.5% in the IBCF system.

When corn is dried from 26 to 18% moisture in the hightemperature phase and finally dried to 15.5% in the cooling phase, the drying costs are \$1.94, \$1.90, and \$1.96 per wet ton at temperatures of 67, 80, and 94°C, respectively, compared to \$2.33, \$2.16, and \$2.28 per wet ton if the corn is dried from 26 to 15.5% in the high-temperature phase. Thus, the drying costs vary inversely with the drying capacity.

6.5.4 Effect of Initial Moisture on System Performance

Table 6.12 contains the simulated IBCF dryer performance parameters when drying corn from 26 to 22% initial moisture contents. The results indicate that when corn is dried from 22% moisture, the drying capacity is higher and therefore the drying costs per wet ton lower. The drying capacity (with dryeration) is 3.8 and 3.0 wet ton per hour, the drying costs are \$1.51 and \$1.90 per wet ton for the 22% and 26% initial moisture content corn, respectively.

The costs per kg of water removed is higher for the 22% initial moisture corn. The reason for the higher drying capacity is that less water is removed per ton of wet corn if the initial moisture is 22% than if it is 26%.

Corn with an initial moisture of 22% or less can also be dried in low-temperature or natural air drying systems (Bakker-Arkema et al., 1981).

6.5.5 Effect of Ambient Temperature on System Performance

The ambient temperature has a direct effect on the specific energy consumption and the drying costs. At lower ambient temperature, the heat loss from the system is greater as well as the energy required to raise the drying air to a given drying temperature, than at a higher ambient temperature. The specific energy consumption is 5334 kJ/kg at 0°C ambient temperature, compared to 5010 and 4514 kJ/kg at 4 and 10°C, respectively. The drying costs (wood chip fuel) are \$2.01, \$1.90, and \$1.77 for drying at 0, 4 and 10°C ambient temperature, respectively. The drying capacity does not change with ambient temperature if the drying temperature remains constant.

6.6 Economics of the CVCF/IBCF System

The CVCF/IBCF drying system is a technically feasible system. It would be economically viable if it results in reduced drying costs compared to a propane fueled IBCF system. A substantial investment is required to convert the propane fueled system to a biomass system. The recovery of the additional capital costs must be through savings in fuel costs.

In this section the fuel costs for operating the CVCF/IBCF system using wood chip and corncob fuels at different ambient and drying conditions are presented. The operating costs include the biomass fuel costs, as well as the cost of the electrical energy required to run the furnace and the dryer fans and the IBCF system control. The biomass costs are compared with the cost of operating a propane fueled IBCF system.

A 12-year budgeting analysis is included to show the effect of fuel costs, labor, repairs and maintenance, taxes, depreciation, and inflation on the annual break-even costs of operating the CVCF/IBCF system. The budgeting analysis includes the life cycle costing of the system. The results are compared with the annual break-even costs for a propane fueled system.

6.6.1 Operating Costs

The experimental drying costs are presented in Table 6.7. The costs represent operating costs; they do not include labor and investment costs. The fuel costs are based upon the following 1983 prices:

Wet wood chips:	F.O.B. cost	\$ 6.00	per	ton
	Drying and storage	0.00		
	Freight	0.16	per	ton/km
Dry wood chips:	F.O.B. cost	15.00	per	ton
	Drying	3.75	per	ton
	Storage	2.00	per	ton
	Freight	0.08	per	ton/km
Dry corncobs:	F.O.B. cost	25.00	per	ton
	Drying and storage	0.00		
	Freight	0.36	per	ton/km

Electricity:	0.07	per	k₩h
Propane:	0.22	per	liter

The cost of biomass fuel depends upon the distance over which the fuel is hauled. The F.O.B. cost of biomass fuels is made up of handling expenses incurred in harvesting and/or gathering and storage. The storage and drying costs are zero for dry corncobs and wet wood chips. In the case of corncobs, the fuel is gathered during or after the harvest season and stored in storage bins which are not used for grain storage during the off-season. The corncobs dry naturally in storage. The corncob fertilizer value is approximately \$25 per ton. In the case of wet wood chips, the fuel is used directly without storage or drying.

The cost of dry wood chips includes the drying and the storage expenses. The fuel is obtained from a saw mill at approximately 50% moisture and dried to 30% moisture (or less). A special bin is required for storage and drying by aeration.

The transportation costs depend upon the quantity per load and the distance. The transportation costs per km (kilometer) for the corncobs is high because of their low density compared with wood chips. The bulk density of dry corncobs is approximately 200 kg/m³ compared to an approximate value of 320 kg/m³ for dry wood chips.

The total costs of the wood chips and corncobs used in this research are assumed to be \$44.70/ton and \$35.00/ton, respectively. High moisture content fuels are more expensive than dry fuels because the net heating value is much less for the wet fuels. The energy costs

(Table 6.7) is \$5.82 per wet ton for Test No. 7 compared to \$2.37 per wet ton for Test No. 6. The moisture content of the fuel (wood chips) for Test No. 7 is 45% compared to 10% for the corncobs used in Test No. 6. The higher the fuel moisture content, the higher is the fuel feed rate required to maintain the same drying air temperature.

The average drying cost for the corn in Table 6.7 is \$2.74/wet ton. This compares with \$5.75/wet ton for a similarly operated propane fueled IBCF system (Silva, 1980). Thus, the operating (fuel) costs for the CVCF/IBCF system are lower than for an equivalent system fueled by propane (note that the investment and labor costs are excluded).

The standardized energy drying costs are included in Table 6.8. The cost for drying with 45 and 19.3% moisture wood chips is \$3.48 and \$2.45 per wet ton, respectively, compared to \$2.25 per wet ton if 14.6% moisture is used; the figure is \$3.72 per wet ton if liquid propane is the fuel.

Table 6.8 shows that dry corncobs are the least expensive fuel. The cost of drying is \$1.58 and \$1.68 per wet ton for 10% and 12% moisture corncobs, respectively, due to the low transportation costs (as discussed in section 6.6.1).

The average standardized energy cost is \$2.27 per wet ton for the conditions in Table 6.8. The costs for similar conditions when drying with propane fueled system is \$3.72/wet ton (Silva, 1980). Thus, the operating (energy) costs are less for biomass fuel than for liquid propane.

6.6.2 Capital Budgeting Analysis

The operating costs presented in Tables 6.7 and 6.8 do not include labor, maintenance, investment, interest on borrowed money, depreciation, and taxes. To analyze these costs, a 380 wet-ton annual corn drying system was analyzed using a capital investment model developed by Harsh (1983). The cost estimates are based upon a simulated energy consumption, drying rate, and operating costs for the CVCF/IBCF system operating in Mode 1, Method D (Table 6.12), at a drying temperature of 80°C. The relevant input data for the budgeting analysis are summarized in Table 6.13.

The biomass furnace can be considered an addition to an IBCF system. The MSU furnace was manufactured at a cost of \$11,070; this includes costs for materials (\$8,570), labor (\$2,000), and miscellaneous expenses (\$500). The retail price for the unit is estimated to be \$16,000. The total cost of the CVCF/IBCF system is \$43,000 (Kalchik, 1984) compared to \$27,000 for the propane fueled system. It is assumed that the additional \$16,000 is borrowed at 12% annual interest rate and is payable over a five-year period.

The accelerated cost recovery system (ACRS) outlined in the 1983 Famers Tax Guide (IRS, 1983) was applied to calculate depreciation. The biomass furnace can be classified as a 5-year property with a recovery period of 12 years when using the ACRS code. A 12year, rather than a 10-year, budgeting analysis is presented. A 10-year recovery is not permissible for a 5-year property under the ACRS method. Also, the expected salvage value of the property is not

Table 6.13.--Estimates and assumptions for a 12-year budgeting analysis (1983) prices) of the CVCF/IBCF drying in Mode 1 (see Table 6.12).

		Fuel	
Parameter	Wood chips	Corncobs	Propane
estimated	20% M.C.	20% M.C.	
Fuel cost			
\$/ton	1.90	1.72	5.32
\$/ton-point	0.18	0.16	0.51
Labor cost			
\$/ton	1.11	1.16	0.40
\$/ton-point	0.11	0.11	0.04
Drying rate			
ton/h	3.00	3.00	3.0
ton-point/h	31.50	31.50	31.5

Initial Investment: \$27,000 propane, \$43,000 biomass Percent Borrowed: 0.% propane, 35% biomass Repayment Period: 5 years Interest Rate: 12% Tax Bracket: 20 Type of Property: 5 year property Depreciation Type: Straight line method Recovery Period: 12 years Number of Units Dried: 4,000 ton-point per year (381 ton dried from 26-15.5% w.b.) Losses due to Corrosion, etc.: \$120 per year Repairs & Maintenance: \$2,000 propane, \$4,500 biomass Percent Return: 15% General Inflation Rate: 6% Fuel Inflation Rate: 10% propane, 2% biomass Biomass Fuel Moisture: 20% w.b. Drying Temperature: 80°C Ambient Temperature: 4°C Ambient Relative Humidity: 75%

subtracted from its basic price. The straight line depreciation method is used to compute the annual depreciation cost as a deductible item in tax computations under the ACRS system.

The results of the 12-year budgeting analysis are presented in Table 6.14. The annual operating costs are expressed in \$/wet tonpoint. The unit represents the cost of drying one ton (wet) when one percentage point is removed (e.g., one ton wet corn dried from 26 to 25% MC, wet basis). This unit is preferred over the more common unit of \$/wet ton. The latter unit cannot be readily used to estimate the drying costs when grain is dried from and to different moisture contents. The total and per wet ton investment expenditures are included in the table.

The total annualized break-even drying costs for the biomass fuels is \$3.00 per wet ton-point compared to \$2.23 for the propane system if the annual rate of inflation of the fuel-cost is 2% for all the fuels. If the propane cost inflation is 10% annually, the total drying costs for the propane fueled system if \$2.26 per wet ton-point. The latter is considered a more realistic figure. Thus, the propane fueled system is the least expensive at the current propane price of \$0.225 per litre. The propane cost would have to increase to \$0.378 per litre for the total costs of the propane system to be equal to that of the biomass fueled system. This constitutes an increase of 68% in the present propane cost.

The variable annual break-even costs of the biomass system (\$0.95 per wet ton-point) are about the same as for the propane fueled

Table G.14.--Economic analysis results of different biomass fuels compared to propane (1983 prices) in drying 380 tons (wet) of corn annually from 26% to 15.5% w.b.

	Initial in	vestment	Annual br	eak even costs, \$/	'ton-point ²
Fuel	Total \$	\$/ton	fixed	variable	total
Wood chips (20% MC)	43,000 ¹ 38,000 ²	112.86 99.74	2.06 1.85	0.95 0.95	3.01 2.80
Corncobs (20% MC)	43,000 38,000	112.86 99.74	2.06 1.82	0.94 0.94	3.00 2.76
Propane ⁴ (1)	27,000	70.87	1.41	1.05	2.46
(2)	27,000	70.87	1.41	.82	2.23
(3)	27,000	70.87	1.41	1.60	3.00
				1 · · · · · · · · · · · · · · · · · · ·	

 1 \$43,000 investment is the sum of the current value of the Shivvers IBCF bin (\$27,000) and the estimated retail price of the biomass furnace (\$16,000).

 2 \$38,000 is the investment with the basic cost of the furnace (27,000 + 11,000).

³Wet ton-point.

⁴Propane (1) 10% fuel rate inflation Propane (2) 2% fuel rate inflation Propane (3) 68% immediate increase in propane cost

system (\$1.05 and \$0.82 at annual fuel cost inflation of 10% and 2%, respectively). The total costs for the biomass system are higher due to the higher investment in the CVCF furnace. The fixed costs are 68% of the total break-even costs in the case of the biomass system, and 57% in the case of the propane system (with 10% annual fuel cost inflation).

There is no significant difference between the drying costs for wood chips and corncobs under the conditions presented in Tables 6.12 and 6.13. As mentioned earlier, the cost of a biomass fuel depends on the distance from which it is obtained, and the handling costs involved in drying and storage. Therefore, it should be remembered that the costs presented in Table 6.14 are affected by the transportation and handling costs, and thus, the costs would be slightly different if the transportation and the handling costs changed (see section 6.6.1).

6.7 Corn Contamination in Drying by Direct Biomass Heating

In the MSU concentric vortex-cell biomass furnace, the flue gases are diluted with ambient air and passed directly through the drain. The products of incomplete combustion and fly ash are potential problems with a direct-heated drying system. The primary combustion products are carbon dioxide, carbon monoxide, ash, soot, aldehydes, ketones, sulful dioxide, oxides of nitrogen, and polycyclic aromatic hydrocarbons (PAH). The ash contains inert compounds of heavy metals. The ash and the soot particles contain a high percentage of the other combustion compounds and may be condensed and absorbed on the grain surface. Table 6.15 shows the contamination data of the corn dried with the MSU CVCF/IBCF system. The following substances were detected in the corn: naphthalene (Nph), fluorine (F1), anthracene (An), benz [a] anthracene (BaA), and benzo [a] pyrene.

During the steady-state operation of the MSU biomass furnace, there is no visible smoke, and only a small amount of fly ash is observed. The fly ash is filtered out of the drying air by a thin layer of corn (approximately 3 cm deep) at the bottom of the drying bin. This layer is a residue which is not transferred to the cooling bin. It is removed when the bin is cleaned at the end of the drying season.

The corn dried with wood chips did not contain a measurable amount of any of the PAH before drying. However, the corn dried with corncobs did show measurable amounts of fluorine and anthracene before drying because of its growth environment, possibly close proximity to a highway (Sailor, 1978).

The PAH concentrations in the biomass dried corn appear to increase slightly with time of exposure. Corn is subjected to hot drying air for a maximum of about 8-12 hours in the in-bin drying system (depending on the grain depth in the bin, the initial moisture content, and the drying temperature). The PAH concentration was in the range of 0.06 ppb (BaP) to 8.6 ppb (Nph) after a 6- to 9-hour drying period. The residual corn at the bottom of the drying bin showed a considerable higher concentration of anthracene (0.6 ppb, benz [a] anthracene (1.60 ppb), and benzo [a] pyrene (0.56 ppb) compared Table 6.15.--Concentration of polycyclic aromatic hydrocarbons on corn dried with biomass energy and LP-gas.

Fuel type	Residence time (h)	Naphthalene (ppb)	Fluorine (ppb)	Anthracene (ppb)	Benz [a] Anthracene (ppb)	Benzo [a] Pyrene (ppb)
Wood chips	0.0	1	1	ł	ł	8
	6.4	1	0.14	0.15	0.28	:
	9.0	1.5	0.17	0.13	0.39	0.06
Corn cobs	0.0	1	0.36	0.10	8	8
	4.0	ł	0.18	1	:	;
	8.7	8.6	0.12	0.12	!	:
Propane	1.0	:	0.18	0.17	:	;
Residue*	8	5.9	0.17	0.60	1.6	0.56

*Thin layer of corn (\mathbb{Z} 3 cm) that remains at the bottom of the drying bin, and is removed when the bin is cleaned at the end of the drying season.

to the corn transferred to the cooling bin. The concentration of the BaA and BaP was less than 0.4 ppb in the corn transferred to the cooling bin.

BaA and BaP have shown some carcinogenic activities in test animals (Souci, 1968). The range of concentrations of these compounds is well below that considered to be dangerous to human or animal health (Anderson et al., 1981). Moreover, since most of the corn dried in the USA is used for livestock, the risks to human health is minimal. The extent to which PAHs from contaminated animal feeds are transferred into meat for human consumption is not clear (Deutsche Forschungsgemeinschaft, 1976). The range of concentration values agrees with those measured by Hütt et al. (1978) who studied corn contamination in high-temperature drying systems using a variety of fossil fuels. The PAH levels are of the same order of magnitude as those found by Joe et al. (1982) for barley drying.

Wood chips and corncobs are similar biomass fuels with respect to their effect on the PAH condensation/absorption by corn. There was one exception. Corncobs resulted in a very small quantity of naphthalene in the dried corn, wood chips did not.

Chakraborty and Long (1968) studied the formation of soot and PAHs in flames. They concluded that high temperatures in the pyrolysis zone favor the formation of carbonaceous residues and lead to a reduction of PAHs. Also, PAHs decrease with increasing oxygen concentration during pyrolysis, almost reaching zero at 20% excess oxygen. They also found that the optimum temperature for PHA synthesis in the pyrolysis zone is 700°C. At temperatures above 1000°C there is no formation of PAHs. In the MSU biomass furnace the primary combustion zone (where pyrolysis occurs) temperature varied from 870°C to 1100°C at steady-state due to the preheating of the primary combustion air. This temperature range is above the optimum range for PAH formation. Thus, the low levels of PAH contamination.

Duplicate corn samples run on different days showed no detectable levels of the following metals: arsenic, cadmium, chromium, mercury, selenium, lead, and thalium. The dectection limits for these metals are given in section 5.1.2.

6.8 General Observations

Some general observations on the CVCF/IBCF system are presented in this section. The adequacy of design of the major system components and maintenance requirements are discussed.

6.8.1 Fuel Feed System

The fuel feed system consists of a self-unloading wagon and a feed hopper. The fuel feed system performed satisfactorily. Wood chips and corncobs without husks flow very smoothly through the system. The fuel hopper is coated with graphite-based paint. This feature, as well as the vibrator attached to the hopper, facilitates the smooth flow through the hopper. Corncobs with a large percentage of husks do not flow as smoothly as wood chips and husk-free cobs. There is no bridging of fuel at the bottom of the hopper.

Backfiring through the feed hopper is effectively prevented by maintaining a slight vacuum in the combustion chamber. The vacuum is maintained by the eductor system and the drying fan. The fuel feed rate is manually controlled by varying the speed of the stoker-auger. The fuel feed rate is adjusted to maintain a specified drying temperature. When properly set, the feed rate is equal to the fuel combustion rate. There is no accumulation of unburned fuel in the combustion chamber during steady-state furnace operation. The drying air temperature fluctuates by \pm 5°C from the set temperature. The fuel feed rate control can be automated to respond to the drying air temperature. However, this increases the cost of the furnace without a corresponding improvement in the furnace operation.

The fuel feed system requires little maintenance.

6.8.2 Grate Performance

The grate in the CVCF furnace requires periodic maintenance to remove clinker from the grate surface. The ash receptacle should be cleaned at least once every other day. Accumulation of ash is about 1 to 2 kg/h depending on the fuel type and the fuel feed rate. Most types of wood contain 0.1 to 2% ash, while corncobs contain approximately 1.6% ash (see Table 2.2). Husklage (a mixture of corncobs and husk) has a higher ash content (about 3%). The ashes should be removed daily.

The formation of clinker is a serious problem in biomass furnaces. The clinker blocks the grate openings and therefore, limits the undergrate combustion air supply. Husklage produces more clinker than wood chips and corncobs. The wood chips used during the testing of the furnace produced relatively small amounts of clinker compared to corncobs and husklage. The clinker should be removed at least once a week if wood chips are burned and more often when husklage is used.

The firebricks randomly spaced on the grate were effective in insulating the grate from the high temperature in the combustion chamber. Also, the undergrate airflow cooled the grate from the underside. Thus, the grate design is satisfactory. However, the grate required replacement due to oxidation and other chemical reactions on the grate.

6.8.3 The Combustion Chamber

The lower combustion chamber is lined with firebricks; the upper chamber and the inner lid are covered with a blanket of insulation with desirable refractory characteristics (the price of the insulation is 25% firebrick). The firebricks maintain dimensional integrity and desirable refractory and heat capacity properties without deleterious effect from biomass fuel abrasion. The insulation and the firebricks effectively protect the metal parts (the inner steel cylinder and the inner lid) from the high combustion flame temperature (1,000-1,500°C) and the oxidizing atmosphere.

The maintenance of the combustion chamber includes replacement of the tuyeres and bricks. It is not known how long these components will last.

6.8.4 Furnace-to-Dryer Duct

The heat from the furnace is recovered by means of heated air blown around the furnace and mixed with the flue gases. The hot air

is blown into the bin plenum by a centrifugal fan via a rectangular duct.

Approximately 95% of the heat loss from the system is through the duct linking the furnace to the dryer. The heat loss varies from 300 to 500 MJ/hr depending on the ambient and the drying air temperatures. The heat loss from the duct can be reduced considerably by insulating the duct and the bin plenum.

6.8.5 Safety

Moving components of the furnace are adequately covered to prevent operator contact with injury. Carbon monoxide poisoning is a potential hazard. Exposure to the drying air inside the drying bin should be limited. Some sparks and a small quantity of fly ash reach the plenum and may result in some occasional smoldering of the collected corn dust.

6.8.6 Miscellaneous

Unprotected bin and furnace components are likely to undergo accelerated corrosion due to exposure to the products of combustion. The rate of deterioration of these components is unknown. After two seasons of furnace operation, the corrosion and soot deposits in the bin interior are minimal.

CHAPTER 7

SUMMARY

A direct combustion concentric vortex-cell biomass furnace has been designed, built, and incorporated in an in-bin counterflow dryer (IBCF). The furnace is 1.2 m in diameter and 3.7 m high and has a maximum energy output of 690 kW. It is made of two concentric steel cylinders. The inside cylinder is lined with firebricks for insulation.

The furnace/dryer system was tested under different ambient and drying conditions to determine the technical and economic feasibility as an alternative system for grain drying. The experimental results were compared with the performance of the propane fueled IBCF dryer.

The results demonstrate that the concentric vortex-cell biomass furnace (CVCF) is a technically feasible alternative to fossil fuel burners for grain drying. The corn drying capacity of the experimental biomass fueled system is 2.0-3.0 wet tons per hour depending upon the drying air temperature, the grain depth, and upon the initial and the final grain moisture content. The drying capacity of the biomass fueled system is approximately 90% of the propane system. The reduction in the drying capacity is a result of the reduction in the flow rate of the drying air mass due to the heating of the air before the fan entrance.

The CVCF/IBCF system operates at about 70% efficiency in converting biomass fuels into energy for grain drying. Most of the heat losses (about 95% of the total) occur between the furnace and the drying bin plenum. The heat loss from the furnace is about 5% of the total heat loss. This value was minimized by covering the top onethird of the furnace (1.2 m) with a shroud which reduces the radiation and convective heat loss from the furnace. Also, the lower half of the furnace is located below the ground level, thereby further reducing the low heat loss from the furnace.

The average net specific energy consumption (SECO, kJ/kg of water removed) of the biomas fueled system is about 6,100 kJ/kg compared to an average of approximately 4,600 kJ/kg for a propane fueled system.

Approximately 140 metric wet tons of corn was dried during the testing of the CVCF/IBCF drying system. The biomass furnace performed satisfactorily. There is no visible discoloration of or objectionable odor in the corn dried with the CVCF/IBCF system. Chemical analyses of the corn did not show dangerous levels of polycyclic aromatic hydrocarbons (PAHs) or heavy metal concentration; the levels detected were of the same order of magnitude as found in corn dried with propane or natural gas.

The CVCF furnace is dependable. Drying air temperature control is stable (within \pm 5°C of the desirable temperature) and is maintained by regulating the fuel feed rate. The vibrator installed on the feed hopper prevents fuel bridging, and maintains a continuous flow of biomass fuel to the combustion chamber.

The grate system requires periodic maintenance to remove clinker, especially after burning corncobs. The period between cleanings depends upon the fuel feed rate and upon the ash content of the fuel. On the average, the grate should be cleaned at least once a week.

The ash accumulation in the receptable is on the order of 1 to 2 kg/h depending on the type of fuel used and the fuel feed rate. This is due to the low ash content (0.2 to 3 percent) of wood and corncobs.

The energy drying costs (exclusive of labor and fixed costs) are 30 to 40% of the energy costs of a propane system. However, the total break-even costs of the biomass system (including energy costs, labor, maintenance, depreciation, and taxes) are about 20% higher than of a propane system (at 1983 prices). The high costs are attributable to the high capital investment (approximately \$16,000) required to convert a propane system into a biomass system. If the propane costs increase by about 70%, the biomass system becomes competitive with the propane fueled system. The concentric vortex-cell biomass furnace does not have an economic advantage as a grain dryer heat source at the current fossil fuel prices and interest rates.

CHAPTER 8

CONCLUSIONS

The main conclusions of this research are:

1. The concentric vortex-cell biomass furnace (CVCF) is a technically viable alternative to propane and natural gas burners for grain drying.

2. The CVCF furnace requires slightly more operator attention than a propane system.

3. The drying air temperature is stable during the steadystate operation of the furnace, and can be maintained at 70 to 95°C by regulating the fuel feed rate.

4. The drying capacity of the CVCF coupled to an in-bin counterflow (IBCF) grain dryer is about 90% of a propane fueled IBCF system operating at the same drying conditions.

5. The average net specific energy consumption of a CVCF/IBCF system is about 30% higher than of a propane fueled system. This is due to the reduced capacity and additional heat loss in a biomass system.

6. The energy costs (exclusive of labor and fixed costs) of the CVCF/IBCF system are 30 to 40% lower than the energy costs of a propane fueled IBCF system. The total break-even cost of operating a biomass system is 20% higher than of the propane system, due to the

high investment of converting a propane fueled system into a biomass fueled system.

7. The CVCF furnace does not have immediate economic feasibility at the current propane prices and interest rates. The propane prices have to increase by about 70% for the biomass system to become competitive with propane systems.

8. The corn dried by the CVCF/IBCF system has no visible discoloration or objectionable odor; and does not contain dangerous levels of carcinogenic polycyclic aromatic hydrocarbons or heavy metals.

9. The CVCF furnace model developed in this thesis accurately predicts the required biomass fuel feed rate and heat loss at different drying airflow rates, drying air temperatures, ambient temperatures, and fuel moisture contents. The model can be modified to simulate the performance of other furnace types.

10. The in-bin counterflow grain drying model presented simulates the intermittent action of the IBCF system. The values of the simulated parameters are close to the experimental values.

CHAPTER 9

SUGGESTIONS FOR FURTHER RESEARCH

The following recommendations are suggested as topics for further research:

- 1. Design of automatic furnace shut down in the event of:
 - a. drying bin empty,
 - b. drying bin failure,
 - c. extremely high or low drying air temperature,
 - d. accidental fire.
- Determination of the optimum dimensions and configuration of biomass furnace eductors.
- Determination of the economic feasibility of insulating the CVCF furnace, the duct work between the furnace and the drying bin, and the drying bin plenum.
- Investigation of alternative insulating materials for the combustion chamber of a concentric vortex-cell biomass furnace (CVCF).
- 5. Determination of the effect of tuyere size and tuyere angle on particulate emission.
- Testing of other biomass materials as fuel, such as coal, apple pomice, rice hulls, etc.

- 7. Application of CVCF furnace to other dryer types.
- Adaptation of the furnace model to simulate other biomass furnaces.
- Dimensional analysis and similitude modeling of the CVCF and the IBCF systems.
- 10. Statistical analysis to determine the variations in the experimental and the simulated values of fuel feed rate, heat loss, grain moisture content, and grain drying capacity of the CVCF/IBCF system.
- The effect of precipitation and wind on the heat loss from the CVCF/IBCF drying system.

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APPENDICES

APPENDIX A

SAMPLE OF CVCF COMPUTER INPUT/OUTPUT DATA

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Sample of CVCF Computer Input/Output Data.

FUEL TYPE: CORNCOES=1,WCOD=0.0.	x00DCHIPS
FUEL FEED RATE,KG/HR:100.	100.00
FUEL MOISTURE, PERCENT(WE)20.	20.00
AMBIENT TEMPERATURE, C:4.	4.00
PERCENT RELATIVE HUMIDITY:75.	75.00
DRYING PRESSURE, KPA1.	1.00
EXCESS AIR, PERCENT:50.	50.00
COMBUSTION AIF, KG/H:	757.73
Air:Fuel Ratio:	7.58
TEMPERATURES: AMBIENT: PREHEATED COME. AIR; FURNACE FLAME: PREDILUTION FLUE GAS: DILUTED FLUE GAS: DRYING (BIN FLENUM): OUTER FURNACE WALL:	4.000 123.990 1243.490 783.540 101.870 79.620 146.990
MASS FLOWS: FUEL FEED, KG/H: FUEL MOISTURE, WE: FURNACE AIR SUPPLY, KG/KG-FUEL: CMM: EXCESS AIR, PERCENT: PREDILUTION FLUE GAS, KG/H: CMM: DILUTED FLUE GAS, KG/H: CMM: DRYING AIR, CMM: DRYING AIR ABSOLUTE HUMIDITY:	100.00 20.00 14.48 19.32 50.00 1547.05 77.14 16308.87 289.02 274.11 .0076
TOTAL HEAT OUTPUT, MJ/H:	1677.20
TOTAL HEAT LOSS, MJ/H:	448.95
BIN PLENUM HEAT LOSS, MJ/H:	58.24
FURNACE EFFICIENCY, PERCENT:	95.38
SYSTEM EFFICIENCY, PERCENT:	73.23
ASH ACCUMULATION, KG/H:	.94
UNBURNED FUEL ACCUMULATION, KG/H:	.00

APPENDIX B

EXPERIMENTAL RESULTS

													_	7
Drying	capacity wet ton/h	1.3	2.1	2.5	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	
Moisture	% w.b.	18.9	:	18.9	18.6	*	:	18.5	18.9	:	:	18.9	18.8	
rate	kg/min	279	291	298	308	310	315	319	326	330	332	335	313	
Airflow	m ³ /min-m ³	6.5	7.5	9.5	11.1	13.0	15.5	19.3	25.3	25.7	36.6	62.8	21.2	8t
Grain	depth, m	1.8	1.7	1.5	1.3	1.2	1.0	0.9	0.7	0.6	0.4	0.2	;	ature 12.4°C Ve humidity 84
Drying	temperature °C	77	77	76	77	78	62	77	77	76	75	75	77	itions: Tempera Relativ
Cvcle	time, h	1.80	0.53	0.62	0.77	0.77	0.85	0.95	0.93	0.80	1.05	0.93	16.0	ambient cond
Cvcle	No.	1	2	m	4	ß	9	7	ω	6	10	11	Average	Average

μ.
No.
Test
ults:
1 res
rimenta
Expe
3.1
e
Tabl

	Drying canacitv	wet ton/h	1.9	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.5
	Moisture	% w.b.	16.0	20.0	18.9	17.5	16.6	16.2	16.7	16.1	17.3
	rate	kg/min	307	312	318	324	328	330	334	340	324
	Airflow	m ³ /min-m ³	8.7	6.6	11.3	13.2	15.6	19.1	24.5	33.8	17.0
ental results: Test No. 2.	Grain depth, m		1.5	1.4	1.2	1.1	0.9	0.7	0.6	0.4	;
	Drying temperature °C		89	89	88	88	06	86	68	16	68
Experime	Cvcle	time, h	1.25	0.83	1.00	1.00	0.95	1.00	0.97	0.83	0.98
Table B.2	Cvcle	No.	1	2	m	4	വ	9	7	œ	Average

Note: Average ambient conditions: Temperature 13.5°C Relative humidity 98%

Cuol a	رمام ما م	Drying	i en j		Airflow	rate	Moisture content	Drying capacity
No.	time, h	temperature °C	dept	E.,	m ³ /min-m ³	kg/min	% w.b.	wet ton/h
1	1.42	73	1.09	3.0	11.9	304	15.7	1.8
2	1.28	76	0.93	2.75	14.3	310	;	1.9
m	1.28	82	0.76	2.2	18.1	322	15.4	2.0
4	1.07	80	1.07	2.5	12.6	315	1	2.1
Ω.	1.00	6/	0.90	2.25	15.2	321	17.0	2.2
9	1.05	76	1.07	2.5	12.6	315	16.5	2.2
Average		78				314		2.2

.

Table B.3.--Experimental results: Test No. 3

Note: Average ambient conditions: Temperature

Temperature 2°C Relative humidity 76%

Table B-4.--Experimental results: Test No. 4.

Cle UCCle temperature depth, m $m^3/min-m^3$ kg/min 0. time, h $^{\circ}C$		-	Drying	Grain	Airflow	rate	Moisture	Drying capacity
0.83 88 1.22 10.6 305 1.02 90 1.62 7.5 293 1.02 90 1.62 7.5 293 1.02 89 1.50 8.4 298 1.53 84 1.95 6.4 293 1.18 86 2.23 5.4 283 1.18 88 2.23 5.4 283 1.18 88 2.23 5.4 283 1.18 88 2.23 5.4 283 1.19 88 2.06 6.0 291	<u>e</u> .	Cycle time, h	temperature °C	depth, m	m ³ /min-m ³	kg/min	% w.b.	wet ton/h
1.02 90 1.62 7.5 293 8 0.82 89 1.50 8.4 298 1 1.53 84 1.95 6.4 293 1 1.18 86 2.23 5.4 283 1 1.18 88 2.06 6.0 201 1 1.18 88 2.06 6.0 201		0.83	88	1.22	10.6	305	13.0	3.1
3 0.82 89 1.50 8.4 298 4 1.53 84 1.95 6.4 293 5 1.18 86 2.23 5.4 293 6 1.18 86 2.23 5.4 283 6 1.18 88 2.06 6.0 291 6 1.00 88 2.06 6.0 291	~	1.02	06	1.62	7.5	293	:	2.8
4 1.53 84 1.95 6.4 293 5 1.18 86 2.23 5.4 283 6 1.18 88 2.06 6.0 291	e	0.82	88	1.50	8.4	298	14.3	2.9
5 1.18 86 2.23 5.4 283 6 1.18 88 2.06 6.0 291	4	1.53	88	1.95	6.4	293	14.9	2.5
6 1.18 88 2.06 6.0 291	5	1.18	86	2.23	5.4	283	14.4	2.4
294 7.4 294	9	1.18	88	2.06	6.0	291	1	2.4
	erage	1.09	88		7.4	294	14.2	2.4

Average ambient conditions: Te

Temperature 5.8°C Relative Humidity 70%

Drying	د بر مان	Airflow	rate	Moisture	Drying
temperature °C	depth, m	m ³ /min-m ³	kg/min	w.b.	wet ton/h
 83	1.22	10.6	291	18.8	1.6
82	1.05	12.6	296	;	2.0

Table B.5.--Experimental results: Test No. 5

Temperature, -0.9°C Relative humidity 87%

2.1

16.1

312

26.3

0.53

8

1.25

ഹ

2.0

1

318

40.5

0.35

82

1.50

9

2.0

16.7

304

20.85

:

82

1.31

Average

2.0

16.3

302

15.5

0.87

80

1.25

e

2.1

ł

307

19.6

0.70

81

1.17

Average ambient condition: Note:

Test No.
results:
Table B.6Experimental

. 9

Cvcle	Cvcle	Drying	Gra in	Airflow	rate	Moisture	Drying canacity
No.	time, h	cemperature °C	depth, m	m ³ /min-m ³	kg/min	% w.b.	wet ton/h
1	1.22	93	1.83	6.2	250	13.8	1.9
2	1.37	95	1.67	6.8	250	13.4	1.8
m	1.43	94	1.51	7.7	255	15.3	1.7
4	1.33	06	1.35	8.7	257	ł	1.7
ഹ	1.33	61	1.20	10.0	262	;	1.7
9	2.08	06	1.04	11.7	267	15.2	1.6
7	1.33	92	0.88	14.0	271	;	1.6
œ	0.42	94	0.72	17.5	275	15.9	1.8
6	1.25	95	0.56	23.2	285	8	1.8
Average	1.31	63		10.21	263	14.7	1.8
Note: A	verage amb1	ent conditions:	Temperature Relative hum	13.3°C idity 90%			

Table B.7.--Experimental results: Test No. 7.

د احدی ا	נייין	Drying	a i e	Airflow	rate	Moisture	Drying
No.	time, h	temperature °C	depth, m	m ³ /min-m ³	kg/min	% w.b.	wet ton/h
П	1.52	83	1.83	6.1	264	13.6	1.7
2	2.05	80	1.66	6.8	269	13.1	1.5
ß	1.83	82	1.48	7.9	275	1	1.5
4	1.58	84	1.31	9.1	281	15.1	1.5
5	1.83	81	1.13	10.8	288	:	1.5
9	1.67	82	0.92	12.9	294	14.0	1.5
7	1.75	82	0.79	16.0	300	:	1.5
Average	1.75	82	1	6.9	281	14.6	1.5

Note: Average ambient condition: Temperatu

Temperature 0.6°C Relative humidity 93% APPENDIX C

CVCF COMPUTER PROGRAM

CVCF COMPUTER PROGRAM

PROGRAM BURNER(OUTPUT, INPUT)

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C*

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C*	THIS PROGRAM	COMPUTES THE HEAT LOSSES FROM THE MSU CONCENTRIC
C*	VORTEX-CELL B	IOMASS FURNACE. IT ALSO COMPUTES THE TEMPERATURES
C*	AND THE MASS	FLOWS IN THE VARIOUS SECTIONS OF THE FURNACE.
C*		
C*	THE PROGRAM C	ONSISTS OF THE MAIN PROGRAM 'BURNER', SUBROUTINES
C*	'PROPATY', 'A	IRPTS', 'FLUPTY', AND THE FUNCTIONS 'RUTA',
C*	'SIMPSON', EN	THAL, 'TABLE', HEATF', 'TADI', AND 'GMOW'.
C*	•	
C*	THE SUBROUTIN	NES FUNCTIONS ARE AS FOLLOWS:
C*	PROPATY :	CONTAINS TABLES OF THERMODYNAMIC PROPERTIES OF
C*		THE MAJOR GASES INVOLVED IN COMBUSTION.
C*	AIRPTS:	COMPUTES THE PROPERTIES OF AIR AT A GIVEN TEMPERATURE
C*		CALLS THE FUNCTION TABLE WHICH INTERPORATES THE DATA
C*		CONTAINED IN THE SUBROUTINE PROPATY.
C*	FLUPTY:	COMPUTES THE DYNAMIC VISCOSITY AND THERMAL
C*		CONDUCTIVITY OF FLUE GASES.
C*	RUTA:	SOLVES FOR THE JACKET INNER WALL TEMPERATURE BY
C*		DOING THE RADIATIVE, CONVECTIVE, AND CONDUCTIVE HEAT
C*		BALANCE.
C*	SIMPSON:	COMPUTES THE ENTHALPY CHANGE OF FLUE GASES AT A
C*	•	GIVEN TEMPERATURE BY THE SIMPSON INTERGRATION OF
C*		THE SPECIFIC HEAT FUNCTIONS IN THE SUBROUTINE ENTHAL
C*	ENTHAL:	CONTAINS SPECIFIC HEAT EQUATIONS FOR GASES.
C*	TABLE:	INTERPORATES THE TABULATED DATA.
C*	HEATF:	DETERMINES THE HEAT REQUIRED TO HEAT THE AIR AND THE
C*		FUEL TO THE COMBUSTION TEMPERATURE ABOVE 25C.
C*	TADI:	DETERMINES THE ADIABATIC FLAME TEMPERATURE GIVEN THE
C*		FUEL HEATING VALUE, THE INITIAL FUEL AND THE AIR
C*		TEMPERATURES, AND THE PRODUCTS OF COMBUSTION.
C*	GMOW :	COMPUTES THE MOLECULAR WEIGHT, SPECIFIC HEAT, AND THE
C*		TOTAL MASS OF FLUE GAS.
	COMMON/FRACT	NS/COM(20), GAS(20), WMOL(20), CP(20), CM2, CM3, CM4, CMO
	COMMON/PROPE	TY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10)
	COMMON/FLUE/	DVCO2(20),CKCO2(20),DVCO(20),CKCO(20),DVH2O(20),
	+CKH20(20),DV	H2(20),CKH2(20),DVN2(20),CKN2(20),DVO2(20),CKO2(20)
	COMMON/SMS/S	MLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10)
	COMMON/PRESS	/PATM
	DIMENSION NA	ME(20),A(20),R(30),X(50),TFUR(50),VISK(20),QL(20)
	DIMENSION GA	SED(10)

EXTERNAL HEATF, FLUPTY, TABLE, PROPATY, RUTA DATA PATM/14.696/ DATA C, H, OXY, CN, SUL, ASH/46.83, 5.95, 45.025, .42, 0., 1.6/ DATA FUEL, XMFW, TAMB, RH, PFF, BINP/90., 12.1, 5.79, 70, 2.125, 3.44/ C* THE A'S ARE THE AREAS OF THE VARIOUS SECTIONS OF THE FURNACE. DATA (A(L), L=1,6)/.732, 10.167, 1.167, 14.009, 2.627, 14.009/ C* THE R'S ARE THE THERMAL RESISTANCES ACROSS VARIOUS SECTIONS OF C* THE FURNACE INCLUDING CONVECTIVE, RADIATIVE AND CONDUCTIVE C* THEMAL RESISTANCES. DATA (R(M), M=1, 18)/.527, 15.814, .978, 5., .312, 2.385, .286, +7.88,9.362,4.029,.125,.125,3.75,15.228,1.0075,.157,.15,.008/ DATA AAO, AA2, AA3, AA4, AP/.09931, .00456, .0324, .0243, 1.459/ DATA (WMOL(K), K=1,8)/44.01,28.01,28.016,46.,30.,18.,32.,2./ TRK(R) = R/1.8TKR(C)=1.8*C $TKF(Z) = 1.8 \times Z - 459.67$ TFK(Z)=(Z+459.67)/1.8 CALL PROPATY (TAMB) C* THE COMS ARE THE COMPONETS OF THE FLUE GASES CONSIDERING THE C* COMBUSTION AIR AND FUEL AS THE REACTANTS. C* THE COMEDS ARE THE COMPONENTS OF FLUE GASES AFTER DILUTION WITH C* EDUCTOR AIR. NAME(1)=9H CORNCOBS NAME(2)=9HWOODCHIPS DO 33 N=1,10 33 COM(N) = COMED(N) = 0. 43 CONTINUE PRINT 133 READ 329, TYPE IF(TYPE .EQ. 1.)PRINT 83,NAME(1) IF(TYPE .EQ. 0.)PRINT 83,NAME(2) TJAK=TPRE=400. WHAT=TYPE IF(TYPE .GE. 1.)GOTO 80 C* C, OXY, CN, SUL, ASH, AND H ARE THE PERCENTAGE COMPONENTS OF FUEL BEING CARBON, OXYGEN, NITROGEN, SULFUR, ASH AND HYDROGEN, C* C* RESPECTIVELY, AS GIVEN IN THE FUEL ULTIMATE ANALYSIS. C = 52.02OXY = 40.61CN=.09 SUL=.01 ASH=1.18 H=6.09 80 CONTINUE PRINT 4 READ 329, FUEL PRINT 200, FUEL PRINT 8 READ 329.XMFW PRINT 200, XMFW XMDB=XMFW/(100-XMFW) PRINT 5

```
READ 329, TAMB
      PRINT 200, TAMB
      PRINT 99
      READ 329, RH
      PRINT 200, RH
      PRINT 6
      READ 329, BINP
      PRINT 200, BINP
      BINP=BINP/.2482342855
C*
      NAME4=4HWIND
C*
      NAME5=8HVELOCITY
C*
      NAME6=3HM/S
C*
      PRINT*, NAME4, NAME5, NAME6
C*
      READ 329, VWIND
      VWIND=0.
C*
      PRINT 200, VWIND
C*
     THE PFF IS THE COMBUSTION AIR PRESSURE AS A FUNCTION OF THE DRYING
C*
     PLENUM AIR PRESSURE (BINP).
      PFF=.3075*BINP+1.232
      IF(BINP .LE. 0.)PFF=2.25
      NAME3=5HR(5)
      TAMB=TAMB+273.15
C* FCFM IS THE TOTAL CFM OF AIR INTO THE FURNACE
C* FCFM INCLUDES THE EDUCTOR AND THE COMBUSTION AIR,
C* AND IS DETERMINED FROM THE CHARACTERISTIC FAN EQUATION.
      FCFM=TABLE(CFMF, SMST, DIFST, KST, PFF)
      W=HADBRH(TKR(TAMB),RH/100.)
      SVO=VSDBHA(TKR(TAMB),W)
      CMO=FCFM/SVO*.4536
      TEK=TAMB+4.3
      CMO=CMO*(-.05*BINP+1.19)
      PRINT 111
      READ 329, EXCS
      PRINT 200, EXCS
      CMOML=CMO/28.97
C* CFM3 IS THE AIRFLOW AROUND THE FURNACE, (CFM)
C* CM3 IS THE AIR MASS FLOW AROUND FURNACE (KG/MIN)
      CMV3=(479.93-10.65*BINP)
      CFM3=CMV3*15.708
      CM3=CFM3/SV0*.4536
      CMV3=CMV3*.3048
      AA=C/12.01115
      BB=H/1.00797
      CC=CN/14.0067
      DD=SUL/32.064
      EE=OXY/15.9994
      STOXY=AA+BB/4.+CC+DD-EE/2.
      FUEL=FUEL/60.
      FUELDB=FUELD=FUEL*(1.-XMFW/100.)
      AMPKG=STOXY*4.76/100.
      AMOLS=STOXY*4.76*FUELD/100.
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AIRMOLS=AMOLS*(EXCS+100.)/100.

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IF (AIRMOLS .LT. AMOLS) FUELDB=AIRMOLS/AMPKG IF(AIRMOLS .LT. AMOLS)AMOLS=AIRMOLS CM2=AIRMOLS*28.97 CMC=CM2*60.CMR=CMC/(FUEL*60.) FUELNB=FUEL*60.-FUELDB*(1.+XMDB)*60. PRINT 899 PRINT 200,CMC PRINT 900 PRINT 200, CMR CMED=CMO-CM2 EXT1=AIRMOLS-AMOLS C* HHV IS THE FUEL HIGHER HEATING VALUE, KJ/KG AS A FUNCTION OF C* THE FUEL COMPOSITION (ULTIMATE ANALYSIS). HHV=18650. IF(TYPE .EQ. 0.)HHV=20965. HHVT=HHV*FUELDB EXT2=CMOML-AMOLS STOCRA=AMOLS*28.97/FUELD ACTRA=CM2/FUELD EQRATIO=STOCRA/ACTRA COM(1) = AA * FUELD/100.COM(3)=.7899*AIRMOLS+CC/2*FUELD/100. COM(6)=XMDB*FUELD/18.015+1.608*AIRMOLS*W+BB/2.*FUELD/100. COM(7)=.2101*EXT1 C* QNA IS THE TOTAL MOLES IN THE FLUE GAS. C* GAS(I) IS THE FRACTIONAL MOLECULAR COMPOSITION OF COMPONENT I C* IN THE FLUE GAS. QNA=COM(1)+COM(3)+COM(6)+COM(7)DO 11 N=1,7 IF(COM(N) .EQ. 0.)GOTO 11 GAS(N) = COM(N) / QNA11 CONTINUE COMED(1) = COM(1)COMED(3) = .7899 * CMOML + CC/2 * FUELD/100.COMED(6)=XMDB*FUELD/18.015+1.6081*CMOML*W+BB/2.*FUELD/100. COMED(7)=.2101*EXT2 QNA2=COMED(1)+COMED(3)+COMED(6)+COMED(7)DO 39 N=1,7 IF(COMED(N) .EQ. 0.)GOTO 39 GASED(N)=COMED(N)/QNA2 39 CONTINUE AIRMASS=CM2 KCYCLE=1 C* TADK IS THE FIRST ESTIMATE OF ADIABATIC FLAME TEMPERATURE C* AS GIVEN BY TILMAN ET AL. (1981). C* TAD2 IS THE ADIABATIC FLAME TEMPERATURE TAKING INTO ACCOUNT C* THE REACTANTS INITIAL TEMPERATURE AND THE HEAT REQUIRED FOR C* PREHEATING THE REACTANTS (FUEL AND AIR). TADK=1920.-2.*XMDB*100.-5.2*ABS(EXCS) TADES=TADK 1300 CONTINUE

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IF(KCYCLE .EQ. 1)CPA=TABLE(ACP, SMLA, DIFA, KA, TPRE)
      CON3=HEATF(TPRE, CM2, FUEL, XMDB, TAMB)
      TAD2=TADI (COM, TADES, QNA, WM1, CMG, CPG, CON3, HHVT, ENF)
      TAD2 = (TAD2 + TADK)/2.
      TPRE=TJAK
      IF(KCYCLE .EQ. 1)TF=TAD2-CM2*CPA*(TPRE-TAMB)/(CMG*CPG)
      IF(TF .LE. TJAK)PRINT 93
      IF(TF .LE. TJAK)GOTO 91
      TADES=TAD2
      B=.2
      GM=GMOW(COM, TF, CPG, CMG, ONA)
      AWS=7.7587
      AWT=.456
      AW1=AWS+AWT
      AGR=.5
      AF=4.4*AGR
      ECO2H2O=483./TF*(.424*(GAS(6)+GAS(1))*100.)**.45
      ESOOT=1.-EXP(-.6*B*SORT(AGR))
      EPS=ESOOT+EC02H2O-(ESOOT*EC02H2O)
      R(19)=(1.-EPS)/(AF*EPS)+1./(AF*.75)+.0612
      STEBTZ=5.669E-8
      SB=STEBTZ
      RU=8.2E-3
      RHOG=WM1/(RU*TF)
      CC1=EPS*STEBTZ*4.*AGR*60.
      VEG=CMG/(RHOG*AGR)*.65/60.
      ANZL=2.027E-3
      TNZL = (TF*2.+TPRE)/3.
      AIRD=TABLE(ADEN, SMLA, DIFA, KA, TNZL)
      VENZL=CM2/60.*.35/(ANZL*AIRD)
      VEMAX=SORT(VEG**2.+VENZL**2.)
C* COMPUTE VISCOSITY & THERMAL CONDUCTIVITY OF FLUE GASES
      CONRA=0.
      CONDMIX=UMIX=0.
      DO 27 I=1.6
      IF(COM(I) .EQ. 0.)GOTO 27
      VISK(I)=FLUPTY(TF,I,1)
      RATIO=1.
      DO 15 J=1.6
      IF(COM(J) .EQ. 0.)GOTO 15
      IF(J .EQ. I)GOTO 15
      VISK(J)=FLUPTY(TF,J,1)
      Pl=1.+SQRT(VISK(I)/VISK(J))*(WMOL(J)/WMOL(I))**.25
      P1=P1**2.
      P2=2.*SQRT(2.)*SQRT(1.+WMOL(I)/WMOL(J))
      PHI=P1/P2
      RATIO=RATIO+PHI*(GAS(J)/GAS(I))
      CONRA=GAS(J)/100.*PHI+CONRA
      CONTINUE
      COND=FLUPTY(TF, I, 2)
```

C*

C*

CONDMIX=CONDMIX+(GAS(I)/100.*COND)/CONRA UMIX=VISK(I)/RATIO+UMIX CONTINUE 27 PRG=CPG*1000.*UMIX/CONDMIX H1=VEMAX*RHOG*CPG*1000./PRG**(2./3.)*.0125 CC2=H1*4.*AGR*60. CF=CC2/60. OFUNC=CMG*CPG*1000./60.*(TAD2-TF) KIT=0 TSKY=.0552*TAMB**1.5 EBS=SB*TSKY**4 TFF=TKF(TF) TF2=.6942*TFF-65.6386 T2=TFK(TF2)EB2=SB*T2**4 TF7=.2449*TFF-259.41 T7=TE7=TFK(TF7) T8=CMG*CPG*TF+CMED*TEK T8=T8/(CMG*CPG+CMED)EB8=SB*T8**4 10 CONTINUE TFM = (T7 + TAMB)/2. CALL AIRPTS(TFM, DEN, SKS, VIS, PRN, CPS) BETA=1./TFM GR=(BETA*9.8*(T7-TAMB)*1.2192**3)/VIS**2 RA=GR*PRN EV1=4. EV2=EV1 IF(VWIND .GE. 3.)EV1=1.42 IF(VWIND .GE. 3.)EV2=.95 HA7=EV1*((T7-TAMB)/2.4384)**.25 IF(RA .GT. 1E+9)HA7=EV2*(T7-TAMB)**(1./3.) QC07=14.*HA7*(T7-TAMB) C* FORCED CONVECTION RE=VWIND*1.2192/VIS HNU=.43+.5*RE**.5*PRN**.38 IF(RE .GT. 1E+3)HNU=.25*RE**.6*PRN**.38 QCOF=4.67*SKS/1.2192*HNU*(T7-TAMB) IF(VWIND .LT. 3.)QCOF=0. QC07=QC07+QC0F TJAF=.1814*TFF-156.6478 TJAK=TFK(TJAF) CALL AIRPTS(TJAK, DEN, SKS, VIS, PRN, CPS) V67=CM2/60./(DEN*.2137) IF(KIT .EO. 0)T67=T7 TD1=T67-TAMB TD1=ABS(TD1) TD2=T67-TJAK TD2=ABS(TD2) TD3=TD1-TD2 TD3=ABS(TD3) TLM=TD3/ALOG(TD1/TD2)

...

```
DE=.254
      CALL AIRPTS(TLM, DEN, SKS, VIS, PRN, CPS)
      H67=SKS*.023/DE*(DE*V67/VIS)**.8*PRN**(1./3.)
      Q67=12.842*H67*(T7-TLM)
      EBA=SB*TAMB**4
      QS7=QC07+Q67-EBA/R(17)
      OC6=067*1.5
      IF(KIT .EQ. 1)QC6=10.16667*H67*(T6-TLM)
      Q567=QC6+Q57*R(17)/(R(16)+R(17))
      RS1=R(17)/(R(16)*(R(16)+R(17)))-1./R(16)
      IF(KIT .EQ. 0)T6=T7*1.5
      K=2
      X(1)=T6*.925
      X(2) = T6 \times 1.5
20
      CONTINUE
      K=K+1
      FX1=RUTA(QS67, RS1, CF, TF, R, X(K-2))
      FX2=RUTA(QS67,RS1,CF,TF,R,X(K-1))
      X(K) = (FX2 * X(K-2) - FX1 * X(K-1)) / (FX2 - FX1)
      ERROR=ABS(X(K)-X(K-1))/2.
      IF(ERROR .LE. 1E-10)GOTO 23
      GOTO 20
23
      CONTINUE
      T6=ABS(X(K))
      KIT=KIT+1
      EB6=SB*T6**4
      TW1 = (OS67 - EB6 * RS1 + T6/R(18)) * R(18)
      EB7=T7**4.*SB
      IF(T7 .LT. TE7)T7=TE7
      T67 = (T6 + T7)/2.
      IF(KIT .EQ. 1)GOTO 10
      QR7=.75*(EB7-EBA)/R(17)+.25*(EB7-EBS)/R(17)
      TF7=TKF(T7)
      AA4=1.1675
      TF4=1.0605*TF7+15.3076
      TAF = .08 * TKF(T8) + 26.
      V4=2.413
      T4=TFK(TF4)
      EB4=SB*T4**4
      TA=TFK(TAF)
      DE=.61
      TW = (T4 + TAMB)/2.
      TD1=T4-TAMB
      TD1=ABS(TD1)
      KEY1=0
1401 CONTINUE
      TD2=T4-TA
      TD2=ABS(TD2)
      DTM = (TD1 - TD2) / ALOG(TD1 / TD2)
      CALL AIRPTS(DTM, DEN, SKS, VIS, PRN, CPS)
      H4=SKS/DE*.023*(V4*DE/VIS)**.8*PRN**(1./3.)
      Q40=AA4*H4*(T4-DTM)
```

```
TIN4=(T4+TAMB)/2.
      TD1=T4-TAMB
      TD1=ABS(TD1)
      TD2=T4-TIN4
      TD2=ABS(TD2)
      DTM = (TD1 - TD2) / ALOG(TD1 / TD2)
      CALL AIRPTS(DTM, DEN, SKS, VIS, PRN, CPS)
      CA4=1.069
      VIN4=CM2/(DEN*CA4)/60.
      HIN4=SK5/.8636*.023*(.8636*VIN4/VI5)**.8*PRN**(1./3.)
      QIN4=AA4*HIN4*(T4-DTM)
      DJ4=(Q40+QIN4)*R(7)+SB*T4**4
      EB1=SB*TW1**4
      EB11=SB*(TW1*.65)**4
      RT1=1/R(1)+1/R(2)+1/R(4)+1/R(10)
      RT2=1/R(2)+1/R(3)+1/R(8)+1/R(9)
      RT3=1/R(4)+1/R(5)+1/R(6)+1/R(9)
      RT4=1/R(6)+1/R(7)+1/R(8)+1/R(10)
      RT5=1/(R(2)**2*RT1)-RT2
      RT6=1/(RT1*R(4)*R(2))+1/R(9)
      RT7=1/(RT1*R(10)*R(2))+1/R(8)
      RT8=1/(RT1*R(10)*R(4))+1/R(6)
      RT9=RT8-RT6*RT7/RT5
      DK1 = EB11/R(1) + DJ4/R(10)
      DK2 = -(EB2/R(3) + DJ4/R(8))
      DK3=DJ4*RT4-EB4/R(7)
      DK4=DK2-DK1/(RT1*R(2))
      DK5=DK3-DK1/(RT1*R(10))
      DJ3=(DK5-DK4*RT7/RT5)/RT9
      DJ2=(DK4-DJ3*RT6)/RT5
      DJ1=(DK1+DJ3/R(4)+DJ2/R(2))/RT1
      EB3=ABS(DJ3*RT3-(DJ1/R(4)+DJ2/R(9)+DJ4/R(6)))*R(5)
      T3=(EB3/SB)**.25
      T13=(T3+TW1*.65)/2.
      BETA=1./T13
      CALL AIRPTS(T13, DEN, SKS, VIS, PRN, CPS)
      GR=.2775*BETA*ABS(T3-T13)/VIS**2
C* EQUTIONS 8-74 TO 8-76 GEBHART FOR FREE CONVECTION
C* BETWEEN HORIZONTAL PLATES, BOTTOM HOTTER.
      HNU=.068*GR**(1./3.)
      IF(GR .LT. 1E+5)HNU=.195*GR**.25
      IF(GR .LT. 1E+4)HNU=1.
      H3=HNU*SKS/.3048
      AA3=1.0681
      OI3=AA3*1.5*H3*(T3-T13)
      CALL AIRPTS(TA, DEN, SKS, VIS, PRN, CPS)
      DT=1.0973
      VMT=.25*CM3
      AT=1.806
      VET=VMT/(AT*DEN)/60.
      RE=VET*DT/VIS
      HT=SKS/DT*.664*PRN**(1./3.)*RE**.5
```

```
TAF = (TAMB + TA)/2.
OT3=AA3*HT*(T3-TAF)
DJ5=(QI3+QT3-DJ3/R(5)+EB3*(1./R(5)+1./R(5)))*R(5)
RT10=1./R(5)+1./R(11)+1./R(13)
RT11=1./R(11)+1./R(12)+1./R(14)
RT12=1./R(13)+1./R(14)+1./R(15)
RT13=R(11)/(R(13)*R(14))+RT12
DK6=DJ5*RT10-EB3/R(5)
DK7 = -(EB8/R(15) + DJ5/R(13))
DK8=DK7-DK6*R(11)/R(14)
DJ7 = -DK8/RT13
DJ6=(DK6-DJ7/R(13))*R(11)
EB5=ABS(DJ6*RT11-DJ5/R(11)-DJ7/R(14))*R(12)
T5=(EB5/SB)**.25
T5=(TA*5+T5)/6.
IF(T5 .LE. TAMB)T5=TA
QTD3=AT*HT*(T5-TAF)
TA=((QT3+QTD3)*.06+CM3*CPS*TAMB)/(CM3*CPS)
KEY1=KEY1+1
IF(KEY1 .LT. 2)GOTO 1401
TF5=TKF(T5)
AT=2.6268
ORT=SB*AT*(T5**4-TSKY**4)
TTF=(T5+TAMB)/2.
CALL AIRPTS(TTF, DEN, SKS, VIS, PRN, CPS)
IF(VWIND .LT. 3.)GOTO 45
RE=VWIND*1.6/VIS
HT5=SKS/1.6*.5*RE**.5*PRN**(1./3.)
GOTO 47
CONTINUE
BETA=1./TTF
GR=43.6955*BETA*(T5-TAMB)/VIS**2
RA=PRN*GR
EV3=7.
HT5=SKS/1.6459*EV3*RA**.2
CONTINUE
X(KCYCLE)=TF
KCYCLE=KCYCLE+1
QCT=AT*HT5*(T5-TAMB)
QLT=QR7+QRT+QCT+QCO7+QT3+QTD3
QLH=(QR7+QRT+QCT)*3.6
IF(KCYCLE .GE. 10)GOTO 1310
CALL AIRPTS(TA, DEN, SKS, VIS, PRN, CPS)
QLFT=QLT+CM2*CPS*(TJAK-TAMB)*60.
OEVAP=XMDB*FUELD*1.353E+5
QLFT=QLFT+QEVAP
TF=(CPG*CMG*60.*TAD2-QLFT)/(60.*CPG*CMG)
X(KCYCLE)=TF
ERR=ABS(X(KCYCLE)-X(KCYCLE-1))/2.
IF(ERR .LE. .05)GOTO 1310
GOTO 1300
```

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1310 CONTINUE
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OINPUT=HHV*FUELD*60.
      FUEF=(1.-OLH/OINPUT)*100.
      GM=GMOW(COMED, T8, CPG2, CMG2, QNA2)
C* CPG2 IS THE SPECIFIC HEAT OF FLUE GASES AFTER EDUCTOR
C* CMG2 IS THE MASS OF THE FLUE GASES.
      CALL AIRPTS(TA, DEN, SKS, VIS, PRN, CPS)
      TXT=CMG2*CPG2*T8+CM3*CPS*TA+OCO7*.06
      TXT=TXT/(CMG2*CPG2+CM3*CPS)
C* TXT IS THE TEMPERATURE OF DILLUTED GASES
C* IMMEDIATELY AFTER THE FURNACE.
      CMOL3 = CM3/28.97
      COM(3) = COMED(3) + .7899 * CMOL3
      COM(6) = COMED(6) + 1.6081 * CMOL3 * W
      COM(7) = COMED(7) + .2101 \times CMOL3
      CMD=CPD=0.
C*
    QMD, CPD, CMD ARE THE TOTAL MOLES, SPECIFIC HEAT & MASS
C* OF THE DILLUTED FLUE GASES.
      QMD=COM(1)+COM(3)+COM(6)+COM(7)
      GM=GMOW(COM, TXT, CPD, CMD, OMD)
      HIF=COM(6)*WMOL(6)/CMD
C* COMPUTE HEAT LOSS BETWEEN FURNACE & DRYING BIN
      BIND=5.49
      AREAB=12.75
      KCYCLE=0
      IF(VWIND .LT. 3.)GOTO 1129
C* DUCT HEAT LOSS
      TH=TXT
      TFILM=(TXT+TAMB)/2.
439
      CONTINUE
      CALL AIRPTS(TFILM, DENA, SKSA, VISA, PRNA, CPSA)
      RED=VWIND*.65/VISA
      CTY = .66
      IF(RED .GT. 5.75E+4)CTY=.91*RED**(-.02445)
      CX=19.
      IF(RED .LT. 5.75E+4)CX=15.
      CRED=CX*RED**(-.28895)
      KCYCLE=KCYCLE+1
      HA=SKSA*CRED*RED**CTY*PRNA**(1./3.)
      HA=HA/.65
      QDUCT=22.58*HA*(TH-TAMB)*.06
      TTBN=TXT-ODUCT/(CPD*CMD)
      TH=(TTBN+TXT)/2.
      TFILM=(TH+TAMB)/2.
      IF(KCYCLE .LT. 2)GOTO 439
      KCYCLE=0
      TAVE=TTBN
      TFILM=(TTBN+TAMB)/2.
433
      CONTINUE
      CALL AIRPTS(TFILM, DENA, SKSA, VISA, PRNA, CPSA)
      REBN=VWIND*BIND/VISA
      IF(REBN .GT. 1E+3)GOTO 1000
```

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C* EQUATION 6-16, HOLMAN
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HNU=(.43+.5*REBN**.5)*PRNA**.38 **GOTO 1001** C* EQUATION 6-17, HOLMAN 1000 HNU=.125*REBN**.6*PRNA**.38 1001 HBIN=HNU*SKSA/BIND QBIN=HBIN*AREAB*(TAVE-TAMB)*.06 KCYCLE=KCYCLE+1 TBP=TTBN-QBIN/(CPD*CMD) TAVE = (TBP + TTBN)/2. TFILM=(TAVE+TAMB)/2. IF(KCYCLE .LT. 2)GOTO 433 GOTO 1100 1129 CONTINUE KCYCLE=0 C* FREE CONVECTION HEAT LOSSES, VWIND=0. TW=TXT TFM = (TW + TAMB)/2. 533 CONTINUE KCYCLE=KCYCLE+1 CALL AIRPTS(TFM, DEN, SKS, VIS, PRN, CPS) BETA=1./TFM GR=9.8*BETA*(TW-TAMB)/VIS**2.*.65**3. GRPR=GR*PRN EV1=EV2=5.25 C* EQUATION 7-25, HOLMAN HNU=EV1*GRPR**.25 IF(GRPR .GT. 1.E+13)HNU=EV2*GRPR**(1./3.) QDUCT=22.58*HNU*SKS*(TW-TAMB)*.0923 TTBN=TXT-QDUCT/(CPD*CMD) TW = (TTBN + TXT)/2. TFM=(TW+TAMB)/2. IF(KCYCLE .LT. 2)GOTO 533 KCYCLE=0 TWB=TTBN TFM=(TWB+TAMB)/2 633 CONTINUE KCYCLE=KCYCLE+1 BETA=1./TFM CALL AIRPTS(TFM, DEN, SKS, VIS, PRN, CPS) BINL=.9138 GR=9.8*BETA*BINL**3*(TWB-TAMB)/VIS**2 GRPR=GR*PRN EV1=EV2=GRPR*3.E-9+1.25 C* EQUATION 7-25, HOLMAN HNU=EV1*GRPR**.25 IF(GRPR .GT. 1.E+13)HNU=EV2*GRPR**(1./3.) QBIN=SKS*HNU/BIND*AREAB*(TWB-TAMB)*.06 TBP=TTBN-QBIN/(CMD*CPD) TWB=(TTBN+TBP)/2.TFM=(TWB+TAMB)/2. IF(KCYCLE .LT. 2)GOTO 633

1100 CONTINUE

CALL AIRPTS(TBP, DEN, SKS, VIS, PRN, CPS) DAIRV=CMD/DEN CUFTA=DAIRV*35.3134/254.469 CFMT=CUFTA*254.469 QLH=QLH+(QBIN+QDUCT)*60. SYEF=(1.-QLH/QINPUT)*100. TBIN=TKF(TBP) COMPUTE DATA FOR PRINTING HHVW=QINPUT/FUEL/1000. HHVD=HHV/1000. ASHF=ASH/100. WKGLB=2.204622 ASH=ASH*FUELD*60./100. ASHLB=ASH*WKGLB TOC=TAMB-273.15 TOF=TKF(TAMB) TPC=TJAK-273.15 TPF=TKF(TJAK) TFC = TF - 273.15TFF=TKF(TF) TXTC=TXT-273.15TXTF=TKF(TXT) TEDC=T8-273.15 TEDF=TKF(T8) TBNC=TBP-273.15 TWC = T7 - 273.15TWF = TKF(T7)PRINT 150, TOC, TOF, TPC, TPF, TFC, TFF, TEDC, TEDF, TXTC, TXTF, +TBNC, TBIN, TWC, TWF FULB=FUEL*WKGLB*60. VWIND=VWIND*3.6 QINPUT=QINPUT/1000. WMPH=VWIND*5./8. CMO=CMO/FUEL CMMC=FCFM*.02837 PDFG=(CM2+CMED+FUEL*(1.-ASHF))*60. PDLB=PDFG*WKGLB CALL AIRPTS(T8, DEN, SKS, VIS, PRN, CPS) CMMED=PDFG/DEN/60. CFMED=CMMED*35.3134 CMDLB=CMD*WKGLB*60. FUEL=FUEL*60. CALL AIRPTS(TXT, DEN, SKS, VIS, PRN, CPS) CMMD=CMD/DEN CFMD=CMMD*35.3134 CMD=CMD*60.BTUM=QINPUT*9.4783E-4 OLH=OLH/1000. QLBTU=QLH*9.4783E-4 PRINT 25, FUEL, FULB, XMFW, CMO, CMMC, FCFM, EXCS, PDFG, PDLB, +CMMED, CFMED, CMD, CMDLB, CMMD, CFMD, DAIRV, CFMT, HIF PRINT 37, QINPUT, BTUM, QLH, QLBTU, FUEF, SYEF, ASH, ASHLB

C*

IF(FUELNB .GT. 0.)PRINT 1400, FUELNB, FWLB 91 CONTINUE PRINT 109 READ 329, TERM IF(TERM .GE. 1.)GOTO 43 111 FORMAT(* *,*EXCESS AIR, PERCENT:*) 109 FORMAT(*0*,/,* *,*CONTINUE? YES=1.; NO=0.*) 99 FORMAT(* *, *PERCENT RELATIVE HUMIDITY:*) FORMAT(* *,*FUEL MOISTURE, PERCENT(WB)*) 8 FORMAT(* *, *AMBIENT TEMPERATURE, C:*) 5 FORMAT(* *,*FUEL FEED RATE,KG/HR:*) 4 FORMAT(* *,*DRYING PRESSURE, KPA*) 6 FORMAT(*1*,*FUEL TYPE: CORNCOBS=1,WOOD=0.*) 133 FORMAT(*0*,/*0*,*TEMPERATURES:*, 150 +/* *,* AMBIENT:*,23X,F8.2,*C *,F8.2,*F*, +/* *,* PREHEATED COMB. AIR:*,11X,F8.2,*C *,F8.2,*F*, +/* *,* FURNACE FLAME:*,17X,F8.2,*C *,F8.2,*F*, +/* *,* PREDILUTION FLUE GAS:*,10X,F8.2,*C *,F8.2,*F*, +/* *,* DILUTED FLUE GAS:*,14X,F8.2,*C *,F8.2,*F*, +/* *,* DRYING (BIN PLENUM):*,11X,F8.2,*C *,F8.2,*F*, +/* *,* OUTER FURNACE WALL:*,12X,F8.2,*C *,F8.2,*F*) FORMAT(*0*,*MASS FLOWS:*, 25 C* +/* *,* WIND SPEED, KPH:*,15X,F8.2,5X,F8.2,* MPH*, +/* *,* FUEL FEED, KG/H:*,15X,F8.2,5X,F8.2,* LB/H*, +/* *,* FUEL MOISTURE, WB:*,12X,F8.2, +/* *,* FURNACE AIR SUPPLY, KG/KG-FUEL:*,F8.2, +/* *,29X,*CMM:*,F8.2,5X,F8.2,* CFM*, +/* *,* EXCESS AIR, PERCENT:*,11X,F8.2, +/* *,* PREDILUTION FLUE GAS, KG/H:*,4X,F8.2,5X,F8.2,* LB/H*, +/* *,24X,*CMM:*,5X,F8.2,5X,F8.2,* CFM*, +/* *,* DILUTED FLUE GAS, KG/H:*,8X,F8.2,5X,F8.2,* LB/H*, +/* *,20X,*CMM:*,9X,F8.2,5X,F8.2,* CFM*, +/* *,* DRYING AIR, CMM:*,15X,F8.2,5X,F8.2,* CFM*, +/* *,* DRYING AIR ABSOLUTE HUMIDITY:*,4X,F8.4) 37 FORMAT(*0*,*TOTAL HEAT OUTPUT, MJ/H:*,9X,F8.2,5X,F8.2,* MBTU/H*, +/* *, *TOTAL HEAT LOSS, MJ/H:*, 11X, F8.2, 5X, F8.2, * MBTU/H*, +/* *, *FURNACE EFFICIENCY, PERCENT:*, 5X, F8.2, +/* *,*SYSTEM EFFICIENCY, PERCENT:*,6X,F8.2, +/* *,*ASH ACCUMULATION, KG/H:*,10X,F8.2,5X,F8.2,* LB/H*) 1400 FORMAT(* *, *UNBURNED FUEL ACCUMULATION, KG/H:*, F8.2, 5X, +F8.2,* LB/H*)

200 FORMAT(1H+,35X,F7.2)

FWLB=FUELNB*WKGLB

- 83 **FORMAT(1H+,33X,A10)**
- 329 FORMAT(F7.3)
- 93 FORMAT(*0*, *THIS MIXTURE WOULD'NT BURN!*)
- 899 FORMAT(*0*,*COMBUSTION AIR, KG/H:*)
- 900 FORMAT(* *,*AIR:FUEL RATIO:*) END

```
FUNCTION RUTA(QS,RS,CF,TF,R,T)
```

DIMENSION R(20)

SB=5.669E-8

```
EB6=SB*T**4
      QUOD=(QS-EB6*RS+T/R(18))*R(18)
      RUTA=SB*QUOD**4/R(19)+QUOD*(1./CF+1./R(18))
      RUTA=RUTA-(T/R(18)+SB*TF**4/R(19)+TF/CF)
      RETURN
      END
C*******
      FUNCTION SIMPSON(TEM, REACT, GM, GN, COM, CP)
      DIMENSION COM(20), CP(20), WMOL(20)
      DATA (WMOL(K),K=1,8)/44.01,28.01,28.016,46.,30.,18.,32.,2./
      HEAT=0.
      DO 20 L=1,7
      IF(COM(L) .EQ. 0.)GOTO 20
      N=20
      H = (TEM - 298.) / N
      HALF=H/2.
      NN=N-1
      CM=COM(L)*WMOL(L)
      SN1=ENTHAL(298., REACT, GM, GN, COM, CP, L)
      SN2=ENTHAL (TEM, REACT, GM, GN, COM, CP, L)
      TXH=298.
      FXH=FXHALF=0.
      TXHALF=298.-HALF
      DO 10 I=1,NN
      TXH=TXH+H
      TXHALF=TXHALF+H
      FXH=ENTHAL(TXH, REACT, GM, GN, COM, CP, L)+FXH
      FXHALF=ENTHAL(TXHALF, REACT, GM, GN, COM, CP, L)+FXHALF
10
      CONTINUE
      TXHALF=TXHALF+H
      FXHALF=ENTHAL(TXHALF, REACT, GM, GN, COM, CP, L)+FXHALF
      SIMPSON=(SN1+SN2+2.*FXH+4.*FXHALF)*H/6.
      HEAT=SIMPSON*CM+HEAT
20
      CONTINUE
      SIMPSON=HEAT
      RETURN
      END
C*
     DETERMINES PROPERTIES OF AIR AND FLUE GASES FROM
C* TABLES OF THE PROPERTIES AT DIFFERENT TEMPERATURES
C*
      FUNCTION TABLE(VAL, SMALL, DIFF, K, DUMMY)
      DIMENSION VAL(20)
      DUM=AMIN1(AMAX1(DUMMY-SMALL,0.0),FLOAT(K)*DIFF)
      I=1.+DUM/DIFF
      IF(I.EQ.K+1)I=K
      TABLE=(VAL(I+1)-VAL(I))*(DUM-FLOAT(I-1)*DIFF)/DIFF+VAL(I)
      RETURN
      END
      FUNCTION ENTHAL (T, REACT, GM, GN, COM, CP, L)
      COMMON/PROPETY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10)
      COMMON/FLUE/DVCO2(20), CKCO2(20), DVCO(20), CKCO(20), DVH2O(20),
```

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+CKH20(20), DVH2(20), CKH2(20), DVN2(20), CKN2(20), DVO2(20), CKO2(20) COMMON/SMS/SMLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10) DIMENSION COM(20), CP(20), WMOL(20) DATA (WMOL(K), K=1,8)/44.01,28.01,28.016,46.,30.,18.,32.,2./ THETA=T/100. SOT=SORT(THETA) SOD=THETA**2. CP(1)=-.89286+7.2967*SQT-.98074*THETA+5.7835E-3*SQD CP(2)=16.526-.16841*THETA**.75-47.985/SQT+42.246/THETA**.75 CP(3)=9.3355-122.56/THETA**1.5+256.38/SQD-196.08/THETA**3. CP(4)=11.005+51.65/SQT-86.916/THETA**.75+55.58/SQD CP(5)=14.69-.40861*SQT-16.877/SQT+17.899/THETA**1.5 CP(6)=34.19-43.868*THETA**.25+19.778*SQT-.88407*THETA CP(7)=8.9465+4.8044E-3*THETA**1.5-42.679/THETA**1.5+56.615/SQD CP(8)=13.505-167.96/THETA**.75+278.44/THETA-134.01/THETA**1.5 ENTHAL=CP(L)/WMOL(L)*4.19002RETURN END SUBROUTINE PROPATY(TAMB) COMMON/PROPETY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10) COMMON/FLUE/DVCO2(20),CKCO2(20),DVCO(20),CKCO(20),DVH2O(20), +CKH20(20), DVH2(20), CKH2(20), DVN2(20), CKN2(20), DVO2(20), CKO2(20) COMMON/SMS/SMLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10) DATA (ADEN(K),K=1,25)/1.7684,1.413,1.1774,.998,.883,.7833,.705, +.6423,.5879,.543,.503,.4709,.4405,.4149,.3925,.3716,.3524,.3364, +.3204,.3076,.2947,.2827,.2707,.2611,.2515/ DATA (ACP(K),K=1,25)/1.006,1.005,1.006,1.009,1.014,1.021,1.0295, +1.039,1.055,1.064,1.075,1.086,1.098,1.11,1.121,1.132,1.142,1.151, +1.16,1.17,1.179,1.188,1.197,1.206,1.214/ DATA (AV(K),K=1,25)/7.49,9.49,16.84,20.76,25.9,31.71,37.9,44.34, +51.34,58.51,66.25,73.91,82.29,90.75,99.3,108.2,117.8,128.2,138.6, +148.85,159.1,170.6,182.1,193.8,205.5/ DATA (AK(L),L=1,25)/18.1,22.27,26.24,30.03,33.65,37.1,40.38,43.6, +46.6,49.5,52.3,55.1,57.79,60.28,62.79,65.25,67.52,70.36,73.2,75.7, +78.2,80.95,83.7,86.4,89.1/ DATA (APR(K),K=1,25)/.74,.722,.708,.7,.689,.683,.68,.68,.68,.682, +.684,.686,.689,.692,.696,.7,.702,.703,.704,.7055,.707,.706,.705, +.705,.705/ DATA SMLA, DIFA, KA/200., 50., 24/ DATA (DVCO2(L), L=1,14)/19.6,27.1,33.6,39.3,44.5,49.5,54., +58.4,62.5,66.5,70.3,74.,77.6,81.2/ DATA (CKCO2(K),K=1,14)/25.9,40.7,54.5,67.2,78.9,89.7,99.9, +109.3,118.3,126.8,134.9,142.8,150.5,158.1/ DATA (DVH2O(L),L=1,14)/13.9,21.2,28.5,35.5,42.1,48.4,54.5,60.3, +65.8,70.8,75.9,80.8,85.4,90./ DATA (CKH2O(J), J=1, 14)/37.6, 60.7, 86.7, 114.6, 143.6, 173.3, +203.3,232.5,260.8,287.1,313.6,339.3,363.6,387.9/ DATA (DVCO(K), K=1,14)/21.9,29.,35.1,40.6,45.6,50.4, +55.1,59.5,63.7,67.8,71.7,75.5,78.2,82.8/

DATA (CKCO(L), L=1, 14)/33.2, 45.5, 57.5, 68.9, 79.6, 89.8,

+99.5,108.6,117.3,125.7,133.7,141.5,149.,156.2/

DATA (DVH2(M),M=1,14)/10.9,14.2,17.1,19.8,22.3,24.6,

C*

C*

C*

C*

```
+26.9,29.,31.,33.,34.9,36.7,38.5,40.3/
DATA (CKH2(N), N=1, 14)/228., 313., 363., 428., 493., 559.,
+625.,689.,752.,814.,874.,932.,989.,1045./
DATA(DVN2(N),N=1,14)/21.7,28.5,34.4,39.7,44.8,49.5,54.,
+58.3,62.4,66.4,70.2,73.9,77.6,81.1/
DATA (CKN2(N), N=1,14)/32.9,44.3,55.6,65.5,77.2,87.2,
+96.6,105.6,114.1,122.3,130.2,137.7,145.1,152.2/
DATA (DVO2(M), M=1, 14)/25.7, 34.1, 41.5, 48.1,
+54.1,59.7,65.1,70.4,75.4,80.2,84.9,89.4,93.8,98.1/
 DATA (CKO2(L), L=1, 14)/34.9, 49.2, 62.6, 74.8,
+85.9,96.3,106.5,116.5,126.3,135.9,145.3,154.6,163.8,172.8/
 DATA SMLFLU, DIFLU, KFLU/400., 200., 13./
 DATA (CFMF(L), L=1,6)/2840.,2500.,2000.,1020.,660.,380./
 DATA SMST, DIFST, KST/.5,.5,5/
 Y=1.E-6
 X=1.E-3
 DO 10 L=1,14
 AV(L) = AV(L) * Y
 DVCO2(L)=DVCO2(L)*Y
 DVCO(L)=DVCO(L)*Y
 DVH2O(L)=DVH2O(L)*Y
 DVH2(L)=DVH2(L)*Y
 DVN2(L)=DVN2(L)*Y
 DVO2(L)=DVO2(L)*Y
 AK(L) = AK(L) * X
 CKCO2(L) = CKCO2(L) * X
 CKCO(L) = CKCO(L) * X
 CKH2O(L) = CKH2O(L) * X
 CKH2(L)=CKH2(L)*X
 CKN2(L) = CKN2(L) * X
 CKO2(L) = CKO2(L) * X
 CONTINUE
 DO 15 K=15,25
 AV(K) = AV(K) * Y
 AK(K) = AK(K) * X
 CONTINUE
 RETURN
 END
 FUNCTION FLUPTY (TEMP, N, K)
 COMMON/PROPETY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10)
 COMMON/FLUE/DVCO2(20), CKCO2(20), DVCO(20), CKCO(20), DVH2O(20),
+CKH20(20), DVH2(20), CKH2(20), DVN2(20), CKN2(20), DVO2(20), CKO2(20)
 COMMON/SMS/SMLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10)
 IF(K .EQ. 2)GOTO 10
 IF(N .EQ. 1)FLUPTY=TABLE(DVCO2,SMLFLU,DIFLU,KFLU,TEMP)
 IF(N .EQ. 2)FLUPTY=TABLE(DVCO, SMLFLU, DIFLU, KFLU, TEMP)
 IF(N .EQ. 3)FLUPTY=TABLE(DVN2, SMLFLU, DIFLU, KFLU, TEMP)
 IF(N .EQ. 4)FLUPTY=TABLE(DVH20,SMLFLU,DIFLU,KFLU,TEMP)
 IF(N .EQ. 5)FLUPTY=TABLE(DVO2,SMLFLU,DIFLU,KFLU,TEMP)
 IF(N .EQ. 6)FLUPTY=TABLE(DVH2, SMLFLU, DIFLU, KFLU, TEMP)
 RETURN
 CONTINUE
```

10

15

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IF(N .EQ. 1)FLUPTY=TABLE(CKCO2, SMLFLU, DIFLU, KFLU, TEMP)
      IF(N .EQ. 2)FLUPTY=TABLE(CKCO, SMLFLU, DIFLU, KFLU, TEMP)
      IF(N .EQ. 3)FLUPTY=TABLE(CKN2, SMLFLU, DIFLU, KFLU, TEMP)
      IF(N .EQ. 4)FLUPTY=TABLE(CKH2O, SMLFLU, DIFLU, KFLU, TEMP)
      IF(N .EO. 5)FLUPTY=TABLE(CKO2,SMLFLU,DIFLU,KFLU,TEMP)
      IF(N .EO. 6)FLUPTY=TABLE(CKH2, SMLFLU, DIFLU, KFLU, TEMP)
      RETURN
      END
      SUBROUTINE AIRPTS(TEMA, D, CKS, VISC, PRN, CPS)
      COMMON/PROPETY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10)
      COMMON/FLUE/DVCO2(20),CKCO2(20),DVCO(20),CKCO(20),DVH2O(20),
     +CKH20(20), DVH2(20), CKH2(20), DVN2(20), CKN2(20), DVO2(20), CKO2(20)
      COMMON/SMS/SMLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10)
      D=TABLE(ADEN, SMLA, DIFA, KA, TEMA)
      CKS=TABLE(AK, SMLA, DIFA, KA, TEMA)
      VISC=TABLE(AV, SMLA, DIFA, KA, TEMA)
      PRN=TABLE(APR, SMLA, DIFA, KA, TEMA)
      CPS=TABLE(ACP, SMLA, DIFA, KA, TEMA)
      RETURN
      END
      FUNCTION HEATF(T, CM, FUEL, XMDB, TAMB)
      COMMON/PROPETY/AK(30), ACP(30), APR(30), ADEN(30), AV(30), CFMF(10)
      COMMON/SMS/SMLA, SMLFLU, DIFA, DIFLU, KA, KFLU, SMST, DIFST, KST, COMED(10)
      XMW=XMDB/(1.+XMDB)
      WATER=FUEL*XMW
      HWATER=0.
      FW=1.-XMW
      FCP=FW*(.064+.00028*(T-273.15))*17.391+4.174*XMW
      HWOOD=FCP*(T-298.15)*FUEL
      CPAIR=TABLE(ACP, SMLA, DIFA, KA, T)
      HAIR=CM*CPAIR*(T-298.15)
C*
      IF(T .GT. 373.)HWATER=WATER*(2000.+2.01*(T-373.))
      HEATF=HWOOD+HAIR+HWATER
      RETURN
      END
      FUNCTION TADI (COM, TEST, GN, WM, CMG, CPG, CON, HHV, ENF)
      DIMENSION COM(20), CP(20), X(100)
      ZERO(A,B)=A-B
      BC=HHV-CON
      K=2
      X(1) = TEST - 600.
      X(2) = TEST + 100.
      WM=GMOW(COM, TEST, CPG, CMG, GN)
      CONTINUE
      K=K+1
      EN1=SIMPSON(X(K-2), 2., WM, GN, COM, CP)
      FX1=ZERO(EN1.BC)
      EN2=SIMPSON(X(K-1),2.,WM,GN,COM,CP)
      FX2=ZERO(EN2,BC)
      X(K) = (FX2 * X(K-2) - FX1 * X(K-1)) / (FX2 - FX1)
      ERR=ABS(X(K)-X(K-1))/2.
      IF(ERR .LE. 1.E-10)GOTO 10
```

GOTO 5 10 CONTINUE TADI=X(K)WM=GMOW(COM, TADI, CPG, CMG, GN) ENF=SIMPSON(TADI, 2., WM, GN, COM, CP) RETURN END FUNCTION GMOW(COM, TG, CPG, CMG, GN) DIMENSION WMOL(20), COM(20), CP(20) DATA (WMOL(K), K=1,8)/44.01,28.01,28.016,46.,30.,18.,32.,2./ DUMMY=ENTHAL(TG, 1., GM, GN, COM, CP, 3) CMG=CPG=0. DO 10 I=1,7 IF(COM(I) .EQ. 0.)GOTO 10 CPG=CP(I)*COM(I)/GN+CPG CMG=COM(I)*WMOL(I)+CMG 10 CONTINUE GMOW=CMG/GN CPG=CPG/GMOW*4.19 RETURN END

IN-BIN COUNTERFLOW DRYING COMPUTER PROGRAM

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APPENDIX D

IN-BIN COUNTERFLOW DRYING COMPUTER PROGRAM

PROGRAM COUNTER(INPUT, OUTPUT, DEBUG=OUTPUT) C***** COUNTERFLOW GRAIN DRYER MODEL C**** F.W.BAKKER-ARKEMA, PROJECT LEADER C**** E.N. MWAURA, PROGRAMMER C**** C**** DESCRIPTION C**** MAIN PROGRAM FOR SIMULATION OF AN IN-BIN COUNTERFLOW DRYER C**** COMMON/MAIN/XMT, THT, RHT, DELT, CFM, XMO, KAB, TOTEN, TOTH20, XMS, +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER COMMON/PRPRTY/SA, CA, CV, CW, RHOP, CP COMMON/HLATENT/HA, HB, HFG COMMON/TENT/K1, K2, XMR COMMON/IFLAGS/J, JM, ICON, DELXM COMMON / PRESS/PATM, BCFMF, PG COMMON /NAME/INAME, IPRODU, IPRODUL, IEMC REAL K1,K2 COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA COMMON/COUNT/ITERCT, TIN, THIN, HIN COMMON/COLD/COOLER, SYSTEM DIMENSION TDRY(50), XMDRY(50) F(T) = T + 459.69ERH(T, XM) = 1. - EXP(-...38195*(T + 50.)*XM**2)C**** INPUT CONDITIONS OF DRYER TO BE SIMULATED HOUR=0.0TOTEN=0. \$TOTH20=0. \$TOTSP=0. REFHR=REFBU=0. TOFENY=0. COOLER=0. PRINT 160 READ 200, SYSTEM PRINT 199, SYSTEM IF(SYSTEM .GT. 0.)GOTO 73 PRINT 74 READ 200, REFHR PRINT 199, REFHR PRINT 75 READ 200, REFBU PRINT 199, REFBU 73 CONTINUE

IF(SYSTEM .EQ. 2.)PRINT 1300 IF(SYSTEM .EQ. 2.)READ 200, COOLER IF(SYSTEM .EQ. 2.)PRINT 199, COOLER IF(SYSTEM .LT. 2.)PRINT 45 IF(SYSTEM .LT. 2.)READ 200, BPC IF(SYSTEM .LT. 2.)PRINT 199, BPC NEQ=2 PRODUCT=1. NEQ1=NEQ IPROD=IFIX(PRODUCT) CALL DATE(IPROD) PRINT 201, INAME, IPRODU, IPRODUL, IEMC READ 200, TIN PRINT 199,TIN PRINT 190 READ 200, TAMB PRINT 199, TAMB PRINT 202 READ 200, RHAMB PRINT 199, RHAMB HI=HADBRH(F(TAMB), RHAMB) PRINT 240,HI PRINT 230 READ 200, FUEL PRINT 199, FUEL IF(TIN.EQ.TAMB.OR.FUEL.EQ.4.) GO TO 5 CALL ABSH(HIN, TAMB, TIN, HI, FUEL, IPROD) PRINT 250, HIN GO TO 8 CONTINUE PRINT 77 READ 200, HI HIN=HI PRINT 250, HIN CONTINUE PRINT 204 READ 200, THIN PRINT 199, THIN PRINT 205 READ 200, XMOW PRINT 199, XMOW NAME1=10HTESTWEIGHT NAME2=7H, LB/BU PRINT*, NAME1, NAME2 READ*, TW PRINT 199, TW RHOP=TW/1.24*(1.-XMOW/100.) XMO=XMOW/(100.-XMOW) RHCN=.9*ERH(THIN, XMO) HINIT=HADBRH(F(THIN), RHCN) 1310 CONTINUE PRINT 207

3

5

8

READ 200, XMF PRINT 199, XMF XMF = XMF / 100. IF(COOLER .EQ. 1. .AND. HOUR .NE. 0.)GOTO 1307 PRINT 208 READ 200, DEPTH PRINT 199, DEPTH 1307 CONTINUE IF(COOLER .NE. 1.)PRINT 203 IF(COOLER .NE. 1.)READ 200, BCFMF IF(COOLER .NE. 1.)PRINT 199, BCFMF IF(COOLER .EQ. 1.)BCFMF=30. IF(COOLER .EQ. 1. .AND. DEPTH .GT. 8.)BCFMF=20. CALL SECANT (DEPTH, BCFMF, CFM, PG, COOLER) C**** PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES GA=60.*CFM/VSDBHA(F(TIN),HIN) PRINT 215, CFM, GA, XMO, PG IF(COOLER .EQ. 0.)PRINT 65 IF(COOLER .EQ. 0.)READ 200, ANSWER IF(COOLER .EQ. 0.)PRINT 199, ANSWER IF(COOLER .EQ. 1.)ANSWER=1. IF(ANSWER .LE. 0.)GOTO 1307 PRINT 218 READ 200, TIME PRINT 199, TIME PRINT 209 READ 200, DBTPR PRINT 199, DBTPR HRPT=10. IF(SYSTEM .EQ. 2.)PRINT 49 IF(SYSTEM .EQ. 2.)READ 200, HRPT IF(SYSTEM .EQ. 2.)PRINT 199, HRPT DELPR=DBTPR IF(COOLER .NE. 1.)PRINT 212 IF(COOLER .NE. 1.)READ 200, HDF IF(COOLER .EQ. 0.)PRINT 199, HDF IF(COOLER .EQ. 1.)HDF=.75 C**** COMPUTE STEP AND ARRAY SIZES DELX=.25IF(SYSTEM .LT. 2.)DELX=BPC*1.24/508.938 IND=INT(DEPTH/DELX) IND1=IND+1 IND11=IND1+1 C**** COMPUTE INLET RH AND INITIALIZE ALL ARRAY POSITIONS NECESSARY RHIN=RHDBHA(F(TIN),HIN) RHT=RHIN DO 1 I=1, IND11 XM(I)=XMOH(I,1)=HINITT(I,1)=TINTH(I,1)=THIN RH(I) = RHCN

1 CONTINUE H(1,1)=HIRH(1)=RHIN C**** CONVERT AIRFLOW TO LB/HR IF(GA .GE. 500.)HC=.363*GA**.59 IF(GA .LT. 500)HC=.69*GA**.49 CON1=2.*GA*CA CON2=2.*GA*CV CON3=HC*SA*DELX CON4=RHOP*CP CON5=RHOP*CW DELT=2.*DELX*(CON4+CON5*XM(1))/(CON1+CON2*H(IND1,1))*.9 IF(COOLER .EQ. 1.)DELT=1. IF(COOLER .EQ. 1.)HOUR=0. C**** CALL IBCFLW FOR SIMULATING IN-BIN COUNTERFLOW DRYING 1400 CONTINUE CALL IBCFLW4 (TAMB, HRPT, TDAVE, XMDAVE) IF(COOLER .EQ. 1.)GOTO 25 **PRINT 1300** READ 200, COOLER PRINT 199, COOLER IF(COOLER .EQ. 0.)GOTO 25 IF(SYSTEM .EQ. 2.)GOTO 1400 RHCN=.9*ERH(TDAVE,XMO) HINIT=HADBRH(F(TDAVE),RHCN) TIN=TAMB THIN=TDAVE HI=HIN=HADBRH(F(TAMB), RHAMB) SYSTEM=2. **GOTO 1310** 25 PRINT 260 DEP1=0. 160 FORMAT(*0*,*COUNTERFLOW? NO=2; YES=1., REFILL=0.*) 74 FORMAT(*0*,*TIME BETWEEN REFILLS, HOURS:*) FORMAT(* *,*BUSHELS PER REFILL:*) 75 45 FORMAT(*0*,*BUSHELS PER CYCLE:*) FORMAT(*0*, *SATISFIED WITH DEPTH/PRESSURE COMBINATION?*, 65 +/* *,*YES=1.; NO=0.*) 1300 FORMAT(*0*,*COOL THE GRAIN? YES=1., NO=0.*) 77 FORMAT(*0*,5X,*ABSOLUTE HUMIDITY,DECIMAL:*) 49 FORMAT(*0*,5X,*OUTPUT INTERVAL: HOUR;*) 170 FORMAT(1X*EQTN FOR LOW TEMP; (1 RUG, 2 MISRA, 3 SABBAH):*) 190 FORMAT(5X*AMBIENT AIR TEMP, F :*) 198 FORMAT(I1) 199 FORMAT(1H+,40X,F10.4) 200 FORMAT(F10.2) 201 FORMAT (* OCOUNTERFLOW GRAIN DRYER SIMULATION*/ +* USING THE *A10, A10* EQUATION FOR *A10 / +* AND EMC BY *A10// +* INPUT CONDITIONS :*/ +5X*DRYING AIR TEMP, F :*) 202 FORMAT(5X*AMBIENT REL HUM, DEC :*)

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203
     FORMAT(*OFINES FACTOR: 1-2(1 CLEAN, 2 DIRTY):*)
204
     FORMAT(5X*INLET GRAIN TEMP, F:*)
205
     FORMAT(5X*INITIAL MOISTURE, W.B.PERC.:*)
207
     FORMAT(5X*FINAL MOISTURE, W.B.PERC.:*)
208
     FORMAT(5X*BED DEPTH, FT:*)
209
     FORMAT(5X*OUTPUT INTERVAL,FT:*)
212
     FORMAT(5X*HYBRID DRYING FACTOR, DEC.:*)
213
     FORMAT(///1X*FAN IS DOWN FOR, HR:*)
215
     FORMAT(//* PRELIMINARY CALCULATED VALUES*//
     +* AIRFLOW, CFM/SO FT
                                       *F8.4/
     +* DRY AIRFLOW RATE, LB/HR-FT2
                                      *F8.4/
     +* INLET MC(DRY BASIS DECIMAL)
                                       *F8.4,/
     +* PLENUM PRESSURE, IN-H2O:
                                       *,F8.4)
     FORMAT(5X*MAX.DRYING TIME, HR:*)
218
230
     FORMAT(5X*TYPE OF FUEL USED (1=NO.2 FUEL*/
     +5X,*2=NAT.GAS; 3=L.P.GAS; 4=BIOMASS):*)
240
     FORMAT(5X, *CALCULATED AMBIENT ABS HUM=*9X, F10.4)
250
     FORMAT(5X*CALCULATED INLET ABS HUM=*11X,F10.4)
260
     FORMAT(5X, *THIS IS THE END OF COUNTERFLOW*)
300
     FORMAT(5X*DRYING AIR TEMP, F :*)
     END
C**
SUBROUTINE IBCFLW4 (TAMB, HRPT, TDAVE, XMDAVE)
C****
     DIMENSION RHK(50), CYCLE(50), TDRY(40), XMDRY(40), X(50)
     COMMON/MAIN/XMT, THT, RHT, DELT, CFM, XMO, KAB, TOTEN, TOTH2O, XMS,
     +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY
     COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER
     COMMON/PRPRTY/SA, CA, CV, CW, RHOP, CP
     COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA
     COMMON/HLATENT/HA, HB, HFG
     COMMON/IFLAGS/K, JM, ICON, DELXM
     COMMON/PRESS/PATM, BCFMF, PG
     COMMON/COUNT/ITERCT, TIN, THIN, HIN
     COMMON/HRS/HR
     COMMON/COLD/COOLER, SYSTEM
     EXTERNAL ZEROIN
     EXTERNAL SOLVE4
     DATA PATM/14.696/
     DATA RHC, AREA/.999999,254.469/
     F(T) = T + 459.69
     ERH(T, XM) = 1. - EXP(-.38195*(T + 50.)*XM**2)
C****
C****
      IF(COOLER .EQ. 1.)REFHR=0.
      IF(REFHR .GT. 0.)SYSTEM=1.
     HRPTS=0.
     XMBIN=XMO
     DRYBUT=0.
     PWATER=PBU=0.
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GLEVEL1=DEPTH
      H2OOUT=0.
      YL=0.0
      HR=0.
      CTIME=25./60.
      KK=0
      CYCLE1=0.
      KBU=0
      KAB=0
      REALT=0.
      KCON=0
      DRM=0.
      DEEP=REFIN=0.
      ITERCT=0
      NODES=INT(.3/DELX)+1
      KAB=0
      IND11=IND1+1
      IND2=IND1
      TOTBTUW=0.0
      TINN=TIN=T(1,1)
      RHIN=RHDBHA(F(TIN),HIN)
      DPCH=2.*DELX
      XMBT=XMO
C****
C****
           BEGIN TIME LOOP
C****
40
      YL=YL+DELT
      IF(CYCLE1 .GT. 0. .OR. SYSTEM .GE. 2.)REALT=.1
      IF(COOLER .EQ. 1.)REALT=0.
      HR=HR+DELT+REALT
      HOUR=HOUR+REALT+DELT
      CYCLE2=HOUR
      HRPTS=HRPTS+DELT+REALT
      REFIN=REFIN+DELT+REALT
C****
C****
           COMPUTE MC FOR DEPTH=0
C****
      DEP=DEP1=0.
      TH(1,1)=(14.TH(1,1)+T(1,1))/15.
      IF(SYSTEM .EQ. 2.)TH(1,1)=(1.5*T(1,1)+TH(1,1))/2.5
      THT=TH(1,1)
      XMT=XM(1)
      RHT=RHIN
      CALL LAYEQ
      XM(1)=XMT
      H(1,2)=H(1,1)
      T(1,2)=TINN
      TH(1,2)=TH(1,1)
      RHK(1)=RHT*100.
C****
C****
           BEGIN DEPTH LOOP
C****
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J=2
      XMV=0.
102
      CONTINUE
      K=J
      JM=J-1
      TH(J,2)=TH(JM,2)
      HFG=HEATLAT(XM(J),TH(J,1))
C****
C****
           USE PREVIOUS VALUE OF H AS INITIAL GUESS
C****
      HJ2=H(JM,2)
      IF(COOLER .EQ. 0.)GOTO 1300
      IF(J .EQ. 2)GOTO 1300
      THDEL=1.25
      THCHK=TH(JM,2)-THDEL
      IF(THCHK .LE. T(1,1))H(JM,2)=HJ2=H(1,1)
      RH(JM) = RHDBHA(F(T(JM, 2)), H(JM, 2))
C****
C****
           CALL SOLVE4 TO COMPUTE TRIAL T, XM, H, RH
C****
1300
         CONTINUE
      DIFF=SOLVE4(HJ2)
C****
         CHECK CONDENSATION FLAG
      IF(ICON) 31,31,30
   30 KCON=KCON+1
      GO TO 43
C****
         SET LIMITS ON H
   31 IF(DIFF) 36,43,32
C****
         SOLVING FOR ABSORPTION CONDITIONS
   32 HLOW=.5*ERH(THT,XMT)
C****
        CHECK FOR FEASIBLE HLOW
   33 IF(XMT-EMC(HLOW, THT)) 34,35,35
C*****
         DECREASE HLOW UNTIL XM .GT. EMC
   34 HLOW=.5*HLOW
      GO TO 33
   35 HLOW=HADBRH(F(THT), HLOW)
      HHI=H(J,2)
      KAB=KAB+1
      GO TO 42
C****
         SOLVING FOR DRYING CONDITIONS
   36 HLOW=H(J,2)
C****
         CHECK FOR SUPERSATURATED GRAIN
      IF(XMT-EMC(RHC,THT)) 38,37,37
   37 HHI=HADBRH(F(THT),RHC)
      GO TO 42
   38 HHI=.5*(1.+ERH(THT,XMT))
C****
         CHECK FOR FEASIBLE HHI
   39 IF(EMC(HHI,THT)-XMT) 63,41,41
C*****
         INCREASE HHI UNTIL EMC .GT. XM
   63 HHI=.5*(1.+HHI)
      GO TO 39
   41 HHI=HADBRH(F(THT), HHI)
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```
C****
C****
         INITIATE SEARCH FOR H, T, XM
C****
42
    CALL ZEROIN(HLOW, HHI, .00001, SOLVE4)
43
      XM(J) = XMT
C****
         END DEPTH LOOP
      J=J+1
      IF(J.LE.IND11) GO TO 102
      DO 105 LM=2, IND1
      T(LM, 1) = T(LM, 2)
      TH(LM,1)=TH(LM,2)
      H(LM, 1) = H(LM, 2)
      XMV=XMV+XM(LM)
      RHK(LM)=RH(LM)*100.
105
      CONTINUE
      ITERCT=ITERCT+1
C****
C****
           CHECK IF LONG ENOUGH OR DRY ENOUGH OR TIME TO SAVE VALUES
C***** FOR PRINTING. IF NONE OF THESE GO TO THE BEGINNING OF THE LOOP
C****
      IF(KBU .EQ. 0)XMBOT=(XM(1)+XM(2))/2.
      IF(KBU .EQ. 0.)GTEMP=(TH(3,1)+TH(2,1)+TH(1,1))/3.
      XMBTM=XMBOT/(1.+XMBOT)
      XMBWB=XMBTM*100.
C***
      CFMTOT=CFM*AREA
      XMV=XMV/FLOAT(IND1-1)
      XMV = XMV / (1.+XMV)
      IF(SYSTEM .EQ. 2. .AND. HRPTS .GE. HRPT)GOTO 400
      IF(HOUR .GE. TIME)GOTO 400
      IF(XMV.LE.XMF) GO TO 400
      IF(SYSTEM .EQ. 2.)GOTO 40
      IF(KBU .GT. 0)GOTO 400
      IF (XMBTM .LE. XMF)GOTO 400
      GOTO 40
C*
400
      CONTINUE
C* SECTION SHIFTS ARRAYS BY DEPTH NODES REMOVED
C*
      IF(SYSTEM .GE. 2.)GOTO 12
      IF(KBU .GT. 0)GOTO 5
      IF (XMBTM .GT. XMF)GOTO 12
5
      IF(SYSTEM .EQ. 1.)CALL VARYD(KBU, DRMN, DRM, CYCLE, CYCLE1, CYCLE2, KK,
     +COOLER)
      IF(CYCLE(KK) .GE. .45)GOTO 89
      HOUR=CYCLE2=HOUR+CTIME
      REFIN=REFIN+CTIME
      HR=HR+CTIME
      CYCLE(KK)=CYCLE(KK)+CTIME
89
      CONTINUE
      IF(SYSTEM.EQ.1.)DRYBUT=(GLEVEL1-DEPTH)*AREA/1.24+PBU
      DRYBU=DELX*2.*AREA/1.24
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IF (SYSTEM.EO.O.) DRYBUT=DRYBUT+DRYBU
      BPH1=DRYBUT/HOUR
      BPH2=DRYBU/CYCLE(KK)
      IF(XMV .LE. XMF)GOTO 3
      IF(KBU .GT. 0)GOTO 40
3
      PRINT 403, KK, CYCLE(KK), DEPTH, PG, CFMTOT, DRYBUT, XMBWB, GTEMP, BPH1,
     +BPH2
12
      CONTINUE
C*
      CALL CRSPR(XMAVE, TAVE, THAVE, XMEINW, XMEOUTW, RHK)
      POWER=PG*CFM*1.5758E-4/.5
      ENERGY=GA*(CA+CV*HIN)*(TIN-TAMB)*HR
      FENERGY=POWER*2546.136*HR
      H2OOUT=RHOP*2.*DELX*(XMBT-XMBOT)
      IF (SYSTEM.EQ.0.) WRMD=RHOP* (XMBIN-XMBOT)* (GLEVEL1-DEEP)
      IF (SYSTEM.EQ.0.) H2OOUT=H2OOUT+WRMD*KK
      IF(SYSTEM .EO. 2.)H2OOUT=0.
      WATER=(XMBIN-XMAVE)*RHOP*DEPTH
      IF(WATER .LT. 0.)WATER=0.
      XMS=XMAVE/(1.+XMAVE)*100.
      TOFENY=FENERGY+TOFENY
      TOTEN=ENERGY+TOTEN
      TOTH2O=H2OOUT+WATER+TOTH2O
      TOTBTUW=TOTEN/TOTH20
      SECO=(TOTEN+TOFENY)/TOTH20
      HR=0.
      IF(SYSTEM .LT. 2.)TDRY(KK)=GTEMP
      IF(SYSTEM .LT. 2.)XMDRY(KK)=XMBOT
      VDA=VSDBHA(F(T(1,1)),H(1,1))
      GA=60.*CFM/VDA
      PRINT 200, PG, POWER, TAVE
      PRINT 220, THAVE, XMS, XMEINW, XMEOUTW, TOTH20, TOTBTUW, SECO, HOUR
C*
C*
      HRPTS=0.
200
     FORMAT(//* STATIC PRESSURE, IN H20:
                                                             *F12.4/
                                                   *F12.4/
     +* HORSE POWER, HP/FT2:
                                                   *F12.4)
     +* AVER.AIR TEMP., F:
220
     FORMAT(* AVER. PROD. TEMP., F:
                                                           *F12.4/
     +* AVER. MOISTURE, W.B. PERC.:
                                                   *F12.4/
     +* INLET MOIST. EOUIL., W.B. PERC.:
                                                   *F12.4/
     +* OUTLET MOIST. EQUIL., W.B. PERC.:
                                                   *F12.4/
     +* WATER REMOVED, LB/FT2
                                                   *F12.4/
     +* SECO (DRYING ONLY), BTU/LB-H2O:*,10X,F12.4/
     +* SECO (WITH FAN), BTU/LB-H20:*,13X,F12.4/
     +* TOTAL DRYING TIME, HR.:
                                                   *F12.4)
     FORMAT(*0*,*CYCLES*,27X,13,/* CYCLE TIME, HRS*,20X,F4.2,
403
     +/ * GRAIN DEPTH, FT*, 19X, F5.2, /* STATIC PRESSURE, IN-H2O*
     +,11X,F5.2,
     +/* AIRFLOW, CFM*, 19X, F8.2, /* GRAIN DRIED, BUSHELS*, 10X, F9.2,
     +/16X,* MCWB*,14X,F5.2,/6X,* TEMPERATURE, F*,10X,F9.2,
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+/ * AVERAGE DRYING RATE, BU/HR*,4X,F9.2,
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+/ * DRYING RATE, THIS CYCLE, BU/HR*, 3X, F6.2)
     IF(REFHR .EQ. 0.)GOTO 91
      IF(REFIN .GE. REFHR)CALL REFILL(REFIN, GLEVEL1, XMAVE, COOLER)
     IF(REFIN .EQ. 0.)PBU=DRYBUT
91
     CONTINUE
     XMBIN=XMAVE
     IF (DEPTH .GE. DPCH) XMBT = (XM(1) + XM(2))/2.
C*
C*
   TERMINATING CONDITIONS
C*
     XMFS=XMS/100.
      IF(XMFS .LE. XMF)GOTO 73
     IF(DEPTH .LE. .995)GOTO 73
     IF(DEPTH .GE. 12. .AND. COOLER .NE. 1.)PRINT 193
193
     FORMAT(*0*,*BIN IS FULL, STOP FILLING!*)
     IF (DEPTH .GE. 12. .AND. COOLER .NE. 1.) GOTO 73
     IF(HOUR .GE. TIME)GOTO 73
     GOTO 40
73
     CONTINUE
     IF(SYSTEM .GE. 2.)RETURN
     IND=IND1-1
     SUMT=SUMM=0.
     DO 55 J=1,KK
     SUMT=SUMT+TDRY(J)
     SUMM=SUMM+XMDRY(J)
55
     CONTINUE
     TDAVE=SUMT/KK
     XMDAVE=SUMM/KK
     DEPTH=2.*DELX*KK
     IF(DEPTH .GT. 12.)DEPTH=12.
     XMWD=XMDAVE/(1.+XMDAVE)*100.
     XMO=XMDAVE
     PRINT 1370, XMWD, TDAVE
     FORMAT(//* FINAL AVERAGE MOISTURE:*,18X,F12.4/
1370
    +* FINAL GRAIN TEMPERATURE:*,17X,F12.4)
     RETURN
     END
C**
SUBROUTINE CRSPR(XMAVE, TAVE, THAVE, XMEINW, XMEOUTW, RHK)
C****
     DIMENSION RHK(50), XMW(50)
     COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA
     COMMON/MAIN/DUM(5), XMO, KAB, SKIP(4), IPROD
     COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER
C****
     IND=IND1-1
     DBPR=DEP=0.
     SUM=SUMT=SUMTH=0.0
     IF(DBTPR .GT. DEPTH)GOTO 5
     PRINT 50
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DO 10 J=1, IND1
     DEP=DEP+DELX
     DBPR=DBPR+DELX
     XMW(J)=XM(J)/(1.+XM(J))*100.
     IF (DBPR .GE. DBTPR) PRINT 100, DEP, XMW(J), TH(J, I), T(J, I), H(J, I), RHK(
    +J)
     IF(DBPR .GE. DBTPR)DBPR=0
10
     CONTINUE
5
     CONTINUE
     DO 20 I=2, IND1
     SUMT=SUMT+T(I,1)
     SUMTH=SUMTH+TH(I,1)
20
     SUM=SUM+XM(I)
     XMAVE=SUM/FLOAT(IND1-1)
     TAVE=SUMT/FLOAT(IND1-1)
     THAVE=SUMTH/FLOAT(IND1-1)
     XMEIN=EMC(RH(1),TH(1,1))
     XMEOUT=EMC(RH(IND1), TH(IND1,1))
     XMEINW=XMEIN/(1.+XMEIN)*100.
     XMEOUTW=XMEOUT/(1.+XMEOUT)*100.
     RETURN
     FORMAT(//* DEPTH M C
50
                           PROD.TEMP AIR TEMP AIR U.R. REL.HUM.*)
     FORMAT(1X, F5.2, F8.2, F9.2, F9.2, F9.5, F10.2)
100
     END
C**
SUBROUTINE DATE(IPROD)
C****
         SUBROUTINE USED FOR INITIALIZING CONSTANTS FOR PRODUCTS
     COMMON/PRPRTY/ SA, CA, CV, CW, RHOP, CP
     COMMON/HLATENT/HA, HB
C**
     COMMON /NAME/INAME, IPRODU, IPRODU1, IEMC
     DATA INAME, IPRODU, IPRODUL, IEMC/10HTROETHOM , 10HTHINLAYER ,
    +10H CORN
                 ,10H DEBOER
                             /
C****
C****
         INITIALIZE CONSTANTS FOR CORN
     SA=239.
     CA=0.242
     CV=0.45
     CW=1.0
     RHOP=38.71
     HA=4.349
     HB=-28.25
     CP=.268
     RETURN
     END
C**
SUBROUTINE ABSH(HIN, TAMB, TIN, HI, FUEL, IPROD)
C*===========
             C****
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C***** FUEL=1 STANDS FOR NO.2 FUEL
C***** FUEL=2 STANDS FOR NATURAL GAS
C***** FUEL=3 STANDS FOR LIQUID PROPANE GAS
C****
     IFUEL=IFIX(FUEL)
     IF(IFUEL.EQ.1) A=7.0143E-5
     IF(FUEL.EQ.2) A=8.175E-5
     IF(IFUEL.EQ.3) A=7.593E-5
     IF(IPROD.EQ.2) CP=0.400
     IF(IPROD.EQ.1) CP=0.268
     HFUEL=A*(1.+HI)*CP*(TIN-TAMB)
     HIN=HI+HFUEL
     FUEL=FLOAT(IFUEL)
     RETURN
     END
C**
SUBROUTINE SECANT(BINL, BCFMF, CFM, PG, COOLER)
C**
     COMMON PF
     DIMENSION X(50)
     FACT=BCFMF
     X(1)=3500.
     X(2) = 12999.99
     K=2
4
     CONTINUE
     K=K+1
     FX1=PCFM(X(K-2), BINL, FACT, COOLER)
     FX2=PCFM(X(K-1), BINL, FACT, COOLER)
     X(K) = (FX2 * X(K-2) - FX1 * X(K-1)) / (FX2 - FX1)
     ERROR=ABS(X(K-1)-X(K))/2.
     IF(ERROR .LE. 1.E-5)GOTO 10
     GOTO 4
     CONTINUE
10
     CFM=X(K)/254.469
     PG=PF
     RETURN
     END
C***
FUNCTION PCFM(CFMX, BINL, FACT, COOLER)
C*===============
           COMMON PF
     A=FACT*1.0038E-8
     B=6.1304E-4
     C=ALOG(1.+B*CFMX)
     F=1./1.1664
     G=13000.-CFMX
     PG=A*CFMX**2*BINL/C
     PF=(G/601.448)**F
     IF(COOLER .EQ. 1.)PF=9.39-1.1*ALOG(CFMX)
```

```
PCFM=PG-PF
     RETURN
     END
C**
FUNCTION HEATLAT(XMC, TH)
C****
C****
         FUNCTION USED FOR COMPUTING THE LATENT HEAT OF VAPORIZATION
C*****OF WATER IN THE GRAIN.
C****
     COMMON/HLATENT/HA, HB
     IF(XMC .GE. .18)GOTO 10
     HEATLAT = (1094. -0.57 * TH) * (1. + HA * EXP(HB * XMC))
     RETURN
10
     HEATLAT=1000.
     RETURN
     END
C**
SUBROUTINE VARYD(KBU, DRMN, DRM, CYCLE, CYCLE1, CYCLE2, KK, COOLER)
C**
     DIMENSION CYCLE(50)
     COMMON/MAIN/XMT, THT, RHT, DELT, CFM, XMO, KAB, TOTEN, TOTH20, XMS,
    +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY
     COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER
     COMMON/PRPRTY/SA, CA, CV, CW, RHOP, CP
     COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA
     COMMON/HLATENT/HA, HB, HFG
     COMMON/IFLAGS/K, JM, ICON, DELXM
     COMMON/PRESS/PATM, BCFMF, PG
     DATA PATM/14.696/
     F(X) = X + 459.69
     CTIME=25./60.
     DELX1=DELX*2.
     IND2=IND1
     IF(KBU .GT. 0)GOTO 10
     KK=KK+1
     CYCLE(KK)=CYCLE2-CYCLE1
     CYCLE1=CYCLE2
10
     CONTINUE
     DEPTH=DEPTH-DELX1
     DRM=DRM+DELX1
     CALL SECANT (DEPTH, BCFMF, CFM, PG, COOLER)
     IND=INT(DEPTH/DELX)
     IND1=IND+1
     IDRM=IND2-IND1
     IF(IDRM .LE. 0)GOTO 35
     INDX=IND1+1
     DO 15 KC=1, INDX
     LL=KC+IDRM
```

.

```
LX=KC+1
      T(LX,1)=T(LX,2)=T(LL,1)
      H(LX,1)=H(LX,2)=H(LL,1)
      RH(LX) = RH(LL)
      TH(KC, 1) = TH(KC, 2) = TH(LL, 1)
      XM(KC) = XM(LL)
15
      CONTINUE
35
      KBU=KBU+1
      DRMN=DRM
      DCONT=2.*DELX
      IF(DRM .GE. DCONT)KBU=0
      IF(DRM .GE. DCONT)DRM=0.
      RETURN
      END
C**
FUNCTION SOLVE4(HJ2)
C****
      COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA
      COMMON/MAIN/XMT, THT, RHT, DELT, CFM, XMO, KAB, TOTEN, TOTH20, XMS,
     +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY
      COMMON/PRPRTY/SA, CA, CV, CW, RHOP, CP
      COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER
      COMMON/IFLAGS/J, JM, ICON, DELXM
      COMMON/HLATENT/HA, HB, HFG
      COMMON/PRESS/PATM, BCFMF, PG
      COMMON/ICHECK/INTEGER
      COMMON/COLD/COOLER, SYSTEM
      DATA PATM/14.696/
      DATA RHC/0.9999999999/
      F(T) = T + 459.69
      ICON=0
      XTEMPER=0.
      IND=IND1-1
C****
C****
           EVALUATE THE CONSTANTS CON1....CON6 AND SET THE INITIAL
C***** GUESS FOR H AND COMPUTE TIME INCREMENT, DELT
      IF(GA .LT. 500.)CHTC=.69*GA**.49
      IF(SYSTEM .LT. 2.)DELTA=.5
      IF(GA .GE. 500.)CHTC=.363*GA**.59
      DELTA=1.
C*
      CON1=2.*GA*CA
      CON2=2.*GA*CV
      CON3=CHTC*SA*DELX
      CON4=RHOP*CP
      CON5=RHOP*CW
      DELT=2.*DELX*(CON4+CON5*XM(2))/(CON1+CON2*H(IND1,1))*.9
      IF(COOLER .EQ. 1.)DELT=1.
C****
      JX=J+1
```

```
JMM=JM-1
      KKC=0
      H(J,2)=HJ2
25
      IF(J.EQ.2) GO TO 75
      IF(KKC.EQ.1) GO TO 50
      DELH=(H(J,2)-H(JMM,2))/2.
      GO TO 100
50
      DELH=H(J,2)-H(JM,2)
      GO TO 100
75
      DELH=0.
      IF(KKC.EQ.1) GO TO 50
      CCON1=GA*(CA+CV*H(J,2))
100
      CCON2=DELX*CHTC*SA
      CCON3=(CCON2-GA*CV*DELH)*DELT
      CCON4=DELT*HFG*GA*DELH
      CCON5=DELX*RHOP*(CP+CW*XM(J))
      CCON6=GA*DELT/(RHOP*DELX)
      THETA=(TH(JM, 1)+TH(J, 2))/2.
      IF(COOLER .EQ. 1.) THETA=(TH(JM, 1)*4.+TH(J, 2))/5.
      T(J,2)=(CCON1*T(JM,2)+CCON2*THETA)/(CCON1+CCON2)
      IF(COOLER .EQ. 1.)T(J,2)=(CCON1*T(JM,2)+CCON2*THETA)/(CCON1+CCON2)
      THETAT=(T(JM, 1) \times 1.+T(J, 2))/2.
      TH(J,2)=(CCON3*T(J,2)-CCON4+CCON5*TH(J,1))/(CCON5+CCON3)
      IF(COOLER .EQ. 1.)TH(J,2)=(CCON3*THETAT-CCON4+CCON5*TH(JM,2))/
     +(CCON5+CCON3)
      IF(TH(J,2) .LT. TH(1,1) .AND. COOLER .EQ. 1.)TH(J,2)=TH(1,1)
      IF(T(J,2) .GT. TH(J,2) .AND. COOLER .EQ. 1.)T(J,2)=TH(J,2)
      IF(COOLER .EQ. 1.)GOTO 3
      IF(J .GT. 2)GOTO 3
      IF(TH(1,1) .GE. TH(2,2))GOTO 3
      IF(SYSTEM .EQ. 2.)GOTO 3
      THTR=TH(1,1)
      TH(1,1)=TH(2,2)
      TH(2,2)=THTR
3
      CONTINUE
C****
C****
           COMPUTE RH AND CHECK FOR CONDENSATION
C****
      RH(J)=RHDBHA(F(T(J,2)),H(J,2))
      IF(RH(J)-RHC) 150,200,200
C****
C*****
           CONDENSATION SIMULATOR
C****
C****
200
      CONTINUE
      TS=T(J,2)
      HS=HADBRH(F(T(J,2)),RHC)
      H(J,2)=HS
      DHDT=HS-HADBRH(F(T(J,2))-1, RHC)
      A=GA*CV
      B=(GA*CA+CCON2)-DHDT*GA*CV*(T(JM,2)-TS)-HS*GA*CV
      C=(GA*CA+CCON2)*(DHDT*TS-HS)-DHDT*(GA*CA*T(JM,2)+CCON2*THETA)
```

```
H(J,2)=(-B+(B*B-4.*A*C)**0.5)/(2.*A)
     CCON1=GA*(CA+CV*H(J,2))
     DELH=H(J,2)-H(JM,2)
     CCON3=(CCON2-GA*CV*DELH)*DELT
     CCON4=DELT*HFG*GA*DELH
     T(J,2)=(CCON1*T(JM,2)+CCON2*THETA)/(CCON1+CCON2)
     TH(J,2)=(CCON3*T(J,2)-CCON4+CCON5*TH(J,1))/(CCON5+CCON3)
     THT=TH(J,2)
     RH(J)=RHDBHA(F(T(J,2)),H(J,2))
     ICON=1
     DELXM=XMT-XM(J)
C****
C****
         FIND XM ACCORDING TO THE THIN-LAYER DRYING EQUATION.
C****
150
     XMT=XM(J)
     IF(RH(J) .GE. RHC)RH(J)=RHC
     THT=TH(J,2)
     RHT=RH(J)
     CALL LAYEO
C****
     SOLVE4=XMT-XM(J)+CCON6*(HJ2-H(JM,2))
C* M EQUATION
     XMT=XM(J)-CCON6*(H(J,2)-H(JM,2))
     H(J,2)=(XM(J)-XMT)/CCON6+H(JM,2)
     IF(COOLER .EQ. 1.)RETURN
     IF(H(2,2) .GE. H(1,1))RETURN
     IF(SYSTEM .EQ. 2.)RETURN
     HTR=H(2,2)
     H(2,2)=H(1,1)
     H(1,1)=HTR
     END
C**
SUBROUTINE LAYEO
C****
        DESCRIPTION
C****
            SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUA-
C****
        TIONS BY J.M. TROEGER AND P.M. DEL GIUDICE
C*****
C****
        USAGE
C****
            USED IN THE FIXED BED AND CROSSFLOW MODELS WITH GRAIN
C****
        TEMPERATURES BETWEEN 80 F AND 160 F
C****
     COMMON/MAIN/XMC, TH, RH, DELT, CFM, XMO, KAB, TOTEN, TOTH2O, XMS,
    +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY
     COMMON /NAME/INAME, IPRODU, IPRODUL, IEMC
     COMMON/COLD/COOLER, SYSTEM
     DATA INAME, IPRODU, IPRODUL, IEMC/10HTROETHOM , 10HTHINLAYER ,
    +10H CORN
                 ,10H DEBOER

C****
C****
                   STATEMENT FUNCTIONS
```

C**** P1(XM,R,T)=EXP(-2.45+6.42*XM**1.25-3.15*R+9.62*XM*SORT(R)+.03*T-.0 102*CFM) P2(R,T)=EXP(2.82+7.49*(R+.01)**.67-.0179*T) P3(P,Q) = -.12*(XMO-XME)**(Q+1.)*P*QQ1(XM,R,T)=-3.98+2.87*XM-(.019/(R+.015))+.016*T Q2(R) = -EXP(.81 - 3.11 + R)TF(P,Q,XO,XF,TO)=P*(XF-XME)**Q-P*(XO -XME)**Q+TO XMN(P,O,XO,TI,TO) = ((TI-TO)/P+(XO-XME)**O)**(1./O)+XMEC**** C**** PROGRAM C**** IF(RH .LT. 0.)RH=.0001 C**** CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS CALL READYTH(TXMO, DELM, XME, IOOPS, XMR) C**** CHECK ABSORPTION FLAG... IF SET GO TO ABSORPTION SIMULATION IF(IOOPS-1)1,6,1 1 IF(COOLER .EO. 1.) GOTO 100 C**** COMPUTE TRANSITION M, P1, Q1, AND FIRST TRANSITION TIME X1M=.4*DELM+XME X2M=.12*DELM+XME TINC=DELT*60. P=P1(TXMO,RH,TH) Q=Q1(TXMO,RH,TH) TX=TF(P,Q,TXMO,X1M,0.0)C**** CHECK IF PRESENT M IS IN FIRST REGION... IF IS IS COMPUTE C**** EOUIVALENT TIME AND ADD TINC IF(XMC.LT.X1M) GO TO 3 TI=TF(P,Q,TXMO,XMC,0.0)+TINCC**** CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME.. C**** IF IT IS COMPUTE NEW M AND RETURN IF(TI.GT.TX) GO TO 2 $XMC = HDF^*XMN(P, 0, TXMO, TI, 0.0)$ RETURN C***** EQUIVALENT TIME+TINC IS IN SECOND REGION--COMPUTE P2, Q2 AND C**** NEW M THEN RETURN 2 **P=P2(RH,TH)** Q=Q2(RH)XMC= HDF*XMN(P,Q,XLM,TI,TX) RETURN C***** M IS NOT IN FIRST REGION--COMPUTE P2, Q2 AND SECOND C**** TRANSITION TIME 3 P=P2(RH,TH)Q=Q2(RH)TX1=TX TX=TF(P,Q,XIM,X2M,TX1)C**** CHECK IF PRESENT M IS IN SECOND REGION... IF IT IS COMPUTE C**** EOUIVALENT TIME AND ADD TINC IF(XMC.LT.X2M) GO TO 5 TI=TF(P,Q,X1M,XMC,TX1)+TINC C**** CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME.. C***** IF IT IS COMPUTE M AND RETURN

```
IF(TI.GT.TX) GO TO 4
     XMC= HDF*XMN(P,Q,X1M,TI,TX1)
     RETURN
C*****
        EQUIVALENT TIME+TINC IS IN THIRD REGION--COMPUTE P3, Q3 AND
C****
        NEW M THEN RETURN
4
     P=P3(P,Q)
     Q=-1.
     XMC = HDF^{*}XMN(P,Q,X2M,TI,TX)
     RETURN
C****
        M IS NOT IN SECOND REGION--COMPUTE P3, Q3, EQUIVALENT TIME+
C*****
        TINC AND NEW M THEN RETURN
5
     P=P3(P,Q)
     Q=-1.
     TI=TF(P,Q,X2M,XMC,TX)+TINC
     XMC = HDF * XMN(P,Q, X2M, TI, TX)
     RETURN
C****
C****
        ABSORPTION SIMULATION
C****
        FIND NEW M AND INCREMENT COUNTER
   6 DIV=-.625*PSDB(TH+459.69)**(.466*RH)*RH*RH*RH
     XMC = HDF^{((XMC-XME)*EXP(DIV*DELT)+XME)}
     KAB=KAB+1
     RETURN
100
     IF(IOOPS-1)10, 20, 10
10
     ALMR=ALOG(XMR)
     A=-1.86178+0.0048843*TH
     B=427.364*EXP(-0.03301*TH)
C**** FIND EQUIVALENT TIME BASED ON CURRENT TEMP AND MC
C**** ADD DELT AND SOLVE FOR NEW MC
     TI=ALMR*(A+B*ALMR)+DELT
     ALMR = (-A - SQRT(A*A+4.0*B*TI))/(2.0*B)
     XMC = HDF^*(DELM^*EXP(ALMR) + XME)
     RETURN
20
     KAB=KAB+1
     RETURN
     END
C**
SUBROUTINE READYTH(TXMO, DELM, XME, IOOPS, XMR)
C*****
C****
C****
        DESCRIPTION
C****
        SUBROUTINE MAKES PRELIMINARY CHECKS AND CALCULATIONS
C****
        FOR THIN LAYER EQUATIONS
C****
C****
        USAGE
C****
        USED WITH LAYEO IN FIXED AND CROSS FLOW DRYER MODELS
C****
     COMMON/MAIN/XMC, TH, RH, DELT, CFM, XMO, KAB, TOTEN, TOTH2O, XMS,
    +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY
     COMMON /NAME/INAME, IPRODU, IPRODUL, IEMC
```

```
IOOPS = 0
C***** COMPUTE EQUILIBRIUM MOISTURE CONTENT, COMPARE TO PRESENT
C****
         MOISTURE CONTENT... IF GREATER SET IOOPS = 1
     XME = EMC(RH, TH)
      IF(XME - XMC) 2, 1, 1
    1 \text{ IOOPS} = 1
C*****
        COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT
C*****
        SET TXMO = THE LARGER VALUE
    2 \text{ IF}(XMO - XMC) 3, 4, 4
    3 \text{ TXMO} = \text{XMC}
     GO TO 5
    4 \text{ TXMO} = \text{XMO}
C****
        COMPUTE MOISTURE RATIO
    5 \text{ DELM} = \text{TXMO} - \text{XME}
     XMR = (XMC - XME)/DELM
     RETURN
     END
C**
FUNCTION EMC(RH,T)
C****
C****
                    S.F.DEBOER, PROGRAMMER IN ENGLISH UNITS
C****
                            AND
C****
                   EDISON W. RUGUMAYO, CONVERTER TO SI UNITS
C***** DESCRIPTION
C*****
                 FUNCTION COMPUTES EQUILIBRIUM MOISTURE CONTENT OF CORN
C***** FROM A RELATIVE HUMIDITY AND TEMPERATURE
C****
        CHECK TEMPERATURE TO DETERMINE EQUATION TO BE USED
     TC=(T-32.)/1.8
      IF(TC - 112.778) 234,235,235
C****
C****
                   DEBOER EQUATIONS
C****
C****
        CHECK IF RH IS GREATER THAN .50 .. IF SO GO TO SECOND PART
  234 IF(RH - .50) 300,300,309
C****
        PART ONE RH .LE. .50 ONLY
C****
         COMPUTE CONSTANTS
  300 \text{ F1} = -.00070596 \text{*TC} + .0874496
     F2 = -.00078354 TC + .1188704
     F3 =-.00096462*TC + .1474512
      S1 = 13.838*(-9.*F1 + 6.*F2 - F3)
     S2 = 13.838*(4.*F3 - 9.*F2 + 6.*F1)
      B = RH - .17
C*****
        FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
C****
         CONTENT
      IF (B) 301,301,302
  301 \text{ EMC} = (S1*RH*RH*RH/1.02 + (F1/.17 - S1*.02833)*RH)
      RETURN
  302 IF(RH - .34) 303,303,304
  303 A = .34 - RH
      EMC = (S1*A*A*A/1.02 + S2*B*B*B/1.02 + (F2/.17 - S2*.02833)*B +
```

+(F1/.17 - S1*.02833)*A)RETURN 304 A = .51 - RH $EMC = 52^{A}A^{A}A^{1}.02 + (F3/.17)^{*}(RH - .34) + (F2/.17 - S2^{*}.02833)$ +*A RETURN C**** PART TWO---RH.GT. .50 ONLY C**** COMPUTE CONSTANTS $309 \ FO = -.00096714 \ TC + .1452064$ F1 = -.00127350 + .1848600F2 = -.00134082 TC + .2293632F3 = -.00192780 TC + .3588280S1 = 13.838*(4.*F0 - 9.*F1 + 6.*F2 - F3)S2 = 13.838*(4.*F3 - 9.*F2 + 6.*F1 - F0)B = RH - .66IF(B) 305,305,306 C**** FIND INTERVAL IN WHICH RH LIES AND COMPUTE EOUILIBRIUM MOISTURE C**** CONTENT 305 A = RH - .49EMC = S1*A*A*A/1.02 + (F1/.17 - S1*.02833)*A + (F0/.17)*(.66 - RH)RETURN 306 IF(RH - .83) 307, 307, 308307 A = .83 - RHEMC = S1*A*A*A/1.02 + S2*B*B*B/1.02 + (F2/.17 - S2*.02833)*B + +(F1/.17 - S1*.028333)*A RETURN 308 A = 1.0 - RH $EMC = S2^*A^*A^1.02 + (F3/.17)^*(RH - .83) + (F2/.17 - S2^*.028333)$ 1*A RETURN C**** C**** THOMPSON EOUATION C**** TC.GE. 113 DEGREES CELCUS C**** COMPUTE EQUILIBRIUM MOISTURE CONTENT 235 EMC = .01*SQRT((-ALOG(1. - RH))/(.0000382*(1.8*TC + 82.)))RETURN END SUBROUTINE REFILL (REFIN, GLEVEL1, XMAVE, COOLER) COMMON/MAIN/XMT, THT, RHT, DELT, CFM, XMO, KAB, TOTEN, TOTH2O, XMS, +TOTSP, IPROD, FM, HDF, XMF, TIME, NEQ, NEQ1, HOUR, REFHR, REFBU, TOFENY COMMON/INPT/BPH, GP, IND1, DELX, DEPTH, DBTPR, XTEMPER COMMON/PRPRTY/SA, CA, CV, CW, RHOP, CP COMMON/ARRAYS/XM(50), RH(50), T(50,2), H(50,2), TH(50,2), GA COMMON/HLATENT/HA, HB, HFG COMMON/IFLAGS/K, JM, ICON, DELXM COMMON/PRESS/PATM, BCFMF, PG COMMON/COUNT/ITERCT, TIN, THIN, HIN DATA PATM/14.696/ DATA RHC, AREA/.999999,254.469/ F(T) = T + 459.69REFFT=REFBU*1.24/AREA DEPTHF=REFFT+DEPTH

INDF=INT(DEPTHF/DELX)+1 INS=IND1+1 INDEX=INDF+1 DO 10 I=INS, INDEX XM(I) = XMOTH(1,1)=TH(1,2)=THIN T(I,1)=T(I,2)=T(IND1,1) H(I,1)=H(I,2)=H(IND1,1)RH(I)=RH(IND1) 10 CONTINUE SUM=0. IND1=INDF DO 30 I=1, IND1 SUM=SUM+XM(I) 30 CONTINUE XMAVE=SUM/IND1 GLEVEL1=DEPTH=DEPTHF PRINT 20, REFBU, DEPTH, HOUR CALL SECANT (DEPTH, BCFMF, CFM, PG, COOLER) GA=60.*CFM/VSDBHA(F(TIN),HIN) REFIN=0. 20 FORMAT(*0*,*BIN REFILLED WITH *,F5.1,* BU TO A DEPTH OF *,F4.1, +* FT*/* *, *AFTER *, F4.1, * HOURS*) RETURN END

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