THESIS

This is to certify that the

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DIRECT COMBUSTION BIOMASS FURNACE
FOR USE WITH GRAIN DRYING

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Marilia Henriette Guillaumon

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A STATE OF THE ART OF
DIRECT COMBUSTION BIOMASS FURNACES
FOR USE WITH GRAIN DRYING

by

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ABSTRACT

A State of the Art of
Direct Combustion Biomass Furnace
for Use in Grain Drying

by

Marilia Henriette Guillaumon

Biomass is a renewable resource which can replace fossil fuels for farmstead applications. The feasibility of utilizing biomass energy for grain drying is examined. Grain drying is relatively energy intensive and presently uses a greater amount of energy than any other sector of the agricultural system except irrigation and fertilizing.

This study discusses recent developments of agricultural residue furnaces and identifies the level of technology conversion.

First, conversion fundamentals and combustion processes are reviewed. Subsequently, biomass characteristics such as methods of introducing fuel to the furnace and different types of grates are discussed. Finally, system models are assessed along with the possible utilization of fluidized beds, pile burners, and suspension burners for biomass furnaces.

The thesis concludes with an evaluation of existing biomass furnaces. Improvements in the design of biomass furnaces are still required. The furnace

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should have an inexpensive technology and should utilize a minimum amount of labor in order to be a viable energy source for a medium sized farm.

Approved: Major Professor

Approved: Department Chairman

DEDICATION

To my mother,

"com amor"

ACKNOWLEDGEMENTS

The author wishes to express her gratitude to those who have contributed significantly to the development of this study.

My sincere appreciation is extended to my major professor, Dr. Fred. W. Bakker-Arkema, for his continuous direction throughout my program. Sincere appreciation is also extended to the members of my committee, Dr. Jon R. Bartholic and Dr. Gary Van Ee.

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But my greatest debt of gratitude is to my mother. She encouraged me to set high goals and taught me how to strive to attain them.

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CHAPTER I

INTRODUCTION

The growing demand and the rising price of oil over the last decade have created very obvious difficulties for all countries relying on oil for a major proportion of their commercial energy requirements. These problems appear certain to increase in the future. Diminishing resources and growing political pressures combine to force up the price and reduce the availability of oil (Hall et al., 1982).

Whereas in the early 1970s oil import bills typically accounted for 10% or less of the total export earnings, in many developing countries today 40-50% of their foreign exchange earnings must be spent to finance oil imports (Hall et al., 1982). Nevertheless, the present energy crisis is not so much due to a shortage of supply, but to an overdependence on non-renewable resources which are distributed unevenly throughout the world. The energy situation is complex, affecting almost every segment of our lives.

Increasing energy consumption is an unavoidable prerequisite of future economic development. Thus, the need to develop indigeneous energy alternatives (renewable and non-renewable) to replace imported oil is both obvious and urgent.

In response to concern for the limited supplies, efforts to develop alternative energy sources are greatly intensified. Viable energy sources include agricultural and forest residues which can be used as fuels at prices per unit of energy that will compete directly with all fossil utility fuels. In agriculture, crop residue is an attractive and viable energy source, because it is readily available and renewable. Probstein et al. (1982) cited an estimation that energy produced from biomass sources in the U.S. by the year 2010 will be less than 10% of the total energy consumed. The results of another estimation suggest that the biomass contributions could be as much as 19%, assuming maximum development of this resource. This upper value depends on a variety of factors, including the availability of cropland, improved crop yields, the development of efficient conversion processes, and proper resource management.

Figure 1 shows the distribution of energy sources throughout the world in 1978.

Objectives

The purpose of this study is to review the current technical potential for producing energy from biomass. Specifically, the focus is to assess the state-of-the-art of biomass utilization for grain drying from the point of view of furnace equipment operation.

The author reviewed the literature and became convinced that a large body of information needed to be brought together to build a clearer picture of the limitations and potential of direct heat from biomass-fired crop drying furnaces. This procedure offered an opportunity to observe the advantages and disadvantages of each different biomass furnace.

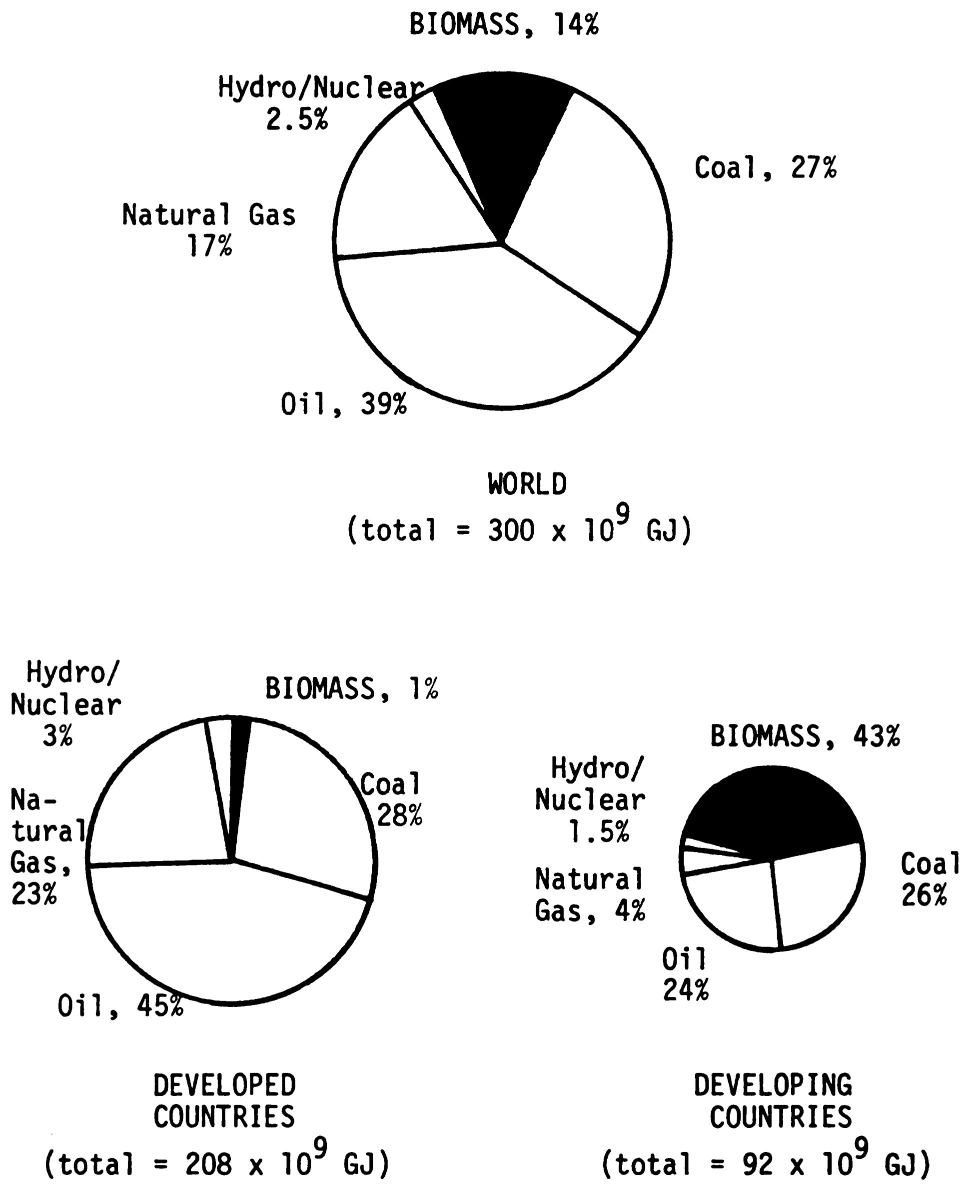


Figure 1. The present role of biomass energy; global distribution of energy use (1978) (source: Hall, 1982).

CHAPTER II

BIOMASS AS AN ENERGY SOURCE

Of the total fossil energy used in the United States, agricultural production requires only 2.2% (Hirst, 1974); a great amount of this energy is used for grain drying. Most of the fossil energy used is in the form of propane (LP gas), and the remainder is natural gas.

For replacing some of this fossil energy, biomass seems to have potential in specific situations. Biomass energy is a general term that refers to renewable energy resources that can be derived from plant and animal materials through a variety of conversion and end-use processes. It is particularly attractive to the agricultural industry because biomass is a by-product of normal crop production and processing operations. Kajewski (1977) calculated that the corn production of four hectares can be dried with the residue of 0.4 hectares. Loewer et al. (1981) concluded that cobs and stalks can compete with propane as a source of energy for grain drying.

The use of biomass as an alternative energy source will reduce the dependence on petroleum and generate a degree of energy independence for grain farmers. This will be a step in making the farm an energy-self reliant entity.

At the present time, biomass supplies only a small amount of the energy being used. However, it could be rapidly expanded in the next two decades due to the acute shortage of energy.

Limitations

The development of biomass energy has considerable potential, but it is also subject to a variety of constraints and limitations, many of which are highly site-specific. In some cases, advanced techniques and highly efficient technologies should be applied, while other circumstances require simplicity and low cost.

Theoretically, there are considerable alternatives of biomass energy sources. Possibilities vary from scavenged crop residues to large, intensively managed energy plantations.

One factor that must be accounted for in considering the use of crop lands for energy is the competition with the food market. There is no assurance that crop land will be available in the future for energy uses. Another source of energy could be crop residues. Probstein et al. (1982) mentioned a study which found that the material left in the field after harvesting could supply up to one percent of the U.S. energy requirements. This figure is based on the recovery of 20% of the crop residue with the remaining 80% required for soil conditioning.

The National Academy of Sciences made an approximation of the quantity of residue generated in the production of a given crop by multiplying the numerical weight of the crop by a residue coefficient for that crop. The residue coefficient is the ratio of the dry weight of ground residue to the weight of the harvested crop at field moisture content. Coefficients for six major crops are:

soybeans	0.55 - 2.60
corn	0.55 - 1.20
cotton	1.20 - 3.00
wheat	0.47 - 1.75
sugar beets	0.07 - 0.20
sugar cane	0.13 - 0.25

Another limitation of using biomass as a fuel is the effect of removing organic matter that could be returned to the soil. Organic matter has an important role in preventing erosion, conserving water and nutrients and maintaining soil structure.

A further factor pertaining to use of crop or crop residue for energy is the seasonality of supply. Crop residues are limited to a certain period of the year, varying from one to two months. Consequently, storage facilities will be required to ensure a constant supply of material throughout the year, affecting the economic cost of using biomass as an energy source.

Economic Costs

A major economic obstacle is that users of biomass fuels must invest heavily in equipment and in facilities for the collection and storage of fuels.

The utilization of crop residues as sources of energy is site-dependent in two respects:

--utilization is confined to agricultural areas

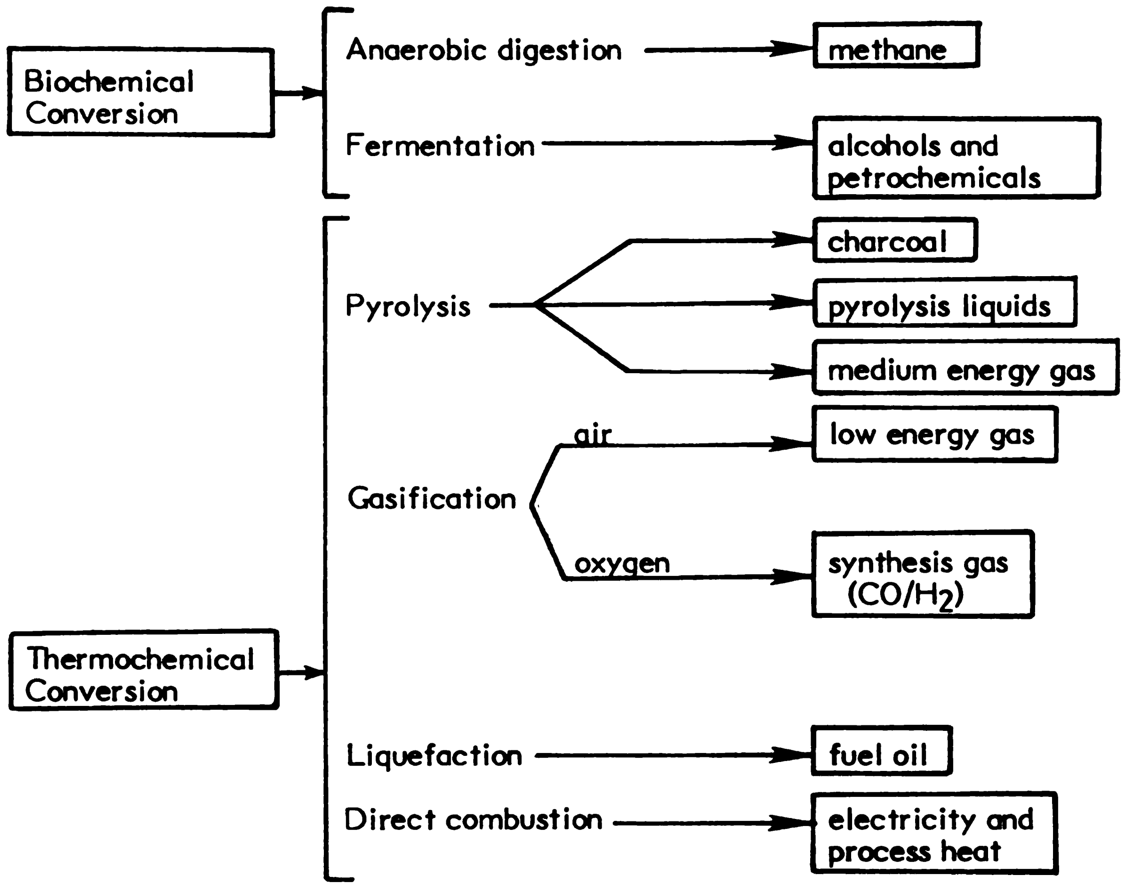
--the energy production and consumption must take place relatively near the site of residue production

Because biomass fuels are relatively bulky and have a low fuel value per unit weight, thus fuel costs are highly site specific and may pose economic constraints not shared by petroleum or natural gas. These characteristics make the distance between producer and user crucial in calculating total energy costs; as distance increases, total transportation costs rise sharply. The low energy/unit weight ratio and consequently transportation costs appear to increase making biomass a tool for self-reliance of a given farm but not a commercially viable product to be transported over large distance, especially in relation to crop residue.

CHAPTER III

CONVERSION METHODS

Conversion of agricultural residues into energy can be accomplished by either biochemical or thermochemical processes.



(from Hall et al., 1982; and Cheremisimoff, 1980)

A biochemical process, using living organisms, generally takes place at or near room temperature and pressure; a thermochemical process generally occurs at higher temperature and pressure (Palz &Chartier, 1980).

It is a matter of selecting the right fuel and the right supply-delivery system to meet the needs of an appropriate application. The following section describes the above conversion systems.

Anaerobic Digestion

In the absence of air, specific microorganisms digest organic materials to produce methane gas. The material is kept within a specific temperature range (usually 32 to 38 °C, or 90 to 100° F), and adequate holding time of the material (usually about 10 days). Anaerobic digestion to produce methane is particularly applicable when a constant supply of biomass input is available and the methane can be used at the same location (Hall, 1981).

The gas form anaerobic digestion has a heat content in a range of 20,000 to 28,000 KJ/m^3 of substrate (537 to 750 BTU/ft^3) depending on the percentage of methane it contains (Hall et al., 1982). The residues from this process can be returned to the soil as a fertilizer.

Fermentation

The sugars present in many agricultural plants can be transformed into alcohol by fermentationn. The products used in alcoholic fermentation are rich in sugar or starch; they include sugar cane, sugar beets, grapes, cassava, potato, and various cereal crops (Stout et al., 1979).

Pyrolysis

Pyrolysis is the thermal decomposition of biomass at elevated temperatures (between 200 °C and 1100 °C or 400 and 2000 °F) in the absence of oxygen. By controlling the reaction time and temperature, the end products can be liquid, gaseous, or solid charcoal (Palz & Chartier, 1980).

Pyrolysis requires relatively dry biomass material (less than 15% MC) for optimum efficiency. However, a higher water content (50-60%) will not prevent the process from taking place. The main advantage of pyrolysis is that it provides fuels with a high energy content, which are easy to store, handle, and use (Palz & Chartier, 1980). Besides that, they burn with a hotter flame, with practically no smoke, and emit very few polluting substances due to their low sulphur content (Hall et al., 1982).

It is estimated that the net thermal efficiency of a pyrolysis system is about 80% (Tillman, 1978).

Gasification

Gasification can be defined as the partial combustion of a solid fuel (control of air supply) which produces a combustible gas (Kutz et al., 1982).

A restricted amount of oxygen or air is admitted to the combustion zone and the products of the subsequent pyrolysis are mainly gaseous, including CO, H_2, CH_4, CO_2, and H_2O (Palz & Chartier, 1980). If the combustion is fed with oxygen, the heating value is approximately 50% greater than if the combustor is fed with air (Tillman, 1978).

The temperature in the bed of a gasifier is approximately 900 °C (1650°F); the produced gas is at a flame temperature in excess of 1370 °C (2500 °F) (Tillman et al., 1977). The advantages of gasification are clean combustion, high combustion efficiency, and greater control over the energy output (Payne et al., 1981).

Liquefaction

Liquefaction is a process in which carbonaceous materials lose oxygen through a reaction with carbon monoxide. After the loss of oxygen and possible addition of hydrogen from either water or pure hydrogen, the material is converted into oil (Braunstein et al., 1981). This method to convert biomass to liquid fuels is a relatively sophisticated technique for farm use and appears only be practical for large scale operations.

Direct Combustion

Direct combustion is the method that will be emphasized in this study. It is an efficient and versatile conversion technique. Direct combustion involves burning biomass with excess oxygen to guarantee complete combustion for generating heat.

In direct combustion systems, three types of furnaces appear to have potential:

1. fluidized bed burners,
2. suspension burners, and
3. pile burners.

CHAPTER IV

FUNDAMENTALS OF DIRECT COMBUSTION

The process of direct combustion is one of the oldest methods of releasing biomass energy. Combustion is the most direct method of obtaining thermal energy from biomass and has been used extensively by humans for centuries. In the early 1970s, as petroleum products became more expensive and supplies less certain, an evaluation of alternative fuel sources has intensified.

In order to assure an effective operation of the direct combustion furnace, it is important to control the air-to-fuel ratio. There are three factors that have been identified as the major factors for its operation: (a) turbulence (for mixing of the air stream), (b) temperature (for the ignition of fuel in air), and (c) time (for ensuring sufficient reaction time for combustion to take place) (Claar et al., 1980).

Combustion Phases

The combustion process of a crop residue occurs in three consecutive, phases: (a) evaporation of moisture, (b) volatilization and burning of volatile matter, and (c) combustion of the fixed carbon. The major products of exothermic reactions are heat, carbon dioxide, sulfur dioxide, nitrogen dioxide, ash, and water (Babcock & Wilcox, 1978; Claar et al., 1980).

Because of its relative simplicity, low cost, and flexibility, direct combustion appears to be one of the most attractive short-term alternative for conversion of energy.

Combustion Process

Combustion is defined by Babcock and Wilcox (1978) as the rapid chemical combination of oxygen with the combustible elements of a fuel.

Since the combustible matter in fuels is composed mainly of carbon and hydrogen, combustion calculations deal mostly with the different relationships among carbons, hydrogen, and oxygen. The chemical products formed during the combustion are carbon dioxide, water, and metallic oxides such as potassium and sodium.

The following equations describe the results of burning carbon and hydrogen with oxygen:

$C + O_2 = CO_2$ + 32,798 KJ/KG of C (14,100 BTU/lb of C)

$2H_2 + O_2 = 2H_2O$ + 14,893 KJ/KG of H_2 (61,000 BTU/lb of H_2)

Sulfur does not have any significance as a heat source in the combustion process. However, sulfur can cause many corrosion and pollution problems.

Characterizing Biomass Fuels

Two methods are used to characterize the fuel's chemical--physical characteristics. In the proximate analysis, the proportions of moisture, ash, and volatile matter is determined and the proportion of fixed carbon is calculated by difference. In the ultimate analysis, the proportions of carbons, hydrogen, sulfur, nitrogen, and ash of a dried fuel are determined and the proportion of oxygen is calculated by difference.

Tables 1A and 1B present the ultimate analysis and the proximate analysis for some agricultural crop residues.

Table 1A
Ultimate Analysis for Some Biomass Fuels

Biomass Fuel	Component, Percentage by Weight						
	Moisture***	Carbon	Hydrogen	Sulfur	Nitrogen	Oxygen	Ash
Corncob*	0.0	48.4	5.6	----	0.3	44.3	----
Cornstalk*	4.94	42.48	5.04	0.13	0.75	42.65	3.96
Pine bark**	----	53.4	5.6	0.1	0.1	37.9	2.9

* from Claar et al. (1980)
** from Babcock and Wilcox (1978)
*** MC (%, dry basis)

Table 1B
Proximate Analysis for Some Biomass Fuels

Biomass Fuel	Component, Percentage by Weight			
	Moisture***	Volatile Matter	Fixed Carbon	Ash
Corncob*	15	76.6	7.0	1.4
Cornstalk*	35	54.6	7.15	3.25
Pine bark**	--	72.9	24.2	2.9

* from Claar et al. (1980)
** from Babcock and Wilcox (1978)
*** from MC (%, dry basis)

Slag Formation

A serious problem when handling biomass fuel is the formation of slag.

Agricultural residues contain a large amount of silicon and soil particles from the harvesting operation. If the furnace temperature exceeds the residue fusion point, which is about 816 °C (1500 °F), it can result in a glassy-like formation on the grate called slag. This, in turn, causes a decrease in the combustion rate and efficiency.

As the slag flows over the grate, it cools and solidifies on the grate openings, preventing the entrance of primary air needed for the combustion zone. Therefore, it is extremely important that the slag is instantly frozen to prevent its flowing. Another alternative is the use of a refractory grate to prevent slag solidifying on the grate openings. This may be accomplished by controlling the temperature in the combustion chamber, so that the temperature is below the fusion point of the agricultural residue ash, but sufficient to ensure complete combustion.

Combustion—Air Requirements

The minimum amount of air required to completely burn a unit of fuel (without any excess oxygen left in the exhaust) is known as the stoichiometric air (Jones & Hawkins, 1960). The theoretical combustion air requirement and the gas analysis may be calculated for the fuel type using the kilogram-mole system.

The amount of air required by the fuel for complete combustion is :

$$Q\ \text{air} = 106.75 \left(\frac{\text{carbon}}{12} + \frac{\text{hydrogen}}{4} + \frac{\text{sulfur}}{32} - \frac{\text{oxygen}}{32}\right) \frac{m^3}{\text{kg of fuel}}$$

Q air = stoichiometric air, (m^3), carbon, hydrogen, sultur, oxygen = proportions of these elements in the fuel, percentage by weight from the ultimate analysis of the fuel (Perry & Chilton, 1973).

However, it is necessary to supply more than the theoretical amount of air into the combustion chamber in order to (a) ensure complete combustion of the fuel, (b) control the temperature which may result in damage to the furnace wall with excessive slag deposit, and (c) cause turbulence in the combustion process. This excess air is expressed either as a percent of theoretical air or as the total air divided by the theoretical air.

Typical furnaces operate at about 50% of excess air. Values higher than that should be limited for the following reasons: (a) the excess air cools the combustion reaction and hence slows the combustion reaction rate; (b) the excess air increases the flue gas velocities and carries partly burned fuel particles out of the furnace; (c) the excess air reduces the overall combustion system efficiency.

The excess air requirement is directly related to the moisture content of the fuel. High moisture content fuels require high air levels to dry the fuel being burned and sustain combustion.

Firing methods must assure complete mixture of fuel and oxygen in order to be certain that all of the carbon burns to CO_2 and not to CO. Failure to meet this requirement will result in appreciable losses in combustion efficiency and in the amount of heat released by the fuel, since only about 28% of the available heat in the carbon is released if CO is formed instead of CO_2 (Babcock & Wilcox, 1978).

Heating Value of Fuels

Babcock and Wilcox (1978) define the heating value of a fuel as the amount of heat expressed in unit energy, generated by the complete combustion, or oxidation, of a unit weight of fuel. The high heat content assumes that the products of combustion are cooled to the initial temperature and all of the water vapor formed during combustion is condensed to liquid. The low heat value assumes that all products of combustion remain in the gaseous state.

Table 2
Heat Values for Some Agricultural Residues

Fuels	Average Moisture Content (%) (Wet Basis)	Lower Heating Value (KJ/Kg)
Groundnut shells	3 - 10	16,700 - 18,800
Coffee husks	13	15,500 - 16,300
Bagasse (cane)	40 - 50	8,400 - 10,500
Cotton husks	5 - 10	16, 700
Coconut husks	5 - 10	16, 700
Rice hulls	9 - 11	13,800 - 15,000

from Stout et al. (1979)

Energy Losses

Not all the energy contained in a fuel is converted to heat. Some of the carbon of the fuel remains in the ashes and some burns incompletely to form CO instead of CO_2. By far the most significant reasons for heat loss are due to:

1. formation of water vapor from the combination of hydrogen of the fuel and oxygen,
2. evaporation of the moisture content of the fuel,
3. conduction through the furnace walls,
4. unburned combustibles in the fuels, and
5. formation of carbon monoxide in the flue gases.

CHAPTER V

FURNACE CHARACTERISTICS

Furnace Volume

Furnace volume is directly related to combustion rate. Biomass is composed of a high amount of volatile matter. Thus, enough space for the expansion of gases is required in a biomass furnace. Furnaces without enough space for burning the fuel may give incomplete, smoky combustion and high temperatures causing softening of the furnace walls, burner wear, and excessive deposits of slag.

Griswold (1946) recommends 28 x 10^{-1} cubic meters of combustion space per 9.3 x 10^{-2} square meters of grate area for burning coal (10 ft^3/ft^2). This value varies according to type of feed system, requiring the least combustion space for an underfeed system and the most for an overfeed system.

Classification of Types of Grates

The perforated structure supporting the combusting fuel and separating the ashes from the fuel is called the grate. Three types of grate systems are employed (Perry & Chilton, 1973):

1. dump grate,
2. stationary grate, and
3. moving grate.

1. Dump grate. This type of grate can be dumped by itself, thereby eliminating manual removal of ashes. This provides some reduction in the time necessary for cleaning a grate, and no slag formation occurs since ashes are continuously dumped.

2. Stationary grates.

a. Flat grates. The flat grate is the oldest method to burn fuel. The fuel pile is on a flat grate which needs a minimum of external control to move the fuel while it burns. The undergrate or underfire air is introduced to the pile and determines the rate of firing while the overgrate or overfire air is blown through nozzles localized above the pile to assure complete combustion. As the fuel dries, its angle of repose changes, causing sudden flowing. Flat grates are considered to have higher thermal inertia fuel pile compared with other types of grates.

b. Inclined grates. This type of grate arrangement uses an overfeed stoker which pushes fresh fuel onto an inclined surface on which the fuel slides to the discharge point by gravity. The fuel bed is disturbed frequently as fuel slides down the grate.

On an inclined grate, the thickness and velocity of the fuel bed are controlled by the slope of the grate. Depending on the properties of the fuel, the angle of inclination varies between 37 and 55 degrees (Sarkanen et al., 1982).

Inclined grate systems separate and distribute the combustion reaction stages into a proper sequence. On the highest part of the grate, heating and drying will occur, as the fuel is moving down, flaming combustion occurs, followed by pyrolysis and char oxidation. The heat release from an inclined grate concentrates on its low end and on the burnout grate, since about one-half of the heat value of the fuel remains in the char. Inclined grates are designed for very wet fuels, accepting products with moisture contents up to 65% with a variety of particle sizes (Sarkanen et al., 1982).

Slag formation is often a problem when using a stationary grate. One way of handling it is using a refractory grate to keep the slagging ash in the fuel bed in a molten state so that it will drain through the openings of the refractory grate in the ash pit.

3. Moving grates. As the system provides a continuous dumping of ash, the moving grate has an effective ash removal and a longer equipment life. Moving grates general constitut either of an overfeed method of firing (the fuel is dropped onto the grate from the hopper) or of a crossfeed method (the fuel is dropped in a perpendicular direction to the airflow). Hardly ever does it appear as an underfeed principle of firing.

Moving grates can be classified into three main categories:

1. travelling,
2. vibrating or oscillating, and
3. mechanical.

Different types of moving grates are shown in Figure 2.

1) Travelling grates. These units can be constructed as two different types: (a) the chain grate and (b) the bar grate. The system works with a slowly moving endless grate chain or grate bars passing under the feeder and carrying a bed of fresh fuel to the central part of the furnace. The fuel bed continues to burn as it moves along, with the bed becoming progressively shallower as combustion continues. By the time the fuel is half way down the length of the grate, it is mostly burned. At the far end of the grate, ash is discharged from the end of the grate into the ash pit.

Two parameters can be varied in travelling grate operations: (a) the velocity of the grate and (b) the thickness of the fuel bed. Because of the wide variability of these parameters, the travelling grate is versatile in operation and capable of coping with varying fuel qualities (Sarkanen et al., 1982).

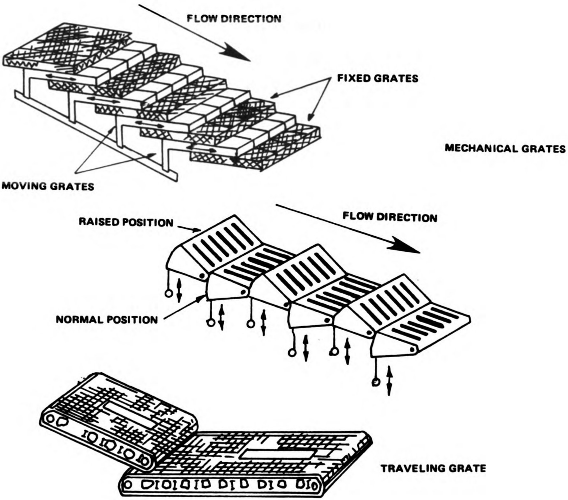


Figure 2. Types of moving grates. Source: Alter and Dunn, 1980.

Another favorable characterstic of the travelling grate is the effectiveness in burning low volatile fuel with a minimum fly-ash carry-over (Babcock & Wilcox, 1975).

2) Vibrating or oscillating grates. This type of grate is usually installed in small units. The grate uses a vibrating or oscillating motion to propel the ash to the end of the grate. The fuel bed moves as one mass so there is no serious mixing of ash and burning particles. The main restrictions faced with this type of grate are the size of the grate, the weight of the fuel bed, and the physical size of the driving apparatus (Perry & Chilton, 1973).

3) Mechanical grates. A mechanical grate has moving components, usually driven cylinders, grate bars, or rotating sector blades. These components will move the fuel bed according to the progress of the combustion.

One type of mechanical grate is a rotating-drum grate stoker. The grate consists of an inclined row of rotating individually driven cylinders. Another type is the rocking grate stoker which consists of a series of movable grates each of which is rocked in a coordinated manner, lifting the refuse and advancing it to the discharge end (Mantell, 1975).

The inclination of these grates varies between 5 and 15 degrees; the grates can handle a variety of wet fuels up to a moisture content of 60% (Sarkanen et al., 1982). Small particles of fuel are not recommended since they can block the space between the small units of the grate causing a disturbance of the grate movement.

Compared to other types of grates, the moving grate requires the most careful maintenance and costs the most to construct, thus increasing the furnace investment.

Grate Area

The grate area can be determined by the fuel burning rate expressed in terms of heat energy released (KJ/hr m^2 or BTU/hr ft^2). Babcock and Wilcox (1978) suggest values varing from 5.1×10^6 KJ/hr m^2 (4.5×10^5 BTU/hr ft^2) for a stationary grate to 8.5×10^6 KJ/hr m^2 (7.5×10^5 BTU/hr ft^2) for traveling grate. Assuming a heating value of 14,000 KJ/kg (6,000 BTU/lb), for wet biomass, it will require a feed rate of a value between 364 and 607 kg wet biomass/hr m^2 of grate area (75 to 125 lb wet biomass/hr ft^2).

Sukup (1982) suggests a value of 340 Kg of wet biomass/m^2 hr (70 lb wet biomass/ft^2 hr) for valid design criterion for initial sizing of the grate.

Classification of Stokers

Different methods of introducing fuel to a pile burner are designed to provide continuous feed, fuel ignition, proper distribution for the combustion air, and free release of the gaseous combustion products (Perry & Chilton, 1973). Stokers can be classified in three main groups, based on the method by which fuel is introduced and by the direction of air inside the furnace:

1. underfeed stokers,
2. crossfeed stokers, and
3. overfeed stokers.

Figure 3 illustrates the design principles of different types of stokers.

1. Underfeed stokers. In the underfeed principle of firing, both fuel and air have the same relative direction. Air and fuel enter the active burning zone from beneath the fuel bed.

2. Crossfeed stoker. In the crossfeed principle, the fuel flows at right angles to the air flow. The most common of this type are the traveling grate stoker, the chain grate, and the bar grate.

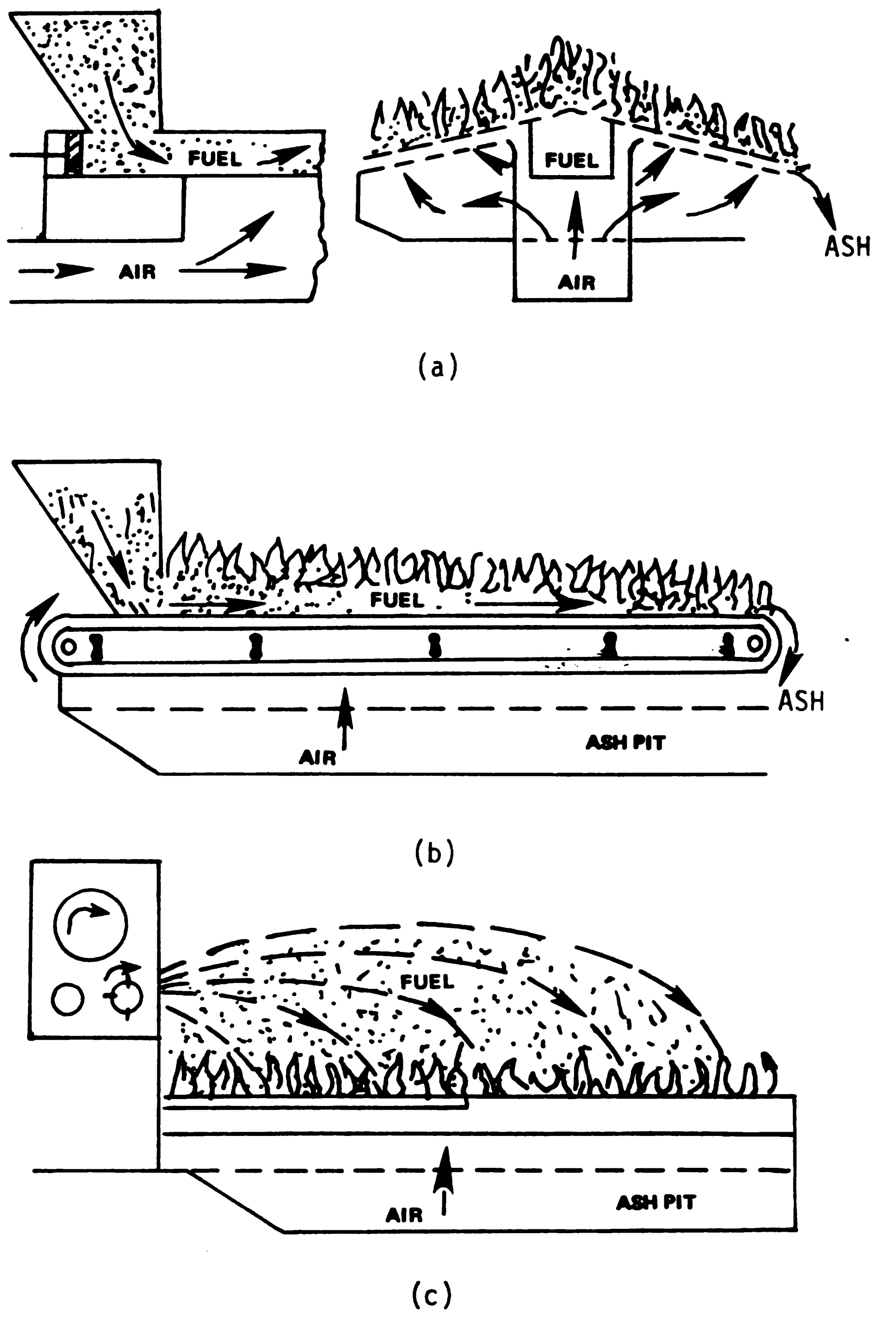


Figure 3. Types of stoker: (a) underfeed, (b) crossfeed, and (c) overfeed. Source: Perry and Chilton, 1973.

3. <u>Overfeed stoker</u>. In the overfeed method, fuel is introduced at the top of the bed, and the fuel and air flow in the opposite direction. Primary air is introduced at the bottom of the bed and regulates the bed temperature to prevent slag formation. Secondary air is introduced above the bed to control the combustion efficiency. The most common type of overfeed system is the spreader stoker.

In the spreader stoker system, the fuel is projected over the fire with a uniform spreading action, permitting part of the fuel to burn in suspension and the remaining particles to burn on the grate. It is important that the fuel is spread evenly over the grate to maintain uniform fuel-to-air ratios.

If the fuel consists of fine particles at low moisture content, more fuel will be burned in suspension, while high moisture content particles will fall and burn on the grate. The largest fuel particles travel the farthest, while the smallest ones are burned before reaching the grate.

A significant advantage of this system is that the particle size can be large, which greatly decreases the grinding cost associated with fuel preparation. The disadvantage of the spreader system is that combustion takes place fairly slowly requiring a larger combustion chamber to achieve the desired temperature.

Junge (1979) reported that 43% of the air in a spreader stoker should be supplied below the grate (underfire air) and 57% above the grate (overfire air). Close control of fuel and air supply is required to achieve the best results.

Efficiency

The objective of good combustion is to release all heat energy while minimizing losses from imperfect combustion and excess air. The efficiency of any furnace may be defined as the ratio of the actual heat utilized for an operation to the total heat available liberated in the furnace. Various ways of calculating the efficiency of a furnace have been used. Therefore, these calculations can use sophisticated methods or simpler methods depending on the accuracy of the results desired.

Methods for Calculating Furnace Efficiency

First method: thermodynamic method.

$$\text{Efficiency (\%)} = \frac{\text{Output}}{\text{Input}} \quad \frac{\text{Input-Losses}}{\text{Input}}$$

a) Input = gross higher heating value in KJ/Kg (BTU/lb) * fueld feed rate in Kg/min (lb/min)

The gross higher heating value is based only on the amount of dry matter of a wet fuel giving the higher heating value.

b) Calculation of the losses occurring in the system due to heat losses and incomplete combustion.

Since furnace tests are conducted under steady-state conditions, the first law of thermodynamics can be applied. the conservation of energy equation for an open system steady-flow is (Jones & Hawkins, 1960):

$$Q_{in} = W_{out} + H_2 - H_1 + \frac{V_2^2 - V_1^2}{2g} + g\frac{g}{c} \ (Z_2 - Z_1)$$

or

$$Q_{out} = W_{in} + H_1 - H_2 + \frac{V_1^2 - V_2^2}{2g_c} + g\frac{g}{c} \ (Z_1 - Z_2)$$

where

Q_{out} = net amount of heat energy lost by the system KJ/min (BTU/min)

W_{in} = net amount of work done on the system including the energy used for the fans KJ (BTU)

H = enthalpy of products entering (1) or leaving (2) the system, KJ/Kg (BTU/lb)

V = velocity of products entering (1) or leaving (2) the system, m/sec (ft/sec)

Z = elevation of products entering (1) or leaving (2) the system, m (ft)

g = acceleration of gravity, m/sec^2 (ft/sec^2)

The value for the change in enthalpy ($H_1 - H_2$) for a chemical reactionis (Jones & Hawkins, 1960):

$$H_1 - H_2 = \Sigma \text{ reactants } N(h_1 - h_0) - H_r - \Sigma \text{ products } N(h_2 - h_0)$$

where:

N = moles of each constituent

h = enthalpy of constituent at inlet (1) or outlet (2), KJ/Kg (BTU/lb)

h_0 = enthalpy of constituent at reference temperature 25 °C (77 °F), KJ/KG (BTU/lb)

H_r = heat of combustion at reference temperature 25 °C (77 °F), KJ/min (BTU/min)

Second method. This method of furnace efficiency was used by Wahby et al. (1981) according to Hughes' definition of boiler efficiency assuming that the furnace is an open system with no work done (W = O) under steady-state conditions.

$$Q + W = H$$

$$Q = H$$

$$\Delta H_r = H_c + (H_p - H_r)$$

$$= H_c + (H_{p2} - H_{p0}) - (H_{r1} - H_{r0})$$

H = heat released KJ (BTU)

H_r = heat of reaction KJ/Kg (BTU/lb)

H_c = heat of combustion KJ/Kg (BTU/lb)

H_{p2} = enthalpy of products at stack temperature (T_2), KJ/Kg (BTU/lb)

H_{p0} = enthalpy of products of reference temperature 25 °C (77 °F), KJ/Kg (BTU/lb)

H_{r1} = enthalpy of air (reactants) at entrance temperature (T_1), KJ/Kg (BTU/lb)

H_{r0} = enthalpy of air (reactants) at reference temperature 25 °C (77 °F), KJ/Kg (BTU/lb)

$$\text{Efficiency (\%)} = \frac{H_c + H_p - H_r}{HHV} * 100$$

HHV = higher heating value of the fuel in KJ/kg (BTU/lb)

Third method. The third method of calculating furnace efficiency is defined as the ratio of the heat available for use to the total heat released in the furnace. Therefore,

$$\text{Efficiency (\%)} = \frac{\text{sensible heat in the stack gas}}{\text{heating value of the fuel}}$$

$$= \frac{m\ c_p\ \Delta T}{\text{heating value}}$$

where

m = mass of the flue gases per Kg (lb) of residue fired

c_p = specific heat of the flue gas cal/g °c, (BTU/lb°F)

T = temperature difference between flue gas and combustion air °C (°F)

Three methods for calculating the efficiency for biomass furnaces have been presented. It would be desirable to have a standard method to calculate efficiency.

The termodynamic efficiency (first method) results in the most accurate calculation, but requires sophisticated testing equipment on the furnace to measure the composition of the combustion products. Other methods are simpler and faster to calculate; however, they are less accurate than the thermodynamics method. The difference among these methods can be as much as 12 percentage points for the same test (Sukup et al., 1982).

Emissions in the Exhaust

A primary concern with direct fired furnaces is the amount and effect of particulate emissions contained in the exhaust gases.

When using a direct firing system, without the need of a heat exchanger, care should be taken concerning the possibility of carcinogens in the exhaust products which could contaminate the grain being dried. To burn cleanly and efficiently, the fuel and combustion air must be brought together in a carefully controlled manner.

As mentioned by Anderson et al. (1981), two groups of compounds are of concern: (a) high concentration of nitrites or nitrates which have a toxic effect and can be absorbed on the surfaces of the grain and (b) polynuclear aromatic hydrocarbons (PAHs) which are highly carcinogenic.

Particulate emissions from biomass furnaces should not be more than the EPA emission standard for incinerators which assumes an emission level up to 0.017 gm per standard cubic meter (0.08 grains per standard cubic foot).

Barret et al. (1983) showed that the particulate emissions from biomass furnaces are substantially greater than the existing liquid petroleum burners.

Payne et al. (1980) and Anderson et al. (1981) have analyzed the products of combustion residue left in the grain dried by a direct biomass furnace. No harmful level of the carcinogenic product was found in the grain lots studied.

Problems with Traditional Furnaces

The problems that arise during the operation of traditional furnaces are (a) slag formation on the grate, (b) corrosion on the metallic parts of the furnace, (c) "back firing" into the feeder chute, and (d) ash contamination of the flue gases.

Considerations to Choose the Conversion Method of Agricultural Residues into Energy

Several important physical properties must be known in order to select the particular process to be used under specific circumstances. One of the most important variables to consider is the moisture content of the fuel. The higher the moisture content of a given weight of biomass, the less the proportion of dry matter to provide energy and the greater the energy requirements to vaporize water.

Some systems accept fuel with moisture contents as high as 60%; others are limited to 15-20% moisture contents.

If crop residues are used to supply energy during planting time, they have to be stored from year to year. In case they are stored outside, the moisture content of the fuel will have a tendency to vary according to the season of the year, and drying of the feedstock may be necessary.

The moisture content is also an important factor in the bulk density of the feed matter, and this has a significant impact on the transportation costs and size of the conversion equipment.

An additional variable which is critical in choosing the design of a conversion plant is the particle size and shape. The smaller the particle, the bigger is the surface area per unit volume. Increasing the surface area, the rate of heat transfer and, consequently, the rate of reaction will increase.

Even though small particles are desirable to achieve high reaction rates, several factors tend to discourage the use of very small particles. If an upward flowing furnace is to be used, small particles may be exhausted from the furnace. Fine particles can damage the moving equipment by falling through the grate and other parts.

The particle shape and texture also have an important effect on the method of burning. Highly fibrous material tends to bridge more easily than spherical material (Shuler, 1980). For some agricultural residues, pelleting may be required, expanding the choice of the conversion method.

Considering these three variables (moisture content, size, and shape), the best technology for converting residues to an useful forms of energy in direct combustion systems can be employed. As has been said before, those systems are classified as fluidized bed, suspension burners, and pile burners. Biomass burners have an efficiency of 60 to 80%. Each type has its own advantages and disadvantages. The selection of a furnace is primarily a function of its application.

The following design objectives for a furnace can be formulated.

1. The furnace should prevent slag formation on the grate surface and minimize particulate matter in the exhaust gases.
2. The furnace system should provide good combustion characteristics and high energy efficiency.
3. The furnace should be constructed with simple and inexpensive manufacturing technology.
4. The furnace system should be operated with minimum labor requirements, automatic control, ease of operation, and simple maintenance.

CHAPTER VII

CLASSIFICATION OF DIRECT COMBUSTION FURNACES

Fluidized Bed Burners

One method of direct combustion involves the use of a fluidized bed burner, which offers several unique characteristics for using low grade biomass fuel. This system can be adapted to either direct combustion or gasification depending on the fuel to air ratio.

Fluidized bed combustion involves supporting the fuel in a partially suspended bed of inert material such as silica, sand, or limestone (Tillman et al., 1981). As the fuel is introduced into the bed, rapid heat transfer from the solid particles to the fuel occurs. When a bed of inert particles is subjected to an evenly distributed flow of air, the particles are forced upward and suspended in the gas stream (see Figure 4A). As the velocity of the gas is increased (see Figure 4B), the bed becomes highly turbulent and rapid mixing of the particles occurs. Velocities of the gas are usually between 0.2 and 3 m/sec (0.5 to 10 ft/sec) (Perry & Chilton, 1973).

Figure 4A: Before fluidization.

Figure 4B: After fluidization.

The turbulence removes the film of water around the fuel particles and helps to keep the temperature uniform throughout the bed. The passage of air for combustion through the bed maintains the particles in a fluidized state. For a fluidized bed system, excess air levels of 100% are common (Tillman et al., 1981).

Fluidized Bed Burner Characteristics

Fluidized bed combustion provides relatively complete combustion, controlled temperatures and homogeneous gas composition, resulting in optimal conditions for minimizing the emission of harmful components.

The size and type of the inert bed material determines the fluidizing characteristics of the bed; thus, different applications require different bed characteristics. Operation of a fludized bed at moderate temperatures (less than 816 °C ,1500° F.) as required for agricultural fuel results in reduced NO_x and SO_x emissions while minimizing accumulation. By adding limestone, the process can desulphurize the combustibles, resulting in extremely low emissions of sulphur dioxide. Figure 5 shows that the porosity of the limestone significantly affects the SO_2 reduction; a peak retention efficiency is reached when the bed temperature is about 816 °C (1500 °F). The SO_2 retention efficiency depends not only on adding limestone, but also on other variables such as the bed temperature, the bed depth, and fluidizing velocities (i.e., 0.2 to 3 m/sec or 0.5 to 10 ft/sec).

Slag formation is highly undesirable in a fludized bed operation. To avoid this problem, a careful control of the temperature inside the furnace or using a fuel with no slag formation is recommended.

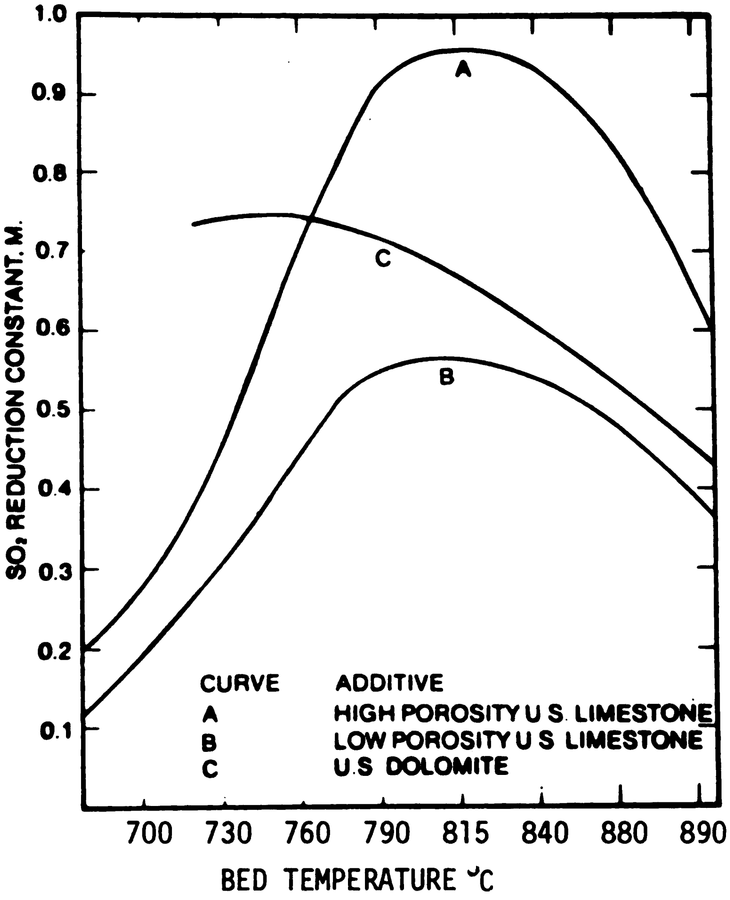


Figure 5. Variation of SO_2 reduction constant M with bed temperature and additive type in a bed 36 inches (91 cm) deep at atmospheric pressure: 6 ft/sec (1.8 m/sec) fludizing velocity, with fines recycled (from Wallish, 1981).

Combustion Efficiency of Fluidized Bed Burners

The combustion efficiency of a fludized bed furnace increases with decreasing particle size, but since the use of small particles limits the maximum permissible fluidizing velocity, the air throughout is reduced. Consequently, the operation of a fluidized bed system with small particles and small fluidizing velocities results in an increase of the furnace size, while is undesirable from an economic point of view. Particle size will also affect the heat transfer coefficient as shown in Figure 6.

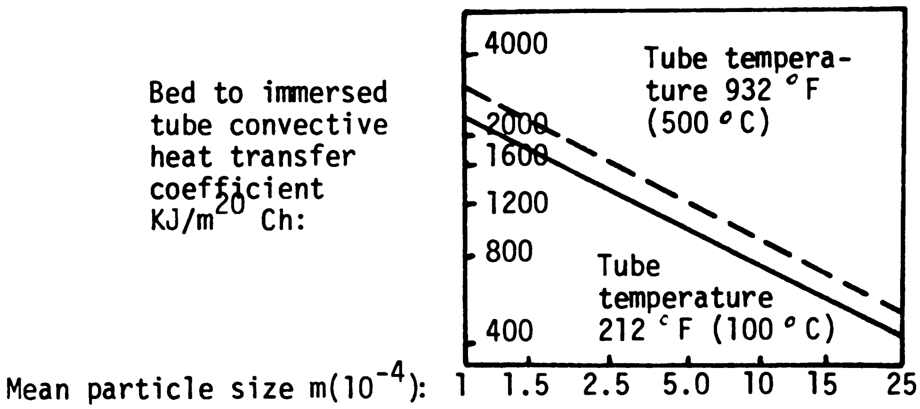


Figure 6: Fluidized bed heat transfer coefficients (from Charagundla & Metrek, 1977).

As the small particles provide more surface contact, the heat transfer coefficient increases with the decreasing of particle size (Charagundla & Metrek, 1977). For an intermittent operation, the fludized bed furnace has an advantage over other types of furnaces in retaining heat over a longer period due to the presence of the inert bed material. In some cases, it loses only about 110 °C during an overnight shutdown, saving auxiliary fuel for preheating during the next start up (Beagle, 1978).

Other characteristics of the fludized bed system are:

1. ability to use fuel with a high moisture content,
2. ability to use fuel with a high ash and non-combustible content,
3. high efficiency due to the action of the inert material as a heat sink,
4. high power requirement and capital outlay, and
5. low pollution levels with a significant reduction in oxides of nitrogen (NO_x) and sulphur dioxide (SO_2) emissions.

The use of volatile chemicals in the feedstock (i.e., pesticides and herbicides) is potentially harmful. It is possible that a volatile material in the feedstock will vaporize as it enters the fluidized bed and exists without passing through the reaction zone.

Fluidized beds are still not highly commercialized for farmstead application due to the high power consumption to fluidize the biomass. Because of the high level of operation and maintenance, the use of fludized bed systems is only justified in large scale energy conversion.

The specifications of some commercially available fluidized bed furnaces are summarized in Table 3. It can be seen that they allow for relatively wet feedstock and moderately large particles.

Feed System for a Fluidized Bed Furnace

Conventional fluidized bed furnaces use overfeed stokers or crossfeed stokers. These two feeder types are acceptable for fuels requiring relatively long residence time in the bed (large, 8 cm or 3 in; or wet particles, 50-60%), but they are unsatisfactory for small particle fuels. In the case of overfeed stokers, fine particles of fuel are partially carried away by the flue gas from the bed resulting in poor carbon utilization. For crossfeed stokers, the large surface area of the feed material results in a short residence time in the bed, which

Table 3
Commercial and Developmental Fludized Bed Combustion

Characteristics	Energy Production of Idaho	Copeland	Incinergy
Particle size, cm	8		8
Moisture content, % (wet basis)	65	65	65
Stage of development	commercial	commercial	prototype
Size 10^6, KJ/hr	127	127	11-21
Particulate emission gm/scm	0.021		0.05

from: Shuler, 1980

causes the particles to become gasified before uniform mixing occurs, resulting, in turn, in a poor combustion.

To solve these problems, a centerfeed stoker has been developed by Moreno and Goss (1983). In this design the fuel is introduced at the bottom center of the bed and is uniformly distributed into the main portion of the bed. Good results were obtained for large (8 cm or 3 in) and wet particles (50-60%) as well as for small particle fuels.

The three design types (overfeed, crossfeed, and centerfeed) are shown in Figure 7.

Evaluation of Existing Fluidized Bed Furnaces

An evaluation of a fluidized bed furnace has been given by Lepori et al. (1980). They evaluated a fluidized bed energy conversion furnace with the following characteristics:

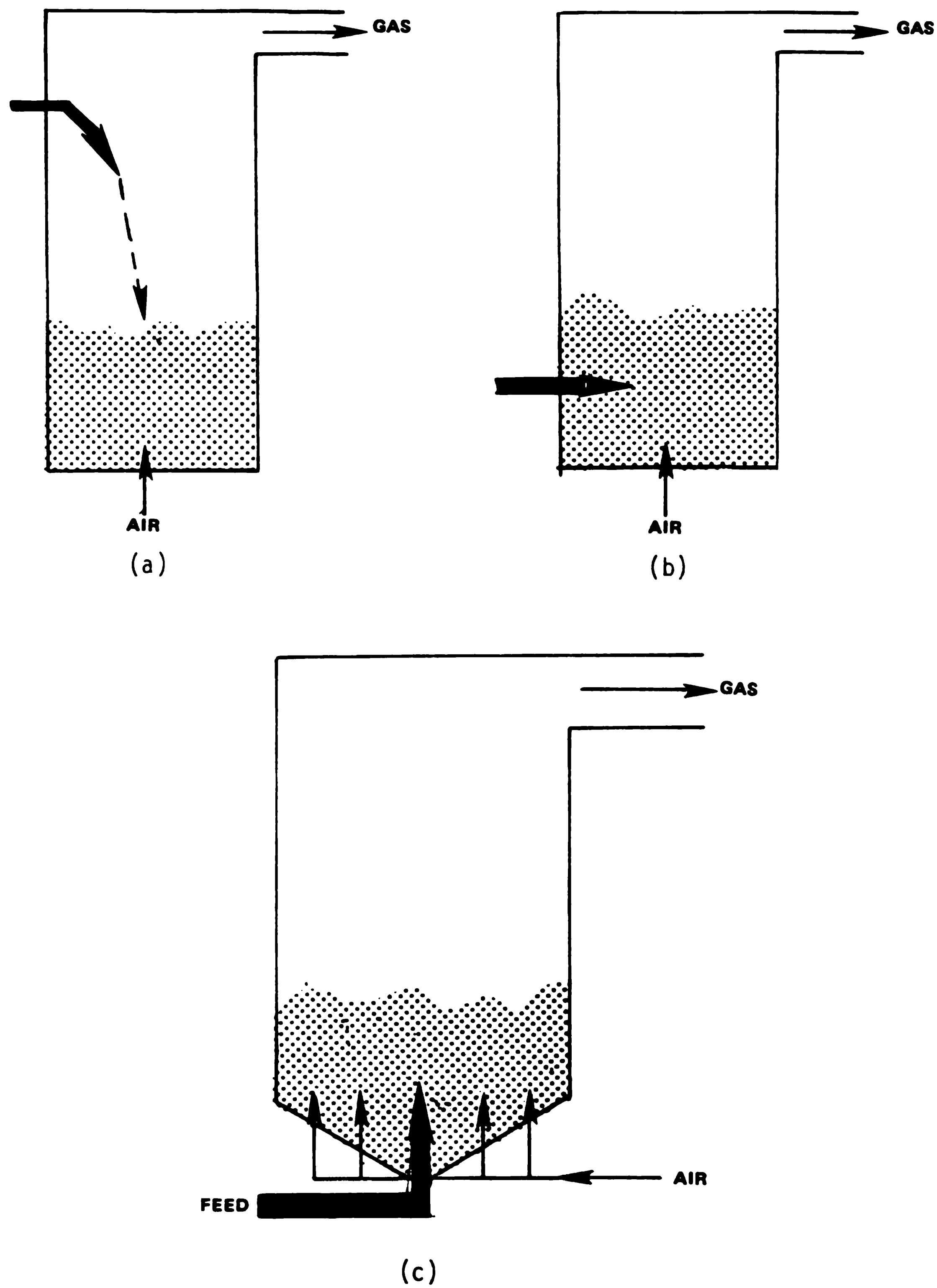


Figure 7. Feed systems for a fluidized bed furnace: (a) top feed, (b) side feed, (c) center feed. Source: Moreno and Goss, 1983.

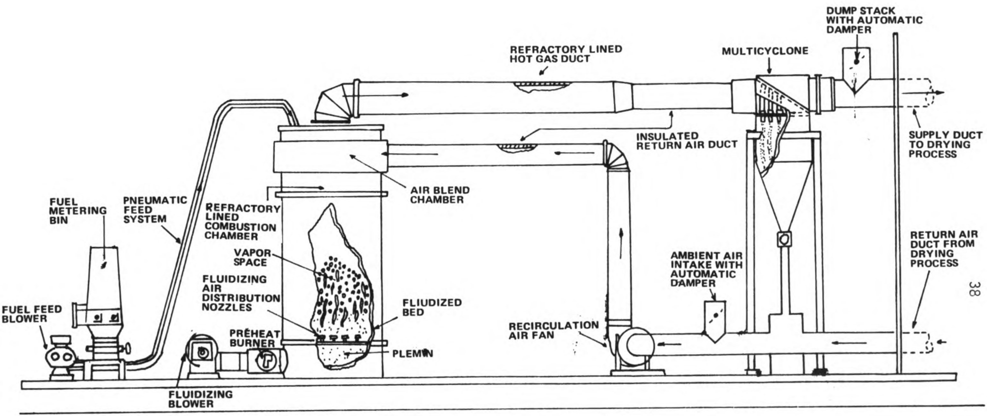


Figure 8. Fluidized bed furnace. Source: York-Shipley, Inc.

furnace diameter:	0.61 m (2 ft)
bed material:	sand
bed particle size:	46.4 micrometers
bed depth:	0.46 m (18 in)
fuel type:	cotton gin trash

Cotton gin trash was used for fuel augered into the lower region of the fluidized bed (crossfeed system). Natural gas was used to preheat the bed particles to about 399°C (750°F) before the fuel feed was introduced. The feed rate was adjusted to maintain the desired bed temperature. The operational characteristics are summarized below:

bed temperature:	760 to 816°C (1400 to 1500°F)
air flow:	100 to 130% more than stoichiometric
heat release:	1055 MJoules/hour (1,000,000 BTU/hour)

An analysis of the hot gases leaving the cyclone showed that the particle emission for a bed temperature of 760°C (1400°F) was 0.011 gm per standard cubic meter (0.053 grains per standard cubic foot) of dry gas; for a temperature of 816°C (1500°F), the particulate emission was about 0.014 gm per standard cubic meter (0.068 grains per standard cubic foot). These values are lower than the federal standards for incinerators allow. In this study no harmful levels of particulate emission were found, which clearly indicates that the fludized bed combustor can provide a reliable, efficient, and environmentally acceptable performance by a biological product.

LePori et al. (1980) reported that temperatures in the vapor space above the bed were higher than the bed temperatures, indicating that combustion reactions were continuing above the bed. The temperature increase was about 70°C (125°F) for a bed temperature of 760°C (1400°F) and about 160°C (290°F) for a bed temperature of 816°C (1500°F).

The potential of the fluidized bed burner still requires additional investigation in order to evaluate its efficiency and problems such as a high power consumption with regard to conversion of biomass to usable energy. However, it has been shown clearly that it offers potential for the agricultural industry in a large scale energy conversion.

Manufacturers of fludized bed furnaces include (a) York-Shipley, Inc., York, Pennsylvania (see Figure 6); (b) TPI--Thermal Processes, Inc., Olympia Fields, Illinois; and (c) EPI--Energy Products of Idaho, Portland, Oregon.

Pile Burners

Two types of pile burners are most frequently used: (a) the traditional Dutch oven grate burner (see Figure 9) and (b) the concentric vortex furnace (see Figure 10).

In a pile burner, combustion takes place unevenly due to the variations in the thickness of the fuel layer. As the fuel dries, its angle of repose changes, causing sudden flowing. Also, uneven distribution of moisture and density of the fuel in the pile is a significant problem.

Table 4 shows some charactersitics of pile burners of the travelling grate type. It can be seen that large and fairly wet pieces of biomass can be handled.

Characteristics of Pile Burner Systems

1. large range of moisture content material
2. large range of particle size
3. high thermal inertia in a fuel pile
4. easy maintenance and operation

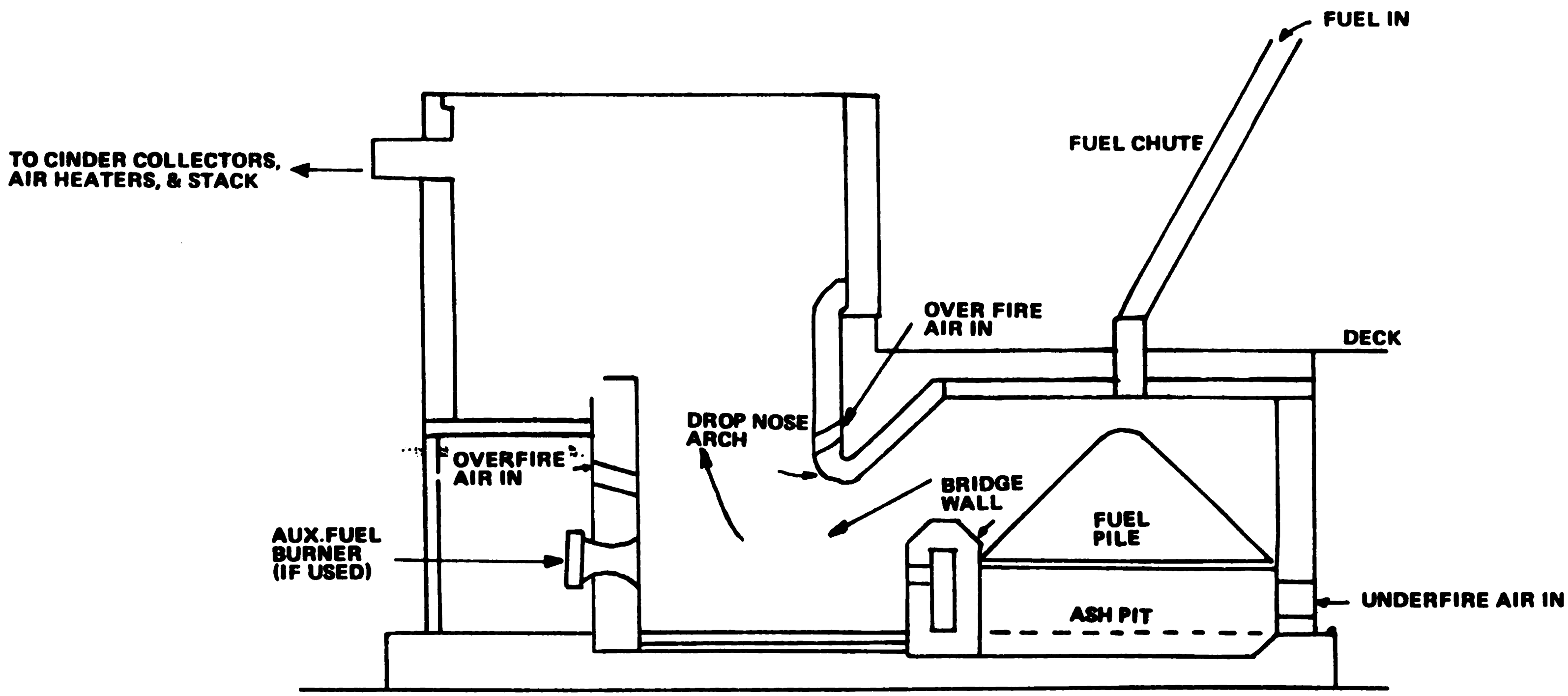


Figure 9. Dutch oven. Source: Levi and O'Grady- 1980.

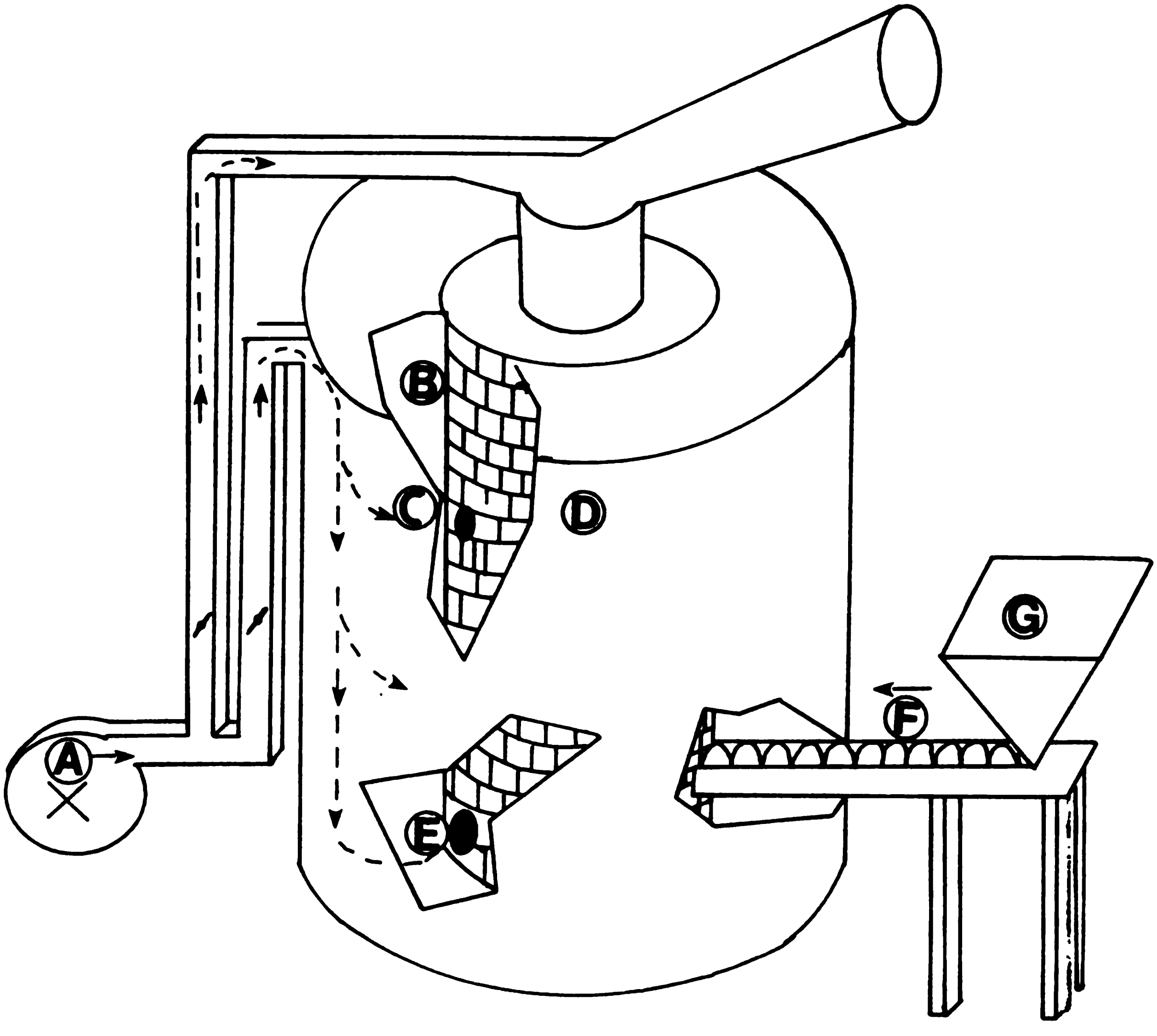


Figure 10. Concentric vortex biomass furnace.

Table 4

Commercial and Developmental Traveling Grate Burners

Characteristics	Irvington Moore	Enertherm	Lockhead Haggerty	Berg and Stark
particle size cm	8	30	30	10
moisture content %, (wet basis)	55	65	60	65
stage of development	commercial	prototype	prototype	commercial
size 10^6 KJ/hr	11-53	11-68	5-32	1-63
particulate emission, gm/scm		0.02	0.01	0.15

from: Shuler (1980)

Evaluation of Existing Pile Burner Furnaces

As reported by Claar et al. (1981), most of the work on the direct-burning of agricultural residues has been in Germany and Denmark. A straw-fired furnace was developed by Orth (1976) and Orth et al. (1977) and by Strehler (1976). Orth has reported the combustion capability of a two-stage furnace that burns and gasifies large round bales of straw.

Pioneer Hi-Breed developed a corncob burning incinerator, direct combustion for drying the whole ear seed corn (Dahlberg, 1977). This design has a fire chamber incinerator with a heat output of 30,590 MJ/hr (29 milhon BTU/hr). Temperature of 650 °C (1200 °F) is needed to ensure complete combustion of all hydrocarbons. Fuel was burned at temperatures of about 1000 C (1832°F). The main problems of the Pioneer Hi-Breed furnace while operating were slag formation on the grate, corrosion, and excessive particulates in the exhaust gases.

Dutch Oven

For this system, biomass is burned in a primary chamber to dry and partially burn the fuel, and then a secondary combustion chamber completes the burning process.

Studies on a Dutch oven system have been conducted at the University of Maine by Smith et al. to develop a wood chip furnace for residential use. However, since the principles are applicable for any size of furnace, this furnace can also be used for a farmstead application.

Figure 11 shows the features of a two chamber furnace. According to the Dutch oven principle, the first chamber initializes the combustion where the fuel is set over a grate, and the other chamber works as an "after burner" to provide sufficient turbulence and retention time to ensure complete combustion. Some heat is lost when hot air passes from one chamber to another. The auger is placed on the base of the fuel bin to meter the fuel to a second screen conveyor which carries the fuel to the firebox. To eliminate the possibility of pyrolysis occurring in the fuel supply line, fuel is fed into the top of the firebox providing a flux break between the conveyor and the firebox.

Evaluation of a Dutch Oven Burner

Smith et al. (1980) recommended passing as much air as possible through the grate. Some of the reasons for this are to (a) allow green chips to be burned; (b) produce the maximum energy release per unit of grate area; (c) cool the grate, extending the grate life; and (d) keep the ashes below the fusion temperature avoiding formation of slag.

The system works as an air-to-air heat exchanger which is suitable for using fuel with high particulate emission levels, since the exhaust gases do not go directly to the dryers. Air is heated by convection and radiation through the

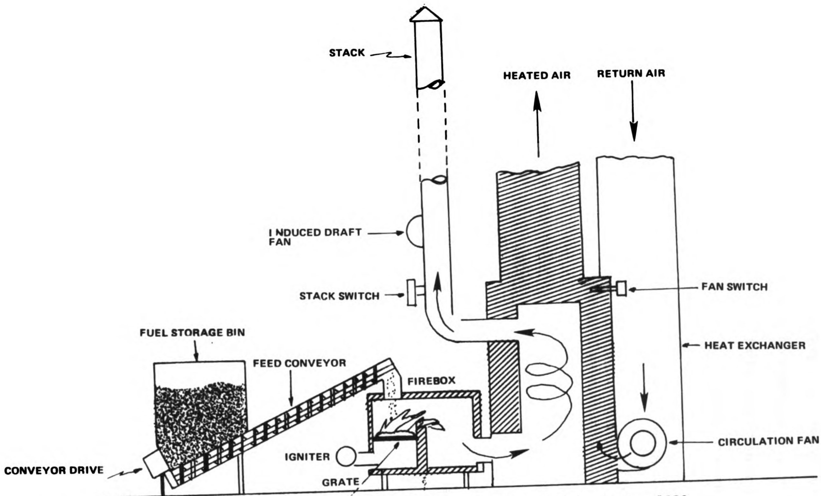


Figure 11. Layout of a residential woodchip burner. Source: Smith et al., 1980.

burner walls before going to the dryer. Indirect heating is a source of heat loss, decreasing furnace efficiency. This method may be acceptable as an alternative method for filtering the exhaust gases. However, if particulate emission is not a problem, the system could be connected directly to a bin dryer, improving the furnace efficiency.

Heat release of 69 MJ/hr (65457 BTU/hr) was obtained by multiplying the value of 6869 kg (15143 lb) of fuel (dry basis) burned by 7082 KJ (6713 BTU) obtained from each unit weight of fuel used divided by the number of furnace running hours. The method to calculate the performance efficiency of 79% for this furnace was not mentioned in the literature reviewed.

Development of Grate Type Husk-Fired Furnace

As reported by Singh (1980), a pile burning inclined grate furnace to provide heat energy for grain drying has been adopted by various rice millers and pulse millers in India. This furnace type was developed to provide heat to a cross flow grain dryer.

The fuel is fed into the box type furnace and is burned in a pile. The fuel is fed at the top of the inclined grate (overfeed method) with an angle of inclination varying between 40 and 50 . A thin layer of fuel is spread on the grate and continues to burn as it slides down by gravity. At the far end, there is a horizontal revolving grate where ash is discharged from the end of the grate into the ash pit. A curtain wall is installed throughout the width of the furnace at the end of the horizontal grate in order to avoid fly ashes going through the exhaust.

Primary air is fed in through the opening for feeding the husk and partly through the grate opening. Additional air is introduced through the secondary inlet to the blower as shown in Figure 12. The blower delivers the products of

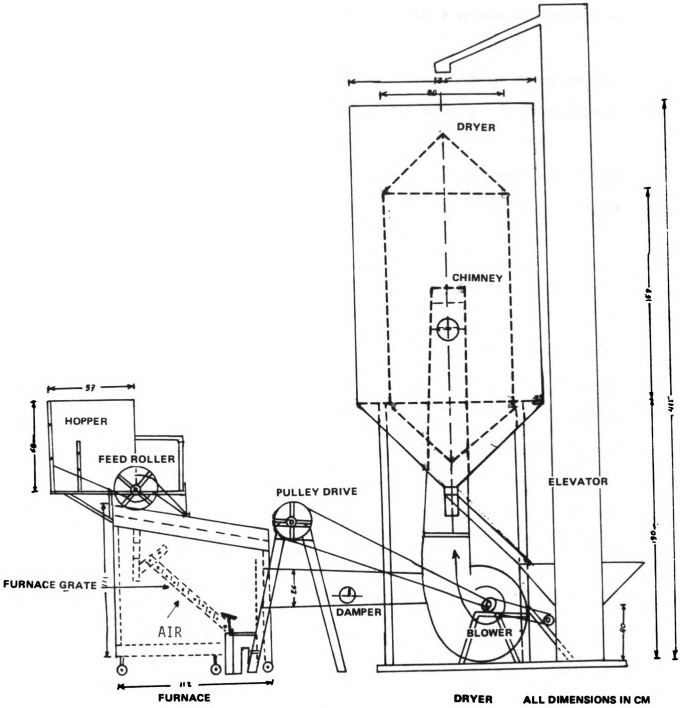


Figure 12. Grate type husk fired furnace coupled with dryer.
Source: Singh et al., 1980a.

combustion mixed with outside air to the dryer with a by-pass arrangement to the chimney.

Flue gas analysis showed that the system is compatible for drying purposes since exhaust gases showed no undesirable consequences on the product being dryed.

The highest furnace efficiency obtained was 64.5% at a feed rate of 14.25 Kg/hr (31 lb/hr) with excess air of 285.7%. Data for heat output and method to calculate efficiency were not provided.

Concentric Vortex Biomass Furnace

Investigations to improve the efficiency of the use of direct combustion systems (incinerators and burners) for converting biomass into thermal energy has been the main focus lately. Continuing studies on biomass furnaces are being conducted by several universities and private companies in an effort to provide a new approach for burning biomass. Concentric vortex systems seem to provide a great potential toward alleviating most of the problems encountered with traditional furnaces. This system provides a good combination of the combustible compounds of a fuel with oxygen through the action for the three factors mentioned earlier: temperature, turbulence, and time.

Vortex Biomass Furnace: Constructin and Operating Features

Figures 10 and 13 shows the construction features of a concentric biomass furnace. It consists of two concentric steel cylinders (D and B) with several levels of tuyeres located in the inner cylinder, fixed at an angle to the cylinder wall. The number of tuyeres are adjustable according to the furnace characteristics. Usually, they are placed at two levels (C is the upper level). The fuel is pushed from the feed hopper (G) into the sloping grate by an automatic auger feeder system (F) in a direction perpendicular to the movement of the overfire combustion air. The combustion air is pushed between the two cylinders by a fan (A) and then through the tuyeres and the gate valve (E) into the furnace. A layer of a refractory cell in the side wall is constructed from fire brick to retain the heat inside the combustion chamber. The heat is radiated from the fire back into the fire.

The gate valve is used to regulate the undergrate air flow rate (i.e., primary air). The primary combustion air is used in the gasification and pyrolysis of the fuel. The secondary combustion air enters into the combustion chamber through the tuyeres to increase the combustion rate.

In the concentric-vortex furnace, combustion air is pre-heated between the two cylinders by convective and radiant heat transfer from the flame spiral. The relatively high air velocities created as air passes through the tuyeres (due to the "venturi" effect) results in a "vortex" action and, hence, enhances mixing of the flue gases. The combustion products are diluted with ambient air to obtain the desired temperature for grain drying.

Any unburned material or "fly ash" is centrifugally separated from the flame spiral into the downward vortex airstream. This material is re-ignited at the top of the fuel pile. The negative pressure 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. Vacuum prevents backfiring through the feed system and accelerates the flue gases from the combustion chamber into the chimney (Wahby et al., 1981).

A concentric vortex biomass furnace is well suited for highly volatile materials such as biomass. Because of the vortex action to condense the slagging fly ash before reaching the grate, problems with clinkers, refractory erosion, and corrosive deposits are minimized.

Advantages of Concentric Vortex Biomass Furnace

1. provides sufficient turbulence to the combustion process to burn efficiently
2. provides sufficient residence time
3. low ashes content
4. low particle emission level at the exhaust gases

Evaluation of Existing Vortex Biomass Furnace

Claar et al. (1980) and Sukup et al. (1982) reported on Miles' furnace. Miles developed and tested a concentric-vortex, mobile field burner for burning grass straw and stubble. All combustion air was supplied as overfire air where the entrances were positioned both at the level of the fuel pile and above it, forming a vortex action inside the furnace.

Iowa State University developed a vortex furnace to burn corn cobs, corn stover, soybean straw, leaves from deciduous trees, and wood chips. The best results were encountered with corncobs. Neither smoke nor unbearable smell and a uniform feeding were responsible for the high furnace efficiency. Tests conducted with this furnace were not limited to its performance, but also considered some alterations for testing the best built material.

Four types of metals were tested to measure the effect of the exhaust gases from combustion on furnace corrosion : (a) mild steel, (b) aluminum, (c) galvanized sheet metal, and (d) brass. As reported by Wahby et al. (1981), in terms of mils per year (MPY), the highest corrosion resistance occurred when a galvanized sheet was being tested, and the lowest corrosion resistance occurred when brass was tested. Heat release for this furnace was about 2.65 x 10^6 KJ/hr (2.5 x 10_6 BTU/hr) with an efficiency of 71% using the 2 method of efficiency.

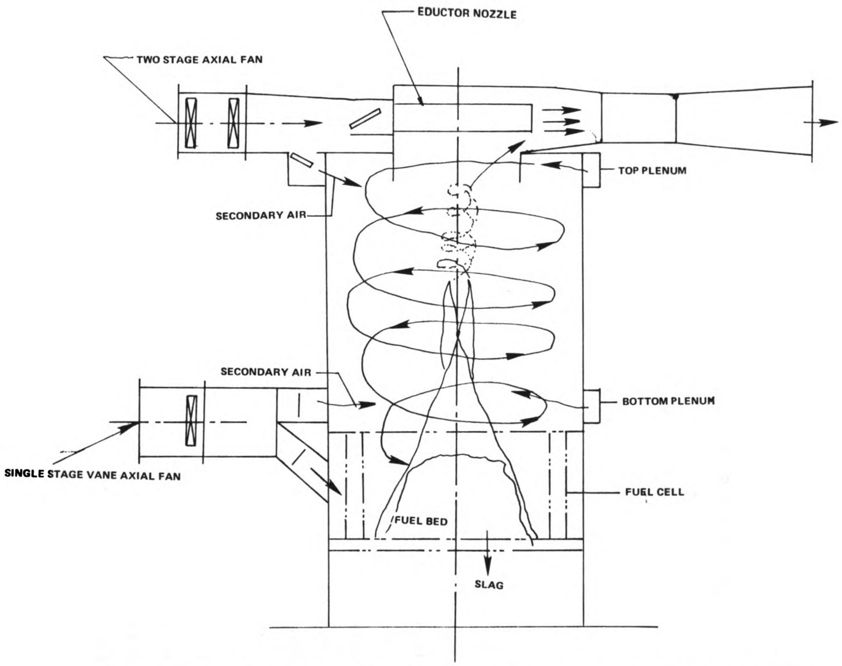


Figure 13. Schematic diagram of Iowa State vortex furnace. Source: Claar et al., 1980.

Table 5 shows the corrosion rate for each metal. A schematic diagram of the Iowa State vortex furnace is shown in Figure 13.

Table 5
Corrosion Rate for Metals

Type of Metal	Corrosion Rate (MPY)
galvanized sheet metal	4 to 164
aluminum	4 to +325 (*)
mild steel	111 to 460
brass	155 to 5600

* positive sign indicates a weight gain in the specimen

from: Wahby et al. (1981)

Sukup biomaster crop residue burner was modeled after Iowa State University furnace. The combustion chamber was lined with firebrick and a second wall was placed around the combustion chamber. Air was drawn between the two walls as a means of collecting additional heat. The temperature inside the furnace was controlled by a thermostat. When furnace temperature reaches the thermostat setting, which is controlled according to the temperature desired in the drying bin, the feed auger shuts off; and when the furnace temperature decreases, the feed auger starts again. All of the combustion air is supplied in the bottom half of the furnace where the fuel pile is located, but above the grate. A centrifugal fan provides draft for the furnace and the airflow for drying grain (see Figure 15). Combustion products are diluted with ambient air to obtain the desired temperature and then forced through the grain.

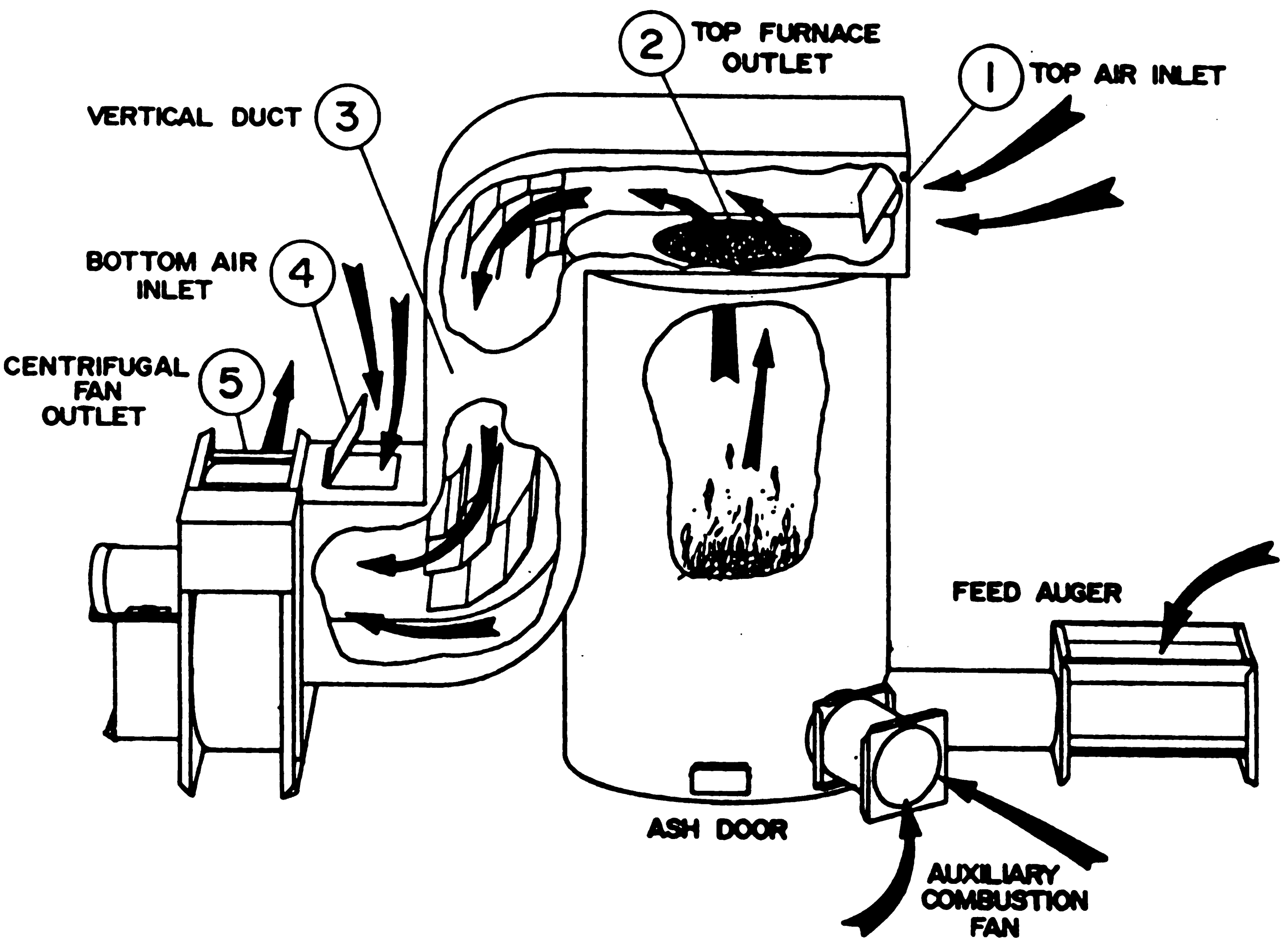


Figure 14. A cut-away drawing of the Sukup biomaster crop residue furnace. Source: Sukup, 1982.

The furnace preferably burns stalks or husklage wit a moisture content up to 35%. The heat released by this furnace was about 3.3 x 10^5 KJ/hr to 2.0 x 10^6 KJ/hr (3.1 x 10^5 to 1.9 x 10^6 BTU/hr) with an efficiency of 78% calculated using the thermodynamic method.

Kranzler et al. (1982) reported a concentric vortex system which burned coarsely chopped vines and leaves in the form of conventional square hay bales.

The vortex principle was applied in this system. In this feature combustion air comes from a single tuyere located at the upper furnace as shown in Figure 15. Air enters tangentially downwards in a vortex spiral; as it approaches the fuel bed, it is preheated by the chamber walls and the inner flame spiral. The downward vortex mixes with the rising volatile gases and entrained particles. The outer downward vortex spiral forces the inner flame into a turbulent and tight upward spiral. An increase in the particle residence time caused by the upward spiral permits a longer path in the combustion zone. An opening in the grate permits accumulated ash to drop into the ash pit.

Kranzler recommended that no air should come from the bottom of the fuel pile to avoid fly ashes in the vortex action. Since there is no underfire air, the pile has a tendency to become static with an ash layer over the fuel pile which hinders the air-to-fuel mixture, thereby decreasing the efficiency.

The feeder system is composed of a biomass storage container which is emptied from the bottom by a hydraulic cylinder injector.

During the operation, the furnace works with a slight negative static pressure. The maximum heat release was 4.0 x 10_5 KJ/hr (3.79 x 10^5 BTU/hr) and an average efficiency of 64% calculated by the third method explained in this study.

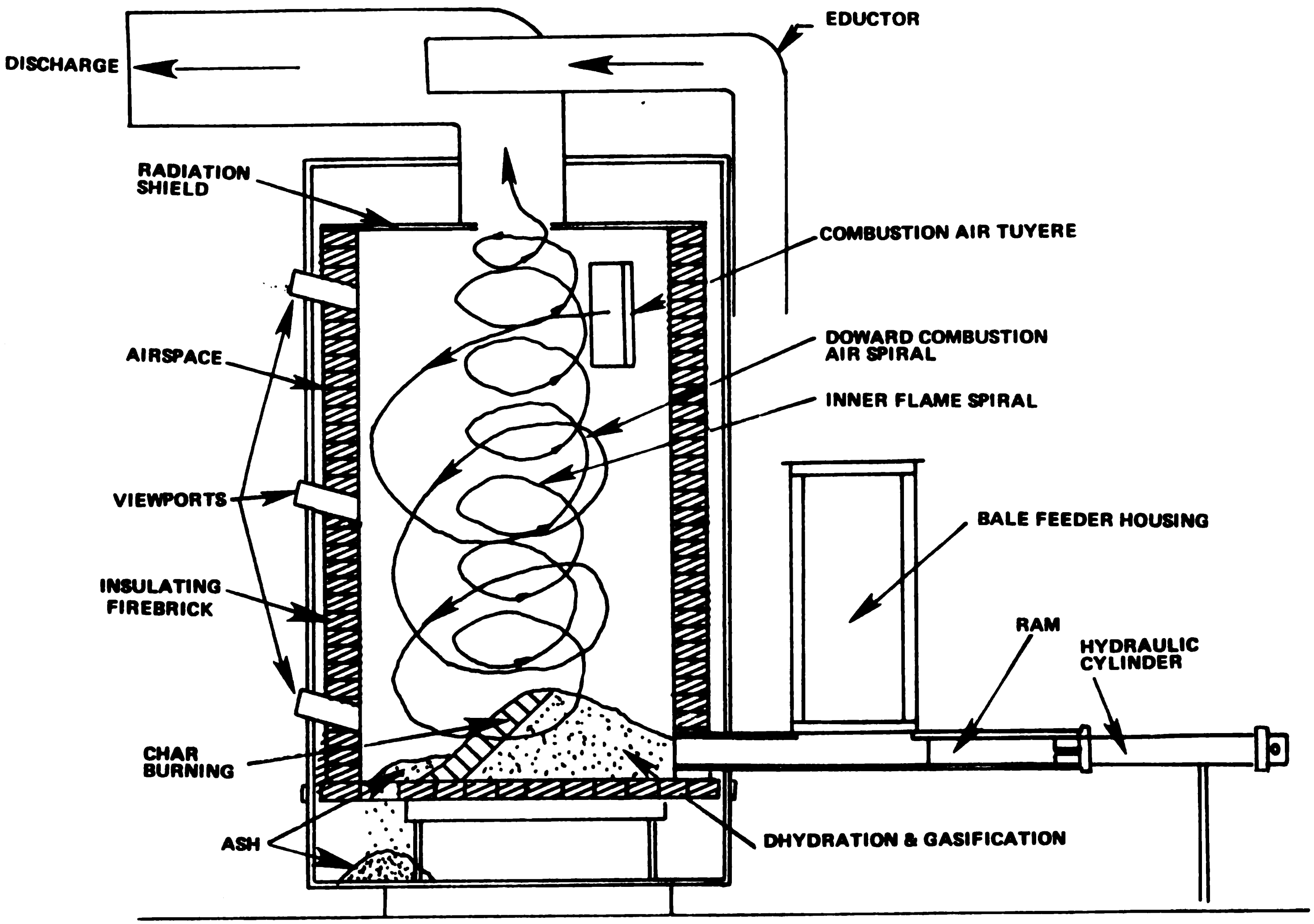


Figure 15. Elevated detail of concentric vortex biomass furnace and ram feeder. Source: Kranzler et al., 1982.

Michigan State University conducted other tests using a concentric vortex biomass furnace. The furnace was tested using wood chips, corn cobs, and shelled corn. It was integrated into an in-bin counter flow dryer to dry corn.

Tuyeres were located above the fuel pile, not directly at the top of the burning pile, to avoid the fact that high velocity air from the tuyeres would agitate the pile, causing excessive upward movement and, consequently, excessive unburned particles. Heat released by this furnace was about 1.93×10^6 KJ/hr (1.83×10^6 BTU/hr). Efficiency data were not provided.

Mwaura et al. (1982) reported the analysis comparing drying costs using propane fuel and biomass fuel. This analysis showed that the operating costs using biomass were $4.64/ton, and while using propane was $5.75/ton. Thus, the drying costs for the concentric vortex furnace was lower than the equivalent system fueled by propane. However, it should be noted that capital investment and labor costs for biomass furnaces are substantially higher than for a propane fueled system.

Figure 16 shows a schematic drawing of the concentric vortex-cell biomass furnace coupled to the bin drying system.

The major manufacturers of vortex furnaces are (a) Lamb-Cargate Industries, Ltd., New Westminster, British Columbia; (b) Konus Systems, Inc., Atlanta, Georgia; (c) Combustion Engineering Industrial Boiler Operations, Windsor, Connecticut; and (d) General Combustion Corporation, Orlando, Florida (Buchele, 1981).

Of all the furnaces studied, the concentric vortex furnace appeared to be in most suitable design for burning biomass for a farm level, considering its efficiency, simplicity, and capital investment.

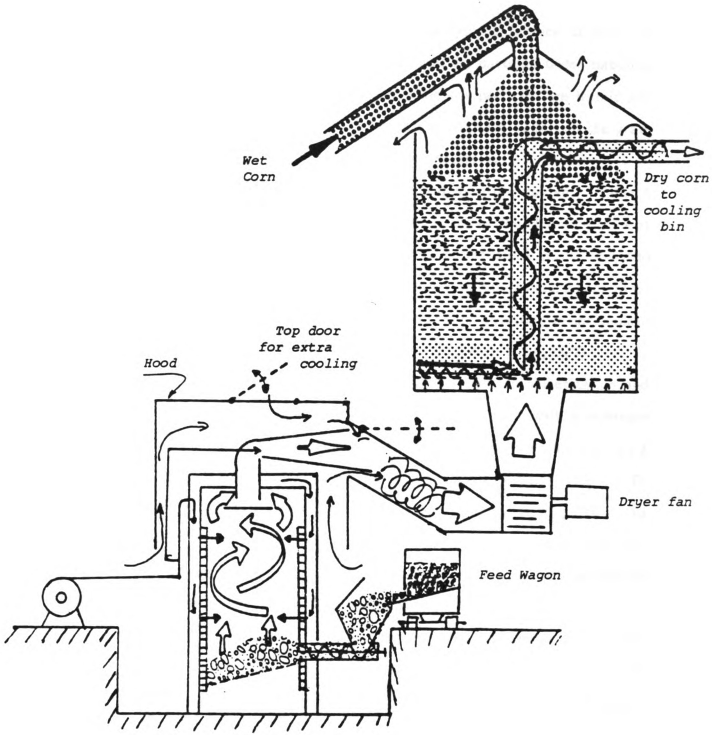


Figure 16. Schematic diagram of Michigan State biomass fired drying system. Source: Mwaura et al., 1982.

Suspension Burners

A common type of suspension burner is the cyclone furnace as shown in Figure 17. Suspension burning involves firing small dry particles under turbulent conditions. All combustion reactions occur while the particles are in mid air. Particles with an exceptionally high moisture content tend to fall on the grate prematurely. A burnout grate is therefore often necessary.

Strict limitations apply to particle size and moisture content. Table 6 shows some of the systems that are currently available and the characteristics of each. In all systems, except the Waycott system, the feedstock must be dried to 15% moisture prior to combustion. Sudden variations of the moisture content of the fuel are the most harmful operational disturbance, resulting in incomplete combustion with subsequent particulate carryover (Sarkanen et al., 1982).

If wet fuels are being used, some preparation such as pulverization and predrying will be required to assure good combustion. Fuels with a moisture content less than eight percent is undesirable because very fine, dry fuel has a high explosion potential and may cause problems while the fuel is stored. To improve the energy efficiency for the suspension burner, large particles of biomass should be ground to a very small particle. The cost of grinding the residue can be very high. Small particles burn more rapidly in a suspension burner than in other types of combustion equipment.

Levi and O'Grady (1980) stated that the essential element in a suspension burner (other than fuel quality) is the control of the amount of combustion air and its turbulence. In suspension burning, too much or too little air will affect the completeness of combustion. The use of 15 to 50% excess air is recommended, depending on the fuel quality. However, sometimes an excess air level of 100% is recommended.

Table 6
Commercially Available Suspension Burners

Characteristics	Energex	Waycott	Coen	Peabody Gordon-Pratt
particle size cm	0.3	1.3	0.1	2.0
moisture content % (wet basis)	15	40	12	12
size, 10^6 KT/hr	6 - 53	21 - 84	5 - 53	9 - 38
particulate emissions, gm/scm	0.008 - 0.05	0.02	0.01	0.01

from: Shuler (1980)

In practice the velocity of the primary ir entering the burner is about 15 m/sec (50 ft/sec). The primary air comprises 10 to 20% of the total combustion air (Perry et al., 1973).

Characteristics of Suspension Burner System

1. strict limitation in particle size
2. strict limitation in moisture content of the fuel
3. sufficient turbulence in the combustion process
4. high power requirement
5 high air/fuel ratio with consequent low exit temperature

Cyclone Furnaces

Cyclone furnaces may be classified as suspension burner furnaces. The fuel is dropped from an extremity inside the furnace. A vigorous circular movement caused by high pressure secondary air introduced tangentially into the cyclone makes the process very effective. The outlet of the cyclone is throttled in order to keep the flyash in the cyclone until it is compeltely burned.

It is essential to have an intimate mixing of the fuel particles and air to provide sufficient turbulence and oxygen to continue combustion. A good option for suspension burner is to use a pneumatically fed system. The fuel material is blown into the combustion chamber through the injection nozzle in such a way that it moves in a spiral path through the burner, ensuring better burning and combustion. A high air volume must be used, since there is no grating, and the ash residue must be conveyed through the tube section.

The time required for the fuel to be burned is greatly related to turbulence—the greater the turbulence, the more rapid the process and the less the time required.

A cyclone furnace may appear as the first stage of a two-stage combustion system or as a single stage combustor. Several configurations have been in use: verticle, horizontal, inclined, fed from underneath, or from above.

Evaluation of Existing Cyclone Furnaces

Husk fired cyclone furnace. An inclined type cyclone furnace was developed at the Indian Institute of Technology (Kharagpur, India) for burning rice husks, ground nut shells, and paddy straw. For this furnace, husks and air are introduced tangentially into the first stage of the combustor. A centrifugal force keeps the fuel particles rotating in fixed circles according to their size. Large particles of husk are thrown outwards by centrifugal force and burned near the wall while small particles remain inwards burning in suspension.

The furnace is fabricated with two stages--a conical shaped chamber and a cyclone chamber on its side at an angle of 30 as shown in Figure 17. The conical chamber provides an outlet for the exhaust gases and ashes. Fire clay and

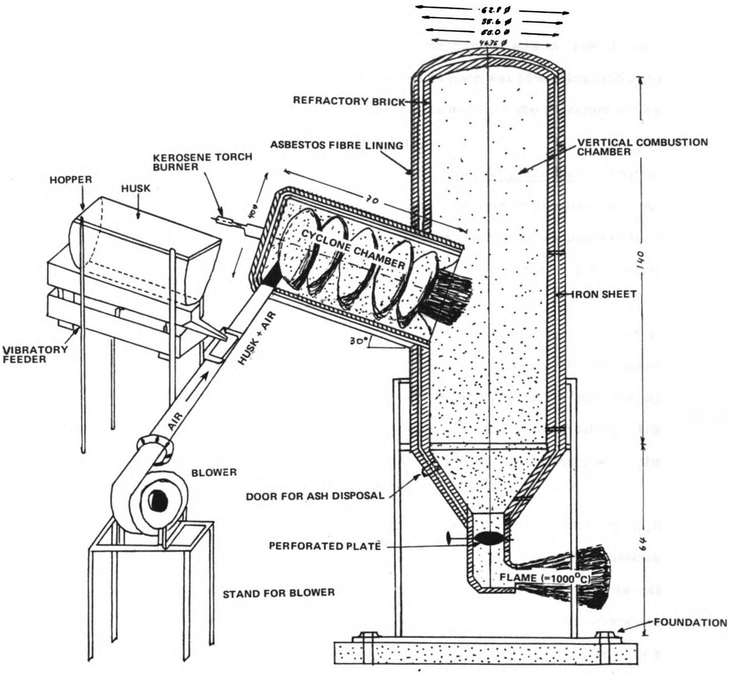


Figure 17. Schematic diagram of a husk fired cyclone furnace.
Source: Singh et al., 1980b.

refractory bricks are lined at the inside wall and a paste of powered asbestos fiber is plastered onto the outside surface of the furnace wall in order to keep the heat loss to about 2.5%. Efficiency of this furnace was 80% calculated using the third method of efficiency. Heat release provided from the literature review were 3.13 x/o^6 KJ/ (2.97 x 10^6 hr BTU/hr).

<u>Cyclone furnace coupled with steam generator and grain dryer</u>. Another example of a furnace employing the principle of cyclone combustion has been described by Singh et al. (1980). The system is designed for producing heat for a steam generator and grain dryer which appear to be very effective when dealing with products which need to be steamed and then dried.

The cyclone furnace is equipped with a circular chamber and attached at the side of the steam generator chamber. Fuel and primary air are introduced together while secondary air is introduced perpendicularly to the fuel and air movement, causing a turbulent cyclone action required for combustion. The primary air blower delivers 6 m^3/min (212 ft^3/min) into the furnace, while the secondary air delivers 10 m^3/min (353 ft^3/min).

For protecting the circular chamber against corrosion due to high temperatures and minimizing heat losses, a layer of refractory brick and fireclay is lined in the inside wall. The ashes from the process are dropped in the ash pit at the end of the steam generator. The hot gases from the cyclone furnace are used to produce steam for the boiler. The exhaust of the boiler is coupled with a grain dryer and then mixed with outside air to produce adequate drying temperature. A blower at the end of the dryer pushes the air through a chimney used by a cross-flow dryer.

The best overall efficiency obtained from the complete system--cyclone furnace, steam generator, dryer--was 76.45% obtained at a husk feed rate of 125 kg/hr (276 lb/hr) and air flow rate of 12.54 m^3/min (450 ft^3/min) method to calculate effiency was not reported. No heat release data were available from the literature reviewed. Tests using paddy straw and groundnut shell as fuel also proved very successful and efficient.

Figure 18 shows some engineering details fo this cyclone furnace, steam generator, and paddy dryer.

Cyclone Furnace Manufacturers

A cyclone burner currently on the market is manufactured by Guaranty Performance Company, Inc. ROEMMC. Using the same principles of a suspension burner, this model showed good performance. The unique characteristic of this furnace is due to secondary air being distributed through several tuyeres along the cyclone chamber. The ROEMMC ranges in size of 16 million KJ/hr to 63 million KJ/hr (15 million BTU/hr to 60 million BTU/hr). To control the combustion temperature, air flow rate control is used. Fuel is pneumatically conveyed to the combustion chamber and inserted at relatively low velocity.

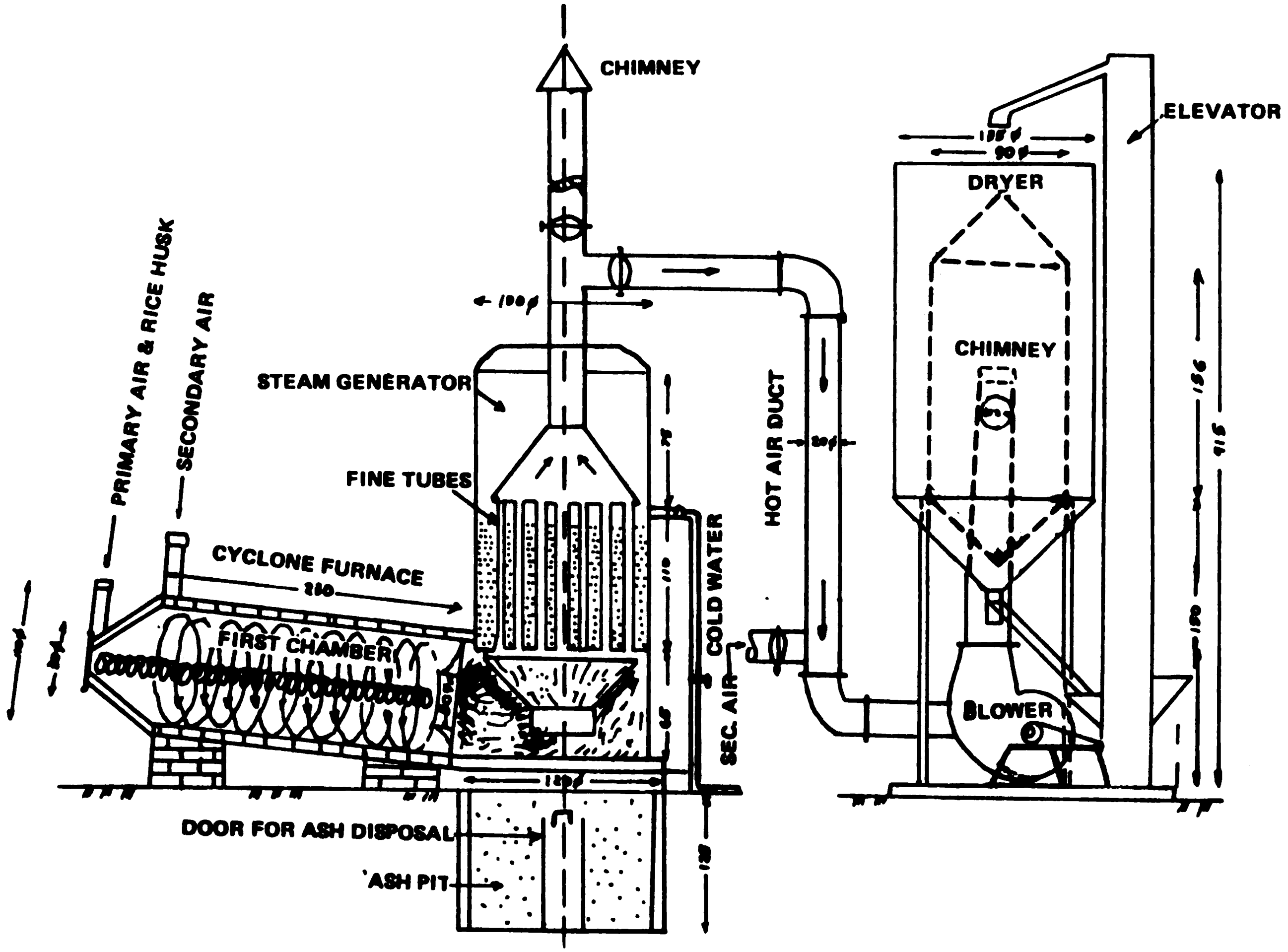


Figure 18. Schematic diagram of a cyclone furnace coupled with steam generator and grain dryer. Source: Singh et al., 1980a.

CHAPTER VII

FINAL COMMENTS

In principle, these furnaces apply old technology to new problems. However, new approaches have been developed and the improvements have resulted in designs for biomass which can be highly competitive with propane and natural gas burners.

At this stage, a biomass furnace is still, in the opinion of the author, not suitable for a medium sized farm due to its high cost of construction, maintenance, and operation.

Various types of residues have been burned and tested in these furnaces in order to produce heat. All of them appear to have potential as biomass fuel. The choice of the right fuel will depend on assessment in the context of the local conditions and constraints under which they will be used. For a corn farm, corncobs appear to be the best fuel source. Corncobs are highly volatile, resulting in a large heat output; they can be burned efficiently and controllably to supply on-farm heat energy, and their energy can be predicted from kernel moisture content. In addition, corncobs require the least energy to collect without depleting soil fertility.

Some of the process parameters considered during the experiments of some of these furnaces are presented in Table 7. To draw conclusions from the data given in this table, in the sense that one type of furnace is more efficient than another, could be erroneous, since the testing has not been conducted under the same conditions for every furnace.

Table 7
Process Parameters of Some Furnaces

Type of Furnace	Sukup	Grate Type Husk Fired	Iowa State	Michigan State	Concentric Vortex and Ram Feeder	Husk Fired Cyclone Furnace	Steam Generator and Grain Dryer
Type of Fuel	Stalks, husklage	Husk	Corn cobs	Corn cobs, shelled corn, wood chips	Hop residue	Rice husk, ground shell, paddy straw	Ground nut shell, paddy straw
Fuel rate (kg/hr)	27 - 217	14.25	53	96	41	20	125
Temperature (C)	1000		540	550 - 1000	700	1000	
Temperature mixing zone (C)	50 - 82		90	100		90	
Efficiency*	78%	64.5%	71%	80%	64%	80%	76.4%
Heat release (KJ/hr)	3.3×10^5 2.0×10^6		2.65×10^6	1.93×10^6	4.0×10^5	3.13×10^6	
Excess air	100 - 400%	285.7%	490%	170%	50 - 250%	110%	53.4%

*Testing of these furnaces was conducted under different conditions affecting the values in this table.

CHAPTER VIII

CONCLUSIONS

The feasibility of producing energy from biomass has been studied. Several different designs of furnaces have been included in this review.

The complexity and sophistication of the different furnaces vary widely from the pile burning on a flat grate to a suspension burner to a fluidized bed furnace. All of these are furnaces whose only purpose is to combine fuel and air under the most efficient and controllable conditions to provide heat for grain drying.

Within the range of furnace designs, no results are available to indicate the value of one system compared to another. However, some basic requirements should be fulfilled. These are:

1. construction of furnace with simple manufacturing technology and operation,
2. limited particulate emissions in the exhaust gases, and
3. maintenance of temperatures below the fusion temperature (816°C - 1500°F) to prevent slag formation on the grate.

Concerning the design characteristics, no highly developed scientific approach exists to build a biomass furnace. Most of the work was done based on practical knowledge and by trial and error.

The choice of one system will mainly depend on (a) type of fuel being used, (b) fuel moisture content, (c) amount of heat output desired, and (d) capital investment.

In conclusion, there is no optimum solution for the use of biomass to produce energy, since the problems vary with different circumstances. The concentric vortex system appears to the author to be the most attractive short term alternative for conversion of biomass into heat because of its relative simplicity, low cost, and automation.

CHAPTER IX

RECOMMENDATIONS FOR FURTHER STUDIES

1. An investigation of a filter unit for reducing particles and spark emission would be useful.

2. A thorough analysis of the exhaust gases has to be made to ensure that no hazardous effect occurs to the grain being dried.

3. An evaluation of the units tested with a variety of biomass fuels should be made.

Conversion Factors

m =	3,2808 ft
m/ sec =	3,2808 ft/sec
Kg =	2,2046 lb
KJ =	0.94783 BTU
KJ/m^3 =	2.6840×10^{-2} BTU/ft^3
KJ/Kg =	4.2993×10^{-1} BTU/lb
KJ/hr m^2 =	8.8047×10^{-2} BTU/hr ft^2
KJ/hr m^2 =	2.0482×10^{-1} lb/hr ft^2

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