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CORN DRYING WITH SOLAR HEATED AIR

By

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A DISSERTATION

Submitted to
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ABSTRACT

CORN DRYING WITH SOLAR HEATED AIR

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Edison Wamara Rugumayo

The supply of the two principal grain drying fuels (LP gas and natural gas) is diminishing throughout the world. As a result there is increased competition for them from non agricultural users. Demand for these fuels is outstripping supply, creating a need for development of alternative energy sources for grain drying. Solar energy is one alternative fuel for grain drying.

Previous research has shown that the diffuse nature of solar energy precludes its use in high temperature dryers. A low temperature fixed bed drying system is therefore the most technically and economically feasible approach.

The objectives of this thesis were to develop and test equations for thin-layer corn drying and moisture adsorption at low temperatures encountered in solar drying and to evaluate the performance of a solar air-heater in conjunction with a fixed bed corn drying system. Experimental tests included

a) Thin-layer corn drying and moisture adsorption using drying air between 4.4°C and 21.1°C and 30% and 60% (for drying) and 85% to 90% (for rewetting) relative humidity.

b) Drying of a bin of corn with a flat-plate solar air heater (0.46 m. wide by 4.88 m. long) to test the thin-layer corn drying and rewetting models, and for evaluating the efficiency of the solar collector.

A new heat transfer coefficient equation for an asymmetrically heated air duct was developed and was used to develop models for calculating the collector efficiency, heated air temperature rise and the operating cost of a solar air heating collector. Between 10:00 A.M. and 2:00 P.M. the efficiency of the experimental collector was calculated as 57%. The average experimental and simulated temperature rises were found to be $7^{o}C$ and $5^{o}C$ respectively.

A thin-layer drying equation and a thin layer moisture adsorption equation were developed by non-linear parameter estimation which simulate the corn drying and moisture adsorption processes more accurately than the thin-layer equations for low temperature drying and adsorption presently available in the literature. The equations were tested in conjunction with the Michigan State University fixed bed drying model and agreed well with the experimentally determined corn moisture contents in the corn bin. The simulated average final corn moisture content was 2% higher than the measured average final corn moisture content. Also, the corn dry matter loss was calculated to be less than 0.5% so that grain market quality was not adversely affected by solar drying process.

Approved ______________________
Major Professor

Approved ______________________
Department Chairman

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LIST OF SYMBOLS

a	constant
a	duct depth, m
A	area, m^2
A_a	area of collector size a, m^2
A_b	area of collector size b, m^2
ABK	rewetting parameter, 1/hr
A_c	area of solar collector, m^2
A_p	perimeter area of solar collector, m^2
AST	apparent standard time, h
b	duct width, m
B	collector width, m
C	coefficient of free convection heat transfer in a tilted collector, $w/(m^2 - {}^{o}C^{1.25})$
C	constant
C	mass concentration coefficient, kg/m^3
C	specific heat, $kJ/kg\text{-}{}^{o}C$
C	speed of light in any medium, cm/sec
cc	cloud cover, dimensionless
CCV	cloud cover, dimensionless
C_h	annual additional cost, \$/year
$C_{h,tot}$	total additional investment, \$
CMM	air flow rate, m^3/min

C_o	speed of light in a vacuum, cm/sec
CRF	capital recovery factor, \$/\$/year
C_{se}	solar energy cost, \$/mW
D	diameter of tube, m
D	diffusion coefficient, cm^2/sec
D	dirt loss factor, dimensionless
DEL	moisture content by delGuidice thin-layer equation, decimal d.b.
DELT	time increment
DEPTH	total bed depth, m
DFK	drying parameter, 1/hr
D_h	duct hydraulic diameter, m
DMISRA	dry matter loss by Misra thin-layer equations, percent
DMS	dry matter loss by Sabbah and delGuidice thin-layer equations, percent
DRUG	dry matter loss by Rugumayo thin-layer equations, percent
DY	day of the month
$E_{b,\lambda}$	spectral emissive power, ly/min-μ
ET	equation of time, min
EXMC	experimental corn moisture content, decimal d.b.
E_{xy}	emissivity factor, dimensionless
f	outer collector cover to non-outer cover heat transfer resistance ratio
F	mass transfer rate, kg/cm^2 sec
f_m	mean friction coefficient, N/cm^2
g	acceleration due to gravity, m/sec^2
G	dry weight, kg/m
G	mass flow rate per unit area, kg/h-m^2

g_c	gravitational acceleration 9.8 m/sec^2
h_c	convective heat transfer coefficient, $w/(m^2-{}^oC)$
h_{fg}	latent heat of vaporazation of water in a product, kJ/kg
h_{rc}	equivalent radiative coefficient, $w/(m^2-{}^oC)$
h_{xy}	convective coefficient, $w/(m^2-{}^oC)$
h_w	wind coefficient of heat transfer, $w/(m^2-{}^oC)$
H	absolute humidity of air, kg/kg
HIN	inlet air absolute humidity, kg/kg
HR	time, hrs
H_s	solar hour angle, degree
i	angle of incidence, degree
i	internal energy, kJ/kg
i_d	annual discount or interest rate, $/$/year
I_{coll}	net energy absorbed, w/m^2
I_h	insolation, w/m^2
$I_{h,b}$	bean radiation, w/m^2
$I_{h,d}$	diffuse solar energy, w/m^2
I_{TOT}	total incident solar energy, w/m^2
INDPR	number of nodes between prints
k	parameter, 1/h
k	thermal conductivity, $w/m-{}^oC$
K	coupling coefficient
K	phenomenological coefficient
K	thickness, m
K	subscript or superscript
K	extinction coefficient, 1/cm
L	latitude angle, degree

L length, m

LST local standard time

m constant

M moisture content, decimal, d.b.

MISRA moisture content by Misra thin-layer equations, decimal d.b.

MR moisture ratio, decimal

n number of days since the beginning of year

n number of glass covers

n refractive index

NEQ equation type

NLPF number of layers per meter

Nu Nusselt heat transfer number, dimensionless

p pressure, N/cm^2

PP pumping power, w or $kg\text{-}m^2/sec^3$

Pr Prandtl fluid number, dimensionless

PS saturated vapor pressure, Pa

PSDB vapor press, Pa

q heat energy, w/m^2

q heat flow rate $kJ/h\text{-}m^2$

Q heat flow rate kJ/h

r angle of refraction, degree

r radius, cm

rh air relative humidity, decimal

R radius, cm

R resistance to heat flow, $(m^2\text{-}{}^{o}C)/w$

Re Reynold's fluid flow number, dimensionless

RH air relative humidity, decimal

RUG moisture content by Rugumayo thin-layer equations, decimal d.b.

S sum of squares function, scalar

S shading factor, dimensionless

SAB moisture content by Sabbah equation, decimal, d.b.

SMC moisture content by Sabbah and delGuidice equations, decimal d.b.

SR recorded insolation, w/m^2

St Stanton heat transfer number, dimensionless

t time, h

t thickness, cm

t expected solar collector life time, years

t temperature, ^oC

t_a ambient air temperature, ^oC

t_b bulk temperature, ^oC

t_c collector temperature, ^oC

t_m mixed mean fluid temperature, ^oC

t_p plate temperature, ^oC

T air temperature, ^oC

T transpose

TA ambient air temperature, ^oK

TAIR drying or rewetting air temperature, ^oK

TBTPR time between output, h

TFE recorded heated air temperature, ^oK

TG glass temperature, ^oK

TGRN grain temperature, ^oK

THIN inlet or initial grain temperature, ^oC

TIN inlet or initial air temperature, ^oC

TM time of day, h

TP absorber plate temperature, ^{o}K

TT Tedlar cover temperature, ^{o}K

TT total time, h

U heat loss coefficient, $w/(m^2-^{o}C)$

U fully developed fluid flow rate, m/h

U^+ constant, dimensionless

U_o overall heat transfer coefficient, $w/(m^2-^{o}C)$

v wind velocity, m/sec

V wind velocity, m/sec

V fluid velocity in duct, m/sec

VA wind speed, m/sec

W weight, gms

W width, m

x distance, m

x x-coordinate

XME equilibrium moisture content, decimal, d.b.

XMO inlet or initial moisture content, decimal d.b.

y y-coordinate

y distance, m

y^+ constant, dimensionless

symbols used as subscripts

a air

b back

b black body

b,coll beam on inclined collector surface

c collector

crit critical

d	downward
D	diameter
e	equilibrium
f	fluid
g	glass
h	hydraulic
H	hydraulic
H	heat
i	inlet
ℓ	laminar
L	long
L	loss
o	initial
o	outlet
o	smooth
p	perimeter
p	plate
p	product
r	radiative
s	solar
s	sky
s	surface
t	time
T	total
u	useful
up	upward
v	vapor

w water

Greek symbols

α altitude angle, degree

α absorptance, dimensionless

α constant

β collector tilt, degree

∂ finite difference

δ solar declination, degree

δ constant

Δ difference

ε emittance, dimensionless

ε error vector

η efficiency, decimal

Θ grain temperature, ^{O}C or ^{O}K

λ wavelength, μm

μ dynamic viscosity, kg/(m-hr)

ρ density, kg/m^3

ρ_{b1} reflectance of beam radiation from one surface, decimal

σ constant variance of observation errors

σ Stefan-Boltzman constant, $5.67x10^{-8}$ $w/(m^2-{}^{O}K^4)$

τ shear stress, N/m^2

τ transmittance, dimensionless

ν frequency, cycles/min

ν kinematic viscosity, m^2/hr

ϕ solar azimuth, degree

$\underline{\phi}$ diagonal matrix

χ fraction of long-wave radiation absorbed

$\underline{\psi}$ covariance matrix of observation errors

CHAPTER ONE

INTRODUCTION

A diminishing supply of petroleum and natural gas coupled with increased competition for these products has made the conservation of energy important in regard to cost and management factors in grain drying. Several universities and other research institutions have been searching for a viable system of drying crops using air heated with solar energy as an alternative to liquid propane (LP) and natural gas.

Solar energy as an energy source has the following desirable characteristics:

a) it is clean and silent;

b) it is abundant and widely available all over the world;

c) it is dependable statistically;

d) it is inexhaustible;

e) its transportation cost to the point of use is free;

f) it is estimated that the sales of solar industry today, in the United States alone, are worth about two hundred twenty-five million dollars per year.

The solar crop drying units reported in use fall into two major categories; they are the covered and the bare plate collectors (Shove, 1977). Within these two categories a variety of designs have been made.

Some of these are:

1) large steel bins with the outside wall surfaces painted black (Haley,1974);
2) steel bins with the outside wall surface painted black, to act as the absorbing surface, and a wall of clear fiber glass around the portion of the bin which the sun rays strike;
3) the 44 cm space between a building's steel roof and its ceiling has fans installed to draw air through the space and up to an elevated center duct in the roof;
4) a suspended plate collector where air is moved along both sides of the suspended absorber plate.

Most of these units have back-up energy systems such as electric or gas air heaters. Either alone or in combination with other energy systems solar crop drying units have worked with some success even though they appear to be proof-of-concept designs and can therefore be improved upon.

1.1 Solar energy collectors

Heating air with solar energy is accomplished by first absorbing the solar energy and then transferring the energy to the air. The absorber may be heated either by focusing the sun's rays on it with a parabolic mirror or by allowing the rays to fall on it directly. The former systems are used to increase the flux density of incoming solar energy and are employed where high temperatures are desired, as in metallurgical and aerospace industries.

Without optical concentration, the flux of incident radiation is, at best, about 1100 w/m^2 (349 $BTU/hr\text{-}ft^2$) and is variable.

The wavelength ranges from 0.3 to 3.0 μm which is considerably shorter than that of the emitted radiation from most energy absorbing surfaces. Thus flat-plate solar collectors are for applications requiring energy at moderate temperatures, up to perhaps 100^{o}C (212^{o}F) above ambient temperatures. They have the advantages of using both beam and diffuse solar radiation, not requiring orientation toward the sun, requiring little maintenance and are simple in mechanical design.

The important parts of a typical flat-plate solar collector are:

1) the "black" solar energy-absorbing surface, with a means for transferring the absorbed energy to a fluid;
2) the envelop(s) which is transparent to solar radiation and is placed above the solar absorber surface to reduce convection and radiation heat losses to the atmosphere;
3) the back and side insulation to reduce heat conduction losses.

Basically, then solar drying units with flat-plate solar collectors are low temperature systems. Well designed units are those that have been engineered based upon consideration of the heat and mass transfer between the crop and the low-temperature drying air and of the "optimum" solar collector design. The word "optimum" does not imply use of optimization techniques in designing the collector. It, rather, refers to designing the solar collector for drying grain to moisture contents which are safe for grain storage. Particular consideration should be given to the flat-plate efficiency and temperature rise. Both are affected by:

a) solar declination;
b) local solar time;
c) time of day and year;
d) latitude;

e) collector inclination;

f) upward heat loss coefficient;

g) wind speed;

h) intensity of solar radiation.

The angles in parts (a), (d) and (e) are illustrated in Figures 1-1 and 1-2.

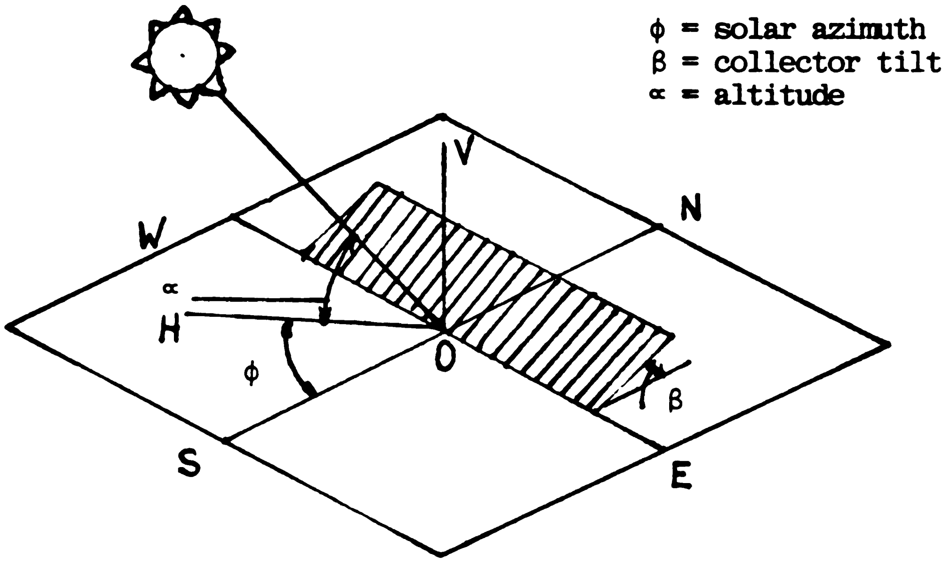


Figure 1-1 Description of Sun-Earth Orientation Angles.

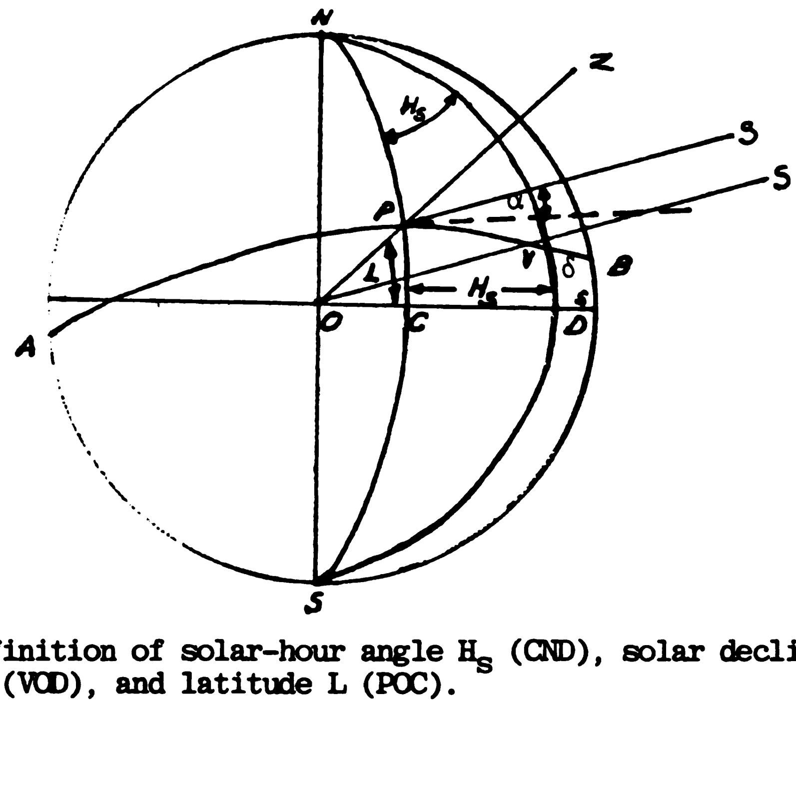


Figure 1-2 Definition of solar-hour angle H_s (CND), solar declination δ_s (VOD), and latitude L (POC).

Once the relationships of these parameters have been established and programmed for evaluation with a high speed computer the design of solar energy air heaters for grain drying will be greatly simplified.

1.2 Fixed bed dryer

The investigation of corn drying with solar heated air would not be complete without considering the heat and mass transfer relationships in the fixed bed dryer where the grain is dried. In a fixed bed dryer model, energy and mass balances can be written on a differential volume at an arbitrary location within the grain bed. In these equations, there are four unknowns, (a) corn moisture content, (b) drying air humidity ratio, (c) drying air temperature, and grain temperature. Therefore, four equations must be set up. However, without loss of generality the air temperature, T, can be taken equal to the grain temperature, Θ. This assumption leads to an establishment of (a) two equations obtained from the conservation of moisture, with no free water accounted for, (b) one energy equation obtained from a combination of the drying air and the drying grain equations. The grain equation can only be obtained from an empirical thin-layer equation. In the Michigan State University drying model, one thin-layer low temperature model is used. No suitable adsorption equation is available yet. The moisture adsorption equation which is currently being used in the Michigan State University model to predict moisture adsorption in corn is inaccurate. The development of an appropriate low-temperature rewetting equation for corn is imperative. Hence, a better knowledge of both the drying and rewetting parameters in a shallow bed of corn should permit improved understanding of the deep-bed solar grain drying. The moisture adsorption equation is developed from the mathematical theory of diffusion.

1.3 Nature of the problem

The problem studied in this thesis can be divided into three major parts:

1. development of model(s) for thin-layer corn drying and moisture adsorption at low temperatures;
2. design of an optimum efficiency flat-plate solar air heater for low temperature in-bin solar corn drying;
3. evaluation of the performance of the solar air-heater in conjunction with a fixed bed corn drying system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Corn thin-layer drying

A survey of the literature on physical mechanisms of the drying of thin layers of grain has been made. Several empirical drying equations have been developed for shelled corn for both high and low temperature operations. The most commonly used empirical thin-layer corn drying equations (Brooker *et al.*, 1974; and Pfost *et al.*, 1976) are modified versions of Thompson *et al.* (1968) equation. These are valid for air temperatures ranging from 26.7°C to 148.9°C. Due to the wide working temperature range these equations have worked rather unsatisfactorily in predicting drying grain moisture contents. Narrow temperature range models appear to be more desirable.

Flood *et al.* (1969), Troeger and Hukill (1970) and Muh (1974) developed empirical drying equations for corn in temperature ranges of (a) 2.2°C to 21.1°C, (b) 32.2°C to 71.1°C, and (c) 26.7°C to 104.4°C, respectively.

Flood *et al.* (1969):

$$MR = \exp(-k\ t^{0.664}) \tag{2-1}$$

where

$$MR = \frac{M - M_e}{M_o - M_e}$$

$$k = \exp(-x\, t^y)$$

$$x = (6.0142 + 1.453 \times 10^{-4} (rh)^2)^{0.5}$$

$$- (1.8\theta + 32)(0.3352 \times 10^{-3} + 3.00 \times 10^{-8} (rh)^2)^{0.5}$$

$$y = 0.1245 - 2.197 \times 10^{-3} (rh) - (1.8\theta + 32)$$

$$(2.30 \times 10^{-5} (rh) + 0.58 \times 10^{-4})$$

Troeger and Hukill (1970):

$$\frac{t}{60} = p_1(M - M_e)^{q_1} - p_1(M_o - M_e)^{q_1}, \text{ for } M_o \geq M \geq M_{x_1} \qquad (2\text{-}2)$$

$$\frac{t}{60} = p_2(M - M_e)^{q_2} - p_2(M_{x_1} - M_e)^{q_2} + t_{x_1}, \text{ for } M_{x_1} > M \geq M_{x_2}$$

$$\frac{t}{60} = p_3(M - M_e)^{q_3} - p_3(M_{x_2} - M_e)^{q_3} + t_{x_2}, \text{ for } M_{x_2} > M \geq M_e$$

where

$$M_{x_1} = 0.40 (M_o - M_e) + M_e$$

$$M_{x_2} = 0.12 (M_o - M_e) + M_e$$

$$t_{x_1} = [p_1(M_{x_1} - M_e)^{q_1} - p_1(M_o - M_e)^{q_1}]/60$$

$$t_{x_2} = [p_2(M_{x_2} - M_e)^{q_2} - p_2(M_{x_1} - M_e)^{q_2}]/60 + t_{x_1}$$

$$p_1 = \exp(-2.45 - 6.42\, M_o^{1.25} - 3.15(rh) +$$

$$9.62\, M_o(rh)^{0.5} + 0.054\theta - 0.036\, V_a + .96$$

$$p_2 = \exp[2.82 + 7.49(rh + 0.01)^{0.67} - 0.0322\theta - .5728$$

$$p_3 = [0.12(M_o - M_e)]^{(q_1 - q_3)}(p_2 q_2 / q_3)$$

$$q_1 = -3.468 + 2.87\,M_o - [0.019/(rh + 0.015)] + 0.02880$$

$$q_2 = -\exp(0.810 - 3.11\,rh)$$

$$q_3 = -1.0$$

Muh (1974):

$$t = A \ln MR + B\,[\ln MR]^2$$

where

$$MR = \frac{M - M_e}{M_o - M_e}$$

$$A = -3.28700 - 0.1044\Theta$$

$$B = -3.34114 + 0.1286\Theta$$

$$(26.7^\circ C \le \Theta \le 37.7^\circ C)$$

$$A = -13.71244 + 0.171559\Theta$$

$$B = 3.69212 - 0.057558\Theta$$

$$(37.7^\circ C < \Theta \le 60^\circ C)$$

$$A = -8.20750 + 0.07983\Theta$$

$$B = 0.44881 - 0.004170\Theta$$

$$(60.0^\circ C < \Theta \le 82.2\ C)$$

$$A = -4.69252 + 0.037060\Theta$$

$$B = -7.75868 + 0.023150\Theta$$

$$(82.2^\circ C < \Theta \leq 104.0^\circ C)$$

Obviously, only the Flood et al. (1969) (called the Sabbah equation in this thesis) and possibly the Muh (1974) equations would apppear of interest for use at the solar heated air temperatures. However, these equations are empirical and complicated to use. An equally accurate, if not better but simple and less empirical equation would be more desirable. Hence, an attempt will be made to develop such an equation from mathematical diffusion theory (and non-linear parameter estimation techniques) similar to the model presented by Chu and Hustrulid (1968).

2.2 Corn moisture adsorption

For proper evaluation of in-bin solar grain drying it is necessary to account for grain moisture adsorption, especially at night and on rainy days. Moreover, proper understanding of the adsorption kinetics will provide useful information on grain quality and a guide for grain conditioning, storing, processing and fumigating. In grain rewetting studies, del Guidice (1959) developed an equation of the form:

$$MR = \exp[-4.309(PS)^{0.466rh}(rh)^3\Delta t] \qquad (2\text{-}4)$$

where

$$MR = \frac{M_t - M_e}{M_{t-1} - M_e}$$

The data used in developing the above relationship included dry bulb temperature in the range of 15.6°C to 40.6°C, relative humidity in the range of 60% to 100% and air velocities of 3 mpm and 12.2 mpm. The del Guidice equation does not perform satisfactorily at air velocities and temperatures outside these ranges. Suc-Won-Park et al. (1974) developed a semi-empirical moisture adsorption equation for yellow (Pioneer 3306) in which the constants are dependent on the initial corn moisture content. The development of an appropriate low-temperature rewetting equation based on mathematical diffusion theory, as in the case of the drying equation was considered imperative. A better knowledge of both the drying and rewetting parameters in a shallow bed of grain should permit improved understanding of the deep-bed solar grain drying operation.

2.3 Research in solar energy

2.3.1 Nature and availability of solar energy

The nature and availability of solar energy are important factors for consideration in the design of flat-plate solar heat collectors. Since collectors of this type can utilize both the direct and diffuse components of solar radiation, and in many localities substantial quantities of solar energy can be collected on partly cloudy days, flat-plate collectors should not be operated on perfectly clear days only.

Solar energy is a form of electromagnetic radiation emitted by the sun because of its temperature. It is propagated at the speed of light C, which can be expressed in terms of wavelength λ, and frequency ν, such that $C = \frac{C_o}{n} = \lambda\nu$ (2-5)

where,

C_o = speed of light in a vacuum, ft/sec or cm/sec

n = refractive index

C = speed of light, 9.8×10^8 ft/sec (3×10^{10} cm/sec)

λ = wavelength (in cm or micrometers, $\mu m = 10^{-6}$ m)

ν = frequency, cycles per unit time

Figure 2-1 shows a portion of the spectrum of electromagnetic radiation. In the thermal radiation range of 0.1 to 100 μm the wavelengths of importance in solar energy and its applications are in the ultraviolet to near-infrared range, that is from 0.20 to about 25 μm. This includes a) the visible spectrum range of 0.35 to 0.75 μm; b) solar radiation outside of the earth's atmosphere which has most of its energy in the range of 0.20 to 4.0 μm; c) solar energy which is received at the ground and is substantially in the range of 0.29 to 3.0 μm.

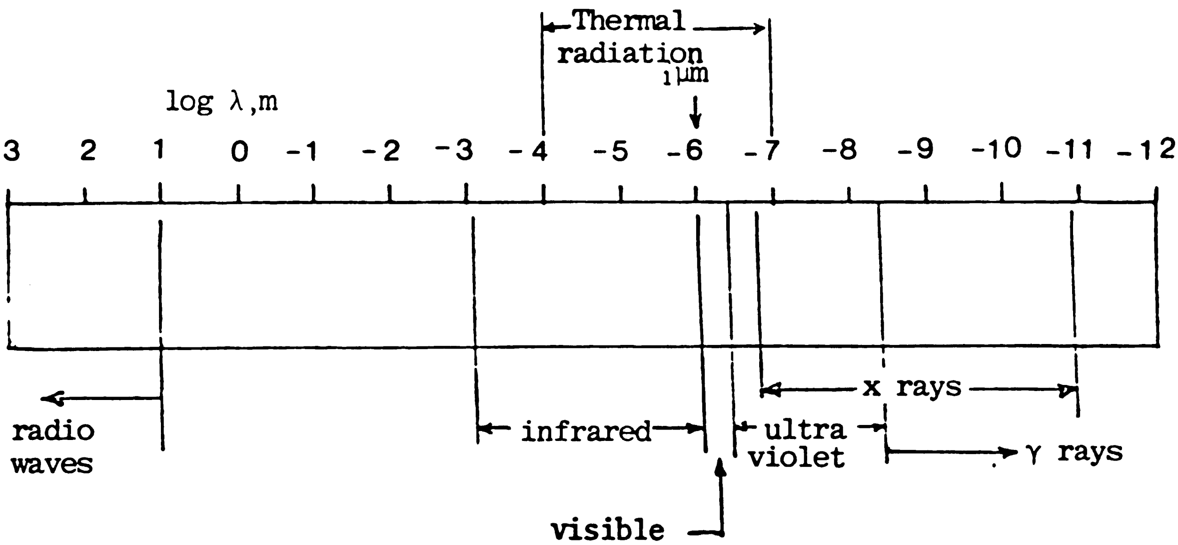


Figure 2-1. Electromagnetic spectrum

The energy distribution in the electromagnetic spectrum is called the spectral emissive power, $E_{b,\lambda}$. The adjective "spectral" denotes that the radiation depends on the wavelength spectrum. If the total radiation spectrum is divided into small wavelength bands of width $\Delta\lambda$, the quantity $E_{b,\lambda}\ \Delta\lambda$ dentoes the amount of radiation emitted in the waveband $\Delta\lambda$. Figure 2-2 shows the variation of the spectral emissive power at a given temperature as a function of λ for black bodies at solar and building temperatures (Kreider and Kreith, 1975). Figure 2-2 clearly illustrates the factor that as solar radiation penetrates the atmosphere of the earth it is partly absorbed and partly scattered by the various constituents of the atmosphere such as clouds, molecules of air, water vapor, ozone, carbon dioxide and suspended particulate matters. Both direct or beam and diffuse solar radiation available at the surface of the earth are functions of these variables. Beam radiation is that solar radiation received from the sun without change of direction. Diffuse radiation, on the other hand, is that solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere.

In addition to spectral variation, therefore, the amount of solar radiation incident on a surface depends on its location, orientation, the time of the year, and time of the day. Johnson (1954) has determined that the rate at which solar energy falls on a surface normal to the rays of the sun at the earth's surface without losing any energy to the atmosphere is 1393 w m^{-2} or 2.0 ly min^{-1} or 2.0 cal min^{-1} cm^{-2} at the mean distance of the earth from the sun. This value is generally referred to as the "solar constant", and its spectral variation is shown in Figure 2-2 as extraterrestrial solar radiation.

The solar radiation actually incident on a horizontal surface is called "insolation (I)". Seasonal variation of insolation has been considered by previous investigators (Buelow, 1967 and Rugumayo, 1974). The former used spherical geometry to develop an expression with many unknowns and its evaluation requires use of both tables and graphs. The latter investigator, on the other hand, used a statistical technique to develop an expression for insolation in a tropical region.

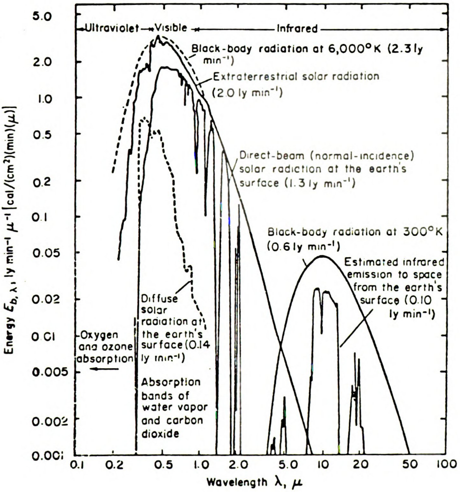


Figure 2-2. Electromagnetic spectra of solar and terrestrial radiation. The black-body radiation at 6000°K is reduced by the square of the ratio of the sun's radius to the average distance between the sun and the earth to give the flux that would be incident on the top of the atmosphere.

Buelow's and Rugumayo's relationships do not distinguish between direct and diffuse solar radiation.

The mathematical relationships for diffuse and direct solar radiation as affected by seasonal variation have been presented Duffie et al. (1974), and Kreider and Kreith (1975). These are considered suitable for use in this thesis because, in addition to distinguishing direct from diffuse solar radiation, they can easily be programmed for use on high speed computers to give hourly values of temperature rise, useful energy and efficiency.

2.3.2 Flat-plate solar energy collector

Flat-plate solar heat collectors have potential for application in air and water heating systems due to their simple construction. Literature reviews (Whillier, 1963) show that it is possible to produce temperatures up to the boiling point of water. Care in the selection of materials of construction and methods of fabrication is essential if costs are to be kept at a level low enough to make solar heating attractive.

A typical flat-plate solar heating collector consists of a radiation-absorbing flat plate beneath one or more transparent covers. The radiation-absorbing plate is a flat metal plate blackened on the side exposed to the sun. The air to be heated passes across the front and/or back surface of the blackened plate. The back side of the absorber place is usually insulated to reduce heat losses. If air passes behind the plate, as it is the case in the present study, the insulation forms one side of the air passage. The transparent cover(s) may be glass plate(s); the glass plate(s) may also be replaced by thin plastic cover(s). To make glass and/or plastic coverings effective, air spaces between the coverings and between the bottom covering and the blackened metal surface is necessary. The number of covers is determined by the temperature difference required and by the economy of using additional layers of cover materials.

2.3.3 Transparent covers

The optical properties of transparent cover materials (usually glass, or thin plastic films) that are of most importance in solar collectors have been extensively studied and reviewed. Whillier (1963) studied the transmittance of solar radiation by a 0.01016 cm thick polyvinylfluoride film commonly known as Tedlar (a Dupont product) and compared it to that of a low-iron sheet of glass (0.3176 cm thick) in the temperature range of $0^{o}C$ to $200^{o}C$. His conclusions were:

1) the transmittance of Tedlar to solar (short wave) radiation at normal incidence is 92 percent. (This is better than any glass, unless the glass is surface treated to reduce reflection losses);
2) the transmittance of glass for long wave radiation in solar absorbers is, for all practical purposes, zero;
3) the transmittance of Tedlar for long wave radiation is constant at about 30 percent, for radiation emitted by surfaces at temperatures anywhere between 0 and $200^{o}C$. This is not necessarily true for all plastics. It is valid for Tedlar because this material is completely opaque to radiation between

wavelengths of 6.9 to 13 microns, and about 45 percent of the radiation emitted by surfaces in the temperature range 0 to 200°C lies in this wavelength region;

4) the solar transmittance of multiple cover collectors is considerably improved by the replacement of the inner glass covers with Tedlar. The protection afforted to the inner Tedlar sheets by the outer glass cover should prolong the Tedlar life considerably (five years, beyond the freely exposed life of five to seven years claimed by the manufactures);

5) Tedlar is cheaper than glass.

The number of transparent cover plates that should be used in a solar collector depends on many factors. Whillier (1964) noted that the addition of an extra glass cover increases the cost of the solar heater by about 15 percent and an extra Tedlar layer the corresponding percentage is about 5 percent. He, however, considered the most important factor to be the temperature at which it is desired to collect the heat, compared to the ambient temperature.

As a guide for choosing the number of transparent glass covers to be used in a flat-plate solar collector, Whillier (1963) presented Table 2-1. In cases where plastic covers are incorporated into flat plate solar collectors the numbers may vary from those proposed in Table 2-1.

2.3.4 Absorber plate

The purpose of the absorber plate is to absorb the incoming solar energy and transfer the heat to the air or water passing over the

Table 2-1. Guide to selection of number of transparent cover plates (Whillier, 1963).

Collection temperature above ambient temperature $(t_c - t_a)$, °C	Typical applications	Number of cover plates: Black-painted absorber $\varepsilon = .9$ or $.95$	Number of cover plates: Selective absorber $\varepsilon = .2$
-10 to +10	Heat source for heat pump Air heating for drying	none	none
10 to 60	Summer water heating Air heating for drying Solar distillation Space heating in non-freezing climates	1	1
60 to 100	Winter water heating Winter space heating	2	1
100 to 150	Summer air conditioning Steam production in summer Refrigeration Cooking by boiling	3	2

surface of the plate. The hourly temperature values at any point of the absorber plate is assumed constant. This requires that the thermal conductivity of the plate be high enough so that any amount of additional heat is conducted through the plate to a surface where it is removed by convection. The desired heat absorbing properties of the surface exposed to the sun can most easily be obtained by coating the surface of the plate with a good solar energy absorbant. Therefore, the plate can be thin and strong enough to require support based only on the strength of the glass cover. A glass covering requires support at spacing greater than 0.457 m to withstand moderate stresses without breakage. The plate surfaces should have good coating holding characteristics. Copper sheet metal meets all of these requirements, is easy to handle, (though more expensive than aluminum) and, therefore, seems to be the best metal. The optimum coating for an absorber plate has characteristics that form a combination of high absorptance α, for solar radiation and low emittance, ε, for long wave radiation. This combination of properties is possible to achieve because there is little overlap in wavelength ranges between incoming solar energy (outside the atmosphere of the earth is 98% at wavelengths less than 3.0 μm) and emitted long wavelength radiation (less than 1% at wavelengths less than 3.0 μm) for a black surface at 127°C. Research by Löf and Tybout (1972) on selective surfaces has produced selective surfaces that have sufficient durability and have low cost to warrant use flat-plate solar collectors. Essentially, such selective surfaces consist of a very thin upper layer which is highly absorbent to short wave solar radiation but relatively transparent to long wave thermal radiation. The substrate has a high reflectance ρ, and a low emittance ε, for long wave radiation.

Presently, the only commercially available selective surface that has been extensively field tested is the selective black surface marketed under the trade name 'Miromit". Electrolytically coated galvanized sheet steel is used as the plate material for solar water heaters in Israel. It has a solar absorptance of 0.92 and a long wave emittance of 0.1. Non-selective, black paint such as lamp-black (which is commercially known as Nextel) has been in general use for both air and water heating.

The use of new and cheaper selective paints on solar collector plates for air heating would certainly be necessary improvements. One such paint in commercial production is Krylon No. 1602 ultra flat-black enamel, manufactured by Borden, Inc., at Columbus, Ohio. It has an absorptance of 0.95 and an emittance of 0.2.

2.3.5 Heat losses

Thermal losses occur in solar collectors by the usual three modes of heat transfer (convection, radiation and conduction) because the blackened absorbing plate in the collector is hotter than the surrounding ambient conditions. The heat transfer losses include: a) upward radiation and convection through the transparent cover plates. A semi-empirical expression for the upward thermal losses q_{up} (for negligible bottom and side losses) was developed by Butz (1973)

$$q_u = \frac{T_f - T_a}{\dfrac{1}{h_w} + \dfrac{(n/C)}{\sqrt[4]{(T_f - T_a)/(n + f)}}} + \frac{\sigma\,(T_f^4 - T_a^4)}{\dfrac{1}{\varepsilon_p} + \dfrac{2n + f - 1}{\varepsilon_g} - n} \qquad (2\text{-}6)$$

where

$$T_f = \frac{T_i + T_o}{2} \qquad (2\text{-}7)$$

T_i, T_o = collector fluid inlet and outlet temperatures, respectively

T_f = average collector fluid temperature

T_a = ambient air temperature

σ = Stefan-Boltzman constant (that is, 5.67×10^{-8} $w/m^2 {}^{\circ}K^4$)

f = outer collector cover to non-outer cover heat transfer resistance ratio

h_w = coefficient of heat transfer from the outmost collector cover. $w/(m^2\ {}^{\circ}C)$

C = factor to account for collector tilt in the expression for coefficient of free convection heat transfer on glass collector covers, $w/(m^2\ {}^{\circ}C^{1.25})$

ε_p = non-selective collector surface emittance

ε_g = glass cover emittance

n = number of glass covers

and

$h_w = 5.7 + 3.8v$ (2-8)

$c = 1.08 - 0.0044\ \beta$ (2-9)

β = surface tilt angle from horizontal

$\varepsilon_p = 0.95$ (2-10)

$\varepsilon_g = 0.90$ (2-11)

$f = 0.76 \times 10^{-0.014V}$, for $v \leq 3.1$ (2-12)

$f = 0.36 \times 10^{-0.008(v-8)}$, for $3.1 < v \leq 6.6$ (2-13)

$f = 0.24 \times 10^{-0.004(v-17)}$, for $v > 6.6$ (2-14)

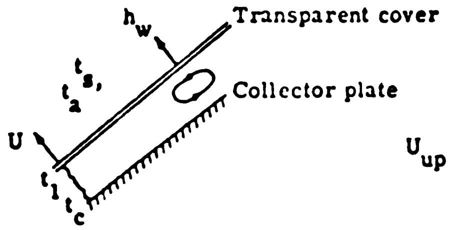
where v is the wind speed in m/s.

The upward heat coefficient, U_{up}, of the collector with covers is obtained from the relation,

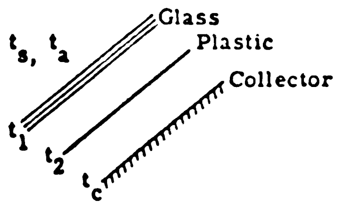
$$q_{up} = U_{up}\ (t_p - t_a) \quad (2\text{-}15)$$

Equations have been derived by Whillier (1964) for calculating U_{up} for various combinations of glass and plastic covers. These are given as equation (2-16).

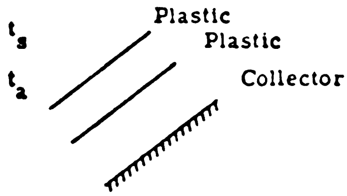
Equation 2-16. Equations for computing collector heat loss coefficient, U_{up}.



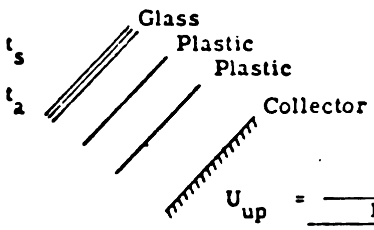
$$U_{up} = \tau \epsilon_c h_{r_{cs}} \left(\frac{t_c - t_s}{t_c - t_a}\right) + \frac{1}{\frac{1}{h_{c1}+E_{c1}h_{r_{c1}}} + \frac{1}{h_w + \epsilon_1 h_{r_{1s}}\left(\frac{t_1-t_s}{t_1-t_a}\right)}}$$



$$U_{up} = \frac{1}{\frac{1}{h_w + \epsilon_1 h_{r_{1s}}\left(\frac{t_1-t_s}{t_1-t_a}\right)} + \frac{1}{\tau E_{c1} h_{E1} + \frac{1}{\frac{1}{h_{c2}+E_{c2}h_{r_{c2}}} + \frac{1}{h_{21}+E_{21}h_{r_{21}}}}}}$$



$$U_{up} = \frac{\tau^2}{1-X}\epsilon_c h_{r_{cs}}\left(\frac{t_c-t_s}{t_c-t_a}\right) + \frac{1}{\frac{1}{h_{c2}+E_{c2}h_{E2}} + \frac{1}{h_{21}+E_{21}h_{c_{21}}} + \frac{1}{h_w+\epsilon_1 h_{r_{1s}}\left(\frac{t_1-t_s}{t_1-t_a}\right)}}$$



$$U_{up} = \frac{1}{\frac{1}{h_w+\epsilon_1 hr_{1s}\left(\frac{t_1-t_s}{t_1-t_a}\right)} + \frac{1}{\frac{\tau^2}{1-X}E_{c1}h_{r_{c1}} + \frac{1}{\frac{1}{h_{c3}+E_{c3}h_{r_{c3}}}+\frac{1}{h_{32}+E_{32}h_{r_{32}}}+\frac{1}{h_{21}+E_{21}h_{r_{21}}}}}}$$

$h_w = 5.7 + 3.8\ V$, (Wind coeff.)

$h_{xy} = C\,(t_x - t_y)^{1/4}$, (convection coeff.)

tilt angle	0	30	60	90
C	1.58	1.38	1.18	0.99

$hr_{xy} = \sigma\,(t_x^4 - t_y^4)/(t_x - t_y)$

(equivalent radiative coeff.)

$E_{xy} = \dfrac{1}{\frac{1}{\epsilon_x}+\frac{1}{\epsilon_y}-1}$, emissivity factor

ϵ = emissivity. $\epsilon_{collector}$ = 0.95 (black paint)
.2 (selective)

$\epsilon_{plastic}$ = 0.63

ϵ_{Glass} = 0.88

$S_x = \dfrac{t_x - t_s}{t_x - t_a}$

t_s = equivalent black body temperature of the sky

t_a = ambient air temperature

t_c = collector - plate average temperature

t_1, t_2, t_3, = temperature of transparent covers

τ = transmittance of plastic for long-wave radiation (0.3 for Tedlar)

X = fraction of long-wave radiation that is <u>completely</u> absorbed at first plastic (X = 0.45 for Tedlar)

When plastic films are used to cover solar collectors, the upward heat losses are greater than with glass because the plastics transmit more long wave radiation. However, when 0.004-inch think Tedlar is used to cover an absorber plate coated with selective paint the higher heat losses are more than compensated for.

b) Downward heat losses through the rear insulation are by conduction in the bottom insulation, and by convection and radiation from the exposed bottom surface to the environment. With sufficient insulation, 7.62 cm to 15.24 cm thick of mineral wool, the downward heat loss coefficient is about one-tenth the upward heat loss coefficient.

c) Edge heat losses are by the same heat transfer modes as those for the downward heat losses. Based on the outer exposed edge area, the edge heat loss coefficient is given by the relation,

$$q_{edge} = U_{edge}\,(DP)\,(t_p - t_a) \qquad (2\text{-}17)$$

where D is the depth of the collector box, and P is the perimenter. Use of sufficient edge insulation usually makes q_{edge} negligible.

The collector heat loss coefficient, U_L, embodies all the above losses, and is calculated as follows:

$$U_L = U_{up} + U_{rear} + U_{edge}\,\frac{A_p}{A_c} \qquad (2\text{-}18)$$

where A_c = area of the absorbing plate

A_p = perimeter of the collector.

2.3.6 Heated air duct

The shape of a collector and the air passage(s) influences the efficiency with which the air passing through the collector is heated. The shape of the air duct also determines the pressure drop of the heating air as it passes through the collector. The velocity of the air and the width of the duct influence the convection and radiative heat transfer coefficients for heat transfer from the absorber plate to the air and hence the heat losses already discussed. The highest heat transfer rate is obtained from a duct having a rectangular cross-section as compared to ducts with either square or circular cross-sections with the same pressure drop per unit length and the same wetted area. The duct having circular cross-section has the lowest heat transfer rate.

The maximum pressure drop that can be tolerated in the collector is governed by the following:

a) the fan pressure drop or power, and

b) the pressure drop necessary to move the air through the grain and through the ducts.

The use of separate small fans and mixing of cold and solar heated air streams is recommended instead of using one large fan which tends to overheat. The fans usually used in grain drying have a maximum static pressure head of about 10 cm of water. Most of this pressure is required to move the air through the grain and through the ducts. Therefore, a collector can only use a small portion of the total pressure drop of the system.

The coefficient of heat transfer by convection, h_c, should be a maximum because the higher it is the lower will be the temperature of the absorbing plate. A low absorbing plate temperature is desirable because radiant heat transfer from the absorbing plate to the top covers will be less and, therefore, the overall heat loss from the collector will be less.

The Reynolds number, which combines the depth of the air duct, the rate of airflow and the air properties is defined as:

$$Re_D = \frac{VD\rho}{\mu} \tag{2-19}$$

Eckert et al. (1960) suggested use of an equivalent hydraulic diameter, D_h, instead of the tube diameter D in equation (2-19) for all heat-transfer applications in which the bulk of the heat transfer is in the boundary layers close to the wall. This eliminates the cases of low Prandtl numbers or those in which the secondary flow effects may be excessive. The hydraulic diameter for a duct with rectangular cross-section of depth a and width b is $2ab/(a + b)$. A survey of the literature on the critical Reynolds number (i.e. a number at which a fluid velocity, V in a duct changes from streamline to turbulent flow) was made by Malik (1967); a summary of the critical Reynolds number for rectangular ducts is presented in Table 2-3.

Table 2-3. Values of Re_{crit} for rectangular ducts.

Investigator	Ratio of b/a	Re_{crit}
Nikuradse (1930)	3.50	2800
Washington and Marks (1937)	2.0 and 40.0	2800
Schiller (1923)	3.52	1600

Table 2-3. con't.

Davis and White (1928)	40.0	2800
Eckert and Irvine (1957)	3.0	5000
Cornish (1928)	2.92	2800

The aspect ratio (width divided by depth) of the duct used in this investigation is 3. Hence, the critical Reynolds number for the duct, according to some of the figures in Table 2-3, falls in the turbulent flow range. Barrow and Lee (1967) observed that about 20 hydraulic diameters are required for flow to develop thermally for a Reynolds number of 70,000. Since the Reynolds number used in this investigation is much less than the one cited above, a duct length of 16 ft (4.87 m) was considered reasonable for flow to be fully developed both thermally and hydraulically.

A Reynolds number (Re) of less than 2100 is generally accepted for laminar flow with a uniform velocity profile in pipes and ducts (Kays, 1966 and Bennett et al. 1962). Above this Reynolds number the flow becomes unstable to small disturbances, and a transition to turbulent type of flow will generally occur.

The hydrodynamic and thermal boundary layers start simultaneously at the entrance of a duct. The thermal boundary layer develops only on one side as the duct is heated only at the top.

Based on the equivalent hydraulic diameter and Reynolds number Kays recommends use of the following expressions for the mean friction coefficient, f_m in non-circular ducts for laminar flow:

$$f_m = \frac{16}{Re} \qquad (2\text{-}20)$$

For turbulent flow the following equations hold,

$$f_m = 0.046\ Re^{-0.2},\ \text{for } 30{,}000 < Re < 10^6 \qquad (2\text{-}21)$$

$$f_m = 0.079\ Re^{-0.25},\ \text{for } 5{,}000 < Re < 30{,}000 \qquad (2\text{-}22)$$

Equation (2-22) is consistent with the 1/7-power velocity distribution. Irvine recommends use of equation (2-22) in a wider range of Reynolds numbers ($Re_{crit} < Re < 50{,}000$) for non-circular ducts.

Using equations (2-20) through (2-22) and the normal D'Arcy formula an expression for pressure drop in the heated air duct can be formulated;

$$\Delta p = 4\ f_m\ L\ v^2/2\ D_h\ g \qquad (2\text{-}23)$$

If pumping power (P.P) is of more interest to the solar air heater designer than the pressure drop, this is given by the relationship,

$$P.P = m\ \Delta\ p \qquad (2\text{-}24)$$

The heat transfer relationships for forced convective heat transfer within the duct are reasonably well represented by an equation comprising at least two of the following four dimensionless numbers: Reynolds, Prandtl, Nusselt, and Stanton. For laminar flow, Sieder and Tate (1936) proposed the following expression.

$$Nu = 1.86\ (Re\ Pr)^{1/3}\frac{D}{L}^{1/2}\left(\frac{\mu}{\mu_s}\right)^{0.14} \qquad (2\text{-}25)$$

The fluid viscosity μ, is evaluated at average bulk temperature. The term μ/μ_s is an empirical correction for the distortion of the velocity profile which results from the effect of high temperature on viscosity. Equation (2-25) applies when the pipe-wall temperature in uniform. This equation obviously cannot be used for extremely long ducts since it would yield a zero heat-transfer coefficient. It is observed by Buelow (1956) that equation (2-25) is valid for air when,

$$Re\ Pr\ \frac{D}{L} > 10 \tag{2-26}$$

The problem of heat transfer with turbulent flow in rectangular ducts has not yet been completely solved. Experimental work reported in the literature shows that forced convective heat transfer within a duct is reasonably well represented by the following relation:

$$Nu = C\ Re^{m}\ Pr^{n} \tag{2-27}$$

The Constants C, m, and n have been evaluated under various types of heating conditions (Siegel and Sparrow, 1960). Both constant axial heat flux and constant axial temperature conditions have been employed. The solar-air heater falls into neither of these simple categories, but may be approximated by the former (Tan and Charters, 1970).

The first such equation was recommended by Dittus and Boelter (1930) for flow in smooth tubes. The equation is of the form,

$$Nu = 0.023\ (Re)^{0.8}\ (Pr)^{0.4} \tag{2-28}$$

for heat flow from the wall to the fluid, and

$$Nu = 0.023\ (Re)^{0.8}\ (Pr)^{0.3} \tag{2-29}$$

for heat flow from the fluid to the wall. Review of work by various investigators has led McAdams (1954) to conclude that an acceptable correlation for heating and cooling of various fluids with turbulent flow in horizontal tubes is given by equation (2-29). The equation is valid for the following conditions: (1) the Reynolds number is in the range of 10,000 to 12,000; (2) the Prandtl number is between 0.7 and 120; (3) the pipe length divided by its diameter is greater than 60; and (4) the physical properties of the fluid are evaluated at the bulk temperature. For asymmetrically heated rectangular ducts, Charters (1970) recommended use of the Dittus-Boelter equation with one modification. The modified equation is of the form,

$$Nu = 0.0182\ (Re)^{0.8}\ (Pr)^{0.4} \qquad (2\text{-}30)$$

Another well-known equation is that of Colburn (1933),

$$\frac{h}{V_a\ \rho\ C_p}\ (Pr)^{2/3} = 0.023\ (Re)^{-0.2} \qquad (2\text{-}31)$$

The fluid properties are evaluated at the arithmetic mean of the wall and bulk fluid temperatures.

Malik (1967) after experimenting with both rough and smooth, asymmetrically heated parallel plate channels with an aspect ratio of 4 and $\frac{L}{D} = 120$, recommended use of the Dittus-Boelter equation in the following form,

$$Nu = 0.023\ (Re)^{0.8}\ (Pr)^{0.4}\ \sqrt{f/f_o} \qquad (2\text{-}32)$$

The values of the relative roughness, $\sqrt{f/f_o}$ for different Reynolds numbers and two different types of absorber plates (one was a flat galvanized steel sheet and another was a corrugated steel sheet) are given in Tables 2-4 and 2-5. The value of the friction coefficient, f_o for a smooth duct was given by the Blasium equation,

Table 2-4. Factor $\sqrt{f/f_o}$ for the duct with a flat galvanized steel sheet absorber plate, (Malik, 1967).

Reynolds Number	Factor $\sqrt{f/f_o}$
10,000	1.18
15,000	1.218
20,000	1.245
25,000	1.280
30,000	1.305
40,000	1.355
50,000	1.390

Table 2-5. Factor $\sqrt{f/f_o}$ for the duct with a corrugated steel sheet absorber plate, (Malik, 1967).

Reynolds Number	Factor $\sqrt{f/f_o}$
10,000	1.435
15,000	1.438
20,000	1.461
25,000	1.509
30,000	1.542
40,000	1.601
50,000	1.656

$$f = 0.316\ Re^{-0.25} \tag{2-33}$$

Equation (2-33) was found to be in good agreement with a simplified relationship for an asymmetrically heated air duct. The relationship is of the form,

$$St = \frac{0.0192\ Re^{-1/4}}{1 + 1.22\ Re^{-1/8}\ (Pr - 2)} \tag{2-34}$$

This equation takes into account only the laminar and turbulent sublayers of the three-layer velocity profile, Kays (1966). The buffer or transition velocity zone is not considered.

For gases and liquids the foregoing relationships are valid for long ducts. When turbulent flow is observed in short ducts the following relationships can be used (McAdams, 1954),

$$\frac{h_{cL}}{h_c} = 1 + (\frac{D}{L})^{0.7} \tag{2-35}$$

for $2 \leq \frac{L}{D} \leq 20$, and

$$\frac{h_{cL}}{hc} = 1 + 6\,\frac{D}{L} \qquad (2\text{-}36$$

for $20 < \frac{L}{D} \leq 60$. In both of the above equations, h_{cL} is the average unit convective heat transfer for the duct of finite length L and h_c is the convective heat transfer for an infinitely long duct.

2.4 In-bin solar drying

In the United States, Buelow and Boyd (1957) were the first to investigate in-bin solar grain drying. This and other recent studies (Foster and Peart, 1976; Shove, 1977; Bakker-Arkema et al., 1977; and

Thompson and Pierce, 1977) have shown that in-bin solar corn drying is feasible. The drying process of a solar fixed bed grain dryer has been simulated by Bakker-Arkema et al. (1977). By making energy and mass balances on a differential volume (S dx) located at an artibrary location in the stationary bed a set of three differential equations is obtained. The model equations are (Bakker-Arkema et al., 1977):

a) for the enthalpy of the air and product,

$$\rho_p (C_p + MC_w) \frac{\partial T}{\partial t} + G_a(C_a + HC_v) \frac{\partial T}{\partial x} +$$

$$G_a [(C_w - C_v)(100 - T) + h_{fg}] \frac{\partial H}{\partial x} = 0 \qquad (2\text{-}37)$$

b) for the humidity of the air,

$$\rho_p \frac{\partial M}{\partial t} + G_a \frac{\partial H}{\partial x} = 0 \qquad (2\text{-}38)$$

and

c) for the moisture content,

$$\rho_p \frac{\partial M}{\partial t} = \text{an appropriate thin layer equation} \qquad (2\text{-}39)$$

Equation (2-37) and (2-38) along with an empirical thin-layer equation consitute the Michigan State University (MSU) solar grain drying model. The auxiliary equations for the grain and bed properties, and the psychrometric relationships (including condensation) required for the solar drying model, have been discussed by Abkker-Arkema (1974). An analytical solution of the system of these equations is impossible. Therefore, numerical techniques have to be used. It should be noted that the MSU solar drying model does not contain an equation for describing corn rewetting (from high humidity air on a cloudy day or at night) so as to accurately model condensation.

CHAPTER THREE

THEORETICAL ANALYSIS

3.1 Thin-layer corn drying and rewetting equations

The mathematical theory of diffusion, first formulated by Fick (1855) and later considered in detail by Crank (1956) and others is the the basis for development of the thin-layer equations. According to this theory, in an isotropic medium, the rate of transfer of the diffusing substance through a unit area of the section is proportional to the concentration gradient measured normal to the section. The rate equation is of the form:

$$F = -D \frac{\partial C}{\partial x} \qquad (3\text{-}1)$$

where F is the rate of transfer per unit area of section, C is the concentration (mass per unit volume), and x the space coordinate measured normal to the section. D, a constant of proportionality, is defined as the coefficient of diffusion and has dimensions $(\text{length})^2$ $(\text{time})^{-1}$. The negative sign in the equation arises because diffusion occurs in the direction of decreasing concentration.

The fundamental differential equation of diffusion, with constant diffusion coefficient, is derived from equation (3-1) and reduces to

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \tag{3-2}$$

Equations (3-1) and (3-2) are known as Rick's first and second laws of diffusion, respectively.

Luikov (1966) and his co-workers in the Soviet Union developed the mathematical relationships describing the drying of capillary porous products based on the following assumptions:

(1) liquid movement is due to surface forces (capillary flow);

(2) liquid movement is due to moisture concentration differences (liquid diffusion);

(3) liquid movement is due to diffusion of moisture on the pore surfaces (surface diffusion);

(4) vapor movement is due to moisture concentration differences (vapor diffusion);

(5) vapor movement is due to temperature differences (thermal diffusion);

(6) water and vapor movement are due to total pressure differences (hydrodynamic flow).

The system of differential equations are of the following form:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} \theta + \nabla^2 K_{13} P$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} \theta + \nabla^2 K_{23} P$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} \theta + \nabla^2 K_{33} P \tag{3-3}$$

where K_{11}, K_{22} and K_{33} are phenomenological coefficients. The other K values are coupling coefficients. Neglecting the pressure and temperature gradients in a corn kernel during the drying and rewetting processes leads to a simplication of Luikov's equations. The ultimate result is

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \tag{3-4}$$

The transfer coefficient K_{11} is called the diffusion coefficient, D. Researchers have used a number of solutions of equation (3-4) for predicting the drying behavior of cereal grains.

For a constant value of D, equation (3-4) can be written as:

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial r^2} + \frac{C}{r} \frac{\partial M}{\partial r} \tag{3-5}$$

where C is zero for planar symmetry, unity for a cylindrical body and 2 for a sphere. A number of solutions to equation (3-5) for various solid shapes have been used as drying equations for grains. The following initial boundary conditions are often assumed in solving equation (3-5):

$$M_{(r,o)} = M_o \tag{3-6}$$

$$M_{(r_o,t)} = M_e \tag{3-7}$$

The analytical solutions of equation (3-5) for the average moisture content of various regularly shaped bodies can be obtained directly by integration (Crank, 1957). Thus, for an infinite plane:

$$MR = \frac{8}{\Pi^2} \sum_{n=o}^{\infty} \frac{1}{(2n+1)^2} \exp[-(2n+1)^2 \, \Pi^2 X^2] \tag{3-8}$$

for a sphere

$$MR = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp -[\frac{n^2 \Pi^2}{9} X^2] \tag{3-9}$$

and for an infinite cylinder:

$$MR = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left[-\frac{\lambda_n^2 X^2}{4}\right] \qquad (3\text{-}10)$$

where λ_n are the roots of the Bessel function of zero order (Perry, 1963). In the above equations the average moisture content and the time are expressed as dimensionless quantities, MR and X, respectively.

$$MR = \frac{M - M_e}{M_o - M_e} \qquad (3\text{-}12)$$

and

$$X = \frac{A}{V} (Dt)^{1/2} \qquad (3\text{-}12)$$

where A represents the surface area and V the volume of the body. For the plane V/A = half thickness; for the sphere V/A = (radius)/3; for the cylinder V/A = (radius)/2. Chu and Hustrulid (1968) found equations (3-8) through (3-12) describe the drying rate of a solid satisfactorily in the moisture ratio, MR range of $\frac{M - M_e}{M_o - M_e} \geq 0.4$.

Chu and Hustrulid (1968) studied diffusion of moisture in corn kernels assuming that the kernel could be represented by a sphere of equivalent radius, R. Previously published results of several thin-layer drying studies were used in the analysis. The specific temperature, relative humidity and moisture content ranges included:

(1) relative humidity 10 - 70%,

(2) air temperature 49°C - 71°C, and

(3) corn moisture content 5 - 35% dry basis.

For a moisture content dependent diffusivity the following equation was recommended:

$$\frac{M - M_e}{M_o^* - M_e} = \frac{6}{\Pi^2} \exp[-\frac{\Pi^2}{R^2} D\ t] \qquad (3\text{-}13)$$

The concentration dependent diffusivity, D, the pseudo initial moisture content M_o^*, and the equivalent radius, R were found to be:

$$D = 1.513 \exp[(0.045\ T_{abs} - 5.485)M - \frac{2513}{T_{abs}}] \qquad (3\text{-}14)$$

where T_{abs} is the absolute air temperature, in degrees K;

$$M_o^* = 1.0655\ M_o - 0.0108 \qquad (3\text{-}15)$$

$$R = \frac{3LWK}{2(LW + WK + LK)} \qquad (3\text{-}16)$$

where L, W, K are the length, width and thickness of the average kernel, respectively. Equations (3-13) through (3-16) worked satisfactorily under the test conditions used. This may not be true for other conditions. In order to improve the effectiveness of the Chu and Hustrulid equation several of its coefficients will be determined for lower air and corn temperatures and mean equivalent radius.

The value of the mean equivalent radius (4 = 0.32 cm) is obtained from data of Chu and Hustrulid (1968). The pseudo moisture content which is important when grain tempering is part of the drying process is replaced with corn initial moisture content. Hence, the resulting semi-theoretical diffusion equation considered for analysis in this thesis is of the form:

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt) \qquad (3\text{-}17)$$

where,

$$K = \frac{\Pi^2 D}{r^2} = C_1 + C_2 M_{t-1} + C_3 \log(M_{t-1}) + C_4 \theta_t M_{t-1}^2 \exp(r h_t^2) \qquad (3\text{-}18)$$

The parameters K and C_1 have units of hr^{-1}, C_2 and C_3 are dimensionless, and C_4 has units of $^0K^{-1}$. The diffusion coefficient, D has units of $cm^2\text{-}hr^{-1}$.

The values of the parameters C_1, C_2, C_3 and C_4 can be estimated to any desirable accuracy by multiresponse sequential procedures that minimize the sum of squares function. Various sequential methods are discussed in detail by Beck and Arnold (1975). The use of any sequential method depends on the type of information known about the model and the parameters to be estimated.

In case the model is non-linear, as in equation (3-18), and the number of measurements at a given time m, is less than the number of parameters p; the measurements are also dependent. A dependent variable is linear in a parameter if (a) the differential equation and the associated boundary and initial equations are linear, and (b) the parameter enters in a non-homogeneous term in a linear manner. In other cases the variable is non-linear since both conditions must be satisfied. For a linear differential equation and associated conditions, the dependent variable may be linear with respect to some parameters and non-linear with respect to several others, then the problem is a non-linear one. In any non-linear parameter estimation problem, invariably some search is required to find the "best" value by minimizing the sum of squares function, S. Usually this search involves an iterative procedure that reduces S from step to step. Such a procedure naturally leads to continually updating the parameter estimates as new observations are added.

Considering equation (3-18), the sum of squares function to be minimized, in vector form is as follows:

$$S_{(K)} = (\hat{\underline{K}} - \underline{K})^T \Psi^{-1} (\hat{\underline{K}} - \underline{K}) \quad (3\text{-}19)$$

where $\Psi^{-1} = \sigma^{-2} \phi^{-1}$ is the weighting factor. If nothing is known regarding the weighting factors before analyzing the data, then all the Ψ^{-1} can be set equal to unity.

The parameter K is estimated from equation (3-19) by differentiating $S_{(K)}$ with respect to $\underline{K}$, setting the result equal to zero, and solving for the estimate, $\underline{K}$ and hence the values of C_1, C_2, C_3 and C_4 are obtained. A modified computer program "NLINA" developed in Beck and Arnold (1975) can be used to estimate the parameters C_1, C_2, C_3 and C_4.

The program which estimates up to six parameters has two subroutines. One is called "MODEL" for handling the models to be used and the other "SENS" for incorporating the model sensitivity coefficients. The sensitivity coefficients are derivatives of the dependent variable $\underline{K}$ with respect to the parameters C_1, C_2, C_3 and C_4. It is assumed that the observations have additive, zero mean errors that are normal and independent. The independent variables, (θ_t, M_{t-1} and rh_t) are errorless and no prior information is known regarding the parameters C_1, C_2, C_3 and C_4. The assumption allows for use of a unit weight function.

In order to make the off-diagonal weighting functions zero, large values of the covariance matrice are chosen. The use of this program is described in Beck and Arnold (1975).

3.2 Derivation of solar collector efficiency, η

The efficiency of a flat-plate collector is defined as the ratio of delivered heat to the insolation. In equation form this is given as

$$\eta = q_u/q_T \qquad (3\text{-}20)$$

where q_T is the total incident solar heat flux and q_u is the useful energy gained by a heat transfer fluid. A specific number of steps is used in obtaining the collector efficiency.

3.2.1 Step 1: Calculation of beam and diffuse components of solar radiation incident on an inclined collector surface. This is necessary because of the seasonal variation of insolation which is a function of the following:

a) Solar Declination, δ_s.

This can be obtained from the relationship given in Duffie and Beckman (1974). The relationship is of the form,

$$\delta_s = (23.45)\ \sin[\frac{360}{365}\ (284 + n)] \qquad (3\text{-}21)$$

where n is the number of days since the beginning of the year.

b) Local Solar Time (LST), H_s.

The value of LST is given in Kreider and Kreith (1975) as the local solar-hour angle measured west from solar noon. H_s is equal to 15 times the number of hours from local solar noon. As an example, 10:00 a.m. local solar time corresponds to a local-hour angle of 30^o. In mathematical relation terms:

H_s = (15) absolute value of (12 - AST) (3-22)

where AST is the apparent standard time.

AST = LST + ET - 4 times the number of degrees of LST west of the meridian; (3-23)

The letters ET, in equation (3-23) stand for the equation of time, in minutes. Its value for any day of the year can be obtained from Figure 3-1 and may be considered constant for the day.

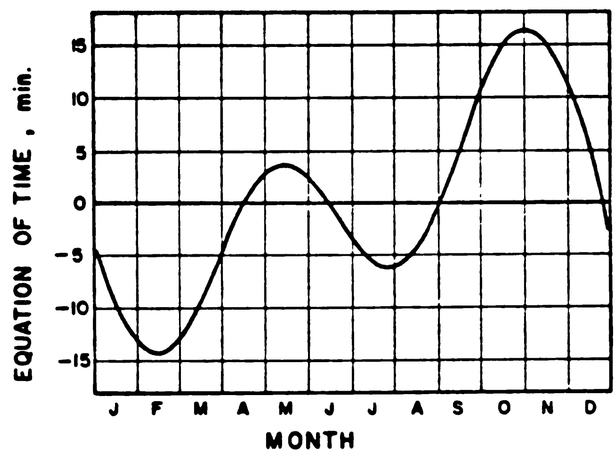


Figure 3-1. The equation of time, ET, in minutes, as a function of time of year.

In the present study solar radiation data were collected during the month of November only. Hence, instead of finding the value of ET from Figure 3-1, an equation obtained by linear regression analysis of data given by Threlkeld (1962) is recommended. The equation is of the form:

ET = 16.79 - (0.11) times day in November (3-24)

Equation (3-24) has a 92 percent correlation coefficient and a 0.498 standard deviation.

c) The angle of solar altitude above the true horizon, α_a.

For horizontal surfaces, the amount of solar radiation incident at the outer edge of the atmosphere depends, in addition to time of the year and the time of the day, on location, expressed by the latitude, L. The angle of solar altitude above the true horizon can be obtained from the following equation in Kreider and Kreith (1975)

$$\sin \alpha_a = \sin \delta_s \sin L + \cos \delta_s \cos L \cos H_s \qquad (3\text{-}25)$$

The diffuse component, I_{hd} is given by the relationship:

$$I_{h,d} = 2.46 + 3.37\, \alpha_a + 19.45\, cc \qquad (3\text{-}26)$$

where cc is cloud cover, $0 \leq cc \leq 10$.

The beam component at a horizontal surface would then be given by the equation:

$$I_{h,b} = I_h - I_{h,d} \qquad (3\text{-}27)$$

where I_h is solar radiation in w/m^2 recorded by a solarimeter on a horizontal surface.

d) Angle of Incidence, i.

For a collector surface inclined at an angle, β from the horizontal of the latitude in question the angle of incidence to the collector surface is given by the equation:

$$\cos i = \sin \delta_s \sin (L - \beta) + \cos \delta_s \cos (L - \beta) \cos H_s \qquad (3\text{-}28)$$

The beam component, I_{b-coll} incident on the inclined collector surface is given by the following equation:

$$I_{b,coll} = \frac{I_{h,b} \text{ Cos } i}{\sin \alpha_a} \qquad (3\text{-}29)$$

3.2.2 Step 2: Calculation of radiation absorbed, I_{coll}

Although glass is still considered the most reliable material available for solar collector covers its cost is higher than the cost of plastic covers. However, in multicover designs the high cost of glass covers can be greatly reduced by using a glass cover together with plastic cover such as Tedlar. Not all types of glass are appropriate for collector use. Some types will transmit more solar radiation than others. The transmittance depends directly on the refractice index of the glass.

Glass with a low refractive index has a low percentage of iron oxide content, low reflectance and absorptance losses and a high transmittance of normal incident radiation. Because Tedlar has a lower refractive index (1.45) than glass (1.5 to 1.526) its light transmittance is high (greater than 90%).

The reflectance of a cover plate (glass or Tedlar) also varies with the incidence angle, i. An expression (the Fresnel equation) to calculate the reflection of beam radiation from one surface of a transparent solid, $_{b1}$ is given in standard optic texts as

$$\bar{\rho}_{b1} = \frac{1}{2} \left[\frac{\sin^2(1 - r_a)}{\sin^2(1 + r_a)} \quad \frac{\tan^2(1 - r_a)}{\tan^2(1 + r_a)}\right] \qquad (3\text{-}30)$$

where r_a is the angle of refraction, and

$$\sin r_a = \frac{\sin i}{n_{1c}} \tag{3-31}$$

where n_{1c} is the refractive index of the collector cover. If the incidence angle is exactly 0°, the special form of the Fresnel equation is used

$$\bar{\rho}_{b1} = \frac{(n_{1c} - 1)^2}{(n_{1c} + 1)^2} \tag{3-32}$$

The reflectance of several covers with the same material is given by

$$\bar{\rho}_{bn} = 1 - \frac{1 - \bar{\rho}_{b1}}{1 + (2n-1)\bar{\rho}_{b1}} \tag{3-33}$$

where n is the number of similar collector covers (polarization ignored).

The transmittance of each cover plate is given by an emperical relationship (Duffie and Beckman, 1974)

$$\tau = e^{-KL} (1 - \rho_{b1})/(1 + \rho_{b1}) \tag{3-34}$$

where K is the extinction coefficient for each cover. Both the glass and Tedlar have the same extinction coefficient of 0.508 cm^{-1}. The letter L represents the distance in a particular cover traversed by the energy rays. L has units of centimeters in this case and it is obtained by the relationship

$$L = t/\cos r_a \tag{3-35}$$

where t is the cover thickness. The thickness of the glass used in this experiment was 0.3175 cm while that of the Tedlar was 0.01016 cm (4 mil). For a system of two covers Duffie and Beckman (1974) give an emperical relationship for the transmittance

$$\tau_{1,2} = (1.006)\tau_1\tau_2 \tag{3-36}$$

where τ_1 and τ_2 are the transmittance factors for the individual covers and each is obtained from equation (3-34).

The fraction, F_c of energy absorbed by a black painted absorber of absorptivity coefficient α is given by an emperical relationship of Duffie and Beckman (1974)

$$F_c = (1.012)\tau_1\tau_2\ \alpha \tag{3-37}$$

The effective transmissivity-absorptivity coefficient $\tau\alpha = F_e$ is given by Whillier (1967)

$$F_e = F_c + a_1\ (1 - e^{-K_1L_1}) + a_2\tau_1\ \ (1 - e^{-K_2L_2}) \tag{3-38}$$

where a_1 and a_2 are constants dependent on the number of cover plates. For a system of two covers $a_1 = 0.1$ and $a_2 = 0.44$. The subscripts 1 and 2 on the extinction coefficient K stand for the first and second cover plates starting from the uppermost cover plate. The distances traversed by energy rays in the first and second cover-plates are represented by L_1 and L_2, respectively; and τ_1 is the transmittance of the first cover plate.

The net energy, I_{coll} absorbed by the collector is obtained from the relationship given by Whillier (1967)

$$I_{coll} = 0.98\ [F_e(1-D)(1-S)]_i\ I_{TOT} = f\ I_{TOT} \tag{3-39}$$

where,

I_{TOT} = total incident solar radiation (it is the sum of direct solar radiation, $I_{b,coll}$ and the diffuse solar radiation from the sky, $I_{h,d}$);

(1-D) = dirt loss factor which is usually taken as 0.98;

(1-S) = shading correction factor. Hottel (1950) made plots of (1-S) versus time of the year for collectors having various combinations of latitude, L and collector tilt, β from horizontal and facing toward the Equator. These plots are for collectors having length, width and depth in the ratios of 10:10:1. The collector used in this research has length, width and depth ratios of 256:24:1. Hence, the (1-S) factor shall be taken as unity.

3.2.3 Step 3: Calculation of heat loss from the absorbing surface to the atmosphere

The heat loss depends on the following variables:

a) temperature of the absorbing surface, T_p;

b) temperatures of the ambient air T_a, and of the sky, T_s. Several relationships for clear skies have been proposed to relate T_s to the other measured meteorological variables. Brunt (1932) and Bliss (1961) related the effective sky temperature to water vapor content of the air and/or air temperature. Swinbank (1963) related the sky temperature to the local air temperature as follows

$$T_s = 0.00552\ T_a^{1.5} \qquad (3\text{-}40)$$

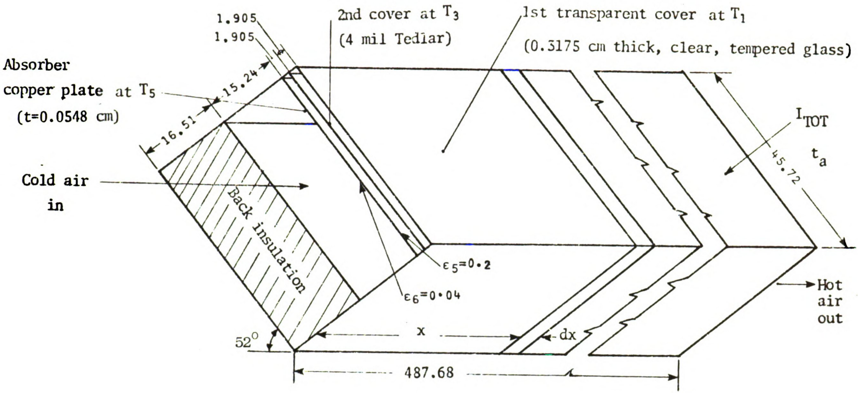


Figure 3-2. Flat-plate collector design sketch.

Note: All the lengths are measured in centimeters (cm).

Where T_s and T_a are both in degree Kelvin Whillier (1967) used even simpler expressions for the sky temperature

1) $T_s = T_a - 6$ (3-41)

which is good for fairly most environments.

2) $T_s = T_a - 10$ (3-42)

which is good for dry temperate climates.

Equation (3-41) was used in this thesis because the ambient air relative humidity for the time the experiment was performed was above 70%);

c) number of top covers and their spacing;

d) tilt of the covers from the horizontal;

e) wind heat transfer coefficient, h_w over the topmost cover and which, according to Whillier (1967) is given by the relationship:

$$h_w = 5.7 + 3.8\ V \tag{3-43}$$

where V is the wind speed in m/sec and h_w is in $w/m^2\ {}^oC$.

The solar collector cross-section and the thermal network of heat loss from the collector are shown in Figures 3-3a and 3-3b, respectively.

3.2.4 Thermal model

A flat-plate collector consists essentially of a metal absorber plate mounted in an insulated housing fitted with one or more glass and/or plastic covers. In this thesis the discussion is restricted to one glass cover and one plastic cover (Tedlar), depicted in cross-section

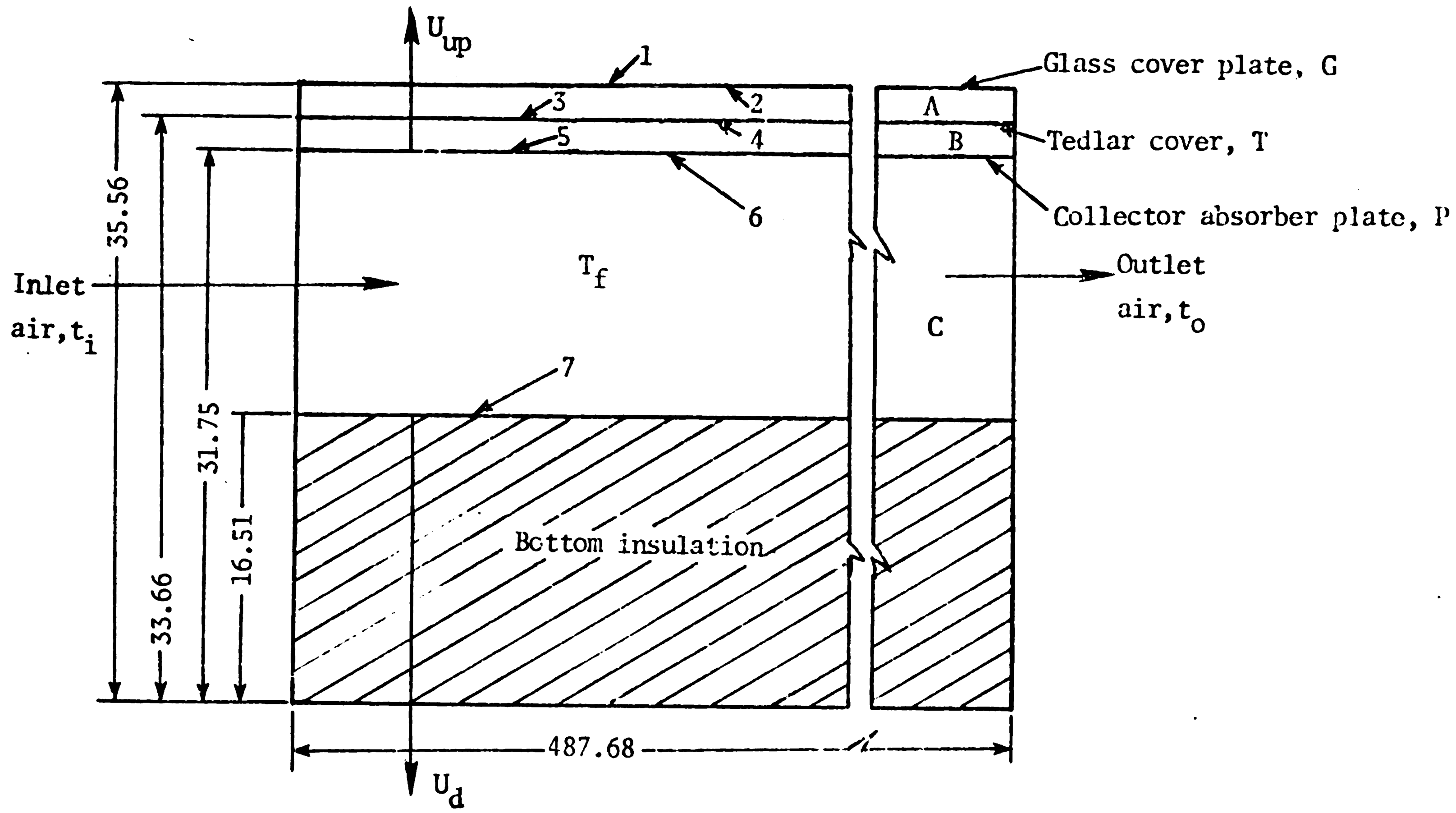


Figure 3-3a. Cross-section of the flat-plate solar collector.

Note: All the lengths are measured in centimeters (cm).

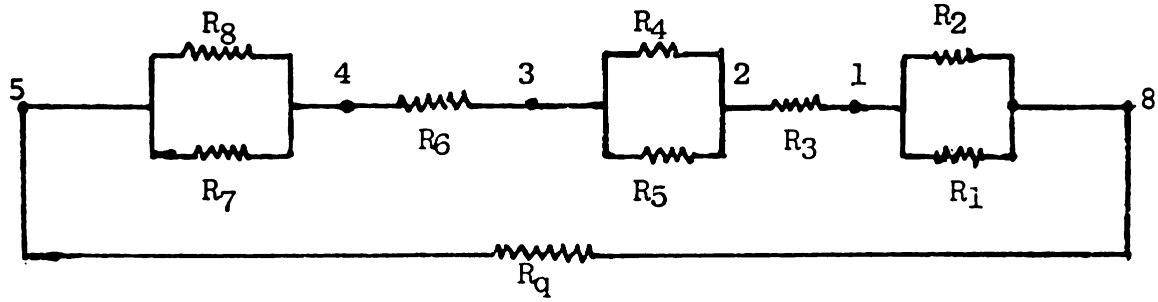


Figure 3-3b. Thermal network of collector heat loss.

Node 1 -- Upper half of glass cover

Node 2 - Lower half of glass cover

Node 3 - Upper half of Tedlar cover

Node 4 - Lower half of Tedlar cover

Node 5 - Black coated upper half of absorber plate

Node 8 - Surroundings

R_1 = Radiation resistance to surroundings

R_2 = Convection resistance, glass-to surroundings

R_3 = Conduction resistance through glass

R_4 = Radiation resistance, Tedlar-to-glass

R_5 = Conduction-natural convection resistance, Tedlar-to-glass

R_6 = Conduction resistance through Tedlar

R_7 = Radiation resistance, absorber-to-Tedlar

R_8 = Conduction-natural convection resistance, absorber plate-to-Tedlar

R_9 = Conduction resistance through the bottom insulation in Figure 3-3a. The approach taken in analyzing the thermal performance of such a collector is essentially that of Hottel and Woertz (1942), as modified by Hottel and Whillier (1955), Bliss (1959) and Eaton and Blum (1975).

The principal assumptions made are:

a) The hourly heat transfer is steady-state and one dimensional, i.e. losses through the sides of the collector housing are negligible. This assumption is reasonable because within one hour weather changes are negligible and the lateral area of the collector housing is small (0.1858 m^2) compared to the area of the absorber plate (2.2297 m^2).

b) The loss from the copper plate to the Tedlar is by both radiation and convection. The same quantity of heat is transferred through the Tedlar to the glass plate covers.

c) No radiant heat is transmitted through glass since it is opaque to long wavelength radiation from sources at only a few hundred degree Kelvin (Hottel and Woertz, 1942).

d) Since air is diathermic, the loss of heat by natural convection from a plate to an air space equals the loss by natural convection from the air space to the next higher cover. Hottel and Woertz (1942) calculated the natural convection heat loss from the absorber plate of the collector using the equation

$$q_{p_{54}} = C(T_5 - T_4)^{5/4} \tag{3-44}$$

Using $$R_8 = \frac{1}{C(T_5 - T_4)^{1/4}} \tag{3-45}$$

$$q_{p_{54}} = (T_5 - T_4)/R_8 \tag{3-46}$$

where C is a constant dependent on the collector tilt. Assuming negligible thermal mass of plates, the total rate of heat loss per unit area from the collector plate to the first cover plate is given by

$$q_{54} = C(T_5 - T_4)^{5/4} + \sigma(T_5^4 - T_4^4)/(\frac{1}{\varepsilon_5} + \frac{1}{\varepsilon_4} - 1) \qquad (3\text{-}47)$$

Using $h_{54} = C(T_5 - T_4)^{1/4} = \frac{1}{R_8}$ (3-48)

$$E_{54} = 1/(\frac{1}{\varepsilon_5} + \frac{1}{\varepsilon_4} - 1) \qquad (3\text{-}49)$$

$$h_{r_{54}} = \sigma(T_5^4 - T_4^4)/(T_5 - T_4) \qquad (3\text{-}50)$$

$$R_7 = 1/\varepsilon_{54}\ h_{r_{54}} \qquad (3\text{-}51)$$

give

$$q_{54} = (h_{54} + E_{54}\ h_{r_{54}})\ (T_5 - T_4) \qquad (3\text{-}52)$$

Using

$$R_{54} = 1/(h_{54} + E_{54}\ h_{r_{54}}) \qquad (3\text{-}53)$$

Equation (3-52) becomes

$$q_{54} = (T_5 - T_4)/R_{54} \qquad (3\text{-}54)$$

Since thermal mass of plates is negligible both R and R are zero. The total rate of heat loss per unit area from Tedlar to the next cover, glass is,

$$q_{54} + \alpha_T\ \tau_g I_{TOT} = \frac{\alpha(T_3^4 - T_2^4)}{(\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_3} - 1)} + C(T_3 - T_2)^{5/4} \qquad (3\text{-}55)$$

Equation (3-55) can also be expressed as follows:

$$q_{54} + \alpha_T \tau_g I_{TOT} = (T_3 - T_2)/R_{32} \tag{3-56}$$

where,

$$R_{32} = 1/(h_{32} + E_{32} h_{r_{32}}) \tag{3-57}$$

$$h_{32} = C(T_3 - T_2)^{1/4} = 1/R_5 \tag{3-58}$$

$$R_4 = 1/E_{32} h_{r_{32}} \tag{3-59}$$

$$E_{32} = 1/(\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_2} - 1) \tag{3-60}$$

$$h_{r_{32}} = \sigma(T_3^4 - T_2^4)/(T_3 - T_2) \tag{3-61}$$

Using $q_{32} = q_{54} + \alpha_T \tau_g I_{TOT}$ (3-62)

makes equation (3-56) become:

$$q_{32} = (T_3 - T_2)/R_{32} \tag{3-63}$$

The energy loss from the glass cover is that due to wind at temperature T_a, and that due to radiation exchange between the cover and the sky at temperature T_s. An energy balance at the glass plate gives

$$q_{54} + \alpha_T \tau_g I_{TOT} + \alpha_g \tau_T \tau_g I_{TOT} = \varepsilon_1 \sigma(T_1^4 - T_s^4) + h_w (T_1 - T_a) \tag{3-64}$$

Using

$$q_{18} = q_{54} + (\alpha_T \tau_g + \alpha_g \tau_T \tau_g) I_{TOT} \tag{3-65}$$

and

$$h_{r_1s} = \sigma\frac{(T_1^4 - T_s^4)}{(T_1 - T_s)} \tag{3-66}$$

$$q_{18} = (h_w + \varepsilon_1 h_{r_1s}\frac{T_1 - T_s}{T_1 - T_a}(T_1 - T_a) \tag{3-67}$$

Putting equation (3-67) into equation (3-63) gives

$$q_{18} = \frac{T_1 - T_a}{R_{18}} \tag{3-68}$$

where

$$R_{18} = \frac{1}{h_w + \varepsilon_1 h_{r_1s}\frac{T_1 - T_s}{T_1 - T_a}} \tag{3-69}$$

$$R_1 = \frac{1}{\varepsilon_1 h_{r_1s}\frac{T_1 - T_s}{T_1 - T_a}} \tag{3-70}$$

$$R_1 = \frac{1}{h_w} \tag{3-71}$$

I_{TOT}: is solar flux incident on the inclined collector surface (w/m^2).

q_{54}: is heat loss from collector plate.

σ: is Stefan-Boltzman constant.

$T_1 = T_2$: temperature of glass.

$T_3 = T_4$: temperature of Tedlar.

$T_5 = T_6$: temperature of collector plate.

α_g, α_T: absorption of glass plate and Tedlar, respectively.

T_a, T_s: ambient and sky temperatures, respectively.

τ_g, τ_T: solar transmission of glass plate and Tedlar, respectively.

ε_1, ε_2, ε_3, ε_4, ε_5, ε_6: emissivity of surfaces 1, 2, 3, 4, 5 and 6.

h_w: is wind coefficient.

Equations (3-54), (3-56) and (3-67) have three unknowns, T_1, T_3 and q_{54}. The procedure for solution of these equations is substitute for q_{54} of equation (3-47) into equations (3-55) and (3-63) and setting the resulting two equations into a form that lends itself to use by the Newton-Raphson method.

The Newton-Raphson method is iterative and converges more rapidly than other methods. The method is described in Barrodale et al. (1971) and Carnahan et al. (1969). In this thesis only a summary of the method is given and it is as follows:

1) In order to find a root or solution of general equations of the form $f(X_k)$ which may be linear or non-linear, set each equal to zero.

2) Choose a starting vector $X_k = X_0 = [X_{10}, X_{20}, \ldots , X_N]$, where X_0 is hopefully near a solution α.

3) Solve the system of the equations

$$\phi(X_k)\delta_k = -f(X_k),$$

where

$$\phi_{ij}(X_k) = \frac{\partial f_i}{\partial X_j}(X_i), \qquad i = 1,2, \ldots , N, \quad j = 1,2, \ldots , N, \tag{3-72}$$

N is the number of unknown variables or equations and

$$f(X_k) = [f_1(X_k), f_2(X_k), \ldots , f_N(X_k)]^t, \tag{3-73}$$

for the increment vector

$$\delta_k = [\delta_{1k}, \delta_{2k}, \ldots, \delta_{Nk}]^t. \tag{3-74}$$

4) Update the approximation to the root for the next iteration

$$X_{k+1} = X_k + \delta_k.$$

5) Check for possible convergence to a root, δ. One such a test might be

$$|\delta_{ik}| < \varepsilon_2, \qquad i = 1,2, \ldots, N \tag{3-75}$$

If equation (3-75) is true for all i, then X_{k+1} is taken to be a root. If the test of equation (3-75) fails for any i, then the process is repeated starting with step 3. The iterative process is continued until the test in step 5 is passed for some k, or when k exceeds some specified upper limit.

In the main program "SOLARUG" elements of the augmented matrix

$$A = [\phi\ (X_k) \text{ and } -f(X_k)] \tag{3-76}$$

are evaluated by a subroutine named CALCN. The system of equations obtained from equations (3-55) and (3-63) is solved by calling on the function SIMUL. These equations are

$$f_1(T_1) = \varepsilon_1\sigma(T_1^4 - T_s^4) + h_w(T_1 - T_a) - [(\alpha_T\tau_g + \alpha_g\tau_T\tau_g)I_{TOT}$$

$$+ E_{35}\ (T_5^4 - T_3^4) + C(T_5 - T_3)^{5/4}] \tag{3-77}$$

$$\frac{\partial f_1(T_1)}{\partial T_1} = 4\ \varepsilon_1\sigma T_1^3 + h_w \tag{3-78}$$

$$\frac{\partial f_1(T_1)}{\partial T_3} = 4\ \sigma E_{35} T_3^3 + \frac{5}{4}\, C(T_5 - T_3)^{1/4} \tag{3-79}$$

$$E_{35} = \frac{1}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1} \tag{3-80}$$

$$f_2(T_3) = \sigma E_{13}(T_3^4 - T_1^4) + C(T_3 - T_1)^{5/4} - [\,\alpha_T \tau_g I_{TOT}$$

$$+ \sigma E_{35}(T_5^4 - T_3^4) + C(T_5 - T_3)^{5/4}] \tag{3-81}$$

$$\frac{\partial f_2(T_3)}{\partial T_1} = -[4\sigma E_{13} T_1^3 + \frac{5}{4}\, C(T_3 - T_1)^{1/4}] \tag{3-82}$$

$$\frac{\partial f_1(T_1)}{\partial T_3} = 4\sigma(E_{13} + E_{35})T_3^3 + \frac{5C}{4}[(T_3 - T_1)^{1/4}$$

$$+ (T_5 - T_3)^{1/4}] \tag{3-83}$$

$$E \quad = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1} \tag{3-84}$$

The increments ΔT_1 and ΔT_3 in T_1 and T_3 are determined by

$$\frac{\partial f_1(T_1)}{\partial T_1}\, \Delta T_1 + \frac{\partial f_1(T_3)}{\partial T_3}\, \Delta T_3 = -f_1(T_1) \tag{3-85}$$

$$\frac{\partial f_2(T_3)}{\partial T_1}\, \Delta T_1 + \frac{\partial f_2(T_3)}{\partial T_3}\, \Delta T_3 = -f_2(T_3) \tag{3-86}$$

or, writing the determinant D of the coefficient matrix (the Jacobian),

$$D = [\frac{\partial f_1(T_1)}{\partial T_1}]\ [\frac{\partial f_2(T_3)}{\partial T_3}] - [\frac{\partial f_1(T_3)}{\partial T_3}]\ [\frac{\partial f_2(T_3)}{\partial T_1}] \tag{3-87}$$

then,

$$\Delta T_1 = \frac{f_2(T_3)\ [\frac{\partial f_1(T_3)}{\partial T_3}] - f_1(T_1)\ [\frac{\partial f_2(T_3)}{\partial T_3}]}{D} \tag{3-88}$$

$$\Delta T_3 = \frac{f_1(T_1)\ [\frac{\partial f_2(T_3)}{\partial T_1}] - f_2(T_3)[\frac{\partial f_1(T_1)}{\partial T_1}]}{D} \tag{3-89}$$

The upward heat loss coefficient, U_{up} shown in Figure 3-3a is calculated from the resistances R_1, R_2, R_4, R_5, R_7 and R_8 shown in Figure 3-3b. Whillier (1963) solved a system of such equations for U_{up}. His result is of the form,

$$U_{up} = \frac{1}{\dfrac{1}{h_w + \varepsilon_1 h_{r1s}\left(\dfrac{T_1 - T_s}{T_1 - T_a}\right)} + \dfrac{1}{\tau_T E_{pg} h_{rpg} + \dfrac{1}{\dfrac{1}{h_{pT} + E_{pT} h_{rpT}} + \dfrac{1}{h_{Tg} + E_{Tg} h_{rTg}}}}} \qquad (3\text{-}90)$$

where,

h_w = 5.7 + 3.8V, (wind coefficient, $w/m^2\ ^oC$, and V is wind speed, m/s)

h_{xy} = $C(T_x - T_y)^{1/4}$, (convective coefficient)

Tilt Angle	0	30	60	90
C	1.58	1.38	1.18	0.99

h_{rxy} = $(T_x^4 - T_y^4)/(T_x - T_y)$, equivalent radiative coefficient

E_{xy} = $\dfrac{1}{\dfrac{1}{\varepsilon_x} + \dfrac{1}{\varepsilon_y} - 1}$ emmissivity factor

ε = emmissivity. εcollector = 0.95 (black paint)
= 0.20 (selective)

εplastic = 0.63

εglass = 0.88

T_s = equivalent black body temperature of the sky

T_a = ambient air temperature

T_g, T_T = temperature of glass and Tedlar, respectively

T_p = collector-plate temperature

τ_T = transmittance of plastic for long wave radiation (0.3 for Tedlar)

The collector heat loss coefficient, U_L is a function of, in addition to U_{up}, downward heat loss coefficient, U_d, and edge heat loss coefficient, U_{edge}. The relation for calculating U_L, is as follows,

$$U_L = U_{up} + U_d + U_{edge} \left(\frac{A_p}{A_c}\right) \tag{3-91}$$

where A_c is the area of the absorbing plate and A_p is the perimeter area of the collector. According to ASHRAE (1960) U_d can be determined from the following relationships

$$R_b = \frac{1}{h_{b-f} + \frac{x}{k_b} + h_{w_{b-s}}} \tag{3-92}$$

and

$$U_d = \frac{1}{R_b} \tag{3-93}$$

where X is insulation thickness in cm; h_{b-f} is the convective heat transfer between the insulation and heat transfer fluid; k_b is the thermo-conductivity coefficient of the insulation; and $h_{w_{b-s}}$ is wind coefficient.

The edge insulation loss coefficient may be obtained from the relation,

$$q_{L-edge} = 0.08\,(D)\,(P)\,(t_p - t_a) \tag{3-94}$$

where D is the depth of the collector box and P its perimeter. From equation (3-94) it is obvious that the edge loss coefficient is,

$$U_{edge} = 0.08\,(D)\,(P) \tag{3-95}$$

Edge losses are important in small solar collectors where the perimeter to collector area ratio is large. This is not the case in the present design where the ratio (A_p/A_c) is small (0.18). The recommended thickness of edge insulation is 2.54 cm and generally, it is at least half the thickness of the rear insulation depending upon the degree of exposure of the edges. Both the rear and edge loss coefficients with insulation of 7.6 cm to 12.7 cm, (as in the present design) thick of mineral wool will result in negligible heat loss through the transparent covers (Whillier, 1964). Hence, in this thesis U_L will be calculated from the relation:

$$U_L = 1.1\ U_{up} \tag{3-96}$$

3.2.5 Step 4: <u>Calculation of useful heat removed from the solar air heater</u>

An equation for useful heat removed by a fluid being heated can be obtained by considering an element of thickness dx at a distance x from the air inlet end, as shown in Figure 3-2. Whillier (1964) made three heat balances (one for the absorber plate, the second for the air stream being heated, and the third for the rear plate with no bottom heat loss) on such element. In order to solve these balances for the useful heat removed the following boundary conditions were used

a) x = 0 and t = t at the air inlet end of the collector;

b) x = L and t = t at the air exit end of the air heater.

The relationship is of the form

$$q_u = \frac{\dot{Q}_u}{A} = \left(\frac{1}{1 + \frac{U_L}{h}}\right)\left(\frac{1 - e^{-U_o/GC_p}}{U_o/GC_p}\right)[f\ I_{TOT} - U_L\ (t_1 - t_a)] \tag{3-97}$$

where,

h is the effective coefficient of heat transfer between the absorbing plate and air stream and it is given by,

$$h = h_c + 1/(\frac{1}{h_{cr}} + \frac{1}{E\, h_{rc}}); \qquad (3\text{-}98)$$

h_c: is convective heat transfer coefficient between the absorber plate and flowing air stream;

h_{cr}: is heat coefficient between rear plate and air stream;

h_{rc}: is equivalent radiative coefficient, and it is given by,

$$h_{rc} = \sigma(T_p^4 - T_r^4)/(T_p - T_r); \qquad (3\text{-}99)$$

E: is the emissivity factor given by the relation,

$$E = 1/(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_r} - 1); \qquad (3\text{-}100)$$

U_o: is overall heat transfer coefficient from air inside heater to ambient and it is given by the relation,

$$U_o = 1/(\frac{1}{U_L} + \frac{1}{h}); \qquad (3\text{-}101)$$

G = W/BL: is the mass flow rate of air per unit collector area (A = BL);

C_p: is specific heat of air;

B and L: are width and length of the collector, respectively;

f: is the effective transmissivity-absorptivity product of the collector cover system (f is the fraction of incident solar energy that is transmitted by the cover plate and absorbed by the absorbing plate);

T_p, T_r: are the absorber plate and rear plate temperatures, respectively.

From equation (3-97) the term,

$$F = (1 - e^{-U_o/GC_p})/(U_o/GC_p) \qquad (3\text{-}102)$$

is known as the "flow factor". Equation (3-97) can be used in equation (3-20) to calculate the collector efficiency at a given total solar radiation rate, I_{TOT} from the known ambient temperature t_a, inlet fluid temperature t_i, fluid flow rate W, and heat transfer properties of the solar air heater.

Among the heat transfer coefficients used in equation (3-98) no sufficiently accurate relationship for finding the convective heat transfer h_c has been formulated. This will be derived from the Navier-Stokes equation with some simplifying assumptions for a three-dimensional flow.

The derivation of the heat transfer coefficient, h_c, is made by finding a correlation for either Nusselt or Stanton numbers for fully developed heat transfer between two parallel plates. The plates are shown in Figure 3-4; the lower plate is insulated and the upper one is exposed to a constant heat flux. The velocity profile is assumed to be parabolic.

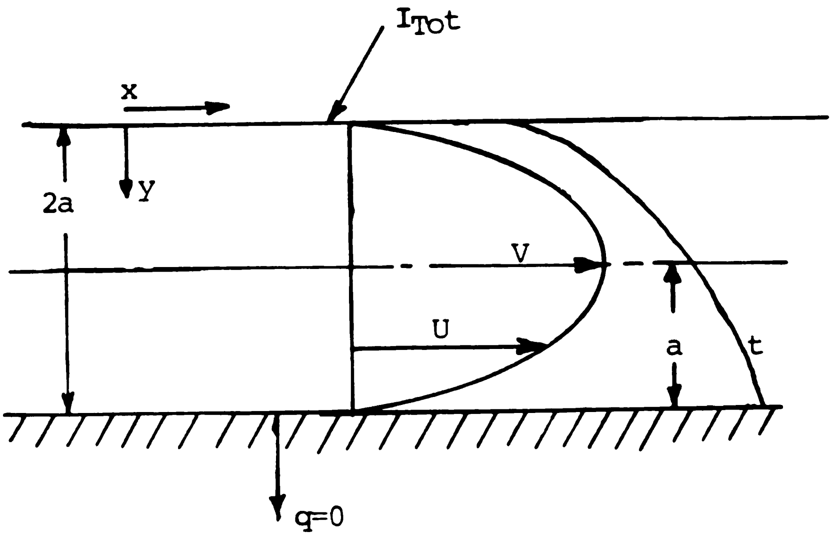


Figure 3-4. Fully developed turbulent flow in an unsymmetrically heated parallel plate channel.

Restricting the problem to constant properties, zero mass diffusion, zero chemical reaction, zero axial conduction and negligible pressure in the x-direction, for gases the following relations can be developed from the Navier-Stokes and conservation of energy equations (Kays, 1966)

$$U\rho \frac{\partial i}{\partial x} = \frac{\partial}{\partial y} \left(k \frac{\partial t}{\partial y}\right) \tag{3-103}$$

where the enthalpy change, ∂i, is given by

$$\partial i = C_p dt \tag{3-104}$$

Substituting equation (3-104) into equation (3-103) gives

$$U\rho C_p \frac{\partial t}{\partial x} = \frac{\partial}{\partial y} \left(k \frac{\partial t}{\partial y}\right) \tag{3-105}$$

According to Kays (1966) when turbulent heat transfer is present the thermal conductivity, k, in equation (3-105) is assumed "turbulent conductivity". Although the "turbulent conductivity" arises from velocity fluctuations and the flow in reality is not steady, the assumption does in effect lump all effects of the fluctuations in this term and then treats the flow as steady. From Fourier's law of heat conduction, with k replaced by $(\varepsilon_H + \alpha)$, the following equation can be written:

$$\dot{Q}/A = \rho C\ (\varepsilon_H + \alpha)\ \frac{\partial t}{\partial y} \tag{3-106}$$

Then equation (3-106) becomes

$$U\rho c\ \frac{dt}{dx} = \rho C\ \frac{\partial}{\partial y}\left[(\varepsilon_H + \alpha)\ \frac{\partial t}{\partial y} \right] \tag{3-107}$$

Restricting consideration to constant values for ρ and C yields

$$\frac{\partial}{\partial y}\left[(\varepsilon_H + \alpha)\ \frac{\partial t}{\partial y}\right] = U\ \frac{dt}{dx} \tag{3-108}$$

For fully developed constant heat rate

$$\frac{\partial t}{\partial x} = \frac{dt_m}{dx} \tag{3-109}$$

and hence,

$$\frac{\partial}{\partial y}\left[(\varepsilon_H + \alpha)\ \frac{\partial t}{\partial y} \right] = U\ \frac{dt_m}{dx} \tag{3-110}$$

The boundary conditions for temperature are

1) $t = t_p$ at $y = 0$

2) $\frac{\partial t}{\partial y} = 0$ at $y = 2a$

The expression for the velocity U in equation (3-110) is obtained from the Navier-Stokes equations. It is of the form

$$\frac{\partial^2 U}{\partial y^2} = \frac{g_c}{\mu}\frac{dP}{dx} = \text{constant} \tag{3-111}$$

and has boundary conditions:

1) $U = 0$ at $y = 0$

2) $U = 0$ at $y = 2a$

Integrating equation (3-111) twice and applying the boundary condition gives

$$U = \frac{g_c}{2\mu}\left[-\frac{dP}{dx}\right] (2ay - y^2) \tag{3-112}$$

At $y = a$, the velocity is maximum and it is of the form,

$$V = (g_c/2\mu)\, a^2 \left[-\frac{dP}{dx}\right] \tag{3-113}$$

The expression for $\frac{dt_m}{dx}$ is obtained by application of the conservation of energy principle to a small volume of the fluid being heated. As shown in Figure 3-5, the rate of creation of energy is zero.

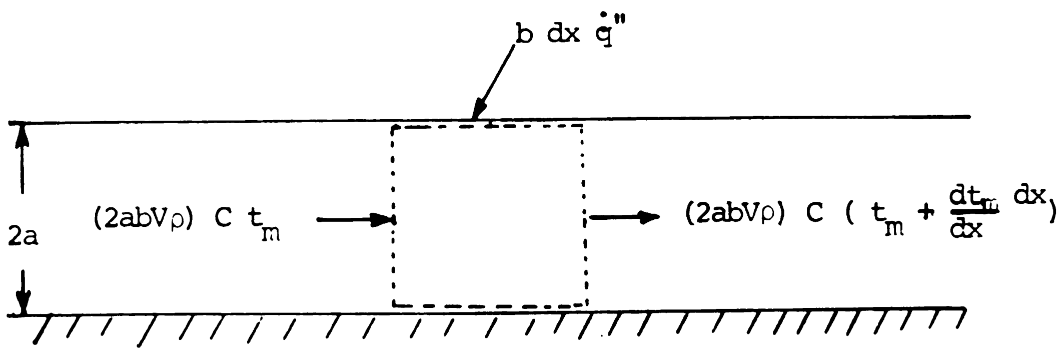


Figure 3-5. A stationary control volume for applying the conservation-of-energy principle.

The conservation-of-energy principle gives,

$$\dot{q}'' = 2a\,V\rho C\,\frac{dt_m}{dx} \tag{3-114}$$

When equations (3-112), (3-113) and (3-114) are substituted into equation (3-110), integration and application of the boundary conditions to this equation will yield the following expression for the fluid temperature t:

$$t - t_p = \frac{\dot{q}''}{2\rho C}\int_0^y \{[\,\frac{y}{a} - \frac{1}{3}\,(\frac{y}{a})^3 - \frac{4}{3}]/(\varepsilon_H + \alpha)\}\,dy \tag{3-115}$$

If y^+ is used as an independent variable and α is replaced by ν/Pr, equation (3-115) becomes

$$t - t_p = \frac{\dot{q}''}{2\rho C \sqrt{g_c \tau_o / \rho}} \int_0^{y^+} \frac{\left[\frac{y}{a} - \frac{1}{3}\left(\frac{y}{a}\right)^3 - \frac{4}{3}\right]}{\frac{\varepsilon_H}{\nu} + \left(\frac{1}{Pr}\right)} \, dy^+ \qquad (3\text{-}116)$$

where $y^+ = y \frac{\sqrt{g_c \tau_o / \rho}}{\nu}$ and positive $\dot{q}''$ is defined as heat transfer from the fluid.

The shear stress τ_o at the wall surface is evaluated from the gradient of the velocity profile at the wall. Considering the expression,

$$\tau_{xy} = \frac{\mu}{g_c} \frac{du}{dy} \qquad (3\text{-}117)$$

for $U = \frac{V}{a^2}(2ay - y^2)$, the apparent turbulent shear stress is given by the equation,

$$\tau = \tau_o \left(1 - \frac{y}{a}\right) \qquad (3\text{-}118)$$

The apparent shear stress varies linearly from a positive maximum at one wall surface to zero at the duct centerline and then to a negative maximum at another wall surface (see Figure 3-6).

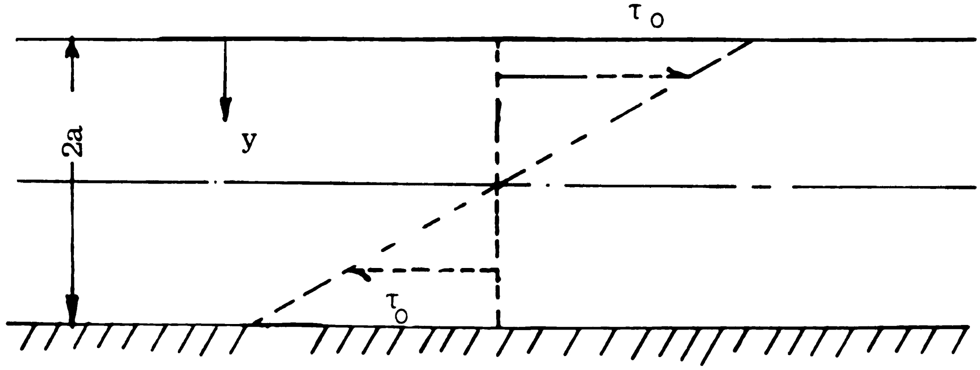


Figure 3-6. Shear stress distribution for fully developed flow in a rectangular duct.

When momentum is considered to be transferred by both molecular and turbulent processes the total apparent shear stress is described by the equation (Kays, 1966).

$$\frac{g_c \tau}{\rho} = (\varepsilon_M + \nu) \frac{du}{dy} \tag{3-119}$$

Introducing the dimensionless constant $U^+ = \dfrac{U}{\sqrt{g_c \tau_o / \rho}}$ into equation (3-119) and substituting equation (3-118) into (3-119) followed by solving for the eddy diffusivity yields:

$$\frac{\varepsilon_M}{\nu} = \frac{1 - (\frac{y}{a})}{\frac{du^+}{dy^+}} - 1 \tag{3-120}$$

A three-layer scheme (laminar sublayer, buffer layer and turbulent core), most commonly known as the "universal velocity profile" (Kays, 1966), can be applied as follows

1. for the laminar sublayer, $o < y^+ < 5$, so that,

$$U^+ = y^+,$$

$$\frac{du^+}{dy^+} = 1,$$

$$1 - \frac{y}{a} \approx 1,$$

and therefore, $\frac{\varepsilon_M}{\nu} = 0 = \frac{\varepsilon_H}{\nu}$ and by analogy,

$$t = t_p = \frac{\dot{q}''}{2\rho C} \frac{1}{\sqrt{g_c \tau_o/\rho}} \int_0^{y^+} - \frac{4}{3} \Pr dy^+ = \frac{-4\dot{q}'' \Pr y^+}{6\rho C \sqrt{g_c \tau_o/\rho}}, \text{ and}$$

using $y^+ = 5$ gives

$$t_p - t_\ell = \frac{10 \dot{q}'' \Pr}{3\rho C \sqrt{g_c \tau_o/\rho}} \qquad (3\text{-}121)$$

2. for the buffer layer, $5 < y^+ < 30$ so that,

$$U^+ = - 3.05 + 5 \ln y^+$$

$$\frac{du^+}{dy^+} = \frac{5}{y^+}$$

$$1 - \frac{y}{a} \simeq 1$$

$$\frac{\varepsilon_H}{\nu} = \frac{y^+}{5} - 1 = \frac{\varepsilon_H}{\nu}$$ and by analogy,

$$t - t_\ell = \frac{\dot{q}''}{2\rho C \sqrt{g_c \tau_o / \rho}} \int_5^{y^+} \frac{-\frac{4}{3}\, dy^+}{\frac{y^+}{5} - 1 + \frac{1}{Pr}}$$

for $y^+ = 30$,

$$t_\ell - t_b = \frac{10}{3} \frac{\dot{q}}{\rho C} \frac{\ln (5\, Pr + 1)}{\sqrt{g_c \tau_o / \rho}} \; ; \qquad (3\text{-}122)$$

3. for the turbulent core, $y^+ > 30$ so that,

$$U^+ = 5.5 + 2.5 \ln y^+,$$

$$\frac{du^+}{dy^+} = \frac{2.5}{y^+} ,$$

$$\frac{\varepsilon_H}{\nu} = y^+ \frac{(1 - \frac{y}{a})}{2.5} - 1$$

By neglecting -1 and $(\frac{1}{Pr})$, (Kays, 1966)

$$\frac{\varepsilon_H}{\nu} = y^+ \frac{(1 - \frac{y}{a})}{2.5}$$

and

$$t - t_b = \frac{\dot{q}''}{2\rho C \sqrt{g_c \tau_o/\rho}} \int_{30}^{y^+} \frac{-\frac{4}{3}(1 - \frac{y}{a})\, 2.5\, dy^+}{y^+ (1 - \frac{y}{a})},$$

$$t - t_b = \frac{-5}{3}\frac{\dot{q}''}{\rho C}\frac{\ln (y^+/30)}{\sqrt{g_c \tau_o/\rho}},$$

At the center of the duct,

$y = a$

$$y^+ = a \frac{\sqrt{g_c \tau_o/\rho}}{\nu}$$

and

$$t_b - t_c = \frac{5}{3}\frac{\dot{q}''}{\rho C}\frac{\ln [(a \sqrt{g_c \tau_o/\rho})/30\ \nu]}{\sqrt{g_c \tau_o/\rho}}, \qquad (3\text{-}123)$$

where t_c is the temperature of the fluid at the center of the duct. Equations (3-121) through (3-123) constitute the complete temperature profile. It generally is preferred to use the mixed mean fluid temperature t_m, and the absorber plate temperature t_p in finding the convective heat transfer h_c, relationship.

The fluid mean temperature t_m is given by the relationship,

$$t_m = \frac{1}{A_c V} \int_{A_c}^{o} U\, t\, dA_c \qquad (3\text{-}124)$$

where U is obtained through application of the 1/7th power law:

$$U^+ = 8.7\,(y^+)^{1/7} \qquad (3\text{-}125)$$

Using $U^+ = \frac{U}{\sqrt{g_c \tau_o/\rho}}$ in equation (3-117) yields,

$$\frac{U}{U_c} = \left(\frac{y}{a}\right)^{1/7}, \qquad (3\text{-}126)$$

and

$$\frac{t - t_p}{t_c - t_p} = \left(\frac{y}{a}\right)^{1/7} \qquad (3\text{-}127)$$

The fluid mean velocity V is given by the equation,

$$V = \frac{1}{A_c} \int_{A_c}^{o} U \, dA_c \qquad (3\text{-}128)$$

Substituting $A_c = 2ab$ and $dA_c = 2bdy$ in equation (3-128) and integrating the resulting expression between the limits of o and a gives:

$$\frac{V}{U_c} = \frac{7}{8} \qquad (3\text{-}129)$$

Substituting equations (3-127) and (3-129), $A_c = 2ab$, and $dA_c = 2bdy$ into equation (3-124) and integrating the resulting expression between the limits of o and a gives the following equation for the mean fluid temperature:

$$\frac{t_m - t_p}{t_c - t_p} = \frac{8}{9} \qquad (3\text{-}130)$$

In order to evaluate $(t_c - t_p)$ the temperature profiles are added as follows:

$$(t_p - t_c) = (t_p - t_\ell) + (t_\ell - t_b) + (t_b - t_c) \qquad (3\text{-}131)$$

Substituting for the righthand temperature differences gives

$$(t_p - t_c) = \frac{\dot{q}''}{\rho C \sqrt{g_c \tau_o/\rho}} \left[\frac{10}{3} \{Pr + \ln(5Pr + 1) + 0.5 \ln\right.$$

$$\left.\left(\frac{a \sqrt{g_c \tau_o/\rho}}{30 \nu}\right)\}\right] \qquad (3\text{-}132)$$

By definition,

$$\frac{g_c \tau_o}{\rho} = f \frac{V^2}{2}, \qquad (3\text{-}133)$$

so that the term $(a \sqrt{g_c \tau_o/\rho})/30 \nu$ can be replaced by,

$$a \frac{\sqrt{g_c \tau_o/\rho}}{30 \nu} = \frac{aV}{30} \sqrt{\frac{f}{2}} \qquad (3\text{-}134)$$

If the relationship,

$$Re = \frac{V D_H}{\nu}, \qquad (3\text{-}135)$$

where $D_H = \frac{2ab}{a + b} = 1.5a$ for $b = 3a$ is substituted into equation (3-134) gives the following expression

$$\frac{a\sqrt{g_c \tau_o/\rho}}{30\ \nu} = \frac{Re}{45}\ \frac{\sqrt{f}}{2} \qquad (3\text{-}136)$$

Substituting equation (3-136) into equation (3-132) gives,

$$(t_p - t_c) = \frac{\dot{q}''}{\rho\, v \frac{\sqrt{f}}{2}}\ [\frac{10}{3}\ \{Pr + \ln(5Pr + 1) + 0.5 \ln$$

$$(\frac{Re\ \frac{\sqrt{f}}{2}}{45})\}] \qquad (3\text{-}137)$$

The convection heat transfer h_c is defined by

$$\dot{q}'' = h_c\ (t_m - t_p) \qquad (3\text{-}138)$$

Replacing $(t_c - t_p)$ by $(t_m - t_p)/0.889$ while noting that $\frac{h_c}{V\rho C} = St$, substitution and solving for St from equation (3-129) will yield the following equation

$$St = \frac{\frac{\sqrt{f}}{2}}{0.889[\frac{10}{3}\ \{Pr + \ln(5Pr + 1) + 0.5\ \ln\ (\frac{Re\ \frac{\sqrt{f}}{2}}{45})\}]} \qquad (3\text{-}139)$$

If the following relationships are substituted into equation (3-139),

$$f_m = 0.079\ Re^{-0.25} \qquad (3\text{-}140)$$

and

$$Nu = St\ Pr\ Re, \qquad (3\text{-}141)$$

simplification of the resulting expression gives:

$$St = \frac{0.067\ Re^{-1/8}}{Pr + \ln(5Pr + 1) + 0.5\ \ln(Re^{7/8}) - 2.7} \tag{3-142}$$

$$Nu = \frac{0.067\ Re^{7/8}\ \ Pr}{Pr + \ln(5Pr + 1) + 0.5\ \ln(Re^{7/8}) - 2.7} \tag{3-143}$$

3.2.6 Preparation of in-bin solar drying equations

The basic equations for simulating the fixed bed solar grain drying process are equations (2-37) through (2-39). The solution to this system of equations can be obtained numerically with the help of a digital computer. This is feasible if these equations are written in a finite difference form. Four possible finite difference methods for computing the numerical derivatives in the model are discussed by Bakker-Arkema et al. (1977). The differencing technique which is chosen to compute the values of T, H and M at specified time-distance nodes is critical. The selected technique determines the stability requirements for Δx and Δt, thus affecting the efficiency and accuracy of the solution.

The technique proposed by Bakker-Arkema et al. (1977) for use in solar energy applications is the implicit method. It is the most stable at very low flow rates. When equations (2-37) through (2-39) are written in implicit finite difference form the following equations are obtained:

$$\rho_p(C_p + C_w M_{x,t - \Delta t})\left[\frac{T_{x,t} - T_{x,t - \Delta t}}{\Delta t}\right] + G_a[C_a + C_v H_{x-\Delta x,t}]$$

$$\left[\frac{T_{x,t} - T_{x-\Delta x,t}}{\Delta x}\right] = G_a\left[\frac{H_{x,t} - H_{x-\Delta x,t}}{\Delta x}\right] [(C_w - C_v)$$

$$(T_{x,t} - 100) - h_{fg}] \tag{3-144}$$

$$\rho_p\left[\frac{M_{x,t} - M_{x,t-\Delta t}}{\Delta t}\right] + G_a \left[\frac{H_{x,t} - H_{x-\Delta x,t}}{\Delta x}\right] = 0 \tag{3-145}$$

$$\rho_p\left[\frac{M_{x,t} - M_{x,t-\Delta t}}{\Delta t}\right] = r_m [T_{x,t}, H_{x,t}, M_{x,t-\Delta t}, t] \tag{3-146}$$

Equations (3-144) through (3-146) can be rearranged to obtain three equations which are explicit functions of $H_{x,t}$:

$$T_{x,t} = \frac{-\Delta t\ G_a(H_{x,t} - H_{x-\Delta x,t})(C_w - C_v) + \rho_p\Delta x(C_w M_{x,t-\Delta t})T_{x-\Delta x,t} + G_a\Delta t(C_a + C_v H_{x-\Delta x,t})T_{x-\Delta x,t}}{- G_a\Delta t(H_{x,t} - H_{x-\Delta x,t})(C_w - C_v) + \rho_p\Delta x(C_p + C_w M_{x,t-\Delta t}) + G_a\ \Delta t\ (C_a + C_v\ H_{x-\Delta x,t})} \tag{3-147}$$

$$M_{x,t} = -\frac{G_a\ \Delta t}{\rho_p\ \Delta x}(H_{x,t} - H_{x-\Delta x,t}) + M_{x,t-\Delta t} \tag{3-148}$$

$$M^*_{x,t} = r_m (T_{x,t}, H_{x,t}, M_{x,t-\Delta t}, t) \tag{3-149}$$

The moisture content $M^*_{x,t}$, in equation (3-149) can be obtained using either the drying or rewetting semi-theoretical equation (3-17). The complexity of the psychrometric conditions in the drying or rewetting equation call for use of a search for the value of $H_{x,t}$ which gives agreement in all the three equations simultaneously.

The search algorithm developed by Bakker-Arkema et al. (1977) is outlined below:

(1) Set initial $H_{x,t} = H_{x-\Delta x,\ t}$.

(2) Calculate $T_{x,t}$ from equation (3-147).

(3) If $RH_{x,t} < 100\%$ go to step (5).

(4) Simulate condensation to find $T_{x,t}$. Set flag.

(5) Calculate $M_{x,t}$ from (3-148).

(6) If condensation flag is set, exit.

(7) Calculate $M^*_{x,t}$ from equation (3-149).

The search terminates when H has reached a specified value of absolute humidity value of 0.0001, and the corresponding values of T and M are computed from equations (3-147) and (3-148), respectively.

√The fixed bed equations are first evaluated at each node through the depth of the dryer and then are incremented one time step. At the end of each depth iteration, the average moisture content and dry matter decomposition are computed. The equations for dry matter decomposition are taken from Thompson (1972) and are based on work by Steele et al. (1969). who developed a quantitative relation between shelled corn production of carbon dioxide (dry matter loss due to grain respiration and mold growth) and time, temperature, moisture content and mechanical damage.

3.2.7 Input data

The dryer inlet hourly data contains the following:

(1) collector outlet air dry bulb temperature,

(2) collector outlet air absolute humidity,

(3) corn temperature.

This data was obtained during the research period. The inlet humidity to the dryer is calculated using the "SYCHART" package of psychrometric functions developed by Bakker-Arkema et al. (1974) and converted to SI units by Rugumayo (1976).

3.3 Economic analysis

In this analysis the cost of additional money invested in a solar system is determined using an approach suggested by Kreider and Kreith (1976) in which the cost of fuel saved during the lifetime of the solar system is taken into account.

Based on the foregoing discussion the initial additional capital cost is converted to an annual basis by use of the equation:

$$C_h = C_{h,tot}\ CRF \tag{3-150}$$

where,

C_h = annual additional cost of the solar system (neglecting power and maintenance costs, which can be made quite small in a well-designed system), \$/year

$C_{h,tot}$ = total additional initial investment in solar hardware, \$

If the initial investment in a collector a with surface area A_a is known the initial cost of collector b with area A_b can be obtained from the relationship:

$$[C_{h,tot}]_b = [C_{h,tot}]_a \left[\frac{A_b}{A_a}\right]^{0.6} \tag{3-151}$$

CRF is capital recovery factor, \$/\$/year and is given by the relationship:

$$CRF = i_d (1 + i_d)^t / [(1 + i_d)^t - 1] \tag{3-152}$$

where i_d = the annual discount (or interest) rate, \$/\$/year

t = the expected lifetime of the solar system, years

In order to compare C_h with the cost of other fuels it is necessary to define the cost of delivered solar energy C_{se}:

$$C_{se} = \frac{\text{additional annual cost of solar collector}}{\text{total annual solar-energy delivered}} \qquad (3\text{-}153)$$

The total annual solar energy delivered is the total useful energy, Q_u collected during the drying period. The value of C_{se}, expressed in dollars per million watts, is the index used for comparing solar drying with other drying systems. The analysis does not take into account the fuel price escalation rate.

CHAPTER FOUR

EXPERIMENTAL INVESTIGATIONS

4.1 Low temperature thin-layer corn drying/rewetting operation

Thin-layer drying and adsorption data were obtained using the experimental set up drawn in Figure 4-1. The temperature of the cold room E, was adjusted to the desired ambient temperatures shown in Table 4-1 using a thermostatically controlled unit. The relative humidity and dry bulb temperature of the air used for drying and/or rewetting of corn were set as desired and controlled by the Aminco air unit as shown in Table 4-1.

For every drying run the temperature of the air used for corn drying was about 5.5°C warmer than that of the cold room. This results in the relative humidity of the heated air being always slightly greater than half that of the room air. Since the moisture content of the wet product is greater than the equilibrium moisture content of the cold room air, a moisture gradient between the drying air and the wet product exists. Two 75 gm samples of the wet product were put into two 10 cm by 12.7 cm by 0.8 cm wire mesh boxes and the boxes were placed in test chamber B shown in Figure 4-1.

Each drying run was followed by a rewetting operation except for the last two tests. The end of each drying operation was determined when there appeared to be no weight change in the corn over a period of time. All rewetting runs, on the other hand, were terminated after ten hours since adsorption appeared to be slower than desorption. The air velocity was not considered to affect either drying or rewetting operations significantly and was, therefore, kept constant at 1.524 m/min.

The moisture content of corn, both initial and final, were determined by the standard air-oven method as described in Brooker et al. (1974). In addition, hourly records of the following important properties were kept:

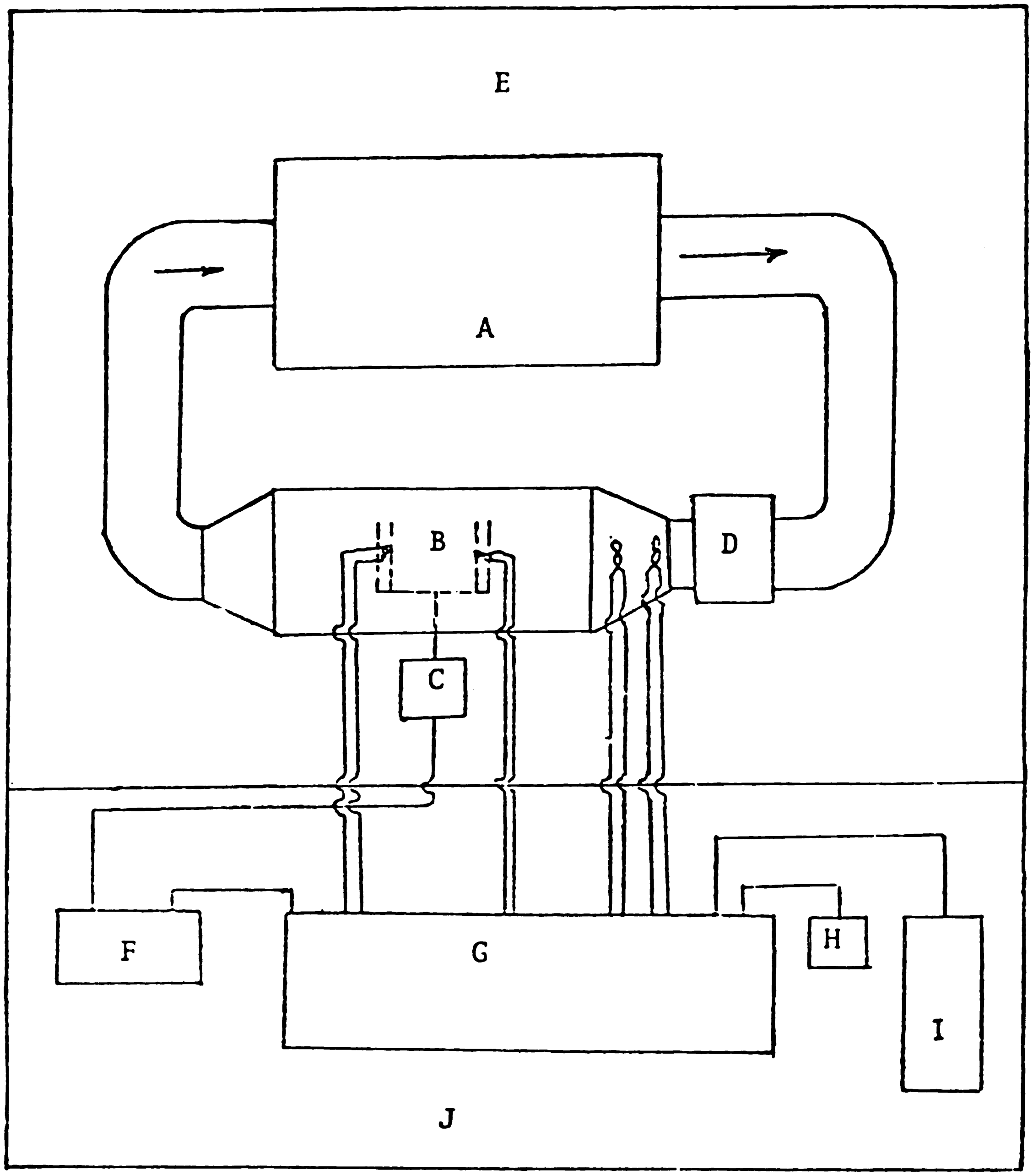
a) Corn weight measured with the load cell, C, and the differential transformer-transducer, F, connected to the multichannel recorder G.

b) Room air wet and dry bulb temperatures measured with calibrated J-type (copper-constantan) thermocouples and the self-powered thermocouple reference junction H, of Figure 4-1. The thermocouples for measuring wet bulb temperature was covered with a wet wick.

c) Dry bulb box air temperature measured as in part (b) at three different locations along the width of the box B of Figure 4-1 to observe possible large temperature variations.

d) Box inlet wet and dry bulb temperatures measured as in part (b).

e) Corn temperature measured at as many (10) locations as possible. The thermocouples for measuring corn temperature were imbedded in the corn kernels. Many thermocouples were used for checking possible large temperature variations.



A. Aminco-Air Unit
B. Test Chamber
C. Daytronic 152A-1 Low Range Weight Recording Load Cell
D. Heater
E. Cold Room
F. Model 300D-71 Daytronic Differential Transformer Transducer
G. 20-Channel Model D2020 Esterline Angus Programmable Data Acquisition System (PDAS)
H. Omega-Selfpowered Thermocouple Reference Junction
I. Type 4070 FACIT Paper Tape Punch
J. Warm Temperature Working Room

Figure 4-1: Schematic Diagram of the Experimental Low-Temperature, Thin-Layer Corn Drying Equipment.

Table 4-1. Thin-layer corn drying and rewetting conditions.

Test No.	Operation	Room Temp. °C	Aminco Outlet or Test Box Inlet Air Temp. °C	Aminco Water Temp. °C	Relative Humidity %
1a	Drying	15.5	21.1	11.4	60
1b	Rewetting	15.5	21.1	21.1	90
2a	Drying	15.5	21.1	8.2	50
2b	Rewetting	15.5	21.1	21.1	90
3a	Drying	15.5	21.1	3.7	40
3b	Rewetting	15.5	21.1	21.1	90
4a	Drying	10.0	15.5	0.4	50
4b	Rewetting	10.0	15.5	15.5	85
5	Drying	4.4	10.0	No water	40
6	Drying	-1.1	4.4	No water	30

Rewetting runs were not made following drying runs 5 and 6 because the Aminco unit had no water for changing the air relative humidity. No drying or rewetting was done at room temperatures less than -1.1°C due to improper functioning of the load cell.

4.2 Solar energy collection and in-bin corn drying

Solar collector and grain drying data were obtained using an experimental set up of Figure 4-2. The flat plate solar collector number 11 in Figure 4-2 has the following components:

a) Two transparent top cover plates. A 0.3175 cm thick tempered, colorless window glass with low iron content was placed above a 4 mil Tedlar cover.

b) A 0.55 mm thick absorber copper plate. The absorber plate surface facing the sun was coated with Krylon No. 1602 (carbon black 50%, silicates 50%) ultra flat black paint. The paint is selective in energy emissivity (ε = 0.2 for long wave radiation) and absorptivity (α = 0.95 for solar energy). The low iron colorless glass plate and the selective coating help to increase the collector efficiency at temperatures typical of the flat plate solar collectors (Goodman and Menke, 1975).

c) Back insulation (16.51 cm thick) consisting of about 12 cm of wool placed between a 3.81 cm thick hard wood board and a 0.70 cm thick plywood board. The hard board was placed at the bottom for protection.

d) Side insulation made of a 3.81 cm thick hard wood.

The arrangement of the various collector parts is shown in Figure 3-2. The two 1.905 cm spaces between glass, Tedlar and the copper plates were covered at both the air inlet and outlet ends by 3.81 cm thick hard wood boards. The 15.24 cm open space formed the passage for the heated air. Cold ambient air was drawn into the passage by a 3 horsepower (HP) axial flow fan shown in Figure 4-3. As the air passed through the duct it picked up heat from the absorber plate.

The heated air from the solar collector moved through a 10.16 cm diameter duct connecting the collector outlet and the axial flow fan inlet end past the fan to the drying corn bin. The duct was wrapped in 7.62 cm thick insulation wool. The bin (1.68 m. diameter and 1.98 m. deep) construction is shown in Figure 4-3.

The collector was inclined at 52^{o} from the horizontal. This angle was chosen by considering the collector location, and the time of the year when drying takes place (the fall in East Lansing, Michigan). The collector faced south so that the sun's rays hit the collector at normal incidence at solar noon.

Data were recorded on a paper recorder number 12 in Figure 4-2 as acquired by the 20-channel Esterline Angus number 14 of the same figure. Data was recorded for the following parameters:

a) Ambient air wet and dry bulb temperatures continuously measured with calibrated J-type (copper-constantan) thermocouples. Calibration was done by taking the thermocouple and mercury-in-glass thermometer readings versus time at the ice point (0^{o}C) and during heating of the ice-water to the water boiling point about (100^{o}C). A linear regression analysis was made on the readings (in mv) of the thermocouple against the thermometer readings (in ^{o}C) to obtain the desired calibrations for the thermocouples used.

b) Total solar radiation on a horizontal surface continuously recorded by means of a solarimeter numbered 15 in Figure 4-2;

and integration of the records to give hour-by-hour reception. The solarimeter was radiometer MK1-G 801-A - Meter with an output of 5 mv per cal cm^{-2} min^{-1} (or 0.0142 w/m^2) and an accuracy of ± 5%. It measures both direct and diffuse radiation in w/m^2.

c) Wind velocity continuously measured by means of a wind vane numbered 17 in Figure 4-2. The continuous readings were integrated to obtain hour-by-hour values in meter per hour. The wind velocity measurements were made at as close to the solar collector surface as was possible. Both the solarimeter and wind vane outputs were calibrated against a transistorized power supply unit numbered 16 in Figure 4-2.

d) Collector plate inlet and outlet temperatures continuously measured with calibrated J-type thermocouples, and integrated over hourly periods.

e) Collector air inlet and outlet temperatures recorded as in (d).

f) Airflow rate measured at the collector outlet and along the 10.16 cm diameter aluminum duct, numbered 10 in Figure 4-2. Measurement of the airflow rate was done with type "C" micromanometer gauge at three almost equal distances within the collector air heater and the 10.16 cm diameter duct. The average of the three readings was used in each case to calculate the airflow in cubic meters per minute.

g) Fan inlet, plenum chamber, corn interstitial and bin outlet air temperatures were recorded as in (d).

h) Initial moisture content of wet corn was determined by the air-oven method.

i) Corn moisture content at various bin locations was checked as in (h) to observe the movement of the drying front and to monitor potential problems.

j) Initial and final weight of corn were determined with a weighing scale. Regular checks on corn depth drop in the bin were made. At the end of corn drying the corn depth drop in the bin was only 2 inches.

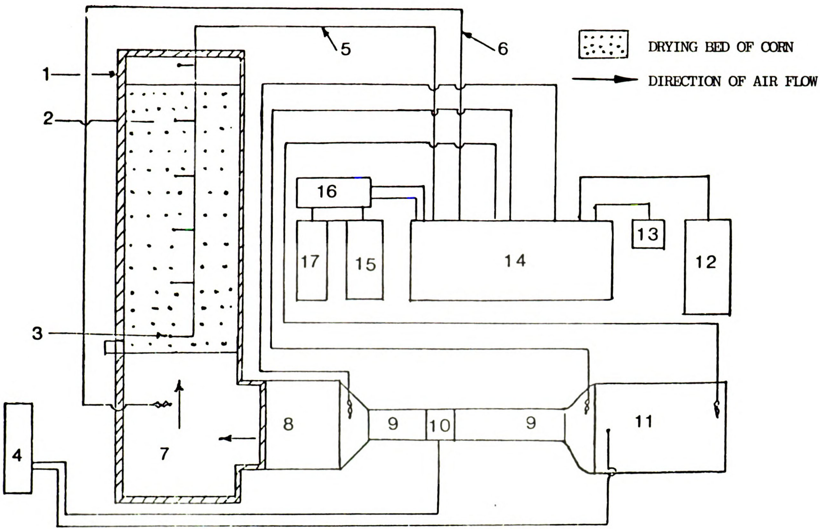


Figure 4-2: Schematic Diagram of the Experimental Solar Collector Bin Dryer Equipment.

Figure 4-2 (cont'd).

1. Bin
2. Grain Sampling Tube
3. Thermocouple Junctions
4. Micromanometer
5-6. Thermocouples
7. Plenum Chamber
8. Axial Flow Fan
9. Air Duct
10. A 4-inch Diameter Adaptor
11. Flat Plate Solar Collector
12. Type 4070 FACIT Paper Tape Punch
13. Omega Self-Powered Thermocouple Reference Junction
14. A 20-Channel Model 2020 Esterline Angus Programmable Data Acquisition System (PDAS)
15. Solarimeter
16. A 6V Model 1020 Transistorized Power Supply Unit
17. Wind Vane

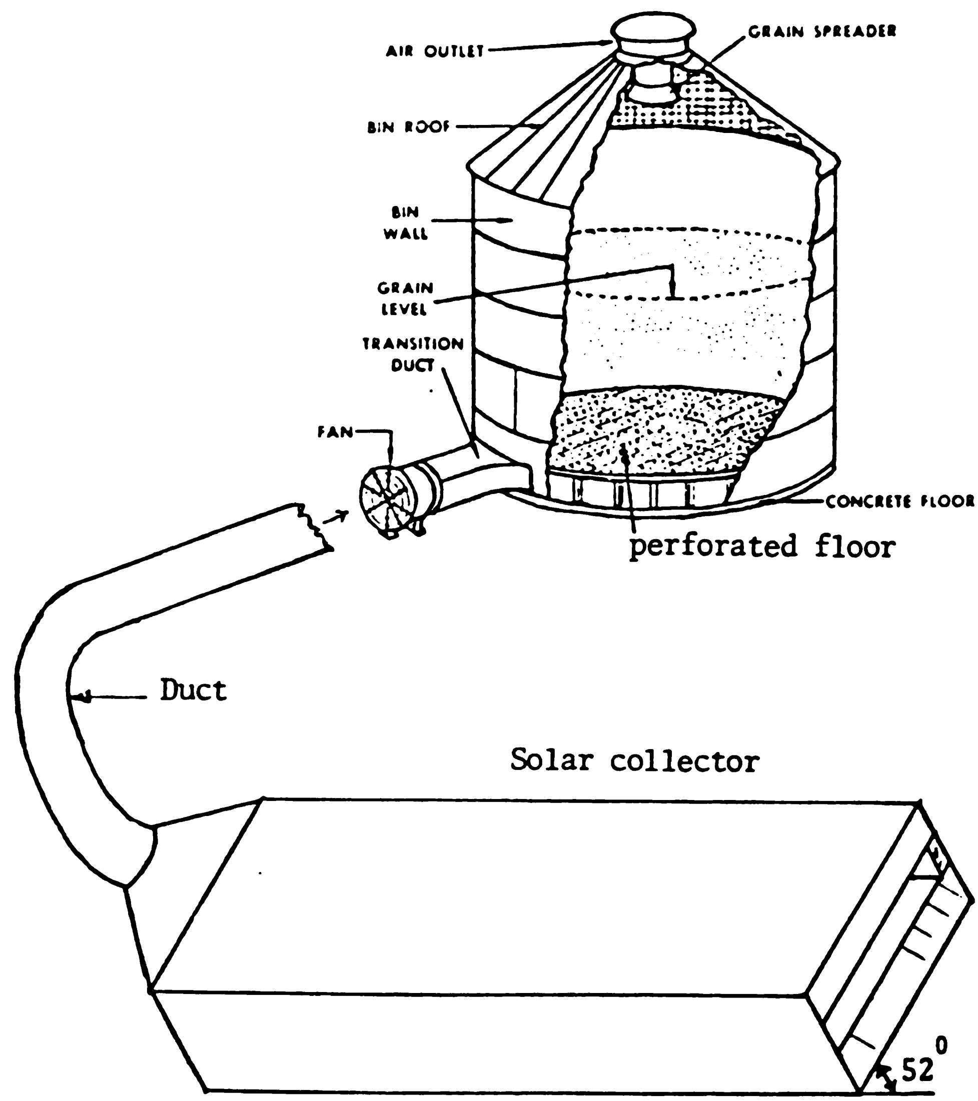


Figure 4-3: Perforated False Floor System for Bin Drying of Corn with air heated in a flat plate solar collector.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

The primary objectives of this study are to develop and evaluate a method for corn drying using low-temperature solar-heated air. The economic consideration is presented only as a means for comparing this type of drying system with conventional ones.

In this chapter experimental and simulated results will be compared. Thin-layer corn drying and moisture absorption equations, efficiency of the flat-plate solar air heater and moisture content of solar dried corn in a fixed bed will be presented.

5.1.1. Thin-layer corn drying results.

Six tables (5-1a through 5-1f) list the experimental thin-layer drying corn moisture content (dry basis), corn drying diffusion parameter (K in hr^{-1}), drying air equilibrium moisture content, relative humidity and vapor pressure. The experimental corn moisture content was calculated from continuous weight recordings as follows:

$$M_t = \frac{W_{t-1} - W_t}{W_t} \qquad (5\text{-}1)$$

Where M is corn moisture content (dry basis) at a time, t; W is corn weight in grams. Equilibrium moisture content, air relative humidity and vapor pressure were calculated using the deBoer equilibrium moisture content equations and the psychrometric chart equations presented by Brooker et al. (1974). The parameter, K (or DIFK) was calculated from equation (3-17) with time, t, set equal to one hour. The flow was kept constant at 1.52 m/min. in all the thin-layer experiments.

The drying parameter, listed in column three of Tables 5-la through 5-1f is plotted against drying time, t in Figures A-1 through A-6 of Appendix A. The plots indicate that the parameter, K is not a constant. Equation (3-18) describes the relationship of the drying parameter, K to the corn moisture content, temperature and air relative humidity. The unknown constants of the drying equation were determined by non-linear parameter estimation (Beck and Arnold, 1975) using data of the six drying tests in the computer program "NLINA" listed in Appendix B. Non-constant values of temperature and relative humidity from each test were used to determine the constants in equation (3-18) instead of the preset values listed in Table 4-1. The values of the constants (C_1=27.5326, C_2=42.6959, C_3=28.3811, and C_4=0.0042) determined with the preset values are slightly different from those obtained with non constant values of temperature and relative humidity. The moisture content (after five hours during drying test one, the corn moisture content is 27.39% instead of the experimental value of 25.15%) predicted by the equation containing values of the constants determined with constant values of temperature and relative humidity for each test is less accurate than the moisture content (25.83% after five hours in test one) predicted the equation developed in this thesis.

The thin-layer corn drying model obtained from equation (3-17) with the parameter, K replaced by equation (3-18) which has the values of the unknown constants determined with non constant values of temperature and relative humidity is as follows

$$M_t=(M_o-M_c)\ \exp\ [(25.5920-38.6298M_{t-1}\ +26.6824\ \log\ (M_{t-1})-$$

$$0.0044\ \Theta_t(M^2_{t-1})\ \exp\ (rh_t{}^2)\ t]\ +\ M_e \qquad (5\text{-}2)$$

The moisture content predicted by equation (5-2) was compared with previously used thin-layer equations for low-temperature drying (Sabbah et al. 1968 and Misra, 1978) Equation (2-1) represents the Sabbah et al. (1968) relationship while the equation by Misra is the following

$$M=(M_o-M_e)\ \exp\ [-(\exp(-7.1735+1.2793\ \ell n\ (1.8T+32)\ +\ 0.0061V))$$

$$t^{(0.0811\ \ell n\ (rh)\ +\ 0.0078\ M_o)}]\ +\ M_e \qquad (5\text{-}3)$$

where

T is drying air temperature in ^oC;

V is air flow rate in m per minute;

rh is air relative humidity, percent

and t is time in hr.

Tables 5-1g through 5-1ℓ list both experimental and simulated corn thin-layer moisture content. Figures 5-1a through 5-1f are plots of experimental and simulated corn thin-layer drying moisture contents.

5.1.2 Discussion of corn thin-layer drying results

The foregoing results show that the drying model developed in the present study shows better agreement with the experimental data of moisture content values than the Sabbah et al. (1968) and the Misra (1978) drying models. The Sabbah et al. (1968) model (SAB) has two independent variables only (grain temperature and air relative humidity) even though it was developed with data of almost the same corn temperature range ($2.2^{\circ}C$ to $21.1^{\circ}C$) as used in this thesis. The effect of corn moisture content is considered together with non constant grain temperature and air relative humidity in developing the corn drying model in the present study. The Misra (1978) equation, on the other hand, was developed using data covering too wide a temperature range ($2^{\circ}C$ to $71^{\circ}C$) to consider it for use in simulating low-temperature corn drying with acceptable accuracy. A further test of the three corn drying equations will be discussed later in the solar or low-temperature deep bed corn drying simulation section.

Table 5-1a. Experimental thin-layer corn drying test one results for drying air temperature of 21.0°C and air relative humidity of 60%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
XME = Equilibrium moisture content
TAIR = Drying air temperature
RH = Air relative humidity
TGRN = Corn temperature
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2777	.0000	292.11	287.05	.1374	.5396	1.5870
1.0	.2718	.0452	293.49	287.66	.1450	.5844	1.6510
2.0	.2693	.0642	293.99	287.88	.1423	.5734	1.6749
3.0	.2684	.0729	293.44	287.72	.1458	.5860	1.6569
4.0	.2658	.0893	292.11	287.27	.1392	.5481	1.6100
5.0	.2515	.2155	293.77	287.88	.1428	.5751	1.6749
6.0	.2481	.2535	293.38	287.72	.1457	.5874	1.6569
7.0	.2473	.2571	292.88	287.44	.1436	.5738	1.6276
8.0	.2300	.3452	292.49	287.77	.1417	.5681	1.6629
9.0	.2329	.4026	293.44	287.94	.1425	.5715	1.6809
10.0	.2303	.4402	293.16	287.61	.1447	.5809	1.6451
11.0	.2219	.5498	293.44	287.88	.1458	.5880	1.6749
12.0	.2193	.5803	293.66	287.99	.1452	.5862	1.6869
13.0	.2025	.8592	293.22	288.16	.1472	.5940	1.7051
14.0	.1982	.9155	293.66	287.99	.1452	.5862	1.6869
15.0	.1974	.9055	293.77	287.99	.1428	.5751	1.6869
16.0	.1948	.9408	293.49	287.88	.1417	.5681	1.6749
17.0	.1932	1.0239	293.49	288.05	.1458	.5886	1.6929
18.0	.1906	1.0632	293.16	287.99	.1447	.5809	1.6869
19.0	.1855	1.1410	293.99	288.11	.1423	.5734	1.6990
20.0	.1805	1.2645	293.99	288.33	.1423	.5734	1.7235
21.0	.1762	1.4504	293.66	288.44	.1452	.5862	1.7358
22.0	.1754	1.4407	292.16	287.55	.1437	.5699	1.6392
23.0	.1745	1.4921	293.05	287.66	.1446	.5797	1.6510
24.0	.1728	1.5201	292.77	287.49	.1435	.5725	1.6333
25.0	.1704	1.7296	293.22	287.72	.1472	.5940	1.6569
26.0	.1687	1.5153	293.77	287.99	.1380	.5509	1.6869
27.0	.1618	2.0383	292.94	287.16	.1445	.5785	1.5984

Table 5-1b. Experimental thin-layer corn drying test two results for drying air temperature of 21.0°C and air relative humidity of 50%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
TAIR = Drying air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2699	.0000	293.16	287.33	.1296	.5076	1.6158
1.0	.2606	.0685	292.83	286.72	.1299	.5074	1.5530
2.0	.2505	.1477	292.61	286.72	.1286	.5004	1.5530
3.0	.2445	.1996	293.77	287.44	.1297	.5112	1.6275
4.0	.2378	.2580	293.22	287.33	.1288	.5043	1.6158
5.0	.2310	.3497	293.22	287.44	.1381	.5486	1.6275
6.0	.2234	.3909	293.49	287.44	.1263	.4999	1.6275
7.0	.2167	.4761	292.11	286.77	.1295	.5021	1.5586
8.0	.2133	.5154	292.05	286.99	.1294	.5013	1.5813
9.0	.2005	.5702	293.11	287.27	.1240	.4830	1.6100
10.0	.2040	.6034	292.99	287.22	.1245	.4855	1.6042
11.0	.2023	.6491	293.44	287.55	.1284	.6031	1.6392
12.0	.1989	.7121	291.72	286.88	.1305	.5053	1.5699
13.0	.1930	.7612	292.38	287.05	.1257	.4894	1.5870
14.0	.1905	.8371	293.33	287.66	.1298	.5097	1.6510
15.0	.1879	.8447	292.27	287.22	.1262	.4920	1.6042
16.0	.1812	.9779	291.94	286.22	.1277	.4999	1.5031

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Table 5-1c. Experimental thin-layer corn drying test three results for drying air temperature of 21.0°C and air relative humidity of 40%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
TAIR = Drying air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2831	.0000	293.55	285.27	.1091	.3858	1.4129
1.0	.2764	.0396	293.61	287.27	.1091	.3867	1.6100
2.0	.2654	.1082	293.66	287.61	.1098	.3913	1.6451
3.0	.2526	.1935	293.94	287.11	.1096	.3919	1.5927
4.0	.2432	.2613	294.22	287.27	.1095	.3925	1.6100
5.0	.2339	.3335	294.16	287.49	.1094	.3916	1.6333
6.0	.2305	.4262	291.16	288.16	.1313	.5063	1.7051
7.0	.2254	.4085	293.77	288.05	.1110	.4004	1.6929
8.0	.2220	.4388	293.77	288.11	.1110	.4004	1.6990
9.0	.2169	.4832	294.11	288.49	.1104	.3981	1.7420
10.0	.2135	.5087	293.16	288.16	.1085	.3796	1.7051
11.0	.2109	.5392	292.66	287.94	.1099	.3867	1.6809
12.0	.2059	.5843	293.22	287.83	.1086	.3805	1.6689
13.0	.1982	.6652	293.38	288.05	.1033	.3794	1.6929
14.0	.1973	.6960	293.77	288.16	.1120	.4078	1.7051
15.0	.1940	.7319	294.11	288.38	.1114	.4054	1.7296
16.0	.1906	.7743	294.11	288.49	.1114	.4054	1.7420
17.0	.1770	.9376	292.55	286.99	.1087	.3772	1.5813

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Table 5-1d. Experimental thin-layer corn drying test four results for drying air temperature of 15.5°C and air relative humidity of 50%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
TAIR = Drying air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2810	.0000	286.88	280.55	.1268	.4647	1.0294
1.0	.2657	.1024	287.49	281.55	.1240	.4507	1.1019
2.0	.2564	.1848	288.27	282.44	.1352	.5107	1.1701
3.0	.2479	.2454	286.83	281.66	.1291	.4786	1.1102
4.0	.2428	.3113	288.72	282.49	.1382	.5266	1.1744
5.0	.2385	.3441	286.88	281.99	.1352	.5044	1.1355
6.0	.2292	.4512	286.83	281.77	.1385	.5186	1.1186
7.0	.2242	.4936	286.88	281.61	.1352	.5044	1.1060
8.0	.2216	.5038	286.49	282.33	.1310	.4998	1.1613
9.0	.2208	.5095	288.94	282.88	.1301	.4971	1.2055
10.0	.2190	.5419	288.22	282.77	.1330	.5004	1.1966
11.0	.2132	.5995	288.22	282.27	.1306	.4957	1.1570
12.0	.2114	.6217	286.88	281.94	.1398	.4894	1.1313
13.0	.2097	.6443	285.99	282.05	.1310	.4912	1.1398
14.0	.2080	.6360	288.66	282.66	.1260	.4698	1.1877
15.0	.2055	.6678	288.22	282.38	.1260	.4674	1.1657
16.0	.2038	.7232	286.99	281.99	.1310	.4912	1.1355
17.0	.2021	.7826	287.11	282.38	.1357	.5078	1.1657
18.0	.1996	.8266	288.27	282.44	.1363	.5155	1.1701
19.0	.1953	.8290	287.22	282.05	.1290	.4800	1.1398
20.0	.1927	.8794	287.94	282.72	.1302	.4914	1.1921
21.0	.1903	.9735	288.27	282.49	.1352	.5107	1.1744
22.0	.1894	.9742	288.16	282.55	.1339	.5043	1.1788
23.0	.1877	1.0467	287.27	282.27	.1373	.5153	1.1570

Table 5-1d. Continued

Time Hr	EXMC Decimal	DIFK Hr-1	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
24.0	.1834	1.0467	288.27	282.44	.1307	.4965	1.1701
25.0	.1817	1.0634	288.44	282.83	.1294	.4896	1.2010
26.0	.1809	1.0951	287.22	282.33	.1306	.4898	1.1613
27.0	.1767	1.2105	288.88	282.99	.1324	.5009	1.2145
28.0	.1758	1.1904	288.77	282.72	.1299	.4946	1.1921
29.0	.1750	1.3005	287.38	282.11	.1353	.5071	1.1441
30.0	.1741	1.2911	288.49	282.61	.1336	.5045	1.1823
31.0	.1716	1.3589	288.55	282.66	.1337	.5054	1.1877
32.0	.1554	1.8339	287.83	277.16	.1316	.4993	.6140

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Table 5-1e. Experimental thin-layer corn drying test five results for drying air temperature of 10.0°C and air relative humidity of 40%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
TAIR = Drying air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2766	.0000	282.55	277.22	.1253	.4324	.8172
1.0	.2716	.0316	282.55	277.11	.1155	.3689	.8108
2.0	.2682	.0530	282.11	276.94	.1136	.3527	.8014
3.0	.2640	.0818	283.22	277.55	.1163	.3782	.8365
4.0	.2589	.1138	281.83	276.94	.1121	.3402	.8014
5.0	.2563	.1370	282.72	277.05	.1184	.3898	.8077
6.0	.2513	.1692	282.38	277.16	.1143	.3593	.8140
7.0	.2496	.1778	281.99	276.88	.1110	.3326	.7983
8.0	.2462	.2059	282.66	277.22	.1133	.3543	.8172
9.0	.2428	.2358	282.33	277.05	.1157	.3695	.8077
10.0	.2411	.2448	282.27	277.11	.1132	.3509	.8108
11.0	.2395	.2638	282.33	276.88	.1166	.3753	.7983
12.0	.2361	.2856	282.11	276.99	.1136	.3527	.8045
13.0	.2344	.3091	282.83	277.38	.1178	.3865	.8268
14.0	.2344	.2956	282.27	277.05	.1116	.3394	.8077
15.0	.2335	.3167	283.22	277.83	.1180	.3893	.8529
16.0	.2352	.2935	282.27	277.22	.1140	.3567	.8172
17.0	.2335	.3094	282.27	277.22	.1148	.3624	.8172
18.0	.2318	.3282	282.33	277.16	.1166	.3753	.8140
19.0	.2301	.3449	282.61	277.38	.1173	.3816	.8268
20.0	.2293	.3502	282.27	277.33	.1164	.3740	.8236
21.0	.2277	.3536	282.55	277.44	.1123	.3460	.8300
22.0	.2268	.3638	282.66	277.22	.1133	.3543	.8172

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Table 5-1f. Experimental thin-layer corn drying test six results for drying air temperature of 4.4°C and air relative humidity of 30%

EXMC = Experimental corn moisture content
DIFK = Drying parameter, K.
TAIR = Drying air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	DIFK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.2965	.0000	280.55	276.22	.1066	.2890	.7616
1.0	.2922	.0229	278.49	273.66	.1094	.2980	.6344
2.0	.2853	.0599	278.27	273.16	.1049	.2636	.6119
3.0	.2827	.0748	278.49	273.27	.1059	.2716	.6168
4.0	.2811	.0837	278.27	273.16	.1049	.2636	.6119
5.0	.2785	.0991	278.49	273.49	.1059	.2716	.6268
6.0	.2759	.1142	278.49	273.44	.1059	.2716	.6243
7.0	.2673	.1649	278.27	273.33	.1049	.2636	.6193
8.0	.2647	.1849	278.27	273.38	.1086	.2903	.6218
9.0	.2613	.2029	278.27	273.11	.1049	.2636	.6122
10.0	.2570	.2329	278.72	273.49	.1068	.2794	.6268
11.0	.2562	.2360	278.27	273.27	.1049	.2636	.6168
12.0	.2553	.2508	278.72	273.61	.1110	.3122	.6319
13.0	.2536	.2628	278.72	273.55	.1110	.3122	.6293
14.0	.2519	.2723	278.49	273.49	.1094	.2980	.6268
15.0	.2493	.2877	278.05	273.05	.1077	.2825	.6094
16.0	.2475	.2948	278.27	273.27	.1049	.2636	.6143
17.0	.2450	.3198	278.27	273.16	.1086	.2903	.6119
18.0	.2433	.3174	279.22	273.83	.1010	.2440	.6421
19.0	.2424	.3443	278.72	273.55	.1110	.3122	.6293
20.0	.2407	.3439	278.27	273.16	.1049	.2636	.6119
21.0	.2398	.3524	277.83	272.99	.1059	.2678	.6066
22.0	.2381	.3654	277.83	272.83	.1059	.2678	.5983
23.0	.2364	.3566	277.83	272.77	.0962	.2139	.5956
24.0	.2355	.3748	277.83	272.88	.1015	.2408	.6010
25.0	.2313	.4235	278.05	272.83	.1077	.2825	.5983

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Table 5-1g. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test one for drying air temperature of 21.0°C and air relative humidity of 60%

HR = Time in hours

EXMC = Measured moisture content, decimal

SAB = Moisture content by Sabbah eqn., decimal

MISRA = Moisture content by Misra eqn.

RUG = Moisture content by Rugumayo eqn., decimal

DIFK = Drying parameter, K in hr^{-1}

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2777	.2777	.2777	.2777	
1.0	.2718	.2484	.2603	.2627	.0452
2.0	.2693	.2373	.2557	.2608	.0642
3.0	.2684	.2318	.2535	.2600	.0729
4.0	.2658	.2248	.2507	.2595	.0893
5.0	.2515	.2209	.2489	.2583	.2155
6.0	.2481	.2188	.2480	.2504	.2535
7.0	.2473	.2152	.2466	.2477	.2571
8.0	.2380	.2109	.2446	.2467	.3452
9.0	.2329	.2085	.2434	.2391	.4026
10.0	.2303	.2080	.2432	.2350	.4402
11.0	.2219	.2061	.2422	.2329	.5498
12.0	.2193	.2037	.2410	.2244	.5803
13.0	.2025	.2027	.2405	.2225	.8592
14.0	.1982	.2004	.2394	.2041	.9155
15.0	.1974	.1975	.2381	.1982	.9055
16.0	.1948	.1957	.2373	.1968	.9408
17.0	.1932	.1965	.2374	.1964	1.0239
18.0	.1906	.1948	.2366	.1941	1.0632
19.0	.1855	.1918	.2352	.1900	1.1410
20.0	.1805	.1902	.2343	.1848	1.2645
21.0	.1762	.1908	.2343	.1821	1.4504
22.0	.1754	.1910	.2347	.1771	1.4407
23.0	.1745	.1903	.2342	.1771	1.4921
24.0	.1728	.1891	.2337	.1755	1.5201

Table 5-1g. Continued

HR	EXMC	SAB	MISRA	RUG	DIFK
25.0	.1704	.1902	.2338	.1768	1.7296
26.0	.1687	.1826	.2305	.1677	1.5153
27.0	.1618	.1882	.2330	.1714	2.0383

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Table 5-1h. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test two for drying air temperature of 21.0°C and air relative humidity of 50%

HR = Time in hours

EXMC = Measured moisture content, decimal

SAB = Moisture content by Sabbah eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

DIFK - Drying parameter, K in hr^{-1}

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2699	.2699	.2699	.2699	
1.0	.2606	.2398	.2522	.2528	.0685
2.0	.2505	.2292	.2480	.2480	.1477
3.0	.2445	.2216	.2448	.2412	.1996
4.0	.2378	.2159	.2426	.2362	.2580
5.0	.2310	.2151	.2423	.2323	.3497
6.0	.2234	.2064	.2386	.2227	.3909
7.0	.2167	.2059	.2387	.2157	.4761
8.0	.2133	.2025	.2372	.2083	.5154
9.0	.2065	.1967	.2347	.2021	.5702
10.0	.2040	.1947	.2338	.1943	.6034
11.0	.2023	.1939	.2332	.1934	.6491
12.0	.1989	.1946	.2337	.1926	.7121
13.0	.1930	.1898	.2316	.1861	.7612
14.0	.1905	.1890	.2309	.1819	.8371
15.0	.1879	.1864	.2300	.1770	.8447
16.0	.1812	.1883	.2309	.1751	.9779

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Table 5-1i. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test three for drying air temperature of 21.0°C and air relative humidity of 40%

HR = Time in hours

EXMC = Measured moisture content, decimal

SAB = Moisture content by Sabbah eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

DIFK = Drying parameter, K in hr^{-1}

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2831	.2831	.2831	.2831	
1.0	.2764	.2451	.2607	.2688	.0396
2.0	.2654	.2319	.2557	.2667	.1082
3.0	.2526	.2239	.2530	.2610	.1935
4.0	.2432	.2169	.2504	.2510	.2613
5.0	.2339	.2109	.2481	.2414	.3335
6.0	.2305	.2145	.2491	.2362	.4262
7.0	.2254	.2016	.2443	.2267	.4085
8.0	.2220	.1979	.2428	.2201	.4388
9.0	.2169	.1934	.2409	.2153	.4832
10.0	.2135	.1904	.2401	.2076	.5087
11.0	.2109	.1891	.2395	.2034	.5392
12.0	.2059	.1863	.2385	.1992	.5843
13.0	.1982	.1833	.2372	.1919	.6652
14.0	.1973	.1830	.2366	.1831	.6960
15.0	.1940	.1801	.2353	.1815	.7319
16.0	.1906	.1780	.2343	.1770	.7743
17.0	.1770	.1792	.2359	.1708	.9376

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Table 5-1j. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test four for drying air temperature of 15.5^{o}C and air relative humidity of 50%

HR = Time in hours
EXMC = Measured moisture content, decimal
SAB = Moisture content by Sabbah eqn, decimal
MISRA = Moisture content by Misra eqn., decimal
RUG = Moisture content by Rugumayo eqn., decimal
DIFK = Drying parameter, K in hr $^{-1}$

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2810	.2810	.2810	.2810	
1.0	.2657	.2520	.2650	.2671	.1024
2.0	.2564	.2442	.2620	.2613	.1848
3.0	.2479	.2372	.2595	.2551	.2454
4.0	.2428	.2340	.2580	.2497	.3113
5.0	.2385	.2299	.2566	.2448	.3441
6.0	.2292	.2283	.2560	.2416	.4512
7.0	.2242	.2245	.2545	.2312	.4936
8.0	.2216	.2189	.2519	.2242	.5038
9.0	.2208	.2150	.2500	.2208	.5095
10.0	.2190	.2143	.2498	.2210	.5419
11.0	.2132	.2124	.2491	.2180	.5995
12.0	.2114	.2114	.2489	.2111	.6217
13.0	.2097	.2096	.2481	.2090	.6443
14.0	.2080	.2042	.2457	.2046	.6360
15.0	.2055	.2034	.2454	.2025	.6678
16.0	.2038	.2055	.2462	.2019	.7232
17.0	.2021	.2056	.2459	.2023	.7826
18.0	.1996	.2046	.2453	.2006	.8266
19.0	.1953	.2007	.2441	.1937	.8290
20.0	.1927	.1985	.2426	.1891	.8794
21.0	.1903	.2007	.2435	.1892	.9735
22.0	.1894	.1989	.2426	.1857	.9742
23.0	.1877	.2006	.2433	.1869	1.0467
24.0	.1834	.1956	.2412	.1807	1.0467
25.0	.1817	.1929	.2399	.1750	1.0634
26.0	.1809	.1941	.2406	.1740	1.0951
27.0	.1767	.1926	.2394	.1744	1.2106
28.0	.1758	.1911	.2388	.1683	1.1904
29.0	.1750	.1952	.2407	.1714	1.3005
30.0	.1741	.1921	.2391	.1694	1.2911
31.0	.1716	.1914	.2386	.1686	1.3589
32.0	.1554	.2046	.2473	.1646	1.8339

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Table 5-1k. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test five for drying air temperature of 10.0°C and air relative humidity of 40%

HR = Time in hours

EXMC = Measured moisture content, decimal

SAB = Moisture content by Sabbah eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

DIFK = Drying parameter, K in hr^{-1}

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2766	.2766	.2766	.2766	
1.0	.2716	.2505	.2635	.2623	.0316
2.0	.2682	.2420	.2607	.2602	.0530
3.0	.2640	.2362	.2585	.2584	.0818
4.0	.2589	.2315	.2573	.2558	.1138
5.0	.2563	.2296	.2565	.2527	.1370
6.0	.2513	.2251	.2550	.2504	.1692
7.0	.2496	.2219	.2542	.2457	.1778
8.0	.2462	.2197	.2530	.2444	.2059
9.0	.2428	.2187	.2527	.2416	.2358
10.0	.2411	.2158	.2518	.2377	.2448
11.0	.2395	.2158	.2517	.2366	.2638
12.0	.2361	.2128	.2507	.2342	.2856
13.0	.2344	.2121	.2499	.2314	.3091
14.0	.2344	.2090	.2494	.2279	.2956
15.0	.2335	.2085	.2481	.2295	.3167
16.0	.2352	.2070	.2483	.2275	.2935
17.0	.2335	.2062	.2479	.2297	.3094
18.0	.2318	.2060	.2477	.2282	.3282
19.0	.2301	.2047	.2470	.2264	.3449
20.0	.2293	.2035	.2466	.2241	.3502
21.0	.2277	.2004	.2458	.2219	.3536
22.0	.2268	.2005	.2458	.2203	.3638

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Table 5-1ℓ. Experimental and simulated corn thin-layer moisture content and drying parameter, K of test six for drying air temperature of 4.4°C and air relative humidity of 30%

HR = Time in hours
EXMC = Measured moisture content, decimal
SAB = Moisture content by Sabbah eqn., decimal
MISRA = Moisture content by Misra eqn., decimal
RUG = Moisture content by Rugumayo eqn., decimal
DIFK = Drying parameter, K in hr^{-1}

HR	EXMC	SAB	MISRA	RUG	DIFK
0.0	.2965	.2965	.2965	.2965	
1.0	.2922	.2692	.2842	.2847	.0229
2.0	.2853	.2605	.2820	.2848	.0599
3.0	.2827	.2548	.2803	.2839	.0748
4.0	.2811	.2503	.2792	.2832	.0837
5.0	.2785	.2464	.2778	.2827	.0991
6.0	.2759	.2434	.2770	.2818	.1142
7.0	.2673	.2407	.2763	.2806	.1649
8.0	.2647	.2393	.2756	.2758	.1849
9.0	.2613	.2366	.2753	.2738	.2029
10.0	.2570	.2345	.2742	.2712	.2329
11.0	.2562	.2326	.2740	.2672	.2360
12.0	.2553	.2322	.2730	.2670	.2508
13.0	.2536	.2309	.2726	.2662	.2628
14.0	.2519	.2291	.2722	.2644	.2723
15.0	.2493	.2283	.2725	.2625	.2877
16.0	.2475	.2256	.2718	.2593	.2948
17.0	.2450	.2260	.2715	.2579	.3198
18.0	.2433	.2202	.2700	.2536	.3174
19.0	.2424	.2237	.2701	.2534	.3443
20.0	.2407	.2214	.2705	.2512	.3439
21.0	.2398	.2214	.2706	.2492	.3524
22.0	.2381	.2209	.2705	.2481	.3654
23.0	.2364	.2164	.2704	.2436	.3566
24.0	.2355	.2174	.2699	.2425	.3748
25.0	.2313	.2192	.2696	.2428	.4235

Figure 5-1a. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 21.0°C and Relative Humidity of 60% for test one.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

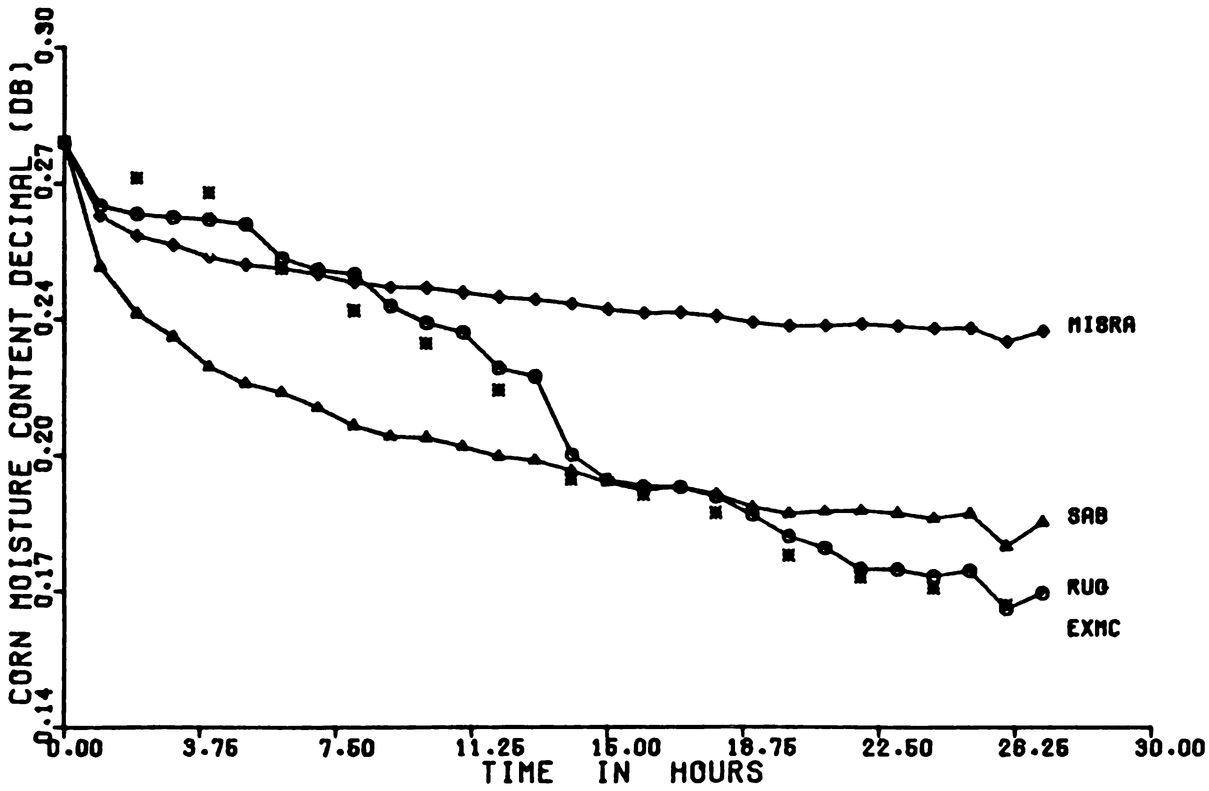


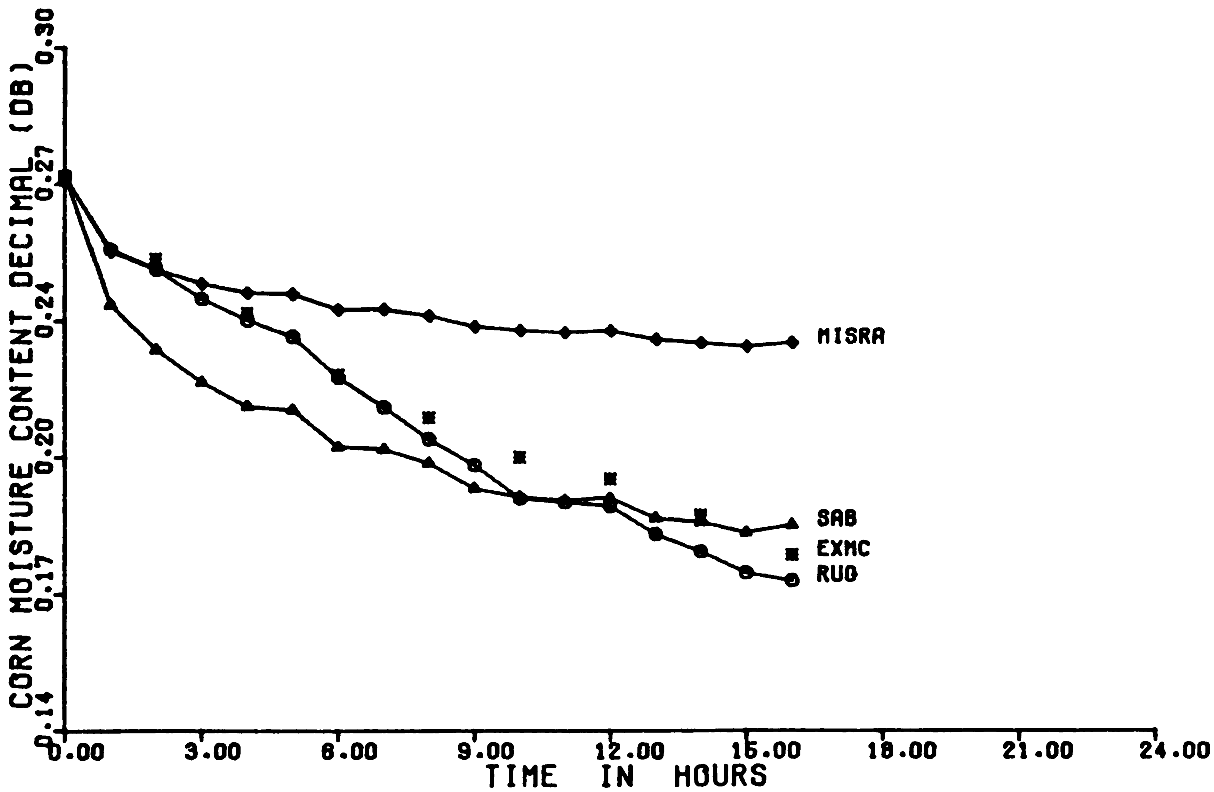
Figure 5-1b. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 21.0°C and Relative Humidity of 50% for test two.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra



... for Drying Air Temperature

Figure 5-1c. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 21.0°C and Relative Humidity of 40% for test three.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

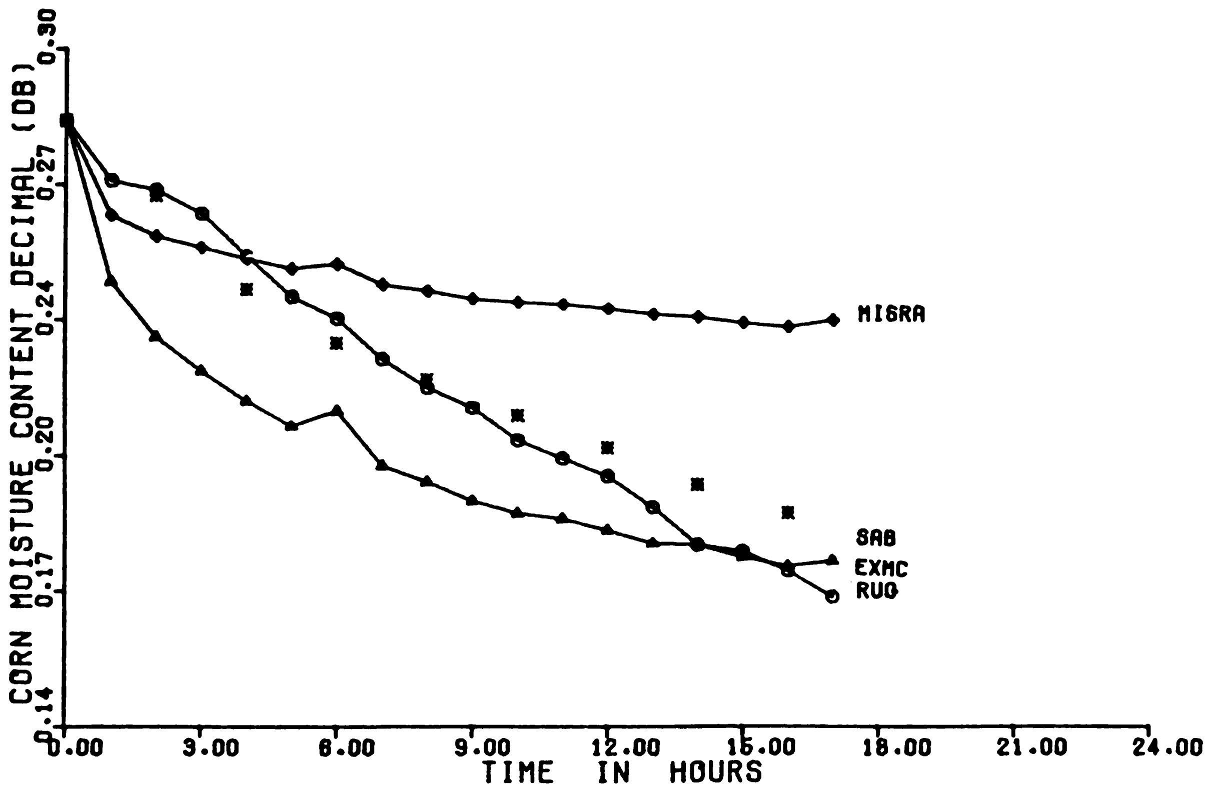


Figure 5-1d. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 15.5^{O}C and Relative Humidity of 50% for test four.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

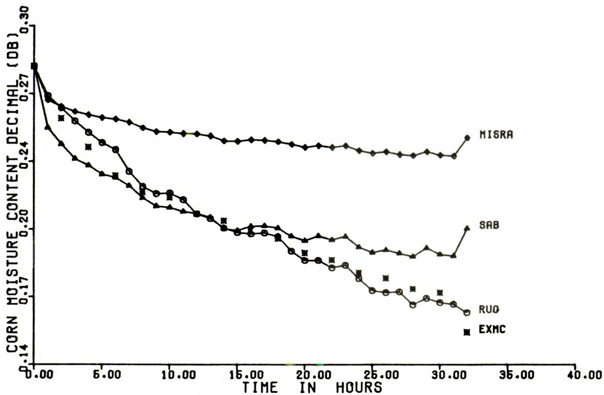


Figure 5-1e. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 10.0°C and Relative Humidity of 40% for test five.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

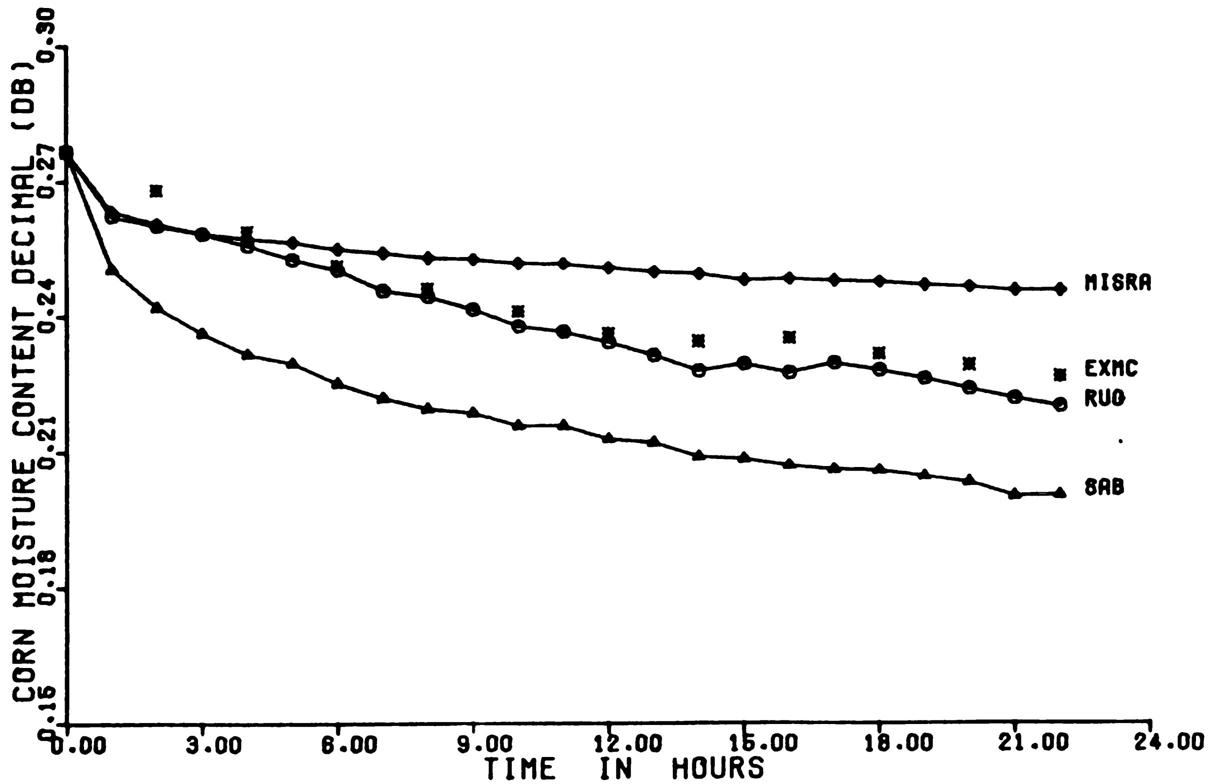


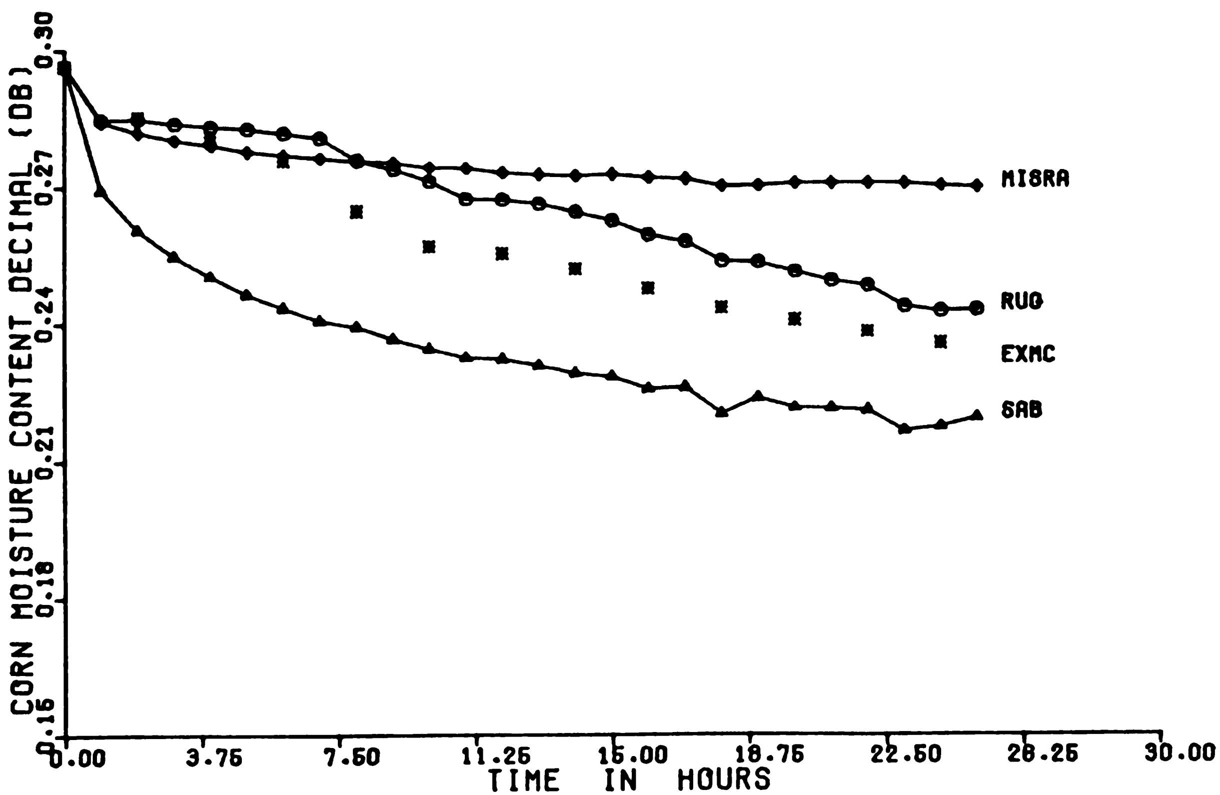
Figure 5.1f. Experimental and Simulated Corn Thin-layer Moisture Content for Drying Air Temperature of 4.4°C and Relative Humidity of 30% for test six.

EXMC = Measured Moisture Content

SAB = Moisture Content by Sabbah

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra



5.2.1 Thin-layer corn rewetting results

Tables 5-2a through 5-2d list experimental values for corn rewetting of variables similar to those in the thin-layer corn drying section. Experimental rewetting corn moisture content was calculated using equation (5-1). Equilibrium moisture content, air relative humidity, vapor pressure and the rewetting parameter, K (or ABK) were calculated as described in section (5.1.1). The same thin-layer drying air-flow rate was used in thin-layer corn rewetting.

The parameter, K for thin-layer corn rewetting listed in column three of Tables 5-2a through 5-2d is plotted against rewetting time, t in Figures A-1 through A-4 of Appendix A. Those plots show that the corn rewetting parameter, K is not constant. The variability of the rewetting parameter, K is described by equation (3-18) which is the same equation as that which describes the variability of the drying parameter, K. The values of the unknown constants were determined as in the case of drying except that corn rewetting data were used instead. Non constant values of grain temperature and relative humidity were used in the determination of the values of the unknown constants instead of the constant values listed in Table 4-1 for similar reasons. The resulting corn thin-layer rewetting equation is:

$$M_t=(M_o-M_e)\ \exp\ [(162.1179-487.9552M_{t-1}+118.6144\ \log\ (M_{t-1}) + 0.69658\ \theta_t\ (M_{t-1}^2)\ \exp\ (rh_t^2)\ t] + M_e \qquad (5\text{-}4)$$

The moisture content predicted by equation (5-4) was compared with that predicted by previously used thin-layer equations for low-temperature rewetting (delGuidice, 1959 and Misra, 1978). The delGuidice (1959) model is presented as equation (2-4) and the Misra equation is:

$$M=(M_o-M_e)\ \exp\ [\ -(\exp(-8.5122+1.2178\ \ln\ (1.8T+32)\ +0.0864\ M_o))$$

$$t^{(2.1876-1.67rh)]}+M_e \qquad (5\text{-}5)$$

where T is rewetting air temperature in ^{o}C;

t is time in hr;

rh is air relative humidity, percent.

Both experimental and simulated corn thin-layer moisture contents, and the rewetting parameter, K are listed in Tables 5-2e through 5-2h. Figures 5-2a through 5-2d are plots of the experimental and simulated corn thin-layer rewetting moisture contents.

5.2-2 Discussion of corn thin-layer rewetting results

The foregoing results show that the model (RUG) developed in this study simulates the experimental rewetting corn moisture content (EXMC) better than either the delGuidice (1959) model (DEL) or the Misra (1978) model (MISRA).

Over-prediction of the experimental moisture content by the delGuidice (1959) is due to the fact that this relationship was developed using data in the high temperature range (15.6^{o}C to 40.6^{o}C rewetting air temperature). The Misra (1978) equation, on the other hand under-predicts the experimental moisture content due to the fact that it was developed using data covering too wide a temperature range (10.0^{o}C to 43.3^{o}C rewetting air temperature). Further testing of the rewetting equations in conjunction with the drying equations will be discussed later in the solar and low-temperature deep bed corn drying simulation section.

Table 5-2a. Experimental thin-layer corn rewetting test one results for rewetting air temperature of 21.0°C and air relative humidity of 90%

EXMC = Experimental corn moisture content
ABK = Rewetting parameter, K.
TAIR = Rewetting air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	ABK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.1618	.0000	292.22	287.16	.2071	.8367	1.5984
1.0	.1754	.3879	291.16	287.61	.2040	.8273	1.6451
2.0	.1830	.5134	292.05	288.05	.2144	.8505	1.6929
3.0	.1906	1.1175	292.05	287.77	.2046	.8312	1.6629
4.0	.1965	1.1622	292.66	288.33	.2123	.8481	1.7235
5.0	.2016	1.7983	292.27	288.18	.2095	.8418	1.7051
6.0	.2033	3.4348	292.16	287.61	.2047	.8317	1.6451
7.0	.2092	2.8677	292.33	287.83	.2121	.8468	1.6689
8.0	.2114	4.4277	292.27	287.88	.2120	.8466	1.6749
9.0	.2116	4.7622	292.27	287.83	.2120	.8466	1.6689
10.0	.2160	1.2439	291.55	287.49	.2380	.8880	1.6333

Table 5-2b. Experimental thin-layer corn rewetting test two results for rewetting air temperature of 21.0°C and air relative humidity of 90%

EXMC = Experimental corn moisture content
ABK = Rewetting parameter, K.
XME = Equilibrium moisture content
TAIR = Rewetting air temperature
RH = Air relative humidity
TGRN = Corn temperature
PSDB = Vapor pressure

Time Hr	EXMC Decimal	ABK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.1812	.0000	291.94	266.22	.2093	.8404	1.5031
1.0	.2031	1.4931	292.27	289.05	.2095	.8418	1.8051
2.0	.2082	2.7131	293.11	289.38	.2101	.8451	1.8439
3.0	.2090	.6628	293.38	289.94	.2386	.8931	1.9102
4.0	.2124	.7866	293.11	288.83	.2385	.8924	1.7796
5.0	.2169	1.1173	290.88	287.55	.2343	.8810	1.6392
6.0	.2176	1.1499	291.66	287.49	.2347	.8834	1.6333
7.0	.2232	1.0858	291.44	287.22	.2447	.8977	1.6042
8.0	.2276	2.6627	290.83	286.99	.2311	.8757	1.5813
9.0	.2316	2.1593	291.99	287.72	.2381	.8893	1.6569
10.0	.2320	.7876	290.99	287.33	.2744	.9374	1.6158

Table 5-2c. Experimental thin-layer corn rewetting test three results for rewetting air temperature of 21.0°C and air relative humidity of 90%

EXMC = Experimental corn moisture content
ABK = Rewetting parameter, K.   XME = Equilibrium moisture content
TAIR = Rewetting air temperature   RH = Air relative humidity
TFRN = Corn temperature   PSDB = Vapor pressure

Time Hr	EXMC Decimal	ABK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.1770	.0000	292.55	286.99	.2352	.8860	1.5813
1.0	.2075	.8083	292.66	288.94	.2321	.8815	1.7923
2.0	.2095	.7493	293.44	289.49	.2386	.8933	1.8570
3.0	.2118	.9930	293.16	289.27	.2323	.8830	1.8309
4.0	.2237	1.4346	292.38	288.88	.2383	.8904	1.7860
5.0	.2246	1.9454	293.66	289.99	.2325	.8844	1.9169
6.0	.2253	1.5326	293.44	289.94	.2386	.8933	1.9102
7.0	.2263	2.3063	291.94	288.61	.2317	.8793	1.7545
8.0	.2267	1.4554	293.27	289.11	.2418	.8976	1.8115
9.0	.2275	2.4645	293.05	288.99	.2322	.8827	1.7987
10.0	.2279	2.0824	292.49	288.99	.2351	.8859	1.7987

Table 5-2d. Experimental thin-layer corn rewetting test four results for rewetting air temperature of 15.5°C and air relative humidity of 85%

EXMC = Experimental corn moisture content
ABK = Rewetting parameter, K.
TAIR = Rewetting air temperature
TGRN = Corn temperature
XME = Equilibrium moisture content
RH = Air relative humidity
PSDB = Vapor pressure

Time Hr	EXMC Decimal	ABK Hr^{-1}	TAIR °K	TGRN °K	XME Decimal	RH Decimal	PSDB Pa
0.0	.1554	.0000	287.83	277.16	.2011	.8103	.8140
1.0	.1817	.5535	288.94	284.38	.2173	.8479	1.3323
2.0	.1826	.6557	289.05	284.16	.2119	.8378	1.3128
3.0	.1851	1.2526	287.83	283.33	.1970	.7995	1.2419
4.0	.1927	1.9720	287.55	283.36	.1988	.8033	1.2466
5.0	.1970	1.3393	288.94	283.88	.2118	.8373	1.2888
6.0	.1979	2.4608	288.61	283.94	.2018	.8146	1.2936
7.0	.1996	1.5823	288.16	283.38	.2110	.8336	1.2466
8.0	.2009	3.2020	287.27	282.77	.2028	.8126	1.1986
9.0	.2038	3.3724	287.66	283.16	.2055	.8202	1.2282
10.0	.2046	1.8032	288.77	283.55	.2143	.8418	1.2605

Table 5-2e. Experimental and simulated corn thin-layer moisture content and rewetting parameter, K of test one for rewetting air temperature of 21.0°C and air relative humidity of 90%.

HR = Time in hours

EXMC = Measured moisture content, decimal

DEL = Moisture content by delGuidice eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

ABK = Rewetting parameter, K in hr^{-1}

HR	EXMC	DEL	MISRA	RUG	ABK
0.0	.1618	.1618	.1618	.1618	
1.0	.1754	.2018	.1629	.1715	.3879
2.0	.1830	.2139	.1643	.1796	.5134
3.0	.1906	.2050	.1646	.1925	1.1175
4.0	.1965	.2120	.1659	.1984	1.1622
5.0	.2016	.2096	.1664	.2019	1.7983
6.0	.2033	.2049	.1666	.2011	3.4348
7.0	.2092	.2118	.1679	.2063	2.8677
8.0	.2114	.2119	.1685	.2082	4.4277
9.0	.2116	.2120	.1691	.2087	4.7622
10.0	.2160	.2373	.1720	.2193	1.2439

Table 5-2f. Experimental and simulated corn thin-layer moisture content and rewetting parameter, K of test two for rewetting air temperature of 21.0°C and air relative humidity of 90%

HR = Time in hours

EXMC = Measured moisture content, decimal

DEL = Moisture content by delGuidice eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

ABK = Rewetting parameter, K in hr^{-1}

HR	EXMC	DEL	MISRA	RUG	ABK
0.0	.1812	.1812	.1812	.1812	
1.0	.2031	.2083	.1820	.1975	1.4931
2.0	.2082	.2100	.1826	.2066	2.7131
3.0	.2090	.2380	.1849	.2146	.6628
4.0	.2124	.2384	.1855	.2178	.7866
5.0	.2169	.2344	.1858	.2245	1.1173
6.0	.2178	.2346	.1864	.2266	1.1499
7.0	.2232	.2444	.1876	.2294	1.0858
8.0	.2276	.2315	.1871	.2274	2.6627
9.0	.2316	.2379	.1883	.2323	2.1593
10.0	.2320	.2739	.1916	.2116	.7876

Table 5-2g. Experimental and simulated corn thin-layer moisture content and rewetting parameter, K of test three for rewetting air temperature of 21.0°C and air relative humidity of 90%

HR = Time in hours

EXMC = Measured moisture content, decimal

DEL = Moisture content by delGuidice eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

ABK = Rewetting parameter, K in hr^{-1}

HR	EXMC	DEL	MISRA	RUG	ABK
0.0	.1770	.1770	.1770	.1770	
1.0	.2075	.2308	.1786	.1604	.8083
2.0	.2095	.2384	.1799	.2125	.7493
3.0	.2118	.2324	.1805	.2178	.9930
4.0	.2237	.2381	.1816	.2205	1.4346
5.0	.2246	.2326	.1821	.2255	1.9454
6.0	.2253	.2384	.1833	.2282	1.5326
7.0	.2263	.2318	.1832	.2271	2.3063
8.0	.2267	.2416	.1847	.2307	1.4554
9.0	.2275	.2324	.1844	.2272	2.4645
10.0	.2279	.2350	.1853	.2294	2.0824

Table 5-2h. Experimental and simulated corn thin-layer moisture content and rewetting parameter, K of test four for rewetting air temperature of 15.5°C and air relative humidity of 85%

HR = Time in hours

EXMC = Measured moisture content, decimal

DEL = Moisture content by delGuidice eqn., decimal

MISRA = Moisture content by Misra eqn., decimal

RUG = Moisture content by Rugumayo eqn., decimal

ABK = Rewetting parameter, K in hr^{-1}

HR	EXMC	DEL	MISRA	RUG	ABK
0.0	.1554	.1554	.1554	.1554	
1.0	.1817	.2140	.1569	.1416	.5535
2.0	.1826	.2120	.1577	.1950	.6557
3.0	.1851	.1983	.1578	.1919	1.2526
4.0	.1927	.1987	.1586	.1940	1.9720
5.0	.1970	.2110	.1601	.2036	1.3393
6.0	.1979	.2025	.1601	.1989	2.4608
7.0	.1996	.2104	.1613	.2060	1.5823
8.0	.2009	.2034	.1612	.2006	3.2020
9.0	.2038	.2053	.1621	.2029	3.3724
10.0	.2046	.2137	.1634	.2099	1.8032

Figure 5-2a. Experimental and Simulated Corn Thin-layer Moisture Content for Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test one.

EXMC = Measured Moisture Content

DEL = Moisture Content by delGuidice

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

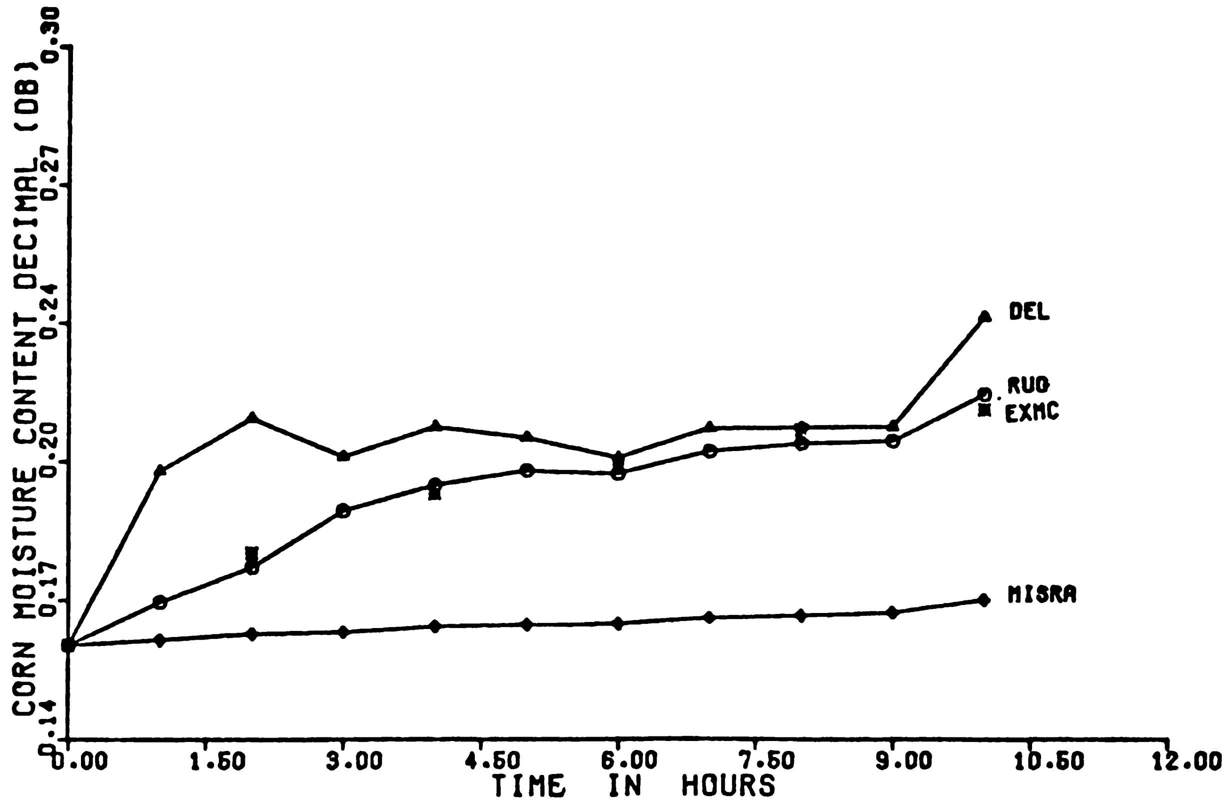


Figure 5.2b. Experimental and Simulated Corn Thin-layer Moisture Content for Rewetting Air

Figure 5-2b. Experimental and Simulated Corn Thin-layer Moisture Content for Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test two.

EXMC = Measured Moisture Content

DEL = Moisture Content by delGuidice

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

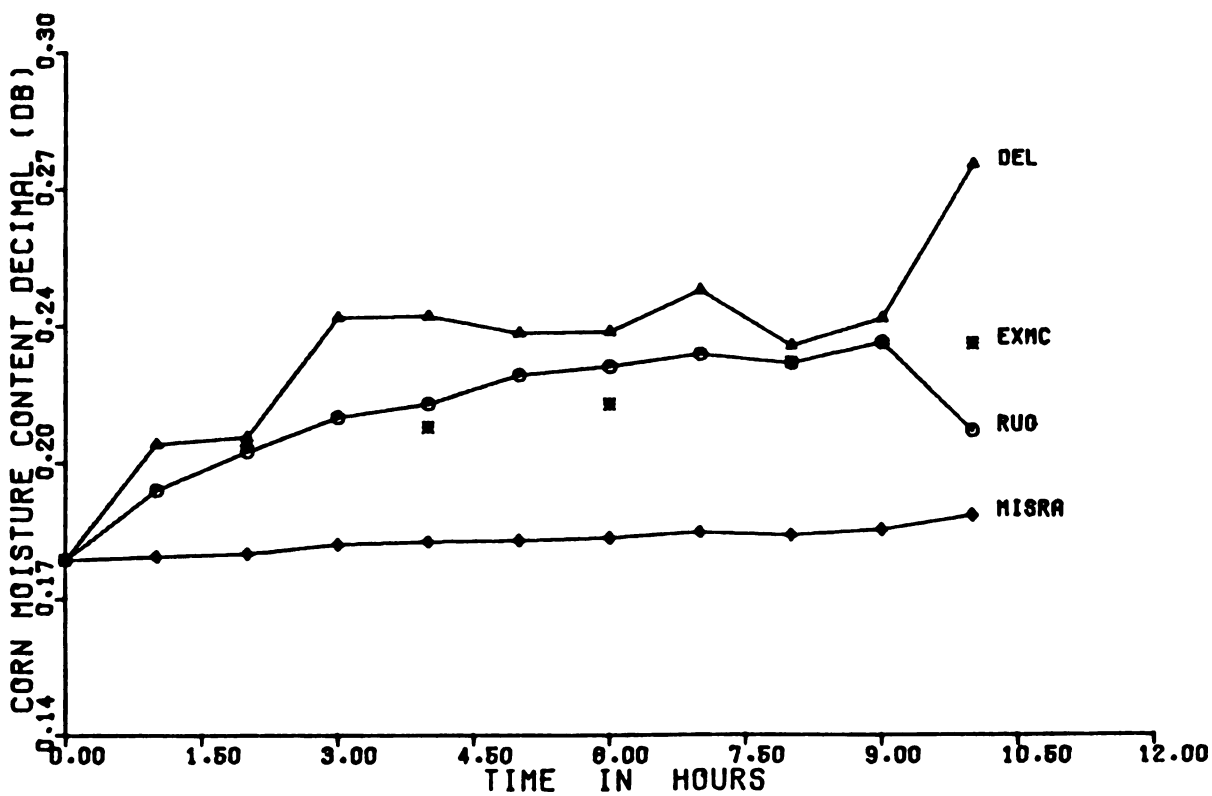


Figure 5-2c. Experimental and Simulated Corn Thin-layer Moisture Content for

Figure 5-2c. Experimental and Simulated Corn Thin-layer Moisture Content for Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test three.

EXMC = Measured Moisture Content

DEL = Moisture Content by delGuidice

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra

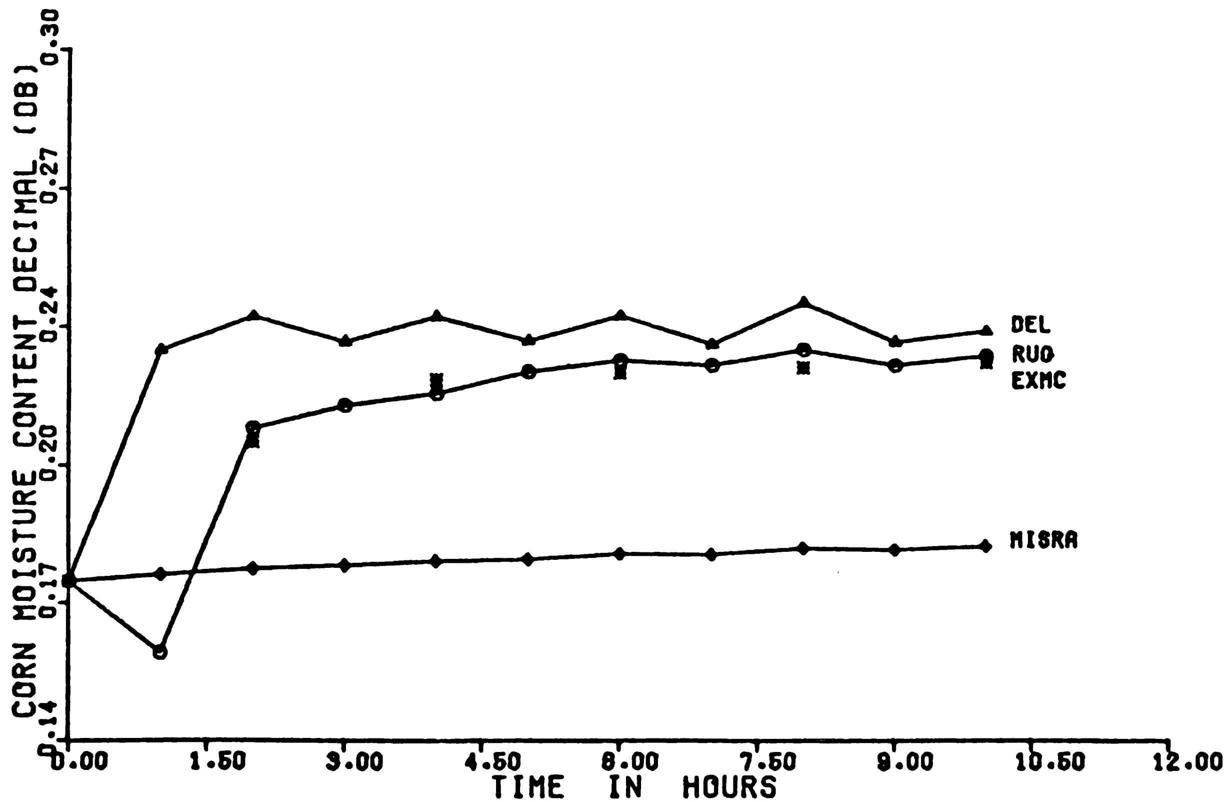


Figure 5-2d. Experimental and Simulated Corn Thin-layer Moisture Content

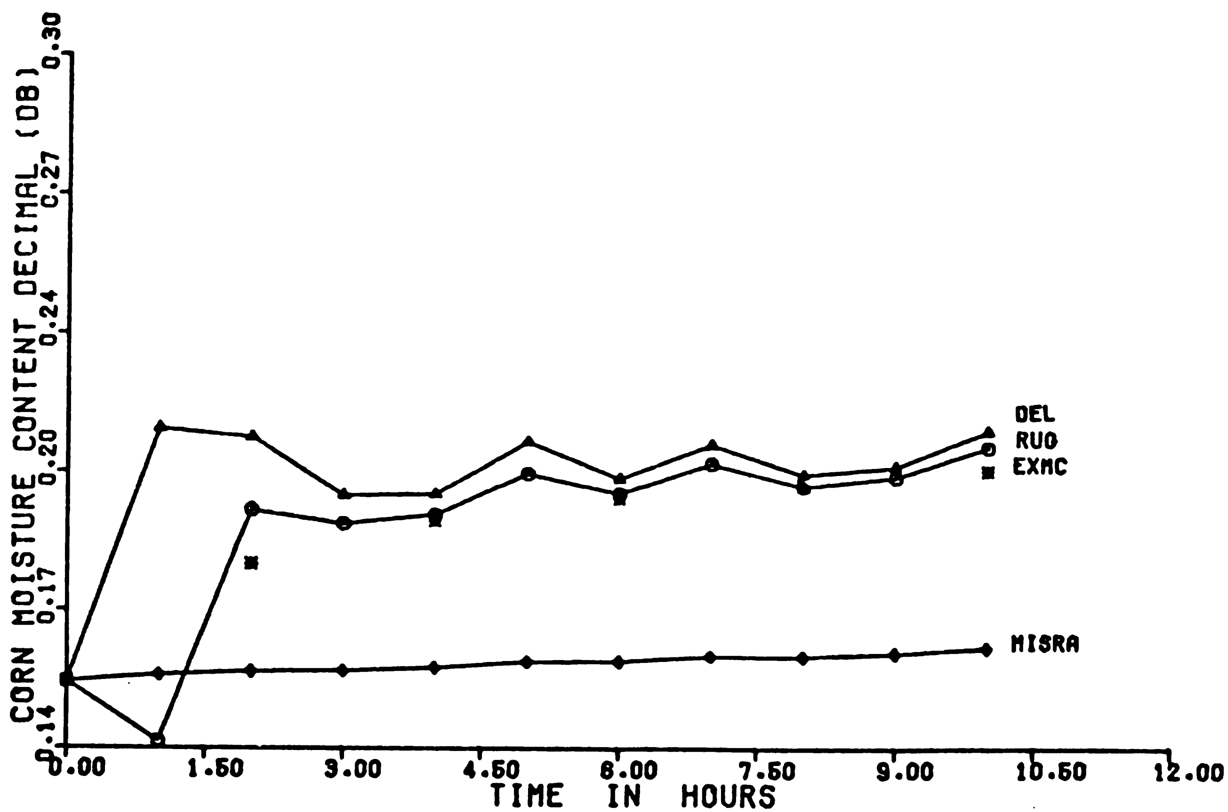
Figure 5-2d. Experimental and Simulated Corn Thin-layer Moisture Content for Rewetting Air Temperature of 15.5°C and Relative Humidity of 85% for test four.

EXMC = Measured Moisture Content

DEL = Moisture Content by delGuidice

RUG = Moisture Content by Rugumayo

MISRA = Moisture Content by Misra



5.3.1. Fixed bed in-bin solar corn drying results

Hourly experimental values of corn temperature, drying air temperature and absolute humidity together with the input variables (XMO=0.32, THIN=8.9^{o}C, CMM=2.84988CMM/M^{2},DEPH=1.9812M,INDPR=1,NLPF=6,TT=313.0, TBTPR=1.0,DELT=1.0 and NEQ=1,2,or 3) for the fixed bed drying computer program are listed in Table C-1 of Appendix C. The absolute humidity was calculated from recorded wet-bulb and dry bulb temperatures of the drying/or rewetting air using the psychrometric chart equations presented by Brooker et al. (1974). The equations were converted into the international system (SI) of units. The hourly corn temperature values listed in Table C-1 of Appendix C is for comparison with the listed air temperature values since the program assumes the air and grain temperatures to be the same. The tables show that this is almost true for most of the time. Differences exist when the grain is starting to warm up. The air temperature changes faster with changes in solar radiation than does grain temperature.

The thin-layer drying equations (2-1), (5-2) and (5-3); and the rewetting equations (2-4), (5-4) and (5-5) combined with the deep bed solar drying equations (Bakker-Arkema et al.,1976) and the DeBoer equilibrium moisture content equations presented by Brooker et al.(1974) were used to calculate simulated corn moisture content from non-constant hourly experimental values of drying air temperature and absolute humidity.

Appendix C-1 lists the computer program "FIXED" used to simulate the corn moisture content in the fixed bed during drying with solar heated air. During the experiment, corn samples were taken from the grain bin at selected time intervals and their grain moisture content determined the air oven method. The experimental and simulated corn moisture contents at various time intervals and bin depths are presented in Table 5-3. The moisture content values are plotted in Figures 5-3a through 5-3g.

Simulated average values for the hourly corn moisture content and dry matter loss obtained using the Steele et al. (1969) and Thompson (1972) equations are presented in Table C-2 of Appendix C. Figures 5-3h and 5-3i are plots of the simulated corn moisture content and dry matter loss, respectively.

ble 5-3. *Experimental and Simulated Corn Moisture Content*, Dry Basis, from In-Bin Drying of Shelled Corn

Table 5-3. Experimental and Simulated Corn Moisture Content, Dry Basis, from In-Bin Drying of Shelled Corn with Solar Heated Air.

Time in Hours	Bin Depth in Meters 0.00	0.30	0.61	0.92	1.22	1.52	Average Moisture Content	Thin-Layer Equations for Simulation by
	Percent Moisture Content (Dry Basis)							
	32.15	32.15	32.15	32.15	32.15	32.15	32.15	Experimental
0.0	30.60	31.90	32.00	32.00	32.00	32.00	31.83	Sabbah and delGuidice
	31.20	31.90	32.00	32.00	32.00	32.00	31.88	Misra
	30.40	31.90	31.90	32.00	32.00	32.00	31.81	Rugumayo
		24.00	33.00	32.28	33.07	32.47	30.96	Experimental
48.0	19.00	25.80	31.00	31.60	31.70	31.70	29.04	Sabbah and delGuidice
	26.50	26.90	28.70	31.60	31.60	31.60	29.69	Misra
	12.40	28.90	32.00	31.70	31.60	31.60	28.44	Rugumayo
		14.77	33.58	37.40	32.35	33.90	30.04	Experimental
72.0	17.10	22.70	29.20	31.50	31.80	31.80	27.96	Sabbah and delGuidice
	24.50	25.00	26.40	30.70	31.60	31.80	28.63	Misra
	9.80	23.70	32.10	31.90	31.70	31.70	27.29	Rugumayo
		14.67	20.45	30.53	34.77	31.01	26.29	Experimental
96.0	14.70	19.30	26.00	31.20	31.70	31.90	26.59	Sabbah and delGuidice
	23.00	23.20	24.00	28.40	31.00	31.90	27.35	Misra
	10.20	14.30	32.10	32.00	31.80	31.80	26.15	Rugumayo

Table 5-3. Continued

Table 5-3. Continued

		13.16	17.33	24.39	33.14	27.43	23.09	Experimental
120.0	13.50	17.00	22.70	29.50	31.20	31.70	25.14	Sabbah and delGuidice
	23.70	22.40	23.00	23.90	26.20	31.60	26.08	Misra
	10.00	10.40	30.90	31.80	31.80	31.70	24.74	Rugumayo
	10.95	11.19	13.87	23.20	30.06	32.93	20.37	Experimental
218.0	11.30	12.80	15.20	18.90	21.40	27.70	19.66	Sabbah and delGuidice
	21.60	20.50	21.00	21.40	21.50	21.90	21.29	Misra
	9.00	9.30	9.40	18.50	29.40	31.50	19.30	Rugumayo
	9.27	9.96	11.77	13.93	17.81	24.04	14.46	Experimental
289.0	10.60	11.60	13.20	15.10	16.50	20.60	16.06	Sabbah and delGuidice
	20.20	19.10	20.10	20.60	20.80	21.00	20.02	Misra
	9.10	9.80	9.50	9.30	10.10	28.40	15.46	Rugumayo
							13.56	Experimental
312.0	10.20	11.10	12.40	14.10	15.20	18.60	14.88	Sabbah and delGuidice
	20.20	18.70	19.40	19.90	20.10	20.50	19.45	Misra
	7.90	9.20	9.50	9.50	9.50	18.60	13.87	Rugumayo

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5.3.2. Discussion of in-bin solar corn drying results

As in thin-layer corn drying and rewetting results, the in-bin corn drying results show that, in general, the thin-layer models developed in this study simulate the moisture content of corn at different times and bin depths with only slightly better accuracy than the combined Sabbah et al. (1968) and delGuidice (1959) model (SMC). Few cases (as at a bin depth 0.3 meters after 48 and 72 drying hours; and at a bin depth of 0.92 meters after 96 and 120 drying hours) exist where this is not true due to bad corn samples.

The combined Sabbah et al. (1968) and delGuidice (1959) equations over-predict the final measured moisture content by 10%. The equations developed in this thesis have only 2% over-prediction of the final average moisture content.

The thin-layer equations developed in this thesis give better overall moisture content prediction than the Misra (1978) models. Up to one hundred and twenty hours of drying the Misra (1978) models give moisture content prediction comparable either the combined Sabbah et al. (1968) and delGuidice (1959) models or the models developed in this thesis (RUG). The Misra (1978) models over predict the final measured moisture content by 43%. These results give further support to the reasons discussed in Sections 5-1 and 5-2 for selecting the thin-layer equations developed in this thesis for use in low temperature corn drying and rewetting studies.

Simulated average hourly corn dry matter loss results show that none of the models used predicted corn moisture content resulting in dry corn with more than 1% dry matter loss. According to Steele et al.

(1969), a dry matter loss of less than 0.5% due to fungi respiration does not affect the market grade of the corn. Desirable properties of high market quality grain are (Brooker et al. (1974):

1. Appropriately low and uniform moisture content.
2. Low susceptibility to breakage.
3. Low percentage of broken and damaged kernels.
4. High test weight.
5. Low mold count.

The moisture content predicted by the combined Sabbah et al. (1968) and delGuidice equations is accompanied by the least amount of dry matter loss. This is due to the fact these models predict less corn over drying at the bottom of the bin than the measured moisture content as shown in Table 5-3. Figure 5-3i illustrates that the moisture content predicted by the Misra (1978) equations is associated with the largest dry matter loss (DMISRA) due to high moisture content predicted in the corn. The moisture content predicted by the models developed in this thesis is such that some corn over drying takes place at the bottom of the bin while at the top of the bin the corn is almost undried. Both corn over drying and high moisture content lead to a high dry matter loss. This problem can be eliminated by using a batch in-bin drying method. This method is characterized by use of large floor areas, limited grain depths and medium drying temperatures and air flows. Most of these characteristics easily lend themselves to solar grain drying.

Figure 5-3a. Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.00 Meters

EXMC = Measured Moisture Content

MISRA = Moisture Content by Misra

RUG = Moisture Content by Rugumayo

SMC = Moisture Content by Sabbah and delGuidice

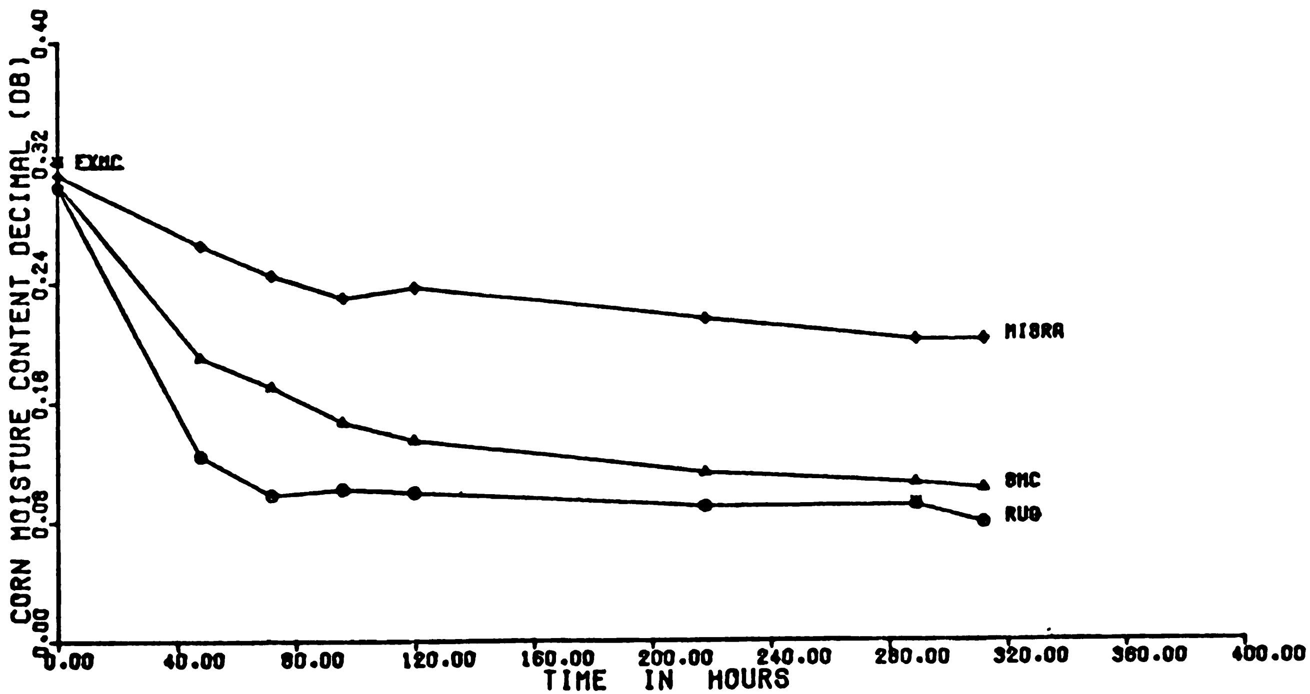


Figure 5.[illegible] Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.30

Figure 5-3b. Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.30 Meters

EXMC = Measured Moisture Content
MISRA = Moisture Content by Misra
RUG = Moisture Content by Rugumayo
SMC = Moisture Content by Sabbah and delGuidice

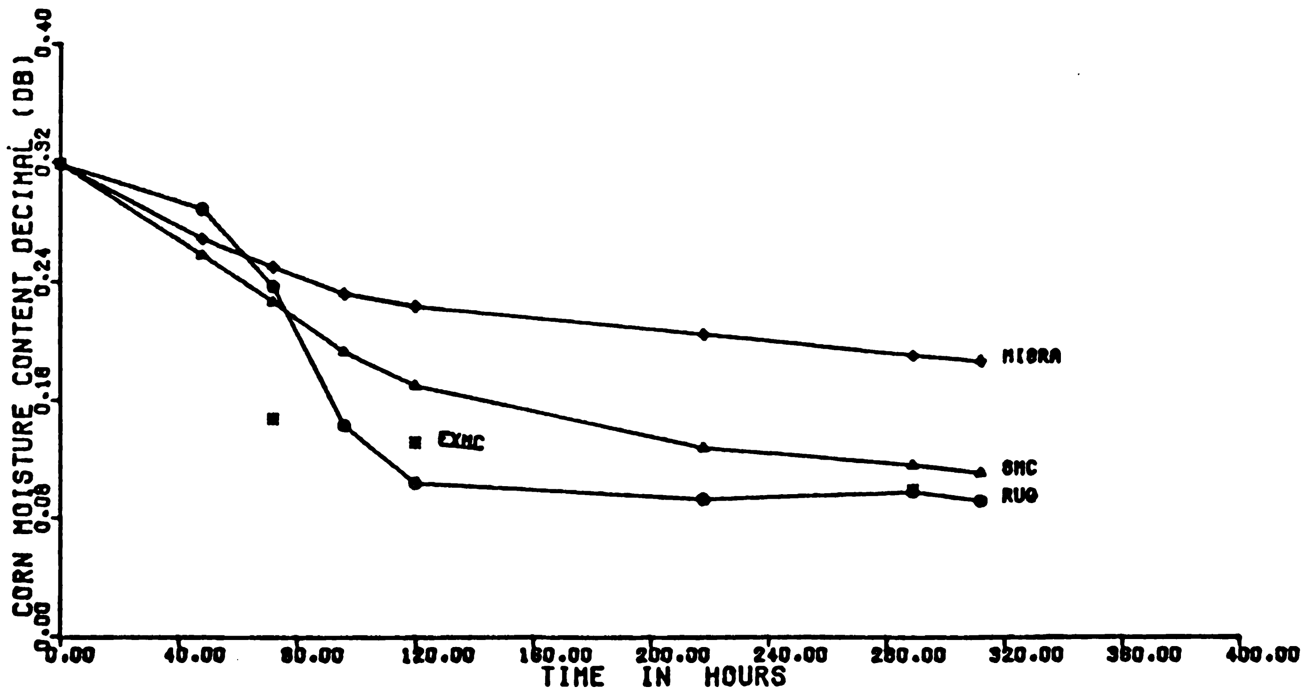


Figure 5.6. Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.61

Figure 5-3c. Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.61 Meters

EXMC = Measured Moisture Content

MISRA = Moisture Content by Misra

RUG = Moisture Content by Rugumayo

SMC = Moisture Content by Sabbah and delGuidice

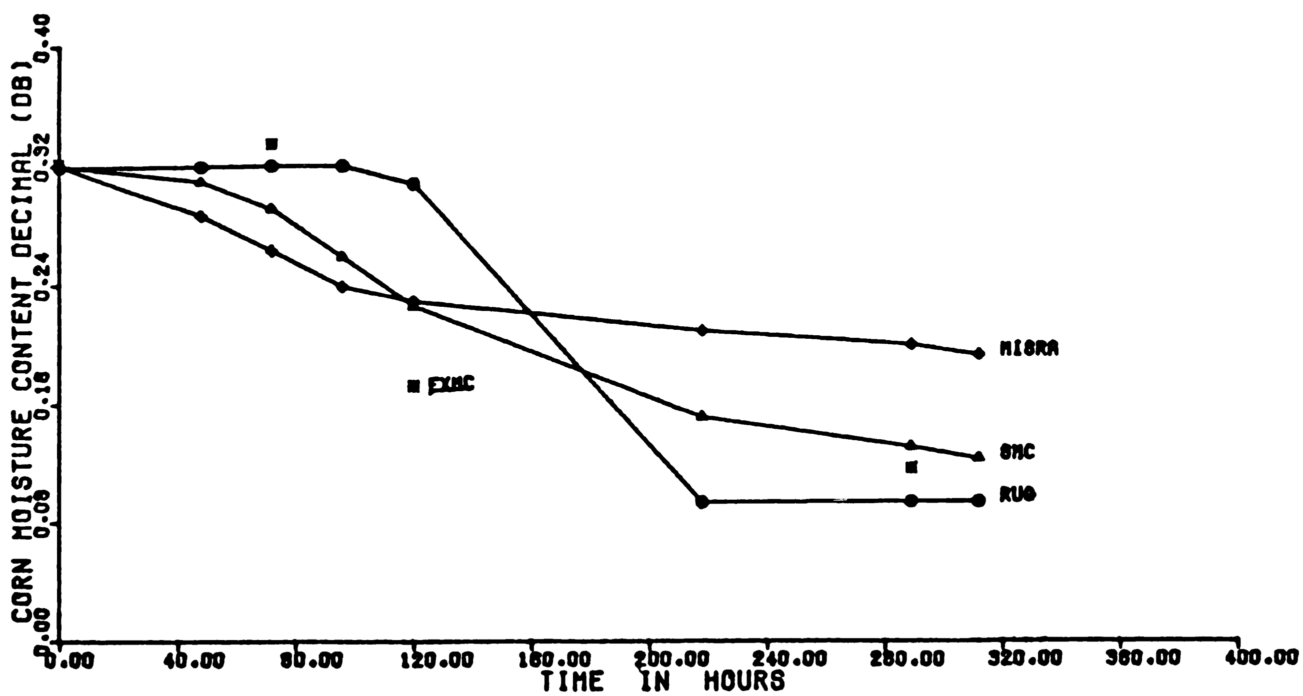


Figure 5.21a Experimental and Simulated Corn Moisture Content for a Bin Depth of [illegible]

Figure 5-3d. Experimental and Simulated Corn Moisture Content for a Bin Depth of 0.92 Meters

EXMC = Measured Moisture Content

MISRA = Moisture Content by Misra

RUG = Moisture Content by Rugumayo

SMC = Moisture Content by Sabbah and delGuidice

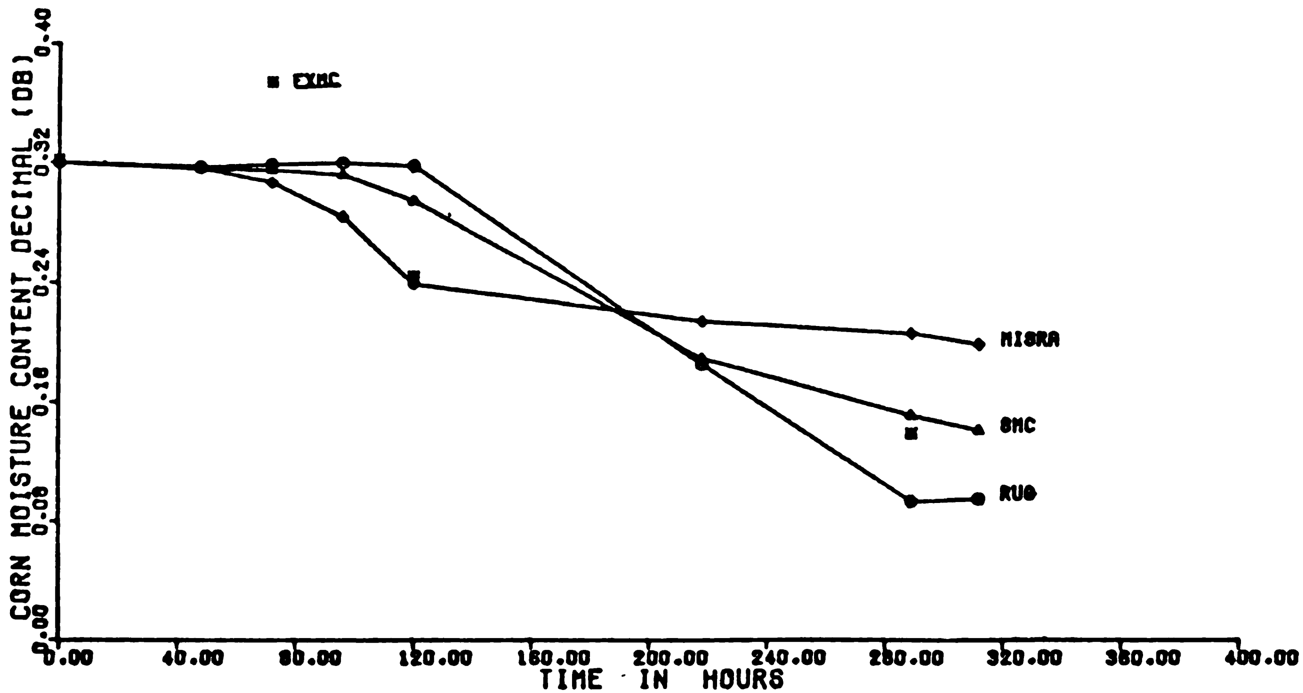


Figure 5-3e *Experimental and Simulated* Corn Moisture Content for a Bin Depth of 1.22

Figure 5-3e. Experimental and Simulated Corn Moisture Content for a Bin Depth of 1.22 Meters

EXMC = Measured Moisture Content

MISRA = Moisture Content by Misra

RUG = Moisture Content by Rugumayo

SMC = Moisture Content by Sabbah and delGuidice

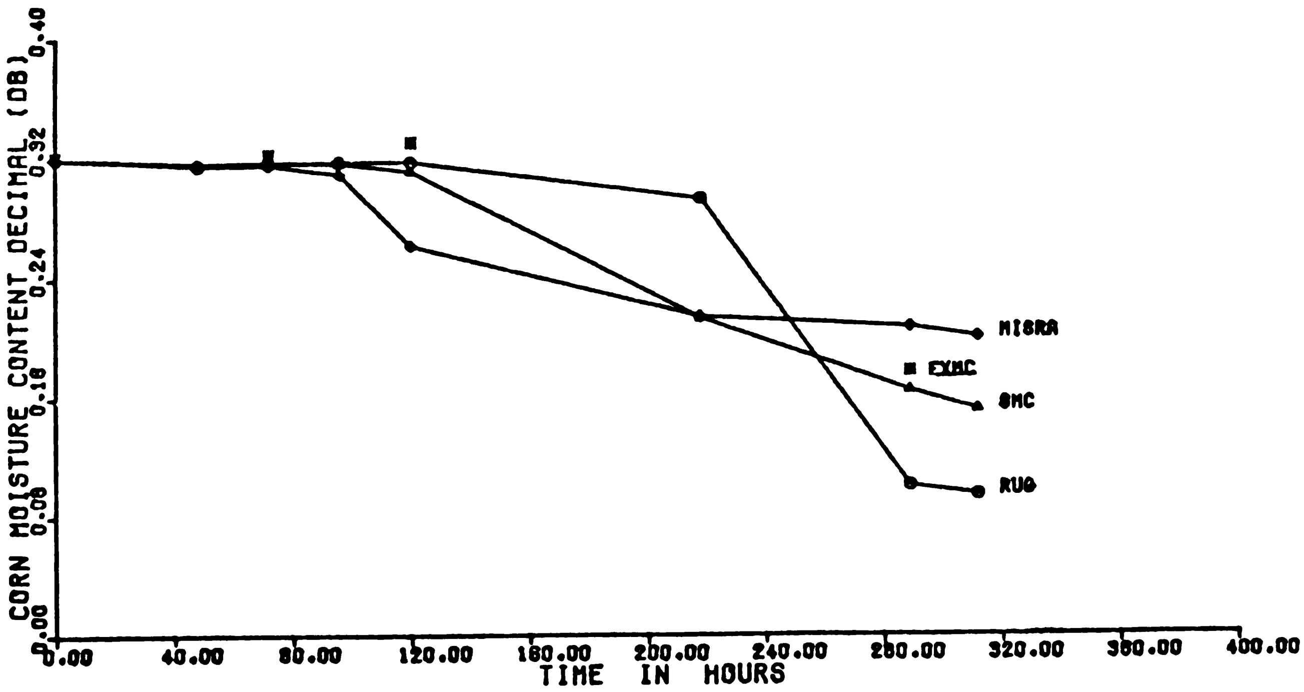


Figure 5-3f. Experimental and Simulated Corn Moisture Content for a Bin Depth of 1.52 Meters

EXMC = Measured Moisture Content

MISRA = Moisture Content by Misra

RUG = Moisture Content by Rugumayo

SMC = Moisture Content by Sabbah and delGuidice

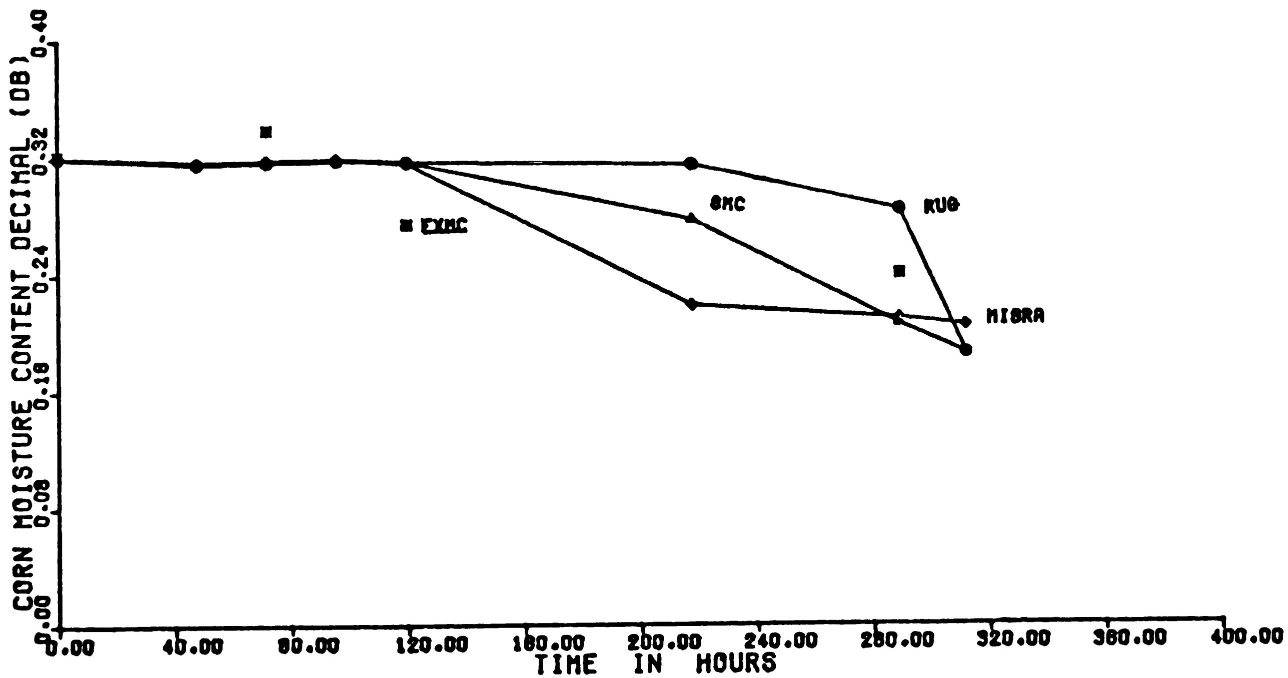


Figure 5.8. Experimental and Simulated Average Corn Moisture Content

Figure 5-3g. Experimental and Simulated Average Corn Moisture Content

EXMC = Measured Moisture Content
MISRA = Moisture Content by Misra
RUG = Moisture Content by Rugumayo
SMC = Moisture Content by Sabbah and delGuidice

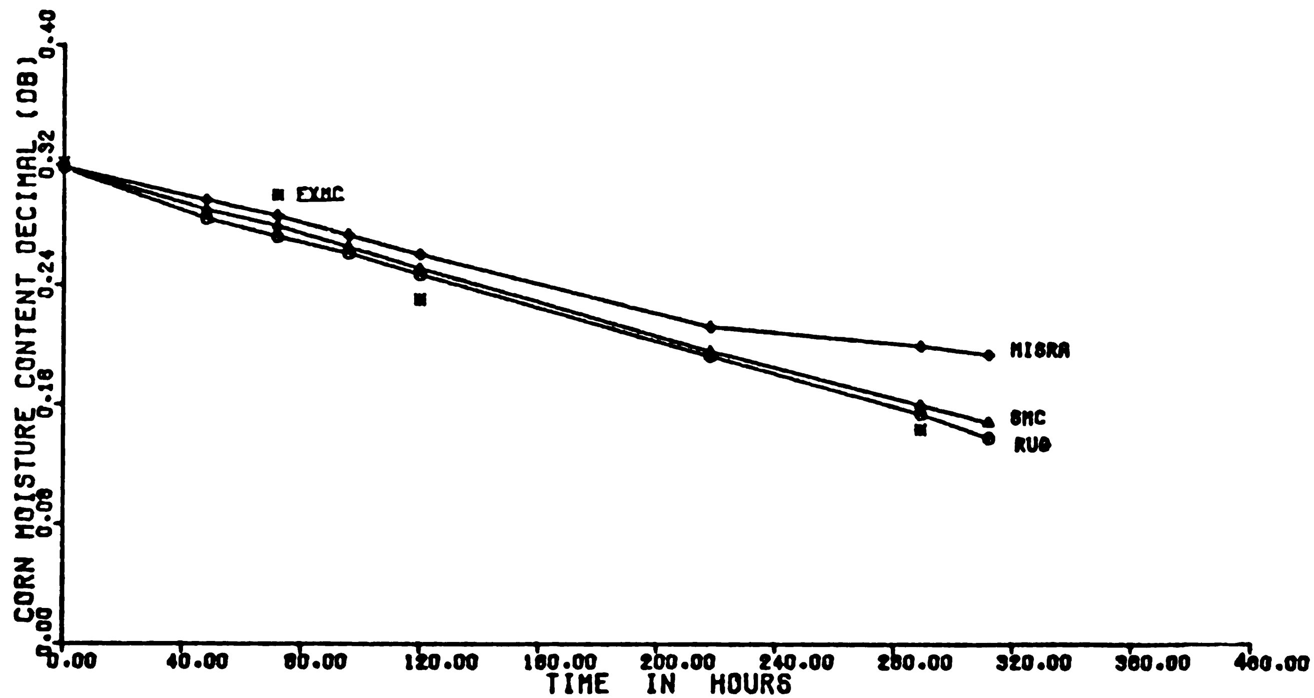


Figure 5-3h. Simulated Average Hourly Corn Moisture Content

RUG = Rugumayo Thinlayer Eqns

MISRA = Misra Thinlayer Eqns

SMC = Sabbah & delGuidice Eqns

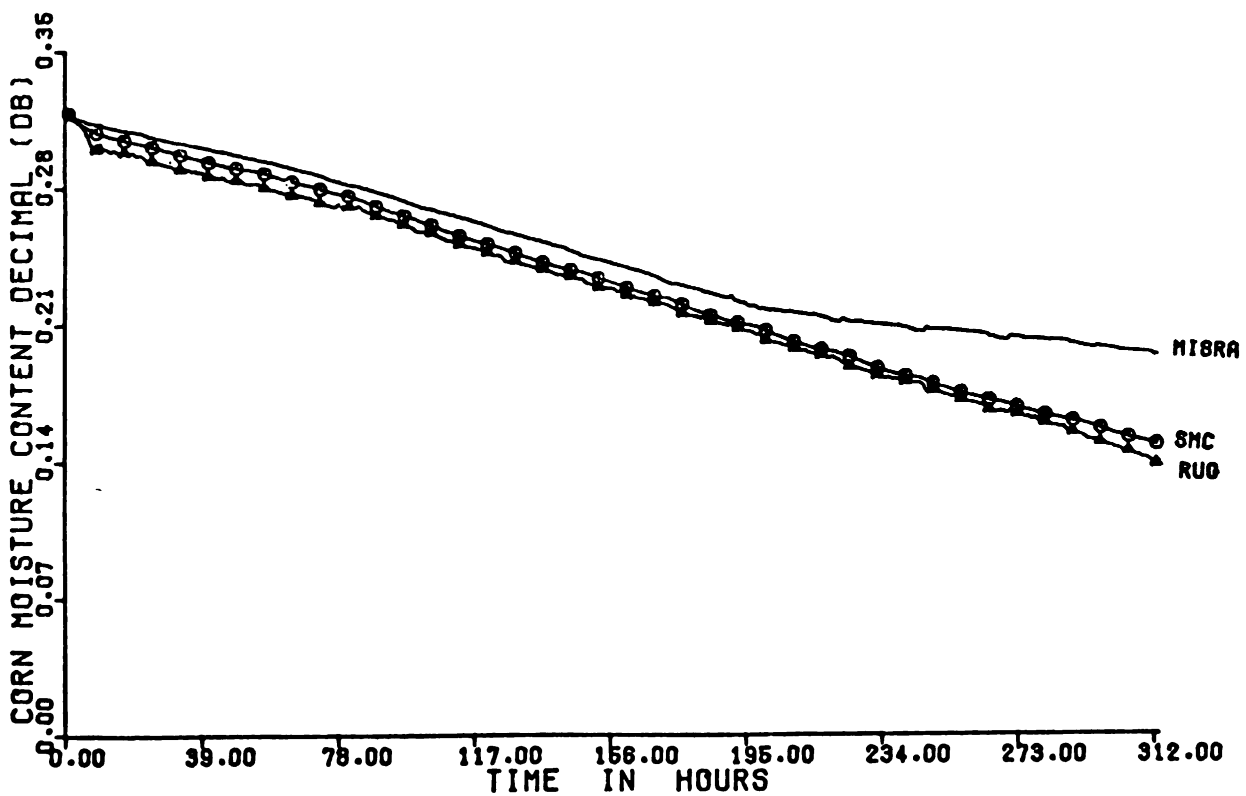
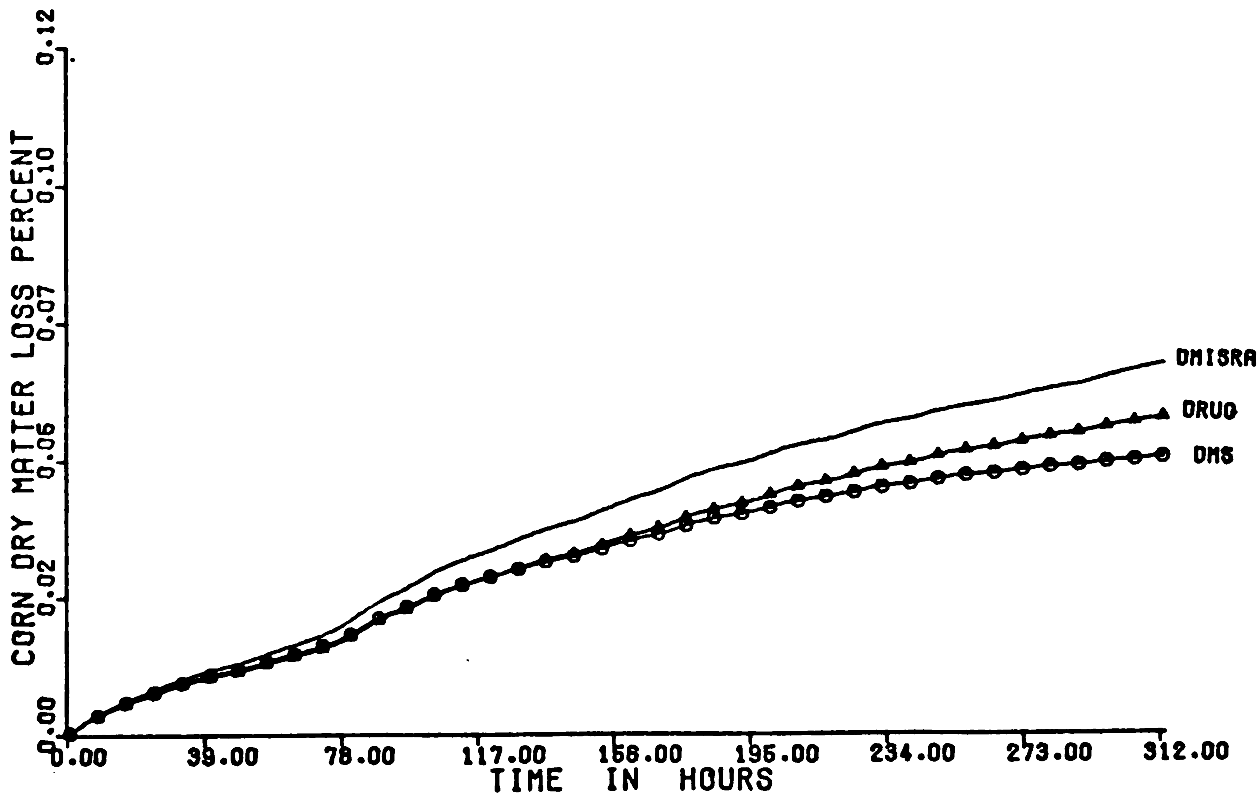


Figure 5-3i. Simulated Average Hourly Corn Dry Matter Loss

DRUG = Dry Matter Loss by Rugumayo Thinlayer Eqns

DMISRA = Dry Matter Loss by Misra Thinlayer Eqns

DMS = Dry Matter Loss by Sabbah & delGuidice Eqns



5.4.1 Solar collector test results

Hourly recorded (time of day, day of the month, cloud cover, insolation, ambient air temperature, heated air temperature, absorber plate temperature and wind speed), calculated (top cover glass temperature and Tedlar cover temperature) parameters listed in Table D-1 of Appendix D and other variables in Table 5-4 were used as in-put to the computer program "SOLARUG" listed in Appendix E. The glass and Tedlar temperatures were calculated as described on page 55 using function "SIMUL" in Appendix E. The value of k_a, μ_a, C_{pa} and Pr are not strongly pressure-dependent and can be used over a fair wide range of pressures. These constant air properties were evaluated at a mean temperature of $275^{O}K$ which is the average of the collector inlet and outlet air temperature for the whole test period.

The computer program output parameters (simulated heated air temperature, diffuse and direct beam components of insolation, total direct and beam radiation incident on the collector surface, net solar radiation absorbed by the collector, upward heat loss coefficient, heat transfer coefficient for a long duct, heat transfer coefficient by Malik (1967), total useful solar heat gained by the air, annual added collector cost, solar cost per kwh and collector efficiency) are presented in Table D-3 of Appendix D. Table D-2 in Appendix D is for illustrating a detailed single page printout that can be obtained from the program "SOLARUG" for any desired hour and date.

The simulated heated air temperature is calculated using the following equation

$$t_2=t_1+\eta q_T/\ (C_p\ G_a) \qquad (5\text{-}6)$$

where,

t_1 = inlet air temperature, ^{o}C

t_2 = outlet air temperature, ^{o}C

η = collector efficiency, decimal

q_T = total solar radiation incident on collector surface, w/m^2

C_p = specific heat of air, $J/kg.^{o}C$

G_a = mass flow rate of air per unit area, $kg/hr\text{-}m^2$

Useful solar heat can be used instead of $\eta\ q_T$. Equation (3-26) is used to evaluate the diffuse component of insolation while the beam radiation is given by equation (3-27). The beam radiation incident on the collector surface is calculated using equation (3-29). Total solar radiation incident on the collector surface is simply the sum of the diffuse radiation and the beam radiation incident on the collector surface.

The net solar energy absorbed by the collector plate is calculated using the equation (3-39). Equation (3-90) gives the upward heat loss while the useful heat removed is calculated using equation (3-97). Review of literature shows that the effective heat transfer coefficient, h contained in equation (3-97) has always been estimated (Whittier, 1964). It should be noted that the effective heat transfer coefficient described by equation (3-98) has only the convective heat transfer coefficient, h_c that needs to be defined precisely in order to determine the value of the effective heat transfer, h.

Malik (1967) developed the emperical equation (2-34) for asymmetrically heated air duct using laboratory data. An attempt has been made in this thesis to derive equation (3-143) from which the convective heat transfer, h_c for a long duct can be calculated. The values of the convective heat transfer by Malik (1967) can be compared with those obtained from the relationship derived in this thesis. The convective heat transfer coefficient, h_c is given by the Nusselt number, Nu as follows:

$$h_c = Nu \frac{k}{D_h} \tag{5-7}$$

where,

h_c = convective heat transfer coefficient, $w/m^{2\,o}C$

Nu = Nusselt number, dimensionless

k = thermal conductivity, w/m^oC

D_h = hydraulic diameter of air duct, m

Once the long duct convective heat transfer coefficient is determined, the value of the convective heat transfer for a short duct such as the one used in this study can be calculated from equation (2-36). The collector efficiency is evaluated using equation (3-20).

The annual added collector cost is calculated from equation (3-150) in which the capital recovery factor (CRF) is given by equation (3-152) and the total additional initial investment is simply the money spent on a solar installation. Equation (3-151) allows for the calculation of the initial investment of various collector sizes. The cost of delivering solar enerby is obtained from equation (3-153).

Temperature distribution in the flat-plate solar collector air heater is illustrated in Figure 5-4a. The air flow rate and the heat transfer coefficient, h_c obtained from the Stanton number equation (2-34) by Malik (1967) and from the Nusselt number equation (3-143) developed in this thesis are plotted in Figure 5-4b. The components of solar radiation incident on the inclined flat-plate solar collector and the collector efficiency are plotted in Figure 5-4c. Total useful solar heat from the flat-plate solar collector air heater and the cost of obtaining the energy are illustrated in Figure 5-4d.

5.4.2 Discussion of the solar collector results

Cloud cover data were obtained from East Lansing weather records. Varification of such records with a tested scientific instrument appears necessary because some abnormally high values of diffuse radiation are obtained from equation (3-26) when the cloud cover values are near the ten score. In order to correct this, depending on the hour of the day and expected sunshine hours during the day, when the calculated diffuse radiation exceeded recorded diffuse plus beam radiation total radiation incident on the collector was made equal to recorded solar radiation. The calculated glass temperature is about the same as the ambient air temperature as illustrated in Figure 5-4a. This shows that there is little upward heat loss from the absorber collector surface as indicated the low value of the upward heat loss coefficient listed in column 7 of Table D-3 of Appendix D.

The calculated Tedlar cover temperature is higher than the glass and ambient air temperatures but much less than the absorber plate temperature. This again leads to low upward heat losses and more heat transfer to the heat transfer fluid (air).

The experimental heated air temperature (TEE) listed in Table D-1 and the simulated heated air temperature (TFS) listed in Table D-3 of

Appendix D have almost the same value. Average simulated temperature (8^{o}C) is 2.0^{o}C less than the mean measured temperature (10^{o}C) for the hours of 10:00 A.M. to 2:00 P.M. The average air temperature (3^{o}C) for the same time, if considered to be the inlet air temperature, results in temperature increases of 5^{o}C and 7^{o}C for simulated and measured temperatures respectively. The average collector efficiency for the same time period if 57%. This efficiency is within the range (40% to 80%) for covered flatplate collectors, Shove (1976).

When the whole time period is considered, the average simulated and recorded heated air temperatures are about 1.5^{o}C and 3.3^{o}C respectively. The corresponding average ambient air temperature is 0^{o}C leading to temperature rises of 1.5^{o}C and 3.3^{o}C for simulated and recorded treated air temperatures respectively. The average collection efficiency for this whole period is about 52% which, again, is within the collection efficiency for covered flatplate collectors.

The importance of collector inclination is to increase the amount of direct beam radiation by allowing the beam radiation to strike the collector surface at or near right angles. Figure 5-4c illustrates the magnitude of all the solar radiation components. The radiation (diffuse + direct beam) incident on the inclined collector surface is either equal to or greater than the recorded insolation.

The three horsepower axial flow fan used in this test had a higher airflow rate (8.8m^3/min or 310.2 cfm for 120 bushels of 24% moisture content, d.b., corn) than desired (3.4 - 6.8 m^3/min or 120 - 240 cfm or 1-2 cfm/bushel) Shove, (1976) and added an average of about 2^{o}C to the solar heated air temperature. An attempt to reduce the air flow resulted in more heat being added to the heated air temperature by the fan.

The value of the heat transfer coefficient calculated using the equation by Malik (1967) is slightly greater than the value of the heat transfer coefficient model developed in this thesis. This due to the differences in solar collector aspect ratio and the equivalent diameter over length ratio. Values of 4 and 120 for aspect ratio and L/D, respectively are recommended for using the Malik (1967) equation. The heat transfer coefficient equation developed in this thesis can be used for aspect and L/D ratios of 3 and 21, respectively.

Figure 5-4d shows that the more solar heat that is obtained from the solar air heating system the cheaper it becomes to operate the system. Using equation (3-153), the calculated cost of delivering solar energy (70 kw hrs) after 312 operating hours is 48¢/kwh. This cost could have been reduced considerably if the solar collector grain drying system was operated for the whole corn harvest period (September through November) instead of just about half the month of November (November 6-19, 1976).

In order to properly evaluate the cost of using solar energy for grain drying it will be necessary to know the yearly quantity of useful solar heat delivered by the system for the whole 20 years the system is estimated to operate. The dollar/kwh cost of solar energy so obtained can then be compared to costs of commonly used fuels (propane costs 40¢/gal. or 2¢/kwh, #2 Fuel oil costs 65¢/gal or 2¢/kwh and electricity costs 6¢/kwh) in grain drying, Shove (1976).

From the results of this analysis alone it is not possible to draw any conclusions regarding the cost effectiveness of using solar energy for grain drying. However, increased oil prices coupled with dwindling world oil reserves appear to lead to increased need to use low temperature solar grain drying regardless of its cost.

Table 5-4. Some of the in-put parameters to the computer program "SOLARUG"

No.	Parameter	Value
1.	East Lansing longitude	84.47^{o}W
2.	East Lansing latitude	42.70^{o}N
3.	East Lansing standard meridian	75^{o}W
4.	Solar Collector inclination (facing South)	52^{o}
5.	Solar collector size	46 cm wide by 488 cm long
6.	Glass cover refractive index	1.5
7.	Glass cover thickness	0.3175 cm
8.	Glass cover extinction, coefficient	0.508 cm^{-1}
9.	Glass cover emissivity	0.88
10.	Two cover plate dependent constant for glass	0.1
11.	Tedlar cover refractive index	1.45
12.	Tedlar cover thickness	(0.01016 cm
13.	Tedlar cover extinction coefficient	0.508 cm^{-1}
14.	Tedlar cover long wave radiation transmittance	0.3
15.	Tedlar cover emissivity	0.25
16.	Two cover plate dependent constant for Tedlar	0.44
17.	Dead air space constant	1.234
18.	Absorptivity of the black paint	0.95
19.	Emissivity of the black painted copper surface	0.2
20.	Emissivity of polished bare copper plate	0.04
21.	Stefan-Boltzman Constant	5.669×10^{-8} $w/m^{2\,o}K^{4}$
22.	Dirt loss factor	0.98
23.	Shading factor	1.00
24.	Air duct size	46 cm wide by 15 cm deep
25.	Emissivity of Acrylic white paint on air duct	0.90
26.	Air flow rate	6.7 m^3/min
27.	Specific heat of air, C_{pa}	1.0055kJ/kg^{o}C
28.	Thermal conductivity of air, k_a	0.024255w/m^{o}C
29.	Prandl Number, Pr	0.715
30.	Dynamic viscosity of air, μ_a	1.7355×10^{-5}kg/m s
31.	Total additional initial investment in solar system	$250.00
32.	Life expectance of the collector	20 years
33.	Interest rate	12% per year

Figure 5-4a. Temperature distribution in the flat-plate solar collector air heater, during the deep bin solar drying test.

● Ambient Air Temperature, °K

▲ Glass Cover Temperature, °K

◆ Tedlar Cover Temperature, °K

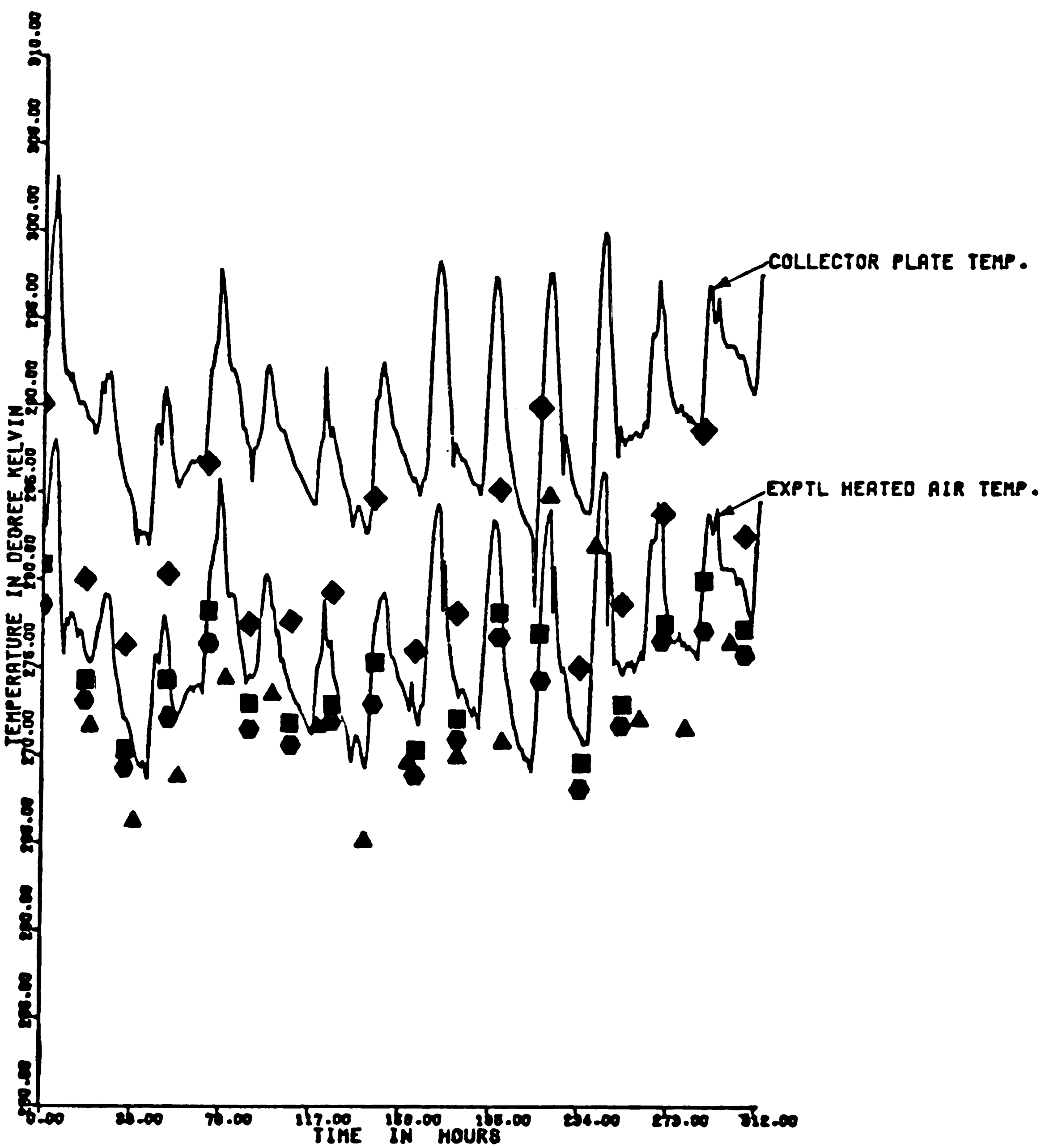
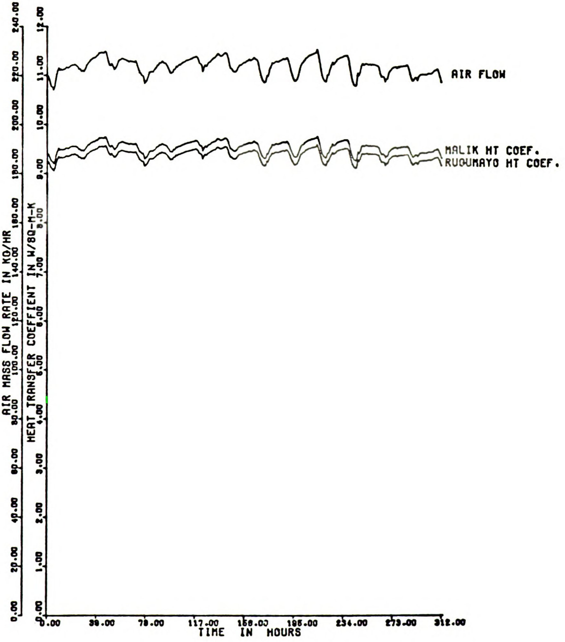


Figure 5–4b. Heat transfer coefficient, h and air flow variation with time in the flat-plate solar collector air heater.



COLLECTOR EFFICIENCY IN PERCENTAGE

Figure 5-4c. Components of solar radiation incident on an inclined flat-plate solar collector and the collector efficiency.

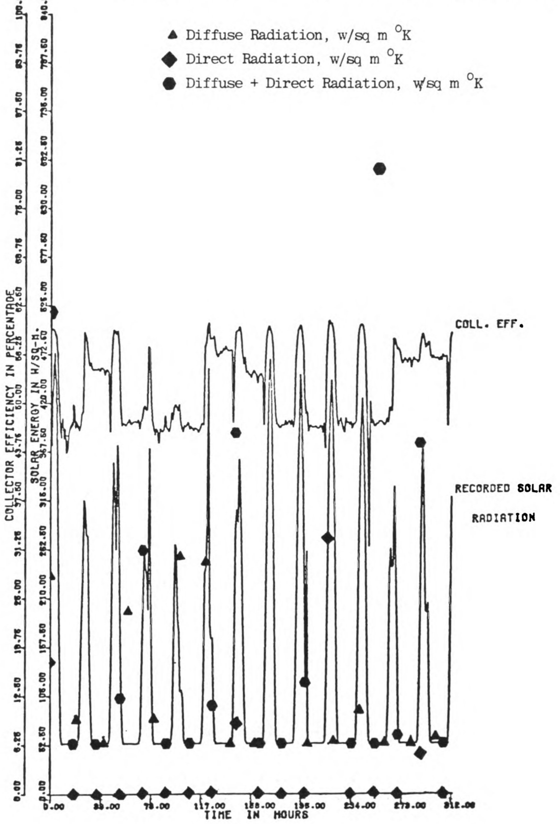
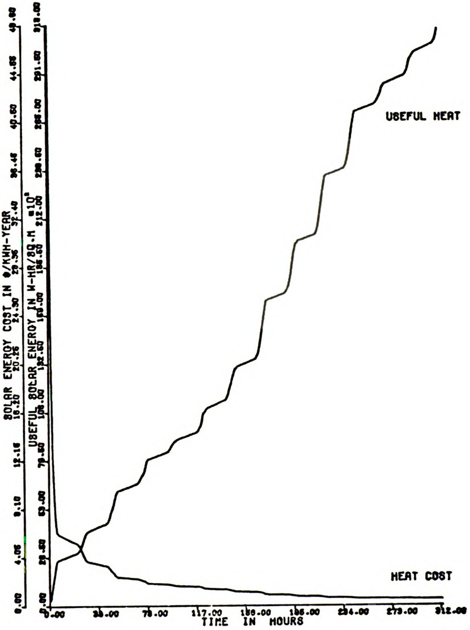


Figure 5-4d. Annual useful solar heat from the flat-plate solar collector air heater and the cost of obtaining the heat energy.



CHAPTER SIX

CONCLUSIONS

Based on the experiments and analyses performed in this study, the following conclusions can be drawn:

1. The thin-layer <u>drying</u> equation for shelled corn developed in this study is

$$M_t=(M_o-M_e)\ \exp\ [(25.5920-38.6298M_{t-1}+ 26.6824\ \log\ (M_{t-1})-$$
$$0.0044\ \theta_t(M^2_{t-1})\ \exp\ (rh^2_t)\ t\ ] + M_e$$

2. The equation developed to describe the low-temperature thin-layer <u>rewetting</u> for shelled corn is

$$M_t=(M_o-M_e)\ \exp\ [(162.1179-487.9552M_{t-1}+118.6144\ \log\ (M_{t-1}) +$$
$$0.69658\ \theta_t\ (M^2_{t-1})\ \exp\ (rh^2_t)\ t] + M_e$$

3. The equations developed to describe thin-layer drying and rewetting are simple, contain pertinent independent variables and produce satisfactory fit between experimental and simulated data from thin-layer drying and rewetting, and in-bin low temperature grain drying.
4. In East Lansing, Michigan corn can be dried with low temperature

solar heated air over an extended period of time without loss of its market quality.

5. The heat transfer coefficient for asymmetrically solar heated air collectors can be calculated using the equation:

$$h_d = \frac{0.067\ k\ Re^{7/8} Pr}{D_h\ (Pr + \ln\ (5\ Pr + 1) + 0.5\ \ln(Re^{7/8}) - 2.7)}$$

6. The computer program "SOLARUG" developed in this thesis should simplify evaluation of solar heated air temperature rise, flat-plate collector efficiency and the cost of operating solar air heating collectors.

CHAPTER SEVEN

SUGGESTIONS FOR FUTURE WORK

Depending on the results of this study, the following recommendations are made for further investigations:

1. Development of a mathematical model for cloud cover. The equation should contain easily measurable independent weather parameters such as air temperature and relative humidity.

2. To extend low temperature thin-layer and deep bed drying and rewetting studies to other crops besides shelled corn.

3. To investigate the collector efficiency, solar heated air temperature rise, cost of grain drying with the solar heated air using weather data from warm climates as in-put to the computer program "SOLARUG".

4. Modifications of the computer program "SOLARUG" to simulate solar water heating.

CHAPTER EIGHT

APPENDICES

APPENDIX A

(Plots of the thin-layer corn drying and rewetting parameter, K in hr^{-1})

Figure A-1. Corn Drying and Moisture Absorption Coefficient, K for Drying Air Temperature of 21.0°C and Relative Hunidity of 60%, and Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test one.

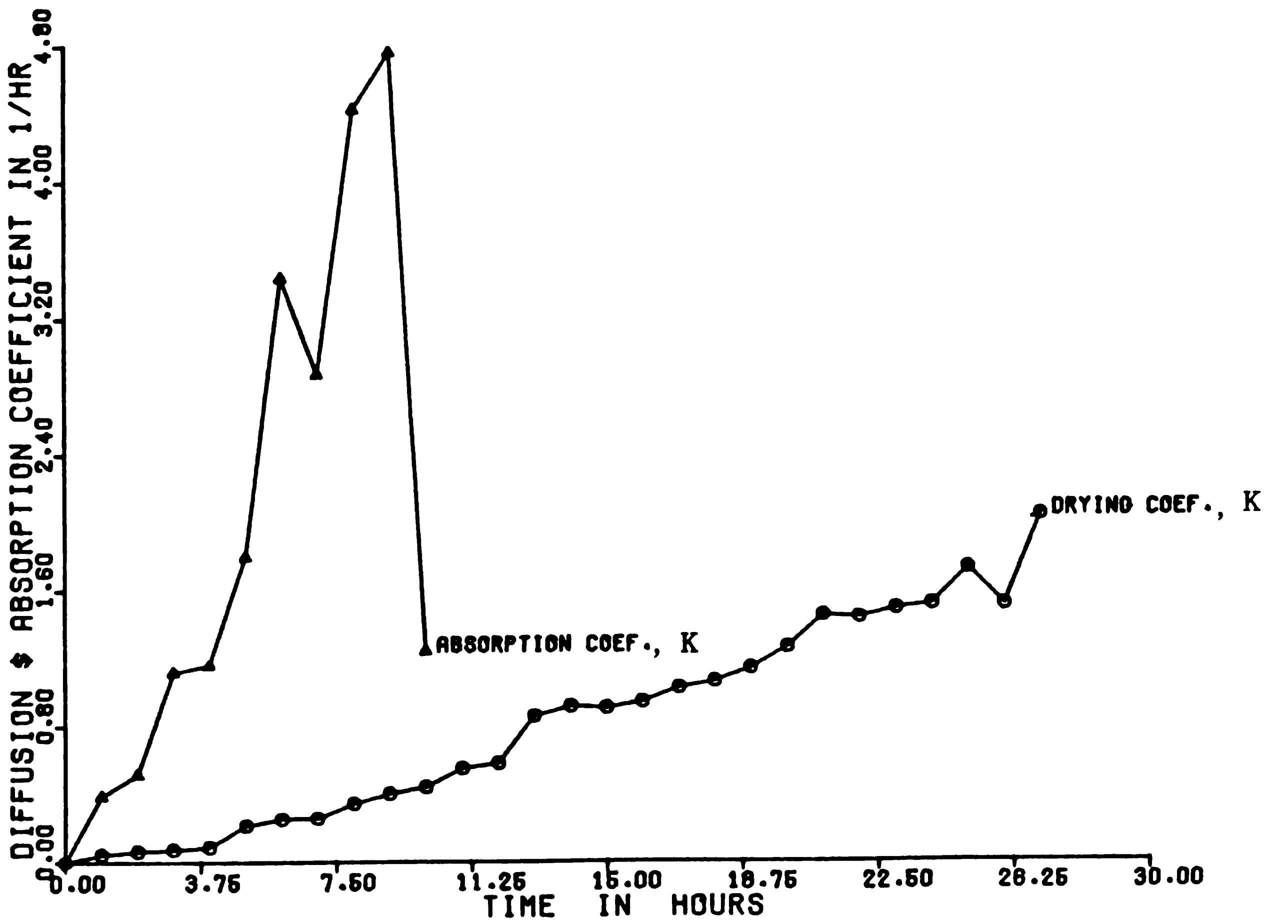


Figure A-2. Corn Drying and Moisture Absorption Coefficient, K for Drying Air Temperature of 21.0°C and Relative Humidity of 50%, and Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test two.

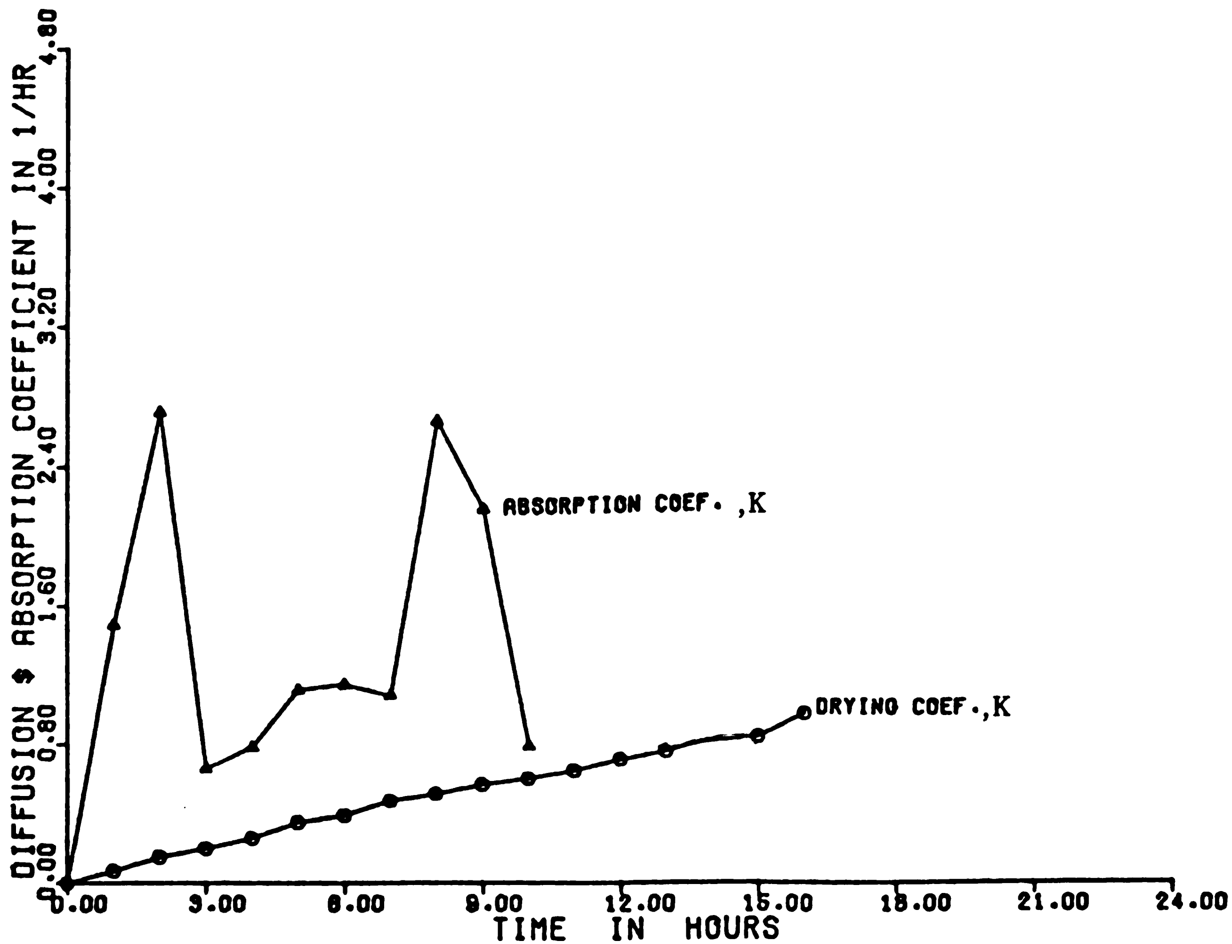


Figure 4.

Figure A-3. Corn Drying and Moisture Absorption Coefficient, K for Drying Air Temperature of 21.0°C and Relative Humidity of 40%, and Rewetting Air Temperature of 21.0°C and Relative Humidity of 90% for test three.

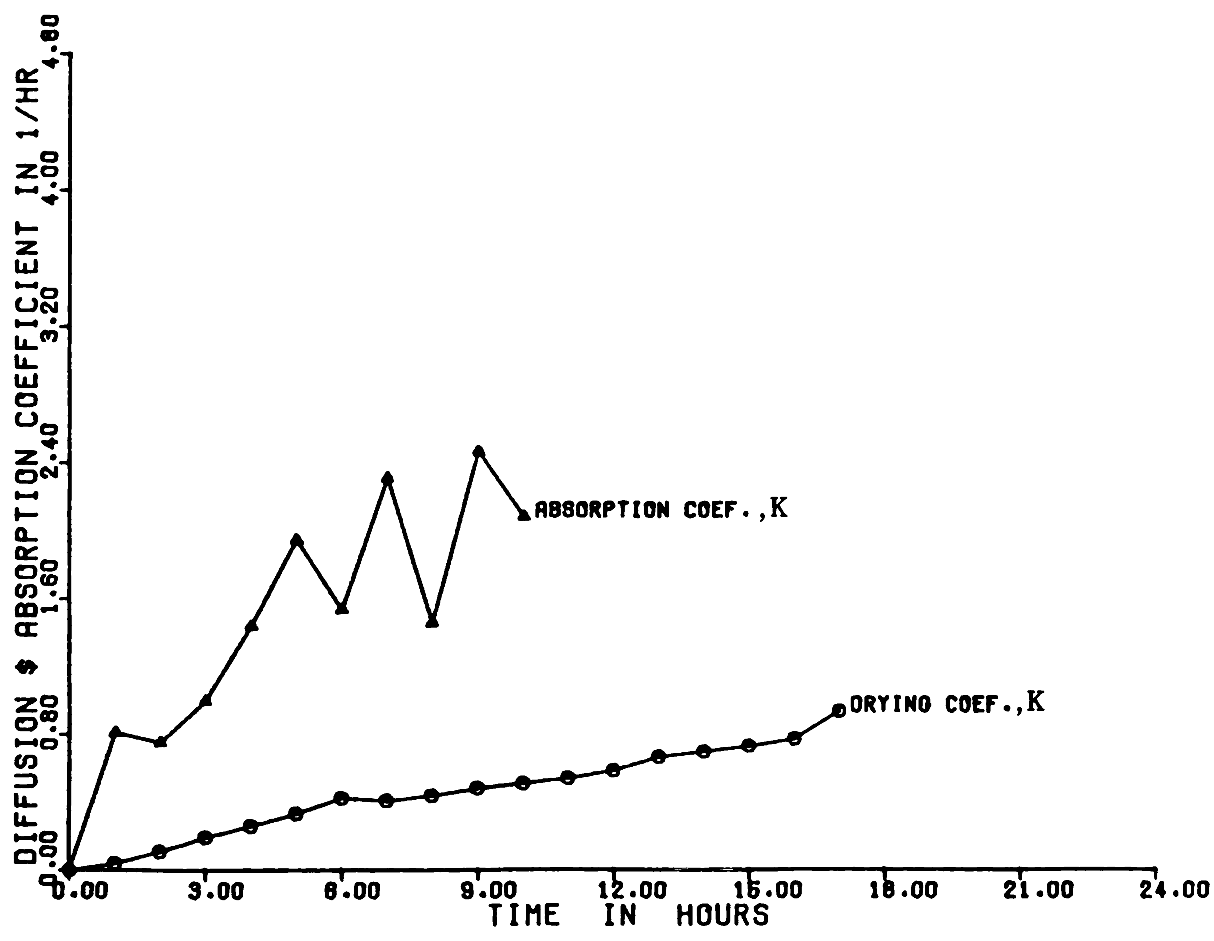


Figure A-4. Corn Drying and Moisture Absorption Coefficient, K for Drying Air Temperature of 15.5°C and Relative Humidity of 50%, and Rewetting Air Temperature of 15.5°C and Relative Humidity of 85% for test four.

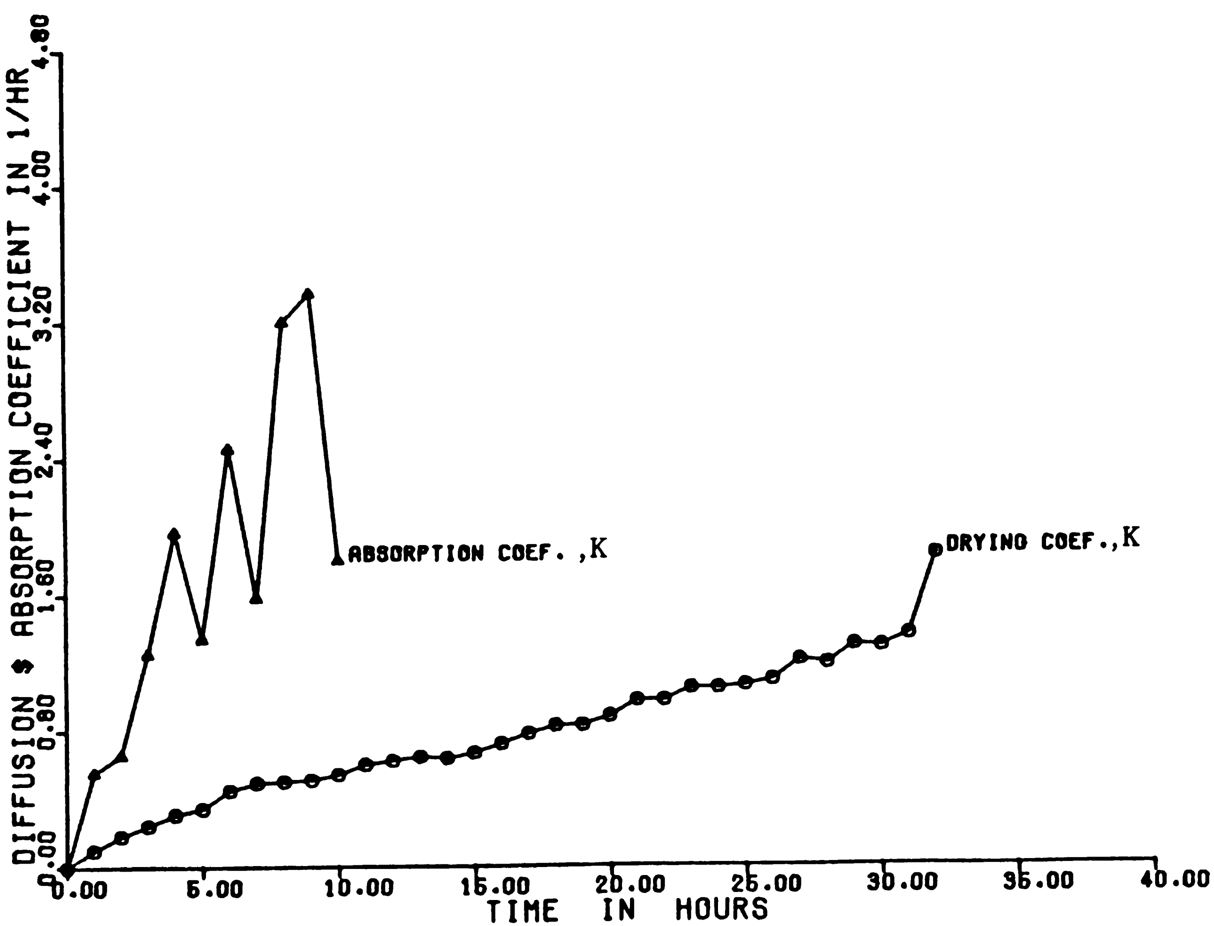


Figure A-5. Corn Drying Coefficient, K for Drying Air Temperature of 10.0°C and Relative Humidity of 40% for test five.

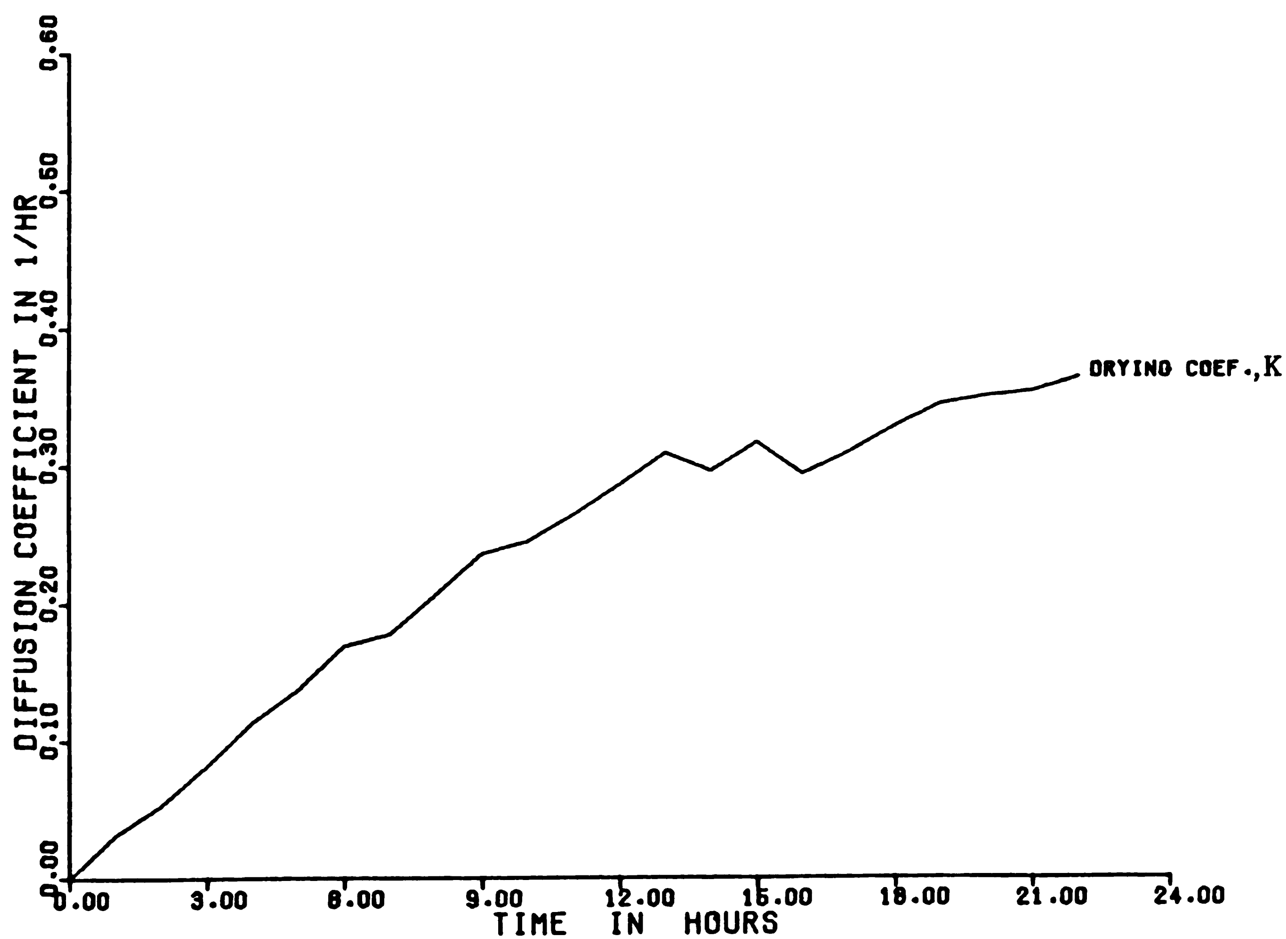
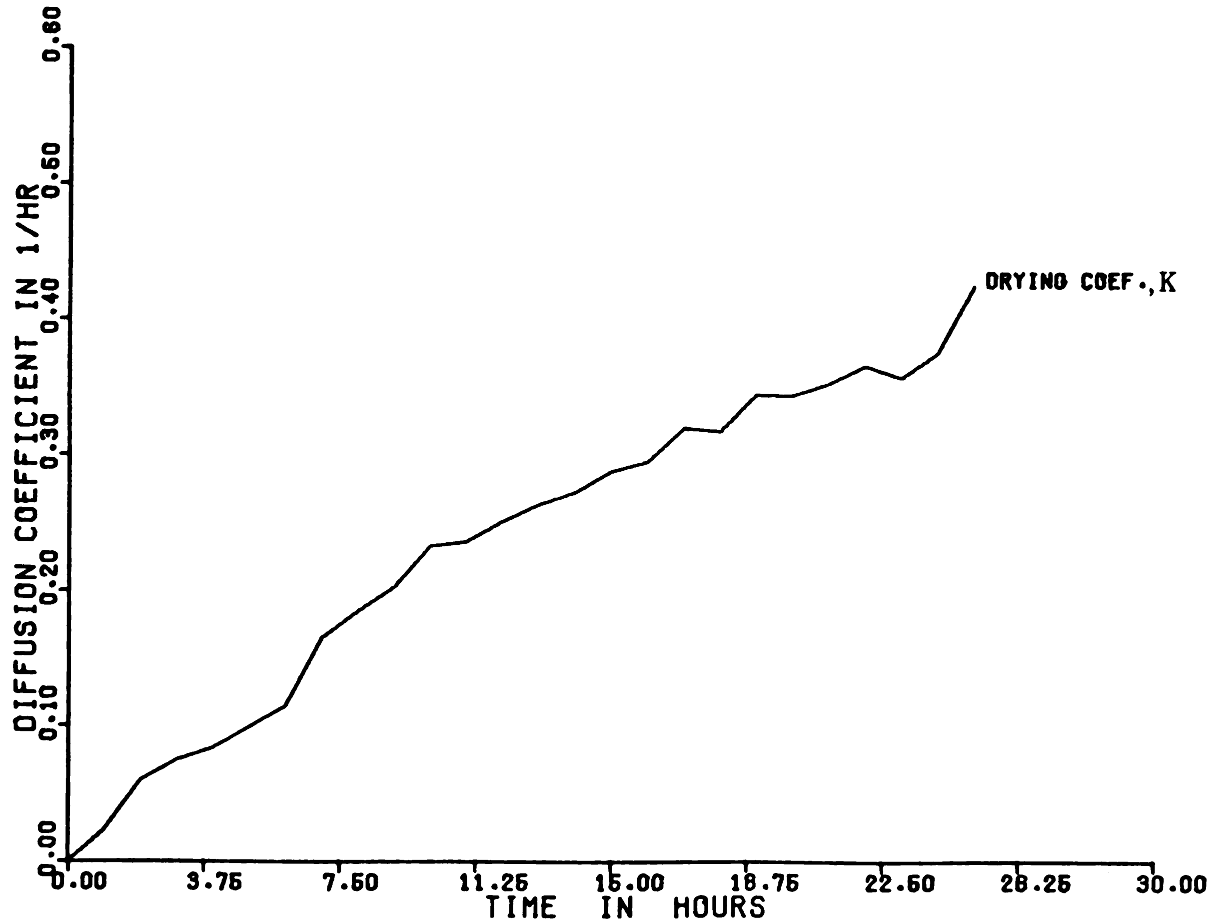


Figure A-6. Corn Drying Coefficient, K for Drying Air Temperature of 4.4°C and Relative Humidity of 30% for test six.



APPENDIX B

(Listing of program "NLINA" used to determine the unknown constants in the thin-layer corn drying and rewetting equations)

Appendix B

```
      PROGRAM NLINA (INPUT,OUTPUT)
      DIMENSION PS(6,6),T(300,8),Y(300),SIG2(300),B(6),Z(6),A(6),P(6,6),
     1BS(6),BSS(6),CG(6),BSV(6),VINV(6,6),BSAV(6),PSV(6,6),R(6,6)
      DOUBLE PRECISION P,PS,PSV,SUMP,PSQ1,PSQ2,PSQ
      COMMON T,Z,BS,I,ETA,PS,P,B,A,Y,SIG2,MODL,VINV,NP
      COMMON DELT
      EPS=1.0E-30
      EPSS=0.0001
  200 CONTINUE
C     START INPUT
      READ 11,N,NP,NT,ITMAX,MODL,IOPT,IPRINT
      IF(N)1000,1000,201
  201 CONTINUE
      PRINT 3
      PRINT  1,N,NP,NT,ITMAX,MODL,IOPT,IPRINT
    3 FORMAT(/1H0,9X,*N*,8X,*NP*,8X,*NT*,5X,*ITMAX*,5X,*MODEL*,6X,*IOPT*
     1,4X,*IPRINT*)
   11 FORMAT(7I10,4F10.0)
    1 FORMAT(/7I10,4F10.4)
C     IF IOPT=0, THEN ON THE 2ND AND SUCCEEDING STAKED CASES, THE DATA
C     DOES NOT HAVE TO BE REPEATED.
C     IF IPRINT=1, EXTRA PRINTOUT OF ETA, RESIDUAL, B(1),... ARE GIVEN.
      READ 44,(B(I),I=1,NP)
      PRINT  311
  311 FORMAT(/10X,*B(1)*,10X,*B(2)*,10X,*B(3)*,10X,*B(4)*,10X,
     2*B(5)*,10X,*B(6)*)
      PRINT 45,(B(I),I=1,NP)
   44 FORMAT(6F14.4)
   45 FORMAT(/6F14.5)
      BS(2)=0.0
      BS(3)=0.0
      BS(4)=0.0
      BS(5)=0.0
      BS(6)=0.0
      IF(IOPT)312,312,313
  312 CONTINUE
```

```
      PRINT 13
   13 FORMAT(/9X,*J*,6X,*Y(J)* ,6X,*SIGMA(J)*,6X,*T(J,1)*,6X,*T(J,2)*,6X
     1,*T(J,3)*,6X,*T(J,4)*,6X,*T(J,5)*,6X,*T(J,6)*,6X,*T(J,7)*,6X,
     2*T(J,8)*)
      DO 10 J=1,N
      READ 14,K,Y(J),SIG2(J),(T(J,KT),KT=1,NT)
      DELT = 1.0
      IF(Y(J).EQ.0.0)  DELT =0.0
   14 FORMAT(I3,1X,F8.5,1X,F3.1,1X,F4.1,2(1X,F6.2),5F6.4)
      PRINT 4,K,Y(J),SIG2(J),(T(J,KT),KT=1,NT)
    4 FORMAT(/I10,10F12.6)
      SIG2(J)=SIG2(J)*SIG2(J)
   10 CONTINUE
  313 CONTINUE
      DO 2 IP=1,NP
      DO 2 KP=1,NP
      PS(IP,KP)=0.0
      P(IP,KP)=0.0
    2 CONTINUE
      PRINT 9
    9 FORMAT(/5X,*P(1,KP)*,9X,*P(2,KP)*,9X,*P(3,KP)*,9X,*P(4,KP)*,9X,*P(
     35,KP)*,9X,*P(6,KP)*)
      DO 6 IP=1,NP
      READ 15,(PS(IP,KP),KP=1,NP)
      PRINT 5,(PS(IP,KP),KP=1,NP)
    6 CONTINUE
    5 FORMAT(6D16.5)
   15 FORMAT(9D14.5)
C*****END  INPUT
      DO 18 IL=1,NP
      BS(IL)=B(IL)
      CG(IL)=0.0
   18 CONTINUE
      DO 19 IP=1,NP
      DO 19 KP=1,NP
      P(IP,KP)=PS(IP,KP)
   19 CONTINUE
      IF(IPRINT)306,306,307
  307 CONTINUE
      PRINT 7
    7 FORMAT(/4X,*J*,9X,*ETA*,7X,*RISD*,7X,*BS(1)*,7X,*BS(2)*,7X,*BS(3)*
```

Appendix B Continued

```
     6,7X,*BS(4)*,7X,*BS(5)*,7X,*BS(6)*)
 306 CONTINUE
     I=0
     MAX=0
  99 CONTINUE
     MAX=MAX+1
C*****START BASIC LOOP, GIVES B(I) AND SY
     SY=0.0
     DO 100 II=1,N
     I=II
     CALL SENS
     CALL MODEL
     RISD=Y(I)-ETA
     SY=SY+RISD*RISD/SIG2(I)
     SUM=0.0
     DO 20 K=1,NP
     DO 20 L=1,NP
     SUM=SUM+Z(L)*P(K,L)*Z(K)
  20 CONTINUE
     DELTA=SIG2(I)+SUM
     DO 29 JJ=1,NP
     A(JJ)=0.0
     CS=0.0
  29 CONTINUE
     DO 30 JA=1,NP
     DO 30 KA=1,NP
     A(JA)=A(JA)+Z(KA)*P(JA,KA)
  30 CONTINUE
     DO 40 JC=1,NP
     CS=CS+Z(JC)*(B(JC)-BS(JC))
     CG(JC)=CG(JC)+Z(JC)*RISD/SIG2(I)
  40 CONTINUE
     C=Y(I)-CS-ETA
     DO 50 IB=1,NP
     B(IB)=B(IB)+(A(IB)*C)/DELTA
  50 CONTINUE
     DO 41 ISV=1,NP
     DO 41 JSV=1,NP
     PSV(ISV,JSV)=P(ISV,JSV)
  41 CONTINUE
```

Appendix B Continued

```
      DO 52 IV=1,NP
      DO 52 IU=IV,NP
      SUMP=0.0
      DO 51 KP=1,NP
      DO 51 JP=1,NP
      IF(KP-IV)48,51,48
   48 CONTINUE
      IF(JP-IU)49,51,49
   49 CONTINUE
      PSQ1=PSV(KP,JP)*FSV(IU,IV)
      PSQ2=PSV(IU,KP)*PSV(IV,JP)
      PSQ=PSQ1-PSQ2
      RP=PSQ/(DABS(PSQ1)+DABS(PSQ2)+1.0E-100)
      RP=ABS(RP)
      RPP=RP-1.0E-12
      IF(RPP)54,54.55
   54 PSQ=0.0
   55 CONTINUE
      SUMP=SUMP+Z(JP)*Z(KP)*PSQ
   51 CONTINUE
      P(IU,IV)=(PSV(IU,IV)*SIG2(I)+SUMP)/DELTA
   52 CONTINUE
      DO 53 IV=2,NP
      IVM=IV-1
      DO 53 IU=1,IVM
      P(IU,IV)=P(IV,IU)
   53 CONTINUE
      IF(IPRINT) 100,100,308
  308 CONTINUE
      PRINT 8,I,ETA,RISD,(B(JC),JC=1,NP)
  100 CONTINUE
    8 FORMAT(/I5,8E12.5)
C**** END  BASIC LOOP, GIVES B(I) AND SY
C**** START BOX-KANEMASU MODIFICATION
      IF(MAX-1)104,104,103
  103 SS=SY/2.0
      IF(SS-SYP)104,104,105
```

Appendix B Continued

```
  105 DO 210 IBS=1,NP
      B(IBS)=BSV(IBS)
  210 CONTINUE
      PRINT 212
  212 FORMAT(1H0,7X,*USE BSV(IBS)*)
      GO TO 211
  104 CONTINUE
      DO 102 IBS=1,NP
      BSS(IBS)=BS(IBS)
  102 CONTINUE
      GAL=2.0
      GMU=1.5
  110 GAL=GAL/2.0
      DO 116 IBS=1,NP
      BS(IBS)=BSS(IBS)+GAL*(B(IBS)-BSS(IBS))
      BSV(IBS)=BS(IBS)
  116 CONTINUE
      INDEX=0
      G=0.0
      DO 115 IP=1,NP
      DELB=BS(IP)-BSS(IP)
      G=G+DELB*CG(IP)
      RATIO=DELB/(BSS(IP)+EPS)
      RATIO=ABS(RATIO)
      IF(RATIO-EPSS)113,113,114
  113 INDEX=INDEX+1
      PRINT 314
  314 FORMAT(/7X,*MAX*,8X,*NP*,5X,*INDEX*,8X,*IP*)
      PRINT 11,MAX,NP,INDEX,IP
  114 CONTINUE
C**** PRINT 122,I,Y(I),ETA,RISD,Z(IP),SYP,DELB,SIG2(I)
  115 CONTINUE
      SYP=0.0
      DO 117 II=1,N
      I=II
      CALL MODEL
      RISD=Y(I)-ETA
      SYP=SYP+RISD*RISD/SIG2(I)
  117 CONTINUE
```

Appendix B Continued

```
      IF(NP-INDEX)106,106,107
 106  H=1.0
      GO TO 132
 107  CONTINUE
      SYN=SYP*0.999
      IF(SYN-SY)112,112,111
 111  IF(GAL-0.21)109,109,110
 109  PRINT 108,GAL,SYP,SY
 108  FORMAT(1H0,3X,*GAL TOO SMALL,GAL=*F12.6,2X,*SYP=*E15.6,2X,*SY=*E15
     5.6)
      PRINT 1001
1001  FORMAT(/10X,*Z(1)*,12X,*Z(2)*,12X,*Z(3)*,12X,*Z(4)*,12X,*Z(5)*
     1,12X,*Z(6)*)
1002  FORMAT(7E16.5)
      DO 1003 J=1,N
      CALL SENS
      PRINT 1002,(Z(I),I=1,NP)
1003  CONTINUE
      GO TO 200
 112  CONTINUE
      SKSUM=SY-GAL*G*(2.0-1.0/GMU)
      IF(SYP-SKSUM)131,131,130
 130  H=GAL*GAL*G/(SYP-SY+2.0*GAL*G)
      GO TO 132
 131  GALP=GAL**20
      H=GAL*GMU
 132  CONTINUE
      DO 118 IBN=1,NP
      B(IBN)=BSS(IBN)+H*(B(IBN)-BSS(IBN))
 118  CONTINUE
 211  CONTINUE
      PRINT 121
 121  FORMAT(1H0        ,7X,*MAX*,                          12X,*H*,14X,*G*,13X,
     1*SY*,12X,*SYP*)
      PRINT 122,MAX,            H,G,SY,SYP
 122  FORMAT(/I10, 1F15.8,4E15.7)
      PRINT 311
      PRINT 309,(B(I),I=1,NP)
```

Appendix B Continued

```
  309 FORMAT(8E15.7)
C**** END  BOX-KANEMASU MODIFICATION
      PRINT 9
      DO 206 IP=1,NP
      PRINT 207,(P(IP,KP),KP=1,NP)
  206 CONTINUE
  207 FORMAT(/6D15.7)
      PRINT 135
  135 FORMAT(/1H0,5X,*CORRELATION MATRIX*)
      DO 136 IR=1,NP
      DO 136 IR2=1,IR
      AR=P(IR,IR)*P(IR2,IR2)
      R(IR,IR2)=P(IR,IR2)/SQRT(AR)
  136 CONTINUE
      DO 137 IR=1,NP
      PRINT 309,(R(IR,III),III=1,IR)
  137 CONTINUE
      DO 126 IPS=1,NP
      PS(IPS,IPS)=(1.0E+7)*P(IPS,IPS)
  126 CONTINUE
      PRINT 127
  127 FORMAT(/1H0,3X,*IPS=*,I4,3X,*PS(IPS,IPS) =*,D15.8)
      DO 119 IP=1,NP
      DO 119 KP=1,NP
      P(IP,KP)=PS(IP,KP)
  119 CONTINUE
      DO 120 IP=1,NP
      BS(IP)=B(IP)
      CG(IP)=0.0
  120 CONTINUE
      PRINT 314
      PRINT 11,MAX,NP,INDEX,IP
      PRINT 7
      IF(NP-INDEX)101,101,123
  123 CONTINUE
```

Appendix B Continued

```
      M=ITMAX
      IF(MAX-M) 99,99,101
  101 CONTINUE
      IF(IPRINT) 133,133,134
  133 IPRINT=IPRINT+1
      GO TO 99
  134 CONTINUE
      GO TO 200
 1000 CONTINUE
      END
```

Appendix B Continued

```
      SUBROUTINE MODEL
      DIMENSION PS(6,6),T(300,8),Y(300),SIG2(300),B(6),Z(6),A(6),P(6,6),
     1BS(6),VINV(6,6)
      COMMON T,Z,BS,I,ETA,PS,P,B,A,Y,SIG2,MODL,VINV,NP
      COMMON DELT
      DOUBLE PRECISION P,PS
      IF(MODL.EQ.1) GO TO 10
      IF(MODL.EQ.2) GO TO 20
   10 CONTINUE
C****  MODEL  ONE FOR MOISTURE DESORPTION FROM A CORN KERNEL IS
C****  DEVELOPED FROM FICK,S LAW. THE PARAMETER K IS A FUNCTION OF
C****  CORN TEMPERATURE IN DEGREE KELVIN ,MOISTURE CONTENT AND TIME
      ETA=(BS(1)+BS(2)*T(I,7)+BS(3)*ALOG10(T(I,7))+BS(4)*T(I,3)
     1*(T(I,7)**2.)*EXP(T(I,5)**2.))*DELT
      GO TO 100
   20 CONTINUE
C****  MODEL  TWO FOR MOISTURE ADSORPTION INTO A CORN KERNEL IS
C****  DEVELOPED FROM FICK,S LAW. THE CONSTANTS ARE ASSIGNED INITIAL
C****  VALUES AS IN MODEL ONE
      ETA=(BS(1)+BS(2)*T(I,7)+BS(3)*ALOG10(T(I,7))+BS(4)*T(I,3)
     1*(T(I,7)**2.)*EXP(T(I,5)**2.))*DELT
  100 CONTINUE
      RETURN
      END
```

Appendix B Continued

```
      SUBROUTINE SENS
      DIMENSION PS(6,6),T(300,8),Y(300),SIG2(300),B(6),Z(6),A(6),P(6,6),
     1BS(6),VINV(6,6)
      COMMON T,Z,BS,I,ETA,PS,P,B,A,Y,SIG2,MODL,VINV,NP
      COMMON DELT
      DOUBLE PRECISION P,PS
      IF(MODL.EQ.1) GO TO 10
      IF(MODL.EQ.2) GO TO 20
   10 CONTINUE
C****  SENSITIVITY COEFFICIENTS, Z(1)TO Z(4) FOR THE FIRST MODEL ARE
      Z(1)=DELT
      Z(2)=DELT*T(I,7)
      Z(3)=DELT*ALOG10(T(I,7))
      Z(4)=DELT*T(I,3)*(T(I,7)**2.)*EXP(T(I,5)**2.)
      GO TO 100
   20 CONTINUE
C****  SENSITIVITY COEFFICIENTS, Z(1)TO Z(4) FOR THE SECOND MODEL ARE
      Z(1)=DELT
      Z(2)=DELT*T(I,7)
      Z(3)=DELT*ALOG10(T(I,7))
      Z(4)=DELT*T(I,3)*(T(I,7)**2.)*EXP(T(I,5)**2.)
  100 CONTINUE
      RETURN
      END
```

APPENDIX C

(Listings of in-bin solar dried corn data and the computer program "FIXED" for simulating corn moisture content and dry matter loss)

Table C-1. Experimental Corn Temperature, Drying Air Temperature and Absolute Humidity, and all other "FIXED" Bed In-put Data.

XMO = Inlet or initial Moisture Content
THIN = Inlet or initial Grain Temperature
CMM = Airflow Rate
DEPTH = Total Bed Depth
INDPR = Number of Nodes between prints
NLPF = Number of Layers per Meter in x-direction
TBTPR = Time between Outputs
TIN = Inlet Air Temperature
TT = Total Time
DELT = Time Increment
NEQ = Equation Number
HIN Inlet Humidity

TIME Hr	THIN °C	TIN °C	HIN Decimal
0.0	8.90	11.39	.00354
1.0	8.92	11.06	.00411
2.0	9.99	13.45	.00480
3.0	9.50	14.95	.00565
4.0	10.29	15.72	.00498
5.0	10.68	15.83	.00444
6.0	10.75	10.56	.00325
7.0	10.60	9.61	.00324
8.0	10.86	7.56	.00371
9.0	11.14	10.33	.00374
10.0	11.04	9.72	.00387
11.0	10.70	10.22	.00366
12.0	10.24	10.06	.00377
13.0	9.79	9.89	.00382
14.0	9.28	9.83	.00355
15.0	8.83	9.56	.00382
16.0	8.57	9.50	.00371
17.0	8.40	8.43	.00381
18.0	8.07	8.28	.00347
19.0	7.96	8.06	.00343
20.0	7.76	7.78	.00342
21.0	7.79	8.45	.00300
22.0	8.04	9.78	.00283
23.0	7.65	9.61	.00330
24.0	7.58	10.06	.00311
25.0	7.53	10.50	.00307

Table C-1. Continued

26.0	7.50	10.56	.00310
27.0	7.47	10.78	.00291
28.0	7.53	10.72	.00307
29.0	7.58	10.95	.00291
30.0	7.68	9.17	.00243
31.0	7.76	8.45	.00238
32.0	7.78	7.67	.00252
33.0	7.67	7.72	.00270
34.0	7.50	7.56	.00244
35.0	7.24	7.33	.00252
36.0	6.97	7.06	.00240
37.0	6.57	6.67	.00236
38.0	6.42	6.33	.00219
39.0	6.07	6.11	.00205
40.0	5.82	6.00	.00180
41.0	5.53	5.83	.00184
42.0	5.22	5.67	.00192
43.0	4.85	5.61	.00217
44.0	4.68	5.61	.00195
45.0	4.63	5.72	.00181
46.0	4.22	7.17	.00207
47.0	4.35	7.22	.00260
48.0	4.25	8.00	.00299
49.0	4.21	9.50	.00250
50.0	4.36	10.56	.00254
51.0	4.61	11.00	.00288
52.0	4.88	11.11	.00283
53.0	5.14	11.78	.00358
54.0	5.47	12.50	.00291
55.0	5.90	11.11	.00242
56.0	6.29	12.00	.00232
57.0	6.46	10.22	.00200
58.0	6.56	9.78	.00209

Table C-1. Continued

59.0	6.51	9.50	.00202
60.0	6.40	9.45	.00198
61.0	6.25	9.61	.00196
62.0	6.08	9.72	.00279
63.0	5.92	9.83	.00216
64.0	5.79	9.89	.00232
65.0	5.61	10.56	.00243
66.0	5.61	10.78	.00246
67.0	5.70	10.89	.00252
68.0	5.72	11.06	.00254
69.0	5.72	11.17	.00250
70.0	5.85	12.61	.00241
71.0	5.92	12.95	.00246
72.0	5.99	13.45	.00204
73.0	6.03	15.06	.00240
74.0	6.26	16.50	.00267
75.0	6.50	17.39	.00266
76.0	6.88	18.00	.00424
77.0	7.28	18.89	.00402
78.0	7.82	20.17	.00464
79.0	8.49	19.22	.00496
80.0	9.07	19.06	.00431
81.0	9.49	18.11	.00444
82.0	9.83	17.50	.00450
83.0	9.92	17.11	.00438
84.0	9.75	17.00	.00407
85.0	9.70	16.83	.00369
86.0	9.45	16.39	.00351
87.0	9.14	15.83	.00330
88.0	8.76	15.28	.00301
89.0	8.57	14.61	.00303
90.0	8.45	14.17	.00316
91.0	8.10	13.89	.00308

Table C-1. Continued

92.0	7.92	13.83	.00312
93.0	7.75	13.89	.00313
94.0	7.71	15.50	.00303
95.0	7.61	15.83	.00351
96.0	7.10	16.28	.00329
97.0	7.50	17.22	.00333
98.0	7.58	18.45	.00302
99.0	7.85	19.06	.00277
100.0	7.93	18.83	.00313
101.0	8.10	18.28	.00329
102.0	8.45	17.45	.00325
103.0	8.50	15.39	.00322
104.0	8.43	15.00	.00298
105.0	8.22	14.72	.00266
106.0	8.07	14.56	.00260
107.0	7.85	14.22	.00248
108.0	7.70	13.72	.00249
109.0	7.56	13.28	.00243
110.0	7.28	12.95	.00237
111.0	7.04	12.67	.00238
112.0	6.86	12.45	.00239
113.0	6.65	12.33	.00228
114.0	6.33	12.11	.00234
115.0	6.14	11.89	.00238
116.0	5.83	11.67	.00236
117.0	5.71	11.45	.00233
118.0	5.68	12.67	.00250
119.0	5.78	12.56	.00250
120.0	5.65	13.11	.00232
121.0	5.64	14.61	.00228
122.0	5.72	15.17	.00291
123.0	5.78	16.39	.00276
124.0	5.93	17.61	.00201

Table C-1. Continued

125.0	6.07	16.67	.00208
126.0	6.25	14.61	.00203
127.0	6.40	14.45	.00281
128.0	6.53	14.11	.00209
129.0	6.61	13.78	.00217
130.0	6.64	13.56	.00221
131.0	6.71	13.00	.00219
132.0	6.68	12.45	.00215
133.0	6.60	12.00	.00205
134.0	6.47	11.45	.00207
135.0	6.17	10.72	.00224
136.0	6.07	10.61	.00227
137.0	6.01	10.89	.00217
138.0	5.72	11.06	.00202
139.0	5.61	10.78	.00189
140.0	5.49	10.45	.00194
141.0	5.21	10.00	.00194
142.0	5.42	11.50	.00231
143.0	5.46	11.95	.00270
144.0	5.53	13.61	.00293
145.0	5.45	15.95	.00291
146.0	5.96	17.56	.00399
147.0	6.31	18.28	.00285
148.0	6.70	19.11	.00276
149.0	7.17	19.33	.00282
150.0	7.58	17.72	.00270
151.0	8.00	17.06	.00238
152.0	8.35	16.28	.00247
153.0	8.46	15.67	.00255
154.0	8.61	15.56	.00261
155.0	8.63	15.17	.00287
156.0	8.64	14.87	.00247
157.0	8.53	14.28	.00251

Table C-1. Continued

158.0	8.43	14.00	.00250
159.0	8.32	13.72	.00236
160.0	8.18	14.72	.00194
161.0	8.04	12.83	.00236
162.0	7.86	12.72	.00225
163.0	7.72	12.67	.00225
164.0	17.96	12.39	.00239
165.0	7.22	12.22	.00234
166.0	7.15	14.17	.00267
167.0	6.17	14.56	.00279
168.0	7.26	16.00	.00263
169.0	7.49	18.39	.00407
170.0	7.74	20.61	.00423
171.0	8.38	22.50	.00452
172.0	8.92	23.61	.00424
173.0	9.53	19.11	.00291
174.0	10.07	19.00	.00245
175.0	10.52	18.22	.00240
176.0	10.79	16.39	.00229
177.0	10.83	16.39	.00236
178.0	10.74	15.17	.00234
179.0	10.42	14.17	.00234
180.0	10.10	13.45	.00228
181.0	9.70	12.95	.00275
182.0	9.28	13.06	.00224
183.0	8.82	12.33	.00225
184.0	8.60	12.28	.00232
185.0	8.39	12.00	.00230
186.0	8.14	11.78	.00230
187.0	8.06	11.45	.00241
188.0	7.92	11.22	.00231
189.0	7.85	5.67	.00221
190.0	7.71	12.39	.00232

Table C-1. Continued

191.0	7.70	13.83	.00294
192.0	7.61	14.89	.00270
193.0	7.58	16.89	.00285
194.0	7.78	19.33	.00396
195.0	8.11	18.75	.00359
196.0	8.68	20.06	.00300
197.0	9.08	22.00	.00458
198.0	9.82	21.06	.00274
199.0	10.32	20.06	.00252
200.0	10.67	19.45	.00280
201.0	10.79	17.17	.00219
202.0	10.67	15.72	.00226
203.0	10.27	14.78	.00224
204.0	9.81	14.00	.00215
205.0	9.40	13.22	.00213
206.0	8.96	8.33	.00207
207.0	8.43	11.83	.00209
208.0	7.96	11.28	.00201
209.0	7.54	10.95	.00204
210.0	7.18	10.61	.00199
211.0	6.95	10.33	.00197
212.0	6.63	10.11	.00192
213.0	6.42	8.78	.00179
214.0	6.00	11.06	.00201
215.0	5.99	11.39	.00236
216.0	5.99	13.28	.00267
217.0	6.17	16.39	.00268
218.0	6.54	19.45	.00433
219.0	7.21	21.89	.00443
220.0	8.01	23.56	.00412
221.0	8.95	18.19	.00232
222.0	9.79	18.25	.00300
223.0	10.22	20.95	.00283

Table C-1. Continued

224.0	10.60	19.06	.00260
225.0	10.90	17.20	.00252
226.0	10.83	15.61	.00217
227.0	11.18	15.95	.00226
228.0	10.14	15.22	.00228
229.0	9.68	14.39	.00213
230.0	9.31	13.56	.00208
231.0	8.90	12.78	.00197
232.0	8.49	12.50	.00194
233.0	8.07	12.11	.00188
234.0	7.93	11.83	.00215
235.0	7.42	11.50	.00209
236.0	7.13	11.17	.00216
237.0	7.06	11.06	.00233
238.0	6.99	12.56	.00248
239.0	7.00	13.06	.00263
240.0	6.97	15.11	.00298
241.0	7.29	18.33	.00365
242.0	7.86	21.50	.00489
243.0	8.39	21.11	.00532
244.0	9.32	21.83	.00523
245.0	10.21	16.56	.00145
246.0	10.95	16.45	.00255
247.0	11.65	15.45	.00254
248.0	12.13	13.45	.00269
249.0	12.31	13.11	.00252
250.0	12.18	13.11	.00220
251.0	11.74	11.89	.00218
252.0	11.25	12.17	.00220
253.0	10.65	11.72	.00225
254.0	10.25	11.61	.00226
255.0	9.97	11.72	.00226
256.0	9.40	11.72	.00223

Table C-1. Continued

257.0	9.53	11.83	.00220
258.0	9.43	11.78	.00224
259.0	9.29	11.78	.00227
260.0	9.33	11.67	.00228
261.0	9.32	11.95	.00221
262.0	9.33	12.06	.00227
263.0	9.40	16.95	.00245
264.0	9.46	18.06	.00241
265.0	9.58	20.56	.00293
266.0	9.90	22.17	.00390
267.0	10.38	22.61	.00430
268.0	11.03	23.50	.00393
269.0	11.63	14.45	.00351
270.0	12.07	14.11	.00321
271.0	12.49	13.28	.00299
272.0	12.79	13.78	.00313
273.0	13.03	15.72	.00315
274.0	12.99	14.83	.00305
275.0	12.86	14.11	.00303
276.0	12.56	13.72	.00306
277.0	12.29	13.61	.00309
278.0	11.79	13.61	.00291
279.0	11.61	13.61	.00305
280.0	11.54	13.33	.00275
281.0	11.39	13.06	.00269
282.0	11.18	12.67	.00262
283.0	10.95	12.67	.00259
284.0	10.88	12.67	.00261
285.0	10.92	12.45	.00258
286.0	10.82	17.39	.00298
287.0	10.83	17.39	.00311
288.0	10.85	18.78	.00336
289.0	10.92	20.95	.00382

Table C-1. Continued

290.0	11.17	23.06	.00410
291.0	11.47	24.45	.00365
292.0	12.00	24.06	.00373
293.0	12.46	23.28	.00374
294.0	12.82	18.39	.00315
295.0	12.99	18.45	.00304
296.0	13.08	17.78	.00290
297.0	13.20	17.11	.00271
298.0	13.15	16.78	.00278
299.0	13.08	16.83	.00282
300.0	13.00	16.83	.00283
301.0	13.00	16.95	.00295
302.0	13.04	16.89	.00291
303.0	13.06	16.78	.00307
304.0	13.10	16.33	.00287
305.0	13.10	16.11	.00267
306.0	13.02	15.89	.00271
307.0	12.88	15.61	.00265
308.0	12.64	15.11	.00259
309.0	12.43	14.67	.00245
310.0	12.31	19.39	.00265
311.0	12.21	19.39	.00268
312.0	12.08	20.50	.00295

Table C-2. Simulated hourly corn moisture content and dry matter loss

RUG = Corn moisture content by Rugumayo eqns
MISRA = Corn moisture content by Misra eqns
SMC = Corn moisture content by Sabbah and delGuidice eqns
DRUG = Corn dry matter loss associated with Rugumayo eqns
DMISRA = Corn dry matter loss associated with Misra eqns
DMS = Corn dry matter loss associated with Sabbah & delGuidice eqns

HOUR	RUG	MISRA	SMC	DRUG	DMISRA	DMS
1.00	.3181	.3188	.3183	.0004	.0004	.0004
2.00	.3163	.3166	.3154	.0008	.0008	.0008
3.00	.3148	.3161	.3142	.0012	.0013	.0012
4.00	.3133	.3154	.3132	.0016	.0017	.0016
5.00	.3114	.3148	.3122	.0021	.0021	.0021
6.00	.3084	.3139	.3112	.0025	.0026	.0025
7.00	.3039	.3131	.3099	.0028	.0030	.0029
8.00	.3003	.3132	.3091	.0032	.0034	.0032
9.00	.2997	.3128	.3084	.0035	.0037	.0035
10.00	.3032	.3129	.3079	.0038	.0040	.0038
11.00	.3001	.3117	.3073	.0040	.0043	.0041
12.00	.2996	.3114	.3067	.0043	.0046	.0044
13.00	.2984	.3108	.3062	.0045	.0049	.0047
14.00	.2992	.3104	.3057	.0048	.0052	.0049
15.00	.2982	.3100	.3053	.0050	.0055	.0052
16.00	.2974	.3076	.3048	.0053	.0057	.0054
17.00	.2980	.3094	.3044	.0055	.0060	.0057
18.00	.2973	.3090	.3040	.0057	.0063	.0059
19.00	.2982	.3090	.3036	.0060	.0065	.0062
20.00	.2970	.3085	.3032	.0062	.0068	.0064
21.00	.2966	.3082	.3028	.0064	.0070	.0066
22.00	.2965	.3078	.3024	.0066	.0072	.0068
23.00	.2947	.3071	.3019	.0068	.0075	.0070
24.00	.2934	.3064	.3014	.0070	.0077	.0073
25.00	.2939	.3061	.3010	.0072	.0080	..0075
26.00	.2930	.3056	.3006	.0074	.0082	.0077
27.00	.2925	.3051	.3001	.0076	.0084	.0079
28.00	.2921	.3047	.2996	.0078	.0087	.0081
29.00	.2915	.3043	.2991	.0081	.0089	.0083
30.00	.2914	.3039	.2987	.0083	.0092	.0085
31.00	.2905	.3034	.2981	.0085	.0094	.0087
32.00	.2900	.3032	.2975	.0087	.0096	.0089
33.00	.2897	.3029	.2970	.0089	.0098	.0091
34.00	.2398	.3027	.2966	.0090	.0100	.0093
35.00	.2898	.3022	.2961	.0092	.0102	.0095
36.00	.2888	.3018	.2957	.0094	.0104	.0097
37.00	.2887	.3014	.2952	.0095	.0106	.0098
38.00	.2881	.3011	.2948	.0097	.0108	.0100
39.00	.2881	.3007	.2943	.0098	.0110	.0102
40.00	.2871	.3004	.2939	.0100	.0112	.0103
41.00	.2864	.3000	.2934	.0101	.0113	.0105
42.00	.2856	.2976	.2929	.0103	.0115	.0106
43.00	.2853	.2992	.2925	.0104	.0116	.0107
44.00	.2851	.2988	.2921	.0105	.0118	.0109
45.00	.2356	.2985	.2917	.0106	.0119	.0110
46.00	.2844	.2981	.2912	.0108	.0121	.0111
47.00	.2838	.2977	.2909	.0109	.0122	.0112
48.00	.2836	.2971	.2906	.0110	.0124	.0114
49.00	.2344	.2969	.2904	.0111	.0125	.0115
50.00	.2845	.2965	.2901	.0113	.0127	.0116
51.00	.2828	.2959	.2898	.0114	.0129	.0118
52.00	.2823	.2955	.2895	.0115	.0131	.0119
53.00	.2824	.2951	.2892	.0117	.0133	.0121
54.00	.2821	.2949	.2889	.0119	.0135	.0123
55.00	.2826	.2944	.2886	.0120	.0137	.0124

Table C-2. Continued

56.00	.2811	.2939	.2881	.0122	.0139	.0126
57.00	.2804	.2938	.2875	.0124	.0142	.0128
58.00	.2796	.2931	.2869	.0126	.0144	.0130
59.00	.2791	.2930	.2864	.0128	.0146	.0132
60.00	.2790	.2926	.2859	.0129	.0148	.0134
61.00	.2784	.2921	.2853	.0131	.0150	.0135
62.00	.2778	.2916	.2847	.0133	.0152	.0137
63.00	.2774	.2912	.2843	.0134	.0154	.0139
64.00	.2781	.2906	.2838	.0136	.0156	.0140
65.00	.2768	.2903	.2833	.0138	.0158	.0142
66.00	.2766	.2898	.2829	.0139	.0160	.0144
67.00	.2761	.2893	.2824	.0141	.0162	.0145
68.00	.2757	.2888	.2820	.0143	.0164	.0147
69.00	.2754	.2884	.2816	.0144	.0166	.0149
70.00	.2749	.2880	.2812	.0146	.0168	.0150
71.00	.2744	.2875	.2807	.0148	.0171	.0152
72.00	.2735	.2869	.2802	.0150	.0173	.0154
73.00	.2729	.2863	.2796	.0151	.0175	.0156
74.00	.2716	.2858	.2791	.0153	.0178	.0158
75.00	.2713	.2850	.2785	.0155	.0180	.0160
76.00	.2708	.2842	.2780	.0157	.0183	.0162
77.00	.2704	.2838	.2776	.0160	.0186	.0164
78.00	.2715	.2831	.2772	.0162	.0189	.0167
79.00	.2709	.2827	.2768	.0165	.0193	.0170

Table C-2. Continued

80.00	.2708	.2821	.2764	.0168	.0197	.0173
81.00	.2709	.2818	.2759	.0172	.0201	.0176
82.00	.2701	.2814	.2754	.0175	.0205	.0180
83.00	.2700	.2811	.2749	.0179	.0210	.0184
84.00	.2709	.2807	.2743	.0183	.0214	.0187
85.00	.2692	.2802	.2737	.0186	.0218	.0191
86.00	.2683	.2797	.2730	.0190	.0222	.0195
87.00	.2674	.2791	.2723	.0194	.0226	.0198
88.00	.2666	.2785	.2715	.0197	.0230	.0201
89.00	.2659	.2780	.2708	.0200	.0233	.0204
90.00	.2651	.2775	.2700	.0203	.0236	.0207
91.00	.2649	.2771	.2694	.0206	.0240	.0210
92.00	.2642	.2765	.2687	.0209	.0243	.0213
93.00	.2636	.2760	.2681	.0211	.0246	.0215
94.00	.2635	.2755	.2675	.0214	.0248	.0217
95.00	.2626	.2750	.2669	.0216	.0251	.0220
96.00	.2616	.2742	.2664	.0219	.0254	.0222
97.00	.2615	.2735	.2659	.0221	.0257	.0225
98.00	.2607	.2730	.2654	.0224	.0261	.0227
99.00	.2599	.2723	.2648	.0226	.0264	.0230
100.00	.2586	.2715	.2641	.0229	.0267	.0232
101.00	.2575	.2709	.2634	.0232	.0271	.0235
102.00	.2576	.2704	.2628	.0235	.0274	.0238
103.00	.2575	.2699	.2622	.0237	.0278	.0240
104.00	.2568	.2694	.2615	.0240	.0281	.0243
105.00	.2573	.2692	.2609	.0243	.0285	.0246
106.00	.2559	.2687	.2602	.0246	.0288	.0248
107.00	.2550	.2682	.2595	.0248	.0291	.0251
108.00	.2543	.2676	.2588	.0251	.0293	.0253
109.00	.2535	.2671	.2581	.0253	.0296	.0255
110.00	.2531	.2666	.2575	.0256	.0299	.0257
111.00	.2525	.2661	.2568	.0258	.0301	.0259
112.00	.2521	.2656	.2562	.0260	.0304	.0261
113.00	.2514	.2651	.2556	.0262	.0306	.0263
114.00	.2509	.2646	.2550	.0264	.0308	.0265
115.00	.2502	.2641	.2544	.0266	.0311	.0267
116.00	.2498	.2635	.2539	.0267	.0313	.0268
117.00	.2494	.2630	.2534	.0269	.0315	.0270
118.00	.2489	.2625	.2529	.0271	.0317	.0272
119.00	.2455	.2621	.2524	.0273	.0319	.0273
120.00	.2479	.2613	.2519	.0274	.0321	.0275
121.00	.2474	.2608	.2514	.0276	.0323	.0276
122.00	.2465	.2603	.2509	.0278	.0325	.0278
123.00	.2456	.2596	.2504	.0279	.0328	.0280
124.00	.2459	.2588	.2499	.0281	.0330	.0281
125.00	.2448	.2581	.2493	.0283	.0332	.0283
126.00	.2425	.2575	.2487	.0285	.0335	.0285

Table C-2. Continued

127.00	.2424	.2571	.2480	.0287	.0337	.0286
128.00	.2425	.2571	.2475	.0289	.0340	.0288
129.00	.2431	.2563	.2469	.0291	.0342	.0290
130.00	.2416	.2560	.2462	.0293	.0345	.0292
131.00	.2412	.2555	.2456	.0295	.0347	.0294
132.00	.2408	.2549	.2450	.0297	.0349	.0295
133.00	.2404	.2544	.2444	.0299	.0352	.0297
134.00	.2398	.2540	.2438	.0301	.0354	.0298
135.00	.2372	.2535	.2432	.0303	.0356	.0300
136.00	.2388	.2531	.2427	.0304	.0358	.0301
137.00	.2339	.2526	.2421	.0306	.0360	.0303
138.00	.2383	.2521	.2416	.0307	.0361	.0304
139.00	.2375	.2515	.2411	.0309	.0363	.0306
140.00	.2367	.2510	.2405	.0310	.0365	.0307
141.00	.2360	.2505	.2400	.0312	.0367	.0308
142.00	.2357	.2500	.2395	.0313	.0368	.0309
143.00	.2354	.2497	.2391	.0314	.0370	.0310
144.00	.2354	.2488	.2387	.0316	.0372	.0312
145.00	.2353	.2482	.2383	.0317	.0373	.0313
146.00	.2347	.2474	.2380	.0319	.0375	.0314
147.00	.2338	.2467	.2378	.0320	.0377	.0316
148.00	.2340	.2457	.2373	.0322	.0379	.0317
149.00	.2322	.2454	.2368	.0324	.0382	.0319
150.00	.2313	.2448	.2362	.0326	.0385	.0321
151.00	.2308	.2442	.2356	.0328	.0387	.0322
152.00	.2305	.2440	.2349	.0330	.0390	.0324
153.00	.2295	.2436	.2342	.0332	.0393	.0326
154.00	.2293	.2431	.2336	.0335	.0395	.0328
155.00	.2290	.2426	.2329	.0337	.0398	.0330
156.00	.2280	.2421	.2323	.0339	.0400	.0332
157.00	.2287	.2415	.2317	.0341	.0403	.0334
158.00	.2273	.2411	.2311	.0343	.0405	.0335
159.00	.2270	.2406	.2304	.0345	.0407	.0337
160.00	.2263	.2401	.2298	.0347	.0409	.0339
161.00	.2255	.2395	.2291	.0349	.0412	.0340
162.00	.2238	.2390	.2285	.0351	.0414	.0342
163.00	.2246	.2386	.2279	.0352	.0416	.0343
164.00	.2239	.2381	.2273	.0354	.0418	.0345
165.00	.2236	.2375	.2268	.0355	.0420	.0346
166.00	.2233	.2370	.2262	.0357	.0421	.0347
167.00	.2226	.2365	.2258	.0359	.0423	.0348
168.00	.2220	.2355	.2253	.0360	.0425	.0350
169.00	.2216	.2349	.2248	.0362	.0427	.0351
170.00	.2207	.2344	.2245	.0363	.0429	.0353
171.00	.2212	.2332	.2242	.0365	.0432	.0354
172.00	.2205	.2324	.2239	.0367	.0434	.0356
173.00	.2199	.2315	.2235	.0370	.0437	.0358
174.00	.2187	.2307	.2227	.0372	.0440	.0360
175.00	.2179	.2311	.2219	.0375	.0443	.0362
176.00	.2164	.2306	.2211	.0378	.0446	.0364
177.00	.2157	.2301	.2203	.0380	.0448	.0366
178.00	.2153	.2298	.2195	.0383	.0451	.0368
179.00	.2148	.2291	.2187	.0385	.0453	.0370
180.00	.2144	.2287	.2180	.0387	.0455	.0372
181.00	.2141	.2283	.2173	.0389	.0457	.0373
182.00	.2133	.2279	.2167	.0391	.0459	.0375
183.00	.2138	.2272	.2160	.0392	.0461	.0376
184.00	.2121	.2268	.2154	.0394	.0463	.0377
185.00	.2120	.2264	.2148	.0395	.0465	.0379
186.00	.2113	.2258	.2142	.0397	.0466	.0380
187.00	.2109	.2253	.2137	.0398	.0468	.0381
188.00	.2103	.2248	.2132	.0399	.0469	.0382
189.00	.2104	.2243	.2126	.0401	.0471	.0383
190.00	.2095	.2239	.2121	.0402	.0472	.0384
191.00	.2107	.2248	.2118	.0403	.0473	.0385
192.00	.2084	.2229	.2114	.0404	.0475	.0386
193.00	.2084	.2219	.2110	.0406	.0476	.0387
194.00	.2073	.2215	.2106	.0407	.0477	.0388
195.00	.2067	.2209	.2103	.0408	.0479	.0390
196.00	.2068	.2198	.2100	.0410	.0481	.0391

Table C-2. Continued

197.00	.2062	.2197	.2095	.0411	.0483	.0392
198.00	.2049	.2195	.2091	.0413	.0485	.0394
199.00	.2052	.2182	.2085	.0415	.0487	.0395
200.00	.2029	.2184	.2077	.0418	.0490	.0397
201.00	.2022	.2182	.2070	.0420	.0492	.0398
202.00	.2020	.2176	.2062	.0422	.0494	.0400
203.00	.2009	.2177	.2054	.0424	.0496	.0402
204.00	.2007	.2175	.2046	.0426	.0499	.0403
205.00	2003	.2171	.2039	.0428	.0501	.0405
206.00	.1995	.2168	.2032	.0430	.0502	.0406
207.00	.1992	.2166	.2025	.0431	.0504	.0407
208.00	.2001	.2172	.2018	.0433	.0505	.0408
209.00	1980	.2161	.2012	.0434	.0507	.0409
210.00	.1979	.2159	.2006	.0435	.0508	.0410
211.00	.1970	.2156	.2000	.0437	.0509	.0411
212.00	.1968	.2153	.1995	.0438	.0510	.0412
213.00	.1960	.2151	.1989	.0439	.0512	.0413
214.00	.1954	.2149	.1984	.0440	.0513	.0414
215.00	.1952	.2151	.1979	.0441	.0514	.0414
216.00	.1944	.2144	.1975	.0442	.0514	.0415
217.00	.1945	.2140	.1971	.0443	.0515	.0416
218.00	.1940	.2134	.1967	.0444	.0517	.0417
219.00	.1930	.2129	.1966	.0445	.0518	.0417
220.00	.1936	.2120	.1964	.0446	.0519	.0418
221.00	.1928	.2116	.1961	.0447	.0521	.0420
222.00	1915	.2112	.1954	.0449	.0523	.0421
223.00	1903	.2127	.1948	.0451	.0525	.0422
224.00	1906	.2121	.1942	.0453	.0527	.0423
225.00	.1838	.2113	.1935	.0455	.0529	.0424
226.00	.1883	.2114	.1928	.0457	.0531	.0426
227.00	.1890	.2114	.1920	.0458	.0533	.0427
228.00	.1871	.2115	.1913	.0460	.0535	.0428
229.00	.1866	.2110	.1905	.0462	.0537	.0429
230.00	1861	.2107	.1898	.0463	.0539	.0431
231.00	.1853	.2106	.1891	.0465	.0541	.0432
232.00	1849	.2104	.1884	.0466	.0542	.0433
233.00	.1841	.2103	.1878	.0468	.0543	.0433
234.00	.1836	.2101	.1871	.0469	.0545	.0434
235.00	.1828	2100	.1866	.0470	.0546	.0435
236.00	.1829	.2097	.1860	.0471	.0547	.0436
237.00	.1823	.2096	.1855	.0472	.0548	.0437
238.00	.1823	2095	.1850	.0473	.0549	.0437
239.00	.1818	.2093	.1845	.0474	.0550	.0438
240.00	.1812	.2087	.1841	.0475	.0551	.0439
241.00	.1809	.2085	.1837	.0476	.0552	.0439
242.00	.1804	2079	.1834	.0477	.0553	.0440
243.00	.1801	.2073	.1833	.0478	.0555	.0441
244.00	.1801	.2066	.1831	.0479	.0556	.0442
245.00	1803	.2068	.1829	.0481	.0558	.0443
246.00	.1792	2062	.1820	.0482	.0560	.0444
247.00	.1751	.2084	.1813	.0484	.0562	.0445
248.00	.1768	.2075	.1807	.0486	.0564	.0446
249.00	.1766	.2075	.1800	.0488	.0565	.0447
250.00	.1768	.2076	.1794	.0489	.0567	.0448
251.00	.1755	.2074	.1787	.0490	.0568	.0449
252.00	.1743	.2073	.1781	.0492	.0570	.0450
253.00	.1744	.2073	.1775	.0493	.0571	.0451
254.00	.1733	.2071	.1769	.0494	.0572	.0451
255.00	.1733	.2070	.1764	.0495	.0573	.0452
256.00	.1724	.2068	.1759	.0496	.0574	.0453
257.00	.1719	.2066	.1754	.0497	.0575	.0453
258.00	.1713	.2064	.1749	.0498	.0576	.0454
259.00	.1707	.2062	.1744	.0498	.0577	.0454
260.00	.1704	.2061	.1739	.0499	.0578	.0455
261.00	.1699	.2059	.1735	.0500	.0579	.0455
262.00	.1695	.2057	.1730	.0501	.0580	.0456
263.00	.1688	.2055	.1726	.0502	.0581	.0456
264.00	.1684	.2053	.1722	.0503	.0582	.0457
265.00	.1667	.2041	.1717	.0503	.0583	.0457
266.00	.1659	.2039	.1713	.0504	.0584	.0458

Table C-2. Continued

267.00	.1656	.2032	.1710	.0505	.0585	.0459
268.00	.1660	.2027	.1707	.0506	.0587	.0459
269.00	.1658	.2025	.1703	.0508	.0588	.0460
270.00	.1647	.2023	.1698	.0509	.0590	.0461
271.00	.1661	.2039	.1693	.0511	.0591	.0462
272.00	.1652	.2039	.1687	.0512	.0593	.0462
273.00	.1646	.2039	.1681	.0513	.0594	.0463
274.00	.1650	.2035	.1676	.0515	.0596	.0464
275.00	.1629	.2029	.1671	.0516	.0597	.0465
276.00	.1631	.2030	.1666	.0517	.0599	.0465
277.00	.1620	2030	.1661	.0518	.0600	.0466
278.00	.1625	.2029	.1656	.0519	.0601	.0467
279.00	.1611	.2028	.1651	.0520	.0602	.0467
280.00	.1604	.2027	.1646	.0521	.0604	.0468
281.00	.1602	.2024	.1642	.0522	.0605	.0468
282.00	.1572	.2024	.1637	.0523	.0606	.0469
283.00	.1586	.2024	.1632	.0524	.0607	.0469
284.00	.1586	2023	.1628	.0525	.0608	.0470
285.00	.1575	.2022	.1624	.0526	.0609	.0470
286.00	.1579	.2020	.1619	.0526	.0610	.0471
287.00	.1566	.2019	.1616	.0527	.0611	.0471
288.00	.1553	.2007	.1612	.0528	.0612	.0472
289.00	.1551	.2006	.1609	.0529	.0613	.0472
290.00	.1546	.2002	.1606	.0530	.0614	.0473
291.00	.1540	.1997	.1603	.0531	.0616	.0473
292.00	.1532	.1991	.1598	.0532	.0617	.0474
293.00	.1518	.1988	.1593	.0533	.0619	.0474
294.00	.1514	.1986	.1588	.0534	.0621	.0475
295.00	.1509	.1984	.1581	.0536	.0623	.0476
296.00	.1509	.1991	.1575	.0537	.0624	.0476
297.00	.1499	.1987	.1569	.0539	.0626	.0477
298.00	.1494	.1985	.1562	.0540	.0628	.0478
299.00	.1483	.1984	.1556	.0541	.0629	.0478
300.00	.1480	.1980	.1550	.0542	.0631	.0479
301.00	.1471	.1977	.1544	.0543	.0632	.0479
302.00	.1468	.1974	.1539	.0544	.0634	.0480
303.00	.1459	.1970	.1534	.0545	.0635	.0481
304.00	.1453	.1968	.1529	.0546	.0637	.0481
305.00	.1453	.1965	.1524	.0547	.0638	.0481
306.00	.1441	.1965	.1520	.0548	.0640	.0482
307.00	.1433	.1964	.1515	.0549	.0641	.0482
308.00	.1432	.1962	.1510	.0550	.0642	.0483
309.00	.1422	.1961	.1506	.0551	.0643	.0483
310.00	.1420	.1960	.1501	.0551	.0645	.0484
311.00	.1409	.1959	.1497	.0552	.0646	.0484
312.00	.1392	.1947	.1492	.0553	.0647	.0484
313.00	.1387	.1945	.1488	.0554	.0648	.0485

APPENDIX D

(Listing of the computer program "FIXED" used to simulate corn drying in a fixed bed with solar heated air)

Appendix D

```
*DECK SOLAR
      PROGRAM FIXED (INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT,TAPE1)
C*****
C*****         M I C H I G A N   S T A T E   U N I V E R S I T Y
C** A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N
C*****       F I X E D   B E D   G R A I N   D R Y E R   M O D E L
C*****               F.W. BAKKER-ARKEMA, PROJECT LEADER
C*****                    M. G. ROTH, PROGRAMMER
C*****                    E.W.RUGUMAYO , MODIFIER
C*****
C*****
C*****    DESCRIPTION
C*****        MAIN PROGRAM FOR THE SIMULATION OF A FIXED BED DRYER
C*****
C*****    SUBROUTINES USED
C*****        BLOCKDATA
C*****        LAYEQ
C*****        READYTH
C*****        ZEROIN
C*****
C*****    FUNCTION SUBPROGRAMS USED
C*****        SYCHART PACKAGE
C*****        EMC
C*****        SOLVE
C*****
      COMMON /MAIN/ XMT,THT,RHT,DELT,CMM,XMO,IAB,TIME
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /PRESS/PATM
      COMMON /NAME/INAME,IPROD,NEQ,NEQ1
      COMMON /ARRAYS/ T(51,2),H(51,2),XM(51),RH(51)
      COMMON /CONS/ CON1,CON2,CON3,CON4,CON5,CON6,CON7,CON12,CON13
      COMMON /FLAGS/ JX,JM,ICON
      DIMENSION XMEPR(51),DM(51),TEQ(51),DEEP(21),WR(51),INAME(3)
C*****    DEFINE EQUILIBRIUM RH FUNCTION (THOMPSON, 1972)
      ERH(T,XM) = 1. - EXP(- .382*(1.8*T + 82.)*XM**2)
      DATA RHC,D,PRT,TIME,ITERCT,IEXIT,JK,KCON,KAB/.9999999999,3*.0,5*0/
      DATA IAB/0/
      F(T) = T + 273.16
      PRTT = 0.0
```

Appendix D Continued

```
C*****    INPUT CONDITIONS OF DRYER TO BE SIMULATED
      READ 150,XMO,THIN,CMM,DEPTH,INDPR,NLPF,TT,TBTPR,DELT,NEQ
C*****    ENERGY REQUIREMENT FOR FORCING AIR FROM SHED
      CFM = 3.2807*CMM
      DEPTHF = 3.2807*DEPTH
      HP=DEPTHF*(CFM**1.944)*3.0792E-6
      HPHOUR=HP*TT
      AKWHR=HPHOUR*.7455
      BTUAIR=HPHOUR/3.929E-4
      ENJAIR = 1055.1*BTUAIR
C*****    COMPUTE STEP SIZE, NUMBER OF NODES AND DEPTH BETWEEN PRINTS
      DELX=1./NLPF
      IND=NLPF*DEPTH
      IND1=IND+1
      DBTPR=INDPR*DELX
C*****    COMPUTE OUTPUT DEPTHS FOR PRINTING
      DO 100 I=1,IND1,INDPR
      JK=JK+1
      DEEP(JK)=D
      D=D+DBTPR
  100 CONTINUE
C*****    COMPUTE EQUILIBRIUM RH AND INITIALIZE ARRAYS
      RHIN=0.9*FRH(THIN,XMO)
      HINIT=HADBRH(F(THIN),RHIN)
      DO 101 I=1,IND1
      XM(I)=XMO
      TFG(I)=0.0
      H(I,1)=HINIT $ T(I,1)=THIN $ RH(I)=RHIN
  101 CONTINUE
      HIN = HINIT
C*****    CONVERT AIRFLOW TO KG/HR AND COMPUTE CONVECTIVE HEAT TRANSFER
C*****    COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
      GA=60.*CMM/VSDBHA(F(THIN),HIN)
      IF(GA - 2441.214) 2,1,1
    1 HC = 2909.458839*GA**.59
      GO TO 3
    2 HC = 6480.645534*GA**.49
    3 CONTINUE
```

Appendix D Continued

```
C*****    PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
      PRINT 210,INAME,IPROD,THIN,XMO,CMM,GA,CA,CP,CV,CW
     1,HC,PATM,HFG,RHOP,SA,DEPTH,DELX,DBTPR,IT,IBTPR,ENJAIR
      PRINT 218,DELT
C*****    PRINT DEPTHS FOR WHICH LATER OUTPUT CORRESPONDS
      PRINT 211,(DEEP(I),I=1,JK)
C*****    COMPUTE CONSTANTS USED BY EQUATIONS WITHIN LOOP
      CON1=GA*DELT
      CON2=CW-CV
      CON12=CON1*CON2
      CON3 = HFG + 117.86*(CW-CV)
      CON13=CON1*CON3
      CON4=RHOP*DELX
      CON5=CON4/CON1
      CON6=CON1/CON4
C*****    BEGIN TIME LOOP
    4 TIME=TIME+DELT
      IF(NEQ.EQ.4) GO TO 300
C*****    CHECK IF TIME TO READ NEW DATA INPUT
      IF(TIME-PRT) 6,5,5
  300 CONTINUE
C*****    READ RECORDED GRAIN TEMP.THINC,INPUT DRYING TEMP.TIN AND
C*****    ABSOLUTE HUMIDITY, HIN
    5 READ 200,THINC,TIN,HIN
      IF(EOF(60).NE.0) GO TO 14
      NEQ1 = NEQ
      V1 = T(1,1) $ V2 = XM(1) $ V3 = H(1,1) $ V4 = RH(1)
    8 H(1,2)=HIN
      T(1,2)=TIN
      RH(1) = RHDBHA(F(T(1,2)),H(1,2))
    6 CONTINUE
C*****    EVALUATE THIN LAYER DRYING EQUATION AT AIR INLET
      THT=T(1,1) $ XMT=XM(1) $ RHT=RHDBHA(F(THT),H(1,1))
      CALL LAYEQ
      XM(1)=XMT
C*****    BEGIN DEPTH LOOP
      DO 102 J=2,IND1
      JX = J
      JM=J-1
```

Appendix D Continued

```
C*****    USE PREVIOUS VALUE OF H FOR INITIAL GUESS
      HJ2=H(JM,2)
C*****    CALL SOLVE TO COMPUTE TRIAL T, XM, H, RH
      DIFF=SOLVE(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) 40,41,41
C*****    INCREASE HHI UNTIL EMC .GT. XM
   40 HHI=.5*(1.+HHI)
      GO TO 39
   41 HHI=HADBRH(F(THT),HHI)
C*****
C*****    INITIATE SEARCH FOR H, T, XM
C*****
   42 CALL ZEROIN(HLOW,HHI,.0001,SOLVE)
```

Appendix D Continued

```
   43 XM(J)=XMT
C*****    END DEPTH LOOP
  102 CONTINUE
      XMAVE=0. $ DMAVE=0. $ WBAVE=0.
      TAVE = 0.0

      DO 103 J=1,IND1
      JX = J
C*****    SHIFT ARRAYS
      T(J,1)=T(J,2)
      H(J,1)=H(J,2)
C*****    COMPUTE EQUILIBRIUM MOISTURE CONTENT
      XMEPR(J)=EMC(RH(J),T(J,2 ))
C*****    SUM MOISTURE CONTENTS
      XMAVE=XMAVE+XM(J)
C*****    CALCULATE DRY MATTER DECOMPOSITION (THOMPSON, 1972)
      XMDB=100.*XM(J) $ XMWB=XMDB/(1.+XM(J)) $ TJ=T(J,1)
      WB(J)=.01*XMWB $ WBAVE=WBAVE+WB(J)
C*****    COMPUTE TEMPERATURE MULTIPLIER FOR EQUIVALENT TIME
      IF(TJ-15.5) 21,22,22
C*****    T.LT.15.5DEG C
   21 AMT = 128.76*EXP(-4.68*((1.8*TJ + 32.)/60.))
      GO TO 26
C*****    (T.GE.15.5DEG C) AND (XM.LE.19WB)
   22 AMT = 32.3*EXP(-3.48*((1.8*TJ + 32.)/60.))
      IF(XMWB-19.) 26,26,23
   23 IF(XMWB-28.) 24,24,25
C*****    (T.GE.15.5DEG C) AND (XM.GT.19WB) AND (XM.LE.28WB)
   24 AMT = AMT + (XMWB-19.)/100.*EXP(.61*((1.8*TJ - 28.)/60.))
      GO TO 26
C*****    (T.GE.15.5DEG C) AND (XM.GT.28WB)
   25 AMT = AMT + .09*EXP(.61*((1.8*TJ - 28.)/60.))
   26 CONTINUE
C*****    COMPUTE MOISTURE CONTENT MULTIPLIER FOR EQUIVALENT TIME
C*****    RESTRICT MOISTURE CONTENT VALUES TO 13 - 35 WB
      IF(XMWB.LT.13.) XMDB=13./.87
      IF(XMWB.GT.35.) XMDB=35./.65
      AMM=.103*(EXP(455./XMDB**1.53)-.0084*XMDB+1.558)
```

Appendix D Continued

```
C*****    COMPUTE EQUIVALENT TIME INCREMENT AND SUM
      TEQ(J) = TEQ(J) + DELT/(AMT*AMM)
C*****    COMPUTE PERCENT DRY MATTER LOSS
      DM(J)=.0883*(EXP(.006*TEQ(J))-1.)+.00102*TEQ(J)
C*****    SUM DRY MATTER LOSSES
      DMAVE = DMAVE + DM(J)
C*****    SUM GRAIN TEMPERATURE
      TAVE = TAVE + T(J,2)
  103 CONTINUE
C*****    AVERAGE MOISTURE CONTENT
      XMAVE =XMAVE/IND1
      WBAVE=WBAVE/IND1
C*****    AVERAGE DRY MATTER LOSS
      DMAVE =DMAVE/IND1
C*****    AVERAGE GRAIN TEMPERATURE
      TAVE = TAVE/IND1
      ITERCT=ITERCT+1
C*****    CHECK IF TIME TO END, MOISTURE CONTENT LOW ENOUGH, OR TIME TO
C*****    PRINT...IF NONE OF THESE GO TO BEGINNING OF TIME LOOP
      SHOO=TIME-PRTT
      IF(SHOO.NE.0)GO TO 451
      WATER=(XMO-XMAVE)*RHOP*DEPTH
      NODES=IND1*ITERCT
      PKCON=KCON*100./NODES
      PKAB=KAB*100./NODES
  451 IF(SHOO.GE.0.)PRTT=PRTT+2.
      IF(TIME + DELT - TT) 400,400,12
  400 IF(NEQ - 4) 11,13,13
   11 IF(TIME - PRT) 4,13,13
C*****    SET FLAG IF EXIT CONDITION MET
   12 IEXIT=1
C*****    MAKE FINAL CALCULATIONS AND PRINT
   13 PRT=PRT+IBTPR
      WATER=(XMO-XMAVE)*RHOP*DEPTH
C*****    COMPUTE PERCENTAGE CONDENSATION AND ABSORPTION
      NODES = IND1*ITERCT
      PKCON=KCON*100./NODES
      PKAB=KAB*100./NODES
```

Appendix D Continued

```
      ITERCT=0 $ KAB=0 $ KCON=0
C*****    COMPUTE EQUILIBRIUM MOISTURE CONTENT FOR PRINTING
      DO 104 J=1,IND1,INDPR
      JX = J
  104 XMEPR(J)=EMC(RH(J),T(J,2))
      PRINT 212,TIME,PKCON,PKAB,XMAVE,WBAVE,WATER,DMAVE,THINC,TAVE
      PRINT 215,(XM(I),I=1,IND1,INDPR)
      PRINT 208,(WB(I),I=1,IND1,INDPR)
      PRINT 213,(T(I,2)    ,I=1,IND1,INDPR)
      PRINT 214,(DM(I),I=1,IND1,INDPR)


      PRINT 217,(H(I,2)    ,I=1,IND1,INDPR)
      PRINT 216,(RH(I),I=1,IND1,INDPR)
      PRINT 219,(XMEPR(I),I=1,IND1,INDPR)
      WRITE(1,220)   TIME,XMAVE,DMAVE
      PRINT*,NEQ1
C*****    CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*****    NING OF TIME LOOP
      IF(NEQ.EQ.4) NEQ1 = NEQ1 + 1
      IF(NEQ1.EQ.4) GO TO 15
      IF(NEQ.EQ.4) GO TO 88
   15 IF(IEXIT-1) 4,14,4
   88 T(1,1) = V1 $ XM(1) = V2 $ H(1,1) = V3 $ RH(1) = V4
      GO TO 8
   14 CONTINUE
C*****
C*****                      F O R M A T S
```

Appendix D Continued

```
C*****
  150 FORMAT(4F10.0,2I10/3F10.0,I10)
  200 FORMAT(2F10.2,F10.5)
  210 FORMAT(1H1,42X49HM I C H I G A N   S T A T E   U N I V E R S I T Y
     1/33X69HA G R I C U L T U R A L   E N G I N E E R I N G   D E P A R
     2 T M E N T/47X41HF I X E D   B E D   D R Y E R   M O D E L///
     3    33XA10,A10,A10,23H THINLAYER EQUATION FORA10,///
     452X31HINPUT PROPERTIES AND CONDITIONS5(/),41X,58HPROD TEMP(DEG C)
     5    DB(DECIMAL)      AIR FLOW (CMM/ M**2)
     6/39X,3(5X,F9.4,5X)/82X,F9.4,8H (KG/HR)
     74(/)11X24HHEAT CAPACITIES(JOU/KG);14X3HAIR14X7HPRODUCT10X11HWATER
     8VAPOR8X12HWATER LIQUID/34X4(12XF7.2)5(/)24X13HH T COEF CONV7X11HAT
     AMOS PRESS6X13HLAT HEAT EVAP4X18HBULK DENS DRY PROD5X14HSPEC SURF A
     BREA/14X5(10XF10.2)10(/)60X16HPROGRAM CONTROLS5(/)
     C29X19HSIMULATE A DEPTH OFF6.2,20H M  BY INCREMENTS OFF7.4,18H M  P
     DRINTING EVERYF5.2,3H  M/29X19HFOR A TOTAL TIME OFF6.2,18H HR PRINT
     EING EVERYF5.2,3H HR/29X,8HENJAIR =F12.2,12H  FROM SHEDD)
  211 FORMAT(10H1DEPTH     15F8.2)
  212 FORMAT(/   ,6X6HTIME =F6.2,20X22HPERCENT CONDENSATION =F6.2,15X20HP
     1ERCENT ABSORPTION =F6.2/6X15HAVERAGE MC DB =F6.4,11X15HAVERAGE MC
     2WB =F6.4,22X13HH20 REMOVED =F7.2/6X17HPERCENT DM LOSS =F6.3,9X23HO
     3BSEVD AVG GRAIN TEMP =,F6.2,7H  DEG C,7X20HAVERAGE GRAIN TEMP =,F6
     4.2)
  213 FORMAT(10HOTEMP       15F8.3)
  214 FORMAT(10HODM LOSS   F7.3,14F8.3)
  215 FORMAT(10HOMC DB     F7.3,14F8.3)
  208 FORMAT(10HOMC WB      F7.3,14F8.3)
  216 FORMAT(10HOREL HUM  15F8.5)
  217 FORMAT(10HOABS HUM  15F8.5)
  218 FORMAT(/29X,7HDELT = ,F7.3,4H HRS)
  219 FORMAT(10HOEQUIL MC  ,F7.3,14F8.3)
  220 FORMAT(4X,F6.2,2(4X,F6.4))
      END
```

Appendix D Continued

```
      BLOCKDATA
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/PRESS/PATM
      DATA SA,CA,CP,CV,CW,RHOP,HFG/784.12,1012.46,1121.24,1882.68,
     +4183.74,620.07,2.326E+06/
      DATA PATM/98595.0251/
      END
```

Appendix D Continued

```
      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
      IF(T - 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 F1 = -.00070596*T + .0874496
      F2 = -.00078354*T + .1188704
      F3 =-.00096462*T + .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 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 = S2*A*A*A/1.02 + (F3/.17)*(RH - .34) + (F2/.17 - S2*.02833)
     +*A
      RETURN
```

Appendix D Continued

```
C*****    PART TWO---RH.GT. .50 ONLY
C*****    COMPUTE CONSTANTS
  309 FO = -.00096714*T + .1452064
      F1 = -.00127350*T + .1848600
      F2 = -.00134082*T + .2293632
      F3 = -.00192780*T + .3588280
      S1 = 13.838*(4.*FO - 9.*F1 + 6.*F2 - F3)
      S2 = 13.838*(4.*F3 - 9.*F2 + 6.*F1 - FO)
      B = RH - .66
      IF(B) 305,305,306
C*****    FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
C*****    CONTENT
  305 A = RH - .49
      EMC = S1*A*A*A/1.02 + (F1/.17 - S1*.02833)*A + (FO/.17)*(.66 - RH)
      RETURN
  306 IF(RH - .83) 307,307,308
  307 A = .83 - RH
      EMC = 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*A/1.02 + (F3/.17)*(RH - .83) + (F2/.17 - S2*.028333)
     1*A
      RETURN
C*****                          THOMPSON   EQUATION
C*****
C*****    T.GE. 113 DEGREES CELCUS
C*****    COMPUTE EQUILIBRIUM MOISTURE CONTENT
  235 EMC = .01*SQRT((-ALOG(1. - RH))/(.0000382*(1.8*T + 82.)))
      RETURN
      END
```

] n.b. ✗

Appendix D Continued

```
*DECK LAYEQ
      SUBROUTINE LAYEQ
C*****
C*****                        L.E. LEREW, PROGRAMMER
C*****
C*****                        E.W.RUGUMAYO, SI-UNIT CONVERTER AND
C*****                        MODIFIER  1978
C*****
C*****   DESCRIPTION
C*****        SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUATIONS
C*****   BY M.A.SABBAH, E.W.RUGUMAYO ,MISRA AND P.M.DEL GUIDICE
C*****
C*****   USAGE
C*****        USED IN THE FIXED BED AND CROSS FLOW MODELS WITH GRAIN
C*****   TEMPERATURE LESS THAN 26.7 DEG CELCIUS ( 80.0 F )
C*****
      COMMON/MAIN/XMC,TH,RH,DELT,CMM,XMO,KAB,TIME
      COMMON/NAME/INAME,IPROD,NEQ,NEQ1
      DIMENSION INAME(3)
      DATA INAME,IPROD/10HSABBAH AND,10H RUGUMAYO ,10HAND MISRA ,10H COR
     1N     /
      DATA TGUESS/1.0/
C*****   CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS
      CALL READYTH(TXMO,DELM,XME,IOOPS,XMR)
      IF(IOOPS - 1) 1,20,1
    1 RSQ = RH*RH
      X = SQRT(6.0142 + .1453E-3*RSQ) - (1.8*TH + 32.)*SQRT(.3353E-3 +
     1.3E-7*RSQ)
      Y = .1245 - .2197E-2*RH - (1.8*TH + 32.)*(.23E-4*RH + .58E-4)
      R=25.592-38.6298*XMC+26.6824*ALOG10(XMC)-0.0044*(XMC**2.)*
     2(TH+273.16)*EXP(RSQ)
      K = 0
      T1 = TGUESS
C*****   CHECK IF DERIVATIVE IS VERY LARGE.. IF SO ASSIGN T1 = 0.0
      IF(XMR.LT..999) GO TO 2
      T1=0.0
      GO TO 4
```

Appendix D Continued

```
C*****    CHECK FOR EQUILIBRIUM CONDITIONS
    2 IF(XMC - XME.LT..0001) GO TO 70
      U=ALOG(-ALOG(XMR))
      IF(NEQ1.EQ.1) U=ALOG(XMR)
C*****    IF Y IS POSITIVE, EQUATION WILL NEVER REACH XME
C*****    T1MAX IS THE CLOSEST APPROACH USED TO LIMIT SEARCH .
      T1MAX = 2000.
      IF(Y.LE.0.) GO TO 3
      IF(X.LE.0.) GO TO 3
      IF(R.GE.0.) GO TO 3
      T1MAX = (0.664/(X*Y))**(1.0/Y)
C*****    NEWTON - RAPHSON TECHNIQUE TO FIND EQUIVALENT TIME
    3 Z1 = X*T1**Y - .664*ALOG(T1) + U
      IF(NEQ1.EQ.1) Z1=U-R*T1
      IF(ABS(Z1).LT..001) GO TO 4
      Z2 = X*Y*T1**(Y-1.) - .664/T1
      IF(NEQ1.EQ.1) Z2=-R
      T2 = T1 - Z1/Z2
      K = K + 1
      IF(T2.LE.0.0) T2 = T1/5.
      IF(T2.GE.T1MAX) GO TO 4
      T1 = T2
      IF(K.LT.20)  GO TO 3
      PRINT 210,K
  210 FORMAT(33H0THE METHOD HAS NOT CONVERGED IN I2,11H ITERATIONS)
      PRINT 211,XMC,TH,RH,XME
  211 FORMAT(* LAYEQ.  XMC=*F8.5* TH=*F8.3* RH=*F8.5* XME=*F8.5)
C*****    ADD DELT TO EQUIVALENT TIME,SOLVE FOR NEW M AND RETURN
    4 T1=T1+DELT
C*****    CORN THIN LAYER EQUATIONS FOR LOW TEMPERATURE DRYING
C*****
    5 IF(TIME.LE.0.0) DELT = 0.0
C*****    RUGUMAYO DRYING EQUATION ONE FOR WHOLE TEMPERATURE RANGE
      IF(NEQ1.EQ.1) XMC=DELM*EXP(R*T1)+XME
      IF(NEQ1.EQ.1) RETURN
      IF(NEQ1.EQ.2) GO TO 6
C*****    SABBAH DRYING EQUATION
      IF(NEQ1.EQ.3) XMC = DELM*EXP(-EXP(-X*T1**Y)*T1**.664) + XME
      IF(NEQ1.EQ.3) RETURN
      IF(NEQ1.EQ.4) GO TO 21
```

```
C*****     MISRA(1978) DRYING EQUATION
     6 XMC = DELM*EXP(-(EXP(-7.1735 + 1.2793*ALOG(1.8*TH + 32.0) +
      20.0061*(MM))*TIME**(0.0811*ALOG(100.0*RH) + 0.0078*XMO)) + XME
       IF(NEQ1.EQ.2) RETURN
    21 NEQ1 = 1
       GO TO 5
C*****
C*****     ABSORPTION SIMULATION
C*****     FIND NEW M AND INCREMENT COUNTER
    20 DIV = -4.309*PSDB(TH + 273.16)**(.466*RH)*RH*RH*RHV
       RSQ=RH*RH
       R1=162.1179-487.9552*XMC+118.6144
      1*ALOG10(XMC)+0.69658*(TH+273.16)*(XMC**2.)*EXP(RSQ)
C
    22 IF(TIME.LE.0.0) DELT = 0.0
C*****     RUGUMAYO ABSORPTION EQUATION FOR WHOLE LOW TEMPERATURE RANGE
       IF(NEQ1.EQ.1) XMC = DELM*EXP(R1*T1)+XME
       IF(NEQ1.EQ.1) GO TO 60
       IF(NEQ1.EQ.2) GO TO 25
C*****     DEL GUIDICE EQUATION (1959)
       IF(NEQ1.EQ.3) XMC = (XMC - XME)*EXP(DIV*DELT) + XME
       IF(NEQ1.EQ.3) GO TO 60
C*****     MISRA(1978) REWETTING EQUATION
    25 XMC = DELM*EXP(-(EXP(-8.5122 + 1.2178*ALOG(1.8*TH + 32.0) +
      20.0864*XMO))*TIME**( 2.1876 - 1.67*RH)) + XME
       IF(NEQ1.EQ.2) GO TO 60
       NEQ1 = 1
       GO TO 22
    60 IF(NEQ.NE.4) KAB = KAB + 1
       IF(NEQ.EQ.4.AND.NEQ1.EQ.3) KAB = KAB + 1
       RETURN
    70 XMC = XME
       RETURN
       END
```

Appendix D Continued

```
      FUNCTION SOLVE(HJ2)
C*****
C*****   COMPUTES T(J,2), XMT, RH(J) AND ICON GIVEN H(J,2)
C*****   SOLVE RETURNS THE DIFFERENCE BETWEEN THE COMPUTED M AND
C*****   THE M PREDICTED BY THE DRYING EQUATION
C*****
      COMMON /ARRAYS/ T(51,2),H(51,2),XM(51),RH(51)
      COMMON /CONS/ CON1,CON2,CON3,CON4,CON5,CON6,CON7,CON12,CON13
      COMMON /FLAGS/ J,JM,ICON
      COMMON /MAIN/ XMT,THT,RHT,DELT,CMN,XMO,KAB,TIME
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      F(T) = T + 273.16
      DATA RHC /.9999999999/
      ICON=0
      H(J,2)=HJ2
C*****   T EQUATION
      T1=CON1*(H(J,2)-H(JM,2))
      T2=CON1*(CA+CV*H(JM,2))
      T3=CON4*(CP+CW*XM(J))
      T(J,2)=(-T1*CON3+T2*T(JM,2)+T3*T(J,1))/(-T1*CON2+T2+T3)
      IF(T(J,2).LT.-17.8) GO TO 7
      TABS=F(T(J,2))
C*****   COMPUTE RH AND CHECK FOR CONDENSATION
      RH(J)=RHDBHA(TABS,H(J,2))
      IF(RH(J)-RHC)111,7,7
C*****   CONDENSATION SIMULATOR
    7 TS=(T2*T(JM,2)+T3*T(J,1))/(T2+T3) $ TABS=F(TS)
      HS=HADBRH(TABS,RHC)
      DHDT=HS-HADBRH(TABS-1.00,RHC)
      T1=HS-H(JM,2)-DHDT*TS
      A=CON12*DHDT
      B=CON12*T1-T2-T3-CON13*DHDT
      C=T2*T(JM,2)+T3*T(J,1)-CON13*T1
      T(J,2)=(-B-SQRT(B*B-4.*A*C))/(2.*A)
      H(J,2)=HS+DHDT*(T(J,2)-TS)
      RH(J)=RHDBHA(F(T(J,2)),H(J,2))
      ICON=1
```

Appendix D Continued

```
C*****    FIND M ACCORDING TO THIN LAYEE DRYING EQUATION
  111 XMT=XM(J)  $ THT=T(J,2)  $ RHT RH(J)
      CALL LAYEQ
      SOLVE=XMT-XM(J)+CON6*(HJ2-H(JM,2))
C*****    M EQUATION
      XMT=XM(J)-CON6*(H(J,2)-H(JM,2))
      RETURN
      END
```

Appendix D Continued

```
      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 LAYEQ IN FIXED AND CROSS FLOW DRYER MODELS
C*****
      COMMON/MAIN/XMC,TH,RH,DELT,CMM,XMO,KAB,TIME
      COMMON/NAME/INAME,IPROD,NEQ,NEQ1
      DIMENSION INAME(3)
      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 IOOPS = 1
C*****   COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT
C*****   SET TXMO = THE LARGER VALUE
    2 IF(XMO - XMC) 3,4,4
    3 TXMO = XMC
      GO TO 5
    4 TXMO = XMO
C*****   COMPUTE MOISTURE RATIO
    5 DELM = TXMO - XME
      XMR = (XMC - XME)/DELM
      RETURN
      END
```

Table D-1. In-put variables of the program "SOLARUG" used to evaluate the flat-plate solar collector air heater.

TM = Time of day, in hours

DY = Day of the month

CCV = Cloud cover, dimensionless

SR = Recorded insolation, w/sq m

TA = Ambient air temperature, ^{o}K.

TFE = Recorded heated air tem., ^{o}K

TG = Top cover glass temp., ^{o}K.

TP = Absorber plate temp., ^{o}K.

TT = Tedlar cover temp., ^{o}K.

VA = Wind speed, m/s.

No	TM	DY	CCV	SR	TA	TG	TT	TP	TFF	VA
1	10.	6	7	375.8	278.5	281.1	290.1	293.5	283.1	2.0
2	11.	6	4	449.9	279.2	282.9	293.8	296.8	284.7	2.6
3	12.	6	3	474.5	280.6	285.0	296.7	299.7	286.9	2.5
4	13.	6	4	443.1	262.4	286.4	297.8	300.9	287.6	2.7
5	14.	6	1	374.2	282.8	287.1	299.9	303.1	288.1	2.9
6	15.	6	1	257.7	281.8	285.5	299.6	300.0	287.3	3.5
7	16.	6	1	138.4	277.6	277.5	287.0	296.7	281.3	3.0
8	17.	6	0	61.7	274.5	273.9	283.2	293.6	277.8	2.1
9	18.	6	0	53.8	274.2	273.2	282.0	291.8	275.8	1.1
10	19.	6	5	54.0	274.4	273.3	282.1	292.0	277.8	0.7
11	20.	6	8	54.2	274.4	273.4	281.9	291.4	277.4	1.1
12	21.	6	10	53.9	274.1	272.9	281.8	291.9	278.1	0.4
13	22.	6	10	54.3	274.2	273.0	281.5	291.0	278.1	0.5

Table D-1. continued.

14	23.	6	10	54.2	274.4	273.0	281.4	290.7	277.5	0.2
15	0.	7	10	54.2	273.7	272.3	280.7	290.1	276.7	0.2
16	1.	7	10	54.0	274.3	272.9	281.0	290.1	277.2	0.2
17	2.	7	10	53.9	274.2	272.9	281.1	290.2	277.0	0.6
18	3.	7	3	54.4	274.5	273.0	281.0	289.9	276.1	0.2
19	4.	7	10	54.2	273.1	271.8	280.1	289.3	275.6	0.3
20	5.	7	10	54.0	273.1	271.8	280.1	289.2	275.4	0.5
21	6.	7	4	53.9	272.9	271.7	279.9	289.1	275.3	0.5
22	7.	7	2	60.3	272.9	271.8	279.7	288.4	275.7	0.8
23	8.	7	7	115.4	272.3	271.9	280.5	288.5	276.7	1.0
24	9.	7	10	190.8	273.0	273.4	282.5	289.4	277.4	1.8
25	10.	7	10	231.5	273.3	274.1	284.2	291.3	277.6	2.1
26	11.	7	9	315.2	274.2	275.5	284.6	290.7	278.4	2.3
27	12.	7	9	305.9	274.4	275.6	285.0	291.8	279.2	2.6
28	13.	7	8	278.1	274.5	275.6	284.9	291.6	279.1	2.7
29	14.	7	9	276.8	274.3	275.6	285.4	291.9	279.1	2.6
30	15.	7	10	165.3	273.4	273.5	282.2	290.3	277.9	2.5
31	16.	7	10	99.7	272.4	272.0	280.3	289.1	275.5	2.9
32	17.	7	10	59.8	271.7	271.0	279.0	288.1	274.6	2.8

Table D-1. continued.

33	18.	7	10	54.3	271.1	270.4	278.3	287.3	274.0	3.1
34	19.	7	10	54.0	270.2	269.5	277.4	286.6	273.0	2.9
35	20.	7	10	54.2	269.7	268.9	276.9	286.0	272.5	2.3
36	21.	7	10	54.0	269.3	268.5	276.4	285.5	272.1	2.2
37	22.	7	10	54.2	269.2	268.5	276.3	285.2	272.0	2.5
38	23.	7	9	54.0	268.7	268.0	275.8	284.8	271.5	2.7
39	0.	8	8	54.3	268.2	267.5	275.3	284.3	271.0	2.7
40	1.	8	2	53.9	267.7	267.0	274.8	283.8	270.5	2.7
41	2.	8	0	54.2	267.0	266.1	273.6	282.0	269.9	1.7
42	3.	8	0	54.2	266.4	265.5	273.5	282.8	269.5	1.1
43	4.	8	8	54.2	266.5	265.6	273.5	282.6	269.3	1.3
44	5.	8	4	54.2	266.9	266.0	273.8	282.7	269.7	1.6
45	6.	8	0	54.2	266.2	265.2	273.3	282.5	269.2	1.0
46	7.	8	1	59.8	265.6	265.1	273.8	282.0	268.7	0.8
47	8.	8	3	137.9	266.8	267.1	275.6	283.0	271.3	0.8
48	9.	8	6	260.6	269.1	271.0	280.2	286.3	273.8	1.1
49	10.	8	8	355.9	270.8	273.5	283.5	298.8	275.7	1.6
50	11.	8	10	322.5	271.1	272.8	282.3	288.9	275.7	1.6
51	12.	8	10	262.6	271.1	272.0	280.7	287.7	275.2	1.5

Table D-1. continued.

52	13.	8	9	374.8	272.9	276.4	285.9	289.7	276.9	1.0
53	14.	8	7	343.5	273.7	277.9	288.1	291.0	278.0	1.0
54	15.	8	6	201.7	273.1	275.1	285.5	290.3	277.4	0.9
55	16.	8	6	102.9	272.1	271.6	280.3	288.8	276.4	0.8
56	17.	8	10	61.5	270.4	269.4	277.9	287.1	273.5	0.5
57	18.	8	10	54.2	270.0	268.8	277.1	286.4	272.9	0.3
58	19.	8	10	54.0	269.4	268.1	276.5	285.8	272.4	0.1
59	20.	8	10	54.2	269.3	268.0	276.2	285.3	272.2	0.1
60	21.	8	10	54.0	269.7	268.4	276.6	285.6	272.5	0.2
61	22.	8	10	54.2	270.1	268.8	277.0	286.0	272.8	0.2
62	23.	8	10	54.2	270.3	269.0	277.2	286.1	273.1	0.3
63	0.	9	10	54.3	270.6	269.3	277.4	286.4	273.5	0.4
64	1.	9	10	54.0	271.0	269.8	277.8	286.7	273.8	0.5
65	2.	9	10	54.2	271.1	270.0	278.0	286.8	273.9	0.8
66	3.	9	10	53.8	270.9	269.7	277.8	286.7	273.6	0.6
67	4.	9	10	54.0	271.2	270.0	278.0	286.9	273.9	0.5
68	5.	9	10	54.2	271.3	270.1	278.1	287.1	274.0	0.5
69	6.	9	8	54.2	270.9	269.7	277.9	287.0	274.0	0.4
70	7.	9	10	65.2	270.5	269.4	277.7	286.6	273.5	0.4

Table D-1. continued.

71	8.	9	10	133.6	272.2	271.9	280.3	287.6	276.3	0.4
72	9.	9	9	210.1	274.6	275.1	283.9	289.8	278.5	1.3
73	10.	9	10	262.7	276.4	277.4	286.7	292.0	280.4	1.4
74	11.	9	10	243.2	276.9	277.6	286.7	292.3	280.9	1.9
75	12.	9	10	234.8	278.0	278.6	287.6	293.3	281.9	2.1
76	13.	9	5	197.6	278.1	278.4	286.5	293.7	282.3	2.6
77	14.	9	8	371.3	281.9	285.2	295.4	297.8	285.8	2.1
78	15.	9	2	210.7	280.4	283.8	295.8	297.2	284.8	1.9
79	16.	9	8	121.2	279.8	279.4	288.0	296.0	283.9	1.8
80	17.	9	3	58.1	277.7	276.6	284.9	294.1	280.8	1.2
81	18.	9	4	53.8	275.9	274.4	282.9	292.4	279.1	0.1
82	19.	9	5	53.9	276.2	274.9	283.0	292.0	279.1	0.7
83	20.	9	7	54.2	276.2	275.0	283.0	292.1	279.2	0.8
84	21.	9	10	53.9	275.7	274.3	282.5	291.7	279.1	0.3
85	22.	9	7	53.8	274.8	273.5	281.8	291.1	277.9	0.4
86	23.	9	10	54.2	273.7	272.4	280.8	290.1	276.8	0.4
87	0.	10	10	54.2	272.9	271.5	279.7	288.7	276.1	0.3
88	1.	10	4	53.9	272.1	270.8	279.3	288.7	275.2	0.2
89	2.	10	4	54.0	271.4	270.1	278.5	287.8	274.1	0.2
90	3.	10	4	54.0	271.4	270.0	278.4	287.6	274.4	0.1

Table D-1. continued.

91	4.	10	5	54.3	271.5	270.0	277.5	285.7	274.6	0.2
92	5.	10	4	53.9	271.3	270.0	278.3	287.6	274.4	0.3
93	6.	10	10	54.0	271.7	270.3	278.5	287.6	274.6	0.2
94	7.	10	10	57.4	272.9	271.4	279.4	288.1	275.2	0.1
95	8.	10	10	74.8	274.2	273.0	280.7	288.6	277.2	0.4
96	9.	10	8	172.9	275.4	275.5	283.7	289.9	278.5	0.5
97	10.	10	10	267.7	276.4	277.6	286.9	292.0	280.2	0.9
98	11.	10	10	263.2	276.4	277.5	286.9	292.3	280.3	1.1
99	12.	10	10	187.9	276.2	276.5	285.3	291.9	279.9	0.9
100	13.	10	10	173.3	275.9	276.0	284.3	290.7	278.5	1.5
101	14.	10	10	110.2	274.0	273.5	282.0	290.0	278.3	1.3
102	15.	10	10	111.1	272.4	271.9	280.6	288.9	276.9	0.7
103	16.	10	10	103.5	272.6	272.1	280.5	288.7	277.1	1.0
104	17.	10	10	57.1	272.4	271.2	279.5	288.6	275.4	0.5
105	18.	10	10	54.2	272.5	271.3	279.5	288.5	275.5	0.7
106	19.	10	10	54.0	271.9	270.7	278.8	288.0	274.8	0.7
107	20.	10	8	54.2	271.7	270.4	278.6	287.6	274.4	0.4
108	21.	10	10	53.8	270.8	269.6	278.0	287.3	273.9	0.4
109	22.	10	10	54.0	270.6	269.3	277.6	286.8	273.6	0.3
110	23.	10	8	54.3	270.2	268.9	277.3	286.4	273.2	0.3

Table D-1. continued.

111	0.	11	8	54.2	269.9	268.6	277.0	286.2	273.0	0.2
112	1.	11	8	54.0	269.8	268.5	276.8	286.0	272.9	0.1
113	2.	11	4	53.8	269.4	268.1	276.5	285.7	272.5	0.1
114	3.	11	0	54.2	269.1	267.8	276.2	285.4	272.3	0.1
115	4.	11	2	54.2	268.8	267.6	275.9	285.1	272.0	0.2
116	5.	11	7	54.0	268.4	267.3	275.6	284.8	271.6	0.5
117	6.	11	10	54.2	268.3	267.1	275.4	284.6	271.3	0.4
118	7.	11	10	61.3	268.2	267.2	275.5	284.4	271.2	0.6
119	8.	11	8	110.9	268.8	268.3	276.7	284.4	273.0	0.4
120	9.	11	8	237.4	269.4	270.5	279.4	286.8	275.0	0.6
121	10.	11	8	243.5	270.8	271.7	280.6	287.8	275.3	1.0
122	11.	11	5	289.4	271.8	274.1	283.0	288.2	275.9	0.8
123	12.	11	7	457.1	274.6	279.6	290.0	292.2	278.9	1.3
124	13.	11	9	181.0	272.3	272.5	281.1	289.3	276.5	0.7
125	14.	11	10	166.8	272.4	272.4	280.5	288.3	276.2	0.6
126	15.	11	10	167.1	272.9	272.9	281.0	288.8	276.6	0.6
127	16.	11	8	95.0	272.1	271.2	279.3	288.0	274.6	0.4
128	17.	11	7	57.1	271.3	270.0	278.0	287.3	274.2	0.4
129	18.	11	3	54.0	270.7	269.3	277.4	286.9	273.7	0.2

Table D-1. continued.

130	19.	11	0	54.0	269.8	268.4	276.6	286.1	272.9	0.2
131	20.	11	0	53.9	269.2	267.8	276.0	285.5	272.2	0.1
132	21.	11	0	54.0	269.1	267.7	275.8	285.2	272.0	0.2
133	22.	11	0	54.3	268.5	267.1	275.2	284.7	271.5	0.1
134	23.	11	3	54.2	267.6	266.3	274.4	283.9	270.4	0.1
135	0.	12	8	54.2	266.8	265.5	273.6	283.1	269.7	0.1
136	1.	12	10	53.9	268.0	266.6	274.5	283.6	270.6	0.1
137	2.	12	10	54.0	268.4	267.0	275.0	284.2	271.2	0.1
138	3.	12	4	54.4	268.1	266.7	274.8	284.2	271.0	0.1
139	4.	12	0	54.2	267.6	266.2	274.3	283.6	270.5	0.1
140	5.	12	0	54.2	266.8	265.5	273.7	283.2	269.7	0.1
141	6.	12	0	54.2	266.4	265.1	273.2	282.7	269.3	0.1
142	7.	12	0	59.6	267.3	267.8	276.7	282.8	270.0	0.1
143	8.	12	1	165.0	269.2	271.3	279.7	284.0	273.0	0.3
144	9.	12	3	284.3	271.8	275.7	284.6	288.0	276.1	0.3
145	10.	12	7	304.7	272.9	275.6	284.7	290.3	277.5	0.5
146	11.	12	7	291.6	273.9	275.7	284.7	290.6	278.0	1.0
147	12.	12	7	359.0	275.1	278.1	287.6	291.9	278.9	1.3
148	13.	12	6	313.1	274.9	277.6	287.3	292.5	279.1	1.4

Table D-1. continued.

149	14.	12	9	240.4	275.7	276.5	285.1	291.7	279.3	1.4
150	15.	12	8	152.5	274.6	274.5	282.9	290.8	278.7	1.5
151	16.	12	5	93.8	273.8	273.1	281.2	289.8	276.4	1.1
152	17.	12	10	57.4	272.7	271.6	279.7	288.9	275.7	1.0
153	18.	12	10	54.2	272.3	271.6	279.5	288.6	275.6	0.7
154	19.	12	7	53.9	272.3	271.1	279.1	288.3	275.2	0.8
155	20.	12	4	53.9	271.5	270.3	278.4	287.8	274.5	0.6
156	21.	12	3	54.0	271.2	269.9	278.0	287.4	274.2	0.3
157	22.	12	8	54.0	271.1	269.8	277.9	287.2	274.0	0.3
158	23.	12	10	53.8	270.7	269.5	277.5	286.8	273.5	0.5
159	0.	13	3	53.9	270.2	269.0	277.0	286.4	273.1	0.4
160	1.	13	0	53.9	269.6	268.3	276.5	285.9	272.6	0.3
161	2.	13	0	54.2	270.9	269.5	277.0	285.7	274.2	0.4
162	3.	13	0	54.0	269.8	268.5	276.6	285.9	272.9	0.3
163	4.	13	0	54.2	269.1	267.8	276.0	285.3	272.2	0.2
164	5.	13	0	54.3	268.8	267.5	275.6	284.9	271.8	0.2
165	6.	13	0	54.0	269.9	268.8	276.6	285.7	272.9	0.8
166	7.	13	0	59.1	270.1	270.5	279.5	285.8	272.9	1.0
167	8.	13	1	148.5	271.4	272.6	281.2	286.7	275.5	1.1

Table D-1. continued.

168	9.	13	1	255.7	273.8	276.2	285.7	290.4	278.6	2.1
169	10.	13	1	341.5	275.4	278.6	289.1	293.3	280.5	2.4
170	11.	13	1	442.5	277.5	282.1	293.6	296.1	282.7	2.3
171	12.	13	2	466.8	278.0	282.3	294.7	297.7	283.8	3.1
172	13.	13	2	432.3	278.9	283.1	295.3	298.3	284.4	3.3
173	14.	13	0	334.3	279.4	283.4	295.6	297.8	284.0	3.2
174	15.	13	0	238.0	275.3	280.5	296.6	296.9	278.3	2.7
175	16.	13	0	119.9	277.1	276.8	285.7	294.1	281.1	2.7
176	17.	13	0	57.3	274.3	273.4	281.9	291.3	277.4	1.5
177	18.	13	0	53.9	273.2	272.1	280.5	289.8	276.3	0.9
178	19.	13	0	53.9	272.1	270.9	278.4	286.5	275.2	0.9
179	20.	13	0	54.0	271.5	270.5	278.8	287.9	274.5	1.3
180	21.	13	0	54.2	271.2	270.2	278.5	287.6	274.1	1.3
181	22.	13	0	54.0	270.9	269.9	278.1	287.1	273.3	1.1
182	23.	13	0	54.0	270.8	269.8	277.9	286.9	273.7	1.3
183	0.	14	0	53.9	271.1	270.1	278.1	287.1	273.8	1.4
184	1.	14	0	53.9	270.6	269.6	277.7	286.6	273.5	1.1

Table D-1. continued.

185	2.	14	0	54.0	270.2	269.1	277.2	286.2	273.0	0. 7
186	3.	14	0	53.9	269.8	268.6	276.8	285.8	272.6	0. 4
187	4.	14	4	53.9	269.3	268.2	276.4	285.5	272.2	0. 7
188	5.	14	8	54.3	270.1	269.0	276.9	285.5	272.8	1. 0
189	6.	14	0	54.2	269.2	268.0	276.3	285.4	272.2	0. 4
190	7.	14	0	59.5	268.8	269.4	278.7	284.9	271.6	0. 3
191	8.	14	0	117.8	270.0	271.0	279.4	285.6	274.0	0. 4
192	9.	14	7	224.5	272.2	273.0	281.4	288.1	276.3	1. 2
193	10.	14	5	328.3	273.9	276.5	286.3	291.2	278.7	1. 9
194	11.	14	3	388.5	275.6	279.4	290.1	293.9	280.9	2. 0
195	12.	14	1	450.0	277.2	282.6	294.2	296.2	282.5	1. 9
196	13.	14	3	426.8	278.0	283.5	295.0	297.4	283.4	1. 6
197	14.	14	3	343.2	278.3	283.2	294.8	297.3	283.3	1. 7
198	15.	14	4	234.6	278.5	282.7	295.2	296.2	282.7	1. 5
199	16.	14	3	118.7	276.8	276.4	285.3	293.6	280.6	1. 5
200	17.	14	1	260.1	273.5	274.7	284.6	290.7	278.2	1. 1
201	18.	14	0	53.8	271.9	270.7	279.3	289.0	275.2	0. 4
202	19.	14	0	54.2	271.3	270.0	278.4	287.8	274.3	0. 2
203	20.	14	0	53.9	270.7	269.5	277.8	287.1	273.7	0. 4
204	21.	14	0	54.2	269.7	268.4	276.9	286.2	272.8	0. 2

Table D-1. continued.

205	22.	14	0	54.2	268.8	267.5	276.1	285.5	271.9	0.1
206	23.	14	0	54.4	268.4	267.1	275.6	284.9	271.4	0.1
207	0.	15	0	54.2	267.8	266.6	275.0	284.3	270.8	0.1
208	1.	15	0	54.3	267.4	266.2	274.6	283.9	270.5	0.1
209	2.	15	0	54.2	267.3	266.0	274.4	283.6	270.4	0.1
210	3.	15	0	54.2	266.8	265.6	274.0	283.3	269.8	0.1
211	4.	15	0	54.2	266.9	265.7	274.0	283.2	269.9	0.1
212	5.	15	0	54.0	266.4	265.2	273.6	282.9	269.6	0.1
213	6.	15	3	54.3	266.2	265.0	273.3	282.5	269.1	0.1
214	7.	15	3	56.7	266.3	264.9	271.5	278.5	270.3	0.4
215	8.	15	0	133.7	267.9	269.7	278.1	283.3	271.7	0.1
216	9.	15	0	253.4	271.3	275.6	284.2	287.0	275.3	0.2
217	10.	15	0	366.0	274.3	280.4	290.0	291.1	278.8	0.4
218	11.	15	0	414.5	276.4	281.9	292.8	294.7	281.5	1.3
219	12.	15	0	444.2	277.6	284.0	295.3	296.7	283.0	1.2
220	13.	15	0	412.5	278.3	284.5	296.0	297.6	283.7	1.4
221	14.	15	0	336.1	279.1	284.8	296.6	297.6	284.0	1.6
222	15.	15	0	224.6	273.7	280.8	295.9	296.3	278.2	1.7
223	16.	15	0	113.4	276.8	276.3	285.1	293.5	280.8	1.1
224	17.	15	0	57.2	274.4	273.3	281.8	291.3	277.1	0.8

Table D-1. continued.

225	18.	15	0	54.0	273.1	272.0	280.1	289.1	275.7	1.1
226	19.	15	0	53.8	272.0	270.7	278.1	286.1	274.8	0.8
227	20.	15	0	54.0	272.2	271.0	279.2	288.4	275.1	0.6
228	21.	15	0	54.2	271.3	270.0	278.3	287.5	274.4	0.3
229	22.	15	0	54.0	270.3	269.0	277.4	286.7	273.4	0.1
230	23.	15	0	53.8	269.4	268.1	276.5	285.8	272.2	0.1
231	0.	16	0	53.9	269.2	267.9	276.2	285.4	272.0	0.1
232	1.	16	0	53.9	268.8	267.5	275.8	284.9	271.6	0.1
233	2.	16	0	54.2	268.7	267.4	275.7	284.8	271.6	0.1
234	3.	16	0	54.2	268.4	267.1	275.4	284.5	271.2	0.1
235	4.	16	0	54.2	268.1	266.8	275.0	284.1	271.1	0.1
236	5.	16	0	54.2	267.7	266.4	274.7	283.9	270.6	0.1
237	6.	16	0	54.0	267.9	266.6	274.8	283.9	270.7	0.1
238	7.	16	0	58.2	268.2	269.0	278.1	283.8	270.7	0.1
239	8.	16	0	126.2	269.7	271.2	279.5	284.9	273.6	0.1
240	9.	16	0	230.7	273.4	276.9	285.4	288.9	277.5	0.2
241	10.	16	0	323.6	276.9	281.9	291.2	293.6	281.5	0.4
242	11.	16	0	392.5	279.3	284.8	295.1	297.0	284.3	0.9
243	12.	16	0	425.3	280.9	286.7	297.6	299.2	285.8	1.3

Table D-1. continued.

244	13.	16	0	394.0	281.3	287.0	298.1	299.9	286.2	1.4
245	14.	16	0	319.8	281.0	286.3	298.0	299.7	286.1	1.6
246	15.	16	0	213.8	273.0	279.7	295.1	295.3	277.5	1.3
247	16.	16	0	106.9	276.4	275.9	284.8	293.5	281.6	1.0
248	17.	16	0	56.7	274.0	272.8	281.6	291.4	279.6	0.3
249	18.	16	0	53.8	273.3	271.8	280.1	289.2	275.3	0.1
250	19.	16	0	53.9	273.1	271.5	278.9	287.1	275.4	0.1
251	20.	16	0	53.8	272.6	271.2	279.6	288.9	275.3	0.1
252	21.	16	0	54.0	271.9	270.4	278.8	288.2	274.8	0.1
253	22.	16	0	53.8	271.7	270.3	278.6	287.8	274.6	0.1
254	23.	16	0	54.2	272.3	271.0	279.1	288.1	275.1	0.3
255	0.	17	0	54.2	272.5	271.2	279.3	288.3	275.3	0.5
256	1.	17	0	54.0	272.4	271.1	279.2	288.1	275.1	0.5
257	2.	17	0	54.0	272.7	271.5	279.5	288.4	275.4	0.6
258	3.	17	0	53.7	272.6	271.3	279.5	288.5	274.8	0.4
259	4.	17	0	54.0	272.4	271.2	279.3	288.3	275.3	0.6
260	5.	17	0	54.3	272.5	271.4	279.4	288.3	275.5	0.8
261	6.	17	0	54.2	273.1	272.0	279.9	288.6	275.9	1.1
262	7.	17	2	56.1	272.8	271.7	280.0	289.1	275.5	0.7

Table D-1. continued.

263	8.	17	9	109.5	273.2	272.6	280.9	288.8	277.3	0. 4
264	9.	17	10	236.8	276.1	276.9	286.2	292.1	280.6	1. 2
265	10.	17	10	263.3	277.7	278.5	288.2	294.2	282.3	2. 5
266	11.	17	10	243.2	277.7	278.3	287.8	294.0	282.2	3. 2
267	12.	17	5	244.2	277.5	278.5	287.6	294.4	282.4	2. 2
268	13.	17	8	329.4	279.5	281.4	291.4	297. 2	284.5	3. 0
269	14.	17	10	248.6	279.1	279.7	288.5	295.9	283.4	2. 1
270	15.	17	10	162.3	279.2	279.1	287.2	295.3	283.3	1. 9
271	16.	17	10	63.2	276.6	275.9	283.8	293.0	279.3	2. 9
272	17.	17	6	54.3	275.8	274.9	282.6	291.8	278.5	2. 0
273	18.	17	0	54.2	274.8	273.7	281.7	291.1	277.8	1. 3
274	19.	17	3	53.9	273.8	272.5	280.7	290. 4	276.9	0. 4
275	20.	17	4	54.3	273.6	272.3	280.4	289. 9	276.5	0. 6
276	21.	17	6	54.3	273.6	272.3	280.3	289. 7	276.5	0. 6
277	22.	17	0	53.9	273.8	272.5	280.4	289. 8	276.7	0. 5
278	23.	17	6	54.0	274.1	272.8	280.7	290. 1	277.1	0. 6
279	0.	18	0	53.9	273.4	272.0	280.0	289. 5	276.3	0. 2
280	1.	18	0	54.2	273.7	272.2	280.2	289. 6	276.5	0. 2
281	2.	18	0	54.0	272.9	271.5	279.6	289. 2	276.1	0. 2

Table D-1. continued.

282	3.	18	0	54.0	273.3	272.0	280.0	289.4	276.3	0.5
283	4.	18	8	53.9	273.2	271.9	279.8	289.1	276.1	0.6
284	5.	18	3	54.3	273.0	271.7	279.7	289.0	276.0	0.4
285	6.	18	0	54.0	272.9	271.6	279.6	288.9	275.8	0.5
286	7.	18	3	57.3	272.4	271.1	279.2	288.6	275.5	0.3
287	8.	18	7	115.9	273.6	272.9	281.0	289.5	278.2	0.2
288	9.	18	10	207.5	275.9	278.3	284.8	292.3	280.6	0.8
289	10.	18	10	325.5	277.1	278.9	288.7	295.4	282.6	1.6
290	11.	18	9	369.8	278.1	280.6	291.0	296.9	283.8	2.0
291	12.	18	10	319.1	278.3	279.8	289.6	296.8	283.7	2.1
292	13.	18	9	195.5	277.8	278.0	286.6	294.8	282.7	1.3
293	14.	18	8	194.5	278.2	278.4	286.8	294.9	282.9	1.5
294	15.	18	10	204.3	279.7	279.9	288.4	296.2	284.1	1.7
295	16.	18	8	95.3	278.7	277.8	285.8	294.8	281.6	0.7
296	17.	18	8	56.2	277.7	276.2	284.3	293.9	280.7	0.3
297	18.	18	8	54.2	277.7	276.3	284.2	293.6	280.7	0.6
298	19.	18	8	53.8	277.9	276.6	284.3	293.4	280.7	0.9
299	20.	18	8	54.0	277.7	276.4	284.3	293.5	280.7	1.0
300	21.	18	8	54.2	277.7	276.3	284.2	293.5	280.6	0.6

Table D-1. continued.

301	22.	18	3	53.9	277.8	276.5	284.2	293.5	280.7	0. 8
302	23.	18	0	54.0	277.5	276.1	283.9	293.1	280.4	0. 6
303	0.	19	0	54.0	276.7	275.2	283.3	292.8	279.8	0. 2
304	1.	19	0	54.3	277.3	276.0	283.7	292.9	280.2	0. 9
305	2.	19	0	54.0	277.1	275.8	283.6	292.3	280.1	0. 8
306	3.	19	0	54.3	276.7	275.5	283.2	292.4	279.6	1. 0
307	4.	19	0	54.3	275.9	274.7	282.5	291.8	278.9	1. 0
308	5.	19	0	54.0	275.3	274.1	282.0	291.2	278.3	1. 0
309	6.	19	0	54.2	275.0	273.9	281.7	290.9	277.9	1. 3
310	7.	19	0	56.9	274.8	275.4	284.8	290.7	277.6	1. 3
311	8.	19	1	106.4	275.6	275.7	284.1	291.4	281.1	1. 5
312	9.	19	0	214.1	277.8	279.9	289.2	294.5	282.4	1. 7
313	10.	19	0	318.0	279.1	282.4	293.0	297.5	284.5	2. 1

Table D-2. Detailed list of hourly variables from the output of the computer program "SOLARUG" of Appendix E.

HOUR	10.00
DATE	11/06/1976
AMBIENT TEMP DEG K	278.50
SOLAR RECORDED W/SQ M	375.80
GLASS TEMP DEG K	281.08
TEDLAR TEMP DEG K	290.10
PLATE TEMP DEG K	293.50
HEATED AIR TEMP DEG K	283.10
DAY LENGTH IN HOURS	9.80
DIFF RAD W/SQ M	234.06
DIR BEAM W/SQ M	141.74
BEAM ON COLL W/SQ M	284.56
TOTAL OF BEAM + DIFF	518.62
NET SOL ABSORBED W/SQ M	357.60
UPWARD HT LOSS COEF W/SQ M K	1.67665
AIR MASS FLOW RATE KG/HR	219.57
HT COEF FOR LDUCT W/SQ M K	9.23050
HT COEF BY MALIK W/SQ M K	9.38907
HT COEF FOR SDUCT W/SQ M K	11.82658
HT COEF W/SQ M K	1.47070
USEFUL HEAT W/SQ M	308.78
COLL EFF PERCENT	59.54
TOTAL USEFUL HEAT W-HR/SQ M	308.78
COL AREA IN SQ M	2.23
INTEREST RATE DECIMAL	.12000
COLL LIFE IN YEARS	20.00
CAPITAL RECOV FACTOR $/$YR	.13388
ANNUAL ADDED COST IN $	33.47
KWH OF SOLAR ENERGY	.69
SOLAR COST IN $/KWH-YEAR	48.61
HOURS OF COLL USE PER YEAR	1.00

Table D-3. Output variables from the program "SOLARUG" used to evaluate the flat-plate solar collector.

TFS = Simulated heated air temperature, °K
DR = Diffuse component of recorded solar radiation, w/sq m
BR = Direct beam component of recorded solar radiation, w/sq m
TR = Total direct and beam radiation on collector, w/sq m
AR = Net solar radiation absorbed by collector, w/sq m
HTM = Heat transfer coefficient by Malik (1967) eqn
KWH = Total solar energy, kWh
HTL = Heat transfer coef. for a long duct, w/sq m °K

UL = Upward heat loss coef., w/sq m °K.
UH = Total useful solar heat, w/sq m
EFF = Collector efficiency, percent
SCT = Solar cost, $/kWh-year
AC = Annual added collector cost, $

No	TFS	DR	BR	TR	AR	UL	HTL	UH	EFF	HTM	AC	KWH	SCT
1	280.7	234.1	141.7	518.6	357.6	1.7	9.2	308.8	59.54	9.39	33.47	.69	48.61
2	282.5	182.0	267.9	709.9	490.9	1.7	9.2	731.4	59.53	9.33	33.47	1.63	20.53
3	284.4	158.2	316.3	789.5	544.9	1.7	9.1	1198.9	59.22	9.26	33.47	2.67	12.52
4	285.0	163.3	279.8	750.7	512.9	1.7	9.1	1639.7	58.72	9.24	33.47	3.66	9.15
5	285.9	82.5	291.7	772.1	509.1	1.8	9.1	2075.1	56.40	9.20	33.47	4.63	7.23
6	285.4	54.1	203.6	714.2	415.9	1.5	9.1	2437.7	50.77	9.25	33.47	5.44	6.16
7	279.7	138.4	0.0	138.4	80.6	1.9	9.2	2503.7	47.72	9.38	33.47	5.58	6.00

Table D-3. continued.

8	276.2	61.7	0.0	61.7	35.9	1.9	9.3	2531.9	45.65	9.46	33.47	5.65	5.93
9	274.9	53.8	0.0	53.8	31.3	1.8	9.3	2557.8	48.11	9.51	33.47	5.70	5.87
10	276.0	99.7	0.0	54.0	31.4	1.9	9.3	2582.3	45.43	9.48	33.47	5.76	5.81
11	275.6	158.1	0.0	54.2	31.6	1.8	9.3	2607.6	46.69	9.49	33.47	5.81	5.76
12	276.3	197.0	0.0	53.9	31.4	1.9	9.3	2631.1	43.63	9.48	33.47	5.87	5.71
13	276.3	197.0	0.0	54.3	31.6	1.8	9.3	2655.1	44.06	9.49	33.47	5.92	5.65
14	275.7	197.0	0.0	54.2	31.6	1.8	9.3	2680.2	46.40	9.50	33.47	5.98	5.60
15	274.9	197.0	0.0	54.2	31.6	1.8	9.4	2705.5	46.73	9.52	33.47	6.03	5.55
16	275.4	197.0	0.0	54.0	31.4	1.8	9.3	2730.9	47.01	9.51	33.47	6.09	5.50
17	275.2	197.0	0.0	53.9	31.4	1.8	9.3	2756.4	47.33	9.51	33.47	6.15	5.45
18	274.7	60.8	0.0	54.4	31.7	1.8	9.4	2783.5	49.67	9.53	33.47	6.21	5.39
19	274.3	197.0	0.0	54.2	31.6	1.8	9.4	2808.8	46.80	9.55	33.47	6.26	5.34
20	274.0	197.0	0.0	54.0	31.4	1.8	9.4	2834.6	47.68	9.55	33.47	6.32	5.30

Table D-3. continued.

21	274.0	80.3	0.0	53.9	31.4	1.8	9.4	2860.0	47.10	9.55	33.47	6.38	5.25
22	274.4	67.2	0.0	60.3	35.1	1.8	9.4	2888.0	46.47	9.56	33.47	6.44	5.20
23	274.9	193.6	0.0	115.4	67.2	1.8	9.4	2942.2	46.97	9.54	33.47	6.56	5.10
24	275.4	275.6	0.0	190.8	111.1	1.8	9.4	3035.0	49.65	9.52	33.47	6.77	4.95
25	275.7	291.5	0.0	231.5	134.8	1.8	9.3	3148.2	48.89	9.49	33.47	7.02	4.77
26	276.6	278.3	36.9	351.6	243.1	1.7	9.3	3355.9	59.09	9.49	33.47	7.48	4.47
27	277.1	274.0	31.9	338.2	233.4	1.8	9.3	3554.3	58.67	9.46	33.47	7.93	4.22
28	277.2	240.3	37.8	320.4	218.9	1.8	9.3	3740.1	57.99	9.47	33.47	8.34	4.01
29	277.1	237.4	39.4	331.7	218.7	1.8	9.3	3925.6	55.93	9.46	33.47	8.75	3.82
30	275.9	228.5	0.0	165.3	109.0	1.8	9.3	4016.2	54.79	9.50	33.47	8.95	3.74
31	273.6	197.0	0.0	99.7	65.7	1.8	9.4	4071.2	55.21	9.55	33.47	9.08	3.69

Table D-3. continued.

32	272.7	197.0	0.0	59.8	39.4	1.8	9.4	4103.8	54.44	9.57	33.47	9.15	3.66
33	272.1	197.0	0.0	54.3	35.8	1.8	9.4	4133.2	54.27	9.59	33.47	9.22	3.63
34	271.2	197.0	0.0	54.0	35.6	1.8	9.4	4162.6	54.30	9.62	33.47	9.28	3.61
35	270.7	197.0	0.0	54.2	35.7	1.8	9.5	4192.0	54.33	9.63	33.47	9.35	3.58
36	270.3	197.0	0.0	54.0	35.6	1.8	9.5	4221.4	54.36	9.65	33.47	9.41	3.56
37	270.2	197.0	0.0	54.2	35.7	1.8	9.5	4250.8	54.40	9.65	33.47	9.48	3.53
38	269.8	177.5	0.0	54.0	35.6	1.8	9.5	4280.1	54.14	9.66	33.47	9.54	3.51
39	269.2	158.1	0.0	54.3	35.8	1.8	9.5	4309.7	54.47	9.68	33.47	9.61	3.48
40	268.7	53.9	0.0	53.9	35.5	1.8	9.5	4339.0	54.49	9.69	33.47	9.67	3.46
41	268.1	54.2	0.0	54.2	35.7	1.7	9.5	4368.5	54.34	9.72	33.47	9.74	3.44
42	267.7	54.2	0.0	54.2	35.7	1.8	9.5	4397.6	53.66	9.72	33.47	9.81	3.41

Table D-3. continued.

43	267.6	158.1	0.0	54.2	35.7	1.8	9.5	4427.0	54.26	9.72	33.47	9.87	3.39
44	268.0	80.3	0.0	54.2	35.7	1.8	9.5	4456.4	54.27	9.72	33.47	9.94	3.37
45	267.4	54.2	0.0	54.2	35.7	1.8	9.5	4485.6	53.96	9.73	33.47	10.00	3.35
46	267.0	47.0	12.8	96.4	53.6	1.7	9.6	4530.3	46.35	9.74	33.47	10.10	3.31
47	269.6	115.0	22.9	172.5	112.3	1.7	9.5	4624.2	54.44	9.69	33.47	10.31	3.25
48	271.6	196.9	63.7	335.2	228.1	1.7	9.4	4820.0	58.40	9.61	33.47	10.75	3.11
49	273.3	251.7	104.2	464.3	320.1	1.7	9.4	5095.8	59.41	9.55	33.47	11.36	2.95
50	273.5	296.8	25.7	348.2	240.8	1.7	9.4	5301.9	59.18	9.55	33.47	11.82	2.83
51	273.4	292.6	0.0	262.6	181.6	1.7	9.4	5456.6	58.91	9.57	33.47	12.17	2.75
52	274.9	258.9	115.9	506.5	346.1	1.6	9.4	5756.8	59.28	9.52	33.47	12.84	2.61
53	276.0	197.8	145.7	550.5	363.0	1.6	9.3	6072.0	57.25	9.49	33.47	13.54	2.47
54	275.3	150.1	51.6	324.7	189.2	1.7	9.3	6233.7	49.80	9.51	33.47	13.90	2.41

Table D-3. continued.

55	274.3	119.2	0.0	102.9	60.0	1.8	9.4	6282.2	47.15	9.54	33.47	14.01	2.39
56	271.6	197.0	0.0	61.5	35.8	1.8	9.4	6311.4	47.39	9.60	33.47	14.07	2.38
57	271.1	197.0	0.0	54.2	31.6	1.8	9.4	6337.0	47.32	9.62	33.47	14.13	2.37
58	270.6	197.0	0.0	54.0	31.5	1.8	9.5	6362.4	47.04	9.64	33.47	14.19	2.36
59	270.4	197.0	0.0	54.2	31.6	1.8	9.5	6388.1	47.37	9.65	33.47	14.24	2.35
60	270.7	197.0	0.0	54.0	31.5	1.8	9.5	6413.8	47.64	9.64	33.47	14.30	2.34
61	271.0	197.0	0.0	54.2	31.6	1.8	9.5	6439.8	47.92	9.63	33.47	14.36	2.33
62	271.4	197.0	0.0	54.2	31.6	1.8	9.4	6465.4	47.34	9.62	33.47	14.42	2.32
63	271.7	197.0	0.0	54.3	31.6	1.8	9.4	6491.1	47.34	9.61	33.47	14.47	2.31
64	272.0	197.0	0.0	54.0	31.5	1.8	9.4	6516.8	47.60	9.60	33.47	14.53	2.30
65	272.1	197.0	0.0	54.2	31.6	1.8	9.4	6542.6	47.62	9.60	33.47	14.59	2.29
66	271.9	197.0	0.0	53.8	31.4	1.8	9.4	6568.3	47.60	9.61	33.47	14.65	2.29

Table D-3. continued.

67	272.2	197.0	0.0	54.0	31.5	1.8	9.4	6594.0	47.59	9.60	33.47	14.70	2.28
68	272.2	197.0	0.0	54.2	31.6	1.8	9.4	6619.9	47.87	9.60	33.47	14.76	2.27
69	272.2	158.1	0.0	54.2	31.6	1.8	9.4	6645.2	46.72	9.60	33.47	14.82	2.26
70	271.7	221.3	0.0	65.2	38.0	1.8	9.4	6676.2	47.59	9.61	33.47	14.89	2.25
71	274.5	250.4	0.0	133.6	77.9	1.8	9.4	6740.4	48.02	9.56	33.47	15.03	2.23
72	276.6	254.5	0.0	210.1	122.4	1.7	9.3	6843.9	49.27	9.50	33.47	15.26	2.19
73	278.2	289.7	0.0	262.7	153.1	1.7	9.3	6974.3	49.62	9.45	33.47	15.55	2.15
74	279.1	295.9	0.0	243.2	141.7	1.8	9.3	7093.9	49.18	9.43	33.47	15.82	2.12
75	280.1	291.7	0.0	234.8	136.8	1.8	9.2	7209.2	49.13	9.41	33.47	16.07	2.08
76	280.7	180.4	17.2	217.5	148.6	1.8	9.2	7333.8	57.25	9.40	33.47	16.35	2.05
77	283.8	216.5	154.8	595.5	392.7	1.7	9.1	7673.4	57.02	9.30	33.47	17.11	1.96
78	283.2	71.6	139.1	552.0	321.8	1.6	9.2	7951.4	50.36	9.32	33.47	17.73	1.89
79	281.7	158.1	0.0	121.2	70.7	1.8	9.2	8009.2	47.73	9.35	33.47	17.86	1.87

Table D-3. continued.

80	278.9	60.8	0.0	58.1	33.9	1.9	9.3	8036.4	46.80	9.41	33.47	17.92	1.87
81	277.3	80.3	0.0	53.8	31.4	1.9	9.3	8061.1	46.00	9.46	33.47	17.97	1.86
82	277.4	99.7	0.0	53.9	31.4	1.8	9.3	8086.3	46.68	9.46	33.47	18.03	1.86
83	277.5	138.6	0.0	54.2	31.6	1.8	9.3	8111.5	46.41	9.46	33.47	18.09	1.85
84	277.5	197.0	0.0	53.9	31.4	1.9	9.3	8135.7	44.91	9.47	33.47	18.14	1.85
85	276.0	138.6	0.0	53.8	31.4	1.8	9.3	8160.8	46.71	9.49	33.47	18.20	1.84
86	275.0	197.0	0.0	54.2	31.6	1.8	9.4	8186.0	46.51	9.52	33.47	18.25	1.83
87	274.3	197.0	0.0	54.2	31.6	1.8	9.4	8211.1	46.32	9.55	33.47	18.31	1.83
88	273.4	80.3	0.0	53.9	31.4	1.8	9.4	8236.2	46.57	9.56	33.47	18.36	1.82
89	272.1	80.3	0.0	54.0	31.5	1.8	9.4	8262.3	48.38	9.59	33.47	18.42	1.82
90	272.6	80.3	0.0	54.0	31.5	1.8	9.4	8287.7	46.94	9.58	33.47	18.48	1.81
91	272.9	99.7	0.0	54.3	31.7	1.8	9.4	8313.0	46.56	9.61	33.47	18.54	1.81

Table D-3. continued.

92	272.7	80.3	0.0	53.9	31.4	1.8	9.4	8338.0	46.37	9.58	33.47	18.59	1.80
93	272.9	197.0	0.0	54.0	31.5	1.8	9.4	8363.3	46.95	9.58	33.47	18.65	1.79
94	273.5	220.6	0.0	57.4	33.5	1.8	9.4	8391.3	48.75	9.57	33.47	18.71	1.79
95	275.5	249.6	0.0	74.8	43.6	1.8	9.4	8427.1	47.87	9.53	33.47	18.79	1.78
96	276.7	234.2	0.0	172.9	100.8	1.8	9.3	8512.7	49.52	9.50	33.47	18.98	1.76
97	278.0	288.8	0.0	267.7	156.1	1.7	9.3	8646.0	49.80	9.45	33.47	19.28	1.74
98	278.3	295.1	0.0	263.2	153.5	1.7	9.3	8776.5	49.56	9.44	33.47	19.57	1.71
99	278.0	290.9	0.0	167.9	109.6	1.8	9.3	8868.6	49.05	9.45	33.47	19.77	1.69
100	276.8	276.8	0.0	173.3	101.0	1.8	9.3	8955.0	49.82	9.49	33.47	19.97	1.68
101	276.0	254.7	0.0	110.2	64.3	1.8	9.3	9007.4	47.62	9.58	33.47	20.08	1.67
102	275.1	226.6	0.0	111.1	64.8	1.8	9.4	9059.3	46.71	9.53	33.47	20.20	1.66
103	275.4	197.0	0.0	103.5	60.3	1.8	9.4	9107.3	46.32	9.53	33.47	20.31	1.65

Table D-3. continued.

104	273.6	197.0	0.0	57.1	33.3	1.8	9.4	9134.2	47.09	9.56	33.47	20.37	1.64
105	273.7	197.0	0.0	54.2	31.6	1.8	9.4	9159.6	46.94	9.56	33.47	20.42	1.64
106	273.0	197.0	0.0	54.0	31.5	1.8	9.4	9185.1	47.25	9.57	33.47	20.48	1.63
107	272.7	158.1	0.0	54.2	31.6	1.8	9.4	9210.9	47.56	9.58	33.47	20.54	1.63
108	272.1	197.0	0.0	53.8	31.4	1.8	9.4	9236.0	46.68	9.60	33.47	20.59	1.63
109	271.8	197.0	0.0	54.0	31.5	1.8	9.4	9261.4	47.01	9.61	33.47	20.65	1.62
110	271.5	158.1	0.0	54.3	31.7	1.8	9.4	9286.8	46.77	9.62	33.47	20.71	1.62
111	271.3	158.1	0.0	54.2	31.6	1.8	9.5	9312.0	46.48	9.62	33.47	20.76	1.61
112	271.1	158.1	0.0	54.0	31.5	1.8	9.5	9337.2	46.76	9.63	33.47	20.82	1.61
113	270.7	80.3	0.0	53.8	31.4	1.8	9.5	9362.4	46.76	9.64	33.47	20.88	1.60
114	270.5	54.2	0.0	54.2	31.6	1.8	9.5	9387.6	46.53	9.64	33.47	20.93	1.60
115	270.3	54.2	0.0	54.2	31.6	1.8	9.5	9412.7	46.27	9.65	33.47	20.99	1.59
116	269.8	138.6	0.0	54.0	31.5	1.8	9.5	9437.9	46.59	9.66	33.47	21.84	1.59

Table D-3. continued.

117	269.5	197.0	0.0	54.2	31.6	1.8	9.5	9463.4	47.18	9.67	33.47	21.10	1.59
118	269.5	219.9	0.0	61.3	35.7	1.8	9.5	9492.4	47.34	9.67	33.47	21.17	1.58
119	271.4	210.0	0.0	110.9	64.7	1.7	9.5	9544.8	47.17	9.65	33.47	21.28	1.57
120	272.8	233.4	4.0	242.4	164.9	1.7	9.4	9683.3	57.17	9.59	33.47	21.59	1.55
121	273.1	249.1	0.0	243.5	165.7	1.7	9.4	9824.0	57.79	9.57	33.47	21.90	1.53
122	273.9	197.0	92.4	386.0	266.9	1.7	9.4	10054.2	59.64	9.56	33.47	22.42	1.49
123	276.5	231.7	225.4	699.1	482.4	1.6	9.3	10475.5	60.25	9.46	33.47	23.36	1.43
124	274.3	256.6	0.0	181.0	124.9	1.8	9.4	10580.8	58.20	9.53	33.47	23.59	1.42
125	274.3	254.1	0.0	166.8	115.1	1.8	9.4	10677.8	58.17	9.55	33.47	23.81	1.41
126	274.6	226.0	0.0	167.1	115.3	1.8	9.4	10775.3	58.31	9.54	33.47	24.03	1.39
127	272.8	158.1	0.0	95.0	65.6	1.8	9.4	10830.9	58.59	9.58	33.47	24.15	1.39
128	272.3	138.6	0.0	57.1	39.4	1.8	9.4	10863.4	56.90	9.59	33.47	24.22	1.38
129	271.9	60.8	0.0	54.0	37.3	1.8	9.4	10893.7	56.19	9.60	33.47	24.29	1.38

Table D-3. continued.

130	271.1	54.0	0.0	54.0	37.3	1.8	9.5	10924.0	55.96	9.63	33.47	24.36	1.37
131	270.4	53.9	0.0	53.9	37.2	1.8	9.5	10954.3	56.28	9.64	33.47	24.42	1.37
132	270.2	54.0	0.0	54.0	37.3	1.8	9.5	10984.9	56.61	9.65	33.47	24.49	1.37
132	269.7	54.3	0.0	54.3	37.5	1.8	9.5	11015.5	56.37	9.66	33.47	24.56	1.36
133	268.6	60.8	0.0	54.2	37.4	1.8	9.5	11046.4	56.99	9.69	33.47	24.63	1.36
134	267.9	158.1	0.0	54.2	37.4	1.8	9.5	11077.1	56.77	9.71	33.47	24.70	1.36
135	268.9	197.0	0.0	53.9	37.2	1.8	9.5	11108.0	57.29	9.69	33.47	24.77	1.35
136	269.4	197.0	0.0	54.0	37.3	1.8	9.5	11138.8	56.96	9.68	33.47	24.84	1.35
137	269.2	80.3	0.0	54.4	37.5	1.8	9.5	11169.6	56.70	9.68	33.47	24.90	1.34
138	268.7	54.2	0.0	54.2	37.4	1.8	9.5	11200.4	56.73	9.69	33.47	24.97	1.34
139	267.9	54.2	0.0	54.2	37.4	1.8	9.5	11231.1	56.76	9.71	33.47	25.04	1.34
140	267.5	54.2	0.0	54.2	37.4	1.8	9.5	11261.9	56.80	9.72	33.47	25.11	1.33
141	268.6	24.7	34.9	175.9	97.7	1.7	9.5	11345.5	47.53	9.71	33.47	25.30	1.32
142	272.1	73.1	91.9	317.0	206.1	1.6	9.5	11522.6	55.86	9.65	33.47	25.69	1.30

Table D-3. continued.

143	274.3	135.3	149.0	471.2	320.6	1.6	9.4	11800.8	59.04	9.56	33.47	26.31	1.27
144	275.3	228.8	75.9	388.5	267.8	1.7	9.3	12030.8	59.19	9.51	33.47	26.82	1.25
145	275.9	235.0	56.6	351.5	243.0	1.7	9.3	12239.4	59.33	9.50	33.47	27.29	1.23
146	276.7	230.9	128.1	498.5	344.0	1.7	9.3	12537.2	59.75	9.47	33.47	27.95	1.20
147	277.0	197.5	115.6	453.1	309.5	1.7	9.3	12803.6	58.77	9.46	33.47	28.55	1.17
148	277.0	233.9	6.5	250.3	165.1	1.8	9.3	12944.8	56.41	9.46	33.47	28.86	1.16
149	276.7	186.5	0.0	152.5	100.6	1.8	9.3	13028.6	55.00	9.48	33.47	29.05	1.15
150	274.5	99.7	0.0	93.8	61.9	1.8	9.4	13081.0	55.86	9.53	33.47	29.17	1.15
151	273.8	197.0	0.0	57.4	37.9	1.8	9.4	13112.0	53.95	9.55	33.47	29.24	1.14
152	273.8	197.0	0.0	54.2	35.7	1.8	9.4	13141.3	54.07	9.55	33.47	29.30	1.14
153	273.4	138.6	0.0	53.9	35.5	1.8	9.4	13170.3	53.79	9.56	33.47	29.37	1.14
154	272.7	80.3	0.0	53.9	35.5	1.8	9.4	13199.1	53.52	9.53	33.47	29.43	1.14

Table D-3. continued.

155	272.5	60.8	0.0	54.0	35.6	1.8	9.4	13227.9	53.25	9.59	33.47	29.49	1.13
156	272.2	158.1	0.0	54.0	35.6	1.8	9.4	13257.0	53.84	9.60	33.47	29.56	1.13
157	271.7	197.0	0.0	53.8	35.5	1.8	9.4	13286.1	54.17	9.61	33.47	29.62	1.13
158	271.3	60.8	0.0	53.9	35.5	1.8	9.4	13315.2	53.90	9.62	33.47	29.69	1.13
159	270.8	53.9	0.0	53.9	35.5	1.8	9.5	13344.1	53.64	9.63	33.47	29.75	1.12
160	272.5	54.2	0.0	54.2	35.7	1.8	9.4	13372.6	52.57	9.61	33.47	29.82	1.12
162	271.1	54.0	0.0	54.0	35.6	1.8	9.5	13401.4	53.36	9.63	33.47	29.88	1.12
163	270.3	54.2	0.0	54.2	35.7	1.8	9.5	13430.5	53.69	9.65	33.47	29.95	1.12
164	270.0	54.3	0.0	54.3	35.8	1.8	9.5	13459.7	53.73	9.66	33.47	30.01	1.12
165	271.3	54.0	0.0	54.0	35.6	1.8	9.5	13488.4	53.14	9.63	33.47	30.07	1.11
166	271.5	24.0	35.1	180.6	100.2	1.7	9.5	13573.7	47.26	9.63	33.47	30.26	1.11
167	274.3	72.4	76.1	277.0	180.1	1.7	9.4	13726.8	55.26	9.58	33.47	30.61	1.09
168	276.6	95.6	160.1	459.8	312.8	1.7	9.3	13995.6	58.45	9.49	33.47	31.21	1.07

Table D-3. continued.

169	278.3	111.3	230.2	599.5	413.2	1.7	9.3	14351.3	59.33	9.43	33.47	32.00	1.05
170	280.4	117.5	325.0	791.6	547.3	1.7	9.2	14825.1	59.85	9.36	33.47	33.06	1.01
171	281.4	132.9	333.9	835.6	576.5	1.7	9.2	15321.6	59.42	9.33	33.47	34.16	.98
172	281.9	119.0	313.3	817.8	558.6	1.7	9.2	15802.7	58.84	9.31	33.47	35.23	.95
173	281.8	58.3	276.0	765.6	504.9	1.7	9.2	16239.7	57.08	9.32	33.47	36.21	.92
174	276.6	30.4	207.6	810.3	473.1	1.4	9.2	16658.6	51.70	9.41	33.47	37.14	.90
175	278.6	119.9	0.0	119.9	70.0	1.8	9.2	16716.7	48.42	9.41	33.47	37.27	.90
176	275.4	57.3	0.0	57.3	33.5	1.8	9.3	16743.8	47.30	9.49	33.47	37.33	.90
177	274.3	53.9	0.0	53.9	31.5	1.8	9.4	16769.2	47.20	9.53	33.47	37.39	.90
178	273.4	53.9	0.0	53.9	31.5	1.8	9.4	16794.5	46.88	9.59	33.47	37.45	.89
179	272.8	54.0	0.8	54.0	31.5	1.8	9.4	16819.8	46.78	9.58	33.47	37.50	.89
180	272.4	54.2	0.0	54.2	31.6	1.8	9.4	16845.3	47.10	9.59	33.47	37.56	.89
181	272.1	54.0	0.0	54.0	31.5	1.8	9.4	16870.7	47.12	9.61	33.47	37.62	.89

Table D-3. continued.

182	272.0	54.0	0.0	54.0	31.5	1.8	9.4	16896.2	47.15	9.60	33.47	37.67	.89
183	272.1	53.9	0.0	53.9	31.5	1.8	9.4	16921.9	47.72	9.60	33.47	37.73	.89
184	271.8	53.9	0.0	53.9	31.5	1.8	9.4	16947.3	47.15	9.61	33.47	37.79	.89
185	271.3	54.0	0.0	54.0	31.5	1.8	9.4	16973.0	47.44	9.62	33.47	37.84	.88
186	270.8	53.9	0.0	53.9	31.5	1.8	9.5	16998.7	47.73	9.63	33.47	37.90	.88
187	270.5	80.3	0.0	53.9	31.5	1.8	9.5	17024.1	47.19	9.64	33.47	37.96	.88
188	271.1	158.1	0.0	54.3	31.7	1.8	9.5	17050.1	47.82	9.63	33.47	38.02	.88
189	270.5	54.2	0.0	54.2	31.6	1.8	9.5	17075.5	46.91	9.64	33.47	38.07	.88
190	270.1	23.3	36.2	189.6	105.2	1.7	9.5	17165.5	47.43	9.66	33.47	38.27	.87
191	272.7	52.2	65.6	230.9	150.0	1.7	9.4	17292.6	55.07	9.62	33.47	38.56	.87
192	274.3	211.6	12.9	241.2	164.1	1.7	9.4	17432.2	57.89	9.55	33.47	38.87	.86
193	276.5	188.3	140.0	487.4	335.9	1.7	9.3	17721.3	59.29	9.48	33.47	39.51	.85

Table D-3. continued.

194	278.4	155.6	232.9	642.0	443.8	1.7	9.3	18104.1	59.62	9.41	33.47	40.37	.83
195	280.0	112.7	337.3	827.6	571.0	1.6	9.2	18600.0	59.93	9.36	33.47	41.47	.81
196	280.8	137.8	289.0	787.8	538.0	1.7	9.2	19065.9	59.14	9.34	33.47	42.51	.79
197	280.8	116.0	227.2	704.7	464.7	1.7	9.2	19467.9	57.04	9.34	33.47	43.41	.77
198	280.5	107.6	127.0	594.6	347.3	1.6	9.2	19770.9	50.97	9.36	33.47	44.08	.76
199	278.1	118.7	0.0	118.7	69.3	1.8	9.3	19828.7	48.71	9.42	33.47	44.21	.76
200	276.7	260.1	0.0	260.1	151.9	1.7	9.3	19956.0	48.92	9.49	33.47	44.50	.75
201	273.3	53.8	0.0	53.8	31.4	1.8	9.4	19980.9	46.35	9.56	33.47	44.55	.75
202	272.5	54.2	0.0	54.2	31.7	1.8	9.4	20006.4	47.03	9.58	33.47	44.61	.75
203	271.9	53.9	0.0	53.9	31.5	1.8	9.4	20031.8	47.08	9.60	33.47	44.66	.75
204	271.0	54.2	0.0	54.2	31.7	1.8	9.5	20057.2	46.85	9.63	33.47	44.72	.75
205	270.1	54.2	0.0	54.2	31.7	1.8	9.5	20082.6	46.89	9.65	33.47	44.78	.75

Table D-3. continued.

206	269.7	54.4	0.0	54.4	31.8	1.8	9.5	20108.1	46.95	9.66	33.47	44.83	.75
207	269.1	54.2	0.0	54.2	31.7	1.8	9.5	20133.6	46.97	9.68	33.47	44.89	.75
208	268.8	54.3	0.0	54.3	31.7	1.8	9.5	20159.0	46.72	9.69	33.47	44.95	.74
209	268.7	54.2	0.0	54.2	31.7	1.8	9.5	20184.3	46.74	9.69	33.47	45.00	.74
210	268.1	54.2	0.0	54.2	31.7	1.8	9.5	20209.8	47.04	9.71	33.47	46.06	.74
211	268.2	54.2	0.0	54.2	31.7	1.8	9.5	20235.3	47.05	9.71	33.47	45.12	.74
212	268.0	54.0	0.0	54.0	31.5	1.8	9.5	20260.2	46.21	9.72	33.47	49.17	.74
213	267.4	60.8	0.0	54.3	31.7	1.8	9.5	20286.0	47.39	9.73	33.47	45.23	.74
214	268.9	81.1	0.0	56.7	33.1	1.7	9.6	20311.0	44.23	9.77	33.47	45.29	.74
215	270.4	51.5	82.2	278.3	180.8	1.6	9.5	20466.2	55.77	9.68	33.47	45.63	.73
216	273.8	74.7	178.7	488.7	332.3	1.6	9.4	20755.8	59.26	9.58	33.47	46.28	.72
217	277.0	90.3	275.7	683.8	471.2	1.5	9.3	21169.8	60.55	9.48	33.47	47.20	.71
218	279.2	96.5	318.8	765.3	529.0	1.6	9.2	21630.2	60.16	9.40	33.47	48.23	.69

Table D-3. continued.

219	280.5	92.5	351.7	843.2	581.8	1.6	9.2	22137.5	60.16	9.35	33.47	49.36	.68
220	281.2	78.7	333.8	835.4	570.6	1.6	9.2	22633.8	59.40	9.33	33.47	50.47	.66
221	281.9	57.0	279.1	788.0	519.6	1.6	9.2	23087.1	57.53	9.33	33.47	51.48	.65
222	277.9	29.3	195.3	794.0	463.9	1.5	9.3	23493.1	51.14	9.42	33.47	52.38	.64
223	275.2	113.4	0.0	113.4	66.3	1.8	9.3	23547.9	48.36	9.42	33.47	52.50	.64
224	275.6	57.2	0.0	57.2	33.4	1.8	9.3	23574.8	47.03	9.50	33.47	52.56	.64
225	274.1	54.0	0.0	54.0	31.5	1.8	9.4	23600.5	47.60	9.55	33.47	52.62	.64
226	272.9	53.8	0.0	53.8	31.4	1.8	9.4	23626.4	48.08	9.60	33.47	52.68	.64
227	273.3	54.0	0.0	54.0	31.5	1.8	9.4	23651.9	47.32	9.56	33.47	52.74	.63
228	272.7	54.2	0.0	54.2	31.7	1.8	9.4	23677.2	46.50	9.59	33.47	52.79	.63
229	271.8	54.0	0.0	54.0	31.5	1.8	9.4	23702.1	46.24	9.61	33.47	52.85	.63
230	270.3	53.8	0.0	53.8	31.4	1.8	9.5	23728.0	48.02	9.64	33.47	52.91	.63
231	270.3	53.9	0.0	53.9	31.5	1.8	9.5	23753.5	47.48	9.65	33.47	52.96	.63

Table D-3. continued.

232	269.9	53.9	0.0	53.9	31.5	1.8	9.5	23779.2	47.51	9.66	33.47	53.02	.63
233	269.9	54.2	0.0	54.2	31.7	1.8	9.5	23804.8	47.25	9.66	33.47	53.08	.63
234	269.5	54.2	0.0	54.2	31.7	1.8	9.5	23830.5	47.55	9.67	33.47	53.13	.63
235	269.5	54.2	0.0	54.2	31.7	1.8	9.5	23855.9	46.73	9.68	33.47	53.19	.63
236	268.9	54.2	0.0	54.2	31.7	1.8	9.5	23881.5	47.31	9.69	33.47	53.25	.63
237	269.1	54.0	0.0	54.0	31.5	1.8	9.5	23907.0	47.30	9.69	33.47	53.30	.63
238	269.3	22.1	36.1	198.8	110.1	1.7	9.5	24001.5	47.67	9.69	33.47	53.52	.63
239	272.3	50.8	75.4	261.4	169.8	1.7	9.5	24146.7	55.43	9.63	33.47	53.84	.62
240	275.8	74.0	156.7	440.2	299.3	1.6	9.4	24406.1	58.93	9.52	33.47	54.42	.62
241	279.4	89.5	234.1	597.0	411.4	1.6	9.2	24763.5	59.86	9.41	33.47	55.21	.61
242	282.0	95.7	296.8	724.0	500.5	1.6	9.2	25198.1	60.02	9.33	33.47	56.18	.60
243	283.3	91.7	333.6	808.7	557.9	1.6	9.1	25682.8	59.95	9.28	33.47	57.26	.58
244	283.9	78.1	315.9	800.1	546.4	1.6	9.1	26156.5	59.20	9.27	33.47	58.32	.57

Table D-3. continued.

245	283.9	56.4	263.4	753.6	497.8	1.6	9.1	26586.6	57.07	9.27	33.47	59.28	.56
246	277.8	28.7	185.1	768.2	448.9	1.4	9.3	26980.9	51.33	9.44	33.47	60.16	.56
247	280.2	106.9	0.0	106.9	62.5	1.8	9.2	27028.7	44.72	9.41	33.47	60.27	.56
248	280.7	56.7	0.0	56.7	33.1	1.9	9.3	27046.6	31.56	9.46	33.47	60.31	.56
249	273.4	53.8	0.0	53.8	31.4	1.8	9.4	27073.6	50.16	9.55	33.47	60.37	.55
250	274.2	53.9	0.0	53.9	31.5	1.8	9.4	27099.1	47.40	9.58	33.47	60.42	.55
251	273.5	53.8	0.0	53.8	31.4	1.8	9.4	27124.9	47.83	9.55	33.47	60.48	.55
252	273.0	54.0	0.0	54.0	31.6	1.8	9.4	27150.3	47.02	9.57	33.47	60.54	.55
253	272.9	53.8	0.0	53.8	31.4	1.8	9.4	27175.6	47.03	9.58	33.47	60.59	.55
254	273.4	54.2	0.0	54.2	31.7	1.8	9.4	27201.2	47.35	9.57	33.47	60.65	.55
255	273.6	54.2	0.0	54.2	31.7	1.8	9.4	27226.9	47.35	9.56	33.47	60.71	.55
256	273.4	54.0	0.0	54.0	31.6	1.8	9.4	27252.6	47.64	9.57	33.47	60.76	.55
257	273.7	54.0	0.0	54.0	31.6	1.8	9.4	27278.3	47.63	9.56	33.47	60.82	.55

Table D-3. continued.

258	273.6	53.7	0.0	53.7	31.4	1.8	9.4	27303.9	47.59	9.57	33.47	60.88	.55
259	273.5	54.0	0.0	54.0	31.6	1.8	9.4	27329.5	47.35	9.56	33.47	60.94	.55
260	273.8	54.3	0.0	54.3	31.7	1.8	9.4	27355.0	47.09	9.56	33.47	60.99	.55
261	274.2	54.2	0.0	54.2	31.7	1.8	9.4	27380.7	47.38	9.55	33.47	61.05	.55
262	273.7	60.4	0.0	56.1	32.8	1.8	9.4	27407.6	47.96	9.55	33.47	61.11	.55
263	275.4	225.2	0.0	109.5	64.0	1.8	9.4	27459.6	47.50	9.53	33.47	61.23	.55
264	278.2	267.8	0.0	236.8	138.4	1.8	9.3	27576.5	49.34	9.44	33.47	61.49	.54
265	280.1	283.3	0.0	263.3	153.9	1.8	9.2	27706.0	49.20	9.39	33.47	61.78	.54
266	280.2	289.5	0.0	243.2	142.1	1.8	9.2	27825.1	48.96	9.40	33.47	62.04	.54
267	280.5	188.3	55.9	309.3	213.4	1.8	9.2	28005.0	58.17	9.39	33.47	62.44	.54
268	282.0	233.0	96.4	455.0	310.7	1.8	9.2	28269.7	58.17	9.32	33.47	63.03	.53
269	281.2	250.3	0.0	248.6	169.8	1.8	9.2	28413.0	57.63	9.35	33.47	63.35	.53
270	281.2	222.7	0.0	162.3	110.8	1.8	9.2	28505.3	56.90	9.36	33.47	63.56	.53

Table D-3. continued.

271	277.4	197.0	0.0	63.2	43.2	1.8	9.3	28541.3	56.99	9.45	33.47	63.64	.53
272	276.6	119.2	0.0	54.3	37.1	1.8	9.3	28572.0	56.50	9.47	33.47	63.71	.53
273	275.9	54.2	0.0	54.2	37.0	1.8	9.3	28602.2	55.64	9.49	33.47	63.77	.52
274	275.1	60.8	0.0	53.9	36.8	1.8	9.3	28631.8	55.01	9.51	33.47	63.84	.52
275	274.8	80.3	0.0	54.3	37.1	1.8	9.4	28661.9	55.39	9.52	33.47	63.91	.52
276	274.7	119.2	0.0	54.3	37.1	1.8	9.4	28692.2	55.71	9.53	33.47	63.97	.52
277	275.0	53.9	0.0	53.9	36.8	1.8	9.4	28722.0	55.38	9.52	33.47	64.04	.52
278	275.4	119.2	0.0	54.0	36.9	1.8	9.3	28751.7	55.08	9.51	33.47	64.11	.52
279	274.5	53.9	0.0	53.9	36.8	1.8	9.4	28781.7	55.65	9.53	33.47	64.17	.52
280	274.8	54.2	0.0	54.2	37.0	1.8	9.4	28811.9	55.67	9.53	33.47	64.24	.52
281	274.4	54.0	0.0	54.0	36.9	1.8	9.4	28841.4	54.52	9.54	33.47	64.31	.52
282	274.5	54.0	0.0	54.0	36.9	1.8	9.4	28871.3	55.41	9.53	33.47	64.37	.52
283	274.3	158.1	0.0	53.9	36.8	1.8	9.4	28901.3	55.73	9.54	33.47	64.44	.52

Table D-3. contunued.

284	274.2	60.8	0.0	54.3	37.1	1.8	9.4	28931.4	55.45	9.54	33.47	64.51	.52
285	274.1	54.0	0.0	54.0	36.9	1.8	9.4	28961.4	55.45	9.55	33.47	64.57	.52
286	273.8	79.2	0.0	57.3	39.1	1.8	9.4	28992.9	55.10	9.56	33.47	64.64	.52
287	276.4	185.7	0.0	115.9	79.1	1.8	9.3	29057.1	55.37	9.51	33.47	64.79	.52
288	278.4	267.1	0.0	207.5	141.7	1.8	9.3	29175.9	57.23	9.44	33.47	65.05	.51
289	279.9	282.6	42.9	377.0	259.7	1.8	9.2	29396.2	58.46	9.37	33.47	65.54	.51
290	281.2	269.3	100.5	484.9	335.1	1.8	9.2	29681.4	58.80	9.34	33.47	66.18	.51
291	281.2	284.8	34.3	359.5	248.0	1.8	9.2	29890.9	58.29	9.34	33.47	66.65	.50
292	280.8	251.8	0.0	195.5	134.9	1.8	9.2	30002.5	57.09	9.38	33.47	66.90	.50
293	281.0	210.9	0.0	194.5	134.2	1.8	9.2	30113.9	57.25	9.38	33.47	67.14	.50
294	281.9	222.2	0.0	204.3	140.9	1.8	9.2	30231.8	57.72	9.34	33.47	67.41	.50
295	279.6	158.1	0.0	95.3	65.7	1.9	9.2	30286.9	57.77	9.39	33.47	67.53	.50

Table D-3. continued.

296	278.8	158.1	0.0	56.2	38.8	1.9	9.3	30318.3	56.04	9.42	33.47	67.60	.50
297	278.9	158.1	0.0	54.2	37.4	1.9	9.3	30348.5	55.69	9.42	33.47	67.67	.49
298	279.0	158.1	0.0	53.8	37.1	1.9	9.3	30378.7	56.01	9.42	33.47	67.73	.49
299	278.9	158.1	0.0	54.0	37.3	1.9	9.3	30408.8	55.72	9.42	33.47	67.80	.49
300	278.9	158.1	0.0	54.2	37.4	1.9	9.3	30438.9	55.70	9.42	33.47	67.87	.49
301	279.0	60.8	0.0	53.9	37.2	1.9	9.3	30469.0	55.70	9.42	33.47	67.94	.49
302	278.7	54.0	0.0	54.0	37.3	1.9	9.3	30499.1	55.72	9.43	33.47	68.00	.49
303	278.0	54.0	0.0	54.0	37.3	1.9	9.3	30529.0	55.40	9.44	33.47	68.07	.49
304	278.5	54.3	0.0	54.3	37.5	1.9	9.3	30559.3	55.79	9.44	33.47	68.14	.49
305	278.4	54.0	0.0	54.0	37.3	1.9	9.3	30589.2	55.46	9.44	33.47	68.20	.49
306	277.8	54.3	0.0	54.3	37.5	1.8	9.3	30619.7	56.13	9.45	33.47	68.27	.49
307	277.1	54.3	0.0	54.3	37.5	1.8	9.3	30650.0	55.88	9.47	33.47	68.34	.49

Table D-3. continued.

308	276.5	54.0	0.0	54.0	37.3	1.8	9.3	30680.2	55.90	9.48	33.47	68.41	.49
309	276.2	54.2	0.0	54.2	37.4	1.8	9.3	30710.6	55.96	9.49	33.47	68.47	.49
310	276.3	20.3	36.6	217.0	120.0	1.8	9.3	30812.6	47.03	9.50	33.47	68.70	.49
311	278.2	68.3	38.1	178.8	116.0	1.8	9.3	30909.0	53.94	9.44	33.47	68.92	.49
312	280.4	71.9	142.2	412.7	280.5	1.7	9.2	31148.6	58.04	9.39	33.47	69.45	.48
313	282.3	87.4	230.6	598.0	412.0	1.7	9.2	31500.9	58.92	9.32	33.47	70.24	.48

APPENDIX E

(Listing of the computer program "SOLARUG"
used to evaluate a flat-plate solar collector)

Appendix E.

PROGRAM SOLARUG:

```
      PROGRAM SOLARUG(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)
      INTEGER DAY,CCV
      INTEGER YEAR
      DIMENSION XOLD(21),XINC(21),A(21,21)
C****     THIS PROGRAM EVALUATES THE PERFORMANCE OF A FLAT PLATE SOLAR
C****     AIR HEATER DESIGNED TO DRY CORN AT MICHIGAN STATE UNIVERSITY,
C****     EAST LANSING
C****     FUNCTION USED
C****1    SIMUL
C****     SUBROUTINES USED
C****2    CALCN
C****3    SOLACOM
C****4    ABSRAD
C****5    UPHEATL
C****6    UHEAT
C****7    ECON
      READ (5,100)ITMAX,IPRINT,N ,EPS1,EPS2,(XCLD(I),I=1,N)
  100 FORMAT(5X,I5,9X,I1,5X,I5,2(3X,E7.1),2(F10.3))
      TQU = 0.0
      THRS = 1.0
   99 READ(5,110) THR,DAY,MONTH,YEAR,SOL,VEL,TP1,CLIN,TA,AMEN,TP2,COUT,
     +COEN,CCV
      IF(DAY.GE.6.) JDAY = DAY - 5
      XOLD(1) = TA + 1.0
      XOLD(2) = ((TP1 + TP2)/2.) - 3.0
      IF(EOF(5).NE.0) GO TO 999
      CALL SOLACOM(DIFI,BCOL,ANGI,THR,JDAY,SOL,CCV,DBEAM,TSOL,SLH)
      CALL ABSRAD(ANGI,ALFG,ALFT,TRMG,TRMT,TSOL,ENGN,REFG)
      DO 9  ITER = 1,ITMAX
      CALL CALCN(XOLD,A,21,ALFG,ALFT,TRMG,TRMT,TA,TP1,TP2,TSOL,VEL)
      DETER=SIMUL(N,A,XINC,EPS1,1,21)
      IF(DETER.EQ.0.0) STOP 1
C****     CHECK FOR CONVERGENCE
```

Appendix E. continued.

```
C****
      ITCON=1
      DO 5 I=1,N
      IF(ABS(XINC(I)).GT.EPS2)  ITCON=0
    5 XOLD(I)=XOLD(I)+XINC(I)
      IF(ITCON.EQ.0) GO TO 9
      GO TO 1
    9 CONTINUE
    1 TP = (TP1 + TP2)/2.0
C****      XOLD(1) = TG
      TG = XOLD(1)
C****      XOLD(2) = TT
      TT = XOLD(2)
      CALL UPHEATL(TG,TT,TP,TA,UPHL,VEL)
      CALL UHEAT(CLIN,COUT,TP,UPHL,ENGN,TA,AREA,QU,TQU,HCL,HCS,CCEFF,G,
     1TR,UALL,HCLM,TSOL,TO)
      CALL ECON(AREA1,TQU,RINT,EXPL,CRF,CHANL,CSE,CE)
      IF(THRS.GT.1.) GO TO 10
      WRITE(6,200) THR,MONTH,DAY,YEAR,TA,SOL,TG,TT,TP,TR,SLH
      WRITE(6,201) DIFI,DBEAM,BCOL,TSOL,ENGN,UPHL,G,HCL,HCLM,HCS,UALL,
     +QU,COEFF,TQU
      WRITE(6,202) AREA1,RINT,EXPL,CRF,CHANL,CSE,CE,THRS
   10 WRITE(7,204) THRS,THR,DAY,MONTH,YEAR,SOL,VEL
      WRITE(7,205) TA,TG,TT,TP,TR,TO,SLH
      WRITE(7,206) DIFI,DBEAM,TSOL,ENGN,TQU,G
      WRITE(7,207) UPHL,HCL,COEFF,HCLM,CHANL,CSE,CE
      WRITE(6,203) THR,DAY,CCV,SOL,TA,TG,TT,TP,TR,TO,DIFI,DBEAM,TSOL,
     +ENGN,UPHL,HCL,TQU,COEFF,HCLM,CHANL,CSE,CE
      THRS = THRS + 1.0
      GO TO 99
  999 STOP
C****      FORMAT STATEMENTS
  110 FORMAT(F10.1,3I10,3F10.1/6F10.1,I10)
C****
  204 FORMAT(2F10.2,3I10,2F10.2)
  205 FORMAT(7(3X,F7.2))
  206 FORMAT(6(2X,F8.2))
  207 FORMAT(7(2X,F8.3))
C****
  200 FORMAT(10(/),10X,*HOUR*,26X,F8.2,//,10X,*DATE*,26X,I2*/*I2*/*I4,
     1//,10X,*AMBIENT TEMP DEG K*,12X,F8.2,//,10X,*SOLAR RECORDED W/SQ M
     2*,9X,F8.2,//,10X,*GLASS TEMP   DEG K*,12X,F8.2,//,10X,*TEDLAR TEMP
     3  DEG K*,12X,F8.2,//,10X,*PLATE TEMP   DEG K*,12X,F8.2,
     4//,10X,*HEATED AIR TEMP DEG K*,9X,F8.2,//,10X,*DAY LENGTH IN HOURS
```

Appendix E. continued.

```
      5*,11X,F8.2,/)
C****
  201 FORMAT(10X,*DIFF RAD  W/SQ M*,14X,F8.2,//,10X,*DIR BEAM W/SQ M*,15
     1X,F8.2,//,10X,*BEAM ON COLL W/SQ M*,11X,F8.2,//,10X,*TOTAL OF BEAM
     2 + DIFF*,10X,F8.2,//,10X,*NET SOL ABSORBED W/SQ M*,7X,F8.2,//,10X,
     3*UPWARD HT LOSS COEF W/SQ M K*,2X,F8.5,//,10X,*AIR MASS FLOW RATE
     4KG/HR*,5X,F8.2,//,10X,*HT COEF FOR LDUCT W/SG M K*,4X,F8.5,//,10X,
     5*HT COEF BY MALUK W/SQ M K*,6X,F8.5,//,10X,
     6*HT COEF FOR SDUCT W/SQ M K*,4X,F8.5,//,10X,*HT COEF W/SQ M K*,13X
     7,F8.5,//,10X,*USEFUL HEAT W/SQ M*,12X,F8.2,//,10X,*COLL EFF PERCEN
     8T*,14X,F8.2,//,10X,*TOTAL USEFUL HEAT J-HR/SG M*,3X,F10.2,/)
C****
  202 FORMAT(10X,*COL AREA IN SQ M*,14X,F8.2,//,10X,*INTEREST RATE DECIM
     1AL*,9X,F8.5,//,10X,*COLL LIFF IN YEARS*,12X,F8.2,//,10X,*CAPITAL R
     2ECOV FACTOR $/$YR*,3X,F8.5,//,10X,*ANNUAL ADDED COST IN $*,8X,
     3F8.2,//,10X,*KWH OF SOLAR ENERGY*,11X,F8.2,//,10X,*SOLAR COST IN $
     4/KWH-YEAR*,6X,F8.2,//,10X,*HOURS OF COLL USE PER YEAR*,4X,F8.2,/)
C****
  203 FORMAT(///3X,F3.0,2(2X,I2),11(1X,F5.1),2(1X,F4.1),1X,F7.1,
     +5(1X,F5.2))
C****
      END
```

Appendix E. continued.

```
      FUNCTION SIMUL(N,A,X,EPS,INDIC,NRC)
      IMPLICIT REAL(A-H, O-Z)
      REAL  A, X, EPS
      DIMENSION IROW(50),JCOL(50),JORD(50),Y(50),A(NRC,NRC),X(N)
C****
      MAX=N
      IF(INDIC.GE.0) MAX=N+1
C****
C****     IS N LARGER THAN 50 .....
      IF(N.LE.50) GO TO 5
      WRITE(6,200)
      SIMUL=0.
      RETURN
C****
C****     BEGIN ELIMINATION PROCEDURE .....
5     DETER=1.
      DO 18 K=1,N
      KM1=K-1
C****
C****     SEARCH FOR PIVOT ELEMENT .....
      PIVOT=0.
      DO 11 I=1,N
      DO 11 J=1,N
C****     SCAN IROW AND JCOL ARRAYS FOR INVALID PIVOT SUBSCRIPTS.....
      IF(K.EQ.1) GO TO 9
      DO 8  ISCAN=1,KM1
      DO 8 JSCAN=1,KM1
      IF  (I.EQ.IROW(ISCAN)) GO TO 11
8     IF(J.EQ.JCOL(JSCAN)) GO TO 11
9     IF(ABS(A(I,J)).LE.ABS(PIVOT)) GO TO 11
      PIVOT=A(I,J)
      IROW(K)=I
      JCOL(K)=J
11    CONTINUE
C****
C****     . INSURE THAT SELECTED PIVOT IS LARGER THAN EPS .....
      IF (ABS(PIVOT).GT.EPS) GO TO 13
      SIMUL=0.
      RETURN
C****
```

Appendix E. continued.

```
C****        UPDATE THE DETERMINANT VALUE .....
13      IROWK=IROW(K)
        JCOLK=JCOL(K)
        DETER=DETER*PIVOT
C****
C****        .NORMALIZE PIVOT ROW ELEMENTS .....
        DO 14 J=1,MAX
14      A(IROWK,J)=A(IROWK,J)/PIVOT
C****
C****       CARRY OUT ELIMINATION AND DEVELOP INVERSE .....
        A(IROWK,JCOLK)=1./PIVOT
        DO 18 I=1,N
        AIJCK=A(I,JCOLK)
        IF(I.EQ.IROWK) GO TO 18
        A(I,JCOLK)=-AIJCK/PIVOT
        DO 17 J=1,MAX
17      IF(J.NE.JCOLK)  A(I,J)=A(I,J)-AIJCK*A(IROWK,J)
18      CONTINUE
C****
C****        ORDER SOLUTION VALUES IF ANY AND CREATE JORD ARRAY .....
        DO 20 I=1,N
        IROWI=IROW(I)
        JCOLI=JCOL(I)
        JORD(IROWI)=JCOLI
20      IF (INDIC.GE.0) X(JCOLI)=A(IROWI,MAX)
C****
C****       ADJUST SIGN OF DETERMINANT .....
        INTCH=0
        NM1=N-1
        DO 22 I=1,NM1
        IP1=I+1
        DO 22 J=IP1,N
        IF (JORD(J).GE.JORD(I)) GO TO 22
        JTEMP=JORD(J)
        JORD(J)=JORD(I)
        JORD(I)=JTEMP
        INTCH=INTCH+1
```

Appendix E. continued.

```
22     CONTINUE
       IF(INTCH/2*2.NE.INTCH)  DETER=-DETER
C****
C****      IF INDIC IS POSITIVE RETURN WITH RESULTS *****
24     IF(INDIC.LE.0) GO TO 26
       SIMUL=DETER
       RETURN
C****     IF INDIC IS NEGATIVE OR ZERO, UNSCRAMBLE THE INVERSE
C****     FIRST BY ROWS.....
26     DO 28 J=1,N
       DO 27 I=1,N
       IROWI=IROW(I)
       JCOLI=JCOL(I)
27     Y(JCOLI)=A(IROWI,J)
       DO 28 I=1,N
28     A(I,J)=Y(I)
C****      .THEN BY COLUMNS .....
       DO 30 I=1,N
       DO 29 J=1,N
       IROWJ=IROW(J)
       JCOLJ=JCOL(J)
29     Y(IROWJ)=A(I,JCOLJ)
       DO 30 J=1,N
30     A(I,J)=Y(J)
C****
C****      RETURN FOR INDIC NEGATIVE OR ZERO .....
       SIMUL=DETER
       RETURN
C****
C****     FORMAT FOR OUTPUT STATEMENT .....
200    FORMAT( 10HON TOO BIG   )
C****
       END
```

Appendix E. continued.

```
      SUBROUTINE SOLACCM(DIFI,BCOL,ANGI,THR,JDAY,SOL,CCV,DBEAM,TSOL,SLH)
      INTEGER CCV
C****     THIS IS THE FIRST STEP IN THE CACULATUON OF THE SOLAR
C****     COLLECTOR EFFICIENCY,ETA.
      NDAY = 310 + JDAY
C****     CALCULATION OF SOLAR DECLINATION,DEC
      API = 57.29577951
      DEC = 23.45*SIN((360.*(284. + FLOAT(NDAY))/365.)/API)
C****     EVALUATION OF EQUATION OF TIME,EQT
      EQT = (16.79 - 0.11*JDAY)/60.0
C****     CALCULATION OF APPARENT STANDARD TIME,AST
      ESTDL = 75.
      STDL = 84.47
      AST = THR + EQT - 4.*(ESTDL - STDL)/60.0
C****     THR IS LOCAL TIME AT EAST LANSING LONGITUDE 84.47 DEG. AND
C****     LATITUDE, ELAT = 42.7
      ELAT = 42.7
C****     THE STANDARD MERUDIAN FOR EAST LANSING IS 75. DEG. WEST
C****     CALCULATION OF LOCAL HOUR ANGLE, AHL
      AHL = 15.*ABS(12.00 - AST)
C****     CALCULATION OF DAY LENGTH,SLH
      TAL = TAN(ELAT/API)
      TAD = TAN(DEC/API)
      DECLAT = TAL*TAD
      SLH = (2./15.)*API*ACOS(-DECLAT)
C****     CALCULATION OF SOLAR ALTITUDE ANGLE,SALT = SIN(ALFA)
      SALT = SIN(DEC/API)*SIN(ELAT/API) + COS(DEC/API)*COS(ELAT/API)*
     +COS(AHL/API)
      IF(SALT.LE.0.0) SALT = 0.0
      ALFA = API*ASIN(SALT)
C****     COLLECTOR INCLINATION TO HORIZONTAL IS BETA
      BETA = 52.0
C****     CALCULATION OF SOLAR INCIDENT ANGLE,ANGI
      COSI = SIN(DEC/API)*SIN((ELAT - BETA)/API) + COS(DEC/API)*
     +COS((ELAT - BETA)/API)*COS(AHL/API)
      IF(CCV.LT.3.AND.SALT.LE.0.0) GO TO 5
      IF(CCV.GT.2.AND.SALT.LE.0.0) GO TO 5
C****     CALCULATION OF DIFFUSE COMPONENT INSOLATION,SOL
      DIFI = 2.46 + 3.37*ALFA + 19.45*CCV
C****     CCV IS CLOUD COVER
      IF(DIFI.GE.SOL.AND.SALT.GT.0.0) GO TO 6
```

Appendix E. continued.

```
C****      DBEAM IS BEAM COMPONENT OF INSOLATION
      DBEAM = SOL - DIFI
C****       CALCULATION OF BEAM COMPONENT ON COLLECTOR
      ANGI = API*ACOS(COSI)
      BCOL = DBEAM*COS(ANGI/API)/SALT
C****      SUM OF DIRECT AND DIFFUSE SOLAR ENERGY FALLING ON COLLECTOR
C****      IS TSOL
      TSOL = BCOL + DIFI
      RETURN
    5 SALT = 0.0
      ALFA = 0.0
      DIFI = 2.46 + 19.45*CCV
      DBEAM = 0.0
      BCOL = 0.0
      IF(DIFI.LE.SOL) DIFI = SOL
      TSOL = SOL
      RETURN
    6 DBEAM = 0.0
      BCOL = 0.0
      TSOL = SOL
      RETURN
      END
```

Appendix E. continued.

```
      SUBROUTINE ABSRAD(ANGI,ALFG,ALFT,TRMG,TRMT,TSOL,ENGN,REFG)
      IMPLICIT REAL (L)
C****      THIS SUBROUTINE CALCULATES ABSORBED SOLAR RADIATION,ENGN
C****      GLASS REFRACTIVE INDEX IS RFIG
      RFIG = 1.5
C****      TEDLAR REFRACTIVE INDEX IS RFIT
      RFIT = 1.45
      API = 57.29577951
C****      ANGLE OF REFRACTION IN GLASS IS RANGG
      RANGG = API*ASIN((SIN(ANGI/API))/RFIG)
C****      ANGLE OF REFRACTION IN TEDLAR IS RANGT
      RANGT = API*ASIN((SIN(ANGI/API))/RFIT)
C****      ANGLE OF SOLAR INCIDENCE IS ANGI
C****      ANGLE OF REFLECTANCE IN GLASS IS REFG
      REFG = 0.5*(((SIN((ANGI - RANGG)/API))**2)/((SIN((ANGI + RANGG)/
     $API))**2) + ((TAN((ANGI - RANGG)/API))**2)/((TAN((ANGI + RANGG)/
     $API))**2))
C****      ANGLE OF REFLECTANCE IN TEDLAR IS REFT
      REFT = 0.5*(((SIN((ANGI - RANGT)/API))**2)/((SIN((ANGI+ RANGT)/
     +API))**2) + ((TAN((ANGI - RANGT)/API))**2)/((TAN((ANGI + RANGT)/
     +API))**2))
C****      THICKNESS OF GLASS IS THKG
      THKG = 0.3175
C****      THICKNESS OF TEDLAR IS THKT
      THKT = 0.01016
      EXCO = 0.508
C****      DISTANCE TRAVERSED  BY SOLAR RAYS IN GLASS IS LNGG
      LNGG = THKG/COS(RANGG/API)
C****      DISTANCE TRAVERSED  BY SOLAR RAYS IN TEDLAR IS LNGT
      LNGT = THKT/COS(RANGT/API)
C****      TRANSMITTANCE OF GLASS,TRMG AND TEDLAR,TRMT
      TRMG = ((1.D - REFG)/(1.0 + REFG))*EXP(-(EXCC*LNGG))
      TRMT = ((1.0 - REFT)/(1.0 + REFT))*EXP(-(EXCC*LNGT))
C****      TRANSMITTANCE OF BOTH GLASS AND TEDLAR IS TRMGT
      TRMGT = 1.006*TRMG*TRMT
C****      ABSOPPTIVITY COEFFICIENT OF BLACK PAINT IS ALFP
      ALFP = 0.95
```

Appendix E. continued.

```
C****      FRACTION OF SOLAR ENERGY ABSORBED BY BLACK COATED COPPER PLATE
      FRC = (TRMGT + 0.006)*ALFP
C****      COVER PLATE DEPENDENT CONSTANTS ARE CPC1 AND CPC2
      CPC1 = 0.10
      CPC2 = 0.44
C****      EFFECTIVE TRANSMISSIVITY - ABSORPTIVITY IS ETAC
      ETAC = FRC + (CPC1*(1.0 - EXP(-(EXCO*LNGG)))) +
     $(CPC2*TRMG*(1.0 - EXP(-(EXCO*LNGT))))
C****      DIRT LOSS FACTORIS DLF AND SHADING CORRECTION FACTOR IS SCF
      DLF = 0.98
      SCF = 1.0
C****      NET SOLAR ENERGY ABSORBED BY THE COLLECTCR IS ENGN
      ENGN = 0.98*(ETAC*DLF*SCF)*TSOL
C****      GLASS ABSORPTIVITY IS ALFG
      ALFG = 1.0 - REFG - TRMG
C****      TEDLAR ABSORPTIVITY IS ALFT
      ALFT = 1.0 - REFT - TRMT
      RETURN
      END
```

Appendix E. continued.

```
      SUBROUTINE CALCN(DXOLD,A,NRC,ALFG,ALFT,TRMG,TRMT,TA,TP1,TP2,TSOL,
     +VEL)
C****
C*****    THIS SUBROUTINE CALCULATES GLASS AND TEDLAR COVER TEMPERATURES
C****     IN DEG. KELVIN USING A NEWTON - RALPHSON METHOD
C****     XOLD(1) = TG IS GLASS TEMPERATURE AND XOLD(2) =  TT IS TEDLAR
C****     TEMPERATURE
C .....AUGMENTED MATRIX.....
C
      DIMENSION XOLD(20),DXOLD(NRC),A(NRC,NRC)
C****
      DATA SC,CONS,EPS1,EPS3,EPS5/5.669E-08,1.234,.88,.25,.2/
C****     SC IS STEFAN - BOLTZMAN CONSTANT
C****     CONS IS A CONSTANT FOR COLLECTOR TILT ANGLE  FROM HORIZONTAL
C****     EPS1 IS EMISSIVITY OF GLASS(.88)
C****     EPS3 IS EMISSIVITY OF TEDLAR (.25)
C****     EPS5 IS EMISSIVITY OF SELECTIVE BLACK PAINT ON COLLECTOR (.2)
C.....SHIFT ELEMENTS OF DXOLD TO XOLD AND CLEAR A ARRAY .....
      DO 1 I=1,2
      XOLD(I)=DXOLD(I)
      DO 1 J=1,3
1     A(I,J)=0.
C****
C..... COMPUTE NON-ZERO ELEMENTS OF A .....
      TS = TA-10.0
      TP = (TP1 + TP2)/2.
      IF(XOLD(1).GE.XOLD(2)) PRINT*,XOLD(1),XOLD(2),TA,TP,TSOL
      SOLT = TSOL
      WCEF = 5.7 + 3.8*VEL
      B = EPS1*SC
      D = (ALFT*TRMG + ALFG*TRMT*TRMG)*SOLT
      EPS35 = 1.0/((1./EPS3) + (1./EPS5) - 1.0)
      EPS13 = 1.0/((1./EPS1) + (1./EPS3) - 1.0)
      E = ALFT*TRMG*SOLT
      IF(XOLD(2).GE.TP) PRINT*,XOLD(1),XOLD(2),TA,TP,SOLT
      F = TP**4. - XOLD(2)**4.
      PT = ((TP - XOLD(2))/2.)**0.25
      GT = ((XOLD(2) - XOLD(1))/2.)**0.25
      G = XOLD(2)**4. - XOLD(1)**4.
```

Appendix E. continued.

```
C****     GLASS TEMP.,(TG) = XOLD(1) $ TEDLAR TEMP.,(TT) = XOLC(2)
C****     DERIVATIVES OF FIRST EQUATION IN ROW ONE OF MATRIX
      A(1,1) = 4.0*B*(XOLD(1)**3.) + WCEF
      A(1,2) = 4.0*SC*EPS35*(XOLD(2)**3.) + 1.25*CCNS*PT
C****     FIRST EQUATION
      A(1,3) = -(B*(XOLD(1)**4. - TS**4.) + WCEF*(XCLD(1) - TA) - (D
     1+ SC*EPS35*F + CONS*PT**5.))
C****     DERIVATIVES OF SECOND EQUATION IN ROW TWC OF MATRIX
      A(2,1) = -4.*SC*EPS13*(XOLD(1)**3.) - 1.25*CONS*GT
      A(2,2) = 4.*SC*EPS13*(XOLD(2)**3.) + 1.25*CONS*GT + 4.*EPS35*SC*(
     2XOLD(2)**3.) + 1.25*CONS*PT
C****     SECOND EQUATION
      A(2,3) = -(SC*EPS13*G + CONS*GT**5. - (E + SC*EPS35*F + CONS*
     3PT**5.))
      RETURN
C****
      END
```

Appendix E. continued.

```
      SUBROUTINE UPHEATL(TG,TT,TP,TA,UPHL,VEL)
C****      THIS SUBROUTINE CALCULATES THE UPWARD HEAT LOSS COEFFICIENT
C****
      DATA SC,CONS,EPS1,EPS3,EPS5/5.669E-08,1.234,.88,.25,.2/
C****      TAUT IS LONG WAVE TRANSMITTANCE BY TEDLAR
      TAUT = 0.3
      TS = TA - 10.0
C****      WIND HEAT TRANSFER COEFFICIENT IS WCEF
      WCEF = 5.7 + 3.8*VEL
C****
      HRGS = SC*((TP**4) - (TS**4.))/(TG - TS)
      VGS = 1.0/(WCEF + EPS1*HRGS*((TG - TS)/(TG - TA)))
      HRPG = SC*((TP**4.) - (TG**4.))/(TP - TG)
C****
      VPG = TAUT*(1.0/(1.0/EPS5 + 1.0/EPS1 - 1.0))*HRPG
      HRPT = SC*((TP**4.) - (TT**4.))/(TP - TT)
      HRTG = SC*((TT**4.) - (TG**4.))/(TT - TG)
C****
      IF(TT.GE.TP) PRINT*,TA,TG,TT,TP
      HPT = CONS*((TP - TT)/2.)**0.25
      IF(TT.LE.TG) PRINT*,TA,TG,TT,TP
      HTG = CONS*((TT - TG)/2.)**0.25
C****
      VPT = 1.0/(HPT + HRPT*(1.0/(1.0/EPS5 + 1.0/EPS3 - 1.0)))
      VTG = 1.0/(HTG + HRTG*(1.0/(1.0/EPS3 + 1.0/EPS1 - 1.0)))
      UPHLC = 1.0/(VGS + (1.0/(VPG + 1.0/(VPT + VTG))))
      UPHL = 1.1*UPHLC
      RETURN
      END
```

Appendix E. continued.

```
      SUBROUTINE UHEAT(CLIN,COUT,TP,UPHL,ENGN,TA,AREA,QU,TQU,HCL,HCS,
     +COEFF,G,TR,UALL,HCLM,TSOL,TO)
C****
      DATA SC,CONS,EPS6,EPS7/5.669E-08,1.234,.04,.09/
C****       EPS6 IS EMISSIVITY OF POLISHED BARE COPPER PLATE (.04)
C****       EPS7 IS EMISSIVITY OF ACRYLIC WHITE PAINT ON AIR DUCT (.90)
C****       THIS SUBROUTINE CALCULATES HEAT TRANSFER COEFFICIENT  AND
C****       CELLECTOR EFFICIENCY
C****
C****       AVEAGE DUCT AIR TEMPERATURE
      TR = (CLIN + COUT)/2.0
C****       FILM TEMPERATURE OF AIR IS TF
      TF = (TR + TP)/2.0
      EF = 1.0/(1.0/EPS6 + 1.0/EPS7 - 1.0)
      HCR = CONS*(TP - TF)**0.25
      HRC = (SC*((TP**4.0) - (TF**4.0)))/(TP - TF)
C****       CMM IS AIR FLOW RATE IN CU M/MIN AND WAS KEPT CONSTANT
      CMM = 6.6633
C****  ALL CONSTANT AIR PROPERTIES ARE EVALUATED AT A MEAN TEMPERATURE
C****       OF 275.0 DEG. KELVIN
C****       CPA IS SPECIFIC HEAT OF AIR
      CPA = 1.005500
C****       TKA IS AIR THERMAL CONDUCTIVITY
      TKA = 0.024255
C****       RHOA = IS DENSITY OF AIR IN KG/CU. M
      RHOA = 101320.0/(287.0*TF)
C****       PRN IS PRANDL NUMBER
      PRN = 0.715
C****       VISC IS AIR DYNAMIC VISCOSITY
      VISC = 1.7355E-05
      CB = 0.4572
      CL = 4.8768
C****       DEPTH IS DUCT DEPTH
      DEPTH = 0.1524
C****       G IS AIR MASS FLOW RATE
      G = 60.0*CMM*RHOA/(CB*CL)
```

Appendix E. continued.

```
C****     CALCULATION OF AIR VELOCITY IN METERS PER SECOND
      VA = CMM/(60.0*DEPTH*CB)
C****     HDAD IS HYDRAULIC DIAMETER OF AIR DUCT
      HDAD = 2.0*CB*DEPTH/(CB + DEPTH)
C****     REYNOLDS NUMBER IS RDN
      RDN = VA*HDAD*RHOA/VISC
C****     CALCULATION OF NUSSELT NUMBER, ANU
      ANU = 0.067*PRN*(RDN**(7.0/8.0))/(PRN + ALOG(5.0*PRN + 1.0) +
     10.5*ALOG(RDN**(7.0/8.0)) - 2.7)
C****     HEAT TRANSFER COEFFICIENT BY MALIK (1967) IS HCLM
      HCLM = 0.03*(RDN**0.8)*(PRN**0.4)*TKA/HDAD
C****     HCL IS HEAT TRANSFER COEFFICIENT
      HCL = ANU*TKA/HDAD
C****     HCS IS HEAT TRANSFER COEFFICIENT FOR SHORT DUCT
      AREA = CB*CL
      HCS = HCL*(1.0 + 6.0*HDAD/CL)
C****     H IS EFFECTIVE HEAT TRANSFER COEFFICIENT
      H = HCS + 1.0/(1.0/HCR + 1.0/(EF*HRC))
C****     UALL IS OVERALL HEAT TRANSFER COEFFICIENT
      UALL = 1.0/(1.0/UPHL + 1.0/H)
C****     QU IS USEFUL HEAT REMOVED BY THE AIR
      QU = (1.0/(1.0 + (UPHL/H)))*((1.0 - EXP(-UALL/(G*CPA/3.6)))/
     +(UALL/(G*CPA/3.6)))*(ENGN - (UPHL*(CLIN - TA)))
C****     TQU IS SUM OF USEFUL HEAT REMOVED BY THE AIR  HEATED
      TQU = TQU + QU
C****     COLLECTOR EFFICIENCY IN PERCENT IS COEFF
      COEFF = (QU/TSOL)*100.0
      TO = CLIN + QU/(G*CPA)
      RETURN
      END
```

Appendix E. cotinued.

```
      SUBROUTINE ECON(AREA1,TQU,RINT,EXPL,CRF,CHANL,CSE,CE)
      CB = 0.4572
      CL = 4.8768
      AREA1 = CB*CL
C****      CHTOT IS TOTAL ADDITIONAL INITIAL INVESTMENT IN SOLAR SYSTEM
      CHTOT = 250.00
C****      RINT IS INTEREST RATE IN DECIMAL
      RINT = 0.12
C****      EXPL IS LIFE EXPECTANCE OF COLLECTOR IN YEARS
      EXPL = 20.0
C****      CRF IS CAPITAL RECOVERY FACTOR IN $/$/YEAR
      CRF = (RINT*(1.0 + RINT)**EXPL)/((1.0 + RINT)**EXPL - 1.0)
      IF(CHTOT.EQ.250.0) GO TO 10
      AREA2 = 300.0

      CHTOT = CHTOT*(AREA2**0.6/AREA1)
C****      CONVERSION OF CHTOT INTO ANNUAL ADDITIONAL COST OF SOLAR SYST
C****      EM DENOTED BY CHANL
   10 CHANL = CHTOT*CRF
C****      KILOWATT-HOURS OF SOLAR ENERGY COLLECTED ARE CSE
      CSE = (TGU*AREA1)/1000.0
C****      ANNUAL COST OF SOLAR ENERGY DELIVERED PER YEAR IN $/MIL.W.YR
      CE = CHANL/CSE
      RETURN
      END
```

CHAPTER NINE

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