SIMULATION OF PEANUT DRYING INCORPORATING

AIR RECIRCULATION

by

DEBORAH F. COOK

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APPROVED:

Dr. D. H. Vaughan, Chairman

Dr. J. S. Cundiff

Dr. J. L. Steele

Dr. J. L. Baker

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Blacksburg, Virginia

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Chapter I

INTRODUCTION

As the price of conventional fuels rise and their availabilty becomes uncertain, more efficient means of using the energy resources available must be developed. Drying of farm crops requires a substantial portion of the energy consumed by agriculture.

An average of nearly 0.76 L of liquified petroleum gas (LPG) per bushel is used for corn drying, while approximately 1.9 L of LPG is required to dry 45.4 kg of peanuts (Vaughan and Lambert, 1980). Assuming a combustion efficiency of 85 percent and using the heat content 91,600 Btu/gal of LPG, these figures become 1.2 MJ/kg at 10 percent moisture content (wb) for drying peanuts, and 0.942 MJ/kg for corn (assumuming 52 pounds per bushel) at 15 percent moisture content (wb).

Virginia farmers grew an estimated 42,000 hectares of peanuts in 1981 (Harner et al., 1981). The LPG consumption for peanut drying in Virginia was 2.3 million gallons in 1981 (Lambert, 1982).

The peanut curing process begins when the peanuts reach maturity on the vine and continues until the peanuts are safe for storage. When Virginia peanuts are dug the wet basis (wb) moisture content is in the 50 to 60 percent range. Under normal conditions they lie in the windrow until the moisture (wb) is reduced to 20-25 percent, and are then dried at air temperatures not exceeding 35 °C, as drying at higher air temperatures produces adverse effects on the flavor (Beasley, 1963).

1.1 OBJECTIVES

This study was undertaken to investigate the energy saving potential for recirculation of air in peanut drying. A recirculation strategy providing energy savings without significant increase in drying time and without adverse effects on peanut quality, was sought. Specific objectives of the research were:

1. To develop a computer simulation model based on Troeger and Butler's (1979) drying equations which,given ambient temperatures, drying temperatures, and initial values of peanut moisture content, would predict:

    a) the moisture content throughout the peanuts,

    b) the air temperature throughout the peanuts, and

    c) the energy required to dry the peanuts.

2. Verify the model with experimental data collected during two drying experiments in laboratory dryers.

3. Adapt the simulation model to incoporate recirculation of various

percentages of drying air.

Chapter II

LITERATURE REVIEW

2.1 BASIC DRYING PRINCIPLES

Drying is defined as the removal of moisture from a material to a moisture content in equilibrium with normal atmospheric air, or to a moisture content that nearly eliminates mold and enzymatic action. Artificial drying, using supplemental heat, permits early harvest thus minimizing field losses, and makes long term storage without deterioration possible (Henderson and Perry, 1980).

Drying takes place in a layer of grain at the intake side of the dryer, and this layer may be almost completely dry before the other layers have lost appreciable moisture (Hukill, 1947). This zone of drying progresses through the grain mass until drying is complete. The volume of the drying zone varies with the temperature and humidity of entering air, the moisture content of the grain, and the velocity of air movement (Hall, 1980).

Hukill (1947) described the movement of one pound of air through drying grain. As the air enters the first layer of grain, moisture is evaporated and the temperature of the air drops as its relative humidity increases. Moisture then evaporates less rapidly in successive layers because of the lower temperature and higher humidity of the air. Eventually the air reaches the point where no more drying occurs. The total heat of the air during this process remains nearly constant; however, small changes in air enthalpy occur. At air temperatures below 49 °C, these variations are quite small and can be neglected. Some of the sensible heat present is used to supply heat for vaporization which is now contained in the air as latent heat.

Theoretically, this process occurs at constant wet bulb temperatures. The wet bulb temperature however, is modified if there are excessive losses of heat by conduction or radiation, or if there is a large difference between the initial and final grain temperatures. A small variation in the wet bulb temperature will occur since the moisture in grain requires more heat for vaporization than does free water. In general, as the air passes through the grain mass, its wet bulb temperature remains fairly constant, its dry bulb temperature drops as evaporation takes place, and its relative humidity increases.

In a grain dryer, the drying rate varies with time from layer to layer. The moisture content of grain depends on the character of the grain and the air used for drying. The following factors combine to determine the moisture content (Hukill, 1947):

1. initial grain moisture content;
2. initial grain temperature;
3. drying rate at full exposure for the type of grain (dependent on drying air temperature);
4. relationship between grain moisture and air humidity at equlibrium;
5. latent heat of drying of the moisture in the grain;
6. depth of grain through which the air passes to reach the given layer;
7. initial air temperature;
8. wet bulb temperature of the air; and
9. volume of air passed through the grain.

2.2 EFFECTS OF VARIED AIRFLOW RATES IN PEANUT DRYING

Person and Sorenson (1974) conducted tests to determine the effects of airflow rate on drying time and fuel consumption for peanut dryers. Rates of 8.04, 12.18, 16.08, and 20.10 $m^3/min/m^3$ were used. Results of the tests showed that the drying rate increased with increasing airflow rate (Figure 1). Increasing the airflow rate increased fuel consumption and decreased fuel efficiencies.

Blankenship and Pearson (1976) dried Spanish, Runner, and Virginia peanuts at airflow rates ranging from 11 to 60 $m^3/min/m^3$ of green peanuts. The average drying rate (per-

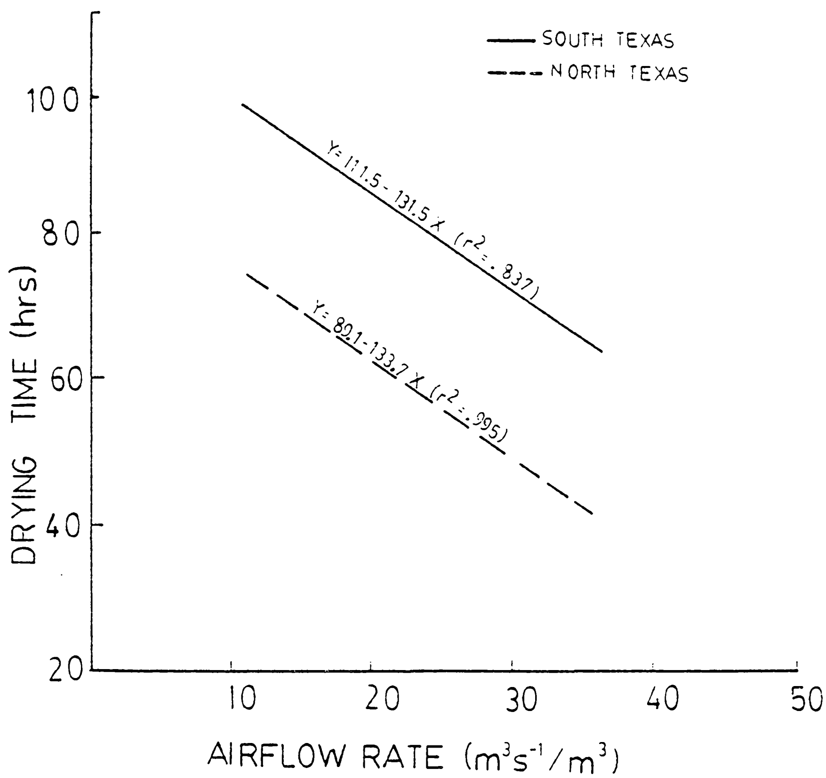

Figure 1: Influence of airflow rate on drying time (Person and Sorenson, 1974).

centage of moisture content loss per hour) varied with the airflow rate. Increasing the drying rates did not significantly affect the percentage of split kernels. They concluded that the amount of increase in drying rate may not justify the increase in electric power and fuel consumption.

Beasley and Dickens (1963) studied the effects of airflow rate on the drying rate of individual peanuts. These tests showed that the time required to dry peanuts to 10 percent moisture content varied little with air velocities of 23 , 70 , and 120 CFM/ft^2. Increasing the airflow above 23 CFM/ft^2 had a small and diminishing effect on the drying of individual peanuts. The authors also concluded that high airflow rates may be used without increasing the tendency of the peanuts to split.

2.3 SIMULATION ANALYSIS OF PEANUT DRYING ENERGY CONSUMPTION

Troeger and Butler (1979) developed a mathematical model for deep-bed peanut drying. Equations representing the drying rate of peanuts, the equlibrium moisture content of peanuts, and peanut temperature were presented. This model was selected for use in this research and is discussed in detail later.

Troeger (1980) developed a simulation analysis of the energy consumed in peanut drying. The analysis determined the effects of ambient conditions, dryer control setting, and initial moisture contents, on energy consumption, and on the time required to dry the peanuts. He used the model developed by Troeger and Butler (1979) to simulate deep-bed peanut drying. The temperature of the air entering the plenum was 35 °C, the recommended maximum. The volume of peanuts dried was the volume of a standard drying wagon, 14.448 m^3. Other parameters evaluated in this study were:

Initial moisture: 15, 20, 25, 30 percent (wb)
Minimum ambient temperature: 5, 10, 15 ,20 ° C
Ambient temperature range: 5, 10, 15 ° C
Dryer airflow rate: 3.05 and 4.72 m^3/s
Temperature rise of the drying air: 8 and 15 ° C.

Table 1 summarizes a portion of the results.

Results indicated that the maximum ambient temperature and the initial moisture were independent. A regression equation, assuming other parameters to be constant, was developed:

$$E = a(MO)^b(TMAX)^c \tag{1}$$

where:

E = energy (kJ/g dry weight at 10 percent moisture)
MO = initial moisture content (percent wet basis)
TMAX = maximum ambient temperature (°C)
a,b,c = regression coefficients.

The regression coefficients were determined by examining the remaining parameters and their effects.

$$a = \exp(-3.6225 + 0.3268(FLO) + 0.2638(DTA)) \quad (2)$$

$$b = -0.8666 - 0.01790(DTR) - 0.07188(DTA) \quad (3)$$

$$c = 1.416$$

where:

FLO = airflow rate (m^3/s)
DTA = ambient air temperature rise during a day (°C)
DTR = drying air temperature rise over ambient air temperature (°C).

Holding all other parameters constant, Troeger developed an equation for drying time in terms of initial moisture content and maximum ambient temperature:

$$t = d(MO)^e(TMAX)^f \quad (4)$$

where:

t = drying time (h)
d,e,f = regression coefficients.

Again, the regression coefficients were determined by analyzing the effects of the remaining parameters.

$$d = \exp(5.1030 - 1.2789(DTR) + 0.01594(FLO)(DTA)) \quad (5)$$

$$e = -1.6013 + 0.06391(DTR) - 4.07(FLO)(DTA)10^{-3} \tag{6}$$

$$f = 1.449$$

TABLE 1

Summary of Troeger's drying simulation (Troeger and Butler, 1979)

Airflow Rate m^3/s	Dryer Temperature Rise °C	Initial Moisture %	Drying Time h	Energy * kJ/g
3.05	8	15	34.7	.776
		20	58.7	1.318
		25	78.7	1.765
		30	97.3	2.181
3.05	15	15	20.8	.836
		20	39.8	1.565
		25	50.2	1.995
		30	60.8	2.400
4.72	8	15	32.3	1.123
		20	54.8	1.901
		25	73.5	2.557
		30	90.3	3.136
4.72	15	15	19.7	1.233
		20	38.3	2.232
		25	48.0	2.948
		30	57.2	3.524

* kJ/g dry weight at 10 percent (wb) moisture content

2.4 *DRYING PEANUTS WITH INTERMITTENT AIRFLOW*

Blankenship and Chew (1978) conducted a study to determine the effects of periodic dryer cycling on total drying time, propane gas and electrical energy (kW-h) consumed, and electrical demand during conventional peanut drying. Florunner peanuts were dug, windrowed with inverters, dried in the windrow for one to seven days, and then harvested. Seven full size (4.3 m x 2.4 m x 1.4 m deep) trailers were filled with peanuts. Propane gas-fired dryers were attached to each trailer.

The initial moisture content of the peanuts dried ranged from 13.8 percent to 32.5 percent (wb). Linear prediction equations were developed based on the results, and drying times and energy consumption values were predicted as shown in Table 2.

These data show that airflow must be continuous for maximum moisture removal at higher moisture levels, but not at the lower moisture levels. None of the drying times predicted for any treatment were more than 4.1 hours longer than the control treatment. They concluded that the electrical energy demand at drying facilities can be reduced by one-third using dryer cycling.

TABLE 2

Predicted results from Blankenship and Chew (1978).

Dryer Operation Schedule		Initial M.C.	Total Drying Time	Electricity Used	LPG Used
On	Off				
Minutes		%	h	kW-H	L
10	5	15	9.2	30.3	55.6
		22.5	24.6	82.8	166.2
		30	40.0	135.2	276.7
40	20	15	4.5	15.0	34.4
		22.5	22.6	76.5	176.8
		30	40.8	138.0	318.7
11.3	3.7	15	5.8	21.8	60.2
		22.5	22.6	85.0	162.0
		30	39.3	148.3	263.4
45	15	15	7.0	21.5	52.6
		22.5	22.8	69.8	172.2
		30	38.6	118.1	291.4
12	3	15	6.2	20.0	65.5
		22.5	22.2	72.3	163.5
		30	38.3	124.6	261.5
48	12	15	7.3	29.4	61.7
		22.5	23.6	93.2	182.8
		30	40.0	157.1	304.3
Continuous		15	5.7	30.3	43.5
		22.5	21.2	105.8	198.7
		30	36.7	181.3	353.9

Troeger and Butler (1978) determined that an interruption (turning the fan off) of airflow ($15m^3/min/m^3$ of peanuts) 25 percent of the time did not decrease the drying rate or adversely affect milling quality for peanuts with initial moisture content up to 30 percent. Interruption of airflow for 50 percent of the time resulted in no reduction of the drying rate of peanuts with an initial moisture content (wb) of up to 25 percent. Interrupting the airflow 75 percent of the time did decrease the drying rate.

Troeger and Butler (1980) dried peanuts with different initial moisture contents by periodically interrupting airflow. Airflow was interrupted to establish the following treatments: (1) 15 minutes on - 45 minutes off; (2) 30 minutes on - 30 minutes off; (3)45 minutes on - 15 minutes off; and (4) 3 hours on - 1 hour off. Twelve laboratory bins (0.6m x 0.6m x 1.2m deep) were used. In eight bins air was heated with LPG, while in the other four air was heated with solar-heated water passed through an air-water crossflow heat exchanger. Maximum plenum temperature did not exceed 35 °C. The temperature rise in the eight bins using LPG was limited to 8 °C above ambient air temperature, while there was no limit on the temperature rise in the bins using solar energy. Two airflow rates (12.5 and 25 $m^3/min/m^3$ of peanuts) were used to dry the peanuts. Florunner peanuts were field cured to the desired moisture content, and then harvested. Four tests, each using a different moisture content, were run in each dryer. Airflow was stopped when the top layer of peanuts dropped below 10 percent moisture content (wb).

Results in Table 3 show that interrupting airflow for 15 min/h reduced heat-energy consumption without increasing drying time. The use of the higher airflow rate (25 $m^3/min/m^3$ of peanuts) reduced drying time by 20 percent while increasing heat-energy consumption by 74 percent (Troeger and Butler, 1980).

TABLE 3

Energy requirements and drying times for intermittent airflow tests (Troeger and Butler,1980)

Airflow Treatment On	Off	Energy kJ/g	Drying Time h
	12.5 m^3 of air/min/m^3 of peanuts		
Continuous		.768	52
45 min	15 min	.690	53
3 h	1 h	.558	70
30 min	30 min	.570	68
15 min	45 min	.507	87
	25 m^3 of air/min/m^3 of peanuts		
Continuous		1.438	47
45 min	15 min	1.257	56
3 h	1 h	.855	59

2.5 PEANUT DRYING SYSTEMS

An investigation of the literature describing peanut drying systems shows that the majority of recently reported data describe solar drying systems. The possibility of combining a solar design with a recirculation system promises greater energy savings.

Harner et al. (1981) reported on improving the efficiency of energy utilization in peanut curing with the use of air recirculation. The roof of the peanut drying facility was retrofitted to incorporate a bare plate solar collector (Figure 2). Two-thirds of the total airflow required by the fans was drawn through the bare plate collector. The remaining air required was drawn through a portable collector attached to the drying facility. Due to natural convection, the exhaust air from the trailers was directed toward the inlets of the bare plate collector, thus some recirculation of exhaust air was achieved.

Ten batches (six trailers each) of peanuts were cured using the system. Energy savings due to recirculation amounted to 3.48 kL of LPG for the ten cures. The moisture removal rate averaged 0.28 percentage points per hour.

In 1977 an integrated shed solar collector was completed in Greensville County, Virginia (Vaughan and Lambert, 1980). The drying system was predominantly used to dry peanuts and

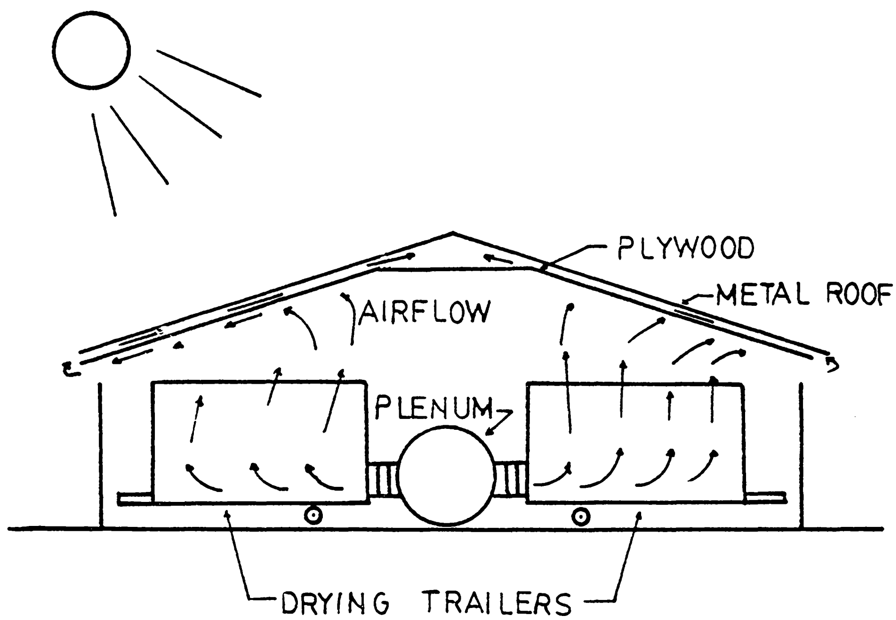

Figure 2: Recirculation of air in Virginia peanut drying shed (Harner et al., 1981).

corn. A pole type peanut shed, having a gable roof with trusses 1.22 m (4 ft) on center, was constructed. Fiberglass panels, instead of metal roofing, were used on the south facing roof. Exterior grade plywood, painted black, was installed below the rafters. A plenum chamber was built behind the south wall, and the wall was covered with fiberglass so that it would also serve as a collector. Black metal lathing (1.27 cm expanded to 3.81 cm) was installed beneath the fiberglass.

One-hundred-seventy Mg (187 tons) of peanuts were dried during the 1977 season. Approximately 2.23 kL (589 gal) of LPG were saved during the part of the season that the system was used. Annual savings, using the integrated shed facility for an entire drying season, were estimated to be 4.45 kL (1176 gal) of LPG.

Troeger and Butler (1978) constructed the two drying sytems shown in Figures 3 and 4. In the first facility, water was heated by solar collectors, stored in tanks, and then used to heat the drying air. In the second facility, air was heated by a solar collector and used directly for drying with no storage. The water system supplied about 60 percent of the total energy required to maintain the temperature of the drying air. Approximately 50 percent of the drying energy was supplied by the air system.

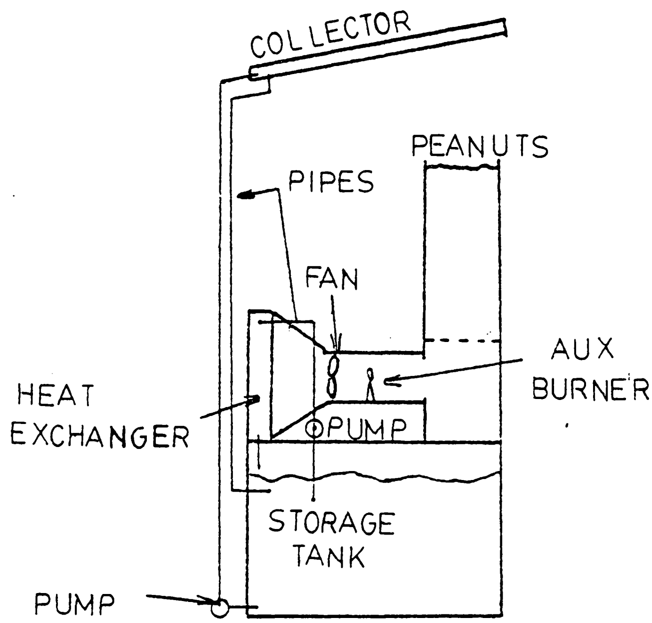

Figure 3: Solar heated water system (Troeger and Butler, 1977).

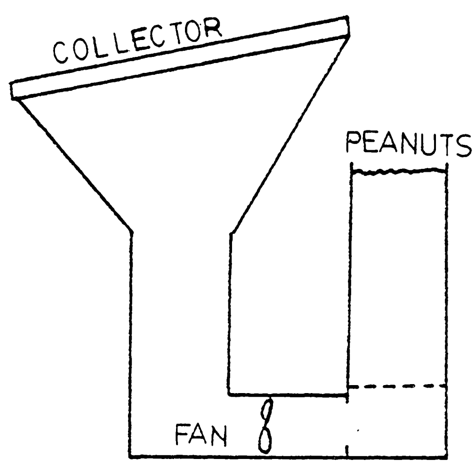

Figure 4: Solar heated air system (Troeger and Bulter, 1977).

Cooling systems powered by solar energy could be available to agriculture in the near future. Person and Sorenson (1977) investigated the possibility of using such a system for peanut drying (Figure 5). In their system, the hot water obtained from a solar collector was converted to cold air using a conventional absorption refrigeration machine. Use of a cooling medium for crop drying depends on a modified heat pump principle. Air leaves the drying product and passes over the evaporator to extract moisture. The air is then heated in the condenser unit before the next pass through the grain mass. This procedure results in a closed air system with little dependence on ambient conditions.

Two sets of peanut drying tests were conducted using the system. The bin was loaded with a 1.5 m depth of partially field-cured peanuts.

The basic psychrometric process for a closed air system is shown in Figure 6. State 1 represents the design conditions of 32 - 35 °C dry bulb temperature with a relative humidity of 40 - 50 percent. State 2 is the condition at which air leaves the dryer. The wet bulb temperature of State 2 is within ± 1°C of the wet bulb temperature at state 1 because the drying process is considered to be adiabatic. The conditions represented by state 2 are changing continuously. In the early stages of the drying process the state

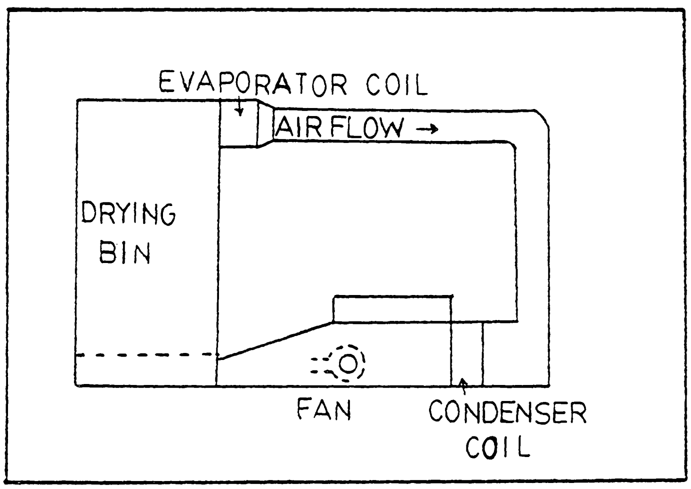

Figure 5: Closed air system for peanut drying (Person and Sorenson, 1977).

point will be near saturation while later in the process it will approach state 1. The change of air properties from state 2 to state 3 represents the effect of the evaporator. The air is then heated sensibly by the condenser coil to state 1 or 4 depending on the system design (Person and Sorenson, 1977).

The theory of a closed air system is not valid in practice due to the heat of compression of the refrigeration machine. The air leaving the condenser approaches state 4 which causes the design dry bulb temperature to steadily increase. To prevent this from occurring, some methods must be used to offset the Δh (change in enthalpy) shown in Figure 6. The most suitable solution found in peanut drying is to pipe an auxiliary condenser coil of capacity Δh in series with the main condenser coil to provide a full flow of refrigerant through the auxiliary condenser at all times. The coil must be sized to remove the exact amount of excess heat.

Tests confirmed that the theoretical principle of the closed air system is valid and the system can be used for drying peanuts. The peanuts were dried to below 10 percent moisture content in an average time of 40 h with no reduction in quality (Person and Sorenson, 1977).

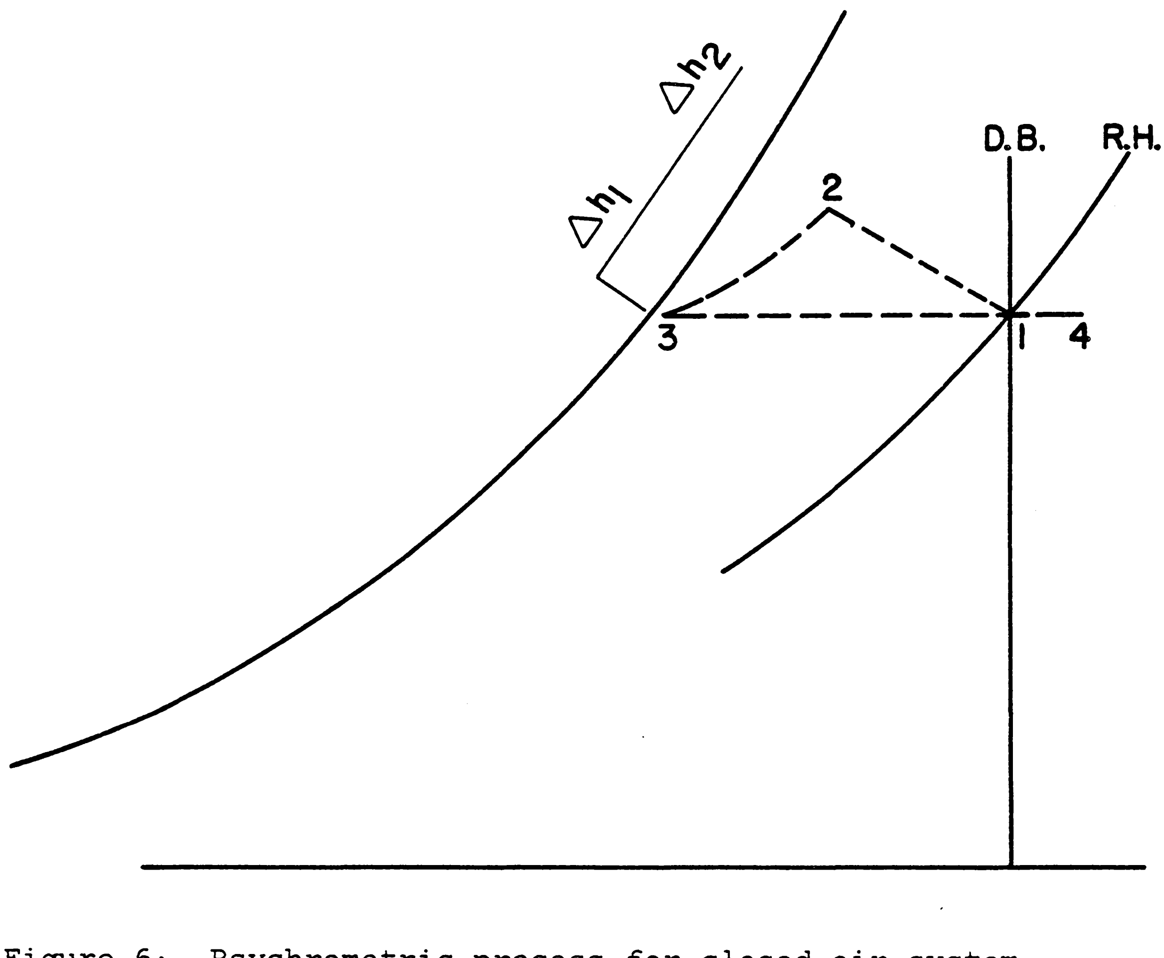

Figure 6: Psychrometric process for closed air system (Person and Sorenson, 1977).

2.6 DESIGN CRITERIA FOR SOLAR SYSTEMS IN PEANUT DRYING

Troeger and Butler (1980) developed design criteria for a flat plate collector, rock storage system that would provide a minimum of 50 percent of the energy required to dry a wagon (4.72 Mg) of peanuts from 20 to 10 percent moisture content (wb) on a three day schedule.

Their computer simulation model for deep-bed peanut drying (Troeger and Butler, 1979) was used to investigate design variables. Average seasonal weather data were used, and an initial rock bed temperature of 40 °C was assumed. They found that a collector area of 156 m^2 would supply 50 percent of the energy for drying a conventional wagon load of peanuts. The required rock storage was 60 m^3.

2.7 RECIRCULATION OF DRYING AIR

Sokhansanj and Sosulski (1981) investigated the effects of recirculating high humidity air on the drying rate, drying efficiency, and changes in grain quality, under wide ranges of drying air humidities and temperatures. During the first set of tests, a conditioner (Aminco - Aire Unit) was used to provide a controlled air temperature and humidity ratio. Metered steam was added to provide higher humidities. A 100 mm column was filled with approximately 7 kg of wheat having a moisture content of 21 percent. Four nominal drying temperatures, 60, 80, 100, 120 °C, were used with three nominal humidity ratios, 0.02, 0.06, and 0.08. The airflow rate was 1.7 m^3/min. As the drying temperature increased, the percentage of seed germination decreased. The increase in the moisture ratio had a slightly detrimental effect on the quality of dough made from the wheat.

For the second set of tests, the dryer was modified to recirculate exhausted drying air. Wheat conditioned to a moisture content of 22 percent was dried with a mixture of ambient and recirculated air. The drying air contained 3, 10, 40, and 70 percent recirculated drying air. Figure 7 shows the drying curves resulting from the four recirculation ratios, and Table 4 shows air enthalpies. Less energy is required to heat the mixed air at the latter stages of drying. The energy requirements are given in Table 5. The residence time represents the length of time the experiment was conducted.

Rumsey et al. (1981) reported on the development of a grain drying model for fixed bed walnut drying which incorporated recirculation. English walnuts were dried from a field moisture ranging from 10 to 30 percent to a moisture content of 8 percent. Many walnut dryers are housed in barns or small buildings; thus recirculation can be readily achieved by making the building air tight and placing the

TABLE 4

Air enthalpies in wheat drying studies (Sokhansanj and Sosulski, 1981)

Percent of Drying Air Recirculated	Enthalpy Difference without Recirculation	Enthalpy Difference with Recirculation		Enthalpy Reduction	
%	kJ/kg	kJ/kg		%	
		Begin	End	Begin	End
3.1	58	51	43	12.1	25.8
10.2	58	51	42.5	13.8	26.7
40.0	57	50	41.3	12.3	27.5
73.7	58	50	34.0	13.8	41.4

TABLE 5

Energy efficiency with recirculation in wheat drying studies (Sokhansanj and Sosulski, 1981)

Ratio	Residence Time(min)	Init MC %	Final MC %	Water(kg) Removed	Energy(MJ) per kg of Water Removed
3.1	14	21.9	14.4	0.58	3.830
10.2	20	21.3	13.2	0.625	5.058
40.0	24	21.4	13.0	0.648	5.778
73.7	34	20.7	12.0	0.663	7.361

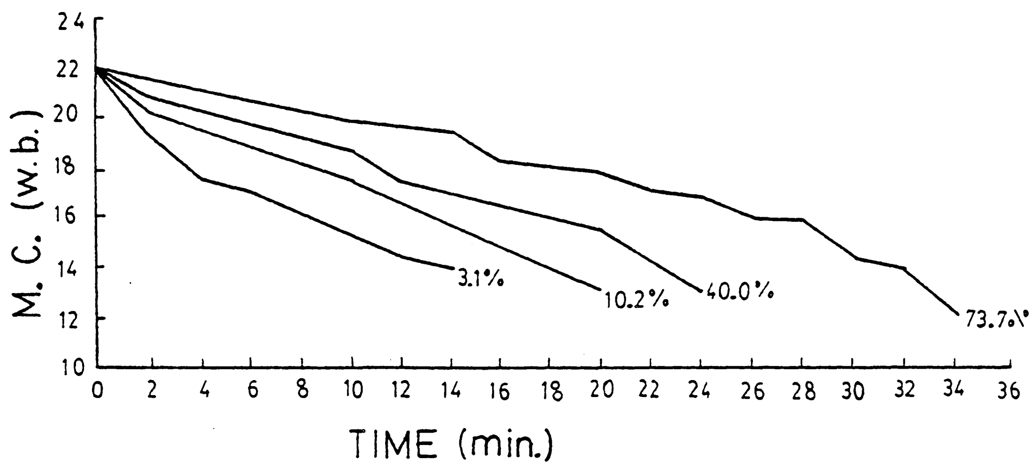

Figure 7: Drying curves of wheat samples (Sokhansanj and Sosulski, 1981).

fan inlet near a door. Energy savings of up to 30 percent were obtained by recirculating 60 percent of the air.

Chapter III

EXPERIMENTAL PROCEDURE

Recirculating crop dryers were designed and constructed, and five drying experiments were conducted. Hourly temperature readings were recorded at specified depths through the bed of peanuts. Wet and dry bulb temperatures were measured manually above and below the column. Peanuts were sampled every 24 hours to determine the moisture content.

A deep-bed peanut drying computer model, based on equations presented by Troeger and Butler (1979) was developed to simulate the drying process. A heat balance was then performed on the overall system. Data obtained during the drying experiment were used to validate the model.

3.1 DRYER CONSTRUCTION

In October, 1981 the construction of three recirculating crop dryers was completed (Figure 8). These dryers were built in four separate sections. Two vertical sections ,2.4 m in length, were used in each dryer. One section housed the drying material and the other section served to recirculate air. The supplemental heat source and fan were installed in the bottom section. A hinged door was installed in the bottom section to control the amount of air recirculated. The top section was simply an air return.

A cross section is shown in Figure 9. The basic structure of the dryers consisted of 0.95 cm (3/8 inch) plywood, as the inside layer, 3.81 cm (1-1/2 inch) polystyrene insulation, and 0.64 cm (1/4 inch) plywood as the outside layer.

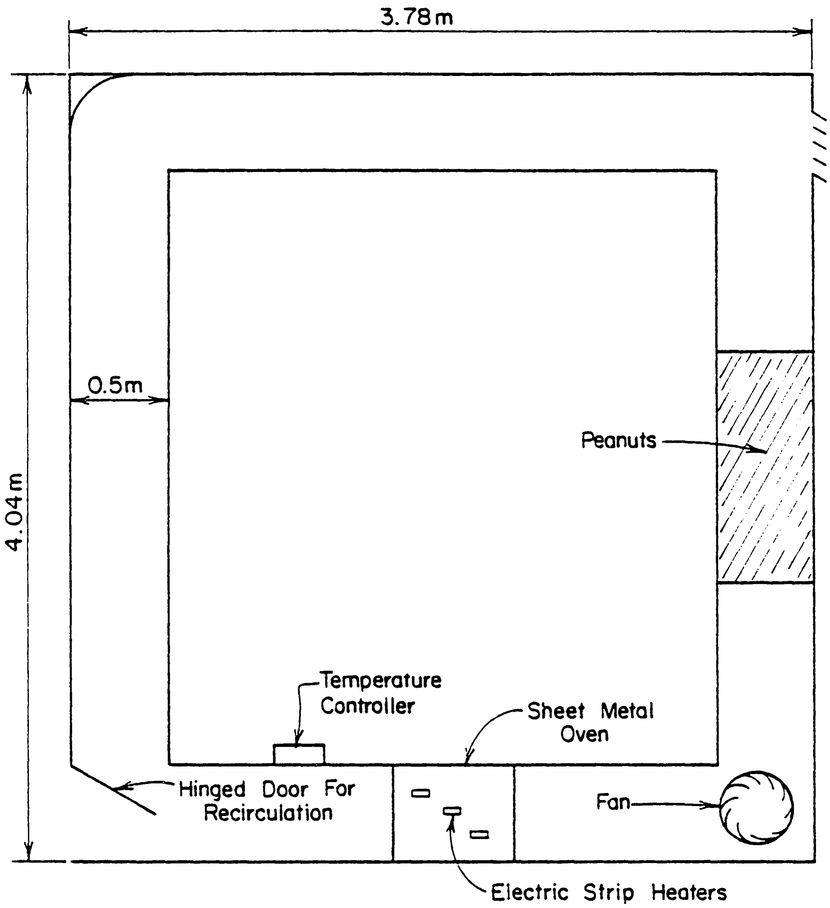

Figure 8: Laboratory crop dryers.

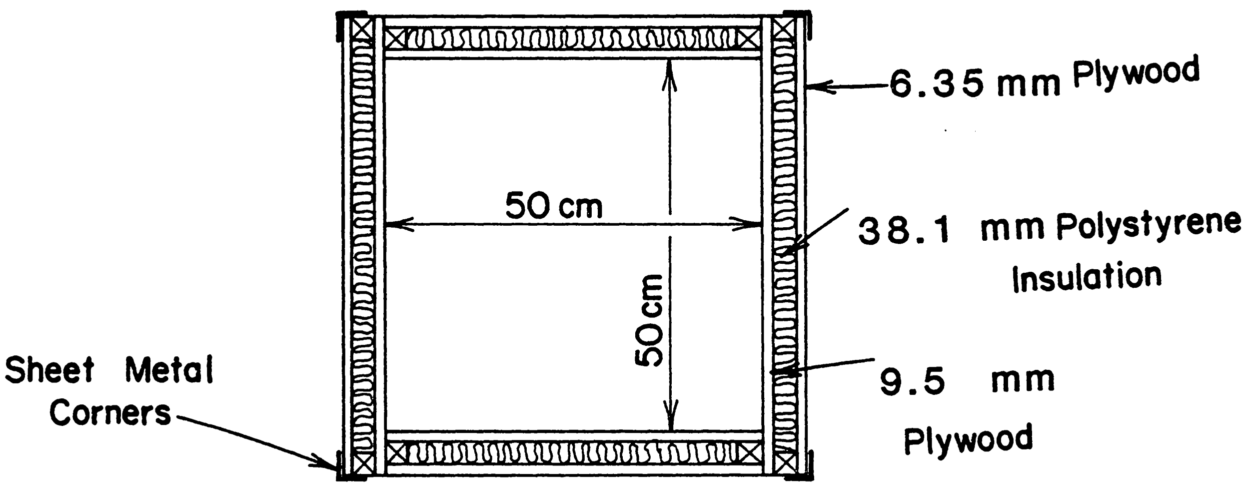

Figure 9: Dryer cross section.

3.1.1 DRYING COLUMN

A 2.4 m vertical section of the dryers (Figure 8) contained the 1.2 m depth of peanuts. A screen mesh like that used in commercial drying trailers (Harrington Manufacturing Company, Inc., Lewiston, North Carolina) was used for the dryer floor. The entire 2.4 m section was removed by a fork lift to load and unload the peanuts (Figure 10).

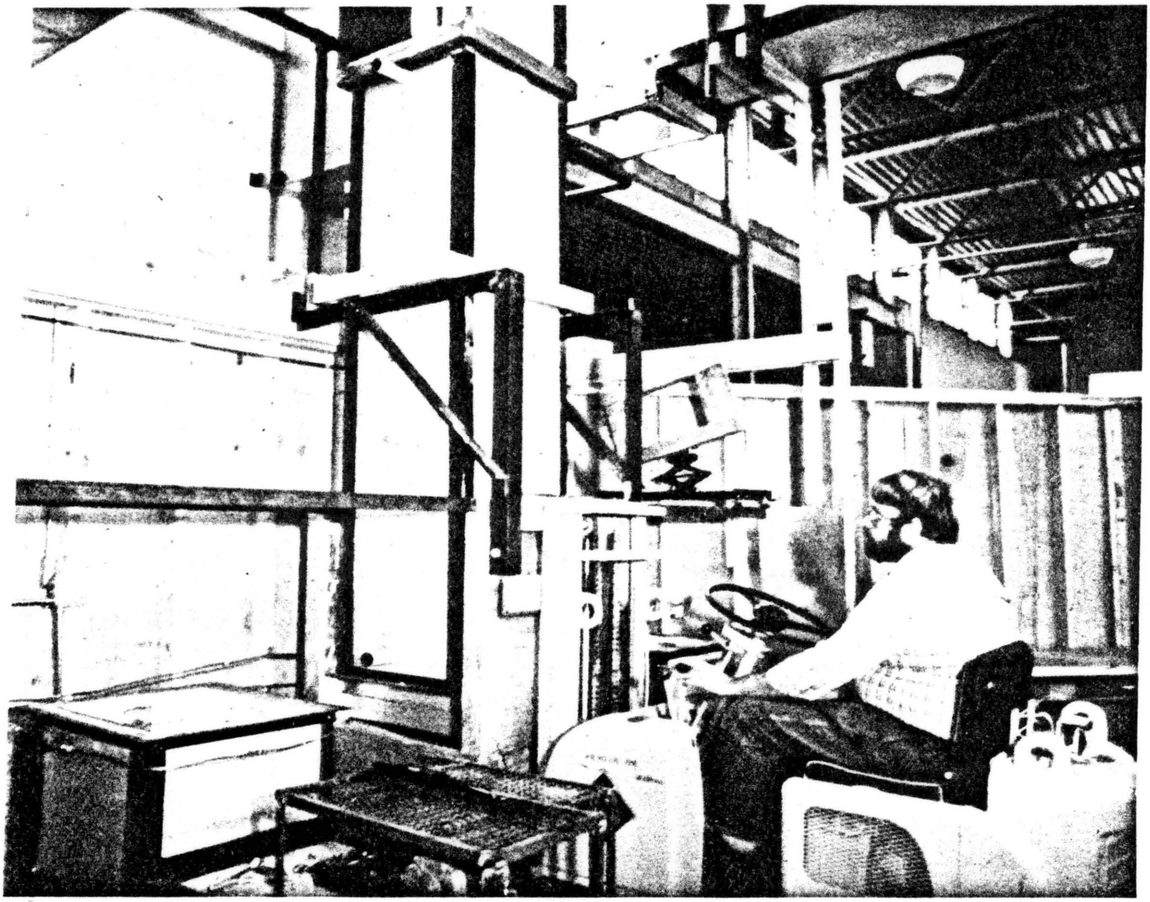

Figure 10: Loading of peanuts into laboratory dryers.

3.1.2 FAN

A double inlet belt driven centrifugal fan was installed in each dryer. A 3/4 horsepower electric motor was mounted on the outside of each dryer to drive the fan; therefore, none of the heat generated within the motor was added to the system. The fan was rated at 1000 cfm of air against 0.25 inch H_2O static pressure.

3.1.3 ELECTRIC RESISTANCE HEATERS

Finned strip heaters (Chromalox OTF - 19 128258) were used to provide the required heat energy to maintain a 35 °C temperature. Three 1500 W, 240 V units were used in Columns 1 and 3, while Column 2 contained two units. The heaters were housed in a four sided sheet metal oven constructed of 20 gauge metal.

3.1.4 TEMPERATURE CONTROLLERS

Digital temperature controllers (Eurotherm Model 918 controller with Type 931/932 SCR unit) were installed to maintain the desired temperature of 35 °C with an accuracy of ± 1 °C. The temperature controller was a precision digital setpoint, solid state, proportional controller which varied the current to the heaters by changing the frequency of pulses from the SCR units. As current demand (heat demand) increased, the pulsing frequency increased until the heaters were operating continuously at maximum output. The temperature sensor for the controller was an iron constantan (ANSI Type J) thermocouple junction located at the thermopile below the drying column (Figure 11).

3.1.5 EXHAUST SYSTEM

Air was exhausted through a louvered metal vent at the top of the dryers into a sheet metal duct leading outside the building. The louvered vent opened under positive pressure to allow air to exit.

3.2 DATA COLLECTION

3.2.1 TEMPERATURE MEASUREMENT

Copper constantan (ANSI Type T) thermocouple junctions were centered in the drying column and located at distances of 0.3, 0.6, and 0.9 m from the drying floor. They were placed as the column was filled with peanuts. A thermopile was also placed immediately above and below the peanut column (Figure 11). Hourly values of these temperatures were recorded on a Honeywell Electronik 24-point temperature recorder. These data were digitized and subsequently placed on computer file.

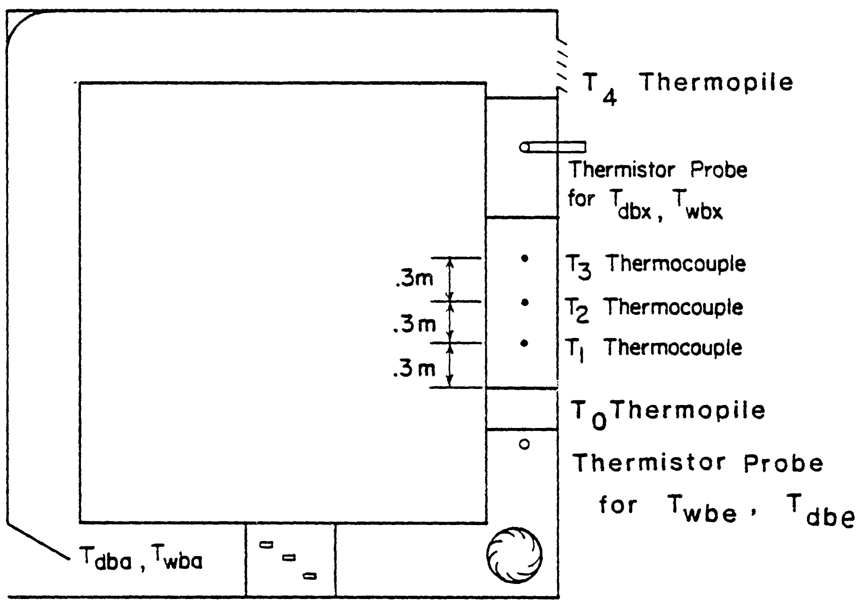

Figure 11: Thermocouple locations.

3.2.2 AIR TEMPERATURE MEASUREMENT

Air temperature, both wet bulb and dry bulb, was measured manually at 0800, 1200, 1600, 2000, and 2400 hours above and below the drying column (Figure 11). A thermistor probe (Omega Type ON - 910 - 44007) was used for measuring these temperatures. The thermistor probe was inserted into the center of the column, and the resistance reading measured with a multimeter. The resistance was subsequently converted to °C. Wet bulb measurements were made by placing a wick-covered thermistor in the air stream. The resistance increased (temperature decreased) and reached a point where it remained constant as water evaporated from the wick at a steady rate. It then decreased as the wick dried out, and the temperature increased to the dry bulb temperature. The wet bulb resistance was recorded during the interval when the resistance remained constant.

Ambient wet and dry bulb readings were recorded at the same time the other temperature readings were taken. The dryers were located in a large shop area (6.1 m x 13.4 m x 6.8 m ceiling height). Ambient wet bulb readings were taken by placing the wick-covered thermistor in an airstream generated by a small blower mounted on a table near the dryer inlet.

3.2.3 STATIC PRESSURE MEASUREMENT

Average static pressures in the drying columns were recorded every 24 hours. Copper tubing was inserted through the four sides of the drying column flush with the inside wall to form a piezometer ring (Figure 12). The static pressure was measured with an inclined manometer (Dwyer Model 400-5) connected to the copper tubing with rubber hose. A piezometer ring was installed above and below the peanuts, and the static pressure drop across the peanuts was taken to be the difference in pressure at the two locations. An air tank was used to remove any condensate from the lines before each reading.

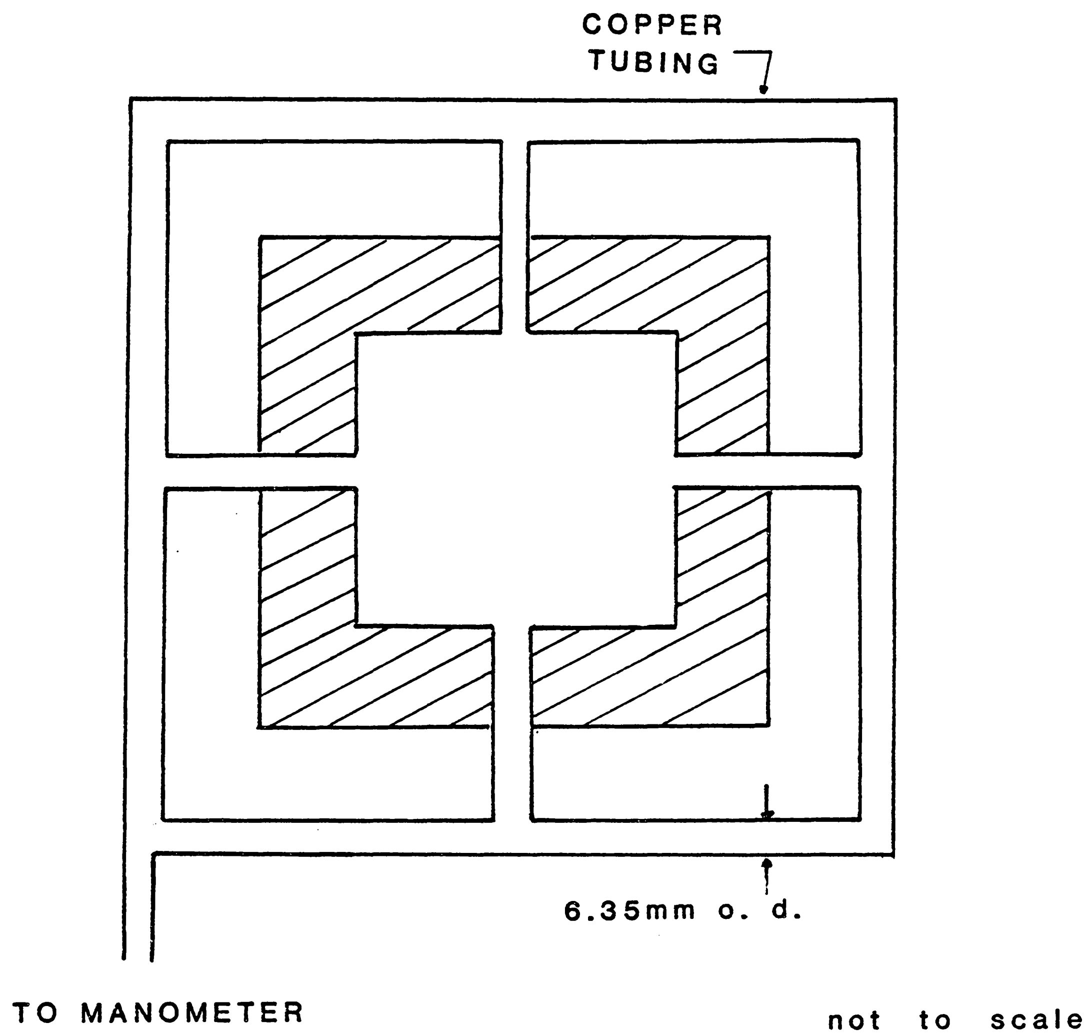

Figure 12: Piezometer ring for measuring static pressure.

3.2.4 AIRFLOW MEASUREMENT

The required fan speed was determined from the fan curve and fan laws. This speed was then set using a magnetic sensor and gear mounted on the blower shaft. This sensor generated a pulse as each tooth passed through the magnetic field, and these pulses were counted with a frequency counter. Fan speed was measured within ± 1 rpm using this procedure. The pressure drop across the peanuts was simulated by placing two perforated metal plates in the drying column. The plates were adjusted relative to each other to close the perforations and simulate the desired static pressure. A hot wire anemometer was then used to measure air velocity at nine locations at the top of the drying column. A large variation in readings occurred, probably because of air turbulence. No flow straightener was used for these measurements.

3.2.5 ENERGY INPUT

Electrical energy input to the resistance heaters was logged with a minicomputer (DEC MINC Model PDP - 11/03) and stored on floppy disk. A current transducer (Scientific Columbus Model CT510A2-2) was placed in the resistance heater circuit. This transducer gave a 0-1 mA output proportional to a 0-25 A input. The mA signal was dropped across a 1 k Ω resistor, and the resulting voltage recorded with the minicomputer. This voltage pulsed as the controller pulsed the SCR unit. Experimentation showed that it could be accurately characterized by sampling at a rate of 128 samples per second for ten seconds. An average, or integrated value, was stored for each sampling period. Four observations per hour were logged. The data were dumped to interactive files on the university's main computer. These files were then used as input data to the simulation model.

3.2.6 MOISTURE CONTENT DETERMINATION

Samples of peanuts, in the shell, were removed every 24 hours for moisture content determination, using a sampling port in the side of the column at the 1.2 m level. At the beginning of the experiments, six samples of 826 cm^3 were taken from each column. Three 826 cm^3 samples were taken at each 24 hour interval following the initial sampling. Samples were weighed and then placed in a forced air oven at 160 °C for 60 hours. The peanuts were weighed after removal from the oven and the moisture content calculated based on weight loss (Proposed ASAE Standard, January 21, 1980).

The entire mass of peanuts was weighed upon completion of the drying experiment. The total moisture removed was calculated:

$$DM = (m\,c_f/100)\,w_f \tag{7}$$

$$M_e = DM\,(100/100-mc_i)$$

where:

DM = dry matter (kg) (8)

mc_f = final wet basis moisture content

mc_i = initial wet basis moisture content

w_f = final weight (kg)

M_e = moisture removed.

Chapter IV

MODEL DEVELOPMENT

4.1 THIN LAYER DRYING MODEL

The thin layer peanut drying model developed by Troeger and Butler (1979) was used to simulate the properties of the peanuts and the drying air. A simplified flow chart of the model is shown in Figure 13, and a complete listing of the FORTRAN program written for the simulation is given in Appendix A. Input and output data required by the model is given in Appendix E. Appendix B presents a list of variables and their description. The total depth of the bed of peanuts was divided into finite layers (Figure 14) and the assumption was made that each layer acted as a fully exposed layer with constant entering air conditions during a finite time interval. The conditions of the air exiting one layer were the entering conditions for the following layer. Four equations were needed to describe the changes in the condition of the peanuts and the drying air.

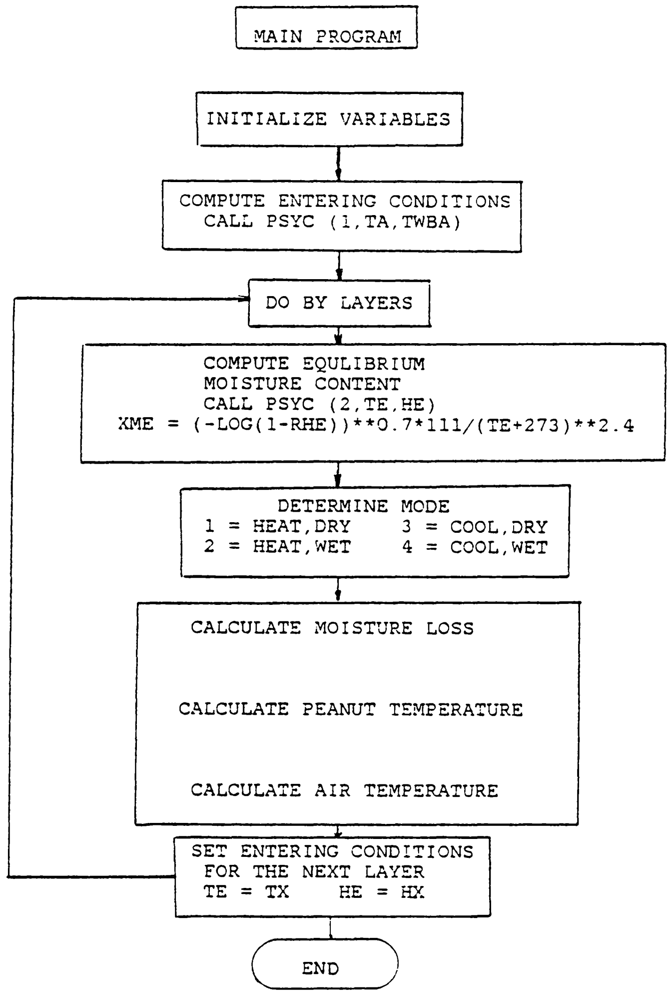

Figure 13: Flow chart of drying model.

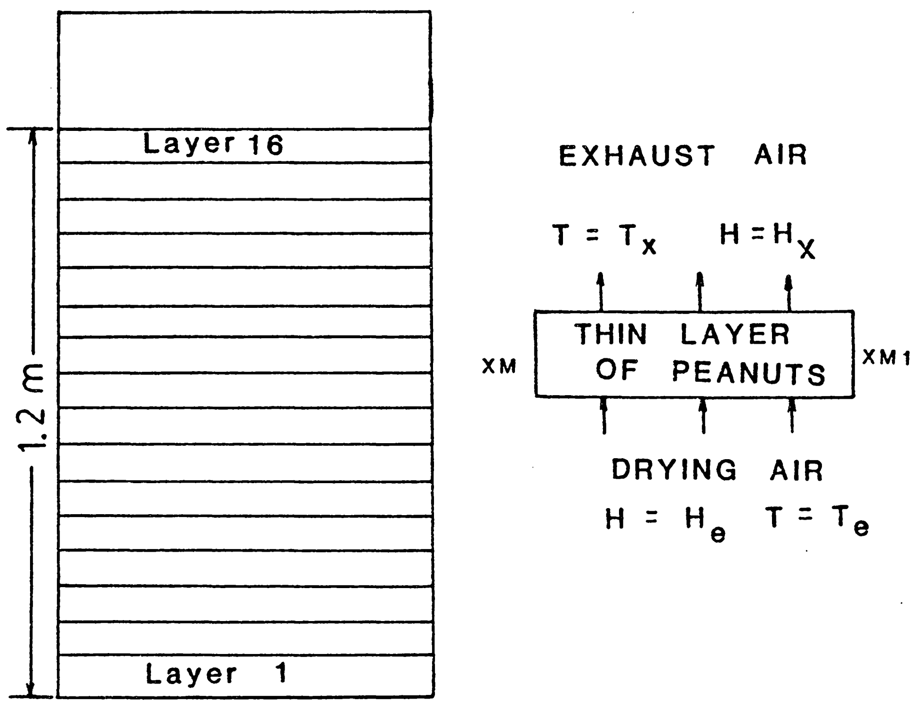

Figure 14: Division of peanuts into thin layers.

4.1.1 SINGLE LAYER DRYING EQUATION

A single layer drying equation for peanuts was developed from the single layer drying model for corn proposed by Troeger and Hukill (1971). The equation for the rate of drying is:

$$dM/dt = -a(M_o - M_e)M_r^{\,b} \tag{9}$$

where:

M = moisture content dry basis (decimal)
t = time (h)
M_o = initial moisture content dry basis (decimal)
M_e = equilibrium moisture content dry basis (decimal)
M_r = moisture ratio (dimensionless) defined by:

$$M_r = (M - M_e)/(M_o - M_e) \tag{10}$$

a,b = functions of drying condition defined as:

(11)

For $M \geq 0.40$:

$$a_1 = 0.02320+0.00045T_a+0.00063T_{dp}+0.00045T_{dp}M_o+0.00800M_o$$

(12)

$$b_1 = 3.264 - 0.0252T_a - 0.0162T_{dp} - 0.0342T_{dp}M_o - 0.6080M_o$$

For $0.12 \leq M < 0.40$:

$$a_2 = a_1(2.40 - M_o) \tag{13}$$

$$b_2 = b_1(0.88 + 0.20M_o) \quad (14)$$

For $M < 0.12$:

$$a_3 = a_1(2.40 - M_o)^2 \quad (15)$$

$$b_3 = b_1(0.88 + 0.20M_o)^2 \quad (16)$$

where:

T_a = dry bulb temperature of the drying air (°C)

T_{dp} = dew point temperature of drying air (°C).

The new moisture for a layer is then:

$$M_2 = (dM/dt)\ t + M_1 \quad (17)$$

where:

subscripts 1,2 = initial and final stages respectively

t = time increment (h).

The equilibrium moisture content is determined from the conditions of the entering air with the following equation:

$$M_e = (-\ln(1 - rh))^{0.7}(111/(T_a + 273))^{2.4} \quad (18)$$

where:

rh = relative humidity (decimal).

Troeger and Butler (1979) used data given by Beasley and Dickens (1963) to determine the coefficients and exponents in Equations 9 through 18 using least squares regression techniques, and fitted the equation form given by Henderson (1952).

4.1.1.1 MODE DETERMINATION

The properties of the drying air and the peanuts were evaluated and a mode was determined for a given time interval in the thin layer drying model (Figure 13). The four possible modes were:

1) heat,dry;
2) heat, wet;
3) cool, dry; and
4) cool, wet.

Heating is occuring if the temperature of the drying air is greater than the peanut temperature. Rewetting of the peanuts occurs if the equilibrium moisture content is greater than the moisture content of the peanuts.

4.1.2 PEANUT TEMPERATURE

The temperature changes in the peanuts were estimated by assuming that the peanut shape can be represented as a finite cylinder. The temperature at the center of the peanut is:

$$(T_p - T_a)/(T_{po} - T_a) = P(Z_1)C(Z_2) \tag{19}$$

where:

T_p = peanut temperature (oC)
T_a = drying air temperature (^oC)
T_{po} = initial peanut temperature (^oC).

$$P(Z_1) = 1.267\exp(-2.461Z_1) \tag{20}$$

$$\text{with } 0.2 \leq P(Z_1) \leq 4.0$$

$$P \leq 1$$

$$C(Z_2) = 1.557\exp(-5.733Z_2) \tag{21}$$

$$\text{with } 0.10 \leq C(Z_2) \leq 1.50$$

$$C \leq 1$$

$$Z_1 = 4a_o t/L^2 \tag{22}$$

$$Z_2 = 4a_o t/D^2 \tag{23}$$

where:

a_o = thermal diffusivity of peanut (m^2/h)
L = peanut length (m)
D = peanut diameter (m)
t = drying time (h).

$P(Z_1)$ and $C(Z_2)$ are restricted to values less than or equal to one to provide the desired smooth change in the temperature of the peanut as it is subjected to new air temperatures.

4.1.3 MASS BALANCE

The moisture lost by a layer of peanuts must equal the moisture gained by the air. During some *i*th interval,

$$H_{xi} - H_{ei} = m_p(M_{i-1} - M_i)/m_{ai}\ t \quad (24)$$

where:

- H_{ei} = entering air humidity ratio (g water/g air)
- H_{xi} = exiting air humidity ratio (g water/g air)
- M_i = moisture content of the peanuts during the ith interval (g water/g dry matter)
- M_{i-1} = moisture content of the peanuts during the (i-1)th (interval (g water/g dry matter)
- m_p = mass of peanuts in layer (g)
- m_{ai} = mass flow rate of air during the ith interval (g/h)
- t = integration interval (h).

The moisture removal predicted by the simulation model is:

$$\sum_{1}^{n} M_s = \sum m_i \quad (25)$$

where:

- m_i = moisture removed during ith interval (kg)
- n = number of integration intervals.

4.1.4 ENERGY BALANCE

The air temperature change was obtained by performing an energy balance on an incremental layer. The temperature change occurred due to the change in the sensible heat of the peanut and of the latent heat used in evaporating the moisture. The exiting temperature during the *i*th interval is given by:

$$T_{xi} = (h_{ei} - 4.1868H_{xi}T_{dpxi} - h''_{fg}H_{xi}x10^{-3} \quad (26)$$
$$+ 1.8756864H_{xi}T_{dpxi} - m_p(X_i - X_{i-1})/m_a\ t)/$$
$$(1.0069254 + 1.8756864H_{xi})$$

where:

h_{ei} = enthalpy of entering air during ith interval (kJ/kg)

T_{dpxi} = dew point temperature of exiting air during ith interval(°C)

m_p = peanut mass (kg)

m_a = air mass flow rate (kg/h)

t = time increment (h)

h''_{fg} = $2.5025353 \times 10^6 - 2.3857642 \times 10^3 T_{dpx}$

X_i = $(C_p + M_i C_w)T_{pi}$

X_{i-1} = $(C_p + M_{i-1}C_w)T_{pi-1}$

C_p = specific heat of peanut (J/g-°C)

C_w = specific heat of water (J/g-°C)

T_{pi} = peanut temperature at end of ith interval (°C)

T_{pi-1} = peanut temperature at beginning of ith interval (°C).

Equations (9), (17), (24), and (26) are applied sequentially to each layer of the dryer for each time step.

4.1.5 PSYCHROMETRIC SUBROUTINE

A subroutine for the basic psychrometric relationships was developed from the equations in ASAE D271.2.

4.1.5.1 PARTIAL VAPOR PRESSURE

The partial vapor pressure of air entering the first layer during the the *i*th time interval is:

$$P_{vai} = \frac{.62194h'_{fgi}P_{swbi} - 1006.9254(P_{swbi} - P_{atm})(T_{wbai} - T_{ai})}{.62194h'_{fgi} + 156.849(P_{swbi} - P_{atm})(T_{wbai} - T_{ai})/P_{atm}} \tag{27}$$

where:

T_{ai} = ambient dry bulb temperature (C)
T_{wbai} = ambient wet bulb temperature (C)
P_{swb} = partial pressure of water vapor at saturation ($T = T_{wb}$)
h'_{fg} = latent heat of vaporization ($T = T_{wb}$)
P_{atm} = atmospheric pressure (Pa)

$$h'_{fgi} = 2.5025\text{x}10^6 - 2.38576\text{x}10^3\ T_{wbai}$$

The partial pressure of water vapor at saturation using the wet bulb temperature is:

$$P_{swb} = R\ \exp\ (A + BT + CT^2 + DT^3 + ET^4/(FT - GT^2)) \tag{28}$$

where:

$R = 2.2105649\text{x}10^7$

$A = -2.7405526\text{x}10^4$

$B = 97.5413$

$C = -1.46244 \times 10^{-1}$

$D = 1.2558 \times 10^{-4}$

$E = -4.8502 \times 10^{-8}$

$F = 4.34903$

$G = 3.9381 \times 10^{-3}$

$273.16 < T < 533.16$

4.1.5.2 RELATIVE HUMIDITY

The partial vapor pressure in terms of dry bulb and wet bulb temperature is given in Equation (27). The saturation vapor pressure for ambient air is obtained by substituting the ambient temperature (°K) into Equation (28). Relative humidity is then defined as:

$$rh = P_{vai}/P_{sai} \tag{29}$$

4.1.5.3 ENTHALPY

The enthalpy of the moist air is equal to the sum of the enthalpies of its components. Specifically for a water-air mixture:

Enthalpy = enthalpy of dry air + enthalpy of water at the dewpoint temperature

enthalpy of evaporation at the dew

point temperature + enthalpy added to

the water vapor after vaporization.

$$h_{ei} = 1.006954\ T_{ei} + 4.1868\ H_{ei}\ T_{dpei} + h''_{fgi}\ H_{ei} x 10^{-3} + 1.8756864\ H_{ei}(T_{ei} - T_{dpei}) \quad (30)$$

$$h''_{fgi} = 2.5025x10^{6} - 2.38576x10^{3}\ T_{dpei}$$

where:

T_e = entering drying air temperature (° C)
H_e = entering humidity ratio
T_{dp} = entering dew point temperature (° C)
h''_{fg} = latent heat of vaporization ($T = T_{dp}$).

4.1.5.4 DEW POINT TEMPERATURE

The dew point temperature is given by:

$$T_{dp} = 255.38 + A_i[\ln(1.45x10^{-3}\ P_{vai}]^{i} \quad (31)$$

where:

A_0 = 19.5322

A_1 = 13.6626

A_2 = 1.17678

A_3 = $-1.89693x10^{-1}$

$A_4 = 8.7453 \times 10^{-2}$

$A_5 = -1.74053 \times 10^{-2}$

$A_6 = 2.14768 \times 10^{-3}$

$A_7 = -1.38343 \times 10^{-4}$

$A_8 = 3.8 \times 10^{-6}$

4.1.5.5 HUMIDITY RATIO

The humidity ratio is defined by:

$$H = 0.6219\ P_v/(P_{atm} - P_v) \qquad (32)$$

where:

H = humidity ratio
P_v = partial pressure (Pa)
P_{atm} = atmospheric pressure (Pa).

4.1.6 RECIRCULATION

The recirculation of drying air was incorporated into the model by mixing the entering ambient air with the mass of recirculated air. The properties of the new mixture became the properties entering the drying peanuts. The humidity ratio of the mixed air is required by the drying model. It is calculated as:

$$H_3 = (M_1H_1 + M_2H_2)/(M_1 + M_2) \qquad (33)$$

where:

M_1 = mass of ambient air in mixture (kg)
M_2 = mass of recirculated air in mixture (kg)
H_1 = humidity ratio of ambient air
H_2 = humidity ratio of recirculated air
H_3 = humidity ratio of mixed air.

4.2 CONSERVATION OF MASS

Conservation of mass and conservation of energy were maintained in the model. A complete listing of the program used to perform the heat and mass balances is given in Appendix C, and variable descriptions are given in Appendix D. The equations of conservation of mass and energy were written for a control volume. This control volume was defined such that the boundries coincided with the outer surface of the dryer.

The law of conservation of mass states that at the end of a given time interval the mass in the control volume must equal the initial mass plus the integral of the input mass flow minus the output mass flow. In equation form:

$$M = M_{in} + \int (m_i - m_o)dt \qquad (34)$$

where:

M_{in} = initial mass (kg)
m_i = input mass flow
m_o = output mass flow.

In this peanut drying simulation the mass flow is the moisture flow.

4.3 CONSERVATION OF HEAT ENERGY

The change in energy in the control volume during some time interval (dt) equals the integral of the input energy flow minus the output energy flow. In equation form:

$$Q = \int (Q_i - Q_o)dt \qquad (35)$$

where:

Q_i = input energy flow
Q_o = output energy flow.

Conservation of energy in this case refers to heat energy. Heat energy was added to the drying system by electrical heaters. It is consumed to elevate and maintain the temperature of the structure, change the enthalpy of the exchanged air, and elevate the temperature of the peanut mass. The energy balance for the *i*th time interval is:

$$Q_{fi} = Q_{si} + Q_{xi} + Q_{mi} + Q_{ei} \qquad (36)$$

where:

Q_{fi} = supplemental heat energy added during the ith time interval (MJ)

Q_{si} = energy to elevate and maintain the temperature of the structure during the ith time interval (MJ)

Q_{xi} = energy in exchanged air during the ith time interval (MJ)

Q_{mi} = energy to elevate and maintain the temperature of the material during the ith time interval (MJ)

Q_{ei} = error term (MJ).

4.3.1 ENERGY TO ELEVATE AND MAINTAIN THE TEMPERATURE OF THE STRUCTURE (Q_s)

The energy to elevate and maintain the temperature of the structure has two components:

1. conductive and convective heat loss; and
2. heat stored in structural materials.

4.3.1.1 CONDUCTIVE AND CONVECTIVE HEAT LOSS (Q_{s1})

The control volume was divided into sections (Figure 15), each section consisting of layers of 0.64 cm plywood, 3.81 cm polystyrene insulation, and 0.95 cm plywood. The temperature drop across any layer is proportional to its thermal resistance. The total thermal resistance is the sum of the resistances for each layer of material plus a surface coefficient h for the inside and outside surfaces. The surface coefficient represents the thermal transmission in unit time to or from a unit area of a surface in contact with its surroundings for a unit difference between the temperature of the surface and the environmental fluid temperature (ASHRAE, 1977). Conductive heat loss during the *i*th time interval is:

$$Q_{sli} = (\sum_{j=1}^{n} A_j/R_j)\ \Delta T_i \qquad (37)$$

where:

Q_{sl} = rate of exchange of conductive heat loss during the ith time interval (kJ/h)

R_j = total thermal resistance of the jth section (h m^2 C/kJ)

A_j = total area of the jth section (m^2)

T_i = temperature difference across the boundary of the control volume during the ith interval (C).

4.3.1.2 HEAT STORED IN STRUCTURAL MATERIALS (Q_{ss})

Heat stored in the structural materials is given by:

$$Q_{ss} = \sum_{j=1}^{n} A_j \sum_{k=1}^{m} \tau_{jk} \cdot \rho_{jk} C_{jk} T_{jk} \qquad (38)$$

where:

A_j = area of the jth section (m^2)

τ_{jk} = thickness of the kth layer in the jth section (m)

ρ_{jk} = density of the kth layer in the jth section (kg/m^3)

C_{jk} = specific heat of material in the kth layer of the jth section (kJ/kg-^{o}K)

T_{jk} = average temperature of the kth layer in the jth section (C).

Assuming all the components of the dryers reach the temperature of the drying air, Equation (38) simplifies to:

$$Q_{ss} = M_j C_j T_d \qquad (39)$$

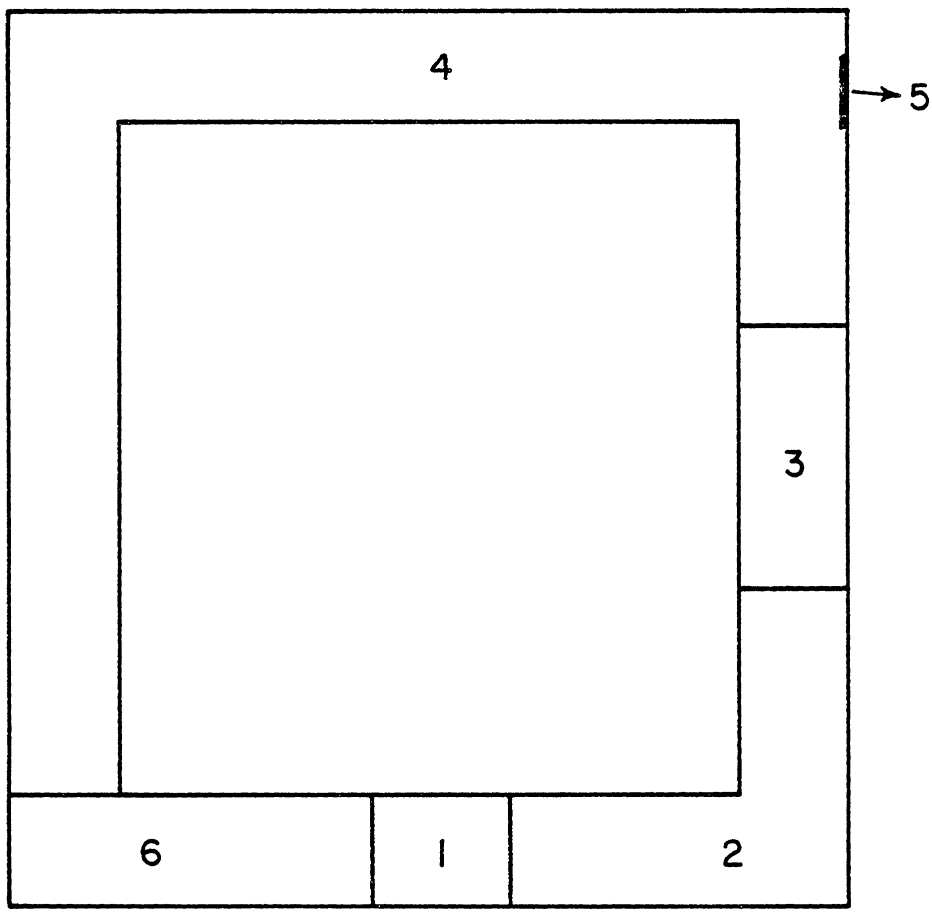

Figure 15: Dryer sections for heat balance.

where:

M_j = mass of the jth component (kg)
C_j = specific heat of material (kJ/kg-°K)
T_d = temperature of the air in the delivery plenum (°C).

The fan was the only component with significant mass to store heat. The mass of the plywood sections was very small in comparison with that of the fan; therefore, the heat stored in the plywood sections was neglected.

The change in Q_{ss} during the *i*th time interval is:

$$Q_{ss} = Q_{ssi} - Q_{ssi-1} \qquad (40)$$

The change in the energy required to elevate and maintain the temperature of the structure for an *i*th interval is given by:

$$Q_{si} = Q_{ssi} + Q_{sli} \qquad (41)$$

4.3.2 ENERGY IN EXCHANGED AIR (Q_x)

The enthalpy of a gas mixture is the sum of enthalpies of the components as given in Equation (30). The change in exchanged air energy during a given time interval is:

$$Q_{xi} = 60\ V_i(h_{xi} - h_{ai})/\ 1000\ V_{sai} \qquad (42)$$

where:

Q_x = energy in exchanged air (J/h)
V = volume flow rate of exchanged air (m^3/min)
h_x = enthalpy of exiting air (kJ/kg)
h_a = enthalpy of ambient air (kJ/kg)
V_{sa} = specific volume (m^3/kg)

4.3.3 ENERGY TO ELEVATE AND MAINTAIN THE TEMPERATURE OF THE MATERIAL (Q_m)

A moisture gradient is established as the drying air passes through the grain mass. It is expedient to divide the material into layers, in this case 16. The sensible heat is then the heat stored in the dry matter plus that stored in the water:

$$Q_m = m_p(C_p + M_f C_w)T_{pf} - m_p(C_p + M_i C_w)T_{pi} \tag{43}$$

where:

m_p = peanut solids per layer (kg)

C_p = specific heat of peanuts (kJ/kg-°K)

C_w = specific heat of water (kJ/kg-° K)

M = dry basis moisture content

T_p = peanut temperature (° C)

subscripts i,f = initial, final respectively.

4.3.4 ERROR TERM (Q_e)

The error term represents the collection of all error associated with the model and the experimental measurements.

4.4 DETERMINATION OF AIRFLOW

Accurate airflow measuring instrumentation was not available; hence, the experimental measurement of airflow was questionable. Thus, a procedure was developed to determine an airflow which would give a simulation predicted moisture loss (M_s) equal to the experimentally measured total weight loss (M_e). Although not all of the supplemental heat energy data (Q_f) were obtained because of problems with the minicomputer software, data were obtained for hours 11 to 27 and hours 87 to 107 during Run 2. It was possible to close the energy balance for these time intervals. The airflow selected gave a simulation predicted total ($Q_s + Q_m + Q_x$) equal to the measured Q_f. The measured value was incrementally changed until a value was obtained which would close the moisture balance ($M_s = M_e$), and close the energy balance as nearly as possible for the hours 11 to 27 and 87 to 107.

4.5 DETERMINATION OF RECIRCULATION PERCENTAGES

The amount of air recirculated in each column was calculated using the psychrometric chart and the wet and dry bulb temperature readings recorded manually every four hours. The humidity ratio of the ambient air, the drying air, and the recirculated air was plotted on the psychrometric chart as shown in Figure 16. The amount of air recirculated was then calculated:

$$\% \text{ Ambient} = X_1/(X_1 + X_2) \tag{44}$$

$$\% \text{ Recirculated} = X_2/(X_1 + X_2) \tag{45}$$

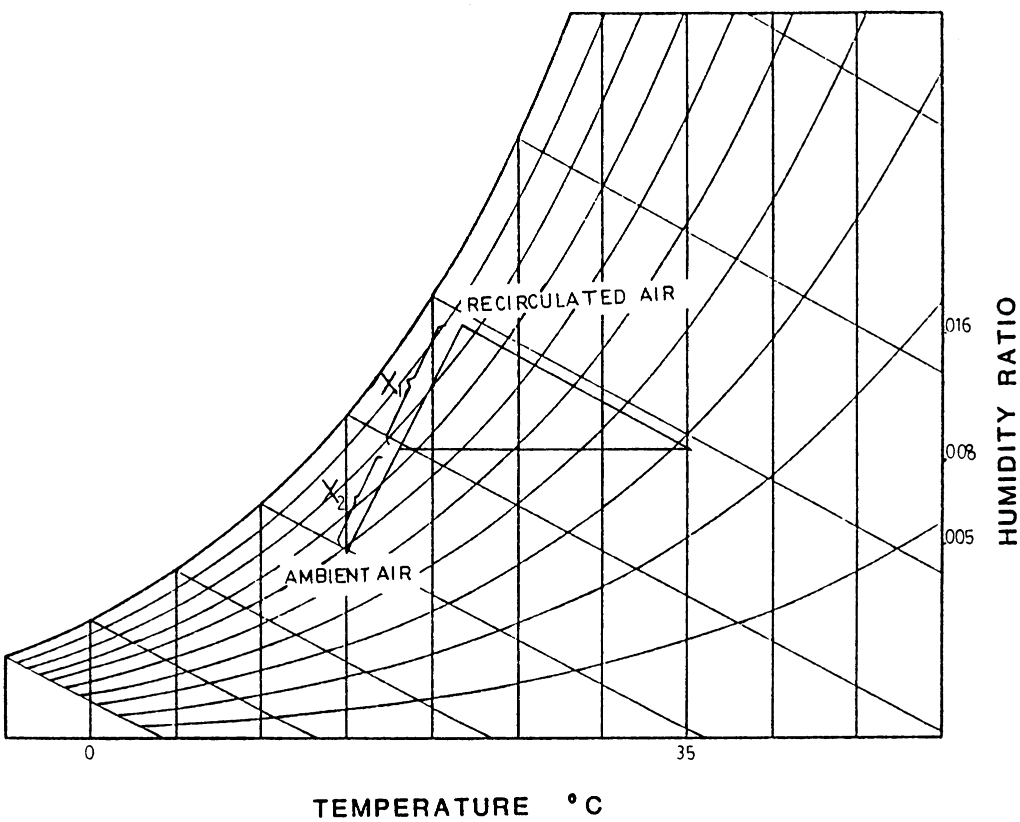

Figure 16: Psychrometric properties of mixture of ambient and recirculated air.

Chapter V

MODEL VERIFICATION

Data collected during two runs consisting of a total of five drying experiments, were used to verify the model. Run 1 consisted of two experiments, Column 1 and Column 3. The initial parameter values for Run 1 are shown in Table 6. Column 3 served as the control since no recirculation was used. Fifty-five percent of the drying air was recirculated in Column 1 throughout the experiment. The experimental moisture content determined by sampling from the sixteenth layer is shown in Figure 17. The points on the moisture content plots show the variation between the three samples taken at each sampling interval. The temperature gradient throughout the depth of peanuts is shown in Figure 18 for Column 1, and Figure 19 for Column 3, where T_1, T_2, T_3, and T_{dbx} are located as shown in Figure 11.

The drying rates in both columns followed the expected trend only up to the 24 hour mark. At this point the peanuts in Column 3 began drying at a slower rate than those in Column 1. This is evidence that the recirculation of up to 55 percent of the air in field-cured peanuts (35 percent moisture content (wb) or less) does not decrease the drying rate.

The experimental temperatures recorded hourly throughout the depth of peanuts at three different locations (Figures 18 and 19) show the lower layers of peanuts reaching the 35 °C temperature level before the upper layers, as expected. The manually recorded temperature measured above the peanuts was plotted as T_{dbx} to represent the top layer of peanuts. The lower layers of peanuts heated smoothly to 35 °C during the early stages of the cure while the top layers were much more sensitive to changes in the ambient air humidity ratio, shown by the variation in the temperature curves.

Run 2 consisted of three experiments utilizing Columns 1, 2, and 3. The initial parameter values for Run 2 are shown in Table 7. Column 3 again served as the control with no recirculation. Sixty-six percent of the drying air was recirculated in Column 1 while 69 percent was recirculated in Column 2.

The experimental moisture content throughout Run 2 is shown in Figure 20. Here the expected relationship between the three experiments was observed. Column 3 with no recirculation dried faster than Column 1 with 66 percent recirculation, which in turn dried faster than Column 2 with 69 percent recirculation. Recirculation of the moist air in Columns 1 and 2 decreased the drying rates of those peanuts. Column 3 reached 10 percent moisture content (wb) at 68

TABLE 6

Initial parameters for the Run 1 experiments

Parameters	Column 1	Column 3
% Recirculation	55	0
Airflow ($m^3/min/m^3$)	8.2	8.2
Initial temp. (° C)	18	18
Initial MC (wb)	34.2	35.1
Initial depth m	1.22	1.22
Initial volume (m^3)	0.305	0.305

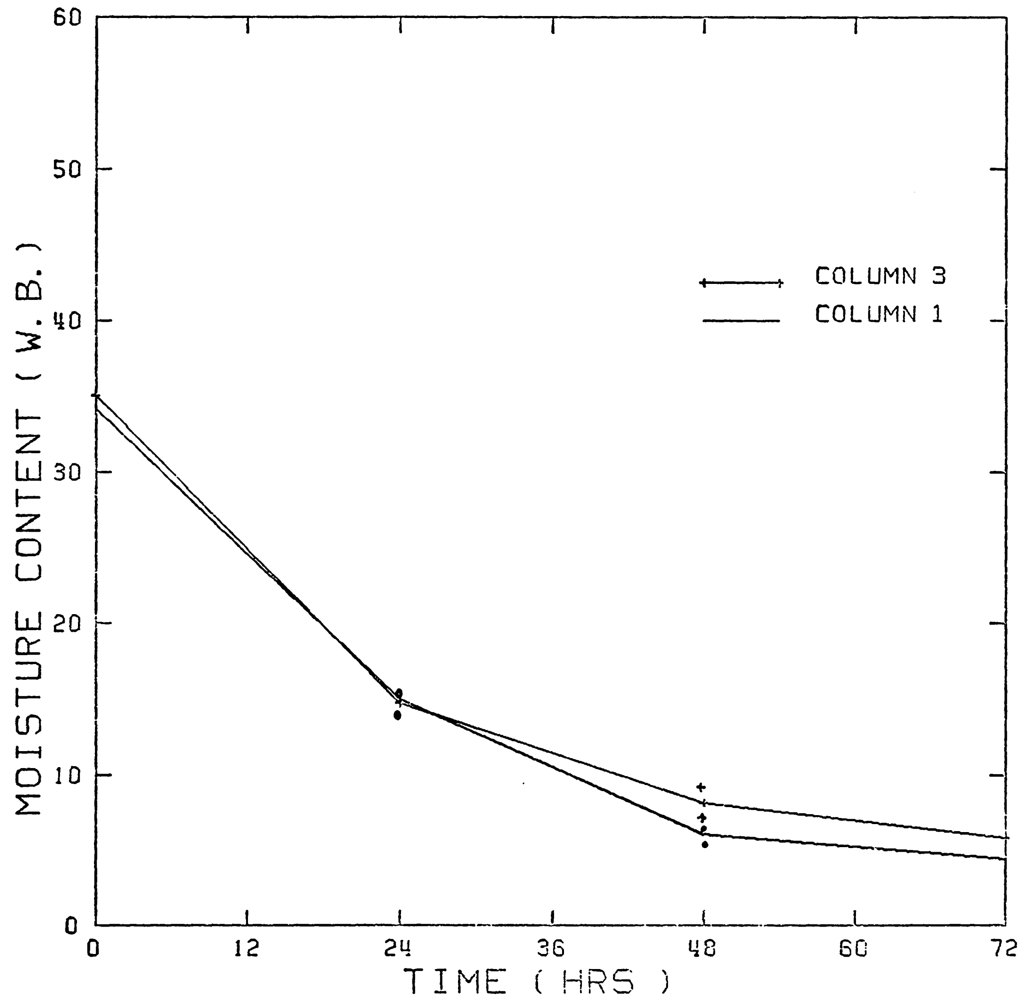

Figure 17: Experimental moisture content of the top layer in Run 1, Column 1 (55% recirculation), and Column 3 (0% recirculation).

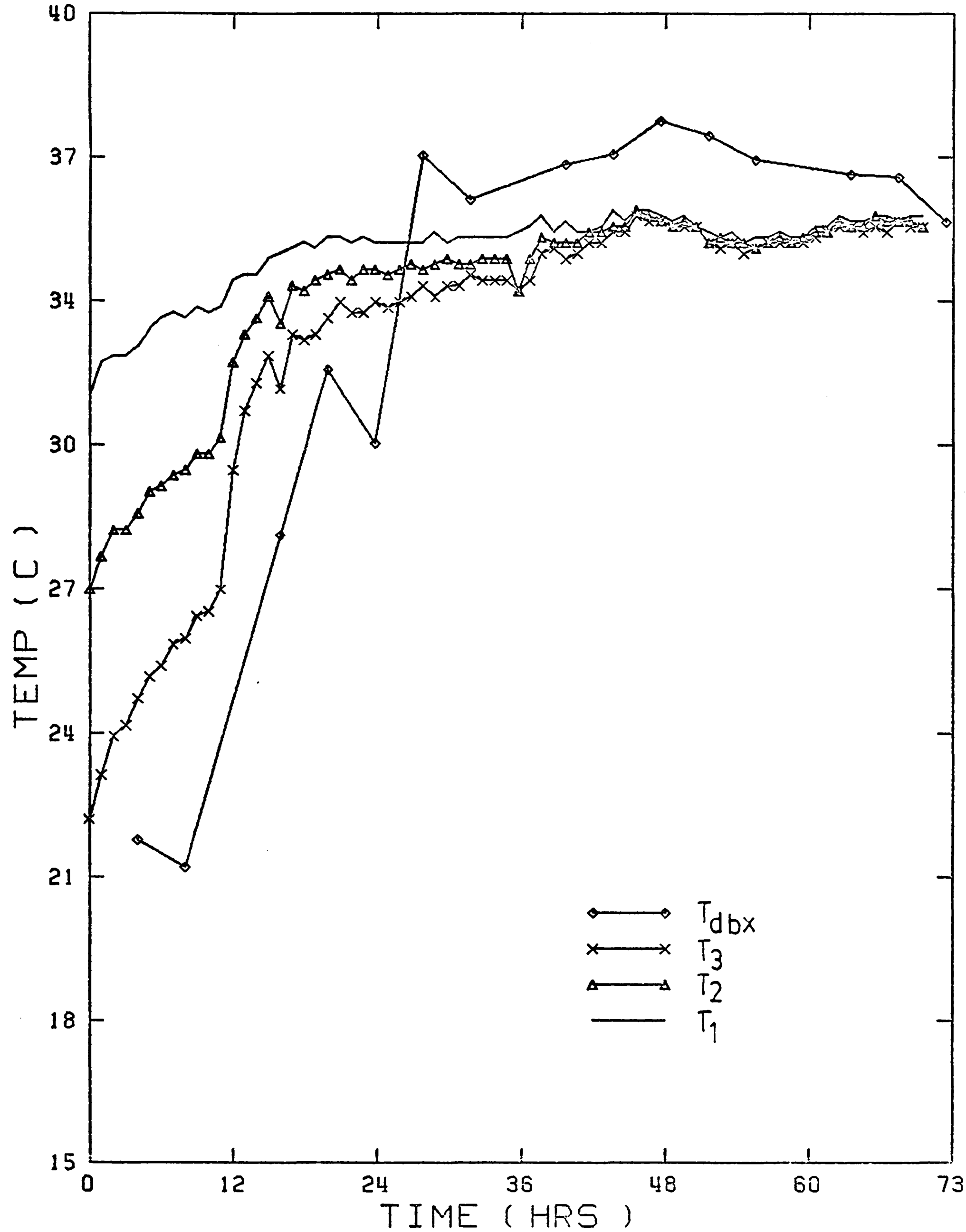

Figure 18: Measured temperature at depths of 0.3, 0.6, 0.9, 1.2 m in Column 1 Run 1, 55% recirculation.

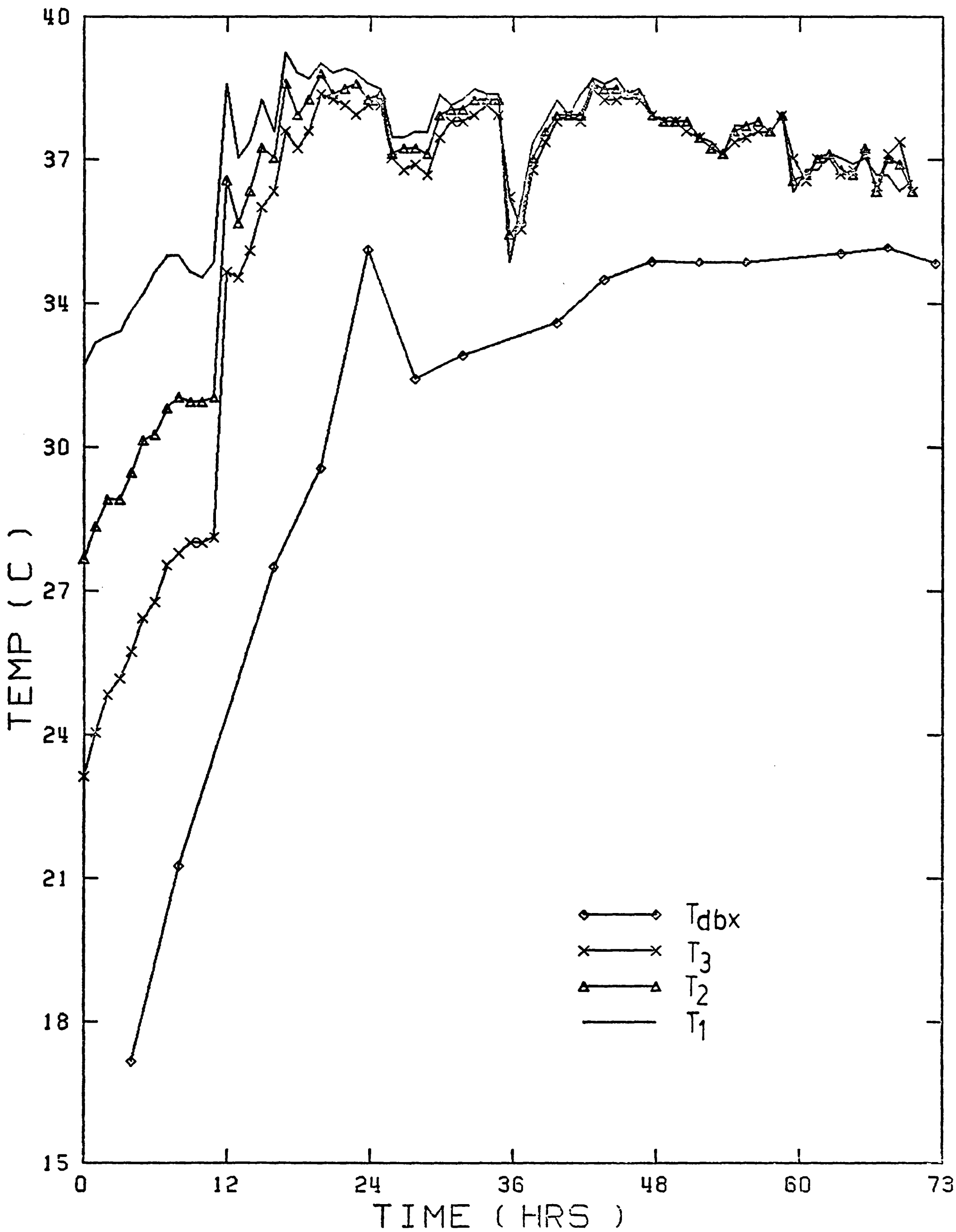

Figure 19: Measured temperature at depths of 0.3, 0.6, 0.9, 1.2 m in Column 3 Run 1, 0% recirculation.

hours, Column 1 at 85 hours, and Column 2 at 95 hours. This is evidence that drying time increases when air is recirculated in drying high moisture content peanuts.

The temperature gradient throughout the depth of peanuts is shown in Figures 21, 22, and 23 for Columns 1, 2, and 3, respectively. Again the expected trend was observed. The bottom layers dried first and the temperature rose quickly in these layers to 35 °C. As the remaining layers dried, the peanut temperature increased to 35 °C. The time at which the temperature reached 35 °C is a good indication of the time required for the drying front to reach that position in the column. For example, in Column 2 (Figure 22) the drying front reached 0.3 m at 34 hours, 0.6 m at 67 hours, 0.9 m at 82 hours, and 1.2 m at 87 hours.

TABLE 7

Initial parameters for Run 2 experiments

Parameters	Column 1	Column 2	Column 3
% Recirculation	66	69	0
Airflow ($m^3/min/m^3$)	8.2	8.2	8.2
Initial temp. (° C)	21	21	21
Initial MC (wb)	48.5	48.6	49.2
Initial depth m	1.22	1.22	1.22
Initial volume (m^3)	0.305	0.305	0.305

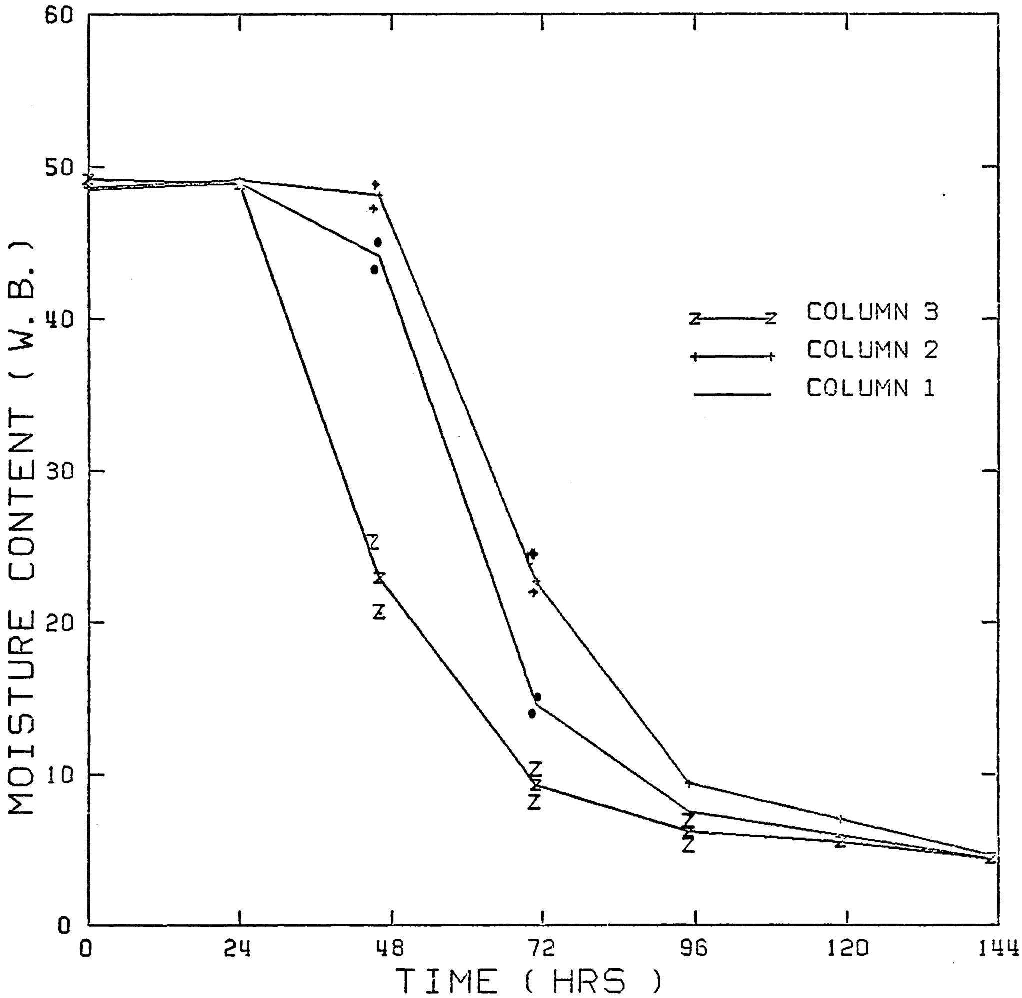

Figure 20: Experimental moisture content of top layer in Run 2, Column 1 (66 % recirculation), Column 2 (69 % recirculation), Column 3 (0 % recirculation).

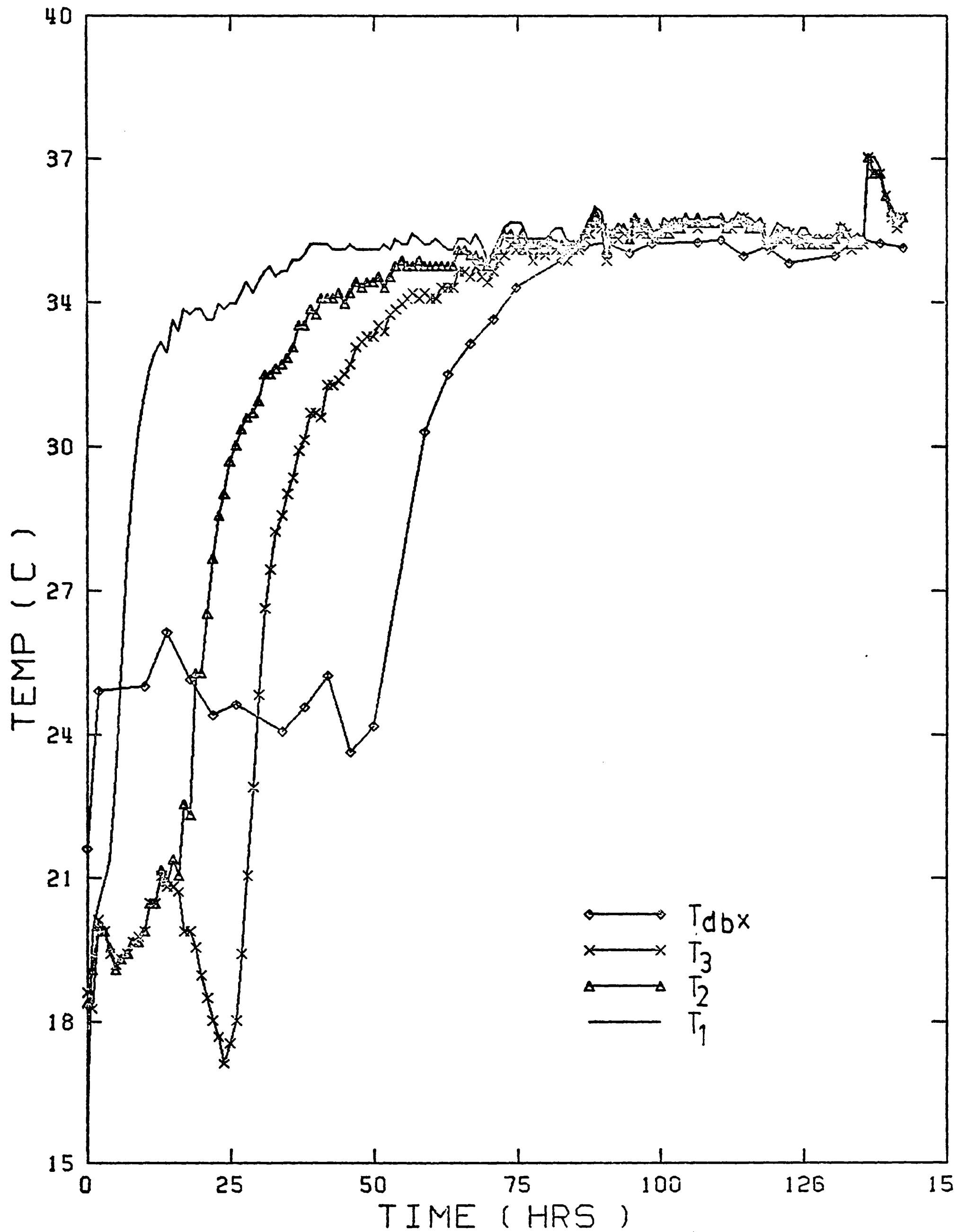

Figure 21: Measured temperature at depths of 0.3, 0.6, 0.9, 1.2 m in Column 1 Run 2, 66% recirculation.

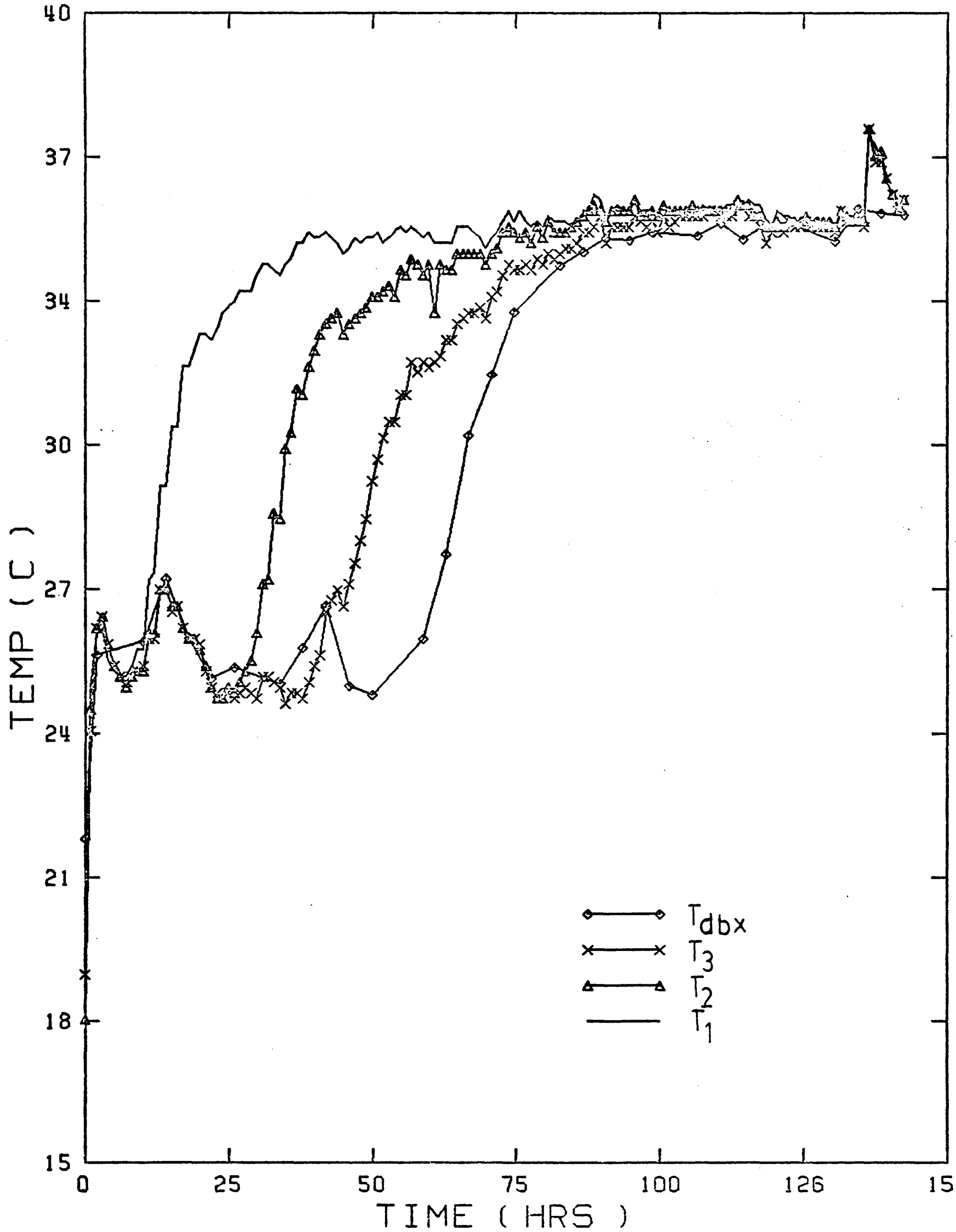

Figure 22: Measured temperature at depths of 0.3, 0.6, 0.9, 1.2 m in Column 2 Run 2, 69% recirculation.

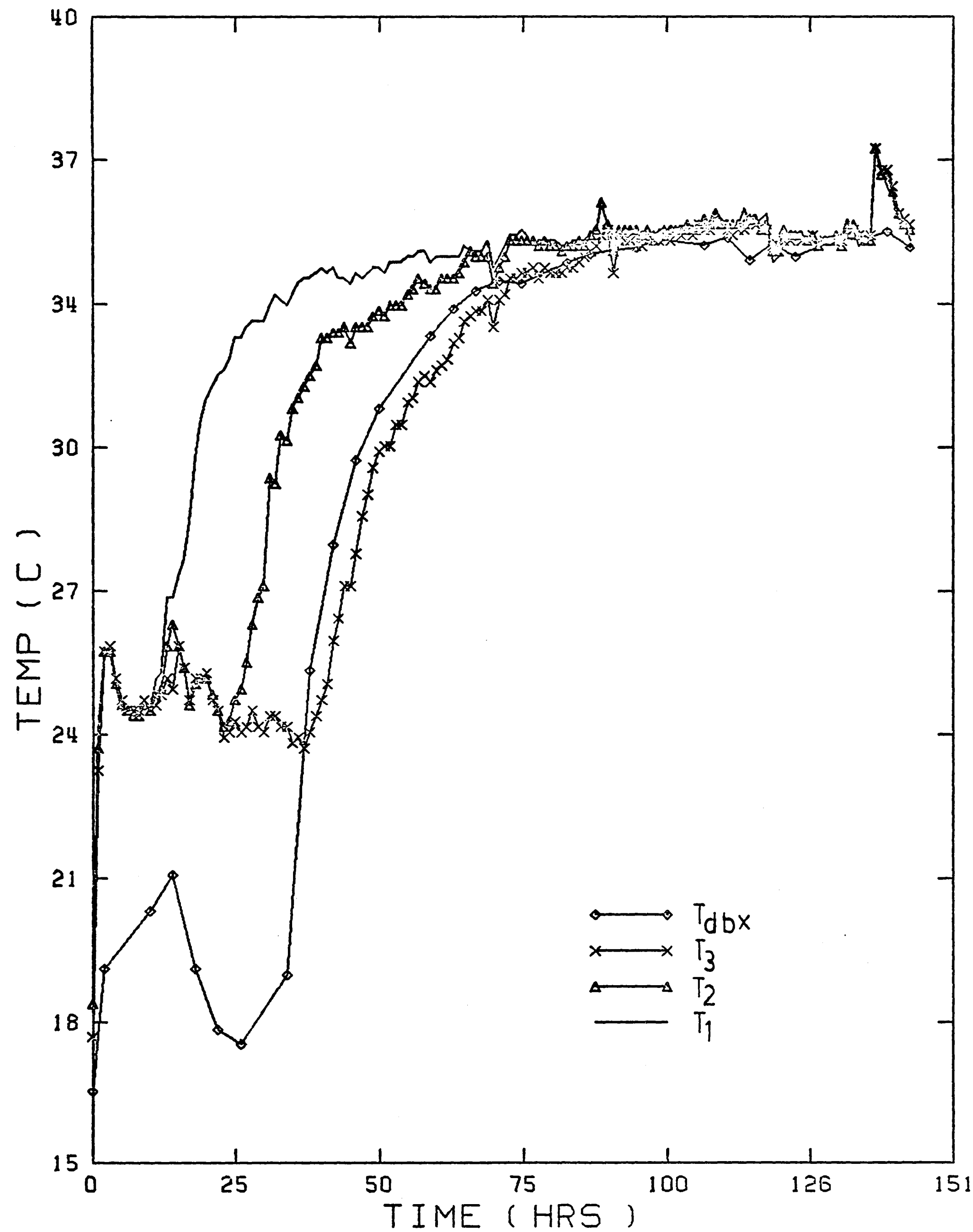

Figure 23: Measured temperature at depths of 0.3, 0.6, 0.9, 1.2 m in Column 3 Run 2, 0% recirculation.

5.1 AIRFLOW CORRECTION

The procedure incorporated to correct the airflow selected a value of 8.2 $m^3/min/m^3$. The simulation model calculated a total moisture loss in Column 3 Run 2 of 55.3 kg with the selected airflow. This compares to a measured weight loss (Equations 7 and 8) of 56.4 kg, a difference of only two percent. The average measured energy input (Q_f) during the hours 11 to 27 was 4.97 MJ/h, and which compares to a calculated value of 4.27 MJ/h. The closure error for the energy balance is then 0.5 MJ/h or approximately 10 percent. The airflow of 8.2 $m^3/min/m^3$ was used for the remaining four tests.

Shedd (1953) reported the resistance to airflow for peanuts. The measured static pressure drop across the peanuts was referenced to his data, and the predicted airflow was within 20 percent of the 8.2 $m^3/min/m^3$ value selected to close the moisture balance.

The simulated moisture content at layer 16 in Column 3 Run 2 is compared to the experimental moisture content in Figure 24. The calculated moisture content agrees well with the simulated moisture content during the early stages of the cure; however, the line departs from the experimental curve at hour 30, indicating some model inaccuracies during these stages of drying. The simulation predicted wet bulb temperature leaving layer 16 is compared to the measured wet bulb temperature in Figure 25. There is very good agreement between experimental and simulated values throughout the cure, while the dry bulb temperature comparison (Figure 26) shows a discrepancy from hours 30 to 50 of the cure. Simulation predicted supplemental energy (Q_f) is given in Figure 27. The simulated moisture contents using data collected from Column 3 Run 2 were compared with the experimental data (Figure 28). If the simulated and experimental values had agreed for the entire experiment then all the data points would have fallen on the diagonal line.

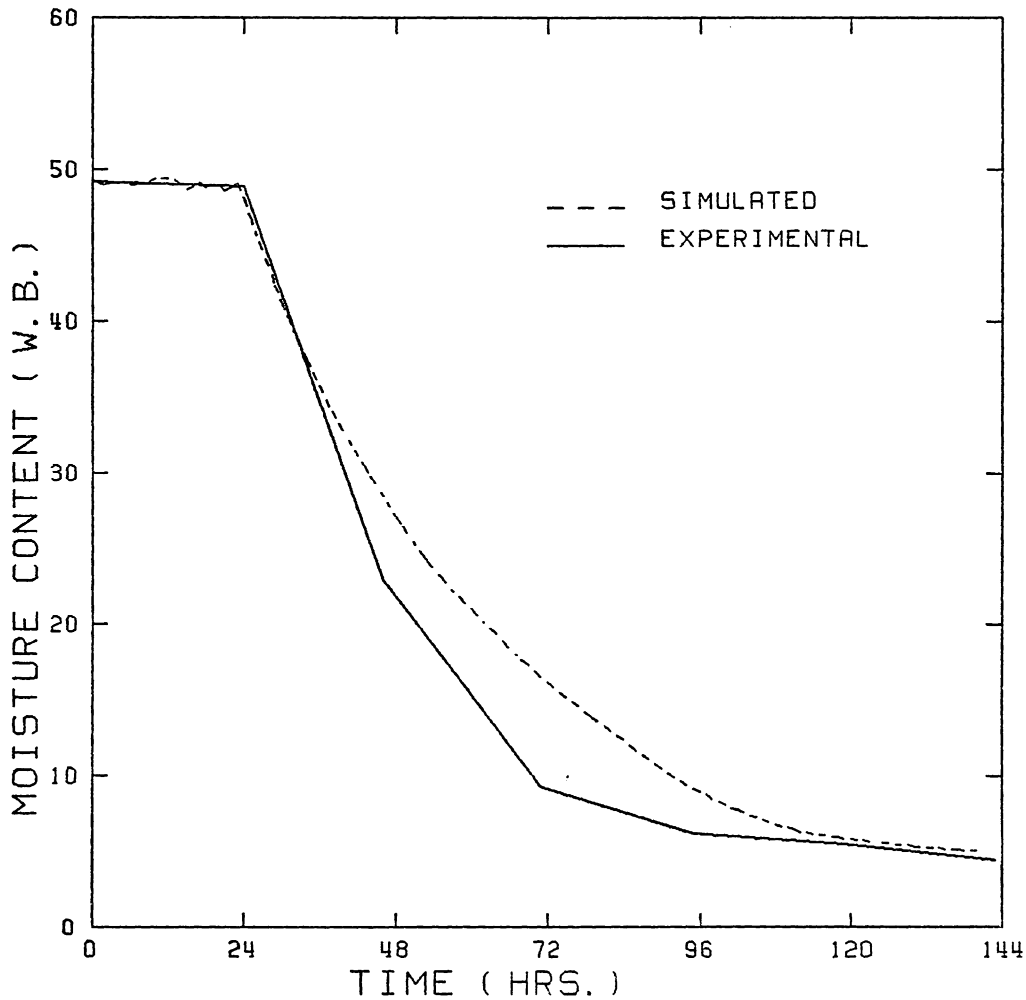

Figure 24: Simulated vs. experimental moisture content of top layer in Column 3 Run 2,(0% recirculation).

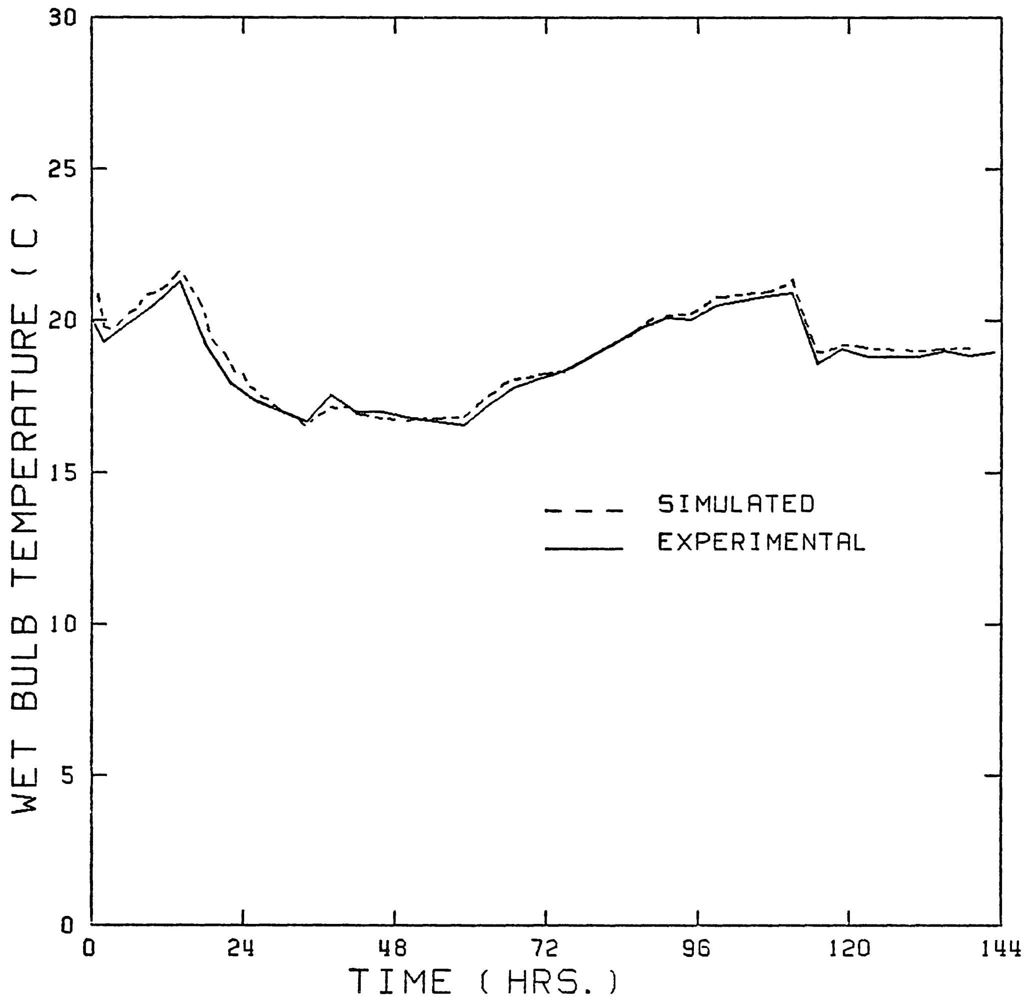

Figure 25: Simulated vs. experimental wet bulb temperature in Column 3 Run 2, (0% recirculation).

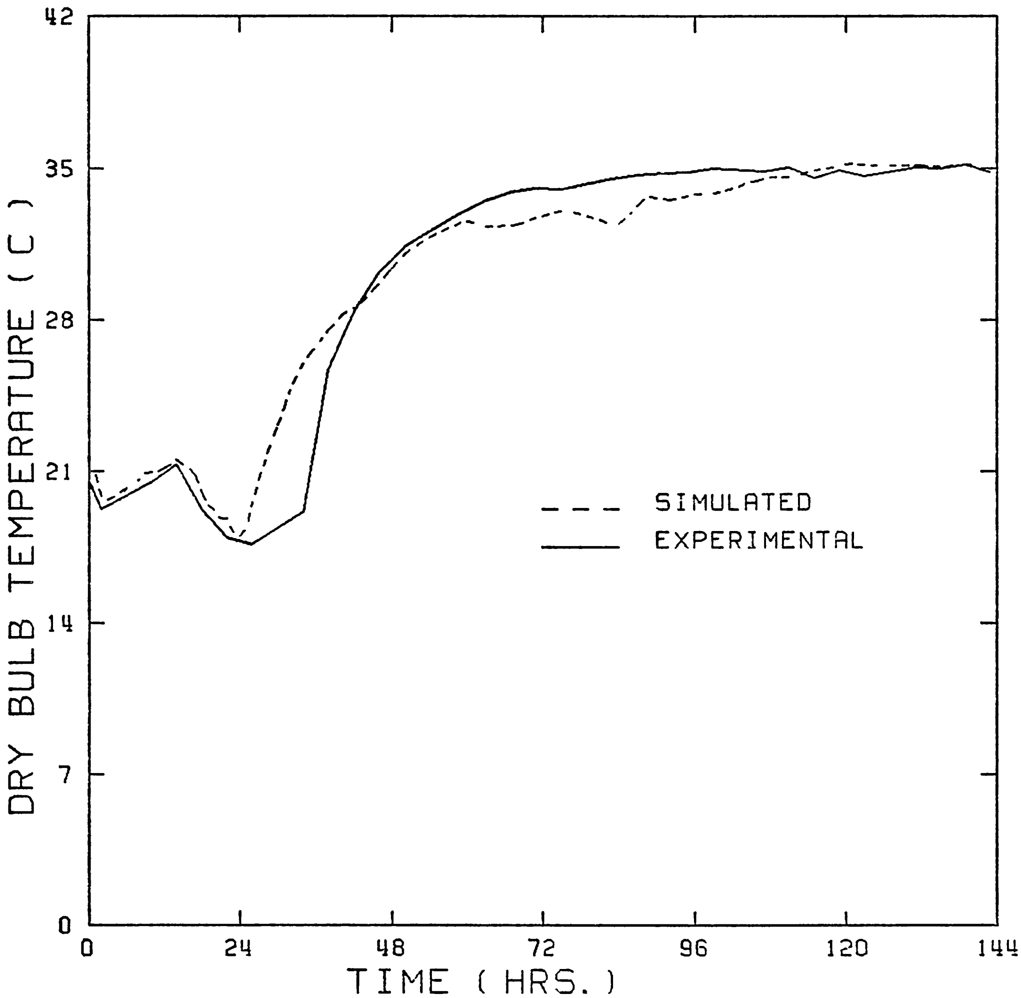

Figure 26: Simulated vs. experimental dry bulb temperature in Column 3 Run 2, (0% recirculation).

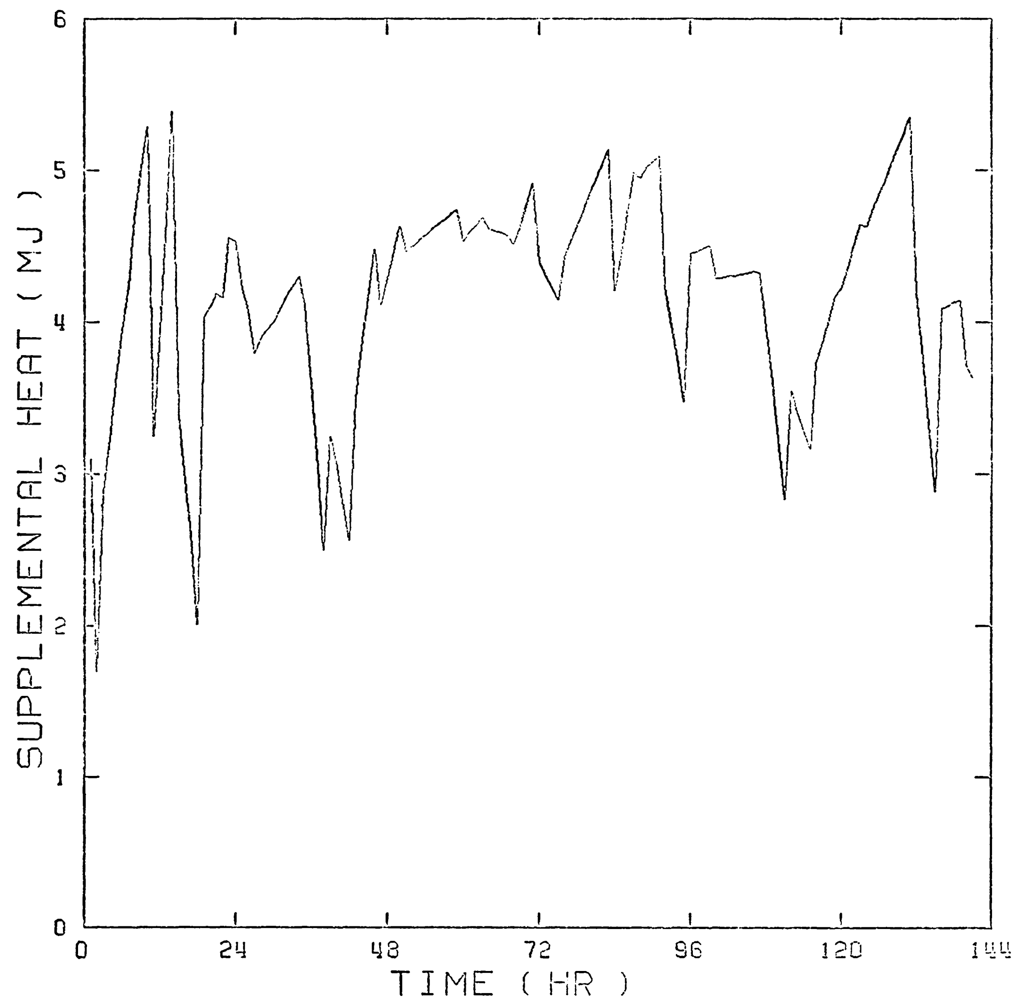

Figure 27: Calculated supplemental energy required in Column 3 Run 2, (0% recirculation).

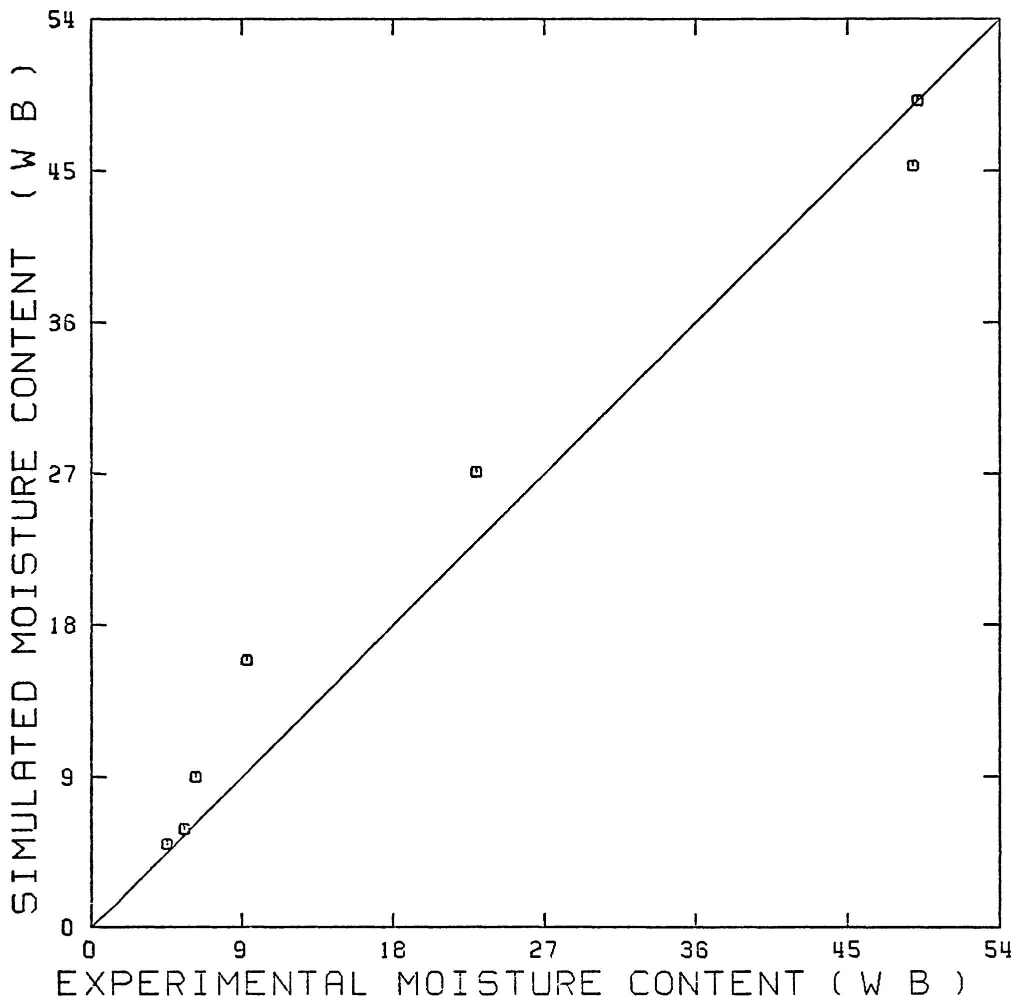

Figure 28: Comparison of simulated vs. experimental moisture content Column 3 Run 2, (0% recirculation).

5.2 *RESULTS*

The remaining four drying experiments were used to verify the model. Moisture content values from the experimental runs are summarized in Table 8 for Run 1 and Table 9 for Run 2. The simulation results, including moisture content, wet bulb temperature, and dry bulb temperature, are shown in Figures 29 to 40. To determine the accuracy of the model, predicted and experimental moisture contents were compared and the differences between the two are summarized in Table 10 for Run 1 and Table 11 for Run 2.

As expected, the model predicted a significant moisture gradient through the 16 layers of the 1.2 meter depth of peanuts. Layer 1, closest to the fan, had a much higher drying rate than layer 16, the top layer. The drying rates of these two layers during Run 2 in Column 3 are compared in Figure 41. The shapes of the two curves are very similar except for the initial 26 hours. Layer 16 was not dried during this time because the drying air was saturated when it reached the top layers. The slopes of the two curves are approximately equal when the air exiting the top layer was no longer saturated.

TABLE 8

Experimental vs. simulated moisture content in the top layer (layer 16) during Run 1.

	Column 1 Run 1		Column 3 Run 1	
Hour	Exp	Sim	Exp	Sim
0	34.2	34.2	35.1	35.1
24	15.0	22.1	14.8	21.7
48	6.1	12.0	8.2	12.9
72	4.5	7.4	5.9	8.4

TABLE 9

Experimental vs. simulated moisture content in top layer (layer 16) during Run 2.

	Column 1 Run 2		Column 2 Run 2		Column 3 Run 2	
Hour	Exp	Sim	Exp	Sim	Exp	Sim
0	48.5	48.5	48.6	48.6	49.2	49.2
24	49.0	49.0	49.1	45.5	48.9	45.3
46	44.1	46.6	48.1	49.4	22.9	27.1
71	14.6	27.6	22.7	36.9	9.3	15.9
95	7.5	12.5	9.4	14.9	6.2	9.0
119	6.0	6.8	7.1	7.0	5.6	5.9
143	4.4	5.5	4.7	5.5	4.5	5.0

TABLE 10

Difference between predicted and observed moisture content in top layer, Run 1.

	Column 1 Run 1	Column 3 Run 2
Hour	Sim-Exp	Sim-Exp
0	0.0	0.0
24	7.1	6.9
48	5.9	4.7
72	2.9	2.5

TABLE 11

Difference between predicted and observed moisture content in top layer, Run 2.

	Column 1 Run 2	Column 2 Run 2	Column 3 Run 2
Hour	Sim-Exp	Sim-Exp	Sim-Exp
0	0.0	0.0	0.0
24	0.0	-3.6	-3.6
46	2.5	1.3	4.2
71	13.0	14.2	6.6
95	5.0	5.5	2.8
119	0.8	0.1	0.3
143	1.1	0.8	0.5

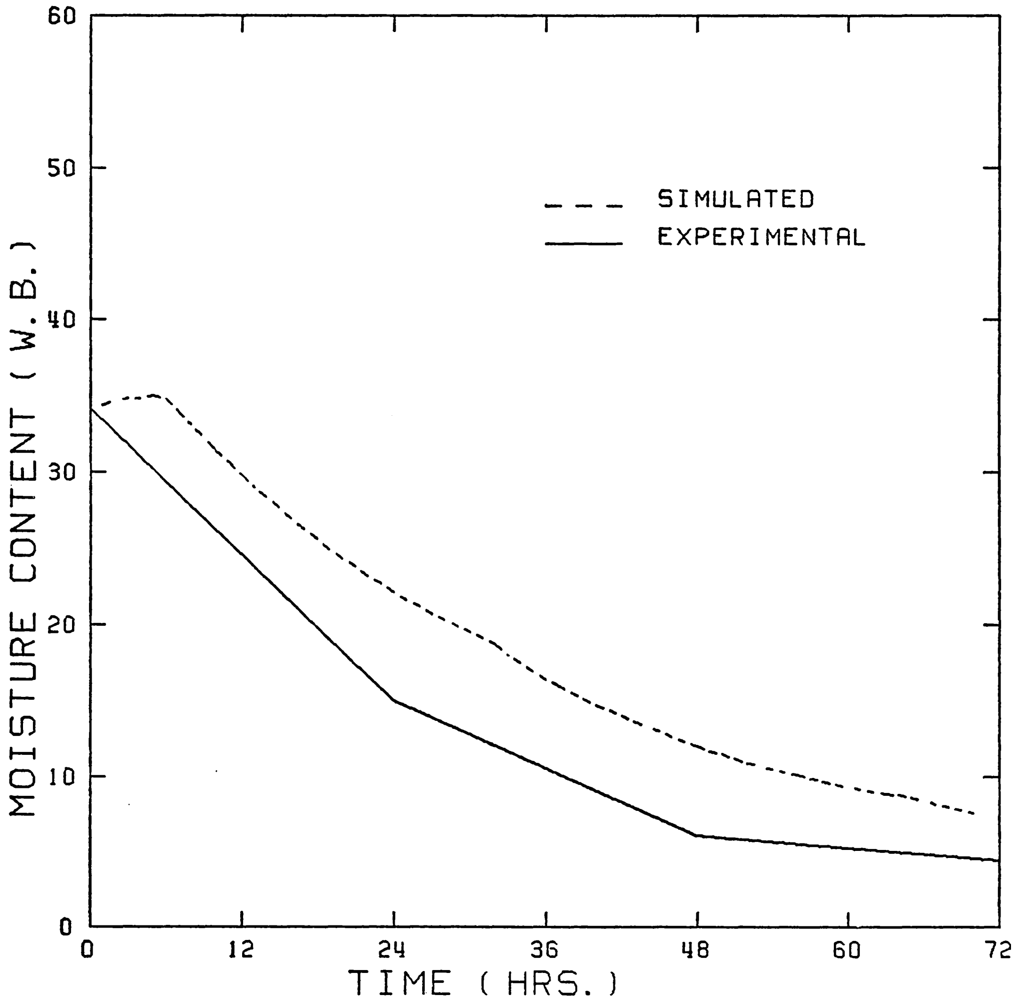

Figure 29: Simulated vs. experimental moisture content of top layer, Column 1 Run 1, (55% recirculation).

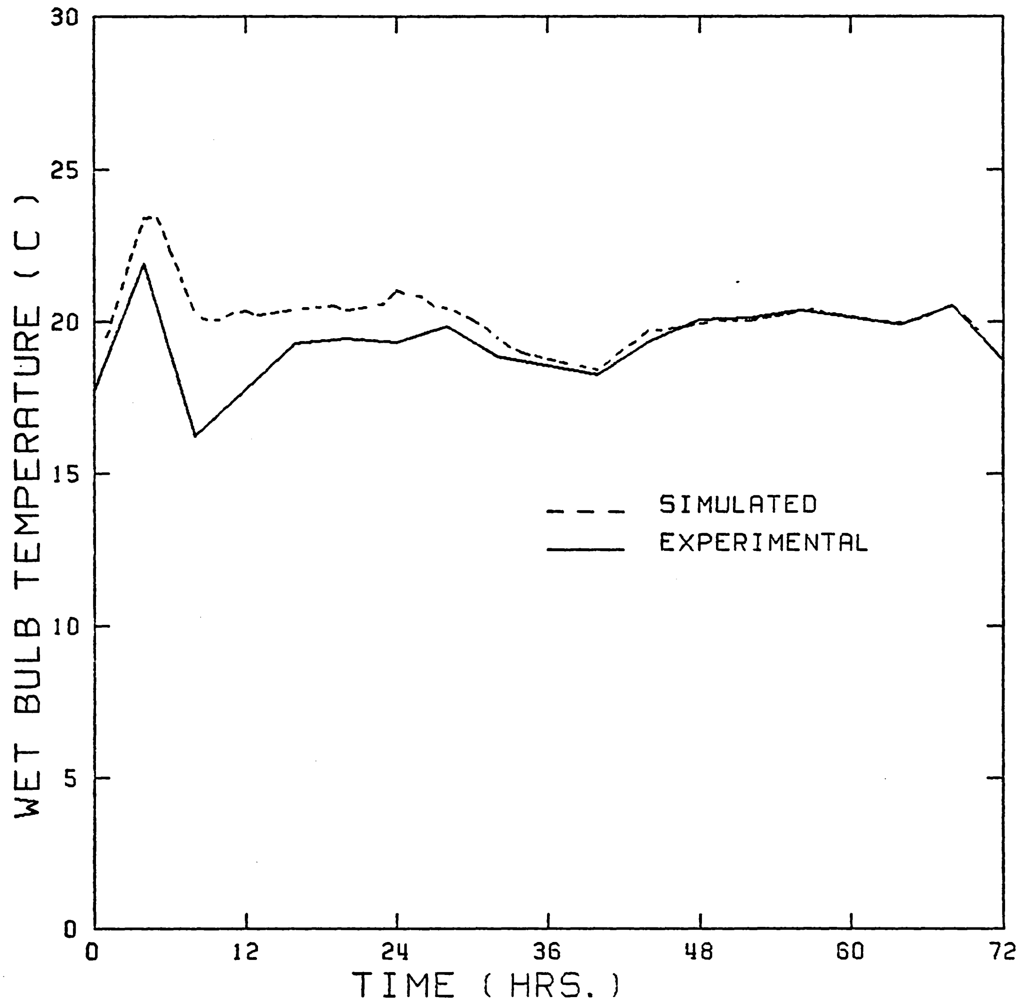

Figure 30: Simulated vs. experimental wet bulb temperature in Column 1 Run 1, (55% recirculation).

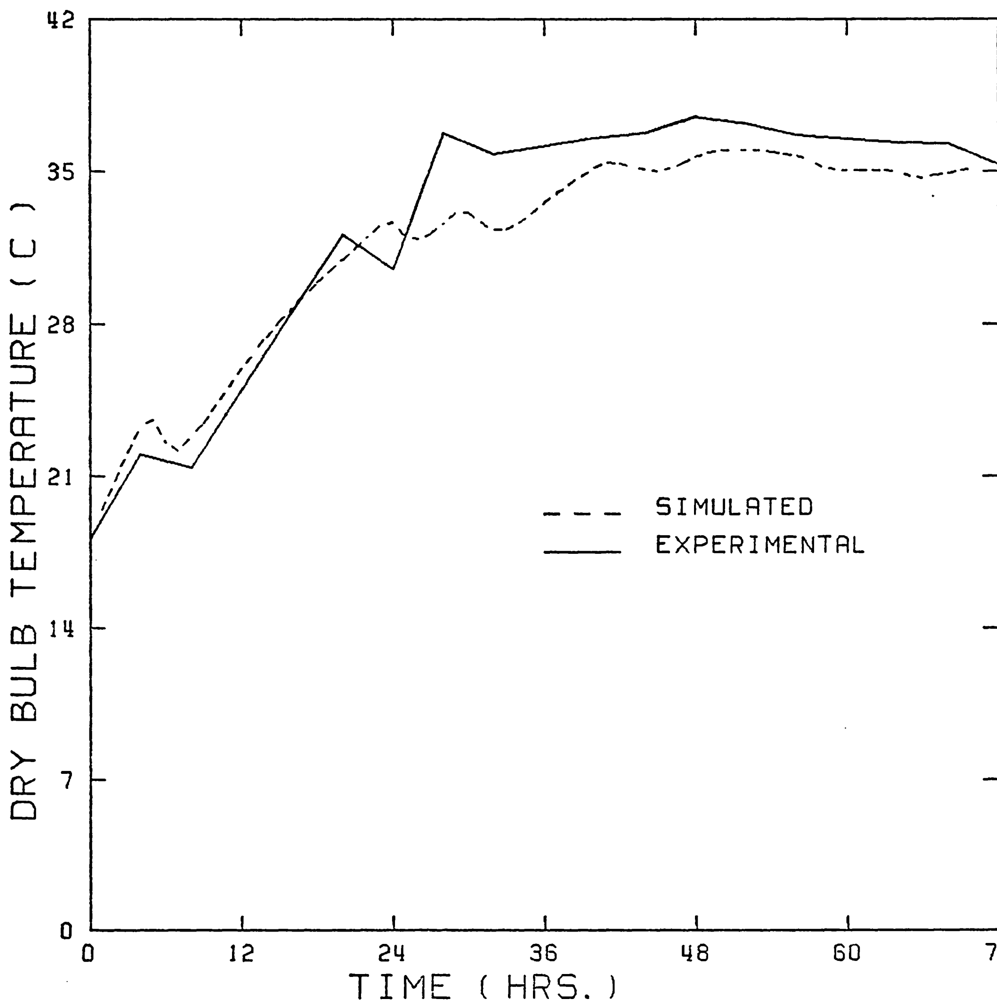

Figure 31: Simulated vs. experimental dry bulb temperature in Column 1 Run 1, (55% recirculation).

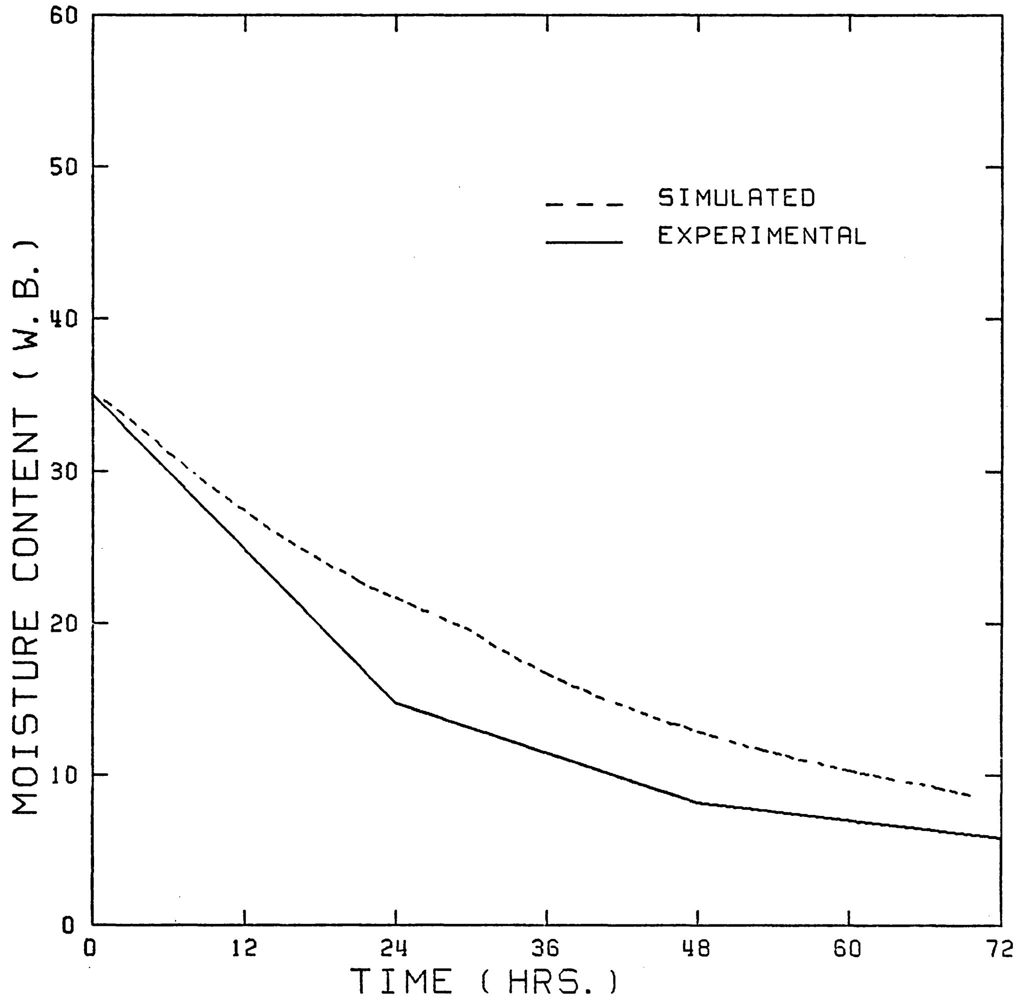

Figure 32: Simulated vs. experimental moisture content of the top layer in Column 3 Run 1, (0% recirculation).

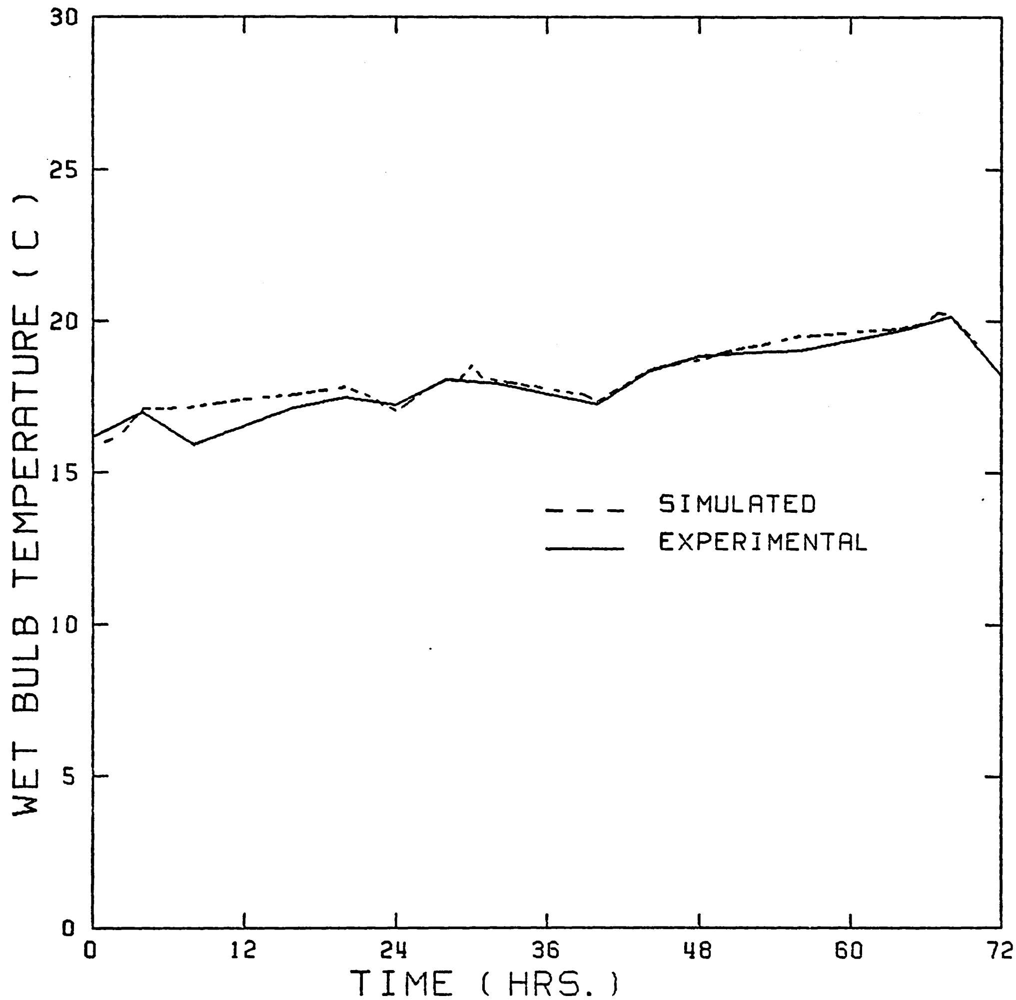

Figure 33: Simulated vs. experimental wet bulb temperature in Column 3 Run 1, (0% recirculation).

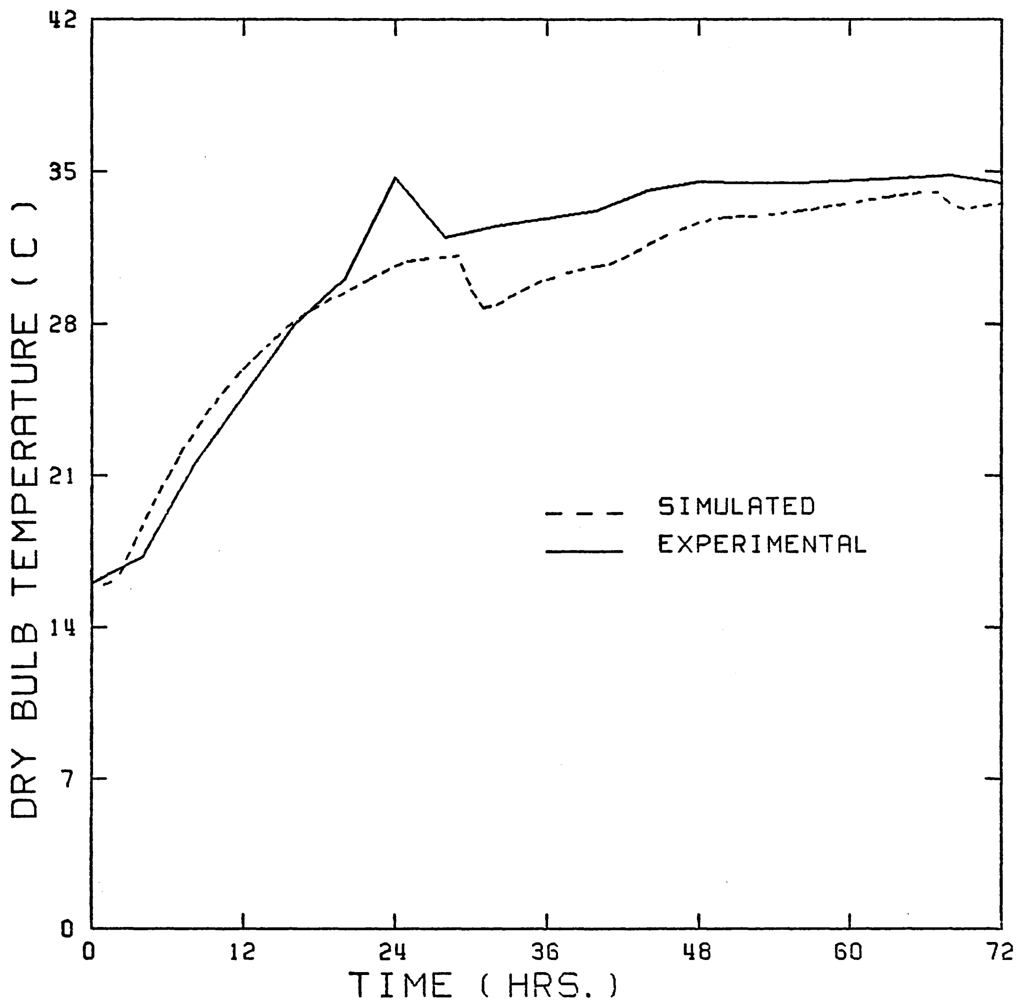

Figure 34: Simulated vs. experimental dry bulb temperature in Column 3 Run 1, (0% recirculation).

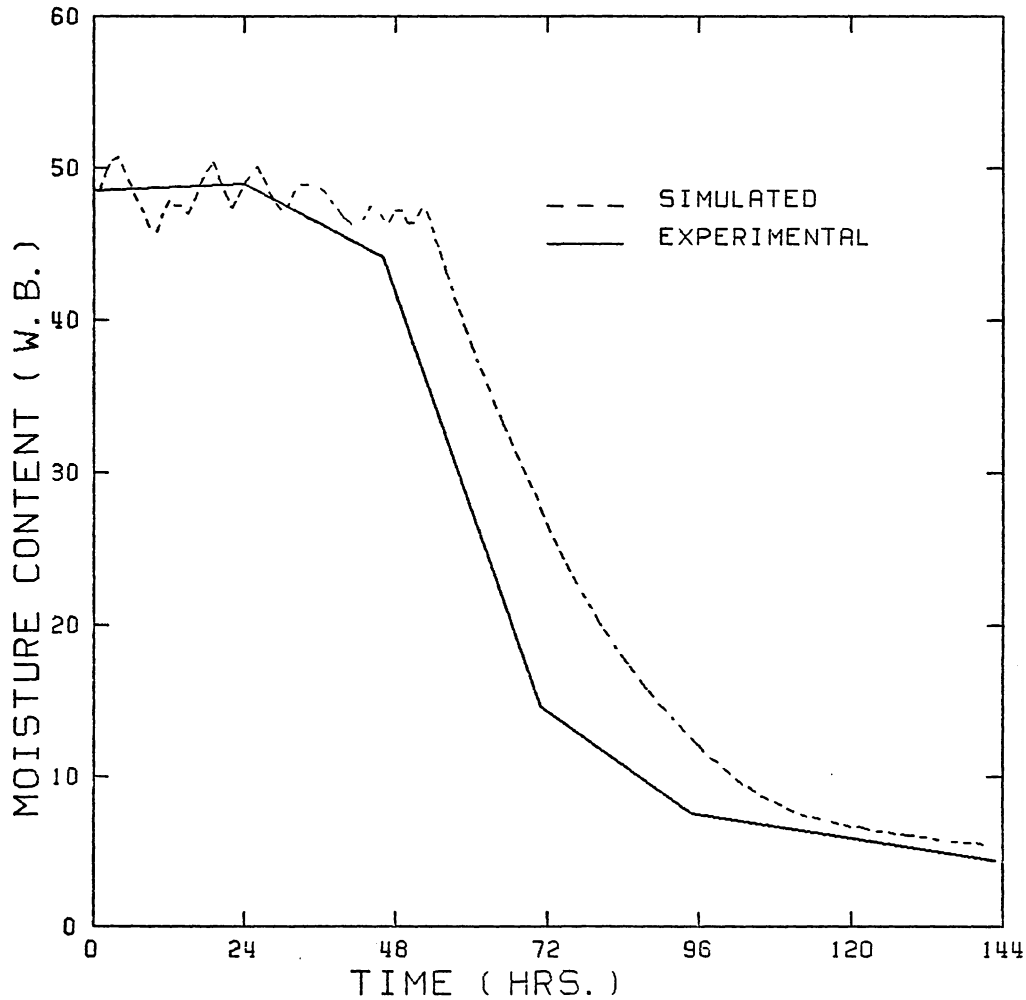

Figure 35: Simulated vs. experimental moisture content of the top layer in Column 1 Run 2, (66% recirculation).

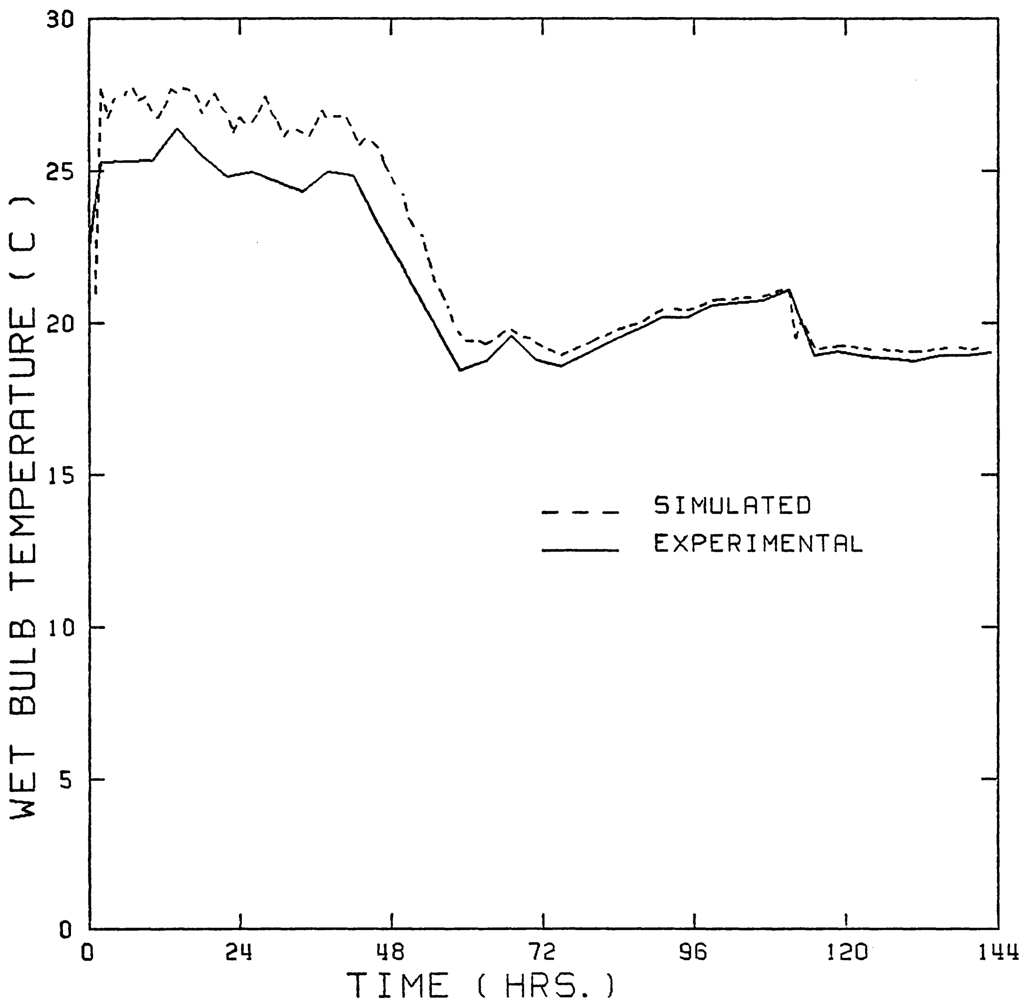

Figure 36: Simulated vs. experimental wet bulb temperature in Column 1 Run 2, (66% recirculation).

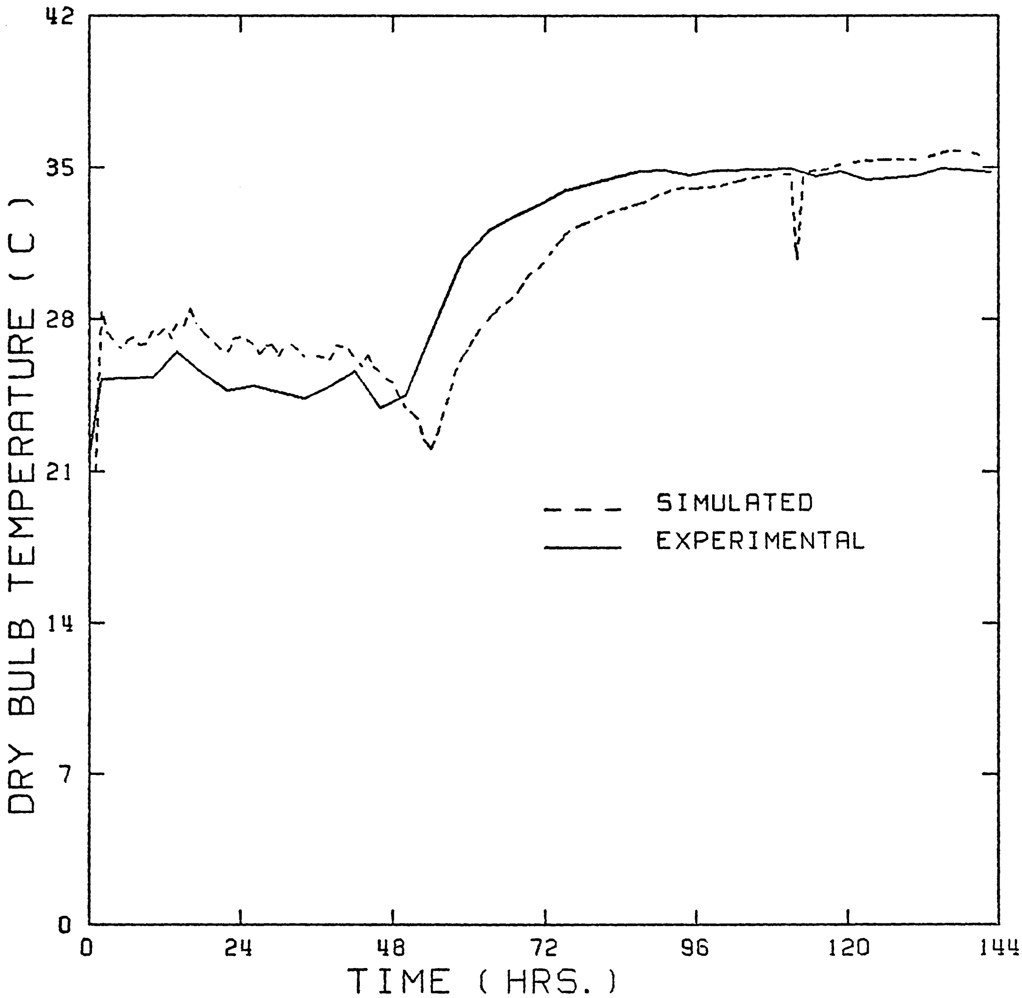

Figure 37: Simulated vs. experimental dry bulb temperature in Column 1 Run 2, (66% recirculation).

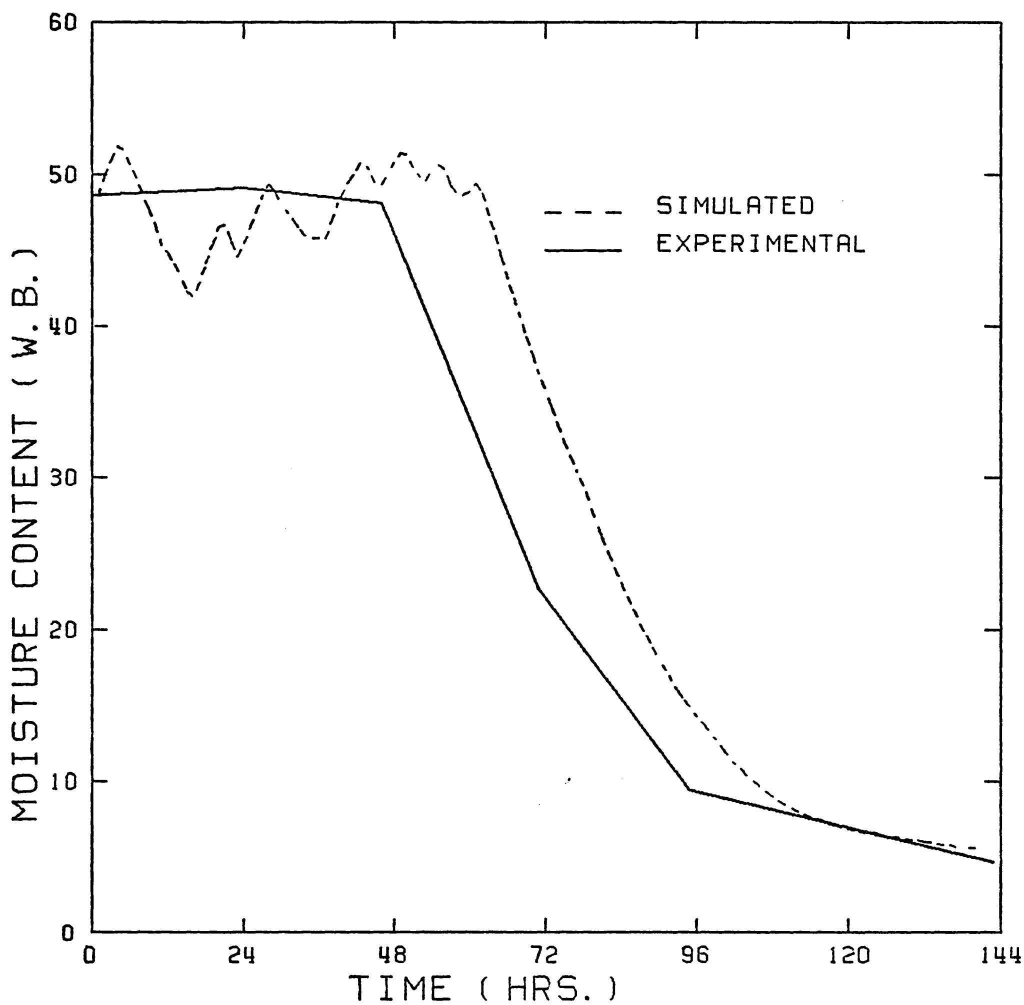

Figure 38: Simulated vs. experimental moisture content of the top layer in Column 2 Run 2, (69% recirculation).

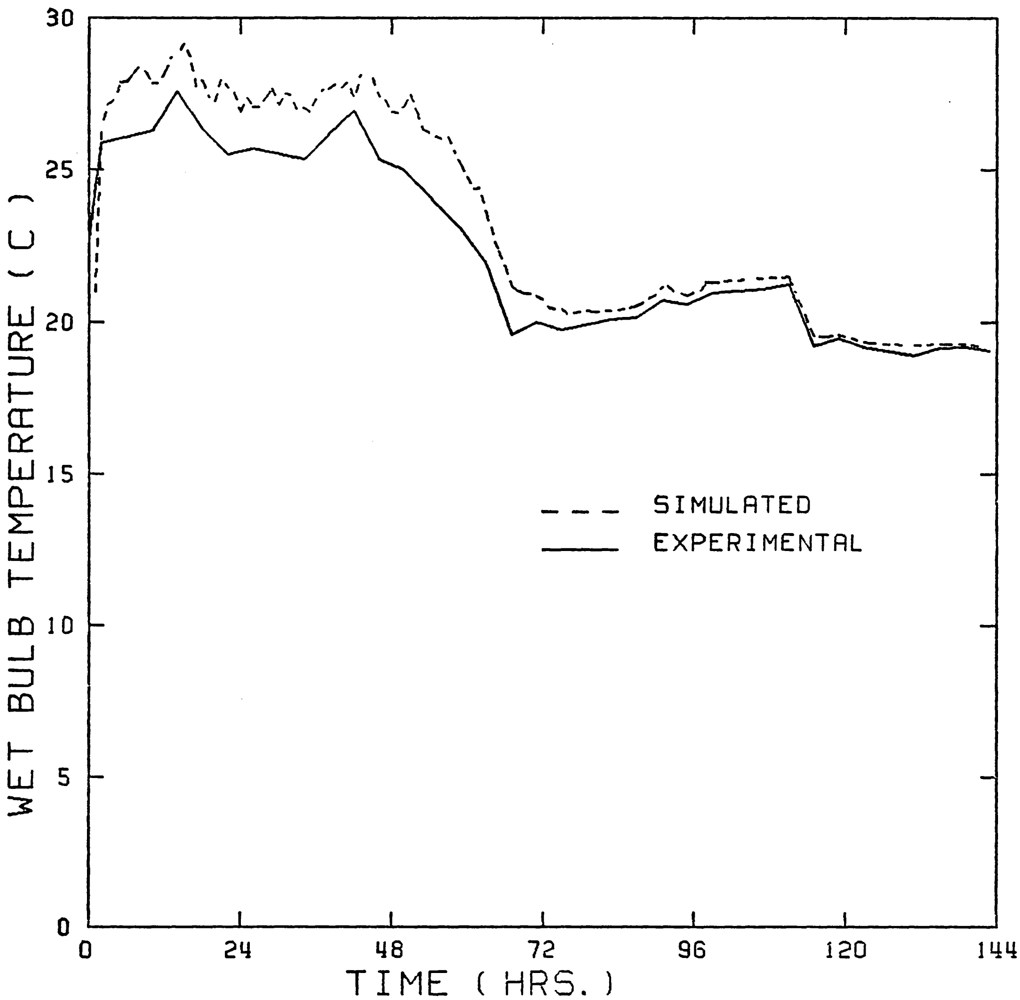

Figure 39: Simulated vs. experimental wet bulb temperature in Column 2 Run 2, (69% recirculation).

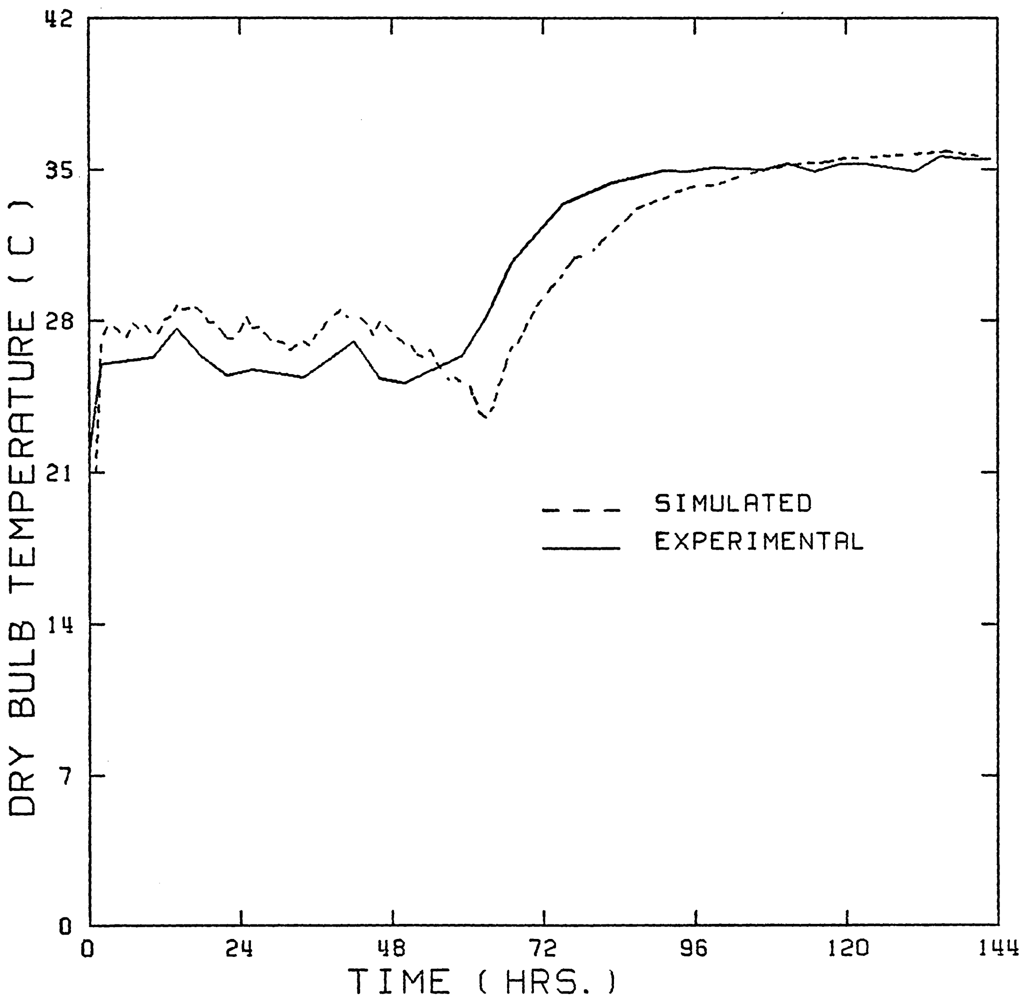

Figure 40: Simulated vs. experimental dry bulb temperature in Column 2 Run 2, (69% recirculation).

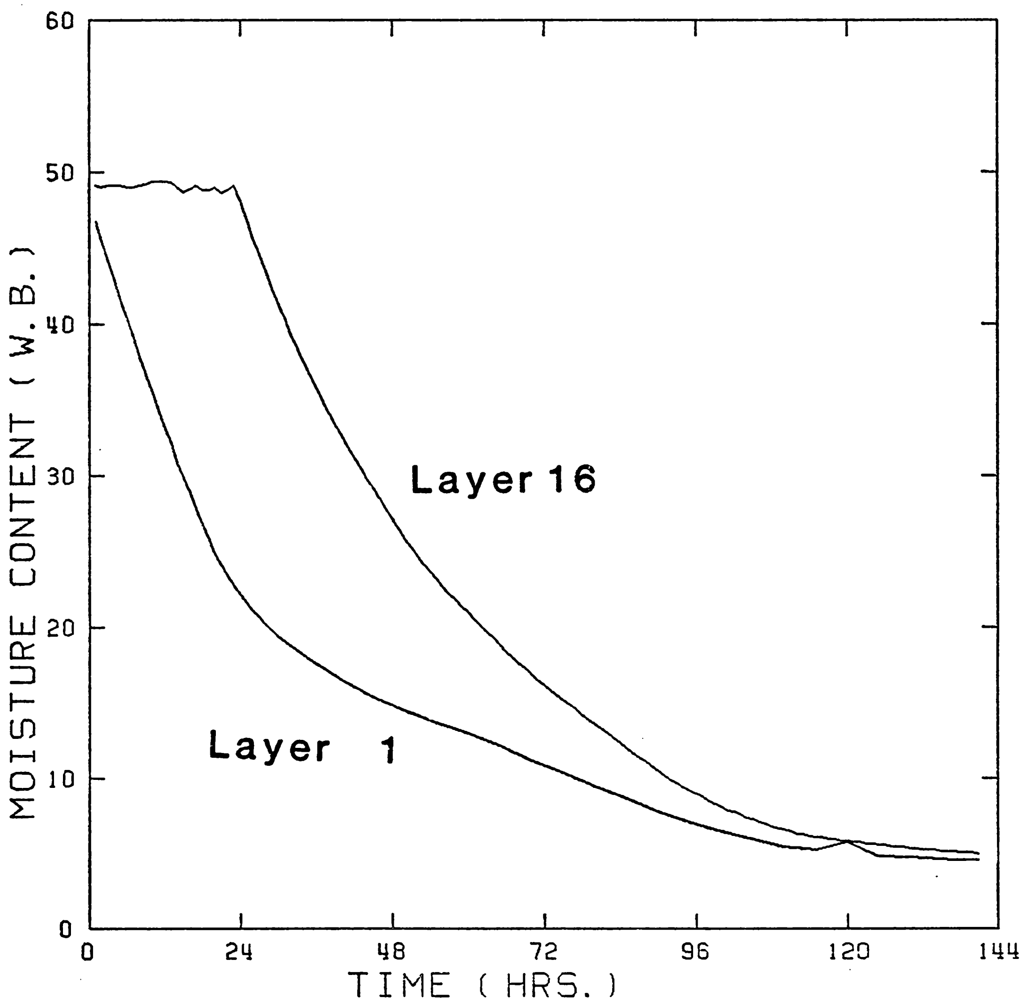

Figure 41: Moisture gradient developed in the top and bottom layers in Column 3 Run 2.

5.3 DISCUSSION OF RESULTS

In all cases the peanuts in the simulation run dried at a slower rate than the experimental data showed (Figures 24, 29, 32, 35, and 38). The slopes of the simulated drying curves followed closely the slopes of the experimental drying curves throughout each cure.

The moisture content results for Run 1 (Figures 29 and 32) show the simulated drying rate to be higher than the experimental rate throughout the cure. Moisture content in Run 2 matched well during the beginning of the cure while discrepancies developed during the middle-range of the cure. The model predicted variation in the moisture content of the top layers (Figures 24, 35, and 38) due to rewetting of the peanuts in the upper layers by the saturated air. Moisture content samples were taken every 24 hours; therefore, the variation during the first hours was not measured experimentally.

Troeger's equation for single layer drying (Equation 9) depends on the moisture ratio (Equation 10). The two drying parameters, a and b, vary depending on whether the moisture ratio is less than 0.12, between 0.12 and 0.40, or greater than 0.40. The slope of the drying curve changes when the moisture ratio reaches one of these points. Examining the moisture content predictions in all runs, it appeared the model would predict more accurately for the experimental data collected if the break points of the moisture ratio were varied. For example, Figure 38 shows the simulated drying curve departing from the experimental curve at 45 hours. At this point the moisture ratio of the top layer was 0.40. The slope of the simulated drying curve was thus decreased as the moisture ratio entered the middle range. The experimental curve maintained a steeper slope during hours 45 to 70.

In the early stages of all the cures, the air exiting the peanuts was saturated. In Run 1 Column 1, the simulated exhaust air was saturated for only 8 hours, while the air exhausted from Column 3 was saturated for 5 hours. Only air exhausted from the fifteenth and sixteenth layers was saturated. Due to the short time interval during which the air was saturated no rewetting of the top layers of the peanuts occurred in Run 1. During Run 2 the simulated exhaust air was saturated for 55 hours in Column 1, for 63 hours in Column 2, and for 23 hours in Column 3. These saturated air conditions throughout the top layers of the peanuts caused rewetting of those top layers in Run 2. Figure 38 shows significant drying of the top layer of the peanuts before rewetting occurs. During the first hour the drying air in that column was saturated after leaving the second layer.

Thus the middle layers were rewetted while the top layers were dried slightly because a small drying potential was present in the air after moisture was lost to the middle layers of peanuts.

Troeger and Butler (1979) dried peanuts with an initial moisture content of 30 percent (wb) and obtained good agreement between the experimental and simulation results. Troeger and Butler's initial moisture content was significantly lower than the moisture content in this experiment. Their model may not be appropriate for green peanuts (50 percent moisture content (wb) peanuts). Data from additional drying tests should be collected to improve the equation representing the rate of moisture removal.

The simulated wet and dry bulb temperatures matched well with the measured temperatures (Figures 25, 26, 30, 31, 33, 34, 36, 37, 39, and 40) with few exceptions. The measured dry bulb temperature at hour 24 in Run 1 appears to be a bad data point.

A large drying potential was present in these experiments because of high airflow and the 35 °C drying temperature. Due to this, a very rapid drying rate existed in the lower layers. The bottom layers were actually dried too rapidly and overdried. Figure 41 shows the high drying rate of the first layer in Column 3 Run 2, which is representative of all the runs. The drying potential should have been reduced to eliminate overdrying.

Heat and mass balances were performed on each column, and the calculated supplemental heat energy input (Equation 36) is shown in Figure 42 for Run 1 and Figure 43 for Run 2. The low rates of supplemental heat required (Figure 42) at 24 and 48 hours coincide with high ambient temperatures during the afternoon. Note that the supplemental heat rate in Column 1 was less than in Column 3 throughout most of the cure, indicating that recirculation reduced energy consumption. The rate of supplemental heat input (Figure 43) for Columns 1 and 2 was approximately equal throughout the cure, as might be expected since the recirculation rates (66 percent in Column 1 and 69 percent in Column 3) were almost equal. For the time interval from hours 18 to 64, the supplemental heat rate in Columns 1 and 2 was higher than Column 3, indicating that recirculation required more energy during this period. Beyond 64 hours, recirculation reduced the energy consumption rate and was therefore beneficial. Summaries of the supplemental heat energy input, broken into its three component parts are given in Table 12 for Run 1, and Table 13 for Run 2. The energy savings due to recirculation are summarized in Table 14. These savings were calculated by comparing the heat energy required to that used in Column 3, with no recirculation. Savings of up to 20 percent were observed. In the second run, using the wetter peanuts, more energy was saved by recirculating 66 percent of the air than 69 percent. As the recirculation percentage increases the humidity of the drying air also increases and reaches a point where energy savings decrease because the air has a low drying potential, as demonstrated in the results of Run 2.

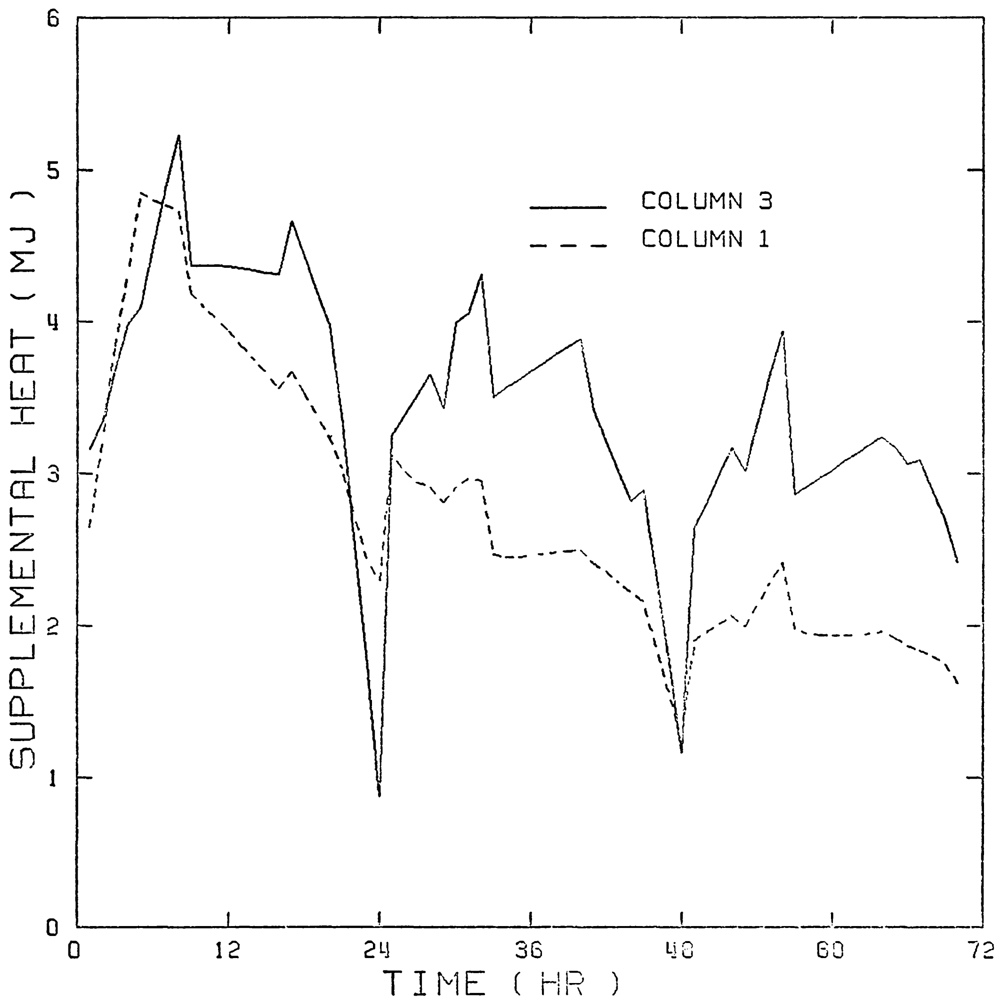

Figure 42: Calculated supplemental heat energy input in Run 1, Column 1 - 55% recirculation, Column 3 - 0% recirculation.

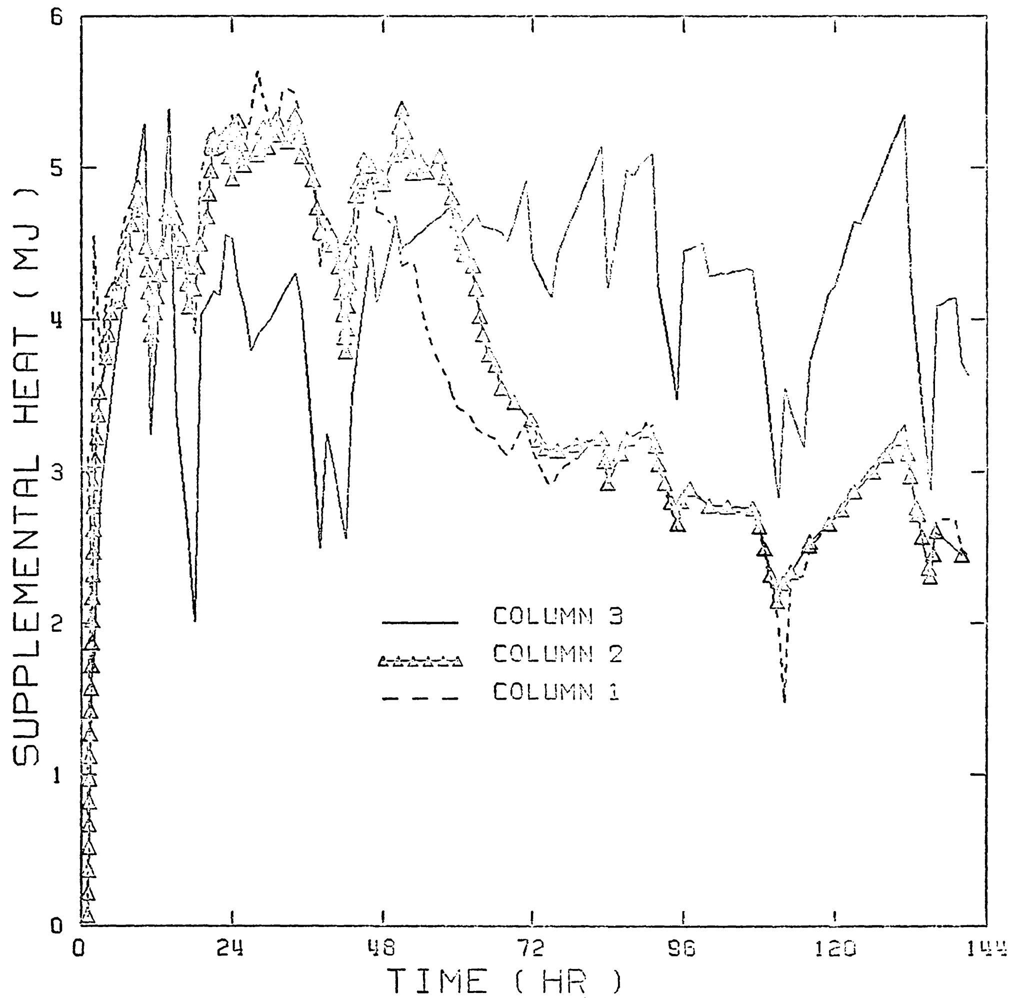

Figure 43: Calculated supplemental heat energy input in Run 2, Column 1 (66 % recirculation), Column 2 (69 % recirculation), Column 3 (0 % recirculation).

TABLE 12

Energy balance terms for Run 1

SUPPLEMENTAL HEAT ENERGY INPUT RUN 1

DESCRIPTION	% RECIRCULATION		QX	QM	QS	QF
Column 1	55	MJ	147	0-	44	191
		%	77	0-	23	100
Column 3	0	MJ	205	0-	36	241
		%	85	0-	15	100

QX = Energy in exchanged air

QM = Energy to elevate and maintain material temperature

QS = Energy to elevate and maintain structure temperature

TABLE 13

Energy balance terms for Run 2

SUPPLEMENTAL HEAT ENERGY INPUT RUN 2

DESCRIPTION	% RECIRCULATION		QX	QM	QS	QF
Column 1	66	MJ	309	0-	198	507
		%	61	0-	39	100
Column 2	69	MJ	324	0-	198	522
		%	62	0-	38	100
Column 3	0	MJ	429	0-	159	588
		%	73	0-	27	100

QX = Energy in exchanged air

QM = Energy to elevate and maintain material temperature

QS = Energy to elevate and maintain structure temperature

TABLE 14

Energy savings produced by recirculation during the experimental runs

		Recirculation %	Total Energy Input MJ	Energy Savings %
Column 1	Run 1	55	191.28	20
Column 3	Run 1	0	240.66	--
Column 1	Run 2	66	506.79	14
Column 2	Run 2	69	521.53	12
Column 3	Run 2	0	587.90	--

		Water Removed kg	Energy Savings (with respect to kg water removed) %
Column 1	Run 1	28.52	---
Column 3	Run 1	28.90	---
Column 1	Run 2	9.17	12.1
Column 2	Run 2	9.00	13.7
Column 3	Run 2	10.0	---

5.3.1 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to evaluate the effects of the wet bulb temperature and airflow rate on the simulation results. Both quantities are difficult to measure accurately in practice.

The wet bulb temperature directly below the peanut mass was varied ± 1 °C for the Column 3 Run 2 cure. Figure 44 shows the resulting moisture content differed as much as 3 percent from the values simulated using the measured wet bulb temperature. Increasing the wet bulb temperature 1 °C caused drying to occur more slowly in the first 48 hours; however, the drying rate was then increased over the original rate during the final hours of the cure. Decreasing the wet bulb temperature 1 °C increased the drying rate in the first hours and decreased it during the final hours. Increasing the wet bulb temperature during the first 48 hours decreased the drying potential of the air because it became saturated faster. During these hours the dry bulb temperature exiting the peanuts was very close to the wet bulb temperature, indicating that the air was saturated. As the dry bulb temperature of air exiting the peanuts rose to 35 °C the increase in wet bulb temperature lost its effect since the air was no longer saturated and all of the available drying potential was not being utilized.

The airflow rate was varied ± 10 percent. The resulting moisture contents again differed as much as 3 percent from the predicted values using the selected airflow rate (Figure 45). Increasing the airflow rate by 10 percent increased the drying rate throughout the cure while decreasing the airflow rate decreased the drying rate. This variation caused the peanuts to reach a given moisture content up to 4 hours before they reached the same moisture content using the determined airflow.

The accuracy of the simulated results are highly dependent on both wet bulb temperature and airflow rate. Small variations in both quantities are capable of changing moisture content values up to six percent.

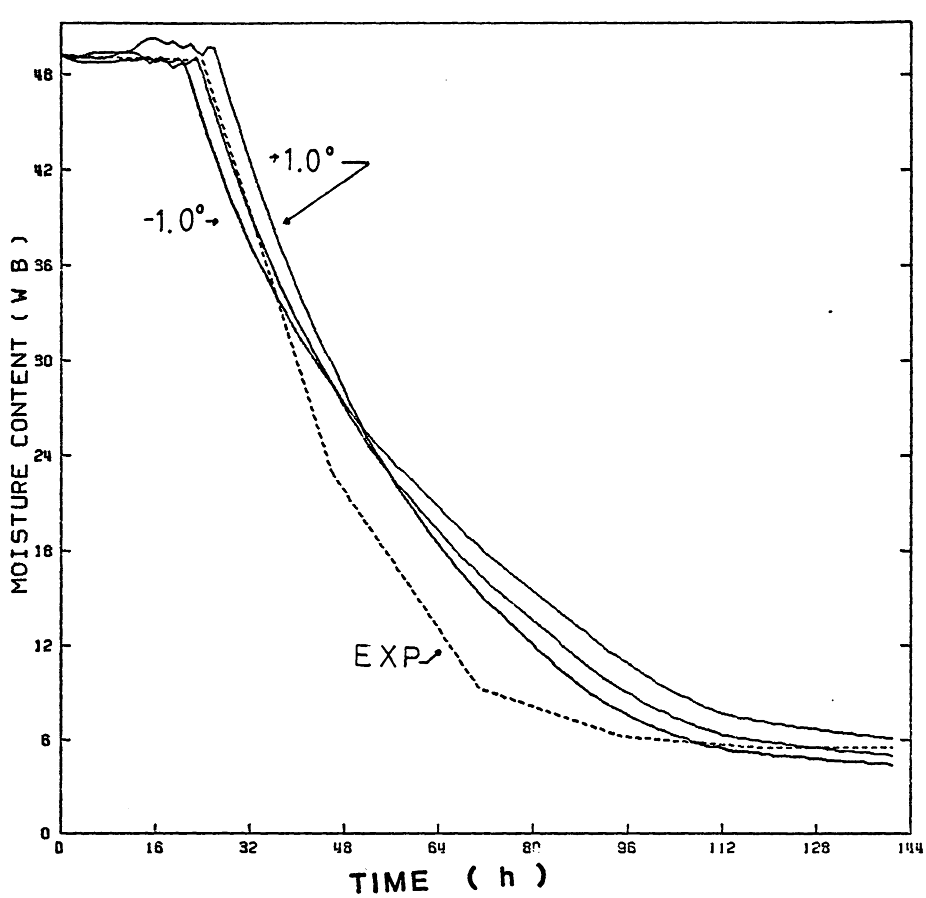

Figure 44: Moisture content calculated for layer 16 (Column 3 Run 2) by varying wet bulb temperatures, ± 1 °C.

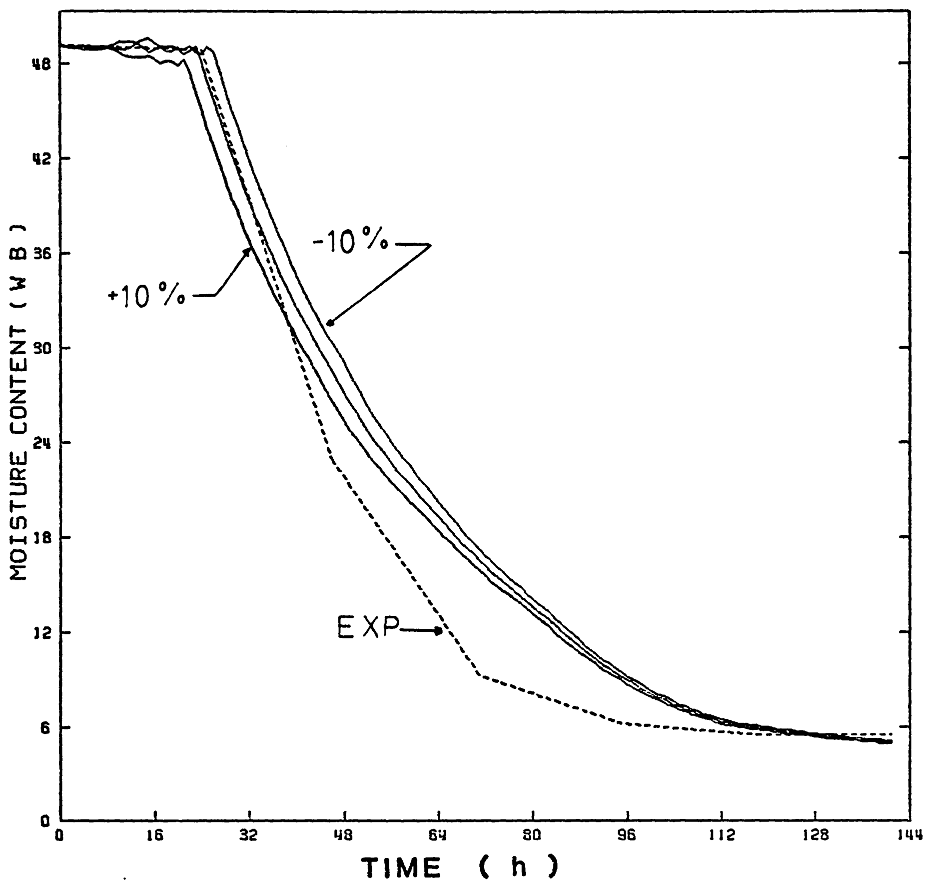

Figure 45: Moisture content calculated for layer 16 (Column 3 Run 2) by varying airflow rates, ± 10 %.

Chapter VI

EVALUATION OF RECIRCULATION STRATEGIES

The model was used to evaluate and compare three different recirculation strategies given in Table 15. Ambient conditions recorded in the laboratory were used and a drying temperature of 35 °C was again chosen. An initial moisture content of 35 percent (wb) was assumed. The drying rates for the three strategies are shown in Figures 46 to 48.

Fifty-seven hours were required to dry the peanuts to 10 percent moisture content using strategies 1, 2, and 3. Since the drying times were approximately equal, the best strategy is the one requiring the minimum supplemental heat. Energy savings are shown in Table 16. Again energy savings were calculated by comparing the heat energy required to the heat energy required if no recirculation were used. All three strategies required approximately the same supplemental heat during the first 24 hours; however, strategy 2 shows an advantage for the remainder of the cure. The supplemental heat energy input is shown in Figure 49.

The three strategies selected recirculate small amounts of air during the first 24 hours when the drying air is moisture laden. More air is recirculated during the next two stages. This type of strategy provides energy savings with only slight increases in drying time.

TABLE 15

Recirculation strategies

	Percent Recirculation		
Strategy	Hours 0 - 24	Hours 25 - 48	Hours 49 - 72
1	0	25	50
2	0	50	75
3	10	33	66

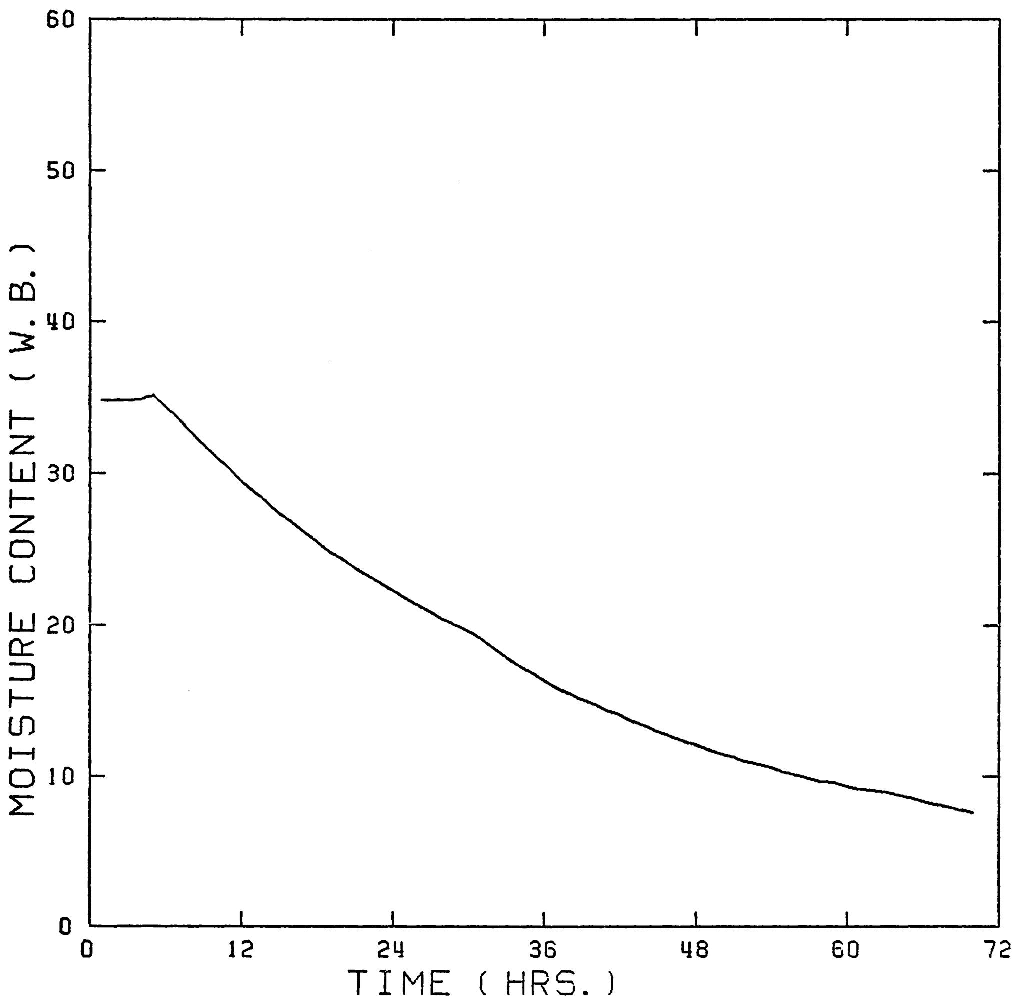

Figure 46: Simulated drying rate using strategy 1 (0,25,50 % recirculation for days 1 through 3, respectively).

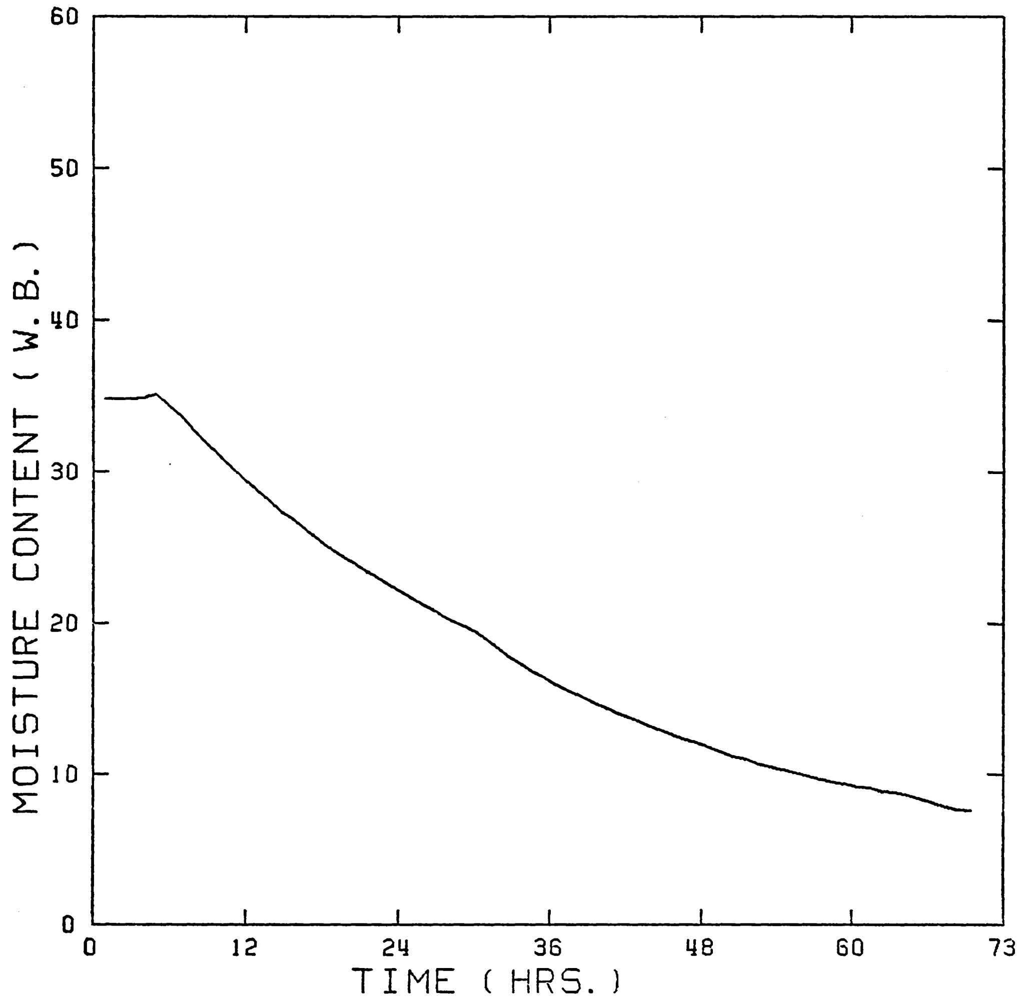

Figure 47: Simulated drying rate using strategy 2 (0,50,75 % recirculation for days 1 through 3, respectively).

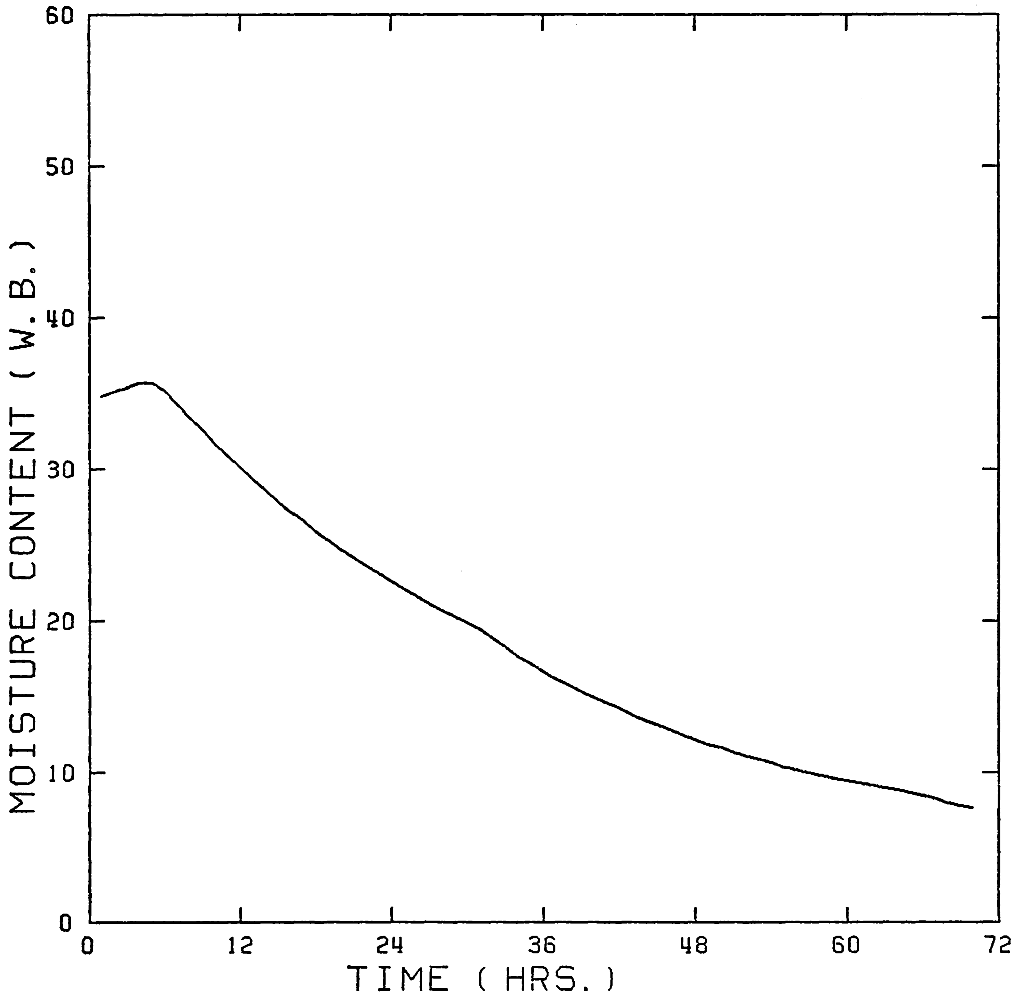

Figure 48: Simulated drying rate using strategy 3 (10,33,66 % recirculation for days 1 through 3, respectively).

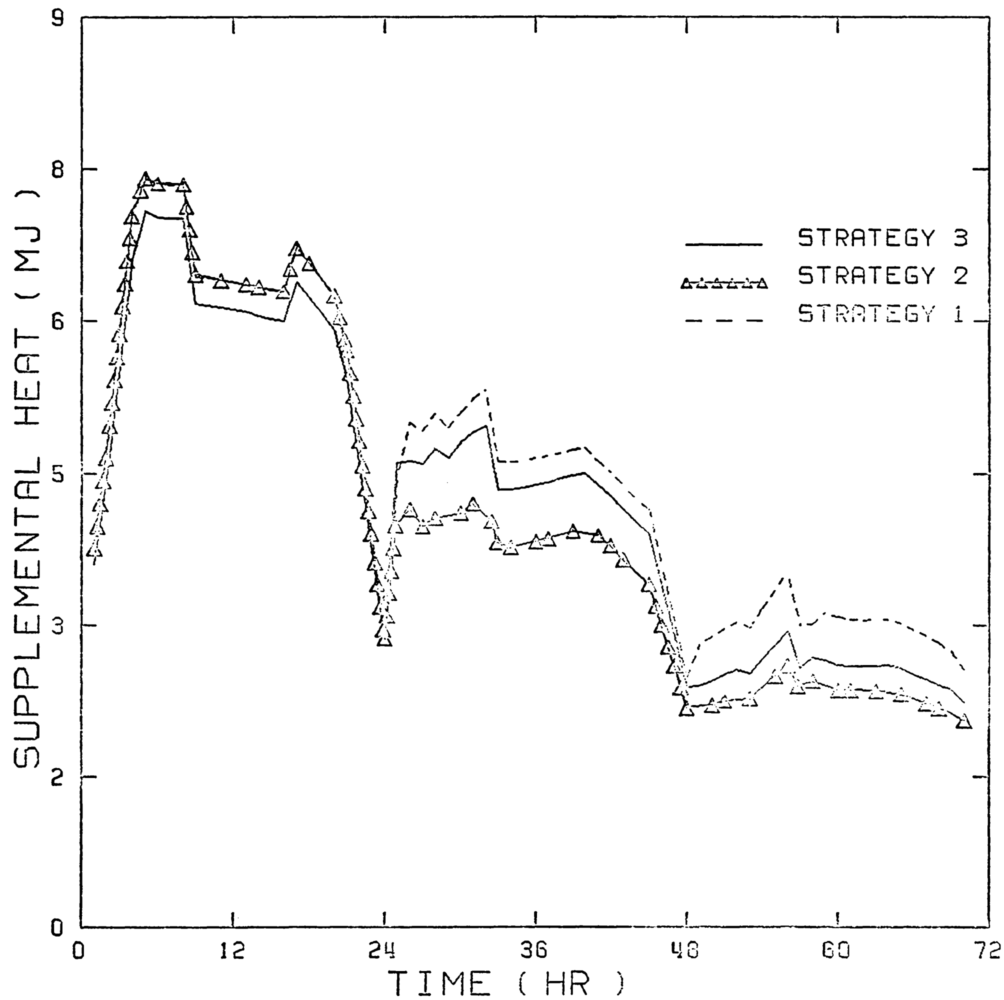

Figure 49: Supplemental heat energy input in recirculation strategy tests.

TABLE 16

Energy savings produced using test strategies

Strategy	Total Energy Input MJ	Energy Savings %
1	302.1	6
2	285.7	11
3	297.4	7

Based on this analysis, savings of at least 20 percent of the supplemental heat energy input can be realized by using recirculation strategies such as those in Table 15.

Chapter VII

SUMMARY AND CONCLUSIONS

To determine the energy saving potential available from recirculating air in peanut drying, a thin layer drying computer simulation model was developed using Troeger and Bulter's (1979) equations, and that model was successfully adapted to incorporate recirculation.

Three laboratory recirculating crop dryers were constructed in Seitz Hall at Virginia Polytechnic Institute and State University to verify the simulation model. Five batches of peanuts were dried in 2 experiments. In the first run, 2 batches of peanuuts with an initial moisture content of 35 percent (wb) were dried for 72 hours to a moisture content of 5 percent (wb). One batch was dried using no recirculation while 55 percent of the drying air was recirculated in the second batch. In the second run, 3 batches of peanuts with an initial moisture content of 50 percent (wb) were dried for 143 hours to a moisture content of 5 percent (wb). Recirculation percentages of 0, 66, and 69 were used.

Dry bulb and wet bulb temperatures were measured manually every four hours above and below the drying column. Ambient wet and dry bulb temperatures were also recorded at the same time. Hourly temperatures were recorded at specific levels in the dryers using a 24 point temperature recorder. Samples were taken from the top of the column of peanuts every 24 hours to determine moisture content.

The data collected were used to verify the thin layer peanut drying model. Recirculation was incorporated into the model by using psychrometric relationships to describe the mixing of ambient air with the air exhausted from the peanut mass. The mixed air was then assumed to be the air entering the bottom layer of peanuts. Heat and mass balances were performed in the simulation to enable the determination of energy savings. Savings of up to 20 percent of the supplemental heat energy input required were observed in the experimental runs.

Finally, three different recirculation strategies were evaluated and compared using the simulation model. The three strategies were:

(1) Hours 0 to 24 - 0 %; hours 25 to 48 - 25 %; hours 49 to 72 - 50 %;

(2) Hours 0 to 24 - 0 %; hours 25 to 48 - 50 %; hours 49 to 72 - 75 %;

(5) Hours 0 to 24 - 10 %; hours 25 to 48 - 33 %; hours 49 to 72 - 66 %.

Recirculation strategies following these patterns proved successful in providing energy savings up to 20 percent without increasing drying time (drying peanuts having an initial moisture content no greater than 35 percent (wb)). Low recirculation percentages should be used in the early stages of the drying because the air is often saturated as it leaves the peanuts. The amount of air recirculated can then be as great as 55 percent without increasing drying time.

Average temperature conditions at different geographic locations can be input to the simulation model to determine the energy savings attainable through air recirculation in drying. The model can be used as an aid to the farmer in determining the amount of air which should be recirculated to save the maximum amount of energy possible without significantly increasing drying time.

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Appendix A

THIN LAYER DRYING MODEL LISTING

```
C     MAIN
      DIMENSION TDBB(168), TWBB(168), TDBEX(31), IERR(16), TP1(16), XM(1
     16), XM1(16), SAT(16), HX(16), IMOD1(16), XMP(16), POUT(9), OUT(168
     2,9), TDPX(16), TWBX(16), XMWB(16), XM1WB(16), RHX(16), XMEM(16), X
     3MRM(16)
      DIMENSION TDBAM(200), TWBAM(200), TDBAMB(200), TDBAB(200), TWBAB(2
     100)
      DIMENSION TDBA(200), TTWBA(200), TWBEX(200), TWBAMB(200)
      DIMENSION TP(16), TX(16), ITIME(31)
      DATA CW/4.1868/,CP/2.9308/,TIMDRY/-1./,IOUT/0/,K/0/
      DATA SS/4HSAT./,SO/1H /
      DATA DEPTH/1.219/,AREA/0.24/,PATM/101325./
      DATA AMB/0.0/,REC/0.0/
      DATA CPA/1.00/,CPV/1.882/
      IPEA=35
      IR1C3=34
      MOUT=26
      IPEPLT=27
      READ (IPEA,140) NREAD,NHR,M,IPHR,ICHK
      READ (IPEA,150) DELT,DELMA,XMOWB,TPO,BD
      READ (IPEA,110) REC1,REC2,REC3
110   FORMAT (3F7.4)
      READ (IPEA,120) T1,T2,T3
120   FORMAT (3F5.1)
      READ (36,130) (ITIME(IQ),TDBEX(IQ),IQ=1,NREAD)
      READ (36,130) (ITIME(IQ),TWBEX(IQ),IQ=1,NREAD)
      READ (36,130) (ITIME(IQ),TDBAB(IQ),IQ=1,NREAD)
      READ (36,130) (ITIME(IQ),TWBAB(IQ),IQ=1,NREAD)
      READ (IR1C3,130) (ITIME(IQ),TDBAM(IQ),IQ=1,NREAD)
130   FORMAT (5(2X,I3,F10.4))
C     INTERPOLATION FOR TEMPERATURE VALUES FOR EACH INCREMENT
      READ (34,130) (ITIME(IQQ),TWBAM(IQQ),IQQ=1,NREAD)
140   FORMAT (I3,I4,I3,2I2)
150   FORMAT (F6.3,F7.2,F7.4,F5.1,F7.2)
      NI=NHR*IPHR
      NREADS=NREAD+1
      DO 170 NN=2,NREAD
      IKOUNT=-1
      IBEGIN=ITIME(NN-1)+1
      IEND=ITIME(NN)
      INT=(ITIME(NN)-ITIME(NN-1))
      RINT=FLOAT(INT)
      DEGREE=TDBEX(NN)-TDBEX(NN-1)
      DEGREW=TWBEX(NN)-TWBEX(NN-1)
      DEGREA=TDBAM(NN)-TDBAM(NN-1)
      DEGDAB=TDBAB(NN)-TDBAB(NN-1)
      DEGWAM=TWBAM(NN)-TWBAM(NN-1)
      DEGWAB=TWBAB(NN)-TWBAB(NN-1)
      ADD=DEGREE/RINT
```

```
      ADDW=DEGREW/RINT
      ADDAM=DEGREA/RINT
      ADDWAM=DEGWAM/RINT
      ADDAB=DEGDAB/RINT
      ADDWAB=DEGWAB/RINT
      DO 160 I=IBEGIN,IEND
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF (I.EQ.IBEGIN) AMULT=0.0
      TDBB(I)=TDBEX(NN-1)+ADD*AMULT
      TWBB(I)=TWBEX(NN-1)+ADDW*AMULT
      TDBAMB(I)=TDBAM(NN-1)+ADDAM*AMULT
      TWBAMB(I)=TWBAM(NN-1)+ADDAM*AMULT
      TDBA(I)=TDBAB(NN-1)+ADDAB*AMULT
      TTWBA(I)=TWBAB(NN-1)+ADDWAB*AMULT
160   CONTINUE
170   CONTINUE
      IF (ICHK.GT.2) GO TO 200
      DO 180 I=1,NHR
      TIMDRY=TIMDRY+1.
180   WRITE (MOUT,190) TIMDRY,TDBB(I),TWBB(I)
190   FORMAT (3F8.3)
      TIMDRY=0.0
C
C     DEEP BED DRYER
C     INITIALIZE DRYER
C
200   XMODB=XMOWB/(1.-XMOWB)
      XMA=XMODB
      DD=DEPTH/FLOAT(M)
      AMP=BD*AREA*DD
      DO 210 J=1,M
      XMP(J)=XMODB
      XM(J)=XMODB
      XM1(J)=XMODB
      TP(J)=TPO
210   TP1(J)=TPO
      DO 580 NN=2,NHR
      IKOUNT=-1
      ADD=(TDBB(NN)-TDBB(NN-1))/FLOAT(IPHR)
      ADDW=(TWBB(NN)-TWBB(NN-1))/FLOAT(IPHR)
      ADDAM=(TDBAMB(NN)-TDBAMB(NN-1))/FLOAT(IPHR)
      ADDWAM=(TWBAMB(NN)-TWBAMB(NN-1))/FLOAT(IPHR)
      ADDDAB=(TDBA(NN)-TDBA(NN-1))/FLOAT(IPHR)
      ADDWAB=(TTWBA(NN)-TTWBA(NN-1))/FLOAT(IPHR)
      DO 220 IN=1,IPHR
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF (IN.EQ.1) AMULT=0.0
      TDBEX(IN)=TDBB(NN-1)+ADD*AMULT
      TDBAM(IN)=TDBAMB(NN-1)+ADDAM*AMULT
```

```
      TWBEX(IN)=(TWBB(NN-1)+ADDW*AMULT)
      TWBAM(IN)=TWBAMB(NN-1)+ADDAM*AMULT
      TDBAB(IN)=TDBA(NN-1)+ADDDAB*AMULT
      TWBAB(IN)=TTWBA(NN-1)+ADDWAB*AMULT


220   CONTINUE
      WRITE (38,230) TDBEX(1),TDBAM(1)
230   FORMAT (2F10.3)
      DO 520 I=1,IPHR
      IOUT=IOUT+1
      TIMDRY=TIMDRY+DELT
C
C     COMPUTE ENTERING CONDITIONS
C
      DO 240 J=1,M
      XM(J)=XM1(J)
240   TP(J)=TP1(J)
      TAMB=TDBAM(I)
      TWAMB=TWBAM(I)
      CALL PSYC (1,TAMB,TWAMB,POUT)
      SHA=POUT(8)
      TA=TDBEX(I)
      TWBA=TWBEX(I)
      CALL PSYC (1,TA,TWBA,POUT)
      HE=POUT(4)
      IF (TIMDRY.LE.T1) REC=REC1
      IF (TIMDRY.GT.T1.AND.TIMDRY.LE.T2) REC=REC2
      IF (TIMDRY.GT.T2) REC=REC3
      AMB=1.0-REC
      WRITE (99,250) REC
250   FORMAT (3F12.3)
      IF (REC.EQ.0.0) GO TO 260
      TR=TDBAB(I)
      TWBR=TWBAB(I)
      CALL PSYC (1,TR,TWBR,POUT)
      HER=POUT(4)
      HE=HE*AMB+HER*REC
      SHA=SHA*AMB+POUT(8)*REC
260   TE=TDBEX(I)
      RHENT=POUT(1)
      DO 270 J=1,M
270   IERR(J)=0
C     MAIN
      DO 510 J=1,M
      SAT(J)=SO
      CALL PSYC (2,TE,HE,POUT)
      RHE=POUT(1)
      TDPE=POUT(2)
      TWBE=POUT(3)
```

```
      HE=POUT(4)
      HS=POUT(5)
      SHE=POUT(8)
      VSA=POUT(9)
      XME=XMEF(TE,RHE)
      XMEM(J)=XME
C
C     MOD1:  1=HEAT,DRY   2=HEAT ,WET   3=COOL,DRY   4=COOL,WET
      MOD1=1
C     IF TEMP ENTERING A LAYER LT PEANUT TEMP MOD1=3
C
      IF (TE.LT.TP(J)) MOD1=3
C
C     IF EQMC GT MC OF PEANUTS MOD1=MOD1+1
C
      IF (XME.GT.XM(J)) MOD1=MOD1+1
      IMOD1(J)=MOD1
      XMR=(XM(J)-XME)/(XMP(J)-XME)
      XMRM(J)=XMR
      IF (XMR.GT.0) GO TO 300
      XMP(J)=XM(J)
      WRITE (MOUT,290) XMR,XMP(J),XM(J),XME
290   FORMAT (1H0,13H*ERROR*XMDOT*,2X,4HXMR=,F6.3,2X,4HXMO=,F6.3,2X,3HXM
     1=,F6.3,2X,4HXME=,F6.3)
300   DELT1=DELT
      DELTS=0
      XMS=XM(J)
C
C     CALCULATE MOISTURE LOSS
C
310   XMDOT=XMDOTF(TE,TDPE,XMP(J),XME,XM(J))
      XM1(J)=XMS+XMDOT*DELT1
      XMDOT1=XMDOTF(TE,TDPE,XMP(J),XME,XM1(J))
      XM2=XMS+((XMDOT+XMDOT1)/2.)*DELT1
      TERM=XM1(J)-XM2
C
C     IF XMDOT DOES NOT CONVERGE, TIME STEP IS HALVED
C
      IF (ICHK.GT.1) GO TO 340
      WRITE (MOUT,320) J,XM(J),XMS,XM1(J),XM2,TERM
320   FORMAT (2X,10HLAYER NO.=,I2,2X,3HXM=,F6.3,2X,4HXMS=,F6.3,2X,4HXM1=
     1,F6.3,2X,4HXM2=,F6.3,2X,5HTERM=,F6.3)
      WRITE (MOUT,330) DELT1,DELTS
330   FORMAT (2X,6HDELT1=,F6.3,2X,6HDELTS=,F6.3)
340   IF (TERM.LT.1.E-2) GO TO 350
      IF (DELT1.LT..01) GO TO 350
      DELT1=DELT1/2.
      GO TO 310
350   CONTINUE
```

```
      DELTS=DELTS+DELT1
      IF (DELTS.GE.DELT) GO TO 360
      XMS=XM2
      GO TO 310
360   XM1(J)=XM2
      DELM=XM(J)-XM1(J)
      DELMDA=DELMA/VSA
C
C     MASS BALANCE
C
      HX(J)=HE+DELM*AMP/(DELMDA*DELT)
      IF (XM1(J).GT.0.OR.XM1(J).LT.2.) GO TO 400
      WRITE (MOUT,370)
      WRITE (MOUT,380)
      WRITE (MOUT,390) TIMDRY,J,XM(J),XM1(J),XME,XMR,HE,RHE,TE,TDPE,TWBE
     1,TP(J)
370   FORMAT (1H0,15H*ERROR*DPBD-32*)


380   FORMAT (/2X,6HTIMDRY,2X,9HLAYER NO.,4X,2HXM,8X,3HXM1,7X,3HXME,8X,3
     1HXMR,7X,2HHE,8X,3HRHE,7X,2HTE,6X,4HTDPE,6X,4HTWBE,6X,2HTP)
390   FORMAT (/,F10.2,4X,I2,4X,4F10.3,1X,E9.4,F10.3,4F10.2)
C
C     MAX MOISTURE LOSS IS LIMITED TO SATURATING THE AIR
C
400   IF (HX(J).LT.HS) GO TO 410
      HX(J)=HS
      SAT(J)=SS
      DELW=HX(J)-HE
      XM1(J)=XM(J)-DELW*DELMDA*DELT/AMP
C
C     CALCULATE PEANUT TEMP
C
410   TP1(J)=TPF(TP(J),TE,I)
      GO TO (420,420,430,430), MOD1
420   IF (TP1(J).LT.TP(J)) TP1(J)=TP(J)
      IF (TP1(J).GT.TE) TP1(J)=TE
      GO TO 440
430   IF (TP1(J).GT.TP(J)) TP1(J)=TP(J)
      IF (TP1(J).LT.TE) TP1(J)=TE
C
C     CALCULATE NEW AIR TEMP
C
440   MOD2=0
      PVX=HX(J)*PATM/(HX(J)+0.6219)
      TDPX(J)=DEW(PVX)-273.16
450   HFG2P=2.502535E6-2.385764E3*TDPX(J)
      XCAP=(CP+XM(J)*CW)*TP(J)
      XCAP1=(CP+XM1(J)*CW)*TP1(J)
      R1=POUT(8)-4186.8*HX(J)*TDPX(J)-HFG2P*HX(J)
```

```
      R2=1875.6864*HX(J)*TDPX(J)-(AMP*(XCAP1-XCAP)/(DELMDA*DELT))
      R3=1006.92540+1875.6864*HX(J)
      TX(J)=(R1+R2)/R3
      GO TO (460,460,480,480), MOD1
460   IF (TX(J).GE.TP1(J)) GO TO 470
      TP1(J)=TX(J)
      IF (TWBE.GT.TX(J)) TP1(J)=TWBE
      IF (MOD2.EQ.1) GO TO 470
      MOD2=1
      GO TO 450
470   IF (TX(J).GT.TE) TX(J)=TE
      IF (TX(J).LE.TP(J)) TX(J)=TP(J)
      GO TO 500
480   IF (TX(J).LE.TP1(J)) GO TO 490
      TP1(J)=TX(J)
      IF (TWBE.LT.TX(J)) TP1(J)=TWBE
      IF (MOD2.EQ.1) GO TO 490
      MOD2=1
      GO TO 450
490   IF (TX(J).LT.TE) TX(J)=TE
      IF (TX(J).LE.TP(J)) GO TO 500
      TX(J)=TP(J)
500   CONTINUE
      CALL PSYC (2,TX(J),HX(J),POUT)


      TWBX(J)=POUT(3)
      RHX(J)=POUT(1)
      SHX=POUT(8)
C
C     SET THE ENTERING CONDITIONS FOR THE NEXT LAYER
C
      TE=TX(J)
      HE=HX(J)
510   CONTINUE
      XMA=0
      DO 530 J=1,M
      XMA=XMA+XM1(J)
      XMEM(J)=XMEM(J)/(1.+XMEM(J))
      XMWB(J)=XM(J)/(1.+XM(J))
530   XM1WB(J)=XM1(J)/(1.+XM1(J))
      XMA=XMA/FLOAT(M)
      XMA=XMA/(1.+XMA)
520   CONTINUE
      WRITE (MOUT,540) TIMDRY
540   FORMAT (/2X,34HCONDITIONS FOR EACH LAYER AT TIME=,F5.0,/)
      WRITE (MOUT,550)
550   FORMAT (2X,9HLAYER NO.,2X,13HMC(W.B.)(I-1),2X,11HMC(W.B.)(I),2X,6H
     1  TX   ,2X,6H TWBX ,2X,6H TDPX ,2X,6H  RHX ,2X,6H  HX   ,2X,6H  XME
     2,2X,6H  XMR  ,/)
```

```
      DO 560 J=1,M
560   WRITE (MOUT,570) J,XMWB(J),XM1WB(J),TX(J),TWBX(J),TDPX(J),RHX(J),H
     1X(J),XMEM(J),XMRM(J)
570   FORMAT (5X,I2,10X,F5.3,8X,F5.3,5X,F5.2,4X,F5.2,3X,F5.2,3X,F5.3,2X,
     1F6.4,3X,F5.3,3X,F5.3)
      WRITE (MOUT,580) M,XMA
580   FORMAT (/3X,22HAVG.MC(W.B.) LAYERS(1-,I2,1H),F7.3)
      IOUT=0
      K=K+1
      OUT(K,1)=SHA
      OUT(K,2)=SHX
      OUT(K,3)=DELMDA
      OUT(K,4)=TX(M)
      OUT(K,5)=XM1WB(M)
      OUT(K,6)=VSA
      OUT(K,7)=TP1(M)
      OUT(K,8)=HS
      OUT(K,9)=TWBX(M)
C     100 CONTINUE
      DO 590 K=1,NHR
      HR=FLOAT(K)
590   WRITE (IPEPLT,600) HR,(OUT(K,KOUT),KOUT=1,9)
600   FORMAT (F5.1,2X,E17.11,2X,E17.11,2X,7F8.3)
      STOP
      END
C     SUBROUTINE PSYC
      SUBROUTINE PSYC (MODE,P1,P2,POUT)
      LOGICAL ERROR
      DIMENSION POUT(9)
      DATA PATM/101325./
      ERROR=.FALSE.



C
C     SATURATION CALCULATIONS
C
      TE=P1
      PS=PWS(TE)
      HS=0.6219*PS/(PATM-PS)
      GO TO (120,160), MODE
C
C     MODE 1   TA,TWBA --->  RH,TDP,TWB,H,HS,PV,PS,SH,VSA
C
120   CONTINUE
      TWBA=P2
      TWB=TWBA
      PSWB=PWS(TWBA)
      PV=PVWBDB(TE,TWBA,PSWB)
      H=0.6219*PV/(PATM-PV)
140   PV=H*PATM/(H+.6219)
```

```
      IF (PV.LE.0) GO TO 240
      TDP=DEW(PV)-273.16
      RH=PV/PS
      SH=ENTHAL(H,TDP,TE)
      VSA=287*(TE+273.16)/(PATM-PV)
      GO TO (260,180,180,180), MODE
C
C     MODE 2   TE,HE ---> RH,TDP,TWB,H,HS,PV,PS,SH,VSA
C
160   CONTINUE
      H=P2
      GO TO 140
C
C     ITERATIVE PROCEDURE TO FIND TWB
C
180   JN=0
      TWB=(TE+2*TDP)/3
200   CONTINUE
      PSWB=PWS(TWB)
      B=BP(PSWB,PATM,PV,TWB)
      TWB1=TE+(PSWB-PV)/B
      TWCV=ABS(TWB-TWB1)/TWB
      IF (TWCV.LT..012) GO TO 220
      TWB=(TWB1+2*TWB)/3
      JN=JN+1
      IF (JN.LT.10) GO TO 200
      GO TO 240
220   TWB=TWB1
      GO TO 260
240   CONTINUE
      ERROR=.TRUE.
260   CONTINUE
      IF (RH.GE..999) RH=.999
      POUT(1)=RH
      POUT(2)=TDP
      POUT(3)=TWB
      POUT(4)=H
      POUT(5)=HS



      POUT(6)=PV
      POUT(7)=PS
      POUT(8)=SH
      POUT(9)=VSA
      IF (ERROR) GO TO 280
      RETURN
280   WRITE (MOUT,300) MODE,JN,P1,P2
300   FORMAT (1H0,15H**ERROR**PSYC**,2X,5HMODE=,I2,2X,10HITER. NO.=,I2,2
     1X,3HP1=,F8.4,2X,3HP2=,F8.4)
      WRITE (MOUT,320) TWB,TWB1,TWCV
320   FORMAT (2X,4HTWB=,F6.2,2X,5HTWB1=,F6.2,2X,5HTWCV=,F8.4)
```

```
      RETURN
      END
C*
      FUNCTION XMEF(TE,RHE)
      ARG1=(111./(TE+273.16))**2.4
      XMEF=ARG1*(-ALOG(1.-RHE))**0.7
      RETURN
      END
C*
      FUNCTION BP(PSWB,PATM,PV,TWB)
      B1=1006.9254*(PSWB-PATM)*(1.+0.15577*PV/PATM)
      HFGP=2.502553E6-2.385764E3*TWB
      BP=B1/(0.62194*HFGP)
      RETURN
      END
C*
      FUNCTION DEW(PS)
      X=ALOG(0.00145*PS)
      ARG1=13.6626*X+1.17678*X**2-0.189693*X**3
      ARG2=0.087453*X**4-0.0174053*X**5+2.14768E-3*X**6
      ARG3=-0.138343E-3*X**7+0.38E-5*X**8
      DEW=255.38+19.5322+ARG1+ARG2+ARG3
      RETURN
      END
C*
      FUNCTION ENTHAL(HR,TDP,TDB)
      HFG2P=2.502535E6-2.385764E3*TDP
      ARG1=1.006925E3*TDB+4.1868E3*HR*TDP+HFG2P*HR
      ENTHAL=ARG1+1.875686E3*HR*(TDB-TDP)
      RETURN
      END
C*
      FUNCTION PVWBDB(TDB,TWB,PSWB)
      HFGP=2.502553E6-2.385764E3*TWB
      ARG1=0.62194*HFGP*PSWB-1.006925E3*(PSWB-101325.0)*(TWB-TDB)
      ARG2=0.62194*HFGP+156.8488*(PSWB-101325.)*(TWB-TDB)/101325.
      PVWBDB=ARG1/ARG2
      RETURN
      END
C*
      FUNCTION PWS(TC)
      T=TC+273.16
C     ARG1=-7511.52/T
      ARG1=-27405.53+97.5413*T-0.146244*T**2


      ARG2=0.12558E-3*T**3-0.48502E-7*T**4
      ARG3=4.34903*T-0.39381E-2*T**2
      PWS=22105650.*EXP((ARG1+ARG2)/ARG3)
      RETURN
```

```
      END
C*
      FUNCTION TPF(TPO,TDB,I)
C     PEANUT TEMPERATURE
      DATA SAO/2.2296E-4/,EL/3.7943E-2/,D/1.5558E-2/,DELT/0.125/,IPHR/8/
      J=I*IPHR
      TIME=(J-1)*DELT
      Z1=4.*SAO*TIME/EL**2
      Z2=4.*SAO*TIME/D**2
      P=-2.4606*Z1
      C=-5.7332*Z2
      IF(P.LT.-100) P=-10.
      IF(C.LT.-100) C=-10.
      P=EXP(P)*1.2665
      C=EXP(C)*1.5566
      IF(P.GE.1.) P=1.
      IF(C.GE.1.) C=1.
      TPF=(TPO-TDB)*P*C+TDB
      RETURN
      END
C*
      FUNCTION XMDOTF(T,TDP,AMO,AME,AM)
      AMR=(AM-AME)/(AMO-AME)
      G=AMR/ABS(AMR)
      A1=0.02320+4.5E-4*T+6.3E-4*TDP+4.5E-4*TDP*AMO+8E-3*AMO
      B1=3.264-.025*T-.0162*TDP-.0342*TDP*AMO-.608*AMO
      A=A1
      B=B1
      IF(AMR.GE.0.40) GO TO 401
      IF(AMR.LE.0.12) GO TO 402
      A=A1*(2.40-AMO)
      B=B1*(0.88+.20*AMO)
      GO TO 401
  402 A=A1*(2.4-AMO)**2
      B=B1*(0.88+0.2*AMO)**2
  401 CONTINUE
      XMDOTF=-A*(AMO-AME)*(AMR*G)**B
      RETURN
      END
```

Appendix B

PROGRAM VARIABLES FOR THIN LAYER DRYING MODEL

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	AMB	%	Percent of ambient air entering dryers in comparision to amount recirculated.
	AMP	kg	Peanut solids per layer.
	AREA	m^2	Cross sectional area of the dryers.
	BD	kg/m^3	Bulk density.
	CP	J/kg^oK	Specific heat of peanut solids.
	CPA	J/kg^oK	Specific heat of water vapor.
	CPV	J/kg^oK	Specific heat of air.
	CW	J/kg^oK	Specific heat of water.
	D	m	Average diameter of the peanut.
	DD	m	Depth per layer.
	DELM	-	Difference in moisture content between successive layers.
	DELMA	m^3	Airflow rate.
	DELMDA	kg/h	Mass flow of dry air.
	DELT	h	Time increment.
	DELW	-	Difference in humidity ratio of entering air and exiting air.

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	DEPTH	m	Depth of peanuts.
	EL	m	Average length of the peanut.
	HE	-	Entering humidity ratio.
	HFGDP	J/kg	Latent heat of vaporization (T = dew point).
	HFGP	J/kg	Latent heat of vaporization (T = wet bulb).
	HS	-	Humidity ratio at saturation.
	HX	-	Exiting humidity ratio.
	IPHR	-	Number of increments per hour.
	M	-	Number of layers.
	NHR	h	Length of simulation.
	NREAD	-	Number of data readings available.
	PATM	Pa	Atmospheric pressure.
	PS	Pa	Partial pressure.
	PSWB	Pa	Partial pressure of water vapor at saturation (T = wet bulb).
	PVA	Pa	Partial pressure of water vapor at saturation (T = dry bulb).
	REC	%	Percent of air recirculated.
	RH	%	Relative humidity.
	SAO	m^2/h	Thermal diffusivity of a peanut.
	SH	J/kg	Enthalpy.
	SHA	J/kg	Enthalpy of entering air.
	TA	°C	Dry bulb temperature of air entering the layer.

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	TDBAB	°C	Dry bulb temperature above the column.
	TDBAM	°C	Dry bulb temperature of the ambient air.
	TDBB(I)	°C	Dry bulb temperature measured below the peanuts at the ith time interval.
	TDP	°C	Dew point temperature.
	TIMDRY	h	Current simulation time.
	TP(J)	°C	Peanut temperature of the jth layer at the previous time interval.
	TP1(J)	°C	Peanut temperature of the jth layer at the present time interval.
	TPO	°C	Initial peanut temperature.
	TR	°C	Dry bulb temperature of the recirculated air.
	TWBA	°C	Wet bulb temperature entering the layer.
	TWBAB	°C	Wet bulb temperature above the column.
	TWBAM	°C	Ambient wet bulb temperature.
	TWBB(I)	°C	Wet bulb temperature measured below the peanuts at the ith time interval.
	TWBR	°C	Wet bulb temperature of recirculated air.
	VSA	m^3/kg	Air specific volume.

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	XM(J)	dec	Moisture content (dry basis) of the jth layer at previous time interval.
	XM1(J)	dec	Moisture content (dry basis) of the jth layer at present time interval.
	XMDOT	-	Rate of change of moisture.
	XME	dec	Equilibrium moisture content (dry basis).
	XMODB	dec	Initial moisture content (dry basis).
	XMOWB	dec	Initial moisture content (wet basis).
	XMR	-	Moisture ratio.

Appendix C

HEAT BALANCE LISTING

```
      DIMENSION DELQX(200),DELQM(200),ENTHAM(200),ENTHEX(200),V(200)
      DIMENSION AMC(200),TP(200),QM(200),DELMDA(200)
      DATA INUM/70/,M/16/
      TERM1=0.0
      TERM2=0.0
      TQX=0.0
      TQM=0.0
      DO 10 JJ=1,INUM
      READ(25,20)ENTHAM(JJ),ENTHEX(JJ),DELMDA(JJ),AMC(JJ),V(JJ),TP(JJ)
   10 CONTINUE
   20 FORMAT(7X,E17.11,2X,E17.11,2X,F8.3,8X,3F8.3)
      CALL QX(ENTHEX,ENTHAM,V,DELQX,DELMDA,TQX)
      CALL AQM(TP,AMC,QM,DELQM,TQM)
      WRITE(26,30)(DELQX(LL),LL=1,INUM)
   30 FORMAT(5(E17.9,3X))
      WRITE(26,40)(DELQM(IE),IE=1,INUM)
   40 FORMAT(10(F9.4,3X))
      STOP
      END
      SUBROUTINE QX(ENTHEX,ENTHAM,V,DELQX,DELMDA,TQX)
      DIMENSION DELQX(200),DELQM(200),ENTHAM(200),ENTHEX(200),V(200)
      DIMENSION AMC(200),TP(200),QM(200),VDOT(200),DELMDA(200)
      DATA INUM/70/
      DO 15 J=1,INUM
      VDOT(J)=V(J)*DELMDA(J)/60.
   15 CONTINUE
      DO 20 JJ=1,INUM
      DELQX(JJ)=60.0*VDOT(JJ)*(ENTHEX(JJ)-ENTHAM(JJ))/(1000*V(JJ))
   20 CONTINUE
      DO 25 JI=1,INUM
      TQX=TQX+DELQX(JI)
   25 CONTINUE
      RETURN
      END
      SUBROUTINE AQM(TP,AMC,QM,DELQM,TQM)
      DIMENSION DELQX(200),DELQM(200),ENTHAM(200),ENTHEX(200),V(200)
      DIMENSION AMC(200),TP(200),QM(200)
      DATA INUM/70/,JD/16/
      DATA AMP/4.951/,CP/2.9308/,CW/4.1868/
      INUMS=INUM+1
      DO 20 J=2,INUMS
      TERM1=AMP*(CP+AMC(J)*CW)*TP(J)
      TERM2=AMP*(CP+AMC(J-1)*CW)*TP(J-1)
      DELQM(J)=TERM1-TERM2
   20 CONTINUE
      DELQM(1)=DELQM(2)
      DO 25 JJ=1,INUM
      TQM=TQM+DELQM(JJ)
   25 CONTINUE
```

```
      RETURN
      END
      DIMENSION QSS(200),QSL(200)
      DIMENSION TDBB(200),TDBAMB(200),TR(200),TDBA(200)
      DIMENSION T(200),ITIME(200),TDB(200)
      DATA A1,A2,A3,A4,A5,A6/2.48,6.13,3.72,16.78,0.233,7.02/
      DATA NHR/70/,AMASS/9.979/,SPH/0.502/,RT/0.3737/,RTM/0.0309/
      DATA REC1/0.1/,REC2/0.330/,REC3/0.66/
      DATA T1/24.0/,T2/48.0/,T3/71.0/
      IPHR=8
      NREAD=16
      READ(15,12)(ITIME(IQ),T(IQ),IQ=1,NREAD)
   12 FORMAT(////////,5(2X,I3,F10.4))
C     INTERPOLATION FOR TEMPERATURE VALUES FOR EACH INCREMENT
      DO 20 NN=2,NREAD
      IKOUNT=-1
      IBEGIN=ITIME(NN-1)+1
      IEND=ITIME(NN)
      INT=(ITIME(NN)-ITIME(NN-1))
      RINT=FLOAT(INT)
      DEGREE=T(NN)-T(NN-1)
      ADD=DEGREE/RINT
      DO 16 I=IBEGIN,IEND
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF(I.EQ.IBEGIN )AMULT=0.0
      TDBA(I)=T(NN-1)+ADD*AMULT
   16 CONTINUE
   20 CONTINUE
      DO 25 IE=1,NHR
      QSS(IE)=0.0
      QSL(IE)=0.0
   25 CONTINUE
      TQSS=0.0
      TQSL=0.0
      TERM1=0.0
      TERM2=0.0
      TERM3=0.0
      TERM4=0.0
      TERM5=0.0
      TERM6=0.0
      DO 35 J=1,NHR
      READ(25,30)TDBB(J),TDBAMB(J)
   30 FORMAT(2F10.3)
   35 CONTINUE
      DO 40 K=1,NHR
      QSS(K)=(AMASS*SPH*TDBB(K))/1000.
      TQSS=TQS+QSS(K)
   40 CONTINUE
      DO 45 JJ=1,NHR
      IF(JJ.LE.T1)REC=REC1
```

```
      IF(JJ.GT.T1.AND.JJ.LE.T2)REC=REC2
      IF(JJ.GT.T2)REC=REC3
      AMB=1.0-REC
      TR(JJ)=AMB*TDBA(JJ)+REC*TDBA(JJ)


45    CONTINUE
      DO 50 I=1,NHR
      DT1=(TDBB(I))-TDBAMB(I)
      DT2=(TDBB(I)-TDBAMB(I))
      DT3=((TDBA(I)+TDBB(I))/2.0)-TDBAMB(I)
      DT4=TDBA(I)-TDBAMB(I)
      DT5=TDBA(I)-TDBAMB(I)
      DT6=TR(I)-TDBAMB(I)
      TERM1=(A1/RT)*DT1
      TERM2=(A2/RT)*DT2
      TERM3=(A3/RT)*DT3
      TERM4=(A4/RT)*DT4
      TERM5=(A5/RTM)*DT5
      TERM6=(A6/RT)*DT6
      IF(REC.EQ.0.0)TERM6=0.0
      QSL(I)=(TERM1+TERM2+TERM3+TERM4+TERM5+TERM6)
      TQSL=TQSL+QSL(I)
50    CONTINUE
      QS=TQSS+TQSL
      WRITE(26,55)(QSS(IR),IR=1,NHR)
55    FORMAT(7(F8.3,2X))
      WRITE(26,60)(QSL(IP),IP=1,NHR)
60    FORMAT(7(E9.3,2X))
      STOP
      END
      DIMENSION DELQX(200),DELQM(200),QSS(200),QSL(200),TQF(200)
      INUM=70
      READ(26,15)(DELQX(LL),LL=1,INUM)
15    FORMAT(5(E17.9,3X))
      READ(26,17)(DELQM(II),II=1,INUM)
17    FORMAT(10(F9.4,3X))
      READ(27,19)(QSS(IR),IR=1,INUM)
19    FORMAT(7(F8.3,2X))
      READ(27,21)(QSL(IP),IP=1,INUM)
21    FORMAT(7(E9.3,2X))
      TERM1=0.0
      TERM2=0.0
      TERM3=0.0
      TQFF=0.0
      DO 50 N=1,INUM
      RN=FLOAT(N)
      TERM1=TERM1+(DELQX(N)/1000.)
      TERM2=TERM2+(DELQM(N)/1000.)
      TERM3=TERM3+((QSS(N)+QSL(N))/1000.0)

      TQF(N)=(DELQX(N)+DELQM(N)+QSS(N)+QSL(N))/1000.
      TQFF=TQFF+TQF(N)
      WRITE(28,29)RN,TQF(N)
29    FORMAT(F5.1,F16.2)
50    CONTINUE
      PERCQX=TERM1/TQFF
      PERCQM=TERM2/TQFF
      PERCQS=TERM3/TQFF
      WRITE(28,88)TQFF,PERCQX,PERCQM,PERCQS
88    FORMAT(///,' TQF ',F8.4,' %  QX = ',F8.4,' %  QM = ',F8.4,' %  QS
     & = ',F8.4)


      STOP
```

Appendix D

PROGRAM VARIABLES FOR HEAT BALANCE

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	AMASS	kg	Mass of fan.
	AMB	%	Percent of ambient air entering in comparison to amount recirculated.
	AMC	dec	Wet basis moisture content.
	AMP	kg	Peanut solids per layer.
	CP	J/kg°K	Specific heat of peanut solids.
	CPA	J/kg°K	Specific heat of water vapor.
	CPV	J/kg°K	Specific heat of air.
	CW	J/kg°K	Specific heat of water.
	DELMDA	kg/h	Mass flow of dry air.
	DELQM	kJ	Change in the sensible heat stored in the material during a given time interval.
	DELQS	kJ	Change in energy required to maintain temperature of structure during a given time interval.
	DELQX	kJ	Change in the exchanged air energy during a given time interval.
	DELT	h	Time increment.
	DT1	°C	Temperature difference between oven and ambient air.
	DT2	°C	Temperature difference between dry bulb below and ambient air.
	DT3	°C	Temperature difference between drying mass and ambient air.

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	DT4	°C	Temperature difference between dry bulb above and ambient.
	DT5	°C	Temperature difference between dry bulb above and ambient air.
	DT6	°C	Temperature difference between recirculated air and ambient air.
	ENTHAM	J/kg	Enthalpy of ambient air.
	ENTHEX	J/kg	Enthalpy of exiting air.
	IPHR	1/h	Number of increments per hour.
	M	-	Number of layers.
	NHR	h	Length of simulation.
	NREAD	-	Number of data readings available.
	PATM	Pa	Atmospheric pressure.
	QE	MJ	Error term.
	QF	MJ	Supplemental heat energy added.
	QM	MJ	Energy required to elevate and maintain the temperature of the material.
	QSL	kJ/h	Conductive heat loss.
	QSS	kJ/h	Heat stored in the structure.
	QX	MJ	Energy in exchanged air.
	REC	%	Amount of air recirculated.
	RT	h m^2°C/kJ	Total thermal resistance of structure layers.

SYMBOLS	FORTRAN VARIABLE	UNITS	DESCRIPTION
	TWBB(I)	°C	Wet bulb temperature measured below the peanuts at the ith time interval.
	V	m^3/kg	Air specific volume.
	RTM	h m^2°C/kJ	Thermal resistance resistance of fan metal.
	SPH	J/g°K	Specific heat of fan.
	TDBAMB	°C	Ambient dry bulb temperature.
	TDBB(I)	°C	Dry bulb temperature measured below the peanuts at the ith time interval.
	TP	°C	Peanut temperature at the previous time interval.
	TWBAMB	°C	Ambient wet bulb temperature.

Appendix E

INPUT AND OUTPUT DATA FOR DRYING MODEL

INPUT DATA

AMBIENT TEMPERATURE FILE

0	16.5000	4	15.5345	8	11.9095	16	12.5832	20	15.0983
24	21.3415	28	21.1603	32	18.5138	40	16.6243	44	19.7431
48	24.5739	52	23.5894	56	21.3833	64	20.8212	68	22.1588
72	22.4375								
0	10.1000	4	9.7766	8	8.6327	16	7.9624	20	10.2282
24	11.3918	28	12.3132	32	11.8863	40	10.6908	44	12.6338
48	14.6746	52	14.6344	56	15.0079	64	14.4158	68	15.4588
72	13.5103								

IPEA DATA

```
16  72 16 8 2
0.125 150.00 0.3417 18.0 198.05
 0.45   0.55
```

DRYING MODEL OUTPUT

RUN 1 COLUMN 1 55% RECIRCULATION

CONDITIONS FOR EACH LAYER AT TIME= 1.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.332	0.331	31.87	20.81	14.94	0.360	0.0106
2	0.332	0.331	30.62	20.64	15.65	0.405	0.0111
3	0.332	0.331	29.40	20.51	16.32	0.453	0.0116
4	0.333	0.331	28.20	20.63	16.95	0.505	0.0121
5	0.333	0.332	27.02	20.63	17.54	0.562	0.0126
6	0.333	0.332	25.88	20.61	18.11	0.623	0.0130
7	0.333	0.332	24.77	20.60	18.64	0.688	0.0135
8	0.333	0.332	23.70	20.59	19.13	0.756	0.0139
9	0.334	0.333	22.68	20.41	19.60	0.828	0.0143
10	0.334	0.333	21.72	20.46	20.02	0.901	0.0147
11	0.335	0.334	20.84	20.53	20.40	0.974	0.0151
12	0.339	0.338	20.39	20.65	20.71	0.999	0.0154
13	0.346	0.346	20.39	20.40	20.38	0.999	0.0150
14	0.342	0.342	20.39	20.40	20.38	0.999	0.0150
15	0.342	0.342	20.38	20.40	20.38	0.999	0.0150
16	0.342	0.342	20.38	20.40	20.38	0.999	0.0150

AVG.MC(W.B.) LAYERS(1-16) 0.335

CONDITIONS FOR EACH LAYER AT TIME= 12.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.238	0.237	36.52	20.52	11.86	0.227	0.0087
2	0.239	0.238	35.95	20.53	12.25	0.241	0.0089
3	0.240	0.239	35.37	20.53	12.64	0.255	0.0091
4	0.241	0.240	34.80	20.54	13.01	0.270	0.0093
5	0.242	0.241	34.22	20.55	13.38	0.285	0.0096
6	0.243	0.243	33.64	20.55	13.74	0.302	0.0098
7	0.245	0.244	33.06	20.55	14.09	0.319	0.0100
8	0.246	0.246	32.48	20.56	14.44	0.337	0.0103
9	0.248	0.247	31.90	20.56	14.79	0.356	0.0105
10	0.250	0.250	31.31	20.70	15.13	0.376	0.0107
11	0.253	0.253	30.71	20.62	15.46	0.398	0.0110
12	0.259	0.258	30.09	20.55	15.81	0.421	0.0112
13	0.282	0.281	29.32	20.47	16.23	0.452	0.0115
14	0.288	0.287	28.52	20.41	16.65	0.487	0.0119

15	0.287	0.286	27.75	20.56	17.05	0.522	0.0122
16	0.290	0.289	26.97	20.55	17.45	0.561	0.0125

AVG.MC(W.B.) LAYERS(1-16) 0.255

CONDITIONS FOR EACH LAYER AT TIME= 24.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.176	0.175	38.71	20.67	10.76	0.188	0.0080
2	0.177	0.176	38.13	20.68	11.18	0.199	0.0083
3	0.178	0.177	37.54	20.70	11.60	0.211	0.0085
4	0.179	0.178	36.96	20.71	12.00	0.224	0.0087
5	0.181	0.180	36.37	20.72	12.40	0.238	0.0090
6	0.182	0.181	36.31	20.88	12.79	0.245	0.0092
7	0.184	0.183	35.69	20.89	13.18	0.260	0.0094
8	0.186	0.185	35.69	21.08	13.57	0.266	0.0097
9	0.188	0.187	35.69	21.19	13.77	0.270	0.0098
10	0.190	0.189	35.56	21.26	13.98	0.275	0.0100
11	0.192	0.191	35.24	21.27	14.20	0.284	0.0101
12	0.195	0.195	34.88	21.43	14.41	0.294	0.0102
13	0.209	0.208	34.46	21.35	14.66	0.306	0.0104
14	0.213	0.213	34.02	21.28	14.92	0.319	0.0106
15	0.213	0.213	33.59	21.21	15.16	0.332	0.0108
16	0.216	0.215	33.15	21.15	15.41	0.345	0.0109

AVG.MC(W.B.) LAYERS(1-16) 0.191

CONDITIONS FOR EACH LAYER AT TIME= 36.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.121	0.121	37.60	18.94	6.39	0.148	0.0059
2	0.122	0.121	37.41	18.93	6.57	0.151	0.0060
3	0.122	0.122	37.22	18.93	6.75	0.155	0.0061
4	0.123	0.123	37.02	18.92	6.93	0.159	0.0062
5	0.124	0.124	36.83	18.91	7.11	0.162	0.0063
6	0.125	0.125	36.62	18.91	7.29	0.166	0.0063
7	0.126	0.126	36.42	18.90	7.48	0.170	0.0064
8	0.127	0.127	36.21	18.90	7.66	0.174	0.0065
9	0.129	0.128	36.00	18.89	7.85	0.179	0.0066
10	0.130	0.130	35.78	18.88	8.04	0.183	0.0067
11	0.132	0.132	35.55	18.88	8.23	0.188	0.0068
12	0.136	0.135	35.32	18.87	8.43	0.193	0.0069
13	0.150	0.150	35.01	18.87	8.69	0.200	0.0070
14	0.155	0.154	34.68	18.86	8.96	0.207	0.0071
15	0.155	0.155	34.36	18.86	9.22	0.215	0.0072
16	0.158	0.157	34.02	18.85	9.49	0.223	0.0074

AVG.MC(W.B.) LAYERS(1-16) 0.133

CONDITIONS FOR EACH LAYER AT TIME= 48.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.095	0.095	38.13	19.98	9.38	0.177	0.0073
2	0.095	0.095	38.00	19.98	9.48	0.179	0.0074
3	0.096	0.095	37.87	19.98	9.58	0.181	0.0074
4	0.096	0.096	37.75	19.98	9.68	0.184	0.0075
5	0.097	0.097	37.61	19.98	9.78	0.187	0.0075
6	0.097	0.097	37.48	19.98	9.88	0.189	0.0076
7	0.098	0.098	37.35	19.98	9.99	0.192	0.0076
8	0.099	0.099	37.21	19.99	10.09	0.195	0.0077
9	0.100	0.100	37.08	19.99	10.19	0.198	0.0077
10	0.101	0.101	36.94	19.99	10.30	0.200	0.0078
11	0.102	0.102	36.79	19.99	10.41	0.203	0.0078
12	0.104	0.104	36.64	19.99	10.52	0.207	0.0079
13	0.112	0.112	36.47	19.99	10.65	0.211	0.0080
14	0.115	0.114	36.28	19.99	10.79	0.215	0.0080
15	0.115	0.115	36.09	19.99	10.92	0.219	0.0081
16	0.117	0.116	35.90	19.99	11.06	0.223	0.0082

AVG.MC(W.B.) LAYERS(1-16) 0.102

CONDITIONS FOR EACH LAYER AT TIME= 60.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.073	0.073	36.61	20.08	10.76	0.210	0.0080
2	0.074	0.073	36.50	20.08	10.85	0.213	0.0081
3	0.074	0.074	36.50	20.12	10.93	0.214	0.0081
4	0.074	0.074	36.39	20.12	11.02	0.217	0.0082
5	0.075	0.075	36.39	20.16	11.11	0.218	0.0082
6	0.076	0.075	36.39	20.19	11.20	0.219	0.0083
7	0.076	0.076	36.27	20.20	11.29	0.222	0.0083
8	0.077	0.077	36.14	20.20	11.39	0.225	0.0084
9	0.078	0.078	36.14	20.24	11.48	0.226	0.0084
10	0.079	0.079	36.00	20.24	11.58	0.230	0.0085
11	0.080	0.080	35.86	20.24	11.68	0.233	0.0085
12	0.082	0.082	35.71	20.25	11.79	0.237	0.0086
13	0.088	0.088	35.61	20.25	11.85	0.239	0.0086
14	0.090	0.090	35.52	20.25	11.92	0.241	0.0087
15	0.090	0.090	35.42	20.25	11.99	0.244	0.0087
16	0.091	0.091	35.32	20.25	12.05	0.246	0.0088

AVG.MC(W.B.) LAYERS(1-16) 0.080

CONDITIONS FOR EACH LAYER AT TIME= 71.

LAYER NO.	MC(W.B.)(I-1)	MC(W.B.)(I)	TX	TWBX	TDPX	RHX	HX
1	0.059	0.059	36.20	19.33	9.06	0.192	0.0072
2	0.059	0.059	36.16	19.33	9.10	0.193	0.0072
3	0.059	0.059	36.11	19.33	9.14	0.194	0.0072
4	0.060	0.059	36.06	19.33	9.19	0.195	0.0072
5	0.060	0.060	36.00	19.33	9.23	0.196	0.0072
6	0.060	0.060	35.95	19.33	9.28	0.197	0.0073
7	0.061	0.061	35.90	19.33	9.32	0.199	0.0073
8	0.061	0.061	35.84	19.33	9.37	0.200	0.0073
9	0.062	0.062	35.78	19.33	9.42	0.201	0.0073
10	0.062	0.062	35.72	19.33	9.46	0.202	0.0074
11	0.063	0.063	35.66	19.33	9.51	0.204	0.0074
12	0.064	0.064	35.59	19.33	9.57	0.205	0.0074
13	0.069	0.069	35.51	19.33	9.63	0.207	0.0074
14	0.071	0.070	35.42	19.33	9.70	0.209	0.0075
15	0.071	0.071	35.33	19.33	9.77	0.211	0.0075
16	0.072	0.072	35.24	19.33	9.84	0.213	0.0075

AVG.MC(W.B.) LAYERS(1-16) 0.063

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SIMULATION OF PEANUT DRYING

INCORPORATING AIR RECIRCULATION

by

Deborah F. Cook

(ABSTRACT)

To determine the energy saving potential available from recirculating air in peanut drying, a thin layer drying simulation model was adapted to incorporate recirculation. A heat and mass balance computer model was developed to enable the determination of heat energy input. Laboratory crop dryers were designed and constructed to conduct experiments to verify the simulation models. Five batches of peanuts were dried using different recirculation strategies and the model successfully predicted the experimental results, including moisture content and wet and dry bulb temperatures. Energy savings of up to 20 percent were realized in the experimental runs. The simulation model was also used to evaluate and compare several recirculation strategies in order to determine successful strategies.