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The Development Of A Fixed Bed Drying Model For Wood Chips Under Forced Air At Ambient Condition

presented by

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THE DEVELOPMENT OF A FIXED-BED DRYING MODEL FOR WOOD CHIPS UNDER FORCED AIR AT AMBIENT CONDITIONS

by

Yonggang Feng

A DISSERTATION

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in partial fulfillment of the requirements
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Department of Forestry

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ABSTRACT

THE DEVELOPMENT OF A FIXED BED DRYING MODEL FOR WOOD CHIPS UNDER FORCED AIR AT AMBIENT CONDITIONS

by

Yonggang Feng

The application of wood energy in industry has been developed rapidly since the 1970s, and a considerable amount of research has been conducted to improve combustion and fuel handling. The major source of wood fuel in the industry is fresh cut wood chips because of the convenience in processing them. However, their high moisture content greatly reduces the net heating value of this wood fuel, as well as its combustion efficiency.

The objective of this study was to develop a fixed bed drying model for wood chips under forced air and at ambient conditions to provide the basic engineering information required for designing a practical wood chip dryer.

Some physical properties of wood chips related to fixed bed drying were evaluated as the basic information in the drying simulation. These properties included (1) the moisture content range of wood chips, (2) wood chip size distribution, (3) bulk shrinkage during drying, and (4) airflow resistance in the wood chip bed.

A thin layer drying experiment was performed in a conditioning chamber to develop a thin layer drying model. Then, this model was employed in a semi-theoretical grain drying fixed bed model in order to simulate a fixed bed dryer. The controlled factors

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included air temperature, air relative humidity, and wood chip size.

An empirical fixed bed drying model was developed through the experiment with a small fixed-bed drying system mounted in a conditioning chamber. Four factors were controlled in the experiment: air temperature, air relative humidity, airflow rate, and wood chip size. One variable, the original moisture content of the wood chips, was not controlled. The final model, including a nonlinear equation and a multiple polynomial equation was determined by using regression routines in a SAS program. A computer program called "CHIP DRY" executing the simulation of the empirical model was written in FORTRAN to provide the following information for the drying process in a dryer: moisture content distribution, average moisture contents, average net heating values, bulk shrinkage, and airflow resistance.

A testing experiment was performed in a fixed bed dryer 14 inches in diameter and 48 inches high to test the feasibility of the models for larger scale dryers and over long periods of drying time. The results of the experiment indicated that the empirical model provided more accurate simulation and used much less computer time than the semi-theoretical model.

Because of the accurate and rapid simulation of the empirical model, this information can serve as the basis for optimum dryer design which, in turn, will provide the best method for wood chip drying.

To my parents and my wife

for their love and support

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LIST OF SYMBOLS

β	constant
θ	particle temperature, °F
ρ_p	product density, lb/bu
υ	specific volume of air, ft^3/lb
a	particle surface area per unit bed volume, ft^2/ft^3
A	single particle surface area
b	constant
BV	bulk volume coefficient
c	fraction of wood consisting of holocellulose
C	shape coordinate
c_{1-2}	constant in airflow resistance formula
c_a	specific heat of dry air, Btu/lb/°F
CA	largest cross section area, in^2
CFM	cubic foot per minute
c_p	specific heat of dry grain kernels, Btu/lb/°F
c_v	specific heat of water vapor, Btu/lb/°F
c_w	specific heat of liquid water, Btu/lb/°F
D	depth factor
EMC	equilibrium moisture content, %
FR	airflow resistance, inch H_2O
FV	airflow velocity, ft/min

G_a

h'

h_{fg}

HHV

k

K_{ii}

k_t

k_x

L

MC

MR

NHV

OMC

OV

P

ΔP

Q_a

r

R^2

RH

S

SVR

SZ

t

T

T_a

G_a	airflow rate, lb/hr/ft^2
h'	convective heat transfer coefficient, Btu/ft^2/°F/hr
h_{fg}	heat of evaporation, Btu/lb
HHV	higher heating value, Btu/lb
k	drying constant, hr^{-1}
K_{ii}	phenomenological coefficient
k_t	time constant
k_x	depth constant
L	length, mm
MC	moisture content, percent
MR	moisture ratio
NHV	net heating value, Btu/lb
OMC	original moisture content, percent
OV	original bulk volume, in^3
P	vapor pressure, psi
ΔP	airflow resistance, inch H_2O
Q_a	airflow rate, CFM
r	particle coordinate
R^2	determination of regression
RH	relative humidity, %
S	surface area, in^2
SVR	surface/volume ratio, in^{-1}
SZ	wood chip size, in^2
t	time, hour
T	temperature, °F
T_a	air temperature, °F

T_g	temperature of the air leaving grain mass, °F
V	volume, in^3
W	air humidity ratio, lb/lb
WV	bulk volume, in^3
x	depth value in the wood chip bed, in
Y	time unit
Z	thickness, mm

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CHAPTER I

INTRODUCTION

1.1 Wood Energy

Wood fuel, as a renewable energy source, has received increasing attention during recent years. Supplied as freshly cut wood chips for industrial energy supply, wood fuel, compared to fossil fuel, has a higher moisture content and a lower net heating value. Since drying is the method commonly used to reduce the moisture content of wood, it is possible to do so economically in order to increase the combustion efficiency of wood fuel boilers in industry. The objective of this study is to develop a model to simulate the wood chip drying process in a fixed bed dryer.

1.1.1 The Importance of Wood Energy

Wood as a source of energy has a long history. One hundred years ago, 75 percent of the four quad (1 quad = 1,000,000 million Btu) energy supply in the United States came from wood fuel (Zerbe, 1977). Industrial development changed the distribution of energy supplies. Although the total energy consumption in the United States was about 75 quads in 1976, but consumption of wood energy

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dropped to 1.1 quads (Tillman, 1978). An important factor leading to this decline was the development of the coal and oil industries.

Since the energy crisis in 1973, renewable energy resources, such as wood, have been examined as supplement to traditional fuels such as coal, oil, and natural gas. Research and development in this area has developed quickly since then.

Today, biomass provides four to five percent of the total energy supply in the United States, 10 percent of this energy is used in the form of electricity (National Wood Energy Association, 1989). Fourteen percent of the world's total energy supply is from wood. This accounts for about 50 percent of all wood harvested (Hall, 1987, Cheremisinoff, 1970).

Under sunlight, trees convert carbon dioxide and water to carbohydrates and oxygen in a process called photosynthesis. Wood energy is generated in this process. The renewable amount of energy from forests in the United States per year is seven to eight quads (Koch, 1989). Forests are the largest solar energy reserve in the world. In the United States, the energy stored in forests is 300 quads. This is about equal to the United States' natural gas reserves and more than its oil reserves (Figure 1.1).

Because of the ease of obtaining wood fuel, including wood waste, forest product industries, such as the pulp and paper industry, lumber and furniture industries, have played an important role in the development of wood energy. In 1983, 1.5 quads of energy were produced by forest products industries in the United States (Koch, 1983). The energy contribution from biomass is predict

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predicted to be three to eight quads in the year 2000 (Del Gobbo, 1978).

This brief review indicates wood energy use is increasing rapidly. Research and studies in this area have mainly focused on practical applications, such as the Michigan Wood Energy Demonstration Project sponsored by Michigan Energy Conservation Program (MECP). The studies relating to this dissertation are also sponsored by MECP.

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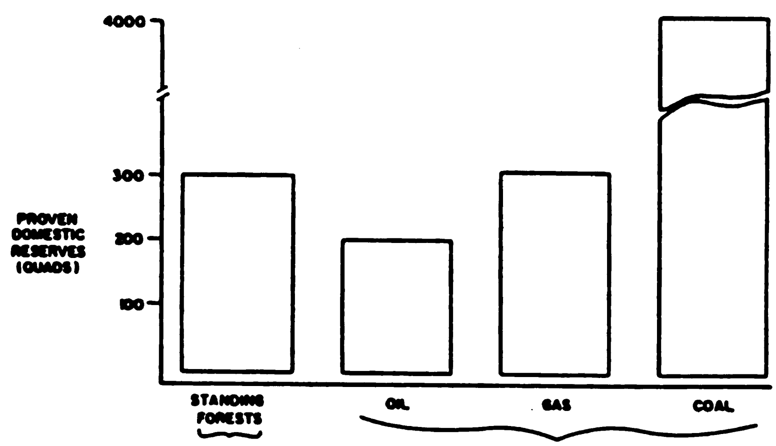

Figure 1.1 Energy reserves in the U.S.: About 300 quads are in standing forests with an annual production of 7 to 8 quads. About 200 quads are in Oil, about 300 quads in gas, and about 4,000 quads in coal. (Drawing from Department of Energy.)

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1.1.2 The Heating Value of Wood

Wood is a complex organic material. It is composed mainly of three components: cellulose, lignin, and hemicellulose. Different species have different chemical compositions. In general, however, the proportion of cellulose, lignin, and hemicellulose are 43 percent, 22 percent, and 35 percent, respectively, in hardwood, and 43 percent, 29 percent, and 28 percent, respectively in softwood (Tillman, 1978). The heat released from a unit of material during the combustion is defined as higher heating value (HHV). The relationship between the chemical composition and the higher heating value can be explained by following formula (Tillman,1978)

$$HHV = C \times 7527 + (1 - C) \times 11479$$

where HHV is the higher heating value (Btu/lb), C is the fraction of wood consisting of holocellulose, the combination of cellulose and hemicelluloses.

The chemical composition and higher heating values for some species of North American woods are listed in Table 1.1:

Table 1.1 Chemical composition and HHV of 7 species of North American Woods (Tillman, 1978).

Tree species	Cellulose %	Lignin %	Hemicellulose %	HHV Btu/lb
Beech	45.2	22.1	32.7	8455
White birch	44.5	18.9	36.6	8334
Red maple	44.8	24.0	31.2	8400
White cedar	48.9	30.7	20.4	8400
Eastern hemlock	45.2	32.5	22.3	8885
Jack pine	45.0	28.6	26.4	8930
White spruce	48.5	27.1	21.4	8890

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The data in Table 1.1 shows that the differences in higher heating value between different species are small.

The pollution level of wood combustion is generally lower than that of fossil fuels. In some circumstances, such as with wood products companies, wood fuel has additional advantages including lower cost, local availability, and easier waste cleanup. However, some disadvantages of wood fuel include its relatively low density, its chemical and biological instability, and its low net heating value, which is associated with its high moisture content.

The moisture content of wood varies by species, normally from 31-249 percent (dry basis) (Hoadley, 1980). At higher moisture contents, a considerable amount of the heat generated in combustion is used to evaporate water. The moisture content (MC) of the fuel directly influences the net heating value. Net heating value (NHV) equals to the heat released from the combustion of the material subtract the heat of water evaporation. Tillman (1978) represented the relationship between the net heating value and the moisture content in the following equation, also plotted in Figure 1.2 (Tillman, 1978)

$$NHV = HHV \times [1 - 0.0114 \times MC]$$

where NHV is net heating value (Btu/lb), HHV is higher heating value (Btu/lb), and MC is moisture content of fuel, total weight basis (percent).

Both net heating value and combustion efficiency are related to the moisture content of wood fuel (Table 1.2).

Table 1.2 The influence of moisture on fuel value and combustion efficiency (Tillman, 1987).

Moisture Content (%)	Net heating Value (Btu/lb)	Combustion Efficiency (%)
0.0	8800	81
16.7	7125	78
28.6	5390	75
37.5	5040	72
44.4	4345	70
50.0	3785	68
54.5	3333	66
58.3	2950	63
61.5	2630	60
64.3	2350	57
66.7	2110	55

Although many methods have been used to dry wood fuel, air drying has been the most common. For example, letting trees die in the winter 10 to 12 weeks before felling can decrease the moisture content of the wood from six to 70 percent, total weight basis (Rogers, 1981). McMinn experimented by cutting trees and letting them air dry for four weeks. Some of the trees were cut into bolts and some left lying with stems and crowns intact for further transpiration. The result indicated a recovered energy gain of about six to nine percent for stacked bolts and 14 percent for intact trees (McMinn, 1985). Stacking firewood outside is another example of air drying. The drying speed for the methods mentioned above varied with the species and the size of the wood bolts.

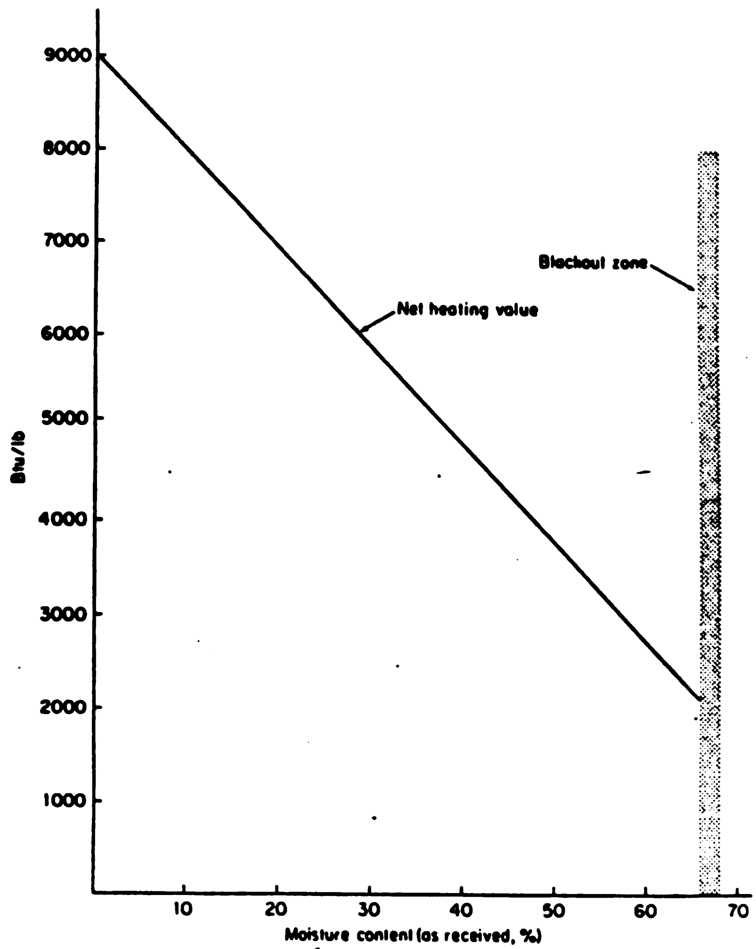


Figure 1.2 Influence of moisture content on the heating value of wood (Tillman, 1987).

Because the air spaces in a wood chip pile are smaller than those in a firewood stack, the airflow resistance is much higher in the wood chip pile. Under natural air convection, the smaller the size of wood particles, the slower the drying speed. Figure 1.3 illustrates the drying processes of wood chips and wood chunks under natural air convection (Sturos, 1983). If the wood fuel is in particle form, proper air drying requires that the particles be large enough to let air convection occur in the accumulation.

In addition to increasing the net heating value, drying wood chips reduces the weight of the fuel and prevents deterioration and self-heating during storage (Springer, 1979). Therefore, finding an efficient way to reduce the moisture content of wood chips is important to the development of efficient wood energy production.

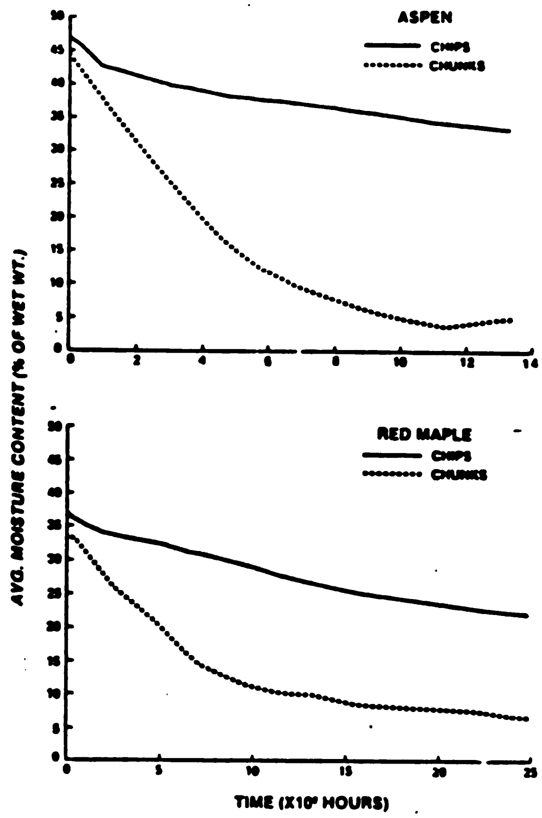


Figure 1.3 **Time required for natural convective drying of aspen and red maple chunks and chips (Sturos,J.B., Coyer,L.A. and Arola,R.A. 1983).**

1.1.3 Wood Energy Facilities in Industry

Most wood energy used today is produced through direct combustion rather than through gasification or liquification. The energy produced for industrial purposes is thermal energy or electrical energy.

There are several types of furnaces especially designed for using wood fuel. The most commonly used types are Dutch ovens, spreader-stoker boilers, fuel cell boilers, and inclined grate boilers. Dutch ovens are the oldest type of furnace used to burn wood. Spreader-stoker boilers are the most commonly used, with a capacity of 25,000 to 500,000 lb/hr of steam. Fuel cell boilers are a two-stage system with a capacity of 10,000 to 30,000 lb/hr of steam (Cheremisinoff, 1980).

Suspension-fired boilers and fluidized bed incinerators are two types of energy systems developed during recent decades. Suspension-fired boilers are used with wood fuel having a moisture content as low as 20 percent and performed at fairly high thermal efficiency. Fluidized bed incinerators, such as rubbish incinerators, are used to burn massive amounts of biomass fuel at a moisture content of around 50 percent.

Wood chips are the ideal fuel, both in terms of combustion efficiency and ease of handling, for most of the furnaces (except the suspension burners) used in the industry today.

1.2 Wood Chips and Related Studies

1.2.1 Wood Chips in Industries

The use of wood energy by industry has increased during recent decades. A review of developments in wood chip applications since 1970 indicate that wood chip production will continue to increase. Today, wood energy facilities are usually designed to burn chip-sized or smaller materials (Koch, 1989). It is much easier to handle small particle fuel, such as wood chips, than firewood blocks. Wood chips can be delivered by trucks from the chipping area to the user's storage yard.

Wood chip users include pulp and paper mills, particle board companies, and power stations. Formerly, most wood products manufacturers used logs as their raw materials and now the wood chips are the most commonly used material. Since the 1970s, four factors have been instrumental in leading to the rapid development of wood chip use: (1) the growth in wood chip demand and local shortages, (2) the development of wood energy, (3) the low cost of raw materials, and (4) the availability of whole tree chipping equipment (FAO, 1975).

Based on recent trends in the development of wood products and wood energy, it is predicted that the worldwide demand for wood will be about 141,000 million ft^3 in the year 2000, as compared to 88,300 million ft^3 in 1975 (FAO, 1990).

Because the net heating value of wood can be increased by drying, a suitable method to dry wood chips for energy gain is expected to be found. As the first step, the research discussed in this dissertation focused on the development of a fixed bed wood chip drying model for green wood chips.

1.2.2 Production and Storage of Wood Chips in Industry

Wood chips are produced mainly by field chipping whole tree chips in harvesting areas. Some chips are saw mill residuals.

The moisture content of green wood is 31 to 249 percent, depending on the tree species, the position in the tree, and the season of harvesting (Hoadley, 1980). Data from an 18 megawatt wood fuel power station in Michigan indicated that the average moisture content of randomly sampled green wood chips was 41.8 percent (total weight basis) for hardwood, 50.6 percent for softwood, and 46.5 percent for the combination of hardwood and softwood (Nicholls, 1991).

In general, wood chips are stored outdoors in large storage piles, a simple and inexpensive method. A conveyer and a bulldozer are normally used to construct the piles in a storage yard. The piles are formed with a mixture of different-sized chips. Because of the high air flow resistance in the wood chip piles, the drying caused by air convection is very slow. The driving force of the airflow in the pile comes mainly from the gravity difference between warm air inside the pile and cold air outside it (Kubler, 1982). The temperature increase inside the piles is caused by the respiration of living ray parenchyma cells and by direct chemical oxidation (Feist, 1973). Self-heating in the wood chip piles is obvious during the first two months of storage.

1.2.3 Studies on Wood Chips

During the last 20 years, most of the research on wood fuel storage focused on variations in moisture content and temperature of wood fuel storage piles.

In 1976 White, et. al., built three piles containing mixed hardwood bark, pine bark, and mixed hardwood and pine sawdust. In this study, he measured internal temperature, moisture content, acidity, and the heating value during five months of outdoor storage. White also evaluated the effects of pile geometry, residue types, and methods of stacking on the fuel potential of the residues. The results of this study indicated that the steep pile sides increased internal drying and that an inexpensive drying method could be found by constructing the storage piles properly (White, 1978).

In the late summer of 1978, White, et. al., constructed another three wood fuel piles. Three fuels (hardwood whole tree chips, bark, and sawdust) were stored in piles 10-, 15- and 20-feet high. After one year of storage, the average moisture content of the chips, bark, and sawdust increased by 84, 108, and 191 percent (dry basis), respectively, over the original moisture content. The temperature in the piles increased rapidly during the first week to a high of 113°F for the whole tree chips and 163.4°F for the bark and sawdust (White, 1983).

Sturos developed two exploratory drying experiments to see whether chunks, with their much larger inter-particle voids, dry more rapidly than chips (Sturos, 1983). In one experiment, he used natural convective ambient air to dry chunks and chips and found that chips dried slower than chunks. In another experiment, he used forced ambient air to dry chunks and chips and found that chips dried faster than chunks.

Studies so far on wood chip drying have been very limited, as have actual applications, though the potential for more widespread application exists. Many companies, power stations for example, have large amounts of waste heat left as a byproduct of their production. The total thermal efficiency of a wood energy system would be increased by predrying wood chips with this waste heat. Therefore, a suitable method of using waste heat or ambient air to economically dry green wood chips is likely to be found.

1.3 Studies on Biomass Material Drying Models

1.3.1 Agriculture Products

The development of simulation models for drying biomass started from drying agricultural products, such as corn, soybeans, and potatoes. In general, two types of models were developed: empirical models and semi-theoretical models. Drying curves were developed through experiments on grain drying (Hukill, 1947). Those results can be viewed as the earliest drying model. Along with the development of computer applications, differential equations related to the heat and mass transfer in the drying process can be solved using a numerical method. Therefore a semi-theoretical model was developed by solving the differential equations numerically to simulate the fixed bed drying process. Both types of models were employed in the designs of drying equipment for agricultural products.

A fixed bed grain drying model (Fixed Bed Dryer Model) was developed for the stationary deep-bed drying of all cereal grains. This model was based on the theoretical calculations on energy and mass balance in grain drying (Brooker, 1974). In this study, a standard finite difference method was used to solve the differential equations of the model.

1.3.2 Wood Particles

Comparing wood chips with grains, the wood chips have higher moisture content and less regular shape and weight. In addition, different wood species have different physical and chemical properties and the drying properties of wood also changes with the species.

Malter performed an experiment with a drying tube to study the drying process of small wood particles. He developed an empirical drying model and compared it to a theoretical model and found that the theoretical model predicted the drying for smaller particles better than did for larger particles (Malter, 1983).

Recently, Schneider developed a forced-air drying model for particulate wood fuel. This model was developed based on the assumption that air leaving the wood fuel bed was saturated with water. The volume of the air required for drying wood fuel was evaluated knowing the amount of moisture to be evaporated and the moisture holding capacity of the drying air. The model was designed to predict the drying time and the cost of drying (Schneider, 1990).

However, no experiments have been done to develop a wood chip drying model that explains the moisture distribution of the wood chip bed during the drying process. Because of the complexity of wood chip properties, several factors that influence the drying process must be considered, such as bulk shrinkage, chip size distribution, and surface/volume ratio. Very limited studies on these properties have been found in the literature.

CHAPTER II

OBJECTIVES

The objective of this study is to develop a fixed bed drying model for wood chip drying under forced air at ambient temperatures. This objective is associated with five sub-objectives outlined in 2.1 to 2.5 below.

2.1 Evaluation of the Physical Properties of Wood Chips Related to the Fixed Bed Drying Process

Original moisture content, bulk shrinkage, size distribution, particle surface/volume ratio, and resistance to airflow are the physical properties of wood chips to be evaluated in this study. These properties are closely related to the drying process and dryer design. In order to obtain the necessary information for designing the dryers and analyzing the drying process, these properties must be evaluated. Because very limited information is available, the values of some of the properties above will be determined through experiment.

2.2 Development of a Thin Layer Drying Model and a Semi-theoretical Fixed-bed Drying Model

In order to simulate fixed bed wood chip drying, a thin layer model will be employed to modify the fixed bed grain drying model. A factorial experiment will be designed to develop a thin layer drying model. Three factors will be included in the experiment: air temperature, air relative humidity, and wood chip size. Multi-factor regression techniques will be used to determine the model.

2.3 Development of An Empirical Fixed Bed Drying Model

Because of many assumptions used in developing a semi-theoretical model, the accuracy of the predicted results of the model may be reduced in the drying simulation. An empirical fixed bed drying model, however, is expected to give more accurate results, and will be developed in this study. A four factorial experiment will be performed in the model development, which will monitor air temperature, air relative humidity, wood chip size, and air flow rate. Statistical analysis, such as ANOVA table and multi-regression, will be used for developing the model.

In order to obtain a quick calculation and an easy application for the empirical wood drying model, a FORTRAN computer program will be written for the model. This program will be designed to simulate the wood chip drying process and to provide basic engineering information for wood chip dryer design.

2.4 Testing and Verification of the Feasibility of the Models Developed

The empirical fixed bed drying model will be developed during a 22-hour drying period in a small dryer. In order to determine whether this model can be used to simulate the drying process in a large dryer, a 14-inch diameter fixed bed dryer will be designed to perform the drying experiment and to test the model simulations. Three experimental conditions will be chosen to process wood chip drying tests. The results from this experiment will be compared to the values derived from both the semi-theoretical model and the empirical model. Compared to the fixed bed experiment, this experiment will use a larger dryer and a longer drying time. Through the experiment and the comparisons, the accuracy and the stability of the models will be evaluated.

CHAPTER III

PHYSICAL PROPERTIES OF WOOD CHIPS RELATED TO FIXED BED DRYING

Some physical properties of wood chips evident in fixed bed drying are important in the development of a fixed bed drying model. Many factors may influence drying processes for wood chips, such as original moisture content, wood chip size, surface/volume ratio, bulk shrinkage, and the airflow resistance of the wood chip bed. Some of these properties have already been studied in depth, such as original moisture content. However, because studies on wood chip drying are limited and data on some related properties are unavailable from the literature review, these properties are evaluated and discussed in this chapter.

Although the wood chip drying model was developed through an experiment on red pine chips, its application may be extended to other types of chips with physical properties similar to those covered in this study.

3.1 Original Moisture Content of Wood Chips

The original moisture content (OMC) of wood chips in this study refers to the moisture content of green wood. Intensive study has been done on green wood moisture content for different species (Peck, 1953).

In this study, the gravimetric method, the standard method developed by the American Society of Testing Methods (ASTM, 1990), is employed for measuring moisture content and the dry basis is used to calculate the moisture content of the wood chip samples.

Wood chips used as fuel are produced by chipping whole tree in harvesting area or by chipping residual in sawmills, and these combine both sapwood and heartwood. The moisture content of these chips depends on the percentage of each type of wood in the total volume of the combination. According to data from a field sampling study in a wood energy power plant in central Michigan, the moisture content of the wood chip sampled from individual trucks was 44.9-163.2 percent, dry basis, (Nicholls, 1991). The average moisture content of the red pine chips used in the experiment of drying model development was 148.4 percent with the highest at 171.2 percent and the lowest at 127.8 percent. The moisture content of wood chips is considered an independent variable in the model development.

3.2 Wood Chip Size and Surface/Volume Ratio

Compared with some agricultural products, such as corn and soybeans, wood chips are less uniform in their shape and size. Wood chip size is mainly determined by the type of chipper, the chipping operation, and the structure of the wood (FAO, 1976).

Usually, wood chip size is distributed across a wide range, even if the chips are produced at the same chipper. Because chip size was considered an important factor in the drying model, measurement was performed on the different size levels individually. It was found in a preliminary size sorting process that the largest cross section area of the chips was proportional to the size of the screen openings. The correlation between the chip size and screen opening was determined in this study. No previous studies in this area were found in the literature review.

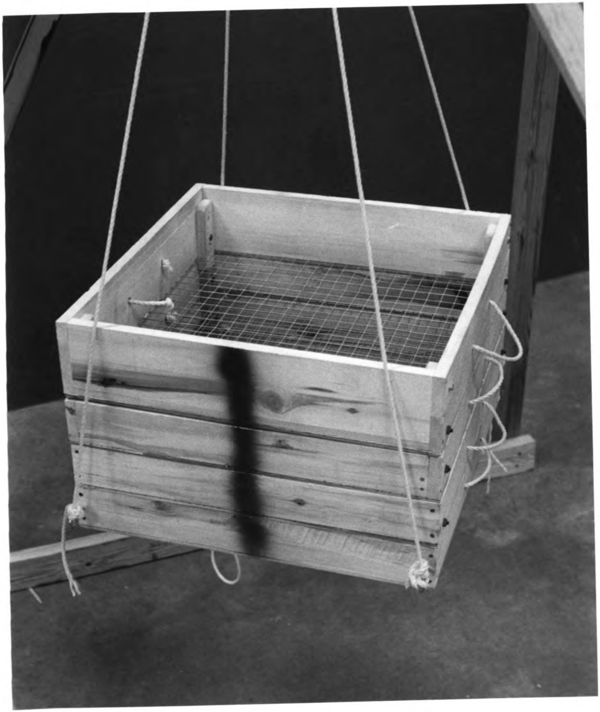
The water contained in a single wood chip is proportional to the volume of the chip at a certain moisture content. During the drying processes, water leaving a wood chip must do so through the chip surface by either vapor transformation or water evaporation. Therefore, the drying rate is directly related to the surface/volume ratio of a wood chip. The shape of a wood chip is much less uniform than that of a kernel of grain and the measurement of the surface/volume ratio of wood chips has not been done before. In this study the surface/volume ratio was determined as an average value for each size level.

3.2.1 Study Methods on Wood Chip Size and Surface/Volume Ratio

Because the size of wood chips was considered a factor in the model development, wood chips were separated by size using a set of wire screens with the holes of four different sizes. The sizes of the screen holes were one-inch, three-quarter-inch, one-half-inch, and one-quarter-inch square (Figure 3.1). The size sorting separated the wood chips into five groups of different sizes labeled from largest to smallest as SZ-0, SZ-1, SZ-2, SZ-3, and SZ-4. Because the sizes of the chips in the SZ-0 and the SZ-4 were not controlled by an upper or a lower limit, respectively, those two groups were not included in the measurement.

Chip size measurements were performed on the wood chip sizes SZ-1, SZ-2, and SZ-3. Three samples were obtained from each size randomly. One hundred wood chips were measured in each sample with a caliper. The typical shape of a wood chip is shown in Figure 3.2. Three dimensions labeled as L (length), W (width), and Z (thickness) were measured for each chip. The largest cross area and surface/volume ratio were determined from these measurements. Results of the measurements are summarized in Table 3.1.

Figure 3.1 A four-level screen used for size sorting wood chips in the laboratory. The size of the screen openings are 1", 3/4", ½", and ¼".



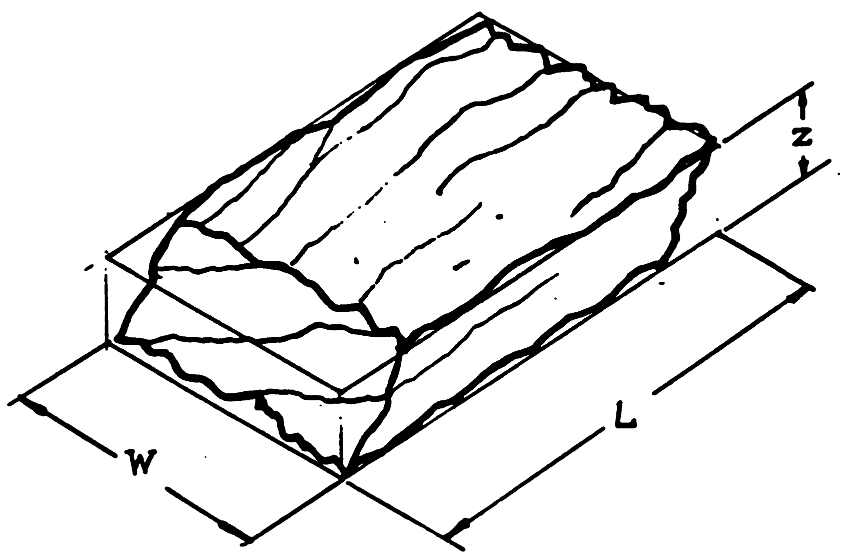


Figure 3.2 A typical wood chip shape and its three dimensions labeled as L (length), W (width), and Z (thickness).

3.2.1.1 Largest Cross Section Area of a Wood Chip

In size sorting, the largest cross section area of a chip was considered the key control factor directly correlating to the size of the screen opening. As shown in Figure 3.2, the length and width measurements of a wood chip are larger dimensions than its thickness. Therefore, the largest cross section area of a wood chip was defined as L x W in^2 and shown in the following formula

$$CA = L \times W$$

where CA is the largest cross section area (in^2), L is the length (in), and W is the width (in) of a wood chip.

The distribution of the largest cross section area of the wood chips with the percentage in total weight was determined for the three different sizes. The average value and standard deviation were also calculated for each sample.

3.2.1.2 Surface/Volume Ratio of a Wood Chip

Surface/volume ratio (SVR) were determined using the following formula

$$SVR = \frac{S}{V}$$

$$S = 2 \times (L \times W + L \times Z + W \times Z)$$

$$V = L \times W \times Z$$

where SVR is surface/volume ratio (1/in), S is surface area (in^2) and V is Volume (in^3).

The distribution of the surface/volume ratio of the wood chips with the percentage in total wight was determined for the three different sizes. The average values and standard deviation were also calculated for each sample.

3.2.2 Results of the Study on Largest Cross Section Area and Surface/Volume Ratio

Results of the measurements of cross section area and surface/volume ratio are summarized in Table 3.2. The average cross section area of wood chips are 529.1 mm^2, 284.1 mm^2, and 144.1 mm^2 for the size SZ-1, SZ-2, and SZ-3 respectively. The average surface/volume ratios are 0.78 mm^{-1}, 1.01mm^{-1}, and 1.41 mm^{-1} for the size SZ-1, SZ-2, and SZ-3 respectively.

A distribution analysis was done for the pooled samples for the 300 chips in each size group. A normal distribution line was chosen to fit the data (Bhattacharyya, 1977). Figure 3.3 and Figure 3.4 illustrate the distributions and the related probability for the largest cross section area and the surface/volume ratio, respectively. The statistical data of the distribution curves are illustrated in Table 3.3 and Table 3.4.

Table 3.1 Analysis data of the three dimensional measurement on three different sized red pine chips.

Sample Size	Group†	Length(mm)		Width(mm)		Thickness(mm)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
	1	28.18	5.10	19.07	6.04	3.99	1.05
SZ-1	2	28.64	5.45	19.09	4.76	4.08	1.09
	3	28.02	5.35	18.81	4.45	3.78	1.18
	1	25.62	5.78	11.73	3.26	3.06	0.99
SZ-2	2	24.59	4.44	12.02	3.07	2.83	0.81
	3	24.48	5.30	12.37	3.72	2.90	0.80
	1	20.15	7.32	7.26	2.14	2.31	0.72
SZ-3	2	19.83	7.07	7.27	2.48	2.21	0.73
	3	20.75	7.93	7.36	2.26	2.20	0.72

† Each group of wood chips contains 100 individual chips.

Table 3.2 Largest cross section area and surface/volume of three different sized red pine chips.

Size	Group†	Cross Section Area mm^2		Surface/Volume Ratio mm^{-1}	
		Mean	Std.Dev.	Mean	Std.Dev.
	1	525.48	144.00	0.84	0.21
SZ-1	2	539.13	138.17	0.73	0.17
	3	522.54	137.84	0.76	0.16
	1	259.39	90.43	1.01	0.33
SZ-2	2	292.68	84.36	1.03	0.23
	3	300.24	104.16	1.00	0.23
	1	143.83	69.49	1.38	0.38
SZ-3	2	140.26	61.08	1.44	0.39
	3	148.08	62.99	1.42	0.38

† Each group of wood chips contains 100 individual chips.

Table 3.3 Largest cross section area (in^2) distribution.

Sample #	Mean	Std.Dev.	Variance	C.V.†
SZ-1	.9397	.2214	0.04902	0.236
SZ-2	.5283	.1457	0.02123	0.276
SZ-3	.3913	.1506	0.02269	0.385

†C.V. - Coefficient of Variation

Table 3.4 Surface/volume ratio ($1/in^2$) distribution.

Sample #	Mean	Std.Dev.	Variance	C.V.†
SZ-1	17.161	3.734	13.939	0.218
SZ-2	23.416	5.436	29.548	0.232
SZ-3	29.571	6.892	47.496	0.233

†C.V. - Coefficient of Variation

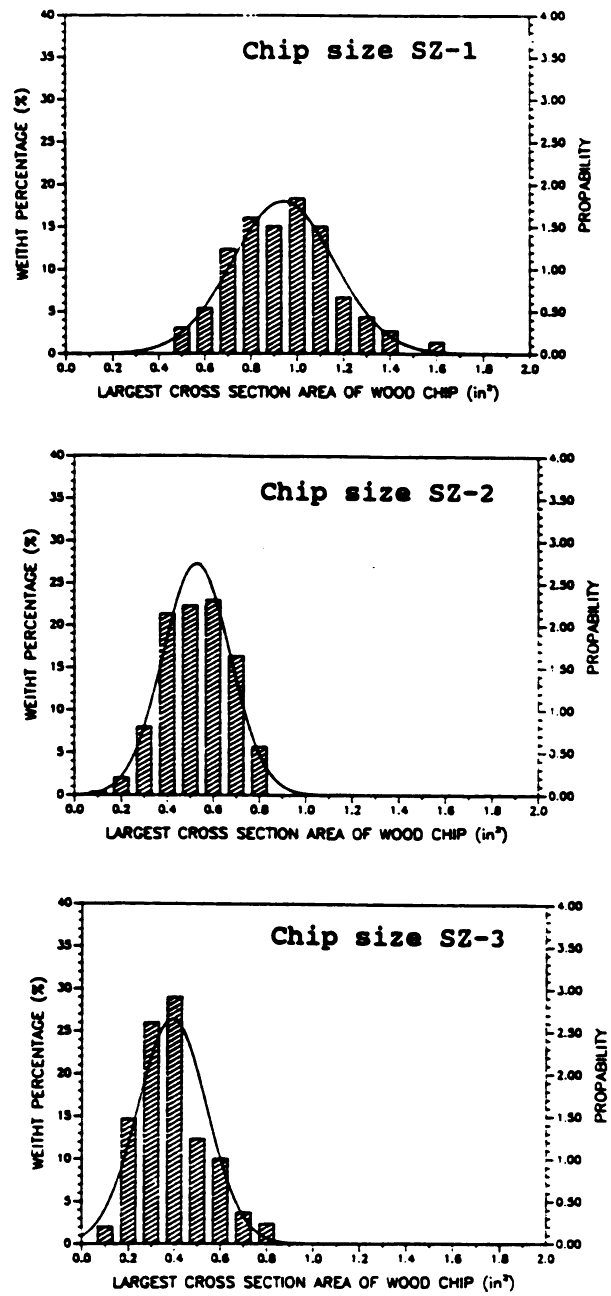


Figure 3.3 **Distribution and probability of largest cross section area of wood chips compared to Table 3.3.**

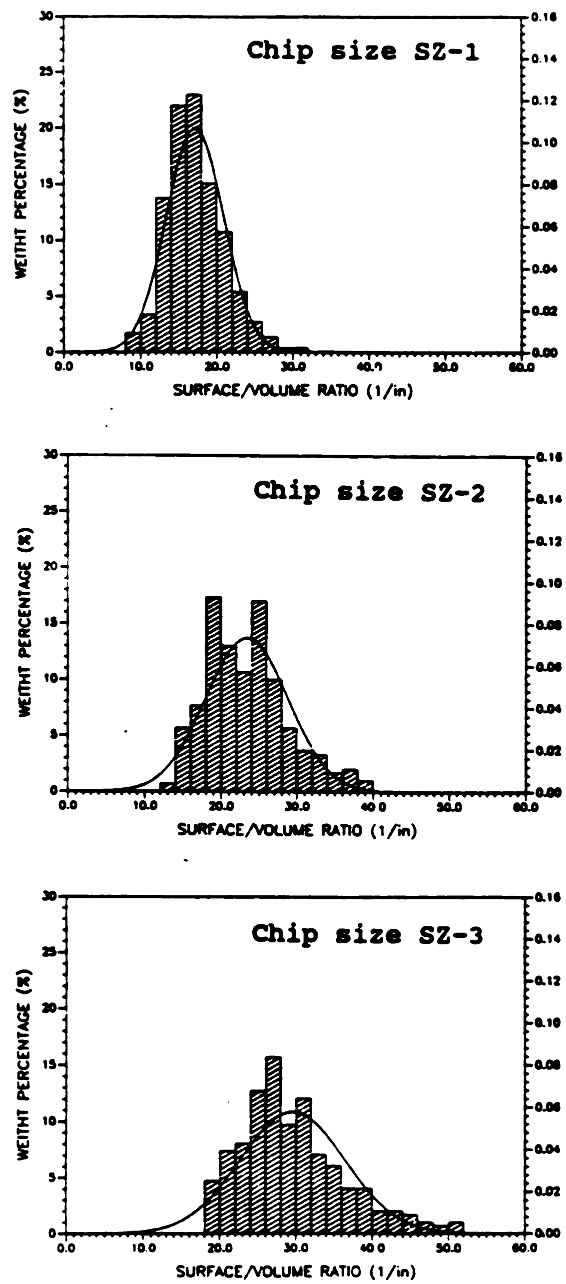


Figure 3.4 Distribution and probability of surface/volume ratio of wood chips compared to Table 3.4.

3.2.3 Discussion on Largest Cross Section and Surface/Volume Ratio

The correlation between wood chip size and the opening size of the screen was anticipated. The distribution of the largest cross section area of wood chip fit a normal distribution. Comparing the different sized samples in Figure 3.3 showed that the distribution range tended to be wider for larger chips than for smaller ones. The distribution curves plotted were based on the percentage in of total weight.

The water movement along the longitudinal grain direction is much faster than across the grain in a tangential or radial direction because of cell structure (Skaar, 1972). Most of the surface area of a typical wood chip is parallel to the longitudinal grain direction (Figure 3.1). Therefore, the two cross-sectioned ends of the wood chip should dry faster than its four other surfaces.

The wood chips used in this study were produced by a sawmill. The distribution of wood chip sizes may differ with different sources of supply. The average largest cross section area of the wood chips was used as a unit to represent the chip sizes in the wood chip drying model discussed in the following chapters.

3.3 Bulk Shrinkage of Wood Chips During Drying

Bulk shrinkage is defined as the shrinkage of the total volume occupied by an accumulation of wood chips corresponding to the change in the moisture content of the chips. In the deep bed model, data on bulk shrinkage was used to determine the bed thickness.

It is known that wood shrinks considerably during the drying process. In general, average shrinkage is different for the three gain directions of wood: about 0.1 percent in the longitudinal direction, eight percent in the tangential direction, and four percent in the radial direction, with variation by species (Hoadley, 1980). Many measurements on wood shrinkage for different species have been recorded, but these data are mainly used to indicate the shrinkage of wood at an even moisture content. Bulk shrinkage in the wood chip bed was caused by the volume change of two parts: the wood chips and the air spaces between the chips. Bulk shrinkage in some agricultural products has been studied (Brooker, 1974). A similar study on wood chips has not been found in the literature review.

3.3.1 Study Methods of Bulk Shrinkage Test

Sawmill produced red pine chips were chosen for the sample testing in this experiment. The freshly cut wood chips were sorted as in the same manner as the size distribution test. Wood chips of two sizes (SZ-1 and SZ-2) were measured and two samples were taken from each size group. The volume of each sample was one-cubic-foot of the freshly cut wood chips at the original moisture content.

Measurements of the wet weight and volume of the chips were done at the same time. To measure the volume, the wood chips were put into the container and leveled with a flat cover. A scale was used to measure the settlement of the cover to determine the reduction of the bulk volume. The total weight of the container and the chips was measured with a balance and the moisture content was calculated according to the weight and the final moisture content of the samples. Measurements were performed during the experiment at recorded intervals depending on the drying speed of the chips: shorter interval at higher drying rate and longer intervals at lower drying rate. Between two measurements, the wood chips were spread evenly on the fine screen for air drying. The experiment was performed in a room with a temperature of 70°F and 62 percent relative humidity. The measurement terminated when constant weight of wood chips was reached.

Three moisture content samples were taken from each bulk shrinkage sample to determine the final moisture content. The moisture content of the chips at a certain measuring point was then calculated. Nonlinear regressions were used to determine the relationship between the bulk shrinkage coefficient and the moisture content.

3.3.2 Results of Bulk Shrinkage Test

Nonlinear bulk shrinkage regressions results on the samples indicate that the regression line fit the experimental data very well (Table 3.5). The following formula was chosen as a bulk shrinkage model

$$BV = b_1 + b_2\, e^{b_3 \times MC}$$
$$BV = \frac{OV - WV}{OV}$$

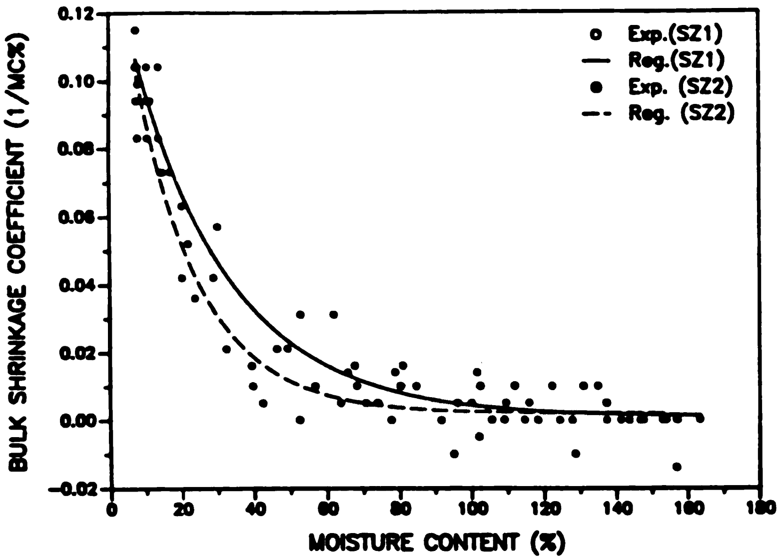
where BV is bulk volume coefficient, MC is the moisture content dry basis (%), OV is the original bulk volume (in^3), WV is bulk volume (in^3), and b_1, b_2 and b_3 are the constants estimated by the nonlinear regression for the bulk shrinkage model.

Table 3.5 Nonlinear regression data on bulk shrinkage test.

Container number	Constant estimated			R^2
	b_1	b_2	b_3	
1-1	-0.003899	0.1363	-0.02775	0.977
1-2	0.004799	0.1449	-0.05526	0.937
2-1	0.004562	0.1877	-0.08277	0.972
2-2	-0.003498	0.1400	-0.04265	0.964

Because of the limitations on wood chip sample supply, only two replications were performed. Based on the T-test ($P<0.05$), there are no significant differences between the regression lines for the different sized samples. However, similar regressions performed on pooled experiment data for SZ-1 and SZ-2 samples indicated graphically a slight difference between the two (Figure 3.5).

To develop a bulk shrinkage formula for the wood chip drying model, the above regression was also performed on the pooled data of four samples (Figure 3.5).



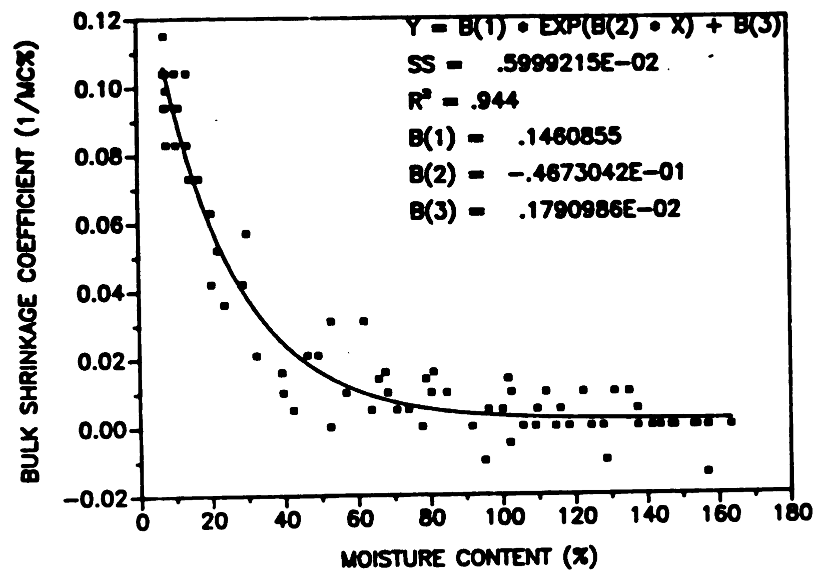


Figure 3.5 **Nonlinear regressions on pooled experiment data for (1) wood chips of SZ-1 and SZ-2 sizes and (2) all chip size samples.**

3.3.3 Discussion on the Bulk Shrinkage of Wood Chips

Unlike the shrinkage that occurs in a wood block when the moisture content reaches the fiber saturation point (approximately 30 percent), bulk shrinkage began to appear in the wood chip drying when the average moisture content reached about 80 percent. There are three principle reasons for the differences between solid wood and wood chips:

(1) During drying, moisture contents for different sized wood chips were not the same. Since wood chip size was distributed over a wide range, the small chips dried more rapidly and started shrinking while the larger chips were still at a very high moisture content. Although the average moisture content was 80 percent, the large chips may have been above this value when the small chips were below even 30 percent (fiber saturation point), which was the point where wood shrinkage started.

(2) Because the surface/volume ratio of the wood chips was much larger than that of a big wood block, wood chips dried much faster. Therefore, there is a considerable moisture content gradient in a wood chip which is caused by fast drying. Partial shrinkage may have occurred at the outer layer of a wood chip and, therefore, caused the early bulk shrinkage.

(3) The stress condition in solid wood and high internal moisture content prevents most shrinkage from occurring.

The experiment showed that bulk shrinkage began at a higher average moisture content for large chips than for small chips.

There was a wider wood chip size distribution among large wood chip samples than among the small chip samples. Therefore the smaller wood chips in the sample of a large chip size, SZ-1 for example, might have dried and shrunk much earlier than the larger sized chips. The wood chips of a small chip sample, SZ-2 for example, were distributed over a smaller range of size and all of them dried at almost the same time. This is why wood chips in a small size sample shrink at a lower average moisture content.

A formula was determined using a nonlinear regression to predict the possible shrinkage at different moisture contents. Because the variation in shrinkage data for different sized chips was very limited, the experimental results did not show significant differences. The bulk shrinkage model was developed using the regression based on the pooled data of the four samples. This model was developed to predict the total bulk volume in the fixed bed drying model discussed in Chapter V and Chapter VI.

Variations in drying rates also may influence bulk shrinkage. However, since the drying gradient in a single chip, which is very sensitive to the drying rate, only occurs for a short period of time during drying under forced air, this gradient was ignored and the average moisture content was used as the measurement.

3.4 Airflow Resistance in a Wood Chip Bed

Airflow resistance is a very important value in calculating energy consumption in the fixed bed drying operation. Research on airflow resistance has been focused on agricultural products drying (Brooker, 1974). Hukill (1955) developed an equation to explain the airflow resistance for different grains

$$\Delta P = \frac{aQ_a^2}{\ln(1 + bQ_a)}$$

where P is airflow resistance (in. H_2O), Q is airflow rate (CFM), and a and b - The constants for certain type of grains.

A chart related to the above equation was made for many types of grains at various moisture contents, and was widely used in the area of agricultural engineering.

A thin layer method was employed to determine airflow resistance during fixed bed drying of grain (Woods, 1987). The material used in the drying experiment was germinated barley. The results indicated that airflow resistance was not affected by the moisture content of the barley, but by compression on the bed.

For the convenience of the model application, especially for calculating the energy consumption, the bed resistance on three different chip sizes was tested.

3.4.1 Study Methods for Airflow Resistance

A column 14-inches in diameter and 48-inches high was made with sheet metal for this study. (This sheet metal column was also used in the model testing experiment discussed in Chapter VI.) The column consisted of seven sections: the bottom, called the base section, was used to support the whole column, and the remaining six sections, called drying sections, formed the main body of the fixed bed dryer. Each drying section was eight-inches high and had a layer of 0.25-inch screen soldered at the bottom to support the wood chips in the section. A small air access tube of 0.20-inch interior diameter was soldered near the upper edge of each drying section as an air pressure measurement outlet. Those outlets were connected to "U" water filled pressure meters during the test.

A 0.33 horsepower, high-pressure blower, an air distribution box, and three bypass flowmeters were installed at the bottom of the column. The bypass flowmeter was calibrated with a standard airflow meter before each measurement.

Red pine wood chips of three different sizes were tested in this experiment: SZ-1, SZ-2, and SZ-3. Wood chips were sorted by the method previously described. During each test, the airflow rate was controlled by the two damper flat valves installed on the air distribution box. The readings from the bypass flowmeter and "U" tube pressure meter were recorded simultaneously. The readings from the bypass flowmeter were converted into flow rate in ft^3/hr according to the calibration.

3.4.2 Results of the Study on Airflow Resistance

The correlation of airflow resistance in the wood chip bed with airflow rate was determined by nonlinear regressions. The following formula was employed in the regressions Analysis

$$FR = c_1\, e^{c_2 FV}$$

where FR is airflow resistance (inch water), FV is airflow rate (ft/min), c_1 is the first constant (inch water), and c_2 is the second constant (min/ft).

Table 3.6 shows the statistical analysis of the regressions. The experimental data and regression lines are plotted in Figure 3.6.

Table 3.6 Nonlinear regression on airflow resistance in wood chip bed with airflow rate.

Wood Chip Size Group	Constant estimated by regression		R^2
	c_1	c_2	
SZ-1	0.02005	0.03096	0.986
SZ-2	0.02591	0.03124	0.998
SZ-3	0.03857	0.03105	0.996

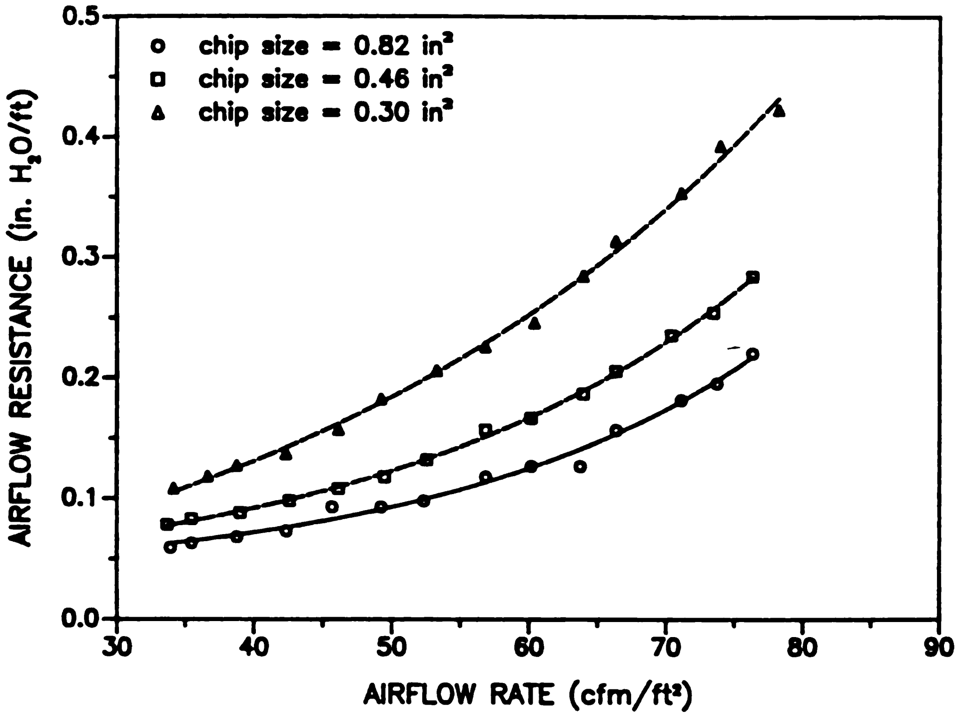


Figure 3.6 Airflow resistance of wood chip bed and airflow rate plotted from Table 3.6.

3.4.3 Discussion on Airflow Resistance

The experiment shows that the wood chip size was well correlated to the airflow resistance; the larger the wood chip size, the less the airflow resistance of the bed. The size of the wood chips is proportional to the volume of empty space in the wood chip bed. Therefore, a bed formed with larger wood chips shows less resistance than one formed with smaller wood chips.

According to Woods's study on the airflow resistance of a thin bed of germinated barley, moisture content did not have a significant effect on airflow resistance (Woods, 1987). However, as mentioned earlier, the moisture content of the wood chips would slightly change the bulk volume of the wood chip bed only when the moisture content is less than 80 percent. Because the shrinkage of an individual wood chip is only eight percent in the tangential, four percent in radial directions and 0.1 percent in the longitudinal direction (Wood Handbook, 1988), and the shrinkage does not occur during most of the drying period, the moisture content's influence on airflow resistance is not considered here.

A nonlinear regression line was found to illustrate the correlation between the airflow resistance and airflow rate for wood chips of different sizes. This formula was employed in the fixed bed drying model to determine the energy consumed in creating internal airflow. Airflow resistance increases sharply as the airflow rate increases. This result indicates that under commonly acceptable drying rates, the airflow rate should be reduced as low as possible to reduce the energy costs caused by airflow resistance.

CHAPTER IV

DEVELOPMENT OF A THIN LAYER DRYING MODEL AND MODIFICATIONS TO THE GRAIN DRYING MODEL

4.1 Previous Studies on Thin Layer Drying Models

4.1.1 Wood Drying Principle

Extensive studies have been done on lumber drying, practically and theoretically. The water in a tree is stored and transferred mainly in the living cells. One portion of the water is found in the cavities of the cells (free water) and the other in the cell wall (bound water) (Hoadley, 1980). At the beginning of the wood drying process, any free water is removed first, by (1) the evaporation of the water at the cell opening and (2) the movement of water from internal cell cavities to the openings by capillary pressure. Normally, the surface evaporation rate and interior water movement rate controls this process (Siau, 1984).

When most of the free water has evaporated, the cell cavities are empty and the bound water starts to dry. The moisture content at this point is called the fiber saturation point. The drying process of bound water is accomplished in three steps:

(1) the diffusion of water molecules from the interior to the surface of the cell wall;

(2) the evaporation of water at the surface of the cell wall; and,

(3) vapor movement from the cell wall surface to the outside of the wood through cell cavities or pits.

This process is controlled mainly by the water diffusion rate within the cell wall (Siau, 1984).

Because the size of wood chips is much smaller than that of lumber, the distances for water and water vapor movement are much shorter in a wood chip. Therefore, under the same drying conditions, wood chips dry much faster than lumber. A preliminary experiment indicated that variations in wood chip size significantly ($P<0.05$) influence drying rate. Therefore, wood chip size was considered a factor in this experiment.

In general, there are two steps to drying biological products: constant rate drying and falling rate drying (Villa, 1973) (Figure 4.1). During the constant drying period, there is a thin layer of liquid water on the surface of a drying particle, and the drying rate is controlled by external water evaporation. During the falling rate drying period, there is no layer of water on the particle surface and the drying rate is controlled by internal moisture movement. In general, constant rate drying occurs at moisture contents above 233 percent (Brooker, 1974). Therefore, most biomass particles, including wood chips, dry at the falling drying rate.

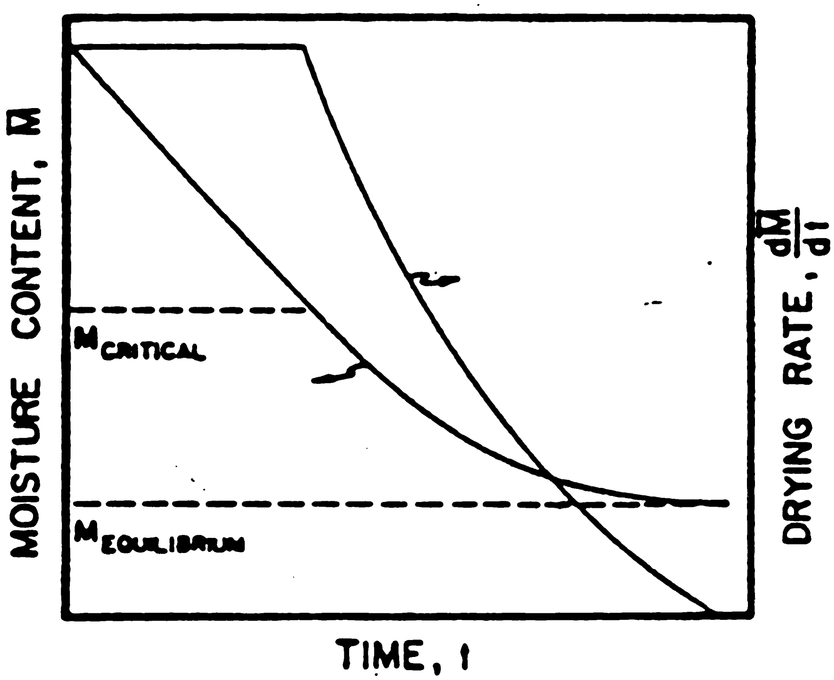


Figure 4.1 Two drying steps for biomass material: constant drying rate and falling drying rate (Brooker, 1974).

4.1.2 Thin Layer Drying Equation

The thin layer drying is defined as the drying process that occurs when a single layer of particles is exposed to the air of a certain temperature and relative humidity. It comes from agricultural engineers' studies on grain drying and is called single-kernel drying (Brooker,1974).

Almost all thin layer drying models were developed for drying agricultural products. Luikov developed a general mathematical model for capillary porous products drying (Luikov,1966)

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

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

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} MC + \nabla^2 K_{32} \theta + \nabla^2 K_{33} P$$

where MC is the moisture content (%), θ is the particle's temperature (°F), P is vapor pressure (Psi), K_{ii} is the phenomenological coefficient, and K_{ij} is the coupling coefficient.

After years of studies, it was found that the pressure term was not significant in most drying temperature ranges and that the coupling effects of temperature and moisture were significant in a few grain products. The temperature gradient in a single particle was not considered in practical grain drying. Therefore, Luikov's model was simplified as follows for cereal grain kernel drying (Brooker, 1974)

$$\frac{\partial MC}{\partial t} = \nabla^2 K_{11}\, MC$$

where K_{11} is the diffusion coefficient, which is also called D. When D is a constant, this equation can be written as follows (Brooker, 1974)

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

where C is a shape coordinate and r is a particle coordinate (ft).

An analytical solution for this equation was written for a sphere as follows (Perry, 1963):

$$MR = \frac{6}{\pi^2}\sum \frac{1}{n^2} e^{[-\frac{\pi^2 n^2}{9} x^2]}$$

Two dimensionless quantities were used in this equation: MR is the moisture ratio and X is dimensionless time (hr)

$$MR = \frac{MC - EMC}{OMC - EMC}$$

$$X = \frac{A}{V}(Dt)^{\frac{1}{2}}$$

where EMC is the equilibrium moisture content, OMC is the original moisture content, A is the single particle surface area, and D is the volume of the particle body.

Later, a simplified solution was written by using only the first term of the analytical solution and was used to predict the drying of grain:

$$MR=\frac{6}{\pi}e^{(\frac{-D\pi^2t}{r^2})}=\frac{6}{\pi^2}e^{(-kt)}$$

Brooker, Bakker-Arkema, and Hall stated that:

"Assuming the rate of moisture loss of a grain kernel surrounded by a medium at constant temperature is proportional to the difference between the kernel moisture and its equilibrium moisture content,

$$\frac{dMC}{dt}=k\,(MC-EMC)$$

Separating the variables and integrating between the proper limits using MC(r,0)=MC(in) and MC(r_0,t)=EMC as initial and boundary conditions yields:

$$MR=e^{-kt}$$

... k the drying constant."

The drying constants of cereal grains have been studied intensively. Pabis and Henderson determined the drying constant k for corn through experiment (Pabis, 1961):

$$k_{corn}=5.4\times10^{-1}e^{-\frac{5023}{\theta_{abs}}}$$

The drying constants for wheat and barley have also been determined (O'Callaghan, 1971):

$$k_{wheat}=2000\,e^{(-\frac{9179}{\theta_{abs}})}$$

$$k_{barlay}=139.3\,e^{(-\frac{7076}{\theta_{abs}})}$$

In 1971, Young evaluated the diffusion equation for describing the thin layer drying of peanuts in the hull. He put trays containing one layer of peanuts into dryers with air temperatures of 90°F, 100°F, and 110°F and dew points of 52°F, 60°F, and 69°F. He compared four diffusion equations with the experimental data (Young,1971).

Some empirical thin layer equations were developed for certain agricultural products. For example, Thompson presented a drying equation for shelled corn in the temperature range of 140° to 300°F:

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

$$A = 1.86178 + 0.00488\theta$$

$$B = 427.3640\, e^{(-0.03301\theta)}$$

Another the drying equation for corn was presented in the temperature range of 36° to 70°F (Sabbah, 1968):

$$MR = e^{-kt^{0.664}}$$

$$k = e^{-xt^{y}}$$

$$x = [6.0142 + 1.453\times10^{-4}(rh)^2]^{0.5} - \theta[3.353\times10^{-4} + 3.0\times10^{-8}(rh)^2]^{0.5}$$

$$y = 0.1245 - 2.197\times10^{-3}(rh) + 2.3\times10^{-5}(rh)\theta - 5.8\times10^{-5}\theta$$

Thin layer equations played an important role in the development of the semi-theoretical fixed bed drying model. The thin layer equation for wood chip drying has not been found in the literature review. In order to simulate the wood chip drying process with the theoretical fixed bed drying model, a thin layer drying model for wood chips had to be developed.

4.1.3 Semi-theoretical Fixed Bed Drying Model

A theoretical fixed bed drying model can be used to simulate a practical drying process in a fixed bed dryer. This model was developed through the integration of the drying processes for many thin layers. The development of the theoretical model was based on the heat and mass balance in the drying process. Based upon eight assumptions, a grain drying model was written as follows (Bakker, 1973)

$$\frac{\partial T}{\partial x}=\frac{-h'a}{G_aC_a+G_aC_vW}(T-\theta)$$

$$\frac{\partial \theta}{\partial t}=\frac{h'a}{\rho_pC_p+\rho_pC_wMC}(T-\theta)+\frac{h_{fg}+C_v(T-\theta)}{\rho_pC_p+\rho_pC_wMC}G_a\frac{\partial W}{\partial x}$$

$$\frac{\partial W}{\partial x}=-\frac{\rho_p}{G_a}\frac{\partial MC}{\partial t}$$

$$\frac{\partial MC}{\partial t}=\textit{an appropriate thin layer equation}$$

where T is air temperature (°F), θ is product temperature (°F), MC is moisture content, W is air humidity ratio (lb/lb), x is bed coordinate (ft), t is time (hr), h' is convective heat transfer coefficient (Btu/ft^2/°F/hr), h_{fg} is heat of evaporation (Btu/lb), c_a, c_p, c_v, and c_w are the specific heat of dry air, dry grain kernels, water vapor, and liquid water, respectively, (Btu/lb/°F), G_a is air flow rate (lb/hr/ft^2), ρ_p is product density (lb/bu), and a is particle surface area per unit bed volume (ft^2/ft^3).

The four differential equations can be solved numerically with a standard finite difference method, and a FORTRAN computer program "Fixed Bed Dryer Model" was developed to execute the calculations of grain drying simulation (Brooker, 1974). The boundary conditions for this fixed bed drying model are listed as follows

$$T(0,t)=T(inlet)$$
$$\theta(x,0)=\theta(initial)$$
$$W(0,t)=w(inlet)$$
$$MC(x,0)=MC(initial)$$

The fixed bed grain dryer model has not been used for wood chip drying before. To employ this model for wood chip drying, a thin layer equation and an equilibrium moisture content equation had to be determined for wood chips.

4.2 Experimental Design of Thin Layer Wood Chip Drying Experiment

The method employed in the thin layer experiment was similar to the one used for agricultural products. A single layer of wood chips was distributed on a layer of screen and exposed to controlled air temperature and air relative humidity in a conditioning chamber (Figure 4.2). The drying processes were determined by measuring the moisture contents of the samples during the drying process.

A preliminary thin layer drying experiment was performed using red pine chips to evaluate the experimental factors. Three factors had significant influences ($P<0.05$) on the drying process: air temperature, air relative humidity, and wood chip size. Therefore, a factorial design with three replications was employed (Table 4.1):

Table 4.1 Thin layer experimental design for wood chip drying.

Independent Variables	Level 1	Level 2	Level 3	Level 4
Air temperature (°F)	68.0	82.5	96.8	111.2
Air relative humidity (%)	40.0	55.0	70.0	85.0
Wood chip size (in^2)	1.32	0.82	0.46	0.30

The range of the drying conditions (air temperature and air relative humidity) covered the normal conditions for ambient air and slightly heated air. Four levels were chosen for the chip size factor (SZ-0, SZ-1, SZ-2, and SZ-3). Size SZ-0 was included here because only a small amount of the wood chip sample was required and was available from size sorting. The upper limit of the size for sample SZ-0 was controlled by a 1.5-inch screen.

In general, the wood chip samples can reach their equilibrium moisture content (EMC) within 22 hours under most drying conditions. Twelve sample containers (sample baskets) could be distributed evenly in the cross section of the laboratory conditioning chamber. Therefore, the samples of four different sizes with three replications in each size could be tested at the same time. Sixteen testing days were required to perform the experiment for the total 4x4x4x3=192 samples of wood chips.

4.3 Procedures of Thin Layer Wood Chip Drying Experiment

4.3.1 Sample preparation for Thin Layer Wood Chip Drying Experiment

Red pine chips were supplied from a sawmill in Gladwin, Michigan, for all of the experimental samples because of the reliable supply of one species. In this sawmill, cants were produced from logs of 10 to 12 inches in diameter. Wood chips were produced by chipping the remaining slabs and edgings. The logs used for production had been harvested about two weeks prior. The wood chips were collected immediately after chipping and stored in sealed plastic bags. The wood chip bags were stored at a constant temperature of 40°F. A preliminary storage experiment indicated no significant changes in the moisture content of the wood chips during a 30-day storage period. Usually, the storage time between chip collecting and size sorting was less than seven days and the longest storage time between the size sorting and the drying testing was 16 days.

In order to minimize the moisture loss during size sorting, wood chips were sorted in a high humidity room with a temperature of 75°F and relative humidity of 88 percent. The size sorting method described in Chapter III was used. Wood chips of four different sizes (SZ-0, SZ-1, SZ-2, and SZ-3) were stored separately in the plastic bags after sorting. According to the experimental design, sixteen days were required to complete the whole experiment. Wood chip samples of each size were kept in 16 bags.

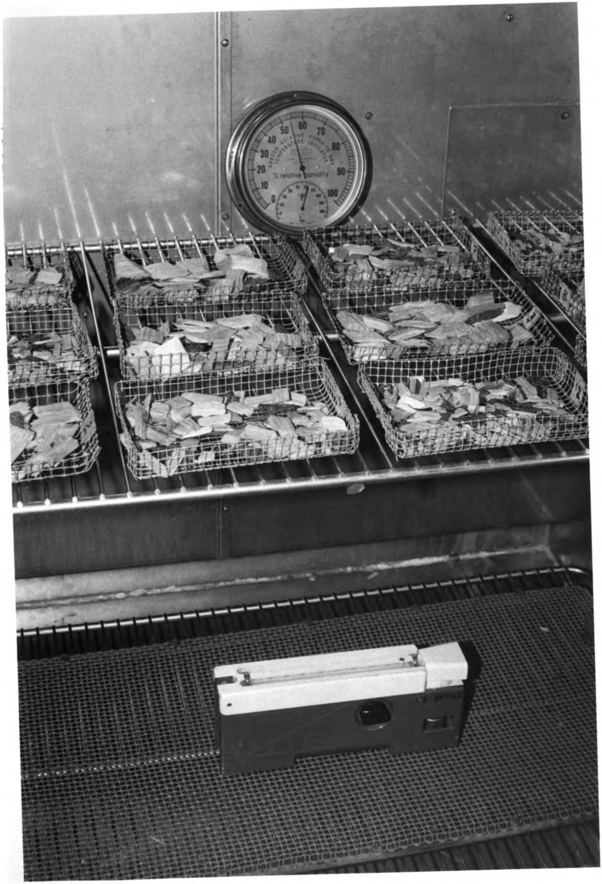
The sample bags were not opened until the time for the experiment and the moisture loss of the samples was minimized during storage.

4.3.2 Equipment Used in the Thin Layer Wood Chip Drying Experiment

The thin layer wood chip drying experiment was performed in an AMINCO Conditioning Chamber (Figure 4.2). Wood chip samples were placed in rectangular baskets (five-inch long by four-inch wide by one-inch high) made of a ¼-inch wire screen. The amount of wood chips contained in each sample was enough to form a single layer of wood chips in each basket. Twelve baskets were evenly placed on the cross section of the chamber.

Because of a slight variation in airflow rate along the cross section, especially from the front to the back, a set of fine screens was placed at the bottom level of the chamber to even the airflow rate. To reduce the experimental error caused by differences in the airflow rate, the area of the chamber was divided into three separated blocks from front to back, and the three replications of each sample were assigned to each of the three blocks. The samples of four different chip sizes were randomly assigned to the four spaces in each block using random numbers.

Figure 4.2 Thin layer wood chip drying experiment performed in a controlled temperature and relative humidity conditioning chamber.


% relative humidity

4.3.3 Measurement of the Thin Layer Wood Chip Drying Experiment

Because wood chip samples reach their constant weight after 22 hours drying under most experimental conditions, each experiment was performed once a day: 23 hours for the drying test and one hour for setting up the new experimental conditions. Although some samples may not have reached their equilibrium moisture content after 23 hours of drying, especially at high relative humidities and at low temperatures, their data can still be used for regression analysis.

Sample moisture contents were determined based on knowing the sample weights vs. the oven dry weights. Since drying was most rapid at the early stages, the weights of samples (including the baskets and the wood chips) were measured every hour for the first 14 hours and, then measured once more after 23 hours. The actual sample weight was calculated by subtracting the basket weight from the total weight. After the moisture measurements, the wood chip samples were placed in beakers and kept in an oven at 217°F until they reached their oven-dry weight. The moisture content for each sample during the drying time was calculated after its oven dry weight was known. The representative drying curves for the four different sizes of wood chips is shown in Figure 4.3. The air temperature and the air relative humidity in the conditioning chamber were measured with a Model 566-2 Psychrometer. The sample weights were measured with a Mettler PJ360 Balance and recorded with a Mettler GA44 Printer.

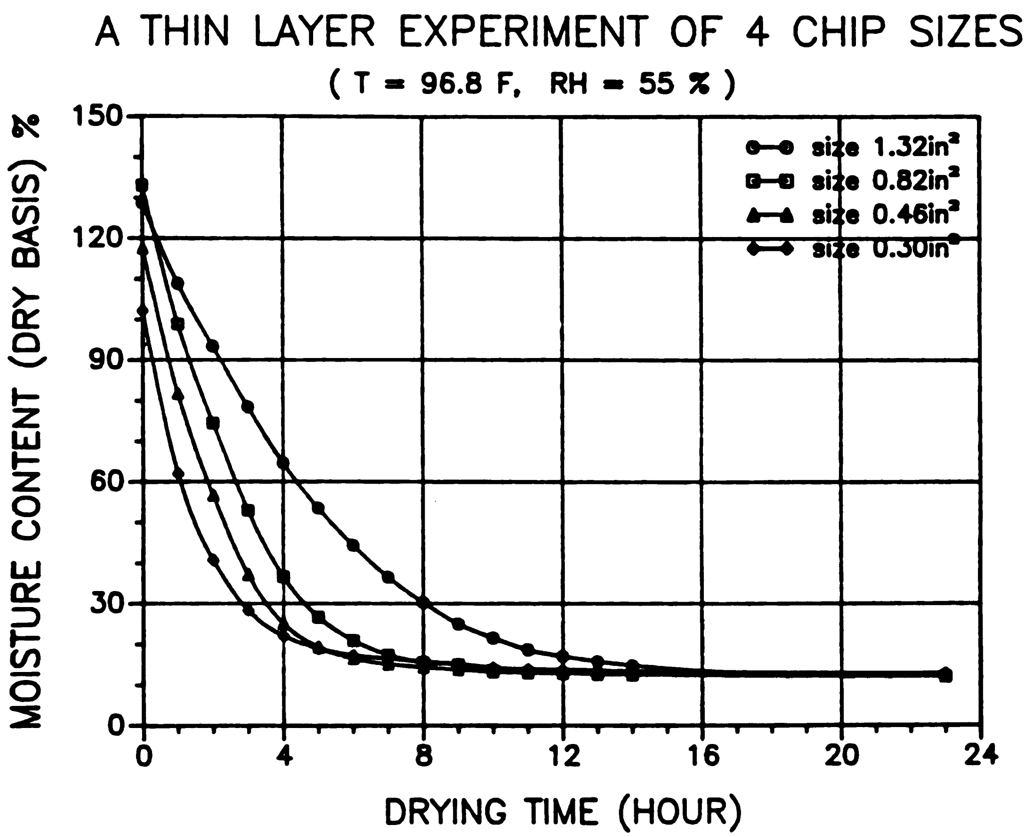


Figure 4.3 Representative drying curves in the thin layer wood chip drying experiment of 4 chip sizes at air temperature 96.8°F and air relative humidity 55%.

4.3.4 Development of a Thin Layer Wood Chip Drying Model

4.3.4.1 Determining Drying Constants for Different Drying Conditions

Although the moisture content of wood chips is generally much higher than that of grain, the drying process for wood chips occurs at a falling drying rate. It can be assumed that the drying process is controlled mainly by moisture transfer inside the wood chips. Therefore, a simplified semi-theoretical solution for the diffusion equation was chosen to simulate the thin layer drying process

$$MR = e^{-kt}$$

where MR is moisture ratio, k is drying constant (1/hr), and t is time (hr).

Moisture ratio is used here in the model to express the moisture content as a dimensionless quantity. In the model, the drying constant (k), the only parameter determined in the regression, represented the most important characteristic in the drying process of the samples.

A LOTUS worksheet was used to calculate the moisture contents and the moisture ratios, and a nonlinear regression computer routine (NONL) in SAS was used to perform the regression for each condition. The drying constants (k) were estimated for a total of 192 experimental conditions. A representative regression curve is shown in Figure 4.4.

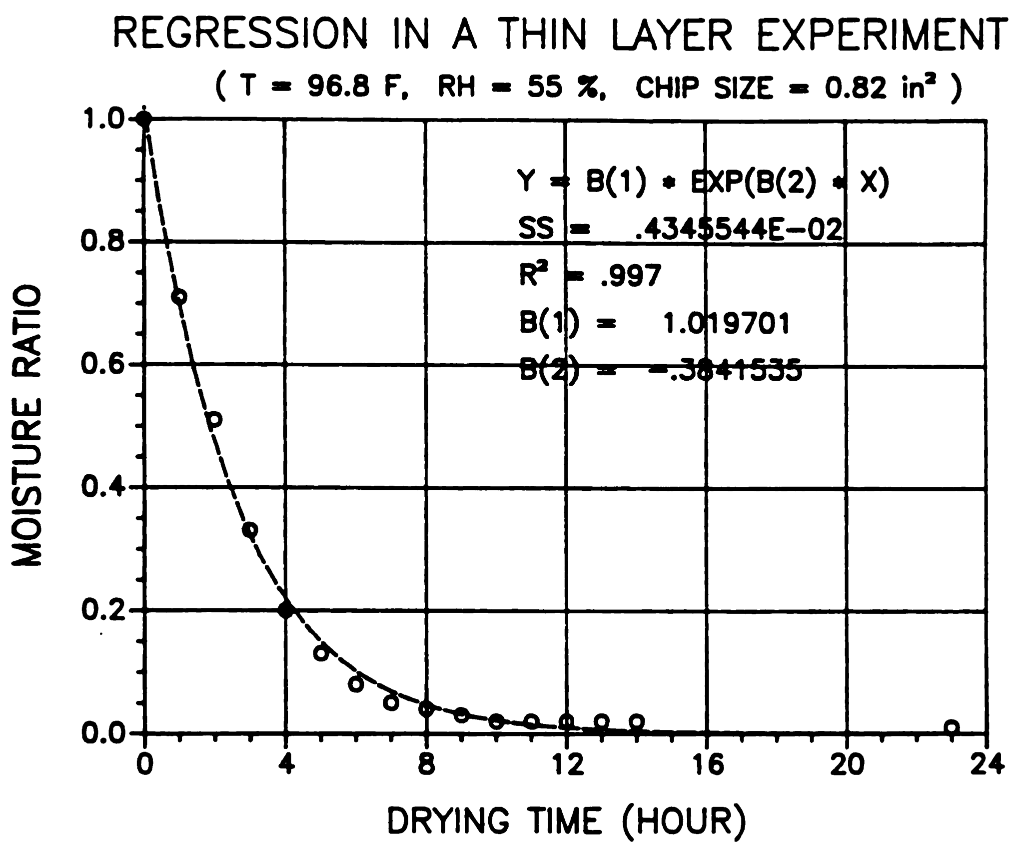


Figure 4.4 A representative regression curve related to the thin layer drying experiment for wood chip sample SZ-1 at the experimental condition of temperature 96.8°F and relative humidity 55.0%.

4.3.4.2 Determining the Relationship Between Drying Constant and Drying Conditions

The correlation between the drying constants and the related experimental conditions (air temperature, air relative humidity, and wood chip size) were determined using multiple regression analysis. A second order polynomial equation was selected as the model to simulate the drying process. This regression was performed by the multiple regression routine (REG) in the SAS program. As this model was used to simulate the thin layer drying process and executed by a computer program, model selection was based on reaching the highest determination of correlation. The results of a backward and forward model selection were also compared and discussed. The residual analysis was performed as part of the model selection to evaluate the fit of the model.

4.3.5 Modification of the Grain Drying Model

The Fixed Bed Dryer Model was chosen as a basic model to simulate the drying process of wood chips in a fixed bed dryer. In this model, the standard finite difference methods were used to solve the four differential equations (Section 4.1.3) on a personal computer. The modifications of the grain model included two parts:

(1) The thin layer wood chip drying model was employed in the fixed bed grain drying model to substitute the thin layer grain drying model. The thin layer wood chip drying model can be written as follows

$$MR = e^{-kt}$$
$$k = F\ (T,\ RH,\ SZ)$$

where F represents the function to calculate the drying constant k (1/hr), T is temperature (°F), RH is relative humidity (percent), and SZ is wood chip size (in^2).

(2) The formula calculating the equilibrium moisture content of wood was employed in the model to substitute the formula used for grains. The equilibrium moisture content equation can be written as follows (USDA, 1988)

$$EMC = \frac{1800}{W}\left[\frac{kh}{1-k_0h} + \frac{k_1k_0h + 2k_1k_2k_0^2h^2}{1 + k_1k_0h + k_1k_2k_0^2h^2}\right]$$

$$W = 330 + 0.452T + 0.00415T^2$$
$$k_0 = 0.791 + 0.000463T + 0.000000844T^2$$
$$k_1 = 6.34 + 0.000775T - 0.0000935T^2$$
$$k_2 = 1.09 + 0.0284 - 0.0000904T^2$$

where EMC is the equilibrium moisture content (percent), T is temperature (°F), h is relative vapor pressure.

4.4 Results and Discussion on the Development of a Semi-theoretical Wood Chip Drying Model

The development of a thin layer wood chip drying model included two parts: (1) a thin layer drying equation and (2) a drying constant equation. The thin layer equation illustrates the relationship between the moisture contents and the drying time; the relationship is represented by the drying constant. The drying constant equation shows the relationship between the drying constants and the experimental conditions.

4.4.1 Thin Layer Drying Equations

A total of 192 nonlinear regressions were performed using a SAS NONL routine for the experiment. The drying constants (k) are listed in Appendix A. A representative regression curve for the thin layer drying experiment is illustrated in Figure 4.4.

4.4.2 Drying Constant Equation

Studentized residuals were calculated and plotted with a SAS REG computer routine to detect failures in the development of the model. One observation of the total 192 was deleted because of its high residual.

An analysis of variance was performed on the results of the nonlinear regressions (Table 4.3). An ANOVA table indicated that three independent variables (T, RH, and SZ) and two of their interactions (T*RH and RH*SZ) were found to be significant ($P<0.05$) in affecting the drying constant (k).

Multiple regression was performed to determine the drying constant formula. The maximum R^2 model selection procedure (MAXR) in the stepwise selection routine (STEPWISE) of SAS program was used to process the model selection. The determination of the final model depended mainly on reaching a higher coefficient of determination (R^2). The parameters of this equation are listed in Table 4.3, and this equation is defined as the Drying Constant Equation shown as follows

$$MR = e^{-kt}$$

$$k = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 RH + \beta_4 (T \times RH)$$
$$+ \beta_5 SZ + \beta_6 (T \times SZ) + \beta_7 (RH \times SZ)$$
$$+ \beta_8 SZ^2$$

β_0 = -0.34677801
β_1 = 0.02609468
β_2 = -0.000068479
β_3 = -0.001117698
β_4 = -0.000140584
β_5 = -0.61144449
β_6 = -0.001859596
β_7 = 0.005912791
β_8 = 0.10995296

where MR is moisture ratio, k is drying constant (1/hr), t is drying time (hr), T is air temperature (°F), RH is air relative humidity (percent), and SZ is wood chip size (in^2).

Table 4.2 Analysis of variance of the drying constant k in the thin layer wood chip drying experiment.

Source	Degree Freedom	Sum of Squares	F Value	Prob. > F
T	3	0.6284	27.62	0.0001*
RH	3	4.3776	192.42	0.0001*
SZ	3	1.6724	73.51	0.0001*
T*RH	9	0.3252	4.76	0.0001*
RH*SZ	9	0.4534	6.64	0.0001*
T*SZ	9	0.1154	1.69	0.0987
T*RH*SZ	27	0.1764	0.86	0.6634
Error	127	0.9631		

* Significant at 5% level.

Table 4.3 Parameter estimates of the drying constant equation after the multiple regression analysis.

Variable	DF	Parameter Estimate	Standard Error	T Test	Prob. > ¦T¦
Intercept	1	-0.34677801	0.27214261	-1.274	0.2042
T	1	0.02609468	0.005458704	4.780	0.0001*
T*T	1	-0.000068479	0.000029235	-2.342	0.0202*
RH	1	-0.001117698	0.002132946	-0.524	0.6009
T*RH	1	-0.000140584	0.000022593	-6.233	0.0001*
SZ	1	-0.61144449	0.11841620	-5.164	0.0001*
T*SZ	1	-0.001859596	0.000824734	-2.255	0.0253*
RH*SZ	1	0.005912791	0.000824734	7.468	0.0001*
SZ*SZ	1	0.10995296	0.04248953	2.588	0.0104*

* Significant at the 5% level.

4.4.3 Discussions on Thin Layer Wood Chip Drying Experiment

The thin layer equation is stated in the form of the simplified solution of a diffusion equation, and the drying constant (k) represents the diffusion coefficient. In general, the drying constant is directly related to the drying rate. The contributions of the independent variables to the drying constant are clearly illustrated by the three-dimensional surface graphs in Figure 4.5.

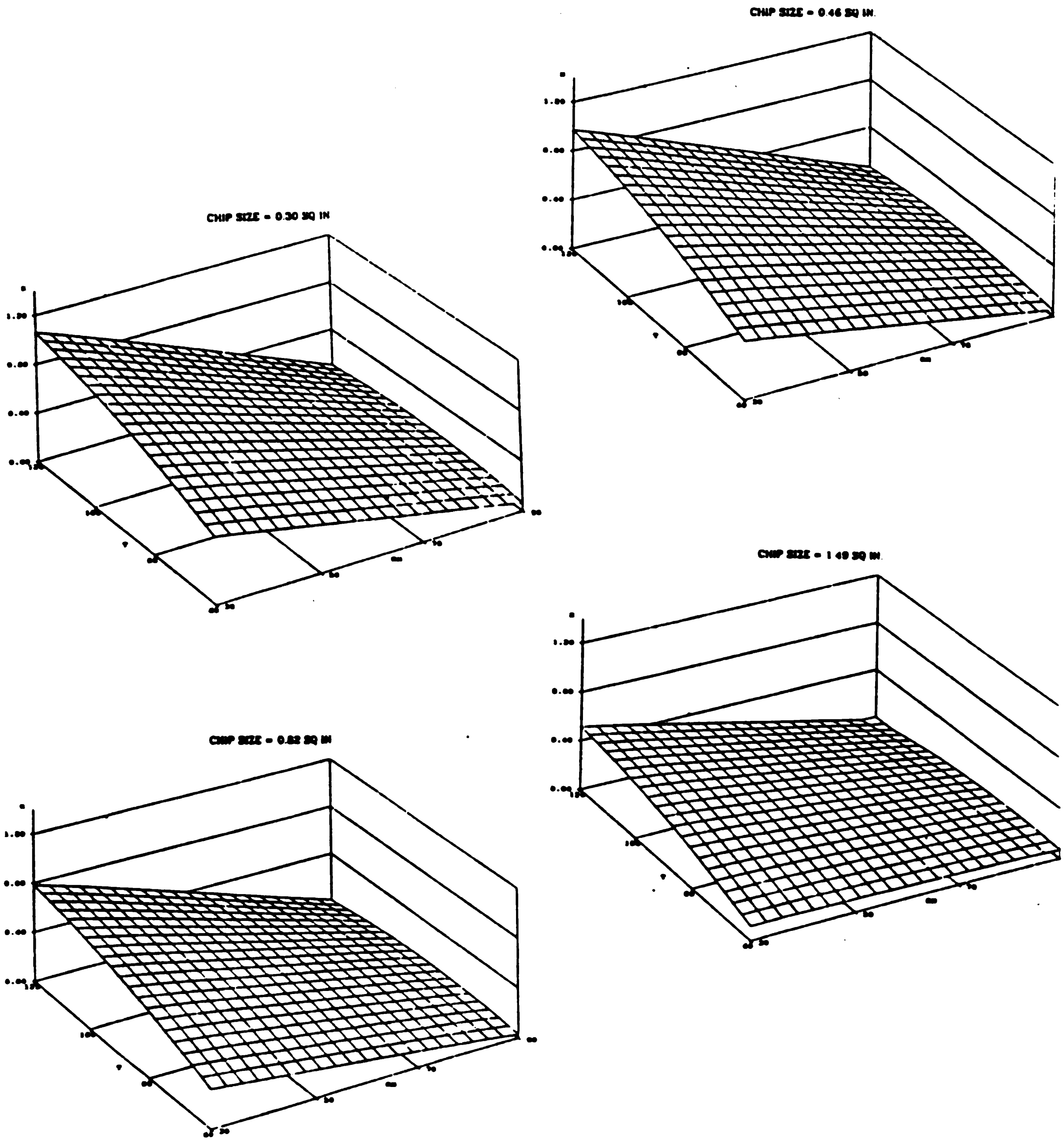


Figure 4.5 The drying constants change with air temperature, air relative humidity, and wood chip size in the thin layer wood chip drying experiment.

4.4.2.1 Air Temperature as Related to the Drying Constant

Air temperature, is one of the most important factors in wood chip drying and is directly related to the drying constant (Figure 4.5). At a certain relative humidity, the enthalpy (heat content of the air) level increases with the air temperature. The higher the enthalpy level of the air, the more energy the air can transfer to the wood chip drying. The large temperature gradient between the wood chips and the air increases the heat transfer between the two. Fast heat transfer is directly related to the drying rate. Finally, because the activity of water molecules is directly related to temperature, vapor pressure at high temperatures is higher than at low temperatures (Siau, 1984). High vapor pressure improves water evaporation and also increases the water carrying capacity of the air. In wood chip drying, the drying rate can be accelerated when the drying temperature is increased.

4.4.2.2 Relative Humidity as Related to the Drying Constant

The drying constant is inversely related to the air relative humidity (Figure 4.5). An analysis of variance indicates that air relative humidity, among all the controlled factors, has the strongest influence on the drying process . Relative humidity is defined as the ratio of water vapor in the air to the amount of water the air can hold at saturation at the same temperature. The water absorption tendency of the air, or the drying force, can only be determined when both temperature and relative humidity are known. At certain temperatures, air at a lower relative humidity has a higher water absorption tendency than that of air at a higher relative humidity. During the drying process, if the relative humidity is low, the vapor pressure at the wet surface of a wood chip is much higher than that of the air. The large gradient in water vapor pressure can increase the rate of water vapor transfer. Meanwhile, vapor transfer reduces the vapor pressure at the surface of the wood and, therefore, increases the water evaporation there.

4.4.2.3 Wood Chip Size as Related to the Drying Constant

The drying constant is inversely related to the wood chip size (Figure 4.5). Analysis of variance shows that the wood chip size, among all the factors, has the second largest influence on the drying constant. The wood chip size refers to the largest cross section area of a chip. There are two reasons for the faster drying of small chips as concluded from the research in Chapter III:

(1) Small wood chips have a larger surface/volume ratio than large chips. For the same amount of wood chips at certain moisture content, small wood chips have more surface area at which water evaporation can occur than the large chips and, therefore, dry faster.

(2) The distance for the mass and energy transfer inside a wood chip is shorter in a small chip than in a big one. The

temperature gradient and the moisture gradient are larger in a small chip than in a big one. The larger the gradients are, the faster the related transfers occur. Under the same drying conditions, smaller wood chips not only heat up rapidly, but also dry more quickly than the larger wood chips.

4.4.2.4 Temperature and Relative Humidity as Related to the Drying Constant

The influence on the drying constant exerted by the interaction of temperature and relative humidity is shown in Figure 4.5. It shows that, the drying constant is inversely related to relative humidity. However, this relationship is much more obvious at a high temperature (120°F) than at a low temperature (60°F). The drying ability of air depends on two values: (1) the absolute humidity of the air at saturation point, and (2) the absolute humidity at a certain air drying condition. The former is directly related to air temperature, and the latter is related to both temperature and relative humidity. The difference between the two values represents the moisture absorption potential of the air. Air at a high temperature and low relative humidity has great drying potential.

4.4.2.5 Relative Humidity and Wood Chip Size as Related to the Drying Constant

The influence exerted by the air relative humidity on the drying constant is greater in drying small wood chips than in drying large ones (Figure 4.5). The drying potential of the air depends mainly on the air relative humidity. At a higher relative humidity, wood chip drying is slow, and the drying process is controlled by the drying capacity of the air. At a low relative humidity, however, drying occurs much faster and the drying process is controlled by the water evaporation at the surface and the water diffusion inside the wood cell. Because the surface/volume ratio is larger and the moisture diffusion distance is shorter in a small chip, the influence on the drying rate relative to wood chip size is much more obvious at a low relative humidity.

4.4.3 Semi-theoretical Fixed Bed Wood Chip Drying Model

Both the thin layer wood chip drying model and the equilibrium moisture content model were employed in the Fixed Bed Dryer Model. A FORTRAN computer program, Grain Drying Model, was modified to perform the calculation of the semi-theoretical fixed bed drying model for wood chips.

The program was executed for the three drying conditions chosen from the large scale model testing experiment (Chapter VI). The results from the simulation were compared with the results of the related large-scale testing experiments and will be discussed in Chapter VI.

CHAPTER V

DEVELOPMENT OF EMPIRICAL FIXED BED DRYING MODEL USING THE REGRESSION METHOD

5.1 Previous studies on Empirical Fixed Bed Drying Model

The development of a fixed bed drying model and related experiments were found in the studies of agricultural products drying.

Fixed bed experiments were performed on ear corn and grain sorghum (Hukill, 1947). It was found that the grain drying curve underestimated the time required for drying grain.

Hukill (1947) developed a grain drying curve, also called bulk drying curves, based on the following assumptions (Figure 5.1):

> " ...the drying rate (1) is independent of air velocity; (2) at a given relative humidity it is proportional to the difference between the grain moisture content and the equilibrium moisture content (expressed on the dry basis), and (3) at a given grain moisture content it is proportional to the difference between the dry-bulb temperature of the air and the dry-bulb temperature of air in equilibrium with the grain."

A mathematical expression of Hukill's curves is shown in the following formula (Hukill, 1953)

$$MR = \frac{2^D}{2^D + 2^Y - 1}$$

$$DM = \frac{cfm \times 60 \times c_a \times (T_a - T_g) \times t_{1/2}}{\upsilon \times h_{fg} \times (OMC - EMC)}$$

$$Y = \frac{t}{t_{1/2}}$$

where D is a depth factor, Y is a time unit, DM is a dry matter content contained in the depth factor, cfm is airflow rate (ft^3/min), c_a is specific heat of the air (Btu/lb/°F), T_a is air temperature (°F), T_g is the temperature of air leaving grain mass (°F), υ is the specific volume of air (ft^3/lb), and $t_{1/2}$ is the time required for a fully exposed layer of grain to dry from original moisture content (OMC) to a moisture content midway between OMC and equilibrium moisture content (EMC).

Bulk drying curves are based on the assumption that a thin layer of grains dries to a moisture ratio (MR) of 0.50 for the first $t_{1/2}$, to a moisture ratio of 0.25 during the second $t_{1/2}$, and to a moisture ratio of 0.125 during the third $t_{1/2}$, etc. The thin layer grain drying experiment in the laboratory did not follow this procedure. However, these bulk drying curves do provide a useful illustration of a fixed bed drying process.

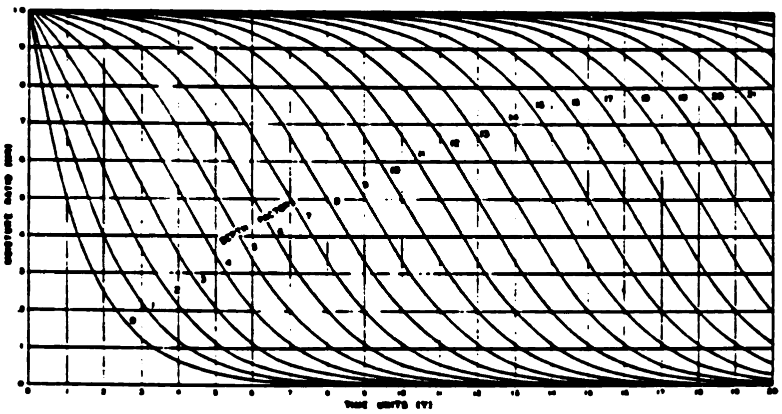


Figure 5.1 Fixed bed grain drying curves (Hukill, 1954).

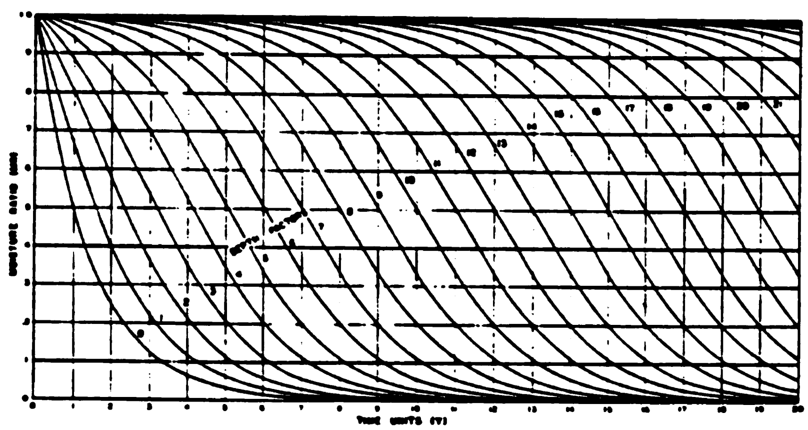


Figure 5.1 Fixed bed grain drying curves (Hukill, 1954).

Most fixed-bed experiments were performed to study the drying procedures for specific agricultural products. For example, a reversed-direction-air-flow drying process for soybean seeds was performed by Sabbah, in 1977. In the study, he found that using a reversed airflow method to a batch-in-bin drying system improved soybean seed quality (Sabbah, 1977).

Another soybean drying process involving a fixed bed drying system was performed to analyze the design of a fixed bed dryer. The experiment indicated that the low temperature drying of soybeans was feasible if the ambient air temperature was raised by five to eight degrees F and the airflow rate was 1.5 ft^3/min/bu (Dalpasquale, 1981).

In 1984, Shove performed an experiment in corn drying bins to evaluate the energy consumed in low temperature corn drying. In this study, he found that a more efficient way to use energy is to provide more air rather than to use a portion of the energy to increase the temperature of a smaller quantity of air (Shove, 1984).

In 1987, Patil performed an experiment using a recirculating crossflow dryer to develop flexible and generalized drying models which could be used to evaluate the performance of different dryer types. He compared the experimental results with the model simulation and found the model developed from diffusion theory was more flexible and applicable.

Because of the difficulties in performing deep bed experiments under different drying conditions, very few experiments have been performed thus far, and no fixed bed drying experiments for wood chips were found in the literature review. Therefore, to develop an empirical fixed bed drying model is an important element in furthering the wood chip drying process.

5.2 Method Used in the Fixed Bed Wood Chip Drying Experiment

5.2.1 Experimental Design for Fixed Bed Wood Chip Drying

As in the thin layer drying experiment, fixed bed drying was a multi-factor experiment. In addition to the three factors involved in the development of the thin layer model, two more variables (airflow rate and original moisture content) were included in the deep bed model.

Because this is a large-scale, multi-factor experiment, a factorial experimental design with a single replication was selected (Table 5.1).

Table 5.1 Experimental design for the empirical fixed bed wood chip drying model.

Independent Variables	Level 1	Level 2	Level 3	Level 4
Air temperature (°F)	68.0	82.5	96.8	111.2
Air relative humidity (%)	40	55	70	85
Air flow rate (cfm/ft^2)	44	67	99	--
Wood chip size (in^2)	0.82	0.46	0.30	--
Moisture content (%)	140-160 (Not controlled)			

The factor levels for air temperature and air relative humidity were identical to those in the thin layer experiment. Three wood chip sizes (SZ1, SZ-2, and SZ-3) were used. The largest wood chip size (SZ-0) was not included in this experiment because it represented only a small percentage of the total weight of the wood chips. The three levels in the airflow rate were selected from the commonly used range of rates used in the forced air drying process for agricultural products. The measure for the air flow rate was cfm/ft^2, or cubic feet (air volume) per minute per square feet (cross section of dryer). The original moisture content of the wood chips was distributed over a narrow range and, therefore, was not controlled but was measured in this experiment. The average moisture content of fifteen samples in each dryer was used in the regression analysis of the model.

5.2.2 Equipment Used in the Fixed Bed Wood Chip Drying Experiment

The AMINCO Conditioning Chamber mentioned in the thin layer experiment was also used to control air temperature and air relative humidity in the fixed bed experiment. Three small fixed bed dryers, two blowers, and three bypass flowmeters were mounted in the chamber (Figure 5.2).

Figure 5.2 The fixed bed wood chip drying experiment was performed in three dryers mounted in a conditioning chamber.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The dryers were made of sheet metal and each one was composed of six sections classified as three portions (Figure 5.3):

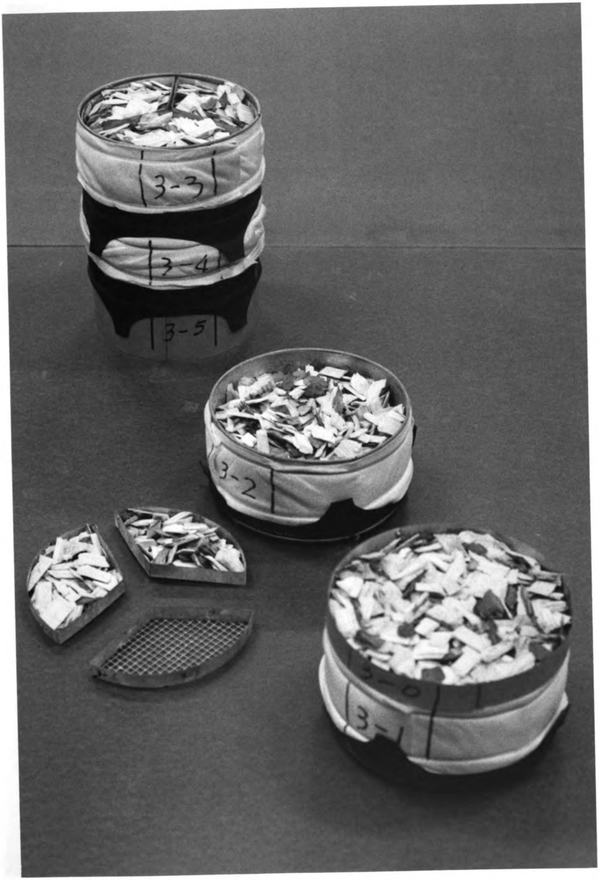
(1) Bottom portion (one section) -- to support the whole column, redistribute air flow evenly, and hold the moisture samples at the very bottom;

(2) Middle portion (four sections) -- to contain wood chips and moisture samples at different levels; and

(3) Top portion (one section) -- to hold a layer of wood chips to prevent excessive moisture loss from the top samples.

The dryer was eight inches in diameter and a total of 19-inches high: two-inch high for the bottom section, four-inches for each middle section, and one-inch for the top section. A layer of wire screen with ¼-inch holes was soldered at the bottom of each dryer section to support the wood chips. The connections of the sections were sealed with heavy duty rubber bands. All the sections were marked with numbers and kept in a constant relative position during the experiment. The middle sections were wrapped with thick tissues to reduce heat transformation through the walls of the columns. Three fan-shaped baskets, containing the moisture samples at each depth level, were placed at the top of each section of the middle portion.

Figure 5.3 The structure of the dryer and the moisture samples in the fixed bed wood chip drying experiment.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A bypass flowmeter was used to control the airflow rate for each dryer because of its low air pressure drop. The bypass flowmeter included a main pass (two inch PVC tube connected with two ball valves in series) and a bypass (19.6 ml/min valve controlled flowmeter). The bypass flowmeters were calibrated with measured compressed air and a standard flowmeter for each experimental condition.

The forced air used for wood chip drying was supplied by two electric blowers (4C446 model, Gralanger) connected in series to increase the static pressure of the air. An air cushion box was made to even the airflow and to support the flowmeters. Particle board was used to support the columns and to hold the top ends of the flowmeter, and a sheet of soft rubber (1/8-inch thickness) was used on the particle board to seal the bottom of the dryers.

In accordance with the experimental design, 4 X 4 X 3 X 3, or 144 experiments, were performed. The three dryers containing different size chips were tested under the same drying conditions (air temperature, air relative humidity, and airflow rate).

The wood chips used in this experiment were also red pine chips. The methods for sample preparation (size sorting and chip storage) were almost the same as those described in Chapter IV. However, there were two minor differences:

(1) The quantity of wood chips used in the fixed bed drying experiment was much larger than that used in the thin layer drying experiment. For convenience in intensive sorting, the wood chips were sorted in a non-conditioning room (T = 70°F, RH = 50-60%)

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instead of in the high humidity room; however, the moisture change caused by the size sorting was not significant ($P<0.05$) because of the large quantity.

(2) The plastic bags used to store the wood chips here were much larger than those used in the thin layer drying experiment. The wood chips in one bag were enough for three to four experiments. It only took five minutes to obtain samples from the storage bag and no significant change ($P<0.05$) in the moisture content was caused by sampling.

5.2.3 Measurement of the Fixed Bed Wood Chip Drying Experiment

Air temperature and air relative humidity in the conditioning chamber were measured by taking the weights of the moisture samples, including the sample container, every two hours for 14 hours of drying, and then again at 22.5 hours. Both a moisture content and a moisture ratio were calculated for each measurement in the same method used in Chapter IV.

In each dryer, the moisture samples were located at 0-inch, four-inches, eight-inches, 12-inches, and 16-inches depth levels from the bottom to the top. Wood chip samples held by three fan-shaped baskets were evenly distributed in the cross section of the dryer at each level. The average moisture content of the three samples was used for statistical analysis. The typical curves of the fixed bed drying experiment are illustrated in Figure 5.4.

MOISTURE CONTENT (DRY BASIS) %

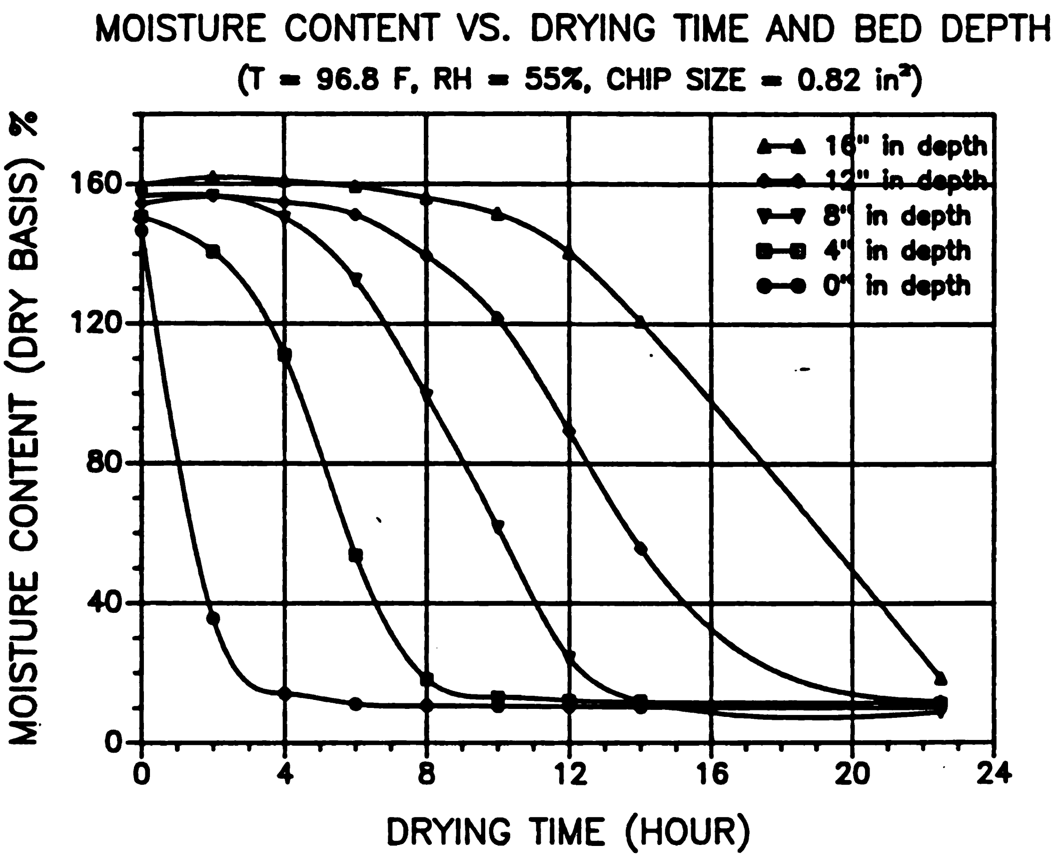

Figure 5.4 Representative drying curves of the fixed bed wood chip drying experiment.

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5.3 Development of the Fixed Bed Wood Chip Drying Model

5.3.1 Determining Depth Constant and Time Constant in the Fixed Bed Wood Chip Drying Model

In the fixed-bed dryer, the wood chip moisture content changes with the drying time and with the depth of the bed. Therefore, both the drying time (t) and the depth in the dryer (x) must be considered in explaining the drying process. This can be illustrated either with drying curves (Figure 5.4) or with a three-dimensional drying surface model (Figure 5.5).

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Hukill's bulk drying curves and the curves developed from this wood chip drying experiment are similar. However, the curves for this experiment are based on the depth and the drying time instead of the depth factor and time unit as in Hukill's curves.

It was found that if the two numerical numbers "2" in Hukill's formula were substituted with two variables (k_x and k_t), the shape of the curves changed. Here, k_x and k_t are defined as the depth constant and the drying time constant, respectively. A modified Hukill's formula is written as follows:

$$MR = \frac{k_x^{\,x}}{k_x^{\,x} + k_t^{\,t} - 1}$$

where t is drying time (hr), x is depth value in the wood chip bed (in), k_x is depth constant, and k_t is time constant.

This formula can also be illustrated by a three-dimensional surface called the drying surface. The experimental results obtained under each experimental condition can be illustrated by a drying surface which indicates the relationship among the moisture ratio, the drying time, and the depth in the bed (Figure 5.5).

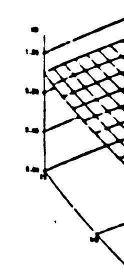
Nonlinear regression procedures (NONL) in the SAS program were performed to determine the k_x and k_t values for each experimental condition. A total of 144 regressions were executed for this experimental design.

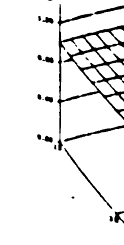
5.3.2 Determining the Models to Explain k_T and k_D

The shape of the drying surface is determined by the depth constant k_x and the drying constant k_t, which becomes obvious when the drying surfaces are plotted by changing k_x and k_t (Figure 5.6). It was found from the experiment that the shape of the drying surface was related to the drying conditions and the properties of the wood chips. Therefore, the two constants, k_x and k_t, were related to the experimental conditions in some way and this relationship could be determined through regression analysis.

Multiple regressions were performed using the SAS computer program to determine the models which would explain the relationship between the constants, k_x and k_t, and the experimental conditions, including air temperature (T), air relative humidity (RH), wood chip size (SZ), airflow rate (V), and original moisture content (OMC). The first four of these variables in the experimental conditions were controlled factors, the last one (OMC) was not.

An analysis of variance was performed to evaluate the influences on k_x and k_t from the four controlled factors and their interactions. Considering the complicated influences from the multi-factors, second order polynomial equations were chosen as the starting models to present k_x and k_t. Backward, forward, and maximum R^2 model selection routines in the SAS program were performed to assist model selection. The final models were determined based mainly on the maximum R^2 to be reached. Studentized residuals were calculated in the multiple regressions to evaluate the observations from this experiment.





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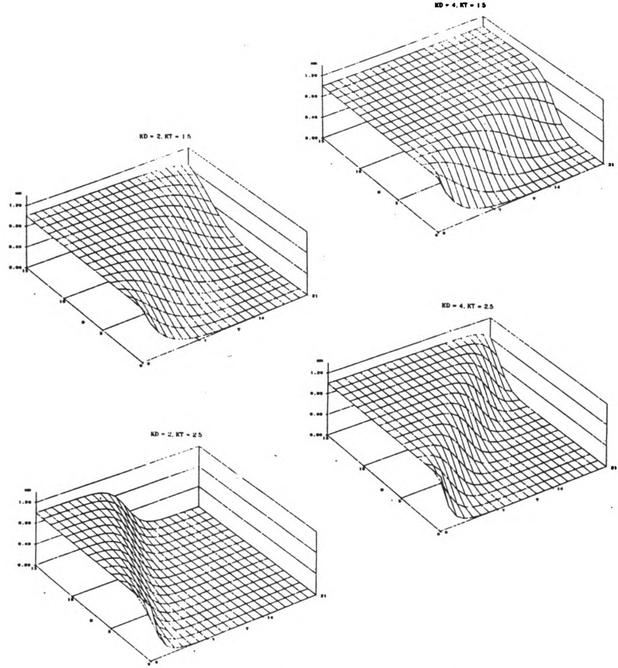

Figure 5.6 The drying surfaces plotted for different k_x and k_t. KD=k_x, KT=k_t, T= drying time (hr), and D= bed depth (in).

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5.3.3 Development of a Computer Program from the Empirical Fixed Bed Wood Chip Drying Model

Because of the complexity of the empirical fixed bed drying model, a FORTRAN computer program "CHIP DRY" was written to execute the calculations using a personal computer.

The main program was designed to calculate the moisture content given the drying time (t) and the depth coordinator (x) under certain drying conditions, such as air temperature (T), air relative humidity (RH), wood chip size (SZ), airflow rate (V), and original moisture content (OMC). For more practical application, several extended functions were also included in this program:

(1) to illustrate the moisture distribution along the depth of the wood chip bed and at different drying times;

(2) to calculate the average moisture content of the wood chips in the dryer at different drying times;

(3) to calculate the average net heating value of the wood chips in the dryer at different drying times;

(4) to calculate the airflow resistance of the dryer for different sized wood chips and different airflow rate; and

(5) to calculate the bulk shrinkage for different drying conditions.

The "CHIP DRY" program provided the basic information for selecting the drying methods under varied conditions. It is expected to be used as a tool in wood chip dryer design.

5.4 Results and Discussion of the Empirical Fixed Bed Wood Chip DryingExperiment

There were two steps taken in developing the empirical fixed bed drying model for wood chips: (1) determining the drying surface for each experimental condition with nonlinear regressions; and (2) determining the relationship between the two constants (k_x and k_t) and the experimental conditions with multiple regressions.

5.4.1 Determining k_x and k_t for Each Experimental Condition using Nonlinear Regressions

A modified Hukill equation was used as the nonlinear regression model to determine k_x and k_t for the 144 experimental conditions. A typical regression can be illustrated by a three-dimensional surface as shown in Figure 5.3. The two estimates, k_x and k_t, are listed in Appendix B. The average coefficients of determination for the total 144 regressions in this experiment is 0.95, which indicates that the model fits the experimental data very well.

The drying surface shows that the drying process occurs only within a zone of certain thickness at a specific depth and at a certain time. This zone is normally defined as a drying zone. In a dryer, air absorbs the moisture from the wet wood chips, and, after a while, it reaches its saturation point and loses its ability to dry. Therefore, the air can only dry the wood chips within a drying zone in the chip bed, and this zone moves in the

same direction as the air does.

5.4.2 The Development of the Models for k_x and k_t

It was found that the drying process can be analyzed by determining two critical values: (1) the moving speed of the drying zone; and (2) the thickness of the drying zone. Comparing the figures plotted with the time constant (k_t) and depth constant (k_x) (Figure 5.4), it was found that the thickness of the drying zone is inversely related to k_x and that the moving speed of the drying zone is directly related to k_t and inversely related to k_x. Under different experimental conditions, the influence on the two critical values from different independent variables can be explained through k_x and k_t.

Determining the models for k_x and k_t was the second step in the development of the empirical fixed bed drying model. Because k_x and k_t were related to the experimental conditions, multiple regressions were performed to determine the models.

5.4.2.1 Analysis of Variance of k_x and k_t

An analysis of variance was performed for both k_x and k_t to determine the significant levels for the independent variables and their interactions (Table 5.3, Table 5.4). The ANOVA tables were important references in the model selection.

Table 5

SOURCE
Model
Error
Total

SOURCE
V
SZ
T
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V*SZ
V*T
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Table 5.2 Analysis of variance of depth constant k_x.

SOURCE	DF	ANOVA SS	MS	
Model	107	67.185	0.628	
Error	34	1.056	0.031	
Total	141	68.241		
SOURCE	**DF**	**ANOVA SS**	**F VALUE**	**PR > F**
V	2	8.803	141.68	0.0001
SZ	2	17.145	275.94	0.0001
T	2	1.198	12.85	0.0001
RH	2	23.477	251.89	0.0001
V*SZ	4	1.359	10.93	0.0001
V*T	6	1.384	7.42	0.0001
V*RH	6	3.137	16.83	0.0001
SZ*T	6	0.495	2.66	0.0319
SZ*RH	6	4.183	22.44	0.0001
T*RH	9	1.302	4.66	0.0005
V*SZ*T	12	1.385	3.72	0.0013
V*SZ*RH	12	0.979	2.62	0.0135
V*T*RH	18	1.623	2.90	0.0036
SZ*T*RH	18	0.713	1.28	0.2632

Table 5.3 Analysis of variance of time constant k_t.

SOURCE	DF	ANOVA SS	MS	
Model	107	70.729	0.661	
Error	34	0.476	0.014	
Total	141	71.205		
SOURCE	**DF**	**ANOVA SS**	**F VALUE**	**PR > F**
V	2	19.154	684.84	0.0001
SZ	2	10.318	368.90	0.0001
T	2	10.428	248.56	0.0001
RH	2	10.448	249.04	0.0001
V*SZ	4	2.773	49.57	0.0001
V*T	6	5.057	60.27	0.0001
V*RH	6	1.903	22.68	0.0001
SZ*T	6	1.768	21.07	0.0001
SZ*RH	6	0.888	10.59	0.0001
T*RH	9	1.406	11.17	0.0001
V*SZ*T	12	2.911	17.34	0.0001
V*SZ*RH	12	0.651	3.88	0.0009
V*T*RH	18	1.503	5.97	0.0001
SZ*T*RH	18	1.521	6.04	0.0001

It was found from the ANOVA tables that almost all of the independent variables were significant. The contribution to the sum square (SS) came basically from several independent variables and their second level interactions. For example, the contribution of SS for k_x came from RH, SZ, V, SZ*RH, V*RH, T, and V*SZ (in intense order) and for k_t from V, SZ, RH, T, V*T, V*SZ, V*RH, and SZ*T. The original moisture content of the wood chips is not a controlled factor and, therefore, was not included in the ANOVA table. The results of the ANOVA tables were compared to the results of the regression of the models to evaluate the selection of the final models.

5.4.2.2 Regression Analysis of k_t and k_x

The multiple regression procedure was performed to determine the models for k_t and k_x. The original moisture content was included as an independent variable in the regression. Because the influences to k_t and k_x from the variables and their interactions were very complicated, second order polynomial equations were chosen as the models to begin with. The maximum R^2 stepwise procedure using a SAS computer program was used to select a suitable model. The final models of k_t and k_x included the items which were significant at 0.05 level in the partial T-test (probability > T). However, some items which were not significant in the T-test were also included in the models because their interactions were significant. The selected models are listed as follo

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follows:

$$\begin{aligned}k_D = {} & \beta_{x0} + \beta_{x1}(V) + \beta_{x2}(V^2) + \beta_{x3}(SZ) + \beta_{x4}(SZ^2) \\ & + \beta_{x5}(T) + \beta_{x6}(RH) + \beta_{x7}(RH^2) + \beta_{x8}(OMC) + \beta_{x9}(OMC^2) \\ & + \beta_{x10}(V \times SZ) + \beta_{x11}(V \times T) + \beta_{x12}(V \times RH) + \beta_{x13}(V \times OMC) \\ & + \beta_{x14}(SZ \times RH) + \beta_{x15}(SZ \times OMC) + \beta_{x16}(T \times OMC) + \beta_{x17}(RH \times OMC) \\ & + \beta_{x18}(RH \times OMC) + \beta_{x19}(V \times SZ \times RH) + \beta_{x20}(V \times T \times OMC) \\ & + \beta_{x21}(SZ \times RH \times OMC)\end{aligned}$$

$\beta_{x0} = -10.37904712$	$\beta_{x1} = -0.31961232$	$\beta_{x2} = 0.000171958$
$\beta_{x3} = 24.27485473$	$\beta_{x4} = 6.44464860$	$\beta_{x5} = -0.30970527$
$\beta_{x6} = 0.27417927$	$\beta_{x7} = 0.000407581$	$\beta_{x8} = 0.24743239$
$\beta_{x9} = -0.000950171$	$\beta_{x10} = -0.02694957$	$\beta_{x11} = 0.004217686$
$\beta_{x12} = -0.000774058$	$\beta_{x13} = 0.001965759$	$\beta_{x14} = -0.63756348$
$\beta_{x15} = -0.18261486$	$\beta_{x16} = 0.000300598$	$\beta_{x17} = 0.001790884$
$\beta_{x18} = -0.001618642$	$\beta_{x19} = 0.000683442$	$\beta_{x20} = -0.000025603$
$\beta_{x21} = 0.003455997$		

$$\begin{aligned}k_t = {} & \beta_{t0} + \beta_{t1}(V) + \beta_{t2}(V^2) + \beta_{t3}(SZ) + \beta_{t4}(T) + \beta_{t5}(RH) \\ & + \beta_{t6}(OMC) + \beta_{t7}(V \times T) + \beta_{t8}(V \times RH) + \beta_{t9}(V \times OMC) \\ & + \beta_{t10}(T \times RH) + \beta_{t11}(T \times OMC) + \beta_{t12}(RH \times OMC) \\ & + \beta_{t13}(V \times T \times RH) + \beta_{t14}(V \times T \times OMC)\end{aligned}$$

$\beta_{t0} = 28.59735622$	$\beta_{t1} = -.041132228$	$\beta_{t2} = 0.000231489$
$\beta_{t3} = -0.29912980$	$\beta_{t4} = -0.28028153$	$\beta_{t5} = -0.07585158$
$\beta_{t6} = -0.15436309$	$\beta_{t7} = 0.005371459$	$\beta_{t8} = 0.000369705$
$\beta_{t9} = 0.002129835$	$\beta_{t10} = 0.000195583$	$\beta_{t11} = 0.001624148$
$\beta_{t12} = 0.000374406$	$\beta_{t13} = -0.000006626$	$\beta_{t13} = 0.000029201$

where V is airflow rate (cfm/ft^2), SZ is wood chip size (in^2), T is air temperature (°F), RH is air relative humidity (%), and OMC is the original moisture content of the wood chips

The ANOVA tables above indicates that k_x is strongly affected by the factors V, SZ, and RH, and the interactions of SZ*RH, V*RH, and V*SZ, and k_t is affected by factors V, SZ, T, and RH and the interaction V*T and V*SZ. Three-dimensional surface graphs were plotted to show the relationship between the constants (k_x and k_t) and the two independent variables (T and RH), and the graphs were plotted for different values in V, SZ, and OMC with two levels for each variable (Appendix C). The following phenomena can be seen by analyzing the surface graphs:

(1) Air temperature is inversely related to k_x and directly related to k_t. This phenomenon indicates that drying speed is increased with an increase in air temperature because both the increase in k_t and the decrease in k_x correlate with the improvement in drying speed.

(2) Air relative humidity is directly related to k_x and inversely related to k_t. This phenomenon indicates that the drying rate is reduced at higher air relative humidity, the decrease in drying rate being caused by both an increase in k_x and a decrease in k_t. ANOVA tables show that both k_x and k_t are strongly affected by air relative humidity.

(3) Airflow rate is inversely related to k_x and is directly related to k_t. This phenomenon indicates that the drying rate increases proportionally with airflow rate. ANOVA tables show that the airflow rate strongly influences k_x and k_t. The thickness of the drying zone is also increased by the reduction of k_x, or by an increase in airflow rate. When air moves faster through the wood

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chip bed, it must travel a longer distance before reaching the saturation point and, therefore, the thickness of the drying zone is increased.

(4) Wood chip size is inversely related to k_x, and this phenomenon indicates that the thickness of the drying zone is reduced when the wood chips are small. The relationship between k_t and wood chip size is not obvious by studying the surface graphs.

(5) k_x is more sensitive to relative humidity for small wood chips than for bigger ones. When the wood chips are small, the drying zone thickness is reduced because the air absorbs moisture quickly from the greater surface area, which correlates to the increase in k_x.

(6) k_x is more sensitive to relative humidity at low flow rates than at high flow rates. When the flow rate is low, air moves slowly in the bed and has more time to absorb the moisture from wood chips and, therefore, the thickness of the drying zone is reduced, which correlates to the increase in k_x.

(7) k_t shows a very slight increase along with the airflow rate when the wood chip size is decreased. It is known that when the wood chips are small, k_x is large, which causes a reduction in the drying zone thickness and a slight decrease in drying rate. The experiment did not show a drying rate reduction, and it should be compensated for by an increasing drying rate related to the increase in k_t.

(8) k_t shows a more sensitive increase with T at a higher airflow rate than at a lower rate. Because the moisture absorption

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tendency of the air is directly related to the air temperature at a certain relative humidity, the increase in the drying rate, or in k_t, is much more obvious when the airflow rate is high.

(9) The original moisture content of the wood chips (OMC) is not a controlled factor in the experiment and the discussion on OMC is based on the observations of the surface graphs of k_x and k_t. The OMC is directly related to k_x and inversely related to k_t. The high original moisture content of the wood chips accelerates the water saturation of the air and reduces the speed of the drying zone movement. Therefore, when drying very wet wood chips, the drying zone is thinner and the drying rate is slower.

5.5 Development of the "CHIP DRY" Computer Program

Although the variables in the empirical fixed bed drying model were minimized in the model selection, the formulas of the model were still very complicated. A computer program was written in FORTRAN to execute the calculation of the model with the assistance of a personal computer.

The basic function of this program was to calculate the moisture content at given drying times and a given depth in the simulated dryer when the drying conditions and wood chip properties are known. Several options are included in the computer program:

(1) To calculate the moisture distribution over drying time and bed depth. The moisture distribution of wood chips in a wood chip dryer shows a very clear view of the drying process.

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(2) To calculate the average moisture content of the chips in the dryer at different drying times. The average moisture content of the chips in the dryer can be used to evaluate the drying efficiency at different time periods of drying.

(3) To calculate the average net heating value (NHV) of the wood chips in the dryer. The changes in the net heating value of wood chips indicate the energy gain through the wood chip drying, and the following formula is used to calculate the net heating value of the wood chips

$$NHV = HHV - [0.0114 \times (HHV) \times MC]$$

where HHV is higher heating value (Btu/lb), NHV is net heating value (Btu/lb), and MC is the moisture content of wood (percent).

(4) To calculate the airflow resistance of the wood chip dryer under different airflow rates for different sized chips. The formula used for this calculation was developed from the airflow resistance experiment in Chapter III. The energy consumption can be evaluated by knowing the airflow resistance value in a wood chip dryer.

(5) To calculate the bulk shrinkage of the wood chips in a fixed bed dryer for different drying conditions. The formula used for this calculation was developed from the bulk shrinkage experiment in Chapter III.

The input data and the calculation results of the program are illustrated in Table 5.5 and Table 5.6, respectively. Listings of the computer program "CHIP DRY" are shown in Appendix D.

Table

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Table 5.4 Example of the input data of the "CHIP DRY" computer program for the simulation of a wood chip dryer.

```
THE CONDITIONS ARE LIST IN THE FOLLOWING TABLE,
PLEASE CHECK IT AGAIN BEFORE THE CALCULATION.

(1) ORIGINAL MOISTURE CONTENT     (%) =  140.0000
(2) INLET AIR TEMPERATURE         (F) =   78.0000
(3) INLET AIR RELATIVE HUMIDITY (%) =     78.0000
(4) INLET AIR FLOW RATE      (FT3/HR) =   78.0000
(5) WOOD CHIP SIZE                (#) =     .5000
(6) THE DEPTH (LET BOTTOM = 0)  (IN) =     8.0000
(7) THE DRYING TIME              (HR) =   10.0000
```

Table 5.5 Example of the results of the wood chip dryer simulation computed by the computer program "CHIP DRY". T is drying time (hr), D is the depth in the dryer (in), AVGMC is average moisture content (%), AVGHV is average net heating value (Btu/lb).

D / T	.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
.0	140.0	94.6	65.7	47.3	35.6	28.2	23.4	20.4	18.5	17.3	16.5
.8	140.0	107.0	80.0	59.5	44.8	34.6	27.8	23.3	20.4	18.5	17.3
1.6	140.0	116.9	94.0	73.4	56.5	43.5	34.1	27.6	23.3	20.4	18.5
2.4	140.0	124.4	106.5	87.7	70.1	54.9	42.8	33.9	27.6	23.3	20.4
3.2	140.0	129.7	116.5	101.0	84.4	68.2	54.0	42.5	33.8	27.6	23.3
4.0	140.0	133.3	124.1	112.2	98.1	82.6	67.3	53.6	42.4	33.8	27.6
4.8	140.0	135.7	129.5	120.9	109.8	96.4	81.6	66.8	53.4	42.4	33.9
5.6	140.0	137.2	133.2	127.3	119.1	108.4	95.5	81.1	66.6	53.4	42.4
6.4	140.0	138.3	135.6	131.7	126.0	118.1	107.7	95.1	80.9	66.6	53.5
7.2	140.0	138.9	137.2	134.6	130.8	125.2	117.5	107.3	94.9	80.9	66.8
8.0	140.0	139.3	138.2	136.5	134.0	130.3	124.8	117.2	107.2	94.9	81.1
AVGMC	140.0	126.8	114.6	102.9	91.7	80.9	70.6	60.8	51.7	43.6	36.5
AVGHV	3015.	3263.	3521.	3796.	4091.	4410.	4754.	5120.	5502.	5887.	6258.

CHAPTER VI

LARGE SCALE MODEL TESTING EXPERIMENT

6.1 Introduction and Objectives of the Large Scale Model Testing Experiment

The model testing experiment was designed to test in the laboratory the semi-theoretical and the empirical models developed and discussed in Chapters IV and V. The semi-theoretical model was developed mathematically using several assumptions, and the empirical model was developed from wood chip drying experiments with small dryers.

The objective of the model testing experiment was to evaluate the results of the model simulation. A larger fixed bed dryer was built for this experiment, and the data obtained were compared with the results of the simulation done with both models.

6.2 Method Used in the Large Scale Model Testing Experiment

6.2.1 Experimental Design of Model Testing Experiment

The model testing experiment was performed with a fixed bed dryer in a room with constant air temperature and constant air re

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relative humidity. Because of the limitation of drying conditions and wood chip supply, the experiments were performed under the following conditions (Table 6.1):

Table 6.1 Experimental conditions for model testing experiment.

Drying conditions	1	2	3
Air temperature (T)	68	70	70
Air relative humidity (%)	73	70	87
Airflow rate ($ft^3/min/ft^2$)	82	82	99
Wood chip size (in^2)	0.46	0.30	0.46
Original moisture content (%)	133	130.74	137.41
Drying hours (hour)	42	44	72
Depth of chip bed (in)	48	48	48

Red pine wood chips were also used as the samples in this experiment, and the methods for size sorting and storage were the same as those in Chapter IV.

6.2.2 Equipment Used in the Large Scale Model Testing Experiment

A fixed bed wood chip dryer, 14-inches in diameter and 48-inches high, was constructed and installed in the temperature and relative humidity controlled conditioning room (Figure 6.1). The structure of this dryer was similar to the one used in the fixed bed drying experiment but much larger. The bottom portion was a section of four-inches high, the middle portion was composed of six sections, each eight-inches high, and the top portion was one section two-inches high. The moisture samples, placed during the

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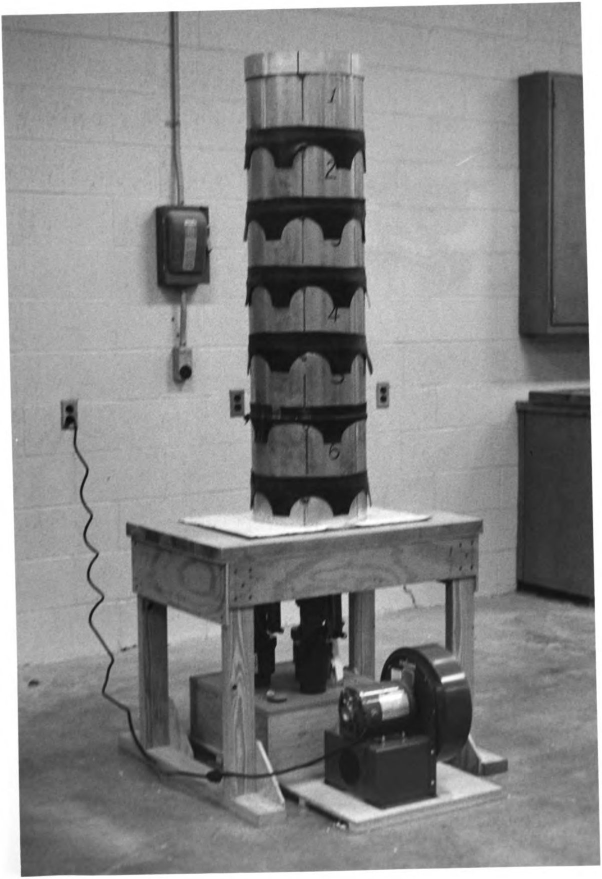
drying experiment, were at seven levels from X=0 inches to X=42 inches with eight-inches intervals. At each depth level, wood chip samples contained in three fan-shaped baskets were evenly distributed in the cross section of the dryer. The connections between the two sections were sealed with heavy duty rubber bands.

A high pressure blower was installed at the bottom of the drying system to supply the air. An air cushion box was used to evenly distribute the air and support the flowmeters. Three bypass flowmeters was placed under the dryer to control airflow.

Fig

Figure 6.1 Fixed bed dryer used in the large scale model testing experiment.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6.2.3 Measurement of the Large Scale Model Testing Experiment

The weights of the moisture samples, including the sample baskets, were measured with a balance during the drying period. The moisture content of the samples was determined in the same method as that used in the fixed bed drying experiment. The interval between two measurements depended on the drying conditions; for example, the interval was longer for slower drying and shorter for faster drying conditions.

6.4 Results and Discussion of the Large Scale Model Testing Experiment

The experimental data and the results of model simulation are listed in Appendix V. Wood chip drying simulations were conducted using both drying models. The comparison of the simulation results and the testing experimental results are illustrated in Figure E1, Figure E2, and Figure E3 for the three experimental conditions.

Comparisons of the results showed that the experimental results were much closer to the simulation results of the empirical model than to those of the semi-theoretical model (Appendix E).

One of the most important reasons for the difference between the experimental results and the semi-theoretical model simulation is the assumptions made in the model development. The assumptions were stated as: "the particle-to-particle conduction is negligible," "the airflow and grainflow are plug-type," "$\partial T/\partial t$ and $\partial W/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial W/\partial x$," etc. (Brooker,

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1974). These assumptions may not be exactly true in all the wood chip drying situations, because the size of the wood chips is larger than that of kernels of grain and their shapes are much more irregular. These characteristics of wood chips may make them incompatible with the model assumptions. It is was also noted that the computer time used to execute the semi-theoretical model is much longer than that needed for the empirical model.

The empirical drying model developed from the experiment in the small dryers gives a good indication of the drying process in the large scale testing experiment. There were no assumptions made in the development of the model. However, when the empirical model was used to simulate a larger dryer, the same airflow distribution along the cross section of the dryers was assumed. It was observed from the experiment that the wood chips close to the wall of the dryer dried faster than those at the center, and this indicates a faster airflow there. Because of the similar results from the simulation and the experiment, the assumption on the same airflow distribution is justified. Another reason for the small difference in the simulation results of the empirical model is that the moisture content of the wood chips in the large scale testing experiment was almost at the edge of the range used for the model development.

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CHAPTER VII

CONCLUSIONS

This study of wood chip drying in a fixed bed dryer has included a literature review, laboratory experiments, statistical analysis, and a new computer program. The results obtained from these efforts suggest the following conclusions.

7.1 Conclusion Regarding the Physical Properties of Wood Chips Related to Drying

1. The bulk volume of wood chips shrinks during drying. The bulk shrinkage occurs very slowly initially until the average moisture content reaches 80 percent and then the rate of shrinkage increases gradually with a decrease in the moisture content. Comparing large sized wood chips with smaller ones, the bulk shrinkage for small chips appears to start at a lower moisture content and the rate increases more quickly once it starts. Shrinkage can be described with a nonlinear formula.

2. The airflow resistance in a wood chip bed is very well correlated to the size of the wood chips and the airflow rate. The resistance is directly related to the airflow and inversely related to the wood chip size. The relationship between the resistance and

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the airflow rate for wood chips of three different sizes can be described with a nonlinear formula.

7.2 Conclusion Regarding a Thin Layer Wood Chip Drying Model and a Semi-theoretical Fixed Bed Model

1. The drying process for thin layer wood chips can be well described with a combination of a nonlinear diffusion equation and a polynomial equation. The thin layer model, developed by performing the regressions on the laboratory experimental data, indicates that the drying process is affected by three factors (air temperature, air relative humidity, and wood chip size) and two of their interactions (air temperature and air relative humidity, air relative humidity and wood chip size).

2. A semi-theoretical fixed bed drying model, developed for grain drying, can be modified by employing the thin layer wood chip drying model and the equilibrium moisture content model for wood material to simulate wood chip drying. The results obtained from the semi-theoretical model are not very accurate for wood chip drying and the time required to obtain the results on the personal computer is time consuming. Because of these limitations, it is considered of limited application in wood chip drying.

7.3 Conclusion Regarding an Empirical Fixed Bed Drying Model for Wood Chips

1. The fixed bed laboratory drying experiment for wood chips can be conducted with a small fixed bed drying system (dryers, blower, and airflow control system) mounted in a conditioning chamber. Four factors (air temperature, air relative humidity, airflow rate, and wood chip size) can be controlled in this experiment.

2. The wood chip drying process can be described by a model, including a nonlinear equation (indicating the moisture content change with drying time and bed depth) and a polynomial equation (indicating the changes in drying constants with drying conditions). Statistical analysis indicates that all the controlled factors (air temperature, air relative humidity, airflow rate, and wood chip size) and an uncontrolled variable (original moisture content of the wood chips), and some of their interactions are significant in the model.

3. A computer program "CHIP DRY" was written in FORTRAN to facilitate the calculation required to compute the results for the empirical fixed bed drying model. The functions of the computer program include determining: (1) the moisture content distribution for the wood chips in a fixed bed dryer, (2) the average moisture content for the different drying periods, (3) the average net heating value for different drying periods, (4) bulk volume change, and (5) airflow resistance of the dryer. The computer time used for the simulation is much shorter than the semi-theoretical model,

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and therefore, this model can efficiently provide engineering design information for the optimization of wood chip dryers.

7.4 Conclusion Regarding the Large Scale Model Testing Experiment

1. The empirical fixed bed drying model developed from the experiment in the small dryer can be used to simulate the drying process in the large scale testing experiment for a longer period of drying time. The results of the empirical model simulation are very close to those obtained from the model testing experiment.

2. Although the drying process in the testing experiment can be simulated by the semi-theoretical model, the results are not as accurate as those obtained from the empirical model and the computer time required to run the computations is very long.

CHAPTER VIII

SUGGESTIONS FOR ADDITIONAL RESEARCH

The future development of wood energy will be determined by energy requirements and also by improvements in wood energy production technology. To find acceptable solutions for improvement in using wood chips for fuel, problems encountered in economically drying wood chips must be solved. This dissertation focused on a basic model development for wood chip drying in a fixed bed dryer. Further studies are required in the following areas:

1. Optimization of wood chip dryer design

The short computer time required for executing the empirical model makes the optimization of wood chip dryer design possible. The final goal of the optimization of the model is to determine the most economical way to dry wood chips under commonly available air and wood chip conditions. With the optimization achieved by a computer program, combined with the drying model, it would be a powerful tool for improved wood chip dryer design.

2. Improvement of the empirical wood chip drying model

Because of limitations of time and materials, the model in this experiment can only simulate the drying process under test conditions. To further improve the practical application of the

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model, more experimental conditions are necessary, especially with regard to moisture content, wood species, and airflow rate. The geometry of wood chips may also be included as a factor in this study: for example, the wood chips from different chippers or a hammermill.

3. Theoretical study

In this study, the semi-theoretical model did not provide as accurate a simulation for wood chip drying as it did for grains. Further analysis is needed to evaluate the principles and the assumptions of the model. Further research will not only improve the model application for freshly cut wood chips, which has a higher moisture content than grain, but will also lead to a thorough understanding of wood particle drying.

4. Practical application

Practical application is an important step to testing the feasibility of the fixed bed wood chip drying model. In this study, larger scale testing experiment was performed only under three conditions. In order to use the drying model in industry, thorough practical application experiments under most of the general drying conditions are necessary.

APPENDIX A

DRYING CONSTANTS OBTAINED IN THIN LAYER DRYING EXPERIMENT

APPENDIX A

Table A1 Drying constants obtained by performing the nonlinear regressions for 192 testings.

No.	Rep.	T(°F)	RH(%)	SZ(in^2)	K
1	1	68.0	40.0	1.49	0.2020
2	2	68.0	40.0	1.49	0.2240
3	3	68.0	40.0	1.49	0.2348
4	1	68.0	40.0	0.82	0.3140
5	2	68.0	40.0	0.82	0.3926
6	3	68.0	40.0	0.82	0.4470
7	1	68.0	40.0	0.46	0.3605
8	2	68.0	40.0	0.46	0.5779
9	3	68.0	40.0	0.46	0.5707
10	1	68.0	40.0	0.30	0.5835
11	2	68.0	40.0	0.30	0.3729
12	3	68.0	40.0	0.30	0.4110
13	1	68.0	55.0	1.49	0.1913
14	2	68.0	55.0	1.49	0.2352
15	3	68.0	55.0	1.49	0.1391
16	1	68.0	55.0	0.82	0.1893
17	2	68.0	55.0	0.82	0.3361
18	3	68.0	55.0	0.82	0.1870
19	1	68.0	55.0	0.46	0.4783
20	2	68.0	55.0	0.46	0.3262
21	3	68.0	55.0	0.46	0.4018
22	1	68.0	55.0	0.30	0.4723
23	2	68.0	55.0	0.30	0.3663
24	3	68.0	55.0	0.30	0.3398
25	1	68.0	70.0	1.49	0.1288
26	2	68.0	70.0	1.49	0.1230
27	3	68.0	70.0	1.49	0.1535
28	1	68.0	70.0	0.82	0.2259
29	2	68.0	70.0	0.82	0.1551
30	3	68.0	70.0	0.82	0.1334
31	1	68.0	70.0	0.46	0.2729
32	2	68.0	70.0	0.46	0.2649
33	3	68.0	70.0	0.46	0.3198
34	1	68.0	70.0	0.30	0.1597
35	2	68.0	70.0	0.30	0.2503
36	3	68.0	70.0	0.30	0.2974

Table A1 (continued)

No.	Rep.	T(°F)	RH(%)	SZ(in^2)	K
37	1	68.0	85.0	1.49	0.0397
38	2	68.0	85.0	1.49	0.0564
39	3	68.0	85.0	1.49	0.0574
40	1	68.0	85.0	0.82	0.0749
41	2	68.0	85.0	0.82	0.0850
42	3	68.0	85.0	0.82	0.1015
43	1	68.0	85.0	0.46	0.0931
44	2	68.0	85.0	0.46	0.1107
45	3	68.0	85.0	0.46	0.1122
46	1	68.0	85.0	0.30	0.1035
47	2	68.0	85.0	0.30	0.1425
48	3	68.0	85.0	0.30	0.1749
49	1	82.4	40.0	1.49	0.2505
50	2	82.4	40.0	1.49	0.2233
51	3	82.4	40.0	1.49	0.3092
52	1	82.4	40.0	0.82	0.3443
53	2	82.4	40.0	0.82	0.3000
54	3	82.4	40.0	0.82	0.5388
55	1	82.4	40.0	0.46	0.5175
56	2	82.4	40.0	0.46	0.6346
57	3	82.4	40.0	0.46	0.4190
58	1	82.4	40.0	0.30	0.8478
59	2	82.4	40.0	0.30	0.6361
60	3	82.4	40.0	0.30	0.7381
61	1	82.4	55.0	1.49	0.2639
62	2	82.4	55.0	1.49	0.1847
63	3	82.4	55.0	1.49	0.1953
64	1	82.4	55.0	0.82	0.3773
65	2	82.4	55.0	0.82	0.4079
66	3	82.4	55.0	0.82	0.3068
67	1	82.4	55.0	0.46	0.3616
68	2	82.4	55.0	0.46	0.5036
69	3	82.4	55.0	0.46	0.4908
70	1	82.4	55.0	0.30	0.3722
71	2	82.4	55.0	0.30	0.5572
72	3	82.4	55.0	0.30	0.7458
73	1	82.4	70.0	1.49	0.1336
74	2	82.4	70.0	1.49	0.1889
75	3	82.4	70.0	1.49	0.2267
76	1	82.4	70.0	0.82	0.2552
77	2	82.4	70.0	0.82	0.2787
78	3	82.4	70.0	0.82	0.3591
79	1	82.4	70.0	0.46	0.2515
80	2	82.4	70.0	0.46	0.2684
81	3	82.4	70.0	0.46	0.2650

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Table A1 (continued)

No.	Rep.	T(°F)	RH(%)	SZ(in^2)	K
82	1	82.4	70.0	0.30	0.2206
83	2	82.4	70.0	0.30	0.2498
84	3	82.4	70.0	0.30	0.4763
85	1	82.4	85.0	1.49	0.0808
86	2	82.4	85.0	1.49	0.1010
87	3	82.4	85.0	1.49	0.0769
88	1	82.4	85.0	0.82	0.1304
89	2	82.4	85.0	0.82	0.1812
90	3	82.4	85.0	0.82	0.0934
91	1	82.4	85.0	0.46	0.1896
92	2	82.4	85.0	0.46	0.1872
93	3	82.4	85.0	0.46	0.1989
94	1	82.4	85.0	0.30	0.2381
95	2	82.4	85.0	0.30	0.1994
96	3	82.4	85.0	0.30	0.2739
97	1	96.8	40.0	1.49	0.2982
98	2	96.8	40.0	1.49	0.3078
99	3	96.8	40.0	1.49	0.5104
100	1	96.8	40.0	0.82	0.4057
101	2	96.8	40.0	0.82	0.6246
102	3	96.8	40.0	0.82	0.5520
103	1	96.8	40.0	0.46	0.7061
104	2	96.8	40.0	0.46	0.6181
105	3	96.8	40.0	0.46	0.9076
106	1	96.8	40.0	0.30	0.9023
107	2	96.8	40.0	0.30	0.8267
108	3	96.8	40.0	0.30	1.0721
109	1	96.8	55.0	1.49	0.2559
110	2	96.8	55.0	1.49	0.1801
111	3	96.8	55.0	1.49	0.2746
112	1	96.8	55.0	0.82	0.2707
113	2	96.8	55.0	0.82	0.4162
114	3	96.8	55.0	0.82	0.4612
115	1	96.8	55.0	0.46	0.5509
116	2	96.8	55.0	0.46	0.5540
117	3	96.8	55.0	0.46	0.5269
118	1	96.8	55.0	0.30	0.3694
119	2	96.8	55.0	0.30	0.5633
120	3	96.8	55.0	0.30	0.7006
121	1	96.8	70.0	1.49	0.1607
122	2	96.8	70.0	1.49	0.2135
123	3	96.8	70.0	1.49	0.2272
124	1	96.8	70.0	0.82	0.2710
125	2	96.8	70.0	0.82	0.2582
126	3	96.8	70.0	0.82	0.3547

Table A1 (continued)

No.	Rep.	T(°F)	RH(%)	SZ(in^2)	K
127	1	96.8	70.0	0.46	0.3940
128	2	96.8	70.0	0.46	0.3821
129	3	96.8	70.0	0.46	0.4059
130	1	96.8	70.0	0.30	0.3181
131	2	96.8	70.0	0.30	0.3473
132	3	96.8	70.0	0.30	0.6163
133	1	96.8	85.0	1.49	0.0764
134	2	96.8	85.0	1.49	0.0896
135	3	96.8	85.0	1.49	0.0828
136	1	96.8	85.0	0.82	0.1005
137	2	96.8	85.0	0.82	0.1320
138	3	96.8	85.0	0.82	0.1443
139	1	96.8	85.0	0.46	0.1170
140	2	96.8	85.0	0.46	0.1124
141	3	96.8	85.0	0.46	0.1833
142	1	96.8	85.0	0.30	0.1689
143	2	96.8	85.0	0.30	0.1897
144	3	96.8	85.0	0.30	0.2403
145	1	111.2	40.0	1.49	0.4037
146	2	111.2	40.0	1.49	0.4939
147	3	111.2	40.0	1.49	0.4282
148	1	111.2	40.0	0.82	0.4626
149	2	111.2	40.0	0.82	0.5511
150	3	111.2	40.0	0.82	0.8312
151	1	111.2	40.0	0.46	0.7885
152	2	111.2	40.0	0.46	0.5846
153	3	111.2	40.0	0.46	0.9043
154	1	111.2	40.0	0.30	0.8042
155	2	111.2	40.0	0.30	0.9193
156	3	111.2	40.0	0.30	0.9235
157	1	111.2	55.0	1.49	0.2447
158	2	111.2	55.0	1.49	0.2514
159	3	111.2	55.0	1.49	0.3303
160	1	111.2	55.0	0.82	0.3388
161	2	111.2	55.0	0.82	0.4436
162	3	111.2	55.0	0.82	0.6463
163	1	111.2	55.0	0.46	0.4086
164	2	111.2	55.0	0.46	0.6124
165	3	111.2	55.0	0.46	0.5353
166	1	111.2	55.0	0.30	0.7387
167	2	111.2	55.0	0.30	0.5245
168	3	111.2	55.0	0.30	0.8745
169	1	111.2	70.0	1.49	0.2170
170	2	111.2	70.0	1.49	0.1718
171	3	111.2	70.0	1.49	0.2442

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Table A1 (continued)

No.	Rep.	T(°F)	RH(%)	SZ(in^2)	K
172	1	111.2	70.0	0.82	0.2263
173	2	111.2	70.0	0.82	0.3340
174	3	111.2	70.0	0.82	0.4242
175	1	111.2	70.0	0.46	0.2623
176	2	111.2	70.0	0.46	0.3514
177	3	111.2	70.0	0.46	0.4582
178	1	111.2	70.0	0.30	0.4267
179	2	111.2	70.0	0.30	0.3620
180	3	111.2	70.0	0.30	0.4500
181	1	111.2	85.0	1.49	0.0732
182	2	111.2	85.0	1.49	0.0566
183	3	111.2	85.0	1.49	0.0666
184	1	111.2	85.0	0.82	0.0961
185	2	111.2	85.0	0.82	0.0958
186	3	111.2	85.0	0.82	0.1528
187	1	111.2	85.0	0.46	0.1235
188	2	111.2	85.0	0.46	0.1692
189	3	111.2	85.0	0.46	0.1690
190	1	111.2	85.0	0.30	0.1033
191	2	111.2	85.0	0.30	0.1486
192	3	111.2	85.0	0.30	0.1990

APPENDIX B

DEPTH CONSTANTS AND TIME CONSTANTS OBTAINED IN FIXED BED DRYING EXPERIMENT

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APPENDIX B

Table B1 The depth constant k_x and time constant k_t obtained by performing nonlinear regressions under different experimental conditions.

No.	V cfm/in^2	SZ in^2	T °F	RH %	OMC %	k_x -	k_t -
1	44	0.82	68.0	40.0	163.47	1.788	1.363
2	44	0.46	68.0	40.0	164.68	2.101	1.509
3	44	0.30	68.0	40.0	153.19	2.767	1.735
4	44	0.82	68.0	55.0	171.20	1.796	1.298
5	44	0.46	68.0	55.0	161.72	2.299	1.359
6	44	0.30	68.0	55.0	153.92	2.611	1.532
7	44	0.82	68.0	70.0	167.99	2.259	1.252
8	44	0.46	68.0	70.0	163.50	2.632	1.310
9	44	0.30	68.0	70.0	151.30	3.830	1.452
10	44	0.82	68.0	85.0	161.25	2.390	1.138
11	44	0.46	68.0	85.0	161.95	2.762	1.158
12	44	0.30	68.0	85.0	151.24	4.124	1.263
13	44	0.82	82.4	40.0	163.55	1.716	1.469
14	44	0.46	82.4	40.0	165.95	1.930	1.534
15	44	0.30	82.4	40.0	152.74	2.341	1.816
16	44	0.82	82.4	55.0	167.39	1.950	1.355
17	44	0.46	82.4	55.0	163.32	2.215	1.442
18	44	0.30	82.4	55.0	150.83	3.025	1.789
19	44	0.82	82.4	70.0	170.37	2.186	1.288
20	44	0.46	82.4	70.0	162.61	2.675	1.387
21	44	0.30	82.4	70.0	151.82	4.125	1.660
22	44	0.82	82.4	85.0	164.54	2.844	1.194
23	44	0.46	82.4	85.0	159.96	3.209	1.226
24	44	0.30	82.4	85.0	153.00	4.418	1.379
25	44	0.82	96.8	40.0	170.00	1.682	1.512
26	44	0.46	96.8	40.0	161.00	2.026	1.723
27	44	0.30	96.8	40.0	153.80	2.145	1.978
28	44	0.82	96.8	55.0	170.68	1.800	1.406
29	44	0.46	96.8	55.0	161.30	2.009	1.525
30	44	0.30	96.8	55.0	153.86	2.296	1.678
31	44	0.82	96.8	70.0	169.67	2.565	1.379
32	44	0.46	96.8	70.0	162.42	3.177	1.549
33	44	0.30	96.8	70.0	153.18	5.046	1.876
34	44	0.82	96.8	85.0	164.87	2.663	1.210
35	44	0.46	96.8	85.0	162.72	3.520	1.275

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Table B1 (continued)

No.	V cfm/in^2	SZ in^2	T °F	RH %	OMC %	k_x -	k_t -
36	44	0.30	96.8	85.0	147.98	5.450	1.484
37	44	0.82	111.2	40.0	168.85	1.801	1.699
38	44	0.46	111.2	40.0	169.08	1.977	1.824
39	44	0.30	111.2	40.0	153.19	2.133	2.072
40	44	0.82	111.2	55.0	170.52	1.967	1.506
41	44	0.46	111.2	55.0	166.75	2.551	1.723
42	44	0.30	111.2	55.0	153.3	2.612	1.914
43	44	0.82	111.2	70.0	169.32	2.462	1.447
44	44	0.46	111.2	70.0	163.70	2.805	1.534
45	44	0.30	111.2	70.0	152.7	3.198	1.682
46	44	0.82	111.2	85.0	162.21	2.735	1.243
47	44	0.46	111.2	85.0	163.26	3.692	1.301
48	44	0.30	111.2	85.0	149.40	5.093	1.469
49	67	0.82	68.0	40.0	155.58	1.604	1.609
50	67	0.46	68.0	40.0	144.75	1.771	1.756
51	67	0.30	68.0	40.0	141.81	2.056	2.041
52	67	0.82	68.0	55.0	160.72	1.675	1.448
53	67	0.46	68.0	55.0	158.54	1.937	1.533
54	67	0.30	68.0	55.0	141.29	2.299	1.824
55	67	0.82	68.0	70.0	160.65	1.904	1.326
56	67	0.46	68.0	70.0	152.61	2.190	1.474
57	67	0.30	68.0	70.0	141.20	2.618	1.721
58	67	0.82	68.0	85.0	163.68	2.252	1.200
59	67	0.46	68.0	85.0	157.46	2.897	1.312
60	67	0.30	68.0	85.0	133.64	3.504	1.488
61	67	0.82	82.4	40.0	164.62	1.648	1.695
62	67	0.46	82.4	40.0	150.73	1.804	1.938
63	67	0.30	82.4	40.0	141.93	1.948	2.225
64	67	0.82	82.4	55.0	158.52	1.827	1.549
65	67	0.46	82.4	55.0	156.36	1.954	1.659
66	67	0.30	82.4	55.0	143.92	2.194	1.957
67	67	0.82	82.4	70.0	167.42	1.963	1.401
68	67	0.46	82.4	70.0	160.65	2.356	1.571
69	67	0.30	82.4	70.0	141.01	2.570	1.748
70	67	0.82	82.4	85.0	161.32	2.081	1.216
71	67	0.46	82.4	85.0	155.97	2.615	1.340
72	67	0.30	82.4	85.0	137.91	3.514	1.549
73	67	0.82	96.8	40.0	157.40	1.670	1.885
74	67	0.46	96.8	40.0	156.74	1.884	2.235
75	67	0.30	96.8	40.0	137.32	2.197	2.994
76	67	0.82	96.8	55.0	153.63	1.850	1.795
77	67	0.46	96.8	55.0	154.17	1.967	1.875
78	67	0.30	96.8	55.0	132.07	2.218	2.523
70	67	0.82	96.8	70.0	163.80	1.865	1.416
80	67	0.46	96.8	70.0	158.94	2.060	1.600

Table B1 (continued)

No.	V cfm/in^2	SZ in^2	T °F	RH %	OMC %	k_x -	k_t -
81	67	0.30	96.8	70.0	131.85	2.596	2.018
82	67	0.82	96.8	85.0	163.03	2.408	1.331
83	67	0.46	96.8	85.0	149.53	2.396	1.511
84	67	0.30	96.8	85.0	129.92	2.843	1.679
85	67	0.82	111.2	40.0	162.67	1.727	2.042
86	67	0.46	111.2	40.0	153.07	1.848	2.555
87	67	0.30	111.2	40.0	139.90	2.070	3.092
88	67	0.82	111.2	55.0	156.67	1.829	1.801
89	67	0.46	111.2	55.0	155.90	1.897	2.084
90	67	0.30	111.2	55.0	141.10	2.126	2.454
91	67	0.82	111.2	70.0	160.48	1.941	1.659
92	67	0.46	111.2	70.0	152.17	2.013	1.849
93	67	0.30	111.2	70.0	140.67	2.831	2.502
94	67	0.82	111.2	85.0	163.70	2.516	1.428
95	67	0.46	111.2	85.0	141.95	2.524	1.687
96	67	0.30	111.2	85.0	138.01	3.868	2.067
97	67	0.82	68.0	40.0	163.88	1.609	1.758
98	67	0.46	68.0	40.0	154.03	1.682	1.968
99	67	0.30	68.0	40.0	139.90	1.943	2.515
100	99	0.82	68.0	55.0	162.53	1.622	1.566
101	99	0.46	68.0	55.0	157.16	1.819	1.734
102	99	0.30	68.0	55.0	137.56	1.992	2.107
103	99	0.82	68.0	70.0	165.77	1.593	1.405
104	99	0.46	68.0	70.0	163.50	1.867	1.542
105	99	0.30	68.0	70.0	135.76	1.988	1.816
106	99	0.82	68.0	85.0	168.80	1.770	1.302
107	99	0.46	68.0	85.0	152.24	2.071	1.469
108	99	0.30	68.0	85.0	137.87	2.563	1.694
109	99	0.82	82.4	40.0	167.55	1.598	2.053
110	99	0.46	82.4	40.0	155.83	1.817	2.545
111	99	0.30	82.4	40.0	139.55	1.859	2.853
112	99	0.82	82.4	55.0	161.62	1.593	1.788
113	99	0.46	82.4	55.0	159.94	1.857	2.084
114	99	0.30	82.4	55.0	138.05	2.148	2.774
115	99	0.82	82.4	70.0	163.56	1.743	1.578
116	99	0.46	82.4	70.0	156.28	1.966	1.725
117	99	0.30	82.4	70.0	127.82	2.192	2.249
118	99	0.82	82.4	85.0	170.45	1.813	1.432
119	99	0.46	82.4	85.0	159.23	2.159	1.599
120	99	0.30	82.4	85.0	133.00	2.655	2.071
121	99	0.82	96.8	40.0	161.79	1.772	2.692
122	99	0.46	96.8	40.0	154.07	2.047	3.572
123	99	0.30	96.8	40.0	146.64	2.327	5.057
124	99	0.82	96.8	55.0	159.27	1.924	2.335
125	99	0.46	96.8	55.0	158.38	2.129	2.809

Table B1 (continued)

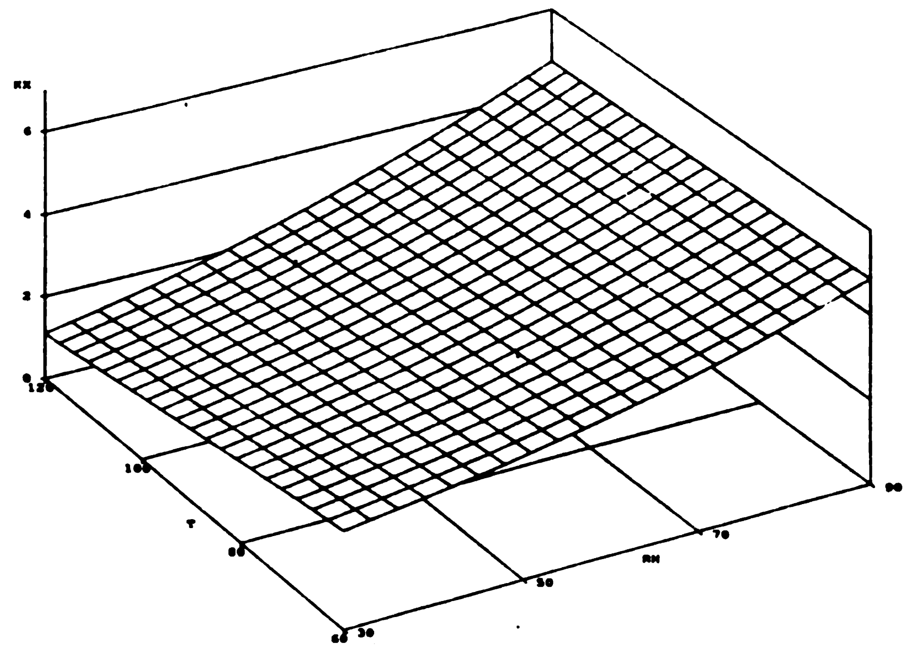
No.	V cfm/in^2	SZ in^2	T °F	RH %	OMC %	k_x -	k_t -
126	99	0.30	96.8	55.0	142.73	2.383	3.522
127	99	0.82	96.8	70.0	166.61	1.908	1.820
128	99	0.46	96.8	70.0	158.50	2.045	1.979
129	99	0.30	96.8	70.0	138.16	2.401	2.648
130	99	0.82	96.8	85.0	162.22	2.177	1.548
131	99	0.46	96.8	85.0	155.46	2.467	1.728
132	99	0.30	96.8	85.0	132.20	3.354	2.428
133	99	0.82	111.2	40.0	162.00	1.838	3.162
134	99	0.46	111.2	40.0	164.54	1.681	2.548
135	99	0.30	111.2	40.0	130.73	2.018	5.165
136	99	0.82	111.2	55.0	161.44	1.930	2.904
137	99	0.46	111.2	55.0	149.56	2.103	3.610
138	99	0.30	111.2	55.0	129.26	3.000	5.556
139	99	0.82	111.2	70.0	159.82	1.895	2.043
140	99	0.46	111.2	70.0	155.96	2.270	2.568
141	99	0.30	111.2	70.0	130.60	3.637	5.105
142	99	0.82	111.2	85.0	166.16	2.328	1.707
143	99	0.46	111.2	85.0	155.17	2.826	1.940
144	99	0.30	111.2	85.0	130.92	4.372	3.359

APPENDIX C

RELATIONSHIP BETWEEN THE CONSTANTS (k_x and k_t) AND THE INDEPENDENT VARIABLES (OMC, T, RH, SZ, AND V)

APPENDIX C

Figure C1 The relationship between the constants (k_x and k_t) and the independent variables is presented with three dimension graphs for the fixed bed drying experiment.



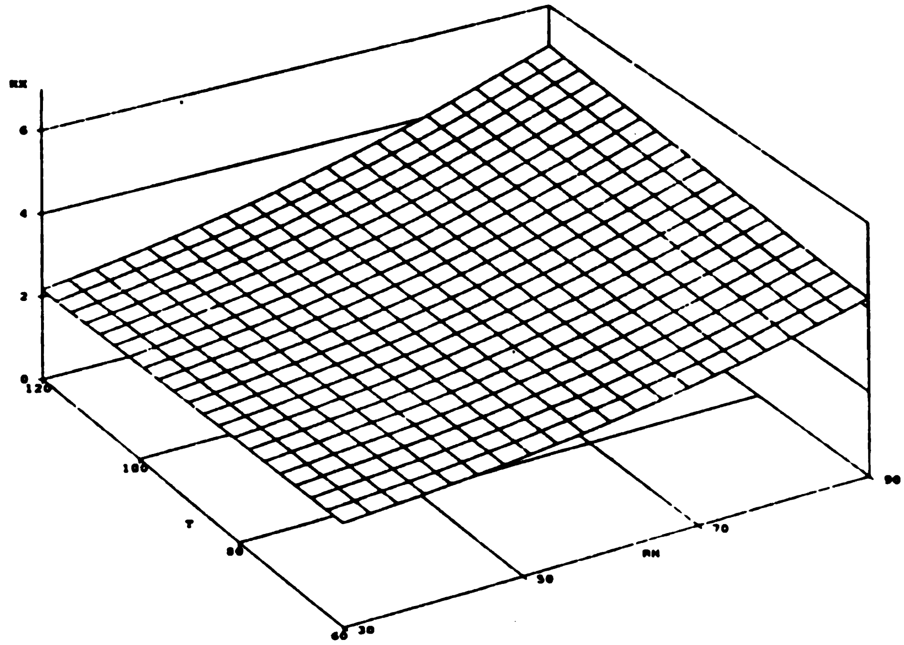
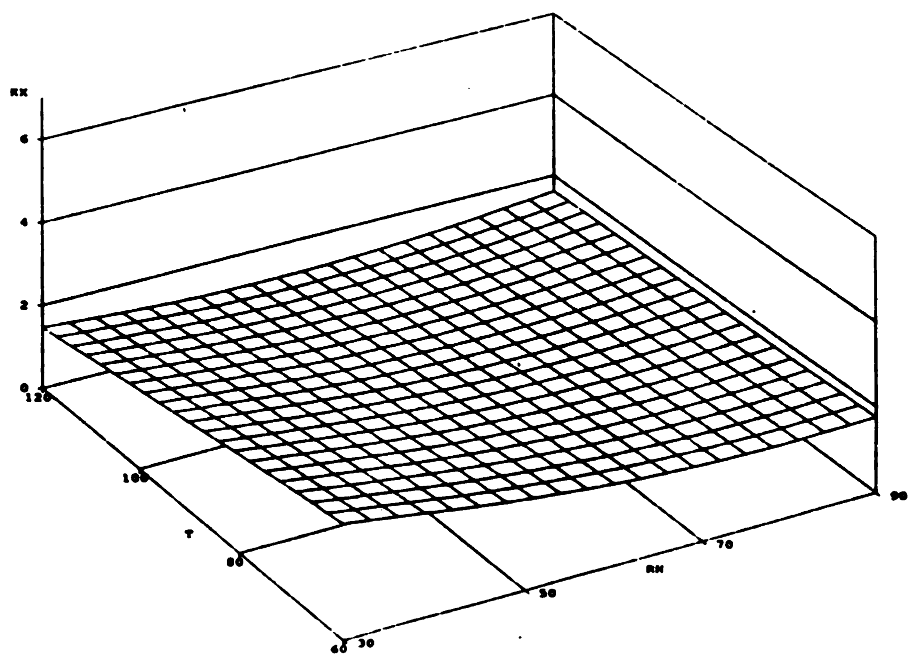


Figure C1 (continued)

V = 42.44, SZ = 0.82, MC = 144



V = 42.44, SZ = 0.82, MC = 166

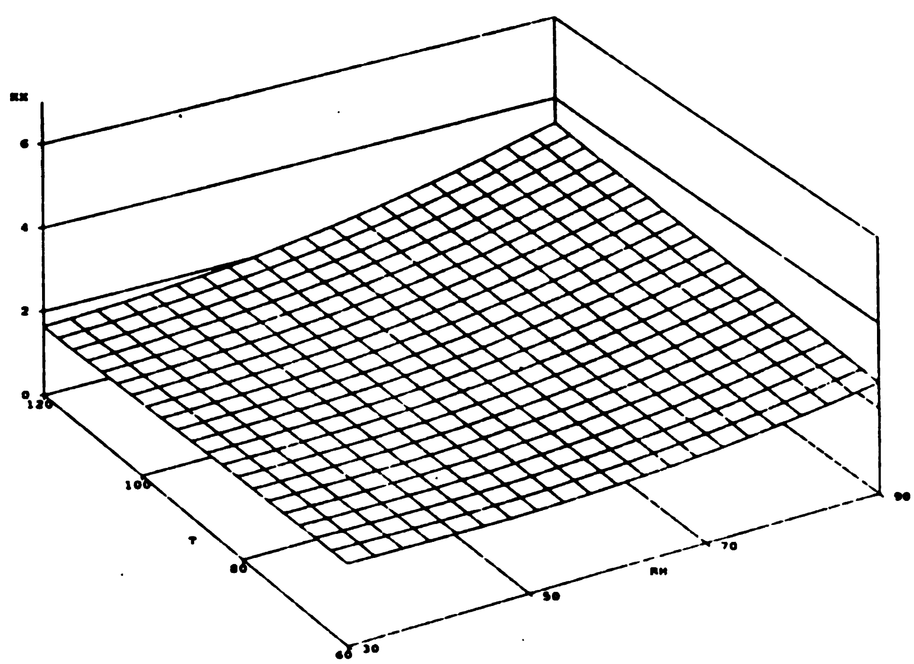
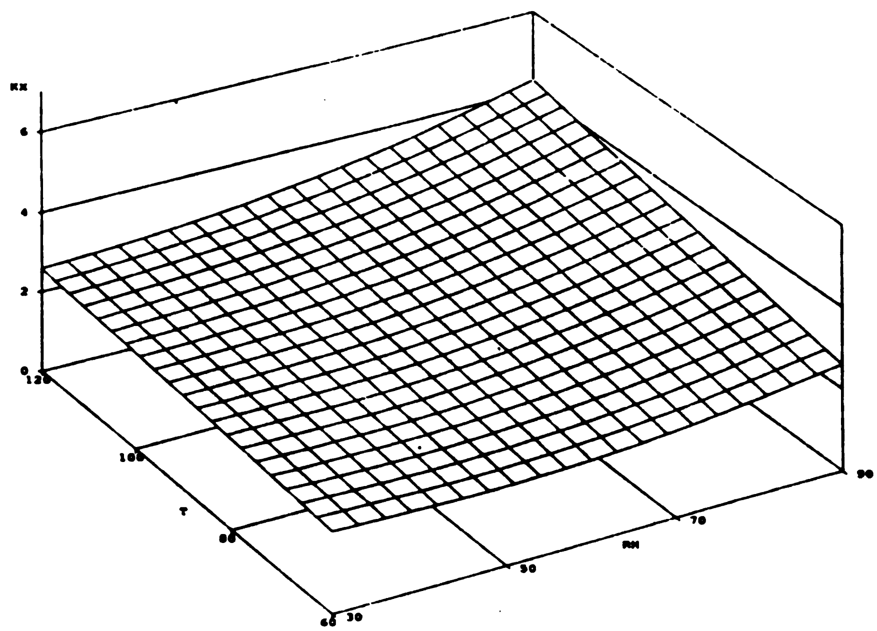


Figure C1 (continued)

V = 99.03, SZ = 0.30, MC = 144



V = 99.03, SZ = 0.30, MC = 166

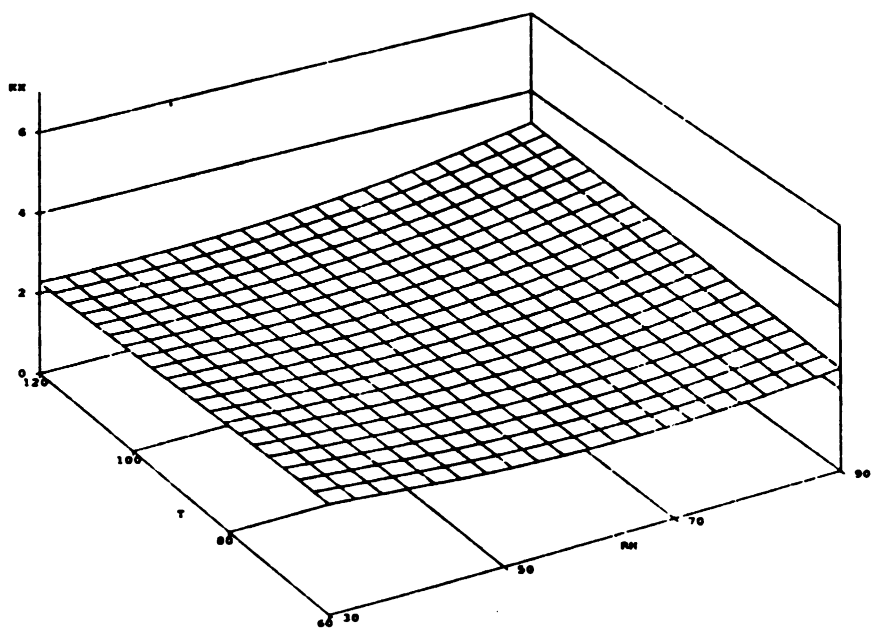
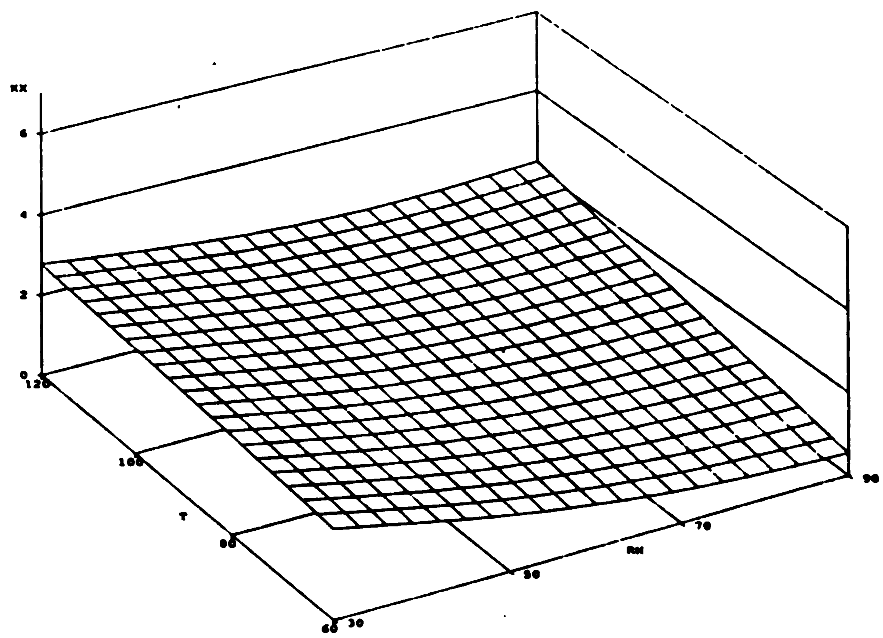


Figure C1 (continued)

V = 99.03, SZ = 0.82, MC = 144



V = 99.03, SZ = 0.82, MC = 166

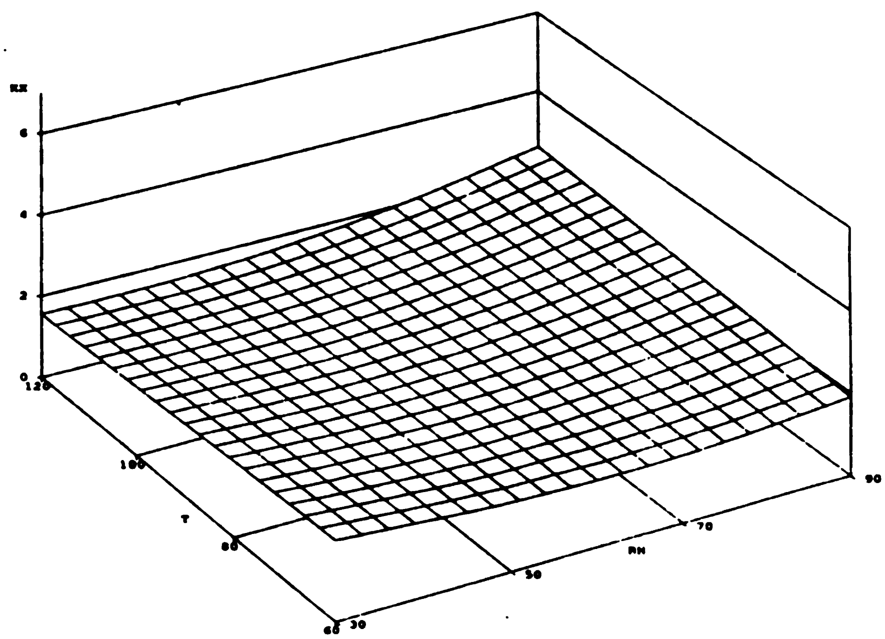
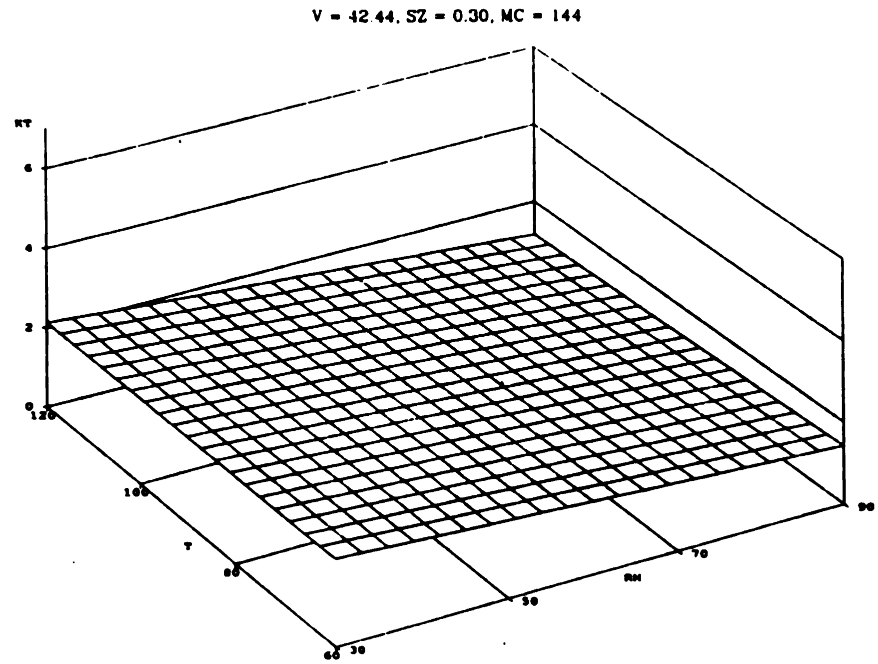


Figure C1 (continued)



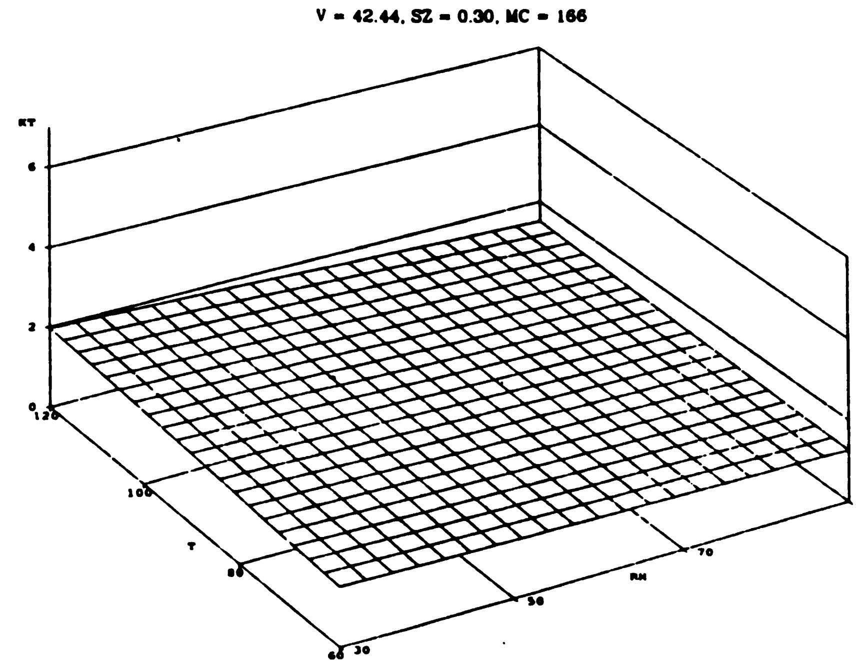
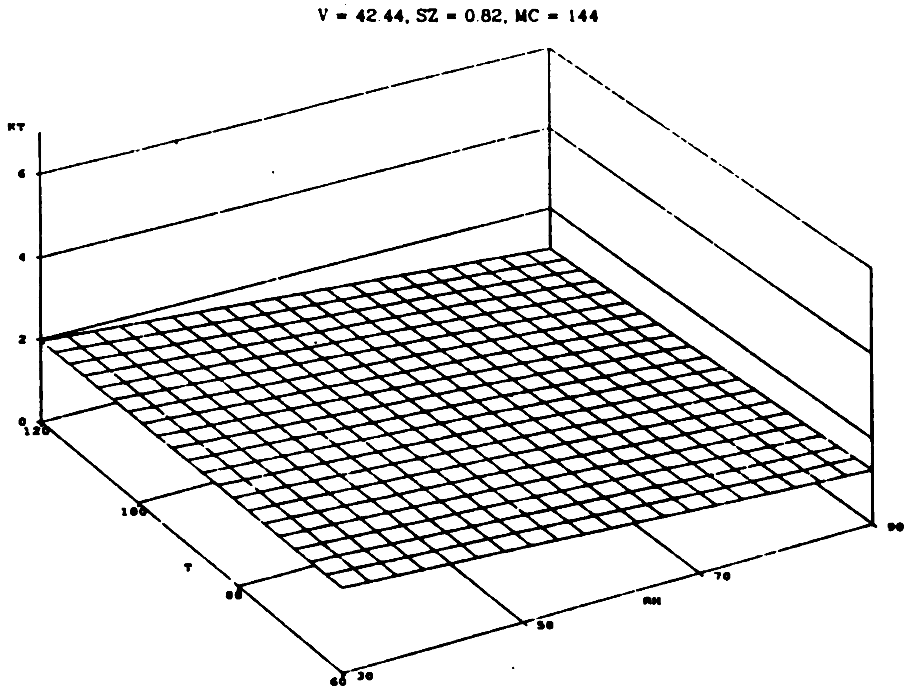


Figure C1 (continued)



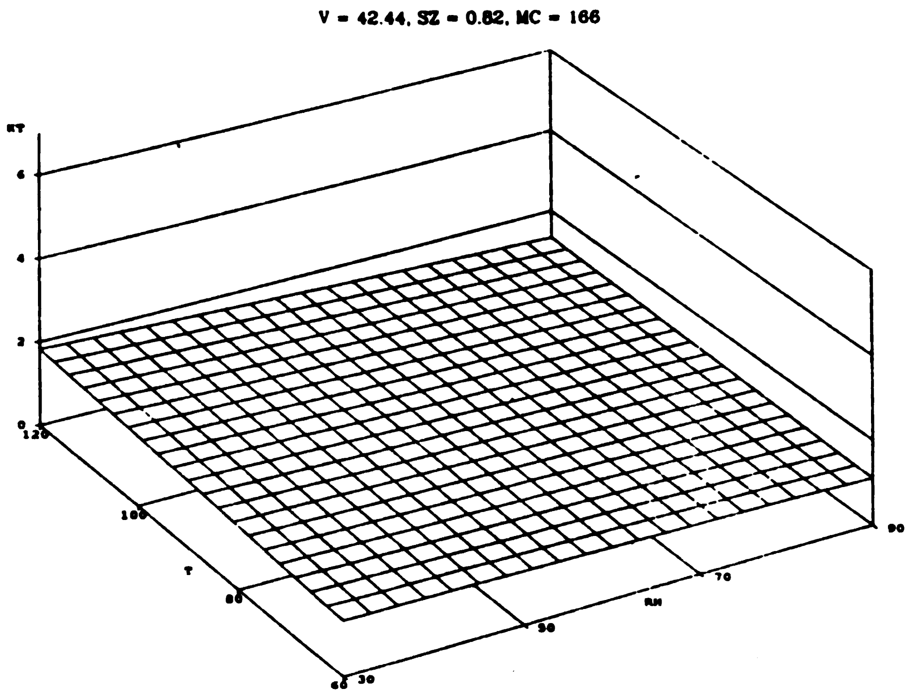
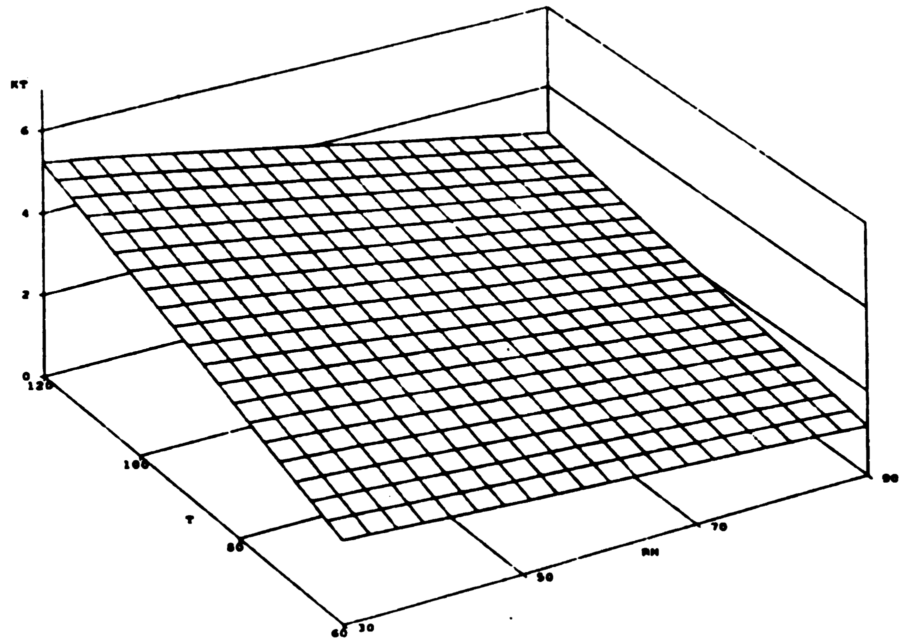


Figure C1 (continued)

V = 99.03, SZ = 0.30, MC = 144



V = 99.03, SZ = 0.30, MC = 166

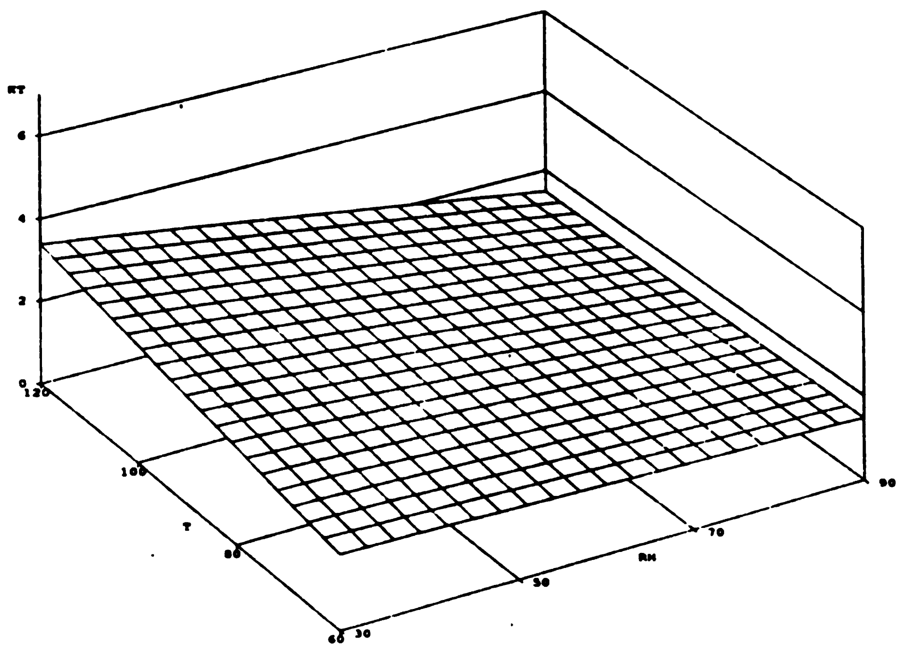
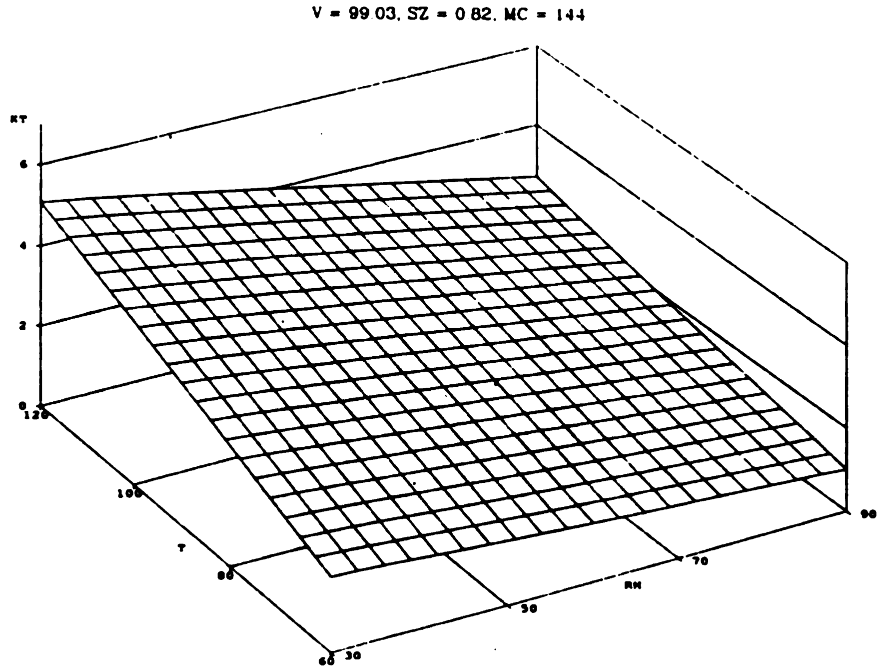
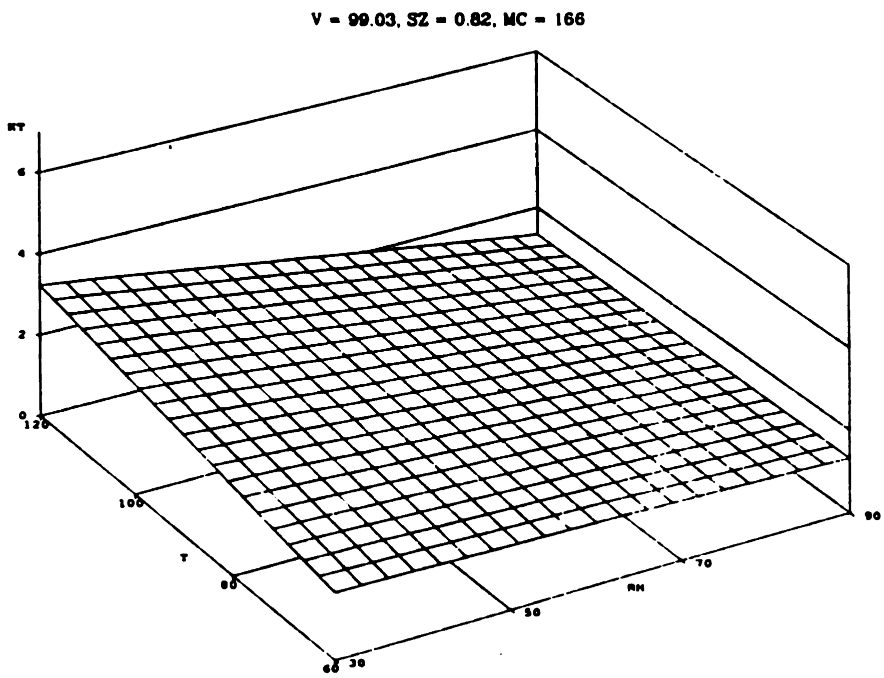


Figure C1 (continued)





APPENDIX D

LISTING OF THE COMPUTER PROGRAM "CHIP DRY"

APPENDIX D

The listings of the computer program "CHIP DRY".

```
C        PROGRAM REG_MAIN

C       FIXED BED WOOD CHIP DRYING MODEL
C
C       DESCRIPTION: MAIN PROGRAM FOR THE SIMULATION OF A FIXED BED DRYER
C
C       FUNCTION USED: EMC TIMEF DEPTHF RATIO
C
        INCLUDE   'FGRAPH.FI'
        CALL GRAPH  ()
        CALL REG ()
        END
C***********************************************************************
        SUBROUTINE REG()
        REAL        OMC, TEMP, RH, FLOW, SIZE, DEEP, TIME, DF, DFF, TF, TFF,
       +EMC, EMCC, DM, TM, SUMMC, AVGM,  RES, REST, RESTT, CR
        INTEGER J,K,JT,JD
        DIMENSION  XM (12,12), SH (12, 12)
        COMMON  T (15) , D(15), AVGMC(15), HV(15), AVGSH(15)
C
C       INPUT CONDITIONS OF DRYER TO BE DIMULATED
C
        WRITE (*,100)
C       OPEN (UNIT=20, FILE='MODEL', STATUS='OLD')
        OMC=150
        TEMP=78
        RH=78
        FLOW=78
        SIZE=.5
        DEEP=8
        TIME=10
        GO TO 5
    2   CONTINUE
        WRITE (*,200)
        READ (*,*) OMC
        WRITE (*,201)
        READ (*,*) TEMP
        WRITE (*,202)
        READ (*,*) RH
        WRITE (*,203)
        READ (*,*) FLOW
        WRITE (*,204)
        READ (*,*) SIZE
        WRITE(*,250)
        READ (*,*) DEEP
        WRITE (*,251)
        READ (*,*) TIME
    5   CONTINUE
        WRITE (*,255) OMC, TEMP, RH, FLOW, SIZE, DEEP, TIME
        WRITE (*,260)
        READ (*,*) J
        IF (J .EQ. 1) GOTO 10
        IF (J .EQ. 2) GOTO 20
        IF (J .EQ. 3) GOTO 30
        IF (J .EQ. 4) GOTO 40
        IF (J .EQ. 5) GOTO 50
        IF (J .EQ. 6) GOTO 60
        IF (J .EQ. 7) GOTO 70
        IF (J .EQ. 0) GOTO 80
   10   CONTINUE
```

Appendix D. (continued)

```
      WRITE (*,261)
      READ (*,*) OMC
      GOTO 5
   20 CONTINUE
      WRITE (*,262)
      READ (*,*) TEMP
      GOTO 5
   30 CONTINUE
      WRITE (*,263)
      READ (*,*) RH
      GOTO 5
   40 CONTINUE
      WRITE (*,264)
      READ (*,*) FLOW
      GOTO 5
   50 CONTINUE
      WRITE (*,265)
      READ (*,*) SIZE
      GOTO 5
   60 CONTINUE
      WRITE (*,266)
      READ (*,*) DEEP
      GOTO 5
   70 CONTINUE
      WRITE (*,267)
      READ (*,*) TIME
      GOTO 5
   80 CONTINUE
C
C     COMPUTE TIME FACTOR (TFF), DEEP FACTOR (DFF) AND EMC
C
      TFF=TF (OMC, TEMP, RH, FLOW, SIZE)
      DFF=DF (OMC, TEMP, RH, FLOW, SIZE)
      EMCC= EMC (TEMP, RH)
      REST= RES (SIZE,FLOW)
      RESTT = REST * DEEP/ 12
C
C     GO THROUGH DEEP LOOP
C
      DELX = DEEP / 10
      DM = 0
      JD = 0
      DO 81 I=1, 11
      JD=JD+1
      D(JD) = DM
      DM = DM + DELX
   81 CONTINUE
C
C     TIME LOOP
C
      DELT = TIME / 10
      TM=0
      JT=0
      DO 82 I=1, 11
      JT = JT + 1
      T(JT) = TM
      TM = TM + DELT
   82 CONTINUE
C
C     DEEP LOOP
C
      WRITE (*,212) (T(I), I=1, 11)
      DO 89 I=1, 11
C
C     TIME LOOP
C
```

Appendix D. (continued)

```
      DO 88 J=1, 11
C      WRITE (*,*) TFF, DFF, EMCC
C
C     COMPUTE MOISTURE RATIO FOR PRINT POINTS
C
      RATIO =DFF**D(I) /((DFF**D(I))+(TFF**T(J))-1)
C
C     CONVERT MOISTURE RATIO TO MOISTURE CONTENT
C
      DBMC=DBMCC (RATIO, EMCC, OMC)
      SH (I,J) = SHRINK (DBMC)
      XM (I,J) =DBMC
   88 CONTINUE
      WRITE (*,211) D(I), (XM (I, JK), JK=1,11)
   89 CONTINUE
C
C     CALCULATE AVERAGE MC AND HEATING VALUE
C
      DO 91 J=1, 11
        SUMMC=0
        SUMSH=0
      DO 90 I=1, 11
        SUMMC=XM(I,J)+SUMMC
        SUMSH=SH(I,J)+SUMSH
   90 CONTINUE
        AVGM=SUMMC/11
        AVGSH=SUMSH/11
        AVGMC(J)=AVGM
        HV(J)=XHV (AVGM)
   91 CONTINUE
      WRITE (*,214)  (AVGMC(I),I=1,11)
      WRITE (*,215)  (HV(I),I=1,11)
      WRITE (*,216)  (AVGSH(I),I=1,11)
      WRITE (*,217)  RESTT
C
C     CHECK IF NEED ANOTHER CALCULATION
C
      WRITE (*,300)
      READ (*,*) K
      IF (K .EQ. 1) GOTO 5
C
C     FORMATE
C
  100 FORMAT (////, 15X,'WELCOME TO USE CHIP-DRY PROGRAM !'
     +     ///,10X,'DEAR USER:'
     +      //, 10X,'THIS PROGRAM IS DESIGNED TO CALCULATE THE MOISTURE'
     +       /, 10X,'CONTENT DISTRIBUTION OF WOOD CHIPS IN A FIXED  BED'
     +       /, 10X,'DURING A FORCED AIR DRYING  PROCESS.  TO  USE THIS'
     +       /, 10X,'MODEL PROPERLY, THE ORIGINAL WOOD CHIP CONDITIONS'
     +       /, 10X,'AND DRYING CONDITIONS SHOULD BE PREPARED FOR THE'
     +       /, 10X,'CALCULATION.')
  200 FORMAT (//,10X,'(1) ORIGINAL MOISTURE CONTENT    (%) = '\)
  201 FORMAT  (/,10X,'(2) INLET AIR TEMPERATURE        (F) = '\)
  202 FORMAT  (/,10X,'(3) INLET AIR RELATIVE HUMIDITY  (%) = '\)
  203 FORMAT  (/,10X,'(4) INLET AIR FLOW RATE    (FT3/HR) = '\)
  204 FORMAT  (/,10X,'(5) WOOD CHIP SIZE               (#) = '\)

  250 FORMAT (//,10X,'THE FOLLOWING VALUES INDICAT THE SPECIFIC'
     +         /,10X,'POINT IN THE DRYER FOR THE CALCULATION.'
     +        //,10X,'(1) THE DEPTH (LET BOTTOM = 0) (IN) = '\)
  251 FORMAT (//,10X,'(2) THE DRYING TIME           (HR) = '\)
  255 FORMAT (//,10X,'THE CONDITIONS ARE LIST IN THE FOLLOWING TABLE,',
     +         /,10X,'PLEASE CHECK IT AGAIN BEFORE THE CALCULATION.',
     +        //,10X,'(1) ORIGINAL MOISTURE CONTENT    (%) = ',F9.4,
     +         /,10X,'(2) INLET AIR TEMPERATURE        (F) = ',F9.4,
```

Appendix D. (continued)

```
     +          /,10X,'(3) INLET AIR RELATIVE HUMIDITY (%) = ',F9.4,
     +          /,10X,'(4) INLET AIR FLOW RATE    (FT3/HR) = ',F9.4,
     +          /,10X,'(5) WOOD CHIP SIZE              (#) = ',F9.4,
     +          /,10X,'(6) THE DEPTH (LET BOTTOM = 0) (IN) = ',F9.4,
     +          /,10X,'(7) THE DRYING TIME            (HR) = ',F9.4)
  260 FORMAT (//,10X,'PLEASE TYPE THE NUMBER (1-7) FOR THE VARIABLE',
     +          /,10X,'YOU WANT TO MAKE MODIFICATION AND ENTER (0)',
     +          /,10X,'IF EVERY VALUE IS OK: '\)
  261 FORMAT (/,10X,'(1) ORIGINAL MOISTURE CONTENT   (%) = '\)
  262 FORMAT (/,10X,'(2) INLET AIR TEMPERATURE       (F) = '\)
  263 FORMAT (/,10X,'(3) INLET AIR RELATIVE HUMIDITY (%) = '\)
  264 FORMAT (/,10X,'(4) INLET AIR FLOW RATE    (FT3/HR) = '\)
  265 FORMAT (/,10X,'(5) WOOD CHIP SIZE              (#) = '\)
  266 FORMAT (/,10X,'(6) THE DEPTH (LET BOTTOM = 0) (IN) = '\)
  267 FORMAT (/,10X,'(7) THE DRYING TIME            (HR) = '\)
C 200 FORMAT (///,52X,F9.4,/,52X,F9.4,/,52X,F9.4,/,52X,F9.4,/,52X,F9.4,
C    +           /,52X,F9.4,/,52X,F9.4)
  210 FORMAT (///7(F7.2))
  213 FORMAT(/15F7.2)
  300 FORMAT (//,10X,'DO YOU WANT TO MAKE ANOTHER CALCULATION?',
     + //,20X,'IF YES, TYPE "1"',//,20X,'IF NO,  TYPE "0" ',\)
  350 FORMAT (//,10X,'UNDER ABOVE CONDITIONS,',
     +          /,10X,'MOISTURE CONTENT (DRY BASIS) = ',F9.4,' %')

  211 FORMAT (F5.1,3X, 11(F6.1))
  212 FORMAT (/,' D / T',2X, 11(F6.1))
  214 FORMAT (/,' AVGMC',2X,11(F6.1))
  215 FORMAT (/,' AVGHV',2X,11(F6.0))
  216 FORMAT (/,' AVGSH',2X,11(F6.1))
  217 FORMAT (/,' AIRFLOW RESISTANCE OF DRYER =',2X,F6.2,2X,'IN.WATER')
      RETURN
      END
C**************************************************************************
      SUBROUTINE GRAPH ()
      INCLUDE   'FGRAPH.FD'

      INTEGER*2      dummy,  DUMMY1 , DUMMY3
      INTEGER*2      coord(3,2,2)
      INTEGER*4      DUMMY4
      CHARACTER*25  text1,TEXT2, TEXT3,TEXT4
      RECORD / xycoord  /     xy, xy1
      RECORD / rccoord  /     curpos
      RECORD / videoconfig / vc

      DATA text1 / '          CHIP-DRY          ' /
      DATA TEXT2 / '    Version 1.0, 1991     '/
      DATA TEXT3 / ' Department of Forestry   '/
      DATA TEXT4 / 'Michigan State University'/
C
C     Find graphics mode.
C
      IF( setvideomode( $MAXRESMODE ) .EQ. 0 )
     +   STOP 'Error:  cannot set graphics mode'
      CALL getvideoconfig( vc )

C
C     Determine physical (pixel) coordinates windows.
C
      coord(3,1,1) = 0
      coord(3,1,2) = 0
      coord(3,2,1) = vc.numxpixels - 1
      coord(3,2,2) = vc.numypixels - 1
C
C     Label windows and frame with rectangles.
C
         dummy  = setcolor( 8 )
```

Appendix D. (continued)

```
          CALL settextposition( 13, 23, curpos )
          CALL outtext( text1 )
          CALL setviewport(  coord(3,1,1), coord(3,1,2) ,
     +                       coord(3,2,1), coord(3,2,2) )
          CALL getviewcoord( coord(3,1,1), coord(3,1,2), xy  )
          CALL getviewcoord( coord(3,2,1), coord(3,2,2), xyl )
          dummy = rectangle( $GFILLINTERIOR, XY.xcoord, xy.ycoord,
     +                       xyl.xcoord, xyl.ycoord )
C
C         Display rectangles in normal and magnified views.
C
            CALL setviewport( coord(3,1,1), coord(3,1,2) ,
     +                        coord(3,2,1), coord(3,2,2) )
            dummy1 = setwindow( .TRUE., 0.0, 0.0, 1000.0, 1000.0 )
            dummy1 = setcolor (2)
            dummy1 = rectangle_w( $GBORDER, 0,0,1000,1000)
            dummy1 = rectangle_w( $GBORDER, 10,10,990,990)
            dummy1 = setcolor (1)
            dummy1 = rectangle_w( $GBORDER, 295,295,705,705)
            dummy1 = rectangle_w( $GFILLINTERIOR, 300,300,700,700)
                DUMMY4 = SETBKCOLOR($BLUE)
                DUMMY3 = SETTEXTCOLOR (14)
          CALL settextposition( 13, 28, curpos )
          CALL outtext( text1 )
                DUMMY3 = SETTEXTCOLOR (6)
          CALL settextposition( 15, 28, curpos )
          CALL outtext( text2 )
                DUMMY3 = SETTEXTCOLOR (7)
          CALL settextposition( 18, 28, curpos )
          CALL outtext( text3 )
          CALL settextposition( 19, 28, curpos )
          CALL outtext( text4 )

      READ (*,*)
      dummy = setvideomode( $DEFAULTMODE )
      RETURN
      END
C***********************************************************************
C       SUBROUTINE DRAW ()
C       INCLUDE  'FGRAPH.FD'

C***********************************************************************
      FUNCTION EMC (TEMP, RH)
C
C     DESCRIPTION: TO COMPUTE EMC FOR WOOD
C
      T=TEMP
      H=RH/100
      B=.791+.000463*T-.000000844*T*T
      B1=6.34+.000775*T-.0000935*T*T
      B2=1.09+.0284*T-.0000904*T*T
      W=330+.452*T+.00415*T*T
      EMC=1800/W*(B*H/(1-B*H)+(B1*B*H+2*B1*B2*B*B*H*H)/(1+B1*B*H+
     +     B1*B2*B*B*H*H))
      RETURN
      END
C************************************************************************
      FUNCTION DF (OMC, TEMP, RH, FLOW, SIZE)
C
C     TO COMPUTE DEEP CONSTANT
C
      DATA BX0, BX1, BX1X1 /
     +-10.37904712, -.31961232, .000171958/
      DATA BX2, BX1X2, BX2X2 /
     +24.27485473,-0.02694957, 6.4446486/
      DATA BX3, BX1X3 /
```

Appendix D. (continued)

```
     +-.30970527, .004217686/
      DATA BX4, BX1X4, BX2X4, BX3X4, BX4X4 /
     +.27417927, -.000774058,-.63756348, .000300598, .000407581/
      DATA BX5, BX1X5, BX2X5, BX3X5, BX4X5, BX5X5 /
     +.24743239, .001965759, -.18261486, .001790884, -.001618642,
     +-.000950171/
      DATA B1B2B4, B1B3B5, B2B4B5/
     +0.000683442, -.000025603, .003455997/
      X1 = FLOW
      X2 = SIZE
      X3 = TEMP
      X4 = RH
      X5 = OMC
      DF =  BX0 + BX1*X1 + BX1X1* X1*X1
     ++ BX2*X2 + BX1X2*X1*X2 + BX2X2*X2*X2
     ++ BX3*X3 + BX1X3*X1*X3
     ++ BX4*X4 + BX1X4*X1*X4 + BX2X4*X2*X4 + BX3X4*X3*X4 + BX4X4*X4*X4
     ++ BX5*X5 + BX1X5*X1*X5 + BX2X5*X2*X5 + BX3X5*X3*X5 + BX4X5*X4*X5
     ++ BX5X5*X5*X5
     ++ B1B2B4*X1*X2*X4 + B1B3B5*X1*X3*X5 + B2B4B5*X2*X4*X5
      RETURN
      END
C***********************************************************************
      FUNCTION TF (OMC, TEMP, RH, FLOW, SIZE)
C
C     TO COMPUTER TIME CONSTANT
C
      DATA BX0, BX1, BX1X1 /
     +28.59735622, -.41132228, .000231489/
      DATA BX2 /
     +-.29912980/
      DATA BX3, BX1X3 /
     + -.28028153, .005371459/
      DATA BX4, BX1X4, BX3X4 /
     +-.07582158, .000369705, .000195583 /
      DATA BX5, BX1X5, BX3X5, BX4X5 /
     +-.15436309, .002129835, .001624148, .000374406 /
      DATA B1B3B4, B1B3B5 /
     +-.000006626, -.000029201 /
      X1 = FLOW
      X2 = SIZE
      X3 = TEMP
      X4 = RH
      X5 = OMC
      TF =  BX0 + BX1*X1 + BX1X1* X1*X1
     ++ BX2*X2
     ++ BX3*X3 + BX1X3*X1*X3
     ++ BX4*X4 + BX1X4*X1*X4 + BX3X4*X3*X4
     ++ BX5*X5 + BX1X5*X1*X5 + BX3X5*X3*X5 + BX4X5*X4*X5
     ++ B1B3B4*X1*X3*X4 + B1B3B5*X1*X3*X5
      RETURN
      END
C***********************************************************************
      FUNCTION DBMCC (RATIO, EMCC, OMC)
      DBMCC =  RATIO * (OMC - EMCC) + EMCC
      RETURN
      END
C***********************************************************************
      FUNCTION XHV (XMC)
      XHV = 9000 - (.0114*9000*100/(1*100/XMC+1))
      RETURN
      END
C***********************************************************************
      FUNCTION RES (SIZE, FLOW)
      CR =.04521114 - 0.03234395 * SIZE
      RES = CR * EXP (0.03108 * FLOW)
      RETURN
      END
C***********************************************************************
      FUNCTION SHRINK (XMC)
      SHRINK = 0.152225 * EXP (-0.0521 * XMC)
      RETURN
      END
```

APPENDIX E

RESULTS OF LARGE SCALE TESTING EXPERIMENT AND DRYING MODEL SIMULATIONS

APPENDIX E

Table E1 Comparison of the results of testing experiment and the simulation results of the empirical drying model and the semi-theoretical drying model. Fixed bed wood chip drying condition: OMC= 133%, T=68°F, RH=73%, SZ=0.46 in^2, V=82 cfm/ft^2.

Drying time (hr)	Depth (in)	Experiment results MC(%)	Empirical model MC(%)	Theoretical model MC(%)
0	0	132.06	133.00	132.80
6	0	16.25	24.50	41.10
12	0	15.14	14.80	19.10
18	0	14.81	14.00	14.10
24	0	14.60	13.90	13.00
30	0	14.91	13.90	12.80
42	0	14.45	13.90	12.70
0	8	132.43	133.00	133.00
6	8	115.83	76.40	123.00
12	8	23.53	23.70	91.40
18	8	14.15	14.80	47.90
24	8	13.84	14.00	23.20
30	8	14.06	13.90	15.30
42	8	13.51	13.90	12.80
0	16	134.13	133.00	133.00
6	16	133.47	124.20	133.90
12	16	119.03	74.00	132.20
18	16	51.62	23.70	125.80
24	16	16.39	14.80	105.10
30	16	16.16	14.00	64.70
42	16	15.48	13.90	17.60
0	24	131.76	133.00	133.00
6	24	130.83	132.20	134.30
12	24	130.04	123.50	134.20
18	24	116.39	73.90	133.90
24	24	67.74	23.70	132.40
30	24	17.41	14.80	126.60
42	24	14.61	13.90	68.30
0	32	130.00	133.00	-
6	32	125.48	132.90	-
12	32	124.19	132.10	-
18	32	122.71	123.50	-
24	32	113.00	74.10	-
30	32	82.05	23.80	-
42	32	14.48	14.00	-
0	40	130.46	133.00	-
6	40	127.87	133.00	-
12	40	126.54	132.90	-
18	40	125.53	132.10	-
24	40	124.19	123.50	-
30	40	114.19	74.20	-
42	40	42.26	14.90	-
0	48	125.11	133.00	-
6	48	124.83	133.00	-
12	48	125.19	133.00	-
18	48	124.52	132.90	-
24	48	123.83	132.10	-
30	48	122.25	123.50	-
2	48	88.46	23.90	-

Table E2 Comparison of the results of testing experiment and the simulation results of the empirical drying model and the semi-theoretical drying model. Fixed bed wood chip drying condition: OMC= 130.7%, T=70°F, RH=70%, SZ=0.30 in^2, V=82 cfm/ft^2.

Drying time (hr)	Depth (in)	Experiment results MC(%)	Empirical model MC(%)	Theoretical model MC(%)
0	0	127.15	130.70	129.90
4	0	16.33	27.60	43.10
12	0	14.14	13.30	13.70
20	0	13.82	13.10	11.80
28	0	13.51	13.10	11.70
36	0	13.28	13.10	11.70
44	0	13.13	13.10	11.70
0	8	129.47	130.70	130.00
4	8	128.36	129.10	124.10
12	8	72.43	70.40	64.40
20	8	13.60	14.80	17.80
28	8	13.20	13.10	12.10
36	8	12.90	13.10	11.70
44	8	12.79	13.10	11.70
0	16	129.58	130.70	130.00
4	16	128.87	130.70	130.80
12	16	127.64	130.50	127.80
20	16	102.60	116.60	97.20
28	16	25.51	24.90	29.40
36	16	14.72	13.30	13.20
44	16	14.46	13.10	11.70
0	24	133.71	130.70	130.00
4	24	132.82	130.70	130.90
12	24	131.93	130.70	130.80
20	24	130.72	130.70	129.10
28	24	114.53	128.70	110.20
36	24	63.39	67.30	41.10
44	24	15.10	13.60	11.70
0	32	130.30	130.70	-
4	32	129.25	130.70	-
12	32	127.95	130.70	-
20	32	126.85	130.70	-
28	32	125.10	130.70	-
36	32	112.17	130.50	-
44	32	79.26	89.60	-
0	40	131.90	130.70	-
4	40	130.78	130.70	-
12	40	130.08	130.70	-
20	40	129.28	130.70	-
28	40	128.21	130.70	-
36	40	126.70	130.70	-
44	40	118.94	130.50	-
0	48	133.10	130.70	-
4	48	132.71	130.70	-
12	48	131.87	130.70	-
20	48	131.27	130.70	-
28	48	130.55	130.70	-
36	48	129.55	130.70	-
44	48	127.90	130.70	-

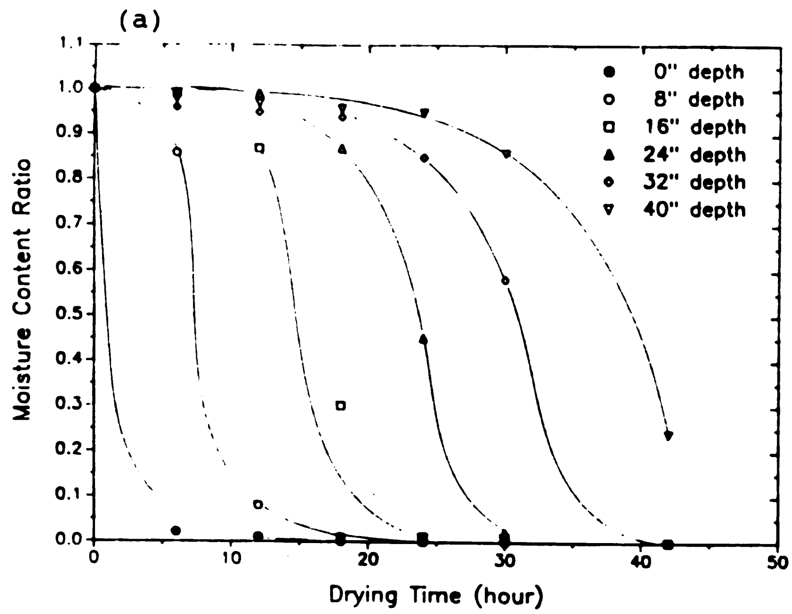
Table E3 Comparison of the results of testing experiment and the simulation results of the empirical drying model and the semi-theoretical drying model. Fixed bed wood chip drying condition: OMC= 137%, T=70°F, RH=86%, SZ=0.46 in^2, V=99 cfm/ft^2.

Drying time (hr)	Depth (in)	Experiment results MC(%)	Simulation model MC(%)	Theoretical model MC (%)
0	0	130.51	137.40	137.40
12	0	19.79	19.50	42.40
24	0	19.45	18.40	22.30
36	0	19.08	18.40	18.40
48	0	18.89	18.40	17.60
60	0	18.73	18.40	17.40
72	0	18.92	18.40	17.40
0	8	132.92	137.40	137.00
12	8	94.03	75.60	117.90
24	8	19.01	19.40	72.80
36	8	18.46	18.40	34.90
48	8	18.15	18.40	21.50
60	8	18.05	18.40	18.30
72	8	16.55	18.40	17.60
0	16	134.61	137.40	137.00
12	16	134.82	136.20	137.20
24	16	92.16	72.70	131.30
36	16	20.82	19.30	109.90
48	16	20.21	18.40	66.50
60	16	20.10	18.40	32.60
72	16	20.15	18.40	20.90
0	24	135.94	137.40	137.00
12	24	136.24	137.40	138.50
24	24	133.34	136.10	137.90
36	24	85.36	70.10	135.50
48	24	19.66	19.20	125.50
60	24	19.07	18.40	95.00
72	24	19.12	18.40	50.70
0	32	148.76	137.40	-
12	32	147.91	137.40	-
24	32	147.06	137.40	-
36	32	140.04	135.90	-
48	32	82.02	67.60	-
60	32	20.51	19.20	-
72	32	18.36	18.40	-
0	40	142.49	137.40	-
12	40	142.21	137.40	-
24	40	140.97	137.40	-
36	40	139.61	137.40	-
48	40	124.46	135.80	-
60	40	75.82	65.10	-
72	40	22.23	19.10	-
0	48	136.67	137.40	-
12	48	136.96	137.40	-
24	48	136.20	137.40	-
36	48	134.80	137.40	-
48	48	133.49	137.40	-
60	48	118.50	135.60	-
72	48	64.97	62.60	-

APPENDIX F

COMPARISON OF THE RESULTS IN THE TESTING EXPERIMENT ANDTHE RESULTS OF EMPIRICAL MODEL SIMULATION

APPENDIX F



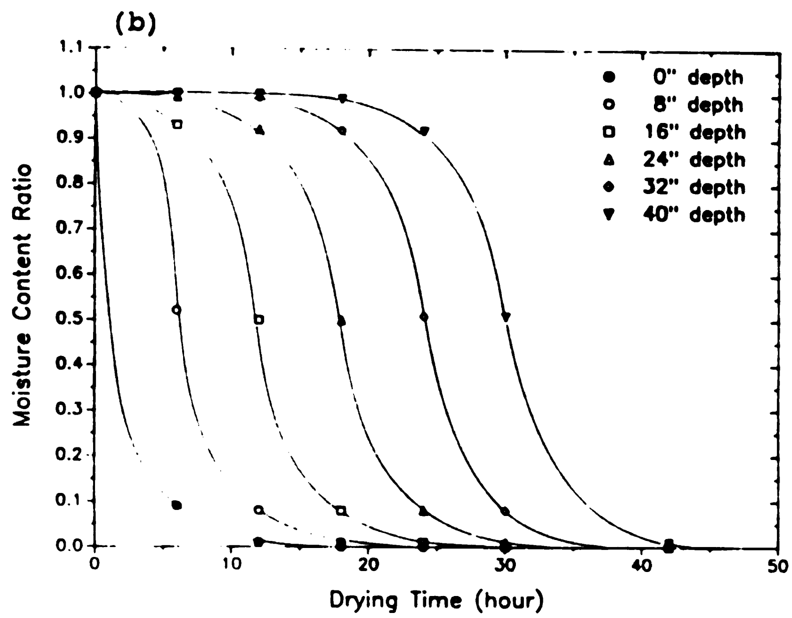
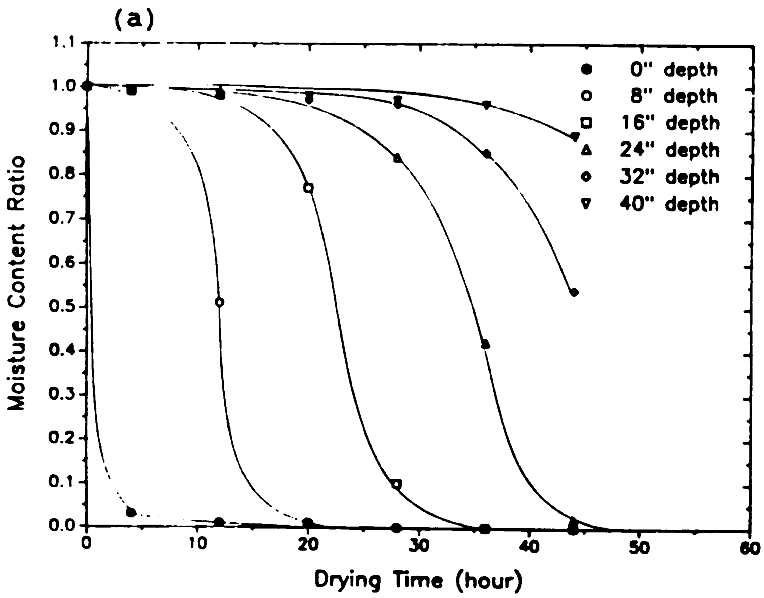


Figure F1 (a) Results of large scale testing experiment and (b) results of empirical fixed bed drying model simulation, experiment condition: OMC= 133%, T=68°F, RH=73%, SZ=0.46 in^2, V=82 cfm/ft^2.



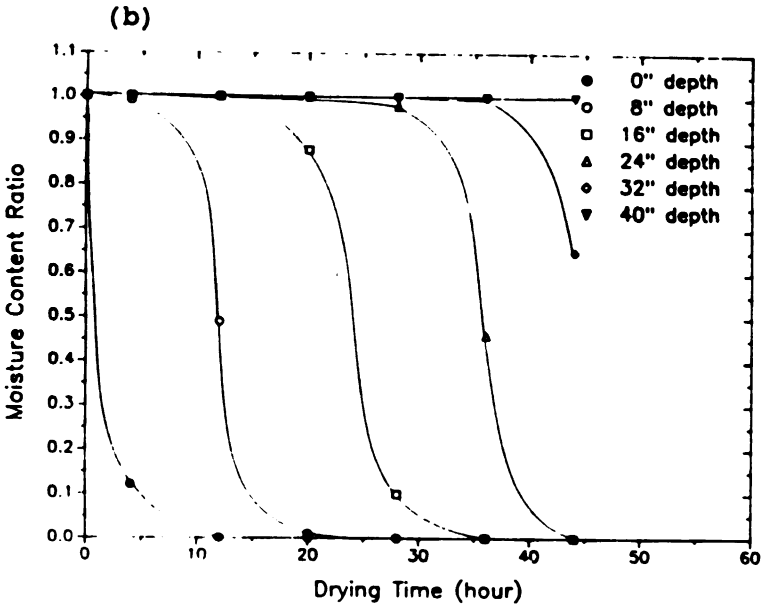


Figure E2 (a) Results of large scale testing experiment and (b) results of empirical fixed bed drying model simulation, experiment condition: OMC= 130%, T=70°F, RH=70%, SZ=0.30 in^2, V=82 cfm/ft^2.

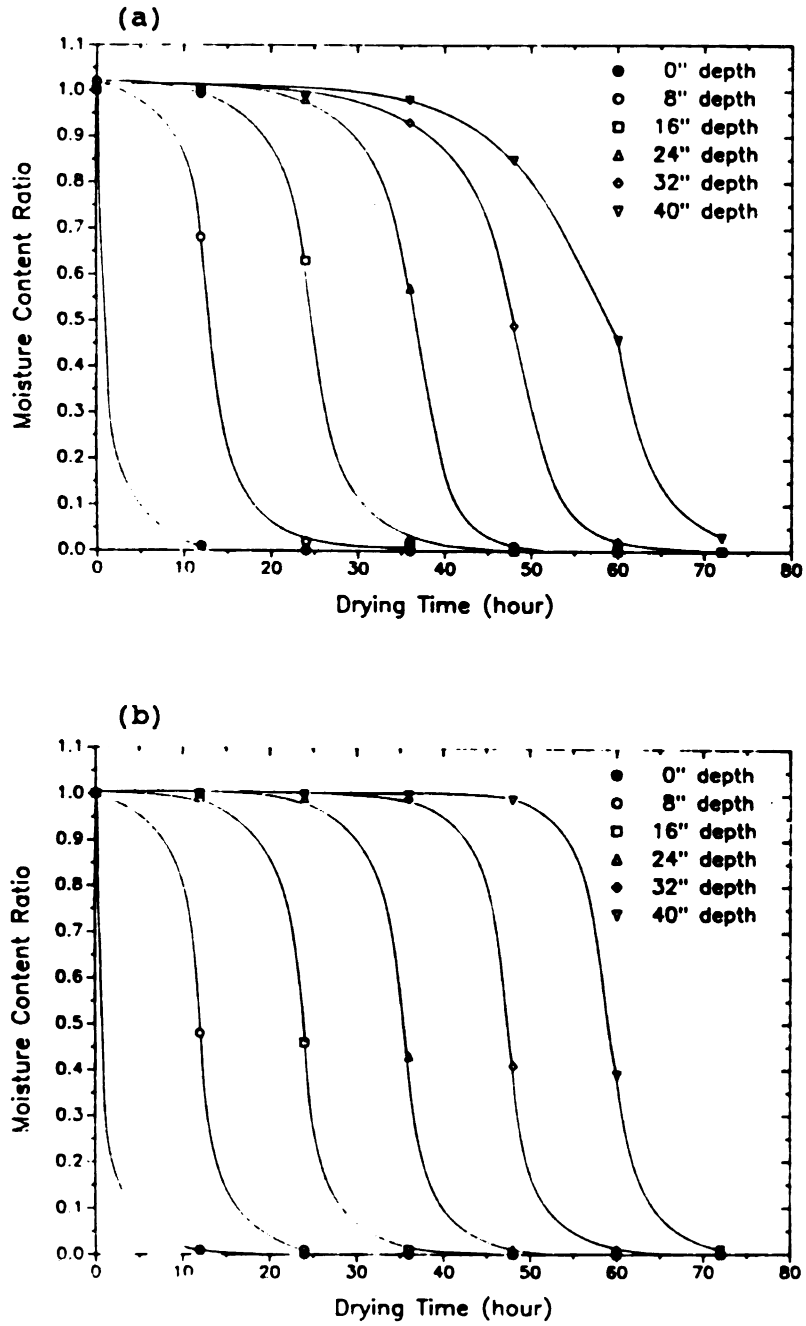


Figure F3 (a) Results of large scale testing experiment and (b) results of empirical fixed bed drying model simulation, experiment condition: OMC= 137%, T=70°F, RH=86%, SZ=0.46 in^2, V=99 cfm/ft^2.

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