FACTORS AFFECTING DRYING PERFORMANCE OF A NATURAL CONVECTION DRIER FOR DEVELOPING COUNTRIES

by

KWAN HEE RYU

B. S., Seoul National University, 1967
M. S., Seoul National University, 1972

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

Approved by :

Major professor

THIS BOOK CONTAINS NUMEROUS PAGES WITH THE ORIGINAL PRINTING BEING SKEWED DIFFERENTLY FROM THE TOP OF THE PAGE TO THE BOTTOM.

THIS IS AS RECEIVED FROM THE CUSTOMER.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The problem of grain drying is becoming increasingly important in developing countries, especially in tropical areas. Effective grain drying is necessary not only to minimize post-harvest losses but also to preserve grain quality. Furthermore, it makes possible increased production through multipple cropping where the off-season crop is harvested in humid weather.

Under humid conditions, it is necessary that some source of added heat energy be provided to supply the heat of vaporization. In developed countries, driers for that purpose have been studied and developed thoroughly. For instance, large centralized drying systems have been used in developed countries such as Europe, the United States and Canada while in some other developed countries such as Japan well-developed and sophisticated driers at farm and/or village levels have been used. These driers, however, have not been introduced succesfully to the developing countries because of lack of road facilities, small land holdings of farmers, their low income and poor technical knowledge, etc.

Several attempts have been made to develop a simple and low-cost drier for developing countries. But, there is no adequate drier for practical use by average farmers in developing countries. "Brook" drier (Brook, 1964), which is basically a batch drier, is simple enough to operate and to build on farm using native materials by farmers themselves. It has a flue as a heat source and utilizes buoyancy force of natural convection as a driving force to move heated air through the grain without any mechanical device. It has been known that the drying floor should be 2 to 2.5 ft above the heat source to prevent the grain in the center from getting scorched, and about one day is needed to dry shelled maize of 4 in. thickness with a drying temperature of 130 ^{o}F(Webb, 1969). Unfortunately, however, there has been no systematic study about the design criteria and performance of "Brook" drier.

Therefore, the purpose of this study is to further develop "Brook" drier for the unskilled farmers in developing countries. The approach proposed in this project is to evaluate and modify a "Brook" drier in order to improve its drying performance.

LITERATURE REVIEW

Grain Drying

Drying is practiced to prevent germination of seeds, to retain maximum quality of the grain, and to reach a level of moisture which does not allow the growth of bacteria and fungi and considerably retards the development of mites and insects. It is essential that food grains be dried quickly and yet effectively. Basically, there are two types of drying, natural and artificial.

Natural methods of drying make use of exposure to the sun and/or the desiccating effect of air currents in fields, farms or villages, but also requires time and effort by man to spread and later collect the produce. In this method, care must be taken to avoid too rapid drying or overdrying and to minimize excessive movement of the grains, which causes breakage or damage to the seed coat, and to eliminate dust and dirt, which accelerates deterioration by permitting an increase in moisture content and fungal contamination. There are three methods for natural drying, which are the most commenly used in tropical areas.

(1) Pre-harvest drying : It is the simplest way of natural drying, which leaves the grain in the field until the moisture content has dropped sufficiently low for storage, e.g., maize cobs are left on the standing plant for 3 to 4 weeks after maturing before they are harvested. Produce left on the plant to dry loses moisture at a rate determined by the drying potential of the air and the reservoir of moisture in the immediate environment of the parent plant. Where, however, the rate of drying is slow after maturity of the crop and especially where the grains or kernels are damaged by pests, it is preferable to remove the produce from the plant and speed up the rate

of drying.

(2) Post-harvest drying before threshing : This method of natural drying is done on the unthreshed crop. The crop is sundried by leaving harvested stalks in the field for several days in loose bundles or shocks. This method of drying facilitates threshing but additional sundrying of the threshed grain is sometimes necessary.

(3) Post-harvest drying after threshing : The produce is spread on a flat piece of ground or on suitable material on the ground to be dried by the sun and natural air currents. The produce should be moved while it is drying in order to assist even drying and should be covered and carried indoors in the evening or before rain. It is at this stage that the produce can become infested and also cracked or broken due to excessive and careless handling. Breakage of the grains is minimized by the use of trays or mats. This floor drying with its demand for large floor areas and labor for spreading, stirring and collecting paddy grain is no longer adequate for the increased grain yields.

Whatever the method of natural drying is, the common drawbacks are as follows :

(1) Only effective during seasons of relatively warm, clear and dry weather.

(2) Quality loss due to the slow rate of drying and the sudden changes of environmental conditions.

Artificial drying uses the air of ambient temperature and some mechanical means of moving it through the produce, or the air heated above ambient temperature with the mechanical means of moving it through the produce with the purpose of increasing the rate of drying. The artificial driers available on the market can be classified as follows :

(1) Deep-bed or deep-layer drier : the grain of 9 to 13 feet depth can be

dried. The grain is usually dried in a storage bin, so it doesn't need to be moved out of the drier. An airflow rate of 5 to 10 cfm/bu is required if drying is carried out with unheated air. However, if relative humidity is over 70 %, heated air is required, and the airflow can be as low as 3 cfm/bu.

(2) Batch or Bin drier : The produce to be dried is placed in a bin or container, and air is forced through the mass until dry. The system is simple but resistance to airflow limits the depth for highly resistant materials since adequate airflow rates are possible only with excessively large power units. Usually, the depth of grain is limited to 3 feet and an airflow rate of 15 to 40 cfm/bu is being used.

(3) Column drier : The material is placed in a hopper and flows by gravity between the perforated retaining walls and is discharged at the bottom by a continuously operating metering valve. It takes advantage of the gravity flow of grain through the drier to reduce the amount of machinery in the drier itself.

Drying Theory

The process of drying involves the transfer of moisture in the form of water vapor from the material to be dried to the surrounding air. A moist substance in contact with air will tend to give up moisture until a point is reached where the moisture content of the substance is balanced by that of the surrounding air. At this point evaporation can no longer take place and drying will cease. This process is reversible, since a dry material in contact with moist air will tend to absorb moisture from the air until a similar balance is reached. The moisture at this point is known as the equilibrium moisture content.

The equilibrium moisture content is a very important property which must be considered when dealing with drying and storage problems because grains are hygroscopic materials.

Many researchers have investigated the relationship between the equilibrium moisture content of grain and the relative humidity of ambient air at a constant temperature, and have developed isotherm equations.

For example,

$$1 - rh = e^{-c\ T\ Me^{n}} \text{ ----- Henderson (1966)} \qquad (1)$$

$$\ln (rh) = -A/R\ T\ e^{-b\ Me} \text{ ---- Chung (1967)} \qquad (2)$$

where rh : relative humidity in decimal

Me : equilibrium moisture content in % (d.b.)

T : air temperature in ^{o}R

R : gas contant

c,n, A and B are constants

In drying process, energy in the form of heat is required to convert water into water vapor. Any material from which water is evaporating, and to which no external source of heat is applied, will be cooled by the evaporation process. The application of heat from an external source is thus necessary to ensure that drying can continue. The rate at which drying will take place will be related to the amount of heat supplied.

The ability of air to absorb and hold water vapor also depends on its temperature. Hot air can hold more water vapor than cooled air, and the rate at which drying can take place will thus be affected by the temperature of the surrounding air.

An input of heat is, therefore, necessary for two reasons : (1) to stimulate evaporation and, (2) to facilitate the absorption of water vapor by the air.

As indicated above, the amount of water vapor in the air is an important factor so far as the rate of drying is concerned. The moisture content of air is measured in terms of its relative humidity. The relative humidity is the amount of water vapor pressure present in the air expressed as a percentage of the total amount of water vapor pressure which the air is capable of holding at any particular temperature. Thus, a relative humidy of 85 percent means that the air already contains 85 percent of its maximum possible water content, and has, therefore, only a very limited ability to absorb more water vapor.

In the above circumstance, rate of drying will be slow, but can be improved by : (1) heating the air, thus decreasing its relative humidity and increasing the amount of water vapor it is able to absorb, and, (2) ensuring that a large volume of air is brought moisture, the amount of air coming into contact with the material is greatly increased.

Henderson(1961) stated that drying from an overall standpoint can be divided into three periods or phases : (1) Constant rate, (2) falling rate, and (3) transition, and the drying procedure for small grains is a falling-rate procedure since the initial moisture is contained within the kernel.

Allen(1960), Hustrulid(1959) and Simmonds(1953) are nearly unanimouns in observing that small grains exposed in thin layers (a layer one kernel deep) dry according to the following equation.

$$\frac{dM}{a\ dt} = -kt\ (Mo - Me) \tag{3}$$

from which

$$\frac{M - Me}{Mo - Me} = a\ e^{-kt} \tag{4}$$

where Mo : initial moisture content, % (d.b.)

Me : equilibrium moisture content, % (d.b.)

M : moisture content after a time t, % (d.b.)

a : constant, dependent on particle shape

t : time, hr

k : drying constant, hr^{-1}

The above equation indicates that the drying rate is proportional to the difference between the moisture content of the material and its equilibrium moisture content is a function of the state characteristics of the drying air as mentioned previously, and therefore, is constant if the air temperature and relative humidity are constant. Thus, the drying rate falls with time since the moisture content decreases with time.

In contrast, Hustrulid(1959), working with maize and assuming that the kernel represented a sphere of homogeneous material, deduced from the mathematics of diffusion that

$$\frac{M - Me}{Mo - Me} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n} e^{-n^2 k t} = \frac{6}{\pi^2} c \qquad (5)$$

where c represents a series which for large values of Kt converges rapidly, so that the equation becomes identical to the equation mentioned previously. It would appear that though the former equation does not exactly describe moisture changes in a thin layer of grain, it is a close approximation, at least over the usual drying range. Pabis(1961) also considered a maize kernel as a slab rather than a sphere but found that the latter was satisfactory, though not so realistic.

The equations mentioned previously represent the expressions most commonly associated with thin layer drying of grain. It should be noted that in this case the drying rate is independent the airflow under the assumption that the rate of moisture movement from inside the grain kernel is the factor limiting the drying rate, rather than the absorptive capacity of the drying air.

In practical drying, however, each kernel can not be exposed to air of the same condition. Thus, the artificial drying procedure can be regarded as a deep-bed drying, which is defined as one in which there is a finite moisture gradient through the drying layer at any time except time zero. Progress has been made toward describing the deep-bed drying process but an acceptable general solution is not available.

Clark(1968) investigated the effect of airflow rate on the drying rate of wheat in two foot beds. He stated that the rate of evaporation increased approximately linearly with rate of airflow for a given air temperature, the rate of increase was greater at higher drying air temperatures and at a given temperature the evaporative rate was not affected by the final bed mean moisture content throughout the range of drying conditions investigated, i.e., the airflow rates of 4 to 27 cfm/bu and the drying temperatures of 105 to 175 ^{o}F.

He also found that at a given rate of airflow the rate of evaporation increased approximately linearly with drying air temperature, the increase was greater at higher rate of airflow and at a given rate of airflow, the rate of evaporation was not greatly affected by the final bed mean moisture content except at the highest rates of airflow. Woodforde(1965) also showed the same results from drying wheat in two foot beds using the air temperatures of 100, 120 and 140 ^{o}F and the airflows between about 19 and 47 cfm/bu.

Boyce(1965) stated that the air leaving the drying bed never becomes saturated and from experimental evidence, it appears that over the drying range studied, i.e., the initial drying temperatures of 125 to 155 ^{o}F, the vapor pressure of the exhaust air does not exceed about 80 percent of the saturation vapor pressure at that temperature.

Various workers such as Gallaher(1951) and Johnson(1954) have considered the problem of determining the energy utilized in vaporizing grain moisture. Generally it is thought that above about 12 % m.c. (d.b.) there is little difference between the heat of vaporization of grain and that of free moisture, but below this level the energy required to evaporate grain moisture increases. It is important to be able to evaluate this energy requirement, because despite the fact that the average final moisture content during grain drying is 14 %, there will usually be considerable drying below this value. Woodforde(1965) stated that the utilization of heat improves with a decrease in the airflow rate and that this is most marked at the lower temperatures at the range of drying conditions studied with 6 inch deep beds of barley, i.e., the temperatures of 110, 150 and 190 ^{o}F and the airflows between 14 to 70 cfm/bu.

Woodforde(1965) also stated that the runs carried out with barley at different air flows showed that the final moisture gradient between the bottom and the top of the grain bed tends to increase with the lower airflows and, under some combinations of temperature and airflow, water may be condensed into upper layers of the bed, with the result that the final moisture content of the grain may be higher than the initial moisture content. He also mentioned that mixing or turning the grain bed at intervals during the period of drying showed a decrease in the final moisture content gradient.

Proposed Driers for Developing Countries

Grain drying and processing technology for large scale commercial operation is well developed in the industralized countries. It is being applied in many developing countries with the establishment of centralized drying and processing plants. In many parts of tropical countries, roads and other forms of communication are not well developed. Consequently, modern drying and processing facilities are being established only in areas with well developed road systems. The tropical farmers growing grain (mainly maize) in the lowland humid tropics in Africa cultivates manually 2-4 acres, giving a total production of 2000 to 8000 lbs. The amount sold per farmer from year to year may vary from 600 to 6000 lbs (Corbett, 1973). In many cases, therefore, difficulties have been encountered in procuring sufficient grain from the small farms of uniform quality and of the same variety in the neighboring areas to keep these plants in full operation.

In tropical areas, almost all of the grain consumed by the rural population is dried with traditional sun drying methods. The lack of modern equipment for small scale operations has seriously hindered the efficient drying of grain at the village or farm levels. It is observed that unless drying operations are undertaken at the level of the farmers, the problem of high moisture content cannot be tackled to prevent deterioration of quality in food grains. Therefore, the development of economical village or farm level drying equipment for use in the developing countries is of urgent necessity.

A number of attempts have been made in an effort to develop a simple grain drier for farmers in developing countries in consideration of small land holdings and poor technical knowledge.

Robinson(1974) proposed a solar drier which consisted of a wooden box. It has air inlet holes on the bottom and air outlets on upper part of side wall to generate air movement. It also uses a plastic cover on the top of the box to generate higher temperatures. The advantages of this drier are as follows :

(1) Generate the high temperature and air movement essential for effective drying.

(2) Rainproof and can be left in continuous operation without attention, and without the necessity for covering up drying material or removing

it into shelter during showers.

(3) Eliminate the possibility of mold or microbial spoilage which is common with open drying methods.

(4) Protect the drying material from rewetting by rain, and the covered drier also gives protection from dust and dirt, from attack by birds and rodents, and from insect infestation.

However, this drier doesn't seem to be a solution to drying problem under humid weather.

Chancellor(1968, 1971) developed a simple grain drier which uses conduction heat from a metal surface under which a fire pit was placed. The grain dried by this drier is stirred to prevent overheating grains in contact with the metal surface by using an ox. The advantages of this drier are as follows.

(1) Heat from fuel permits drying of grain in humid weather, but fumes from the fuel is prevented from coming in contact with the food grains.

(2) Operating costs can be minimized by use of crop residues or other local materials as fuel.

(3) The manufacture of the structure does not require highly industrialized facilities.

From the field test, he concluded that a 16 ft diameter, simple grain drier, designed to conduct heat, can dry 1000 lb of rice from 24 percent moisture to 14 percent moisture in 4 hr by using two alternating animals for stirring and 157 lb of moderately dry straw for fuel in humid or rainy atmospheric conditions, and the rate of moisture removal from rice(19 % moisture) at 160 ^{o}F was almost 0.18 lb per sq ft per hour.

However, he added that rice heated above 160 ^{o}F ststained browning of the grains. Therefore, uniform stirring is very important to insure that no grains become overheated. The cost of the drier doesn't seem to be reasonably cheap for average farmers in developing countries since the cost of all materials for the drier was approximately $ 160 and labor required for drier installation was about 100 man hour.

In Japan, a simple batch drier has been used for many years. The drier has a rectangular bin with perforated floor, which is connected with a duct to an axial fan and a kerosene-fired burner to provide heated air at 110 to 130 ^{o}F. In recent years circulating batch driers have gained rapid popularity for farm drying in Japan. In this type of drier, grain flows slowly around a central perforated plenum chamber. Heated air from the plenum chamber is blown through the slow moving grain. These driers are provided with mechanisms for mechanically loading, unloading or circulating the grain to minimize labor requirements. Both the flat bed and circulating batch driers can dry 1.0 to 1.5 metric ton rice in 8 to 10 hours. These driers have good potential in tropical areas provided these can be locally produced and made available at reasonable prices to the farmers.

Since imported driers are expensive for the tropical farmers, Kahn(1973) proposed a low-cost, simple and flat-bed batch drier with 1 to 1.5 tons per 4-6 hours drying capacity. The design utilizes locally available materials and is simple enough for manufacture by small machine shops in developing countries. The unit consists of a rectangular, flat bed bin with a perforated floor and an axial fan which can be coupled to different kinds of heating units. Suitable heating units for kerosene, diesel oil, rice hulls and LPG are under development. Where there is no electricity available, an engine-driven fan is used to force air through the storage bin. When small petrol engines are used, the constant speed and load conditions involved in driving a fan 24 hours a day impose severe requirements on an engine. In addition, expenditures are required for fuel, lubricants and maintenance materials. Consequently, it is still likely to be expensive for average farmers in those areas.

Brook(1964) modified a bush drier which is known as a Samoan cocoa drier. It is a batch drier basically and it consists of a rectangular pit. The laterite soil from the pit is used to build the walls which bound the pit and support the drying floor. The enclosed space forms the plenum chamber in which the gas tight flue made of oil drums is placed, the fire-box being located outside the plenum chamber. Air heated in the chamber rises through the drying floor. Lindblad and associates(1974) gave a design of this type of drier to introduce it to the farmers in Dahomey, Africa. Webb(1969) also gave a design of "Brook" drier for Nigerian farmers and stated that the drying floor should be 2 to 2.5 ft above the firebox to prevent the crop in the center from getting scorched. He also stated that about one day is needed to dry 1000 lbs of shelled maize with a 6ft x 6ft drying box under the suggested conditions, i.e., the drying temperature of about 130 °F and the layer 4 in. thick. Thorshaug(1974) stated that it takes 2 to 3 days to dry about 1800 - 2200 lbs of unshelled maize from 25 % to 12 % with the layer 1 to 1.4 ft thick in a 7.3 ft x 8 ft drier. He also stated that the layer of shelled maize should not be more than 4 in. thick and the layer of maize cobs should not exceed 1 to 1.4 ft. He also mentioned that to dry the crops from about 25 % moisture down to 12 % costs something like 300 to 400 F.CFA (1 $ = 250 F. CFA) per ton. Since this type of drier could be built on the farm using, primarily, native materials, and mostly, by farmers themselves and it is fairly simple to operate, it is being built in some tropical countries such as Nigeria and Dahomey. Unfortunately, however, there has been no systematic study about the design criteria and performance of this type of drier.

Natural Convection and Buoyancy Force

It is known that natural or free-convection heat transfer is observed as a result of the motion of the fluid due to density changes arising from the heating process. The movement of the fluid in free convection results from the buoyancy forces imposed on the fluid when its density in the proximity of the heat-transfer surface is decreased as a result of the heating process.

The ratio of the density of the fluid at the two points is (Kutateladze, S.S. 1963) :

$$\rho_o / \rho = 1 + \beta (T - T_o) \tag{6}$$

where To : the reference temperature.

T : the temperature at a given point.

ρ_o : the density at the reference point, lbm/ft^3.

ρ : the density at a given point, lbm/ft^3.

β : the coefficient of thermal expansion.

Hence :

$$\rho_o - \rho = \rho \beta (T - To) \tag{7}$$

The buoyancy (Archimedes') force per unit volume is given by the above equation multiplied by g and taken with the opposite sign.

OBJECTIVES

The broad objective of this study was to develop a simple and low-cost grain drier which can be used at the farm or village levels in tropical areas in order to improve drying procedure.

The specific objectives were as follows :

(1) To evaluate "Brook" drier in terms of airflow rate, drying temperature, drying floor height, grain depth and air inlet size.

(2) To modify "Brook" drier to improve grain drying performance.

(3) To analyze its drying performances in terms of drying rate and the utilization of heat.

(4) To find the appropriate drying procedures for "Brook" drier.

MATERIALS AND METHODS

This study consisted of two phases of experiments. In Phase I, it was intended to evaluate the conventional "Brook' drier in order to find the relationships between the rate of airflow and other factors such as the air inlet size, the height of drying floor, the grain depth and the temperature difference between inlet air temperature and mean drying air temperature. Phase II experiments was conducted to modify "Brook" drier on the basis of the results from Phase I and to examine the drying performance of the "Brook" drier through a drying test with shelled corn.

Phase I :

Grain used for Phase I was yellow shelled corn at about 18 % moisture content(wet basis). It had been stored in a cooler after it was combine-harvested in fall, 1974.

For evaluating a "Brook" drier, two model driers were constructed (Figure 1). As shown in Figure 2, the material to be dried, A, is contained in a removable perforated metal sheet, B, mounted on a plenum chamber, C. The box was constructed of plywood and has a cross-sectional area of 9 ft^2 : the grain rests on a perforated galvanized steel sheet secured on the angle bar, D, attached to the wall, E. The heating unit, F, cosisted of 9" dia. galvinized-plate vent pipe and three 1 KW heating elements which were placed inside the enclosed cylinder as shown in Figure 2. Air is supplied into the plenum chamber through the air inlet, G, in Figure 2, which is made of steel plate and changeable to other sizes, and forms a horizontal rectangle with the ratio of 1 to 1.5. The wall, E, was constructed of two 1/4 in. thick plywood sheets, 3/4 in. apart in which the air space was filled up with glass wool. To make the plenum chamber air tight an adhesive tape was used on the inside

THIS BOOK CONTAINS SEVERAL DOCUMENTS THAT ARE OF POOR QUALITY DUE TO BEING A PHOTOCOPY OF A PHOTO.

THIS IS AS RECEIVED FROM CUSTOMER.

THIS BOOK CONTAINS NUMEROUS PICTURES THAT ARE ATTACHED TO DOCUMENTS CROOKED.

THIS IS AS RECEIVED FROM CUSTOMER.

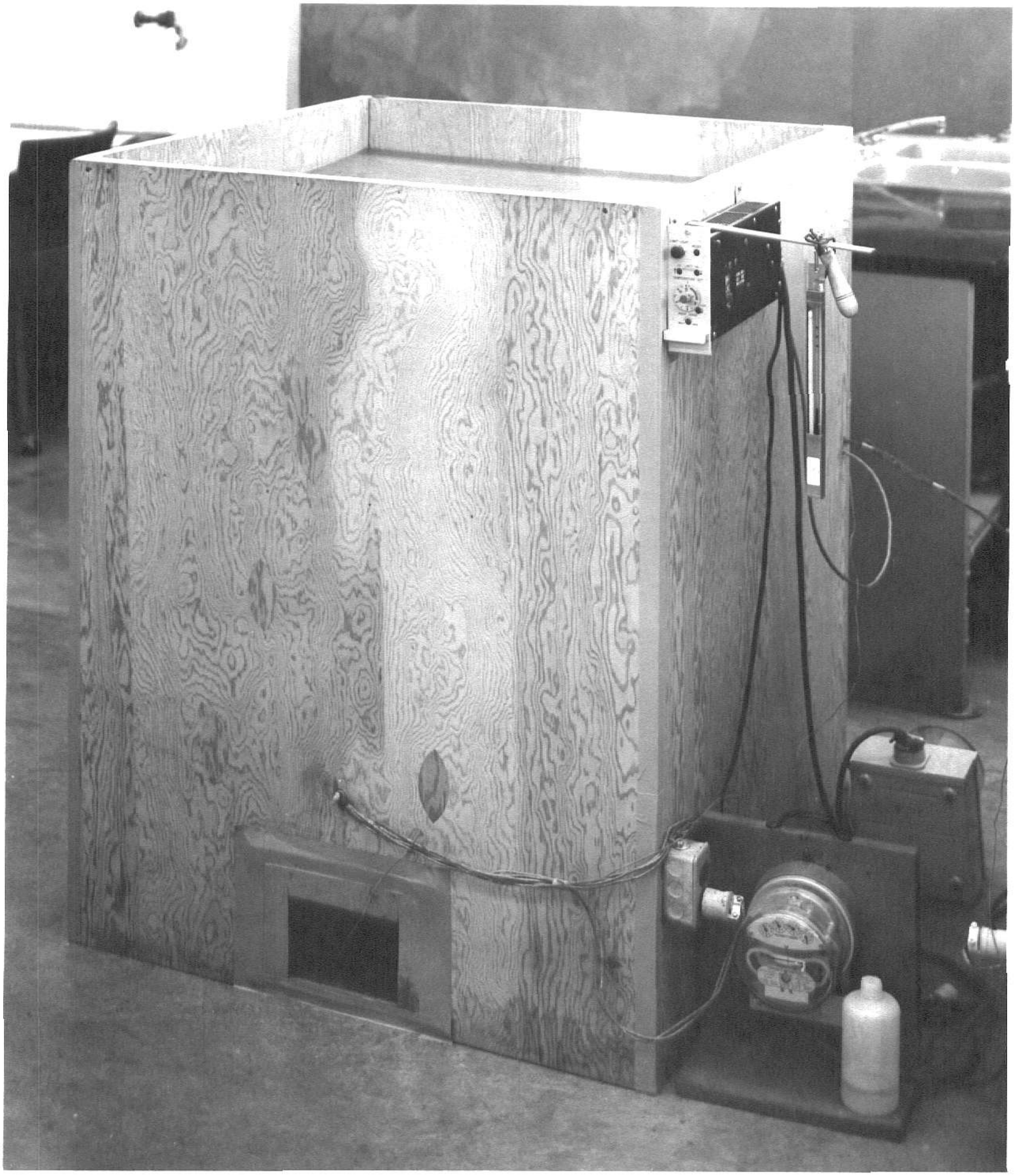

Figure 1. "Brook" drier model used in Phase I experiment.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

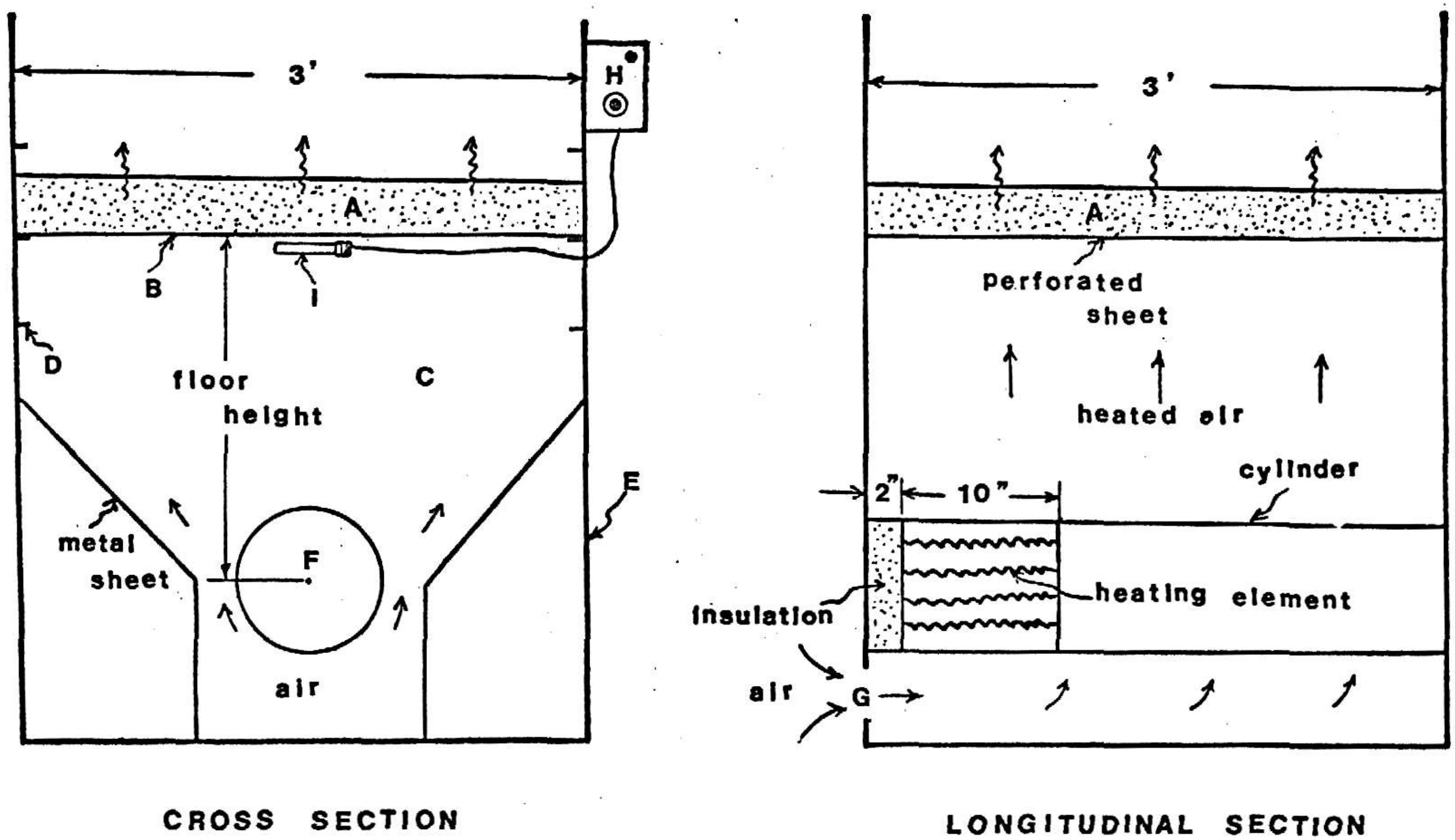

Figure 2. Schematic diagram of a model drier.

Table 1. The comparison of the simulated models with the conventional "Brook" drier.

Classification	"Brook" drier	Model drier
Size of drying bed	8' x 7.3'	3' x 3'
Height of drying floor from the center of flue	50"	15.5", 21.5", 27.5"
Diameter of flue	22"	9"
Clearance between the wall and flue at the bottom of plenum chamber	2.7"	1"
Size of air inlet	240 in^2	17, 34, 51 in^2
Materials of wall	1' thick mud	two-¼" thick plywood sheets 3/4" apart, filled with glass wool between inside and outside walls

and outside egde.

These models were simulated from the design configuration suggested by Lindblad(1974). The comparison of the simulated models with Lindblad's drier (1974) are shown in Table 1.

The inlet drying temperatures were controlled by the R 7187D Honeywell controller, H, the L 7038 Honeywell Thermistor, I. They were measured by the copper-constantan thermocouple placed just below the drying floor inside the plenum chamber at 6 different locations, and recorded by a Honeywell recorder.

In the preparation of a sample for the tests, the corn at 18 % moisture content corn had to be dried to the desired moisture content which does not affect the other properties of corn, i.e., bulk density and thermal conductivity, in order to minimize its influence on airflow rate from test to test. The initial moisture contents of corn for the tests were about 7 percent which was in equilibrium with the drying air conditions. Before the corn could be placed on the drying floor, it was hand-screened over a standard 12/64 in. sieve to remove all cracked corn and foreign material. It had been found by trial and error that a weight of grain of 70 lb. would produce a bed depth of approximately 2 inches.

The heat input was measured at ten-minute intervals by the use of a watt-hour meter after about 2 hours which are required to stabilize the grain temperature. The basis for determining watts from watt-hour meter disc rpm is that the disc constant(Kh) (printed on face of watt-hour meter) is in terms of watt hours per disc revolution, i. e., watt=60 x Kh x rpm.

The data which was recorded for each run included the air inlet temperature, the plenum temperatures at 6 different locations just below the drying floor, the air temperature leaving at the surface of grain and the power consumption at ten-minute intervals.

The experiments for Phase I are divided into three categories,i.e., inlet size test, drying floor height test and temperature rise test. In the air-inlet size test the relationships of air flow rate with air inlet size and grain depth at a given temperature rise and floor height were studied so that the inlet size could be determined properly from the experiment. The drying floor height test was conducted in order to study the effect of floor height on airflow rate. In this test, a room fan was used for simulating natural wind at a velocity of 5 mph to examine the wind effect on airflow rate. The last test was to study the effect of temperature rise on airflow rate.

Airflow rate was calculated from the energy consumption using the relationship given by :

$$Q = Ca \times \frac{q \times 60}{v} \times T \tag{8}$$

where Q : energy consumption (Btu/hr)

Ca : specific heat of air (Btu/lb. ^{o}F)

q : airflow rate (cfm)

v : specific weight of air (lb/ft^3)

T : temperature rise (^{o}F)

To measure the heat loss, the air inlet was tightly closed and the grain surface was covered with a galvanized sheet(No. 30) and the clearance between the sheet and the wall was sealed by use of an adhesive tape. In calculating airflow rate the specitic heat of air was assumed to be 0.24 Btu/lb. ^{o}F throughout the tests. The energy required to increase the sensible heat of water vapor in the air and the variance of the specific weight of the ambient air were neglected.

In Table 2, experimental factors examined in this experiment are tabulated. The experimental designs are listed in Table 3.

Table 2. Experimental factors examined in Phase I.

Grain	Shelled yellow dent corn at about 7 % moisture content(w.b.)
Environmental conditions*	74.5 ± 1.0 °F, 72 ± 7 % R.H.
Air inlet size	0, 17, 34, 51 in^2
Grain depth	2, 4, 6 in
Drying floor height	15.5, 21.5, 27.5 in
Temperature rise (Difference between inlet air temperature and drying air temperature)	20, 40, 60 °F
Wind	0, 5 mph
Condition of grain surface	open, closed

* : Refer to Table 18 in Appendix.

Table 3. Experimental design for Phase I.

Classification	Treatments	Remark
I	Inlet size : 17 in^2	Floor height : 27.5 in
	34 "	Temperature rise : 40, 60 ^oF
	51 "	No wind
	Grain depth: 2 in	
	4 "	
	6 "	
II	Floor height : 15.5 in	Inlet size : 34 in^2
	21.5 "	Grain depth : 4 in
	27.5 "	Temperature rise : 60 ^oF
		Wind : 0, 5 mph
III	Temperature rise : 20 ^oF	Inlet size : 34 in^2
	40 "	Floor height : 27.5 in
	60 "	Grain depth : 4 in
		No wind

Phase II :

Grain used for the Phase II tests was shelled yellow dent corn, which had been newly harvested in September, 1975, at about 20.5 % moisture content wet basis, and all the corn was wetted to about 24 % using revolving drum and then kept in a cooler at least 3 days until ready for tests to allow even moisture distribution inside the kernel.

The mean initial moisture content of the bed was obtained from samples taken as the drier was being filled.

The experiments for Phase II are divided into two categories, i.e., the comparative test in natural convection drying between the modified and unmodified model, and the forced air drying test with different grain depths. The experimental factors and the experimental designs are listed in Table 4 and 5, respectively.

The same model driers as those for Phase I were used for Phase II, but some modifications were needed. For the comparative test the modified drier was changed to increase its height 50 percent above that of the unmodified one. The floor height used for the unmodified drier was 20.5 in. on the basis of simulation from the conventional drier. The air inlet size for the modified and unmodified model were 39 and 14 in^2., respectively. The inlet size for the unmodified, 14 in^2., was determined from the ratios of the model to the conventional drier in terms of the drying floor size and the floor height which have a linear relationship with the rate of air flow from the results of Phase I. In addition to the comparison of two models, the effects of mixing-in-bed on drying performance were also examined.

For the forced air drying, the drier was modified to have the same height as the unmodified drier on the basis of the results of Phase I which showed no significant effect of the floor height on the rate of airflow with 5 mph wind,

Table 4. Experimental factors examined in Phase II.

Grain	Shelled yellow dent corn at about 25 % moisture content(w.b.)
Environmental conditions*	77.0 ± 1.7 °F, 54 ± 4 % R.H.
Drier model	Unmodified, modified
Conditions of bed during drying	Undisturbed, mixed
Grain depth	2, 4, 6 in
Driving force for air movement	Natural convection, forced draft

* : Refer to Table 19 in Appendix.

Table 5. Experimental design for Phase II.

Classification	Treatment	Remark
	Unmodified model	Temperature rise : 60 °F
	Undisturbed bed	Grain depth : 4 in
Natural convection	Modified model	No wind
	Undisturbed bed	
	Mixed bed	
	Grain depth : 2 in	Temperature rise : 60 °F
Forced draft	4 "	Airflow rate : 15 cfm/bu
	6 "	No wind

and it was also modified to fit an air duct and a centrifugal fan driven by a variable speed electric motor(Figure 3). The air duct consisted of 8 foot long vent pipe with 6 in. in diameter and an element to straighten airflow inside the duct. The opening between the heating cylinder and the wall was modified as shown in Figure 4 based on the results of Phase I which showed a significant difference in the drying temperature between the front and back side of the drier, due to the higher static pressure of the back side of the air duct inside the drier.

At the center of the duct the maximum velocity was measured using a hot-wire anemometer(Model B-22 : Hastings-Raydist, Inc.). The average velocity was assumed to be 2/3 of the maximum velocity. The speed of the fan was adjusted by a variable speed motor to get the air velocity required for each run.

The inlet air temperature into the drier and the drying temperature of the air at six different locations just below the drying floor were measured by the same thermocouple and recorder used in Phase I. The wet-bulb temperature of the ambient temperature was measured by means of a ventilated thermometer unit : in this unit the sock on the wet-bulb element was kept wet continuously by distilled water.

During the test, the samples were obtained at certain intervals different from four subsections in the bed. A Steinleit moisture tester was used to determine the time when the desired moisture content had reached approximately. After the sample was measured by the Steinleit tester, it was returned to the bed every time. At the conclusion of each run a sample was taken from the top and bottom of the bed for the determination of moisture gradient within the bed.

The moisture content of each individual grain sample was determined by exposing 10 g of whole grain in a thermostatically controlled forced draft

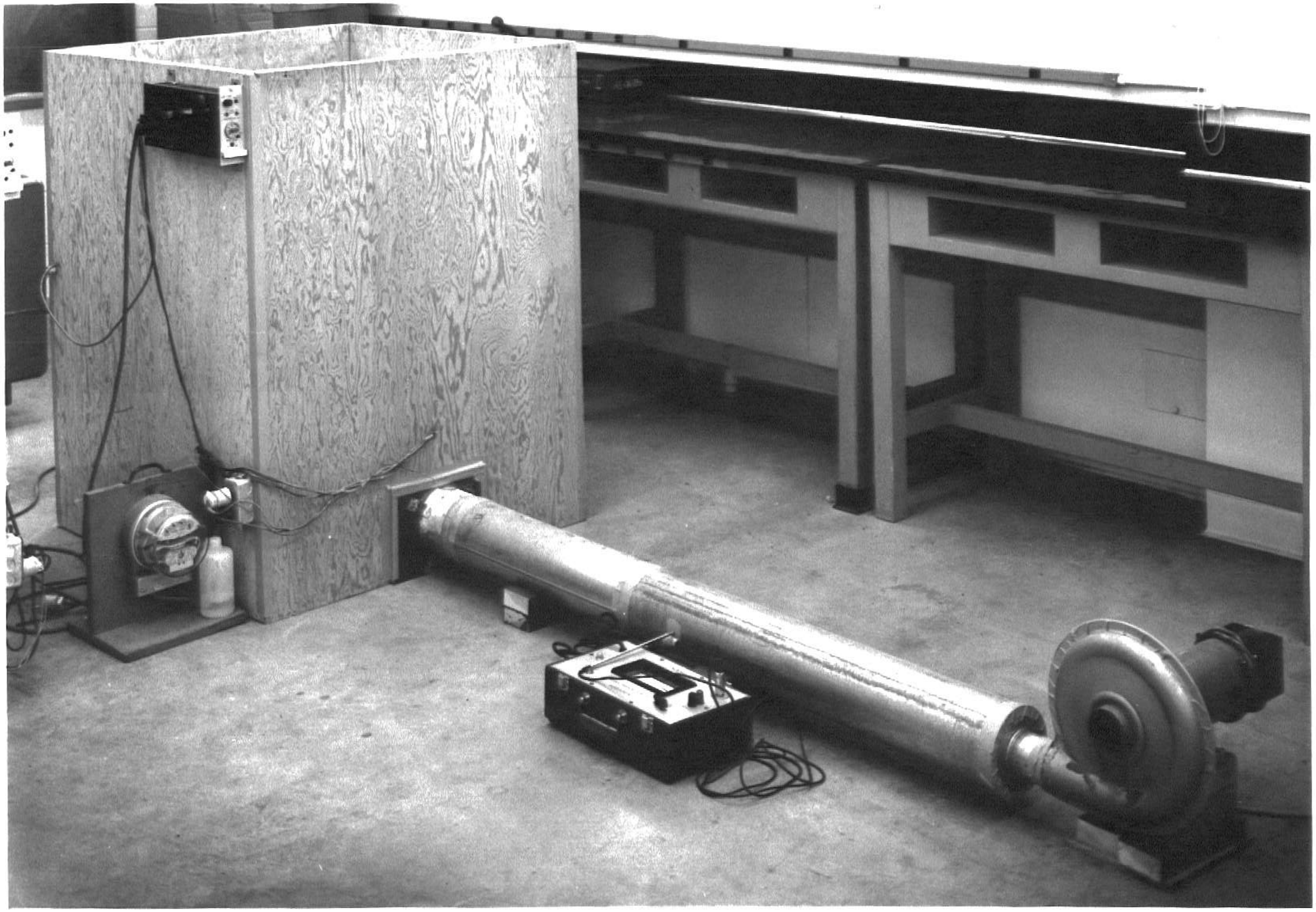

Figure 3. Model drier for foced draft drying in Phase II experiment.

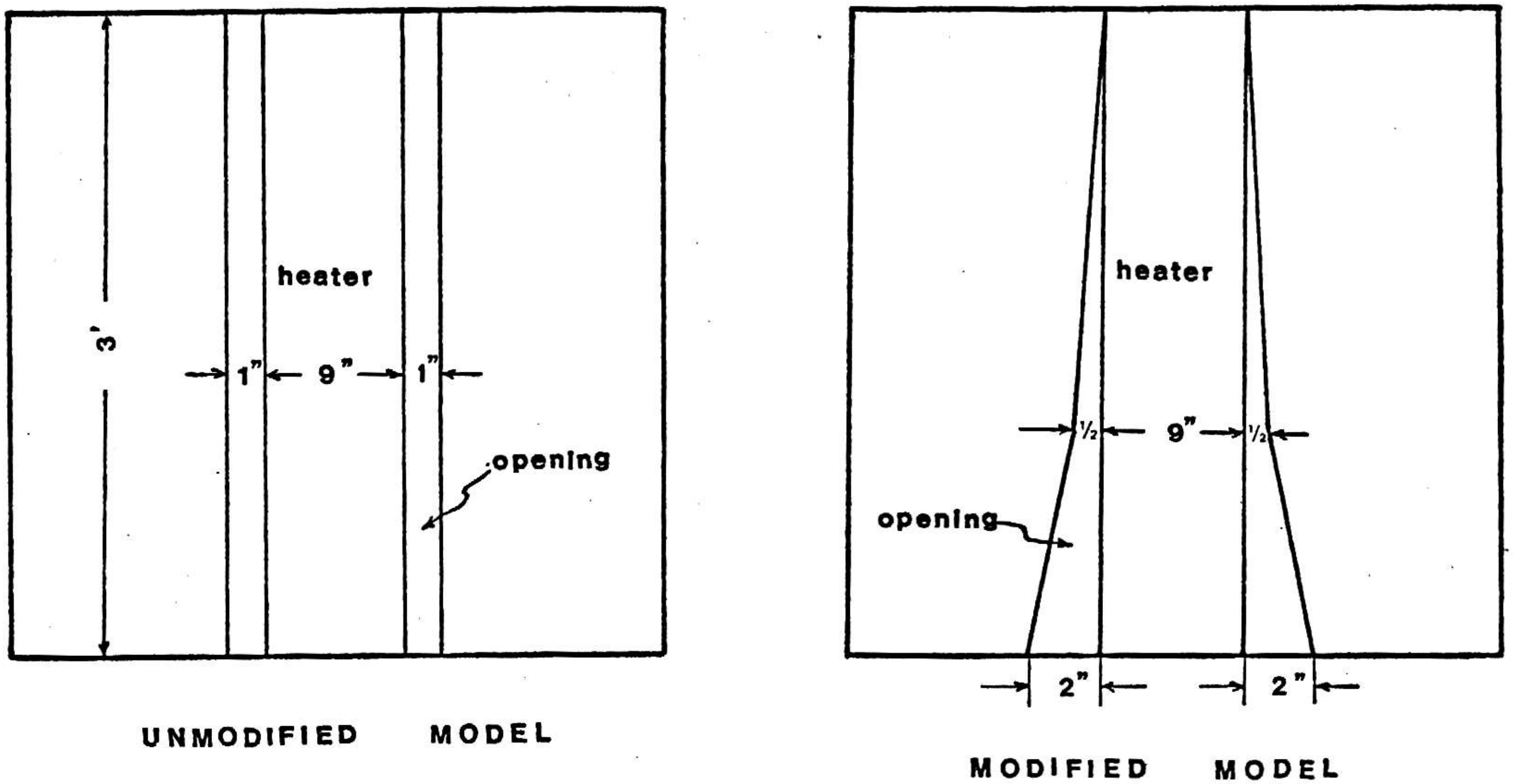

Figure 4. Comparison of the opening around heating cylinder.

oven for 72 hours at 220 ^oF. The final mean moisture content in the bed was calculated from the initial moisture content and the weight loss due to evaporation of water under the assumption that the measured weight loss at the end of each run was due soley to the evaporation of water and the weight loss due to sampling for the determination of moisture content by oven method during drying.

A number of tests were made to obtain information on the results of mixing a bed of corn during drying. The bed of 4 in. depth was thoroughly mixed by hand for about two minutes at the intervals of 1, 2 and 4 hours after the start of drying. The mixing was done while warm air was passing through the bed. At the end of each run the bed was sampled at the top and bottom to determine the final mean moisture gradient.

The total heat input during drying was obtained by a watt-hour meter to determine the utilization of heat. Since the grain temperatures at the beginning of drying were different from run to run, the heat required to raise the temperature of grain to the reference temperature, which was considered to be the average ambient temperature, 77 ^oF, was taken into account. In calculating this it was assumed the specific heat of corn to be 0.513 Btu/lb. ^oF(ASAE Yearbook, 1975). The utilzation of the net heat into the grain was also determined, excluding the heat loss through the wall obtained from Phase I.

RESULTS AND DISCUSSION

Phase 1 experiment was conducted to find the relationships between the rate of airflow and other factors, i.e., the depth of grain in bed, the size of air inlet, the height of drying floor and the temperature rise from inlet air to drying air. First, a number of tests were made to study the effects of the size of air inlet and the grain depth on the rate of airflow at the given temperatures, i.e., 40 ^{o}F and 60 ^{o}F. The airflow data obtained from the test are listed in Table 6 and 8. Figure 5 and 6 shows the effects of the air inlet size on the rate of airflow with the different grain depths for the given temperature rise, 40 and 60 ^{o}F, respectively.

A statistical analysis of the airflow data was made as shown in Table 7 and 9. The results showed significant effects of the inlet size and the grain depth. And there was a significant interaction between the inlet size and the grain depth.

From the multiple range test with 0.05 level, there was no significant difference in airflow between the inlet sizes of 34 and 51 in^2 at the depths of 4 and 6 in for the temperature rise, 60 ^{o}F, and between the inlet sizes of 34 and 51 in^2 at the grain depth of 4 in and between all the inlet sizes at the grain depth of 6 in for the temperature rise of 40 ^{o}F. At the sizes of air inlet above which the airflow rate did not increase significantly, the velocities of the air through the inlet were 53, 39, 35 and 52 ft/min,respectively. Assuming the resistance of the air through the inlet to be a function of air velocity, the allowable velocity of the air through the inlet should be less than 53 ft/min.

The effects of the grain depth on airflow rate are shown in Figure 7. The data in Figure 7 are transformed on log-log paper, yielding the straight lines (Figure 8). The following equations were obtained for airflow rate :

Table 6. Airflow rate by natural convection for testing the effects of air inlet size and grain depth with a temperature rise of 40 ^{o}F.

Unit : cfm

		Grain depth (in)		
		2	4	6
	17 in^2	8.05	7.12	6.26
Air inlet size	34 "	13.31	8.38	6.54
	51 "	14.67	8.54	6.53

Table 7. Analysis of variance for airflow rate data for testing the effects of air inlet size and grain depth with a temperature rise of 40 ^{o}F.

Source	Degrees of freedom	Sum of squares	Mean squares	F (calculated)
Air inlet size	2	26.1952	13.0976	226.75*
Grain depth	2	98.8044	49.4022	855.26*
Interaction	4	25.2841	6.3210	107.43*
Error	9	0.5199	0.0578	
Total	17	150.8035		

* : Significant at 0.05 level.

Table 8. Airflow rate by natural convection for testing the effects of air inlet size and grain depth with a temperature rise of 60 ^{o}F.

Unit : cfm

		Grain depth (in)		
		2	4	6
	17 in^2	9.82	8.90	8.01
Air inlet size	34 "	15.40	12.41	9.28
	51 "	19.39	12.43	9.45

Table 9. Analysis of variance for airflow rate data for testing the effects of air inlet size and grain depth with a temperature rise of 60 ^{o}F.

Source	Degrees of freedom	Sum of squares	Mean squares	F (calculated)
Air inlet size	2	74.8248	37.4124	402.72*
Grain depth	2	108.2203	54.1102	582.46*
Interaction	4	36.7487	9.1872	98.89*
Error	9	0.8364	0.0929	
Total	17	220.6302		

* : Significant at 0.05 level.

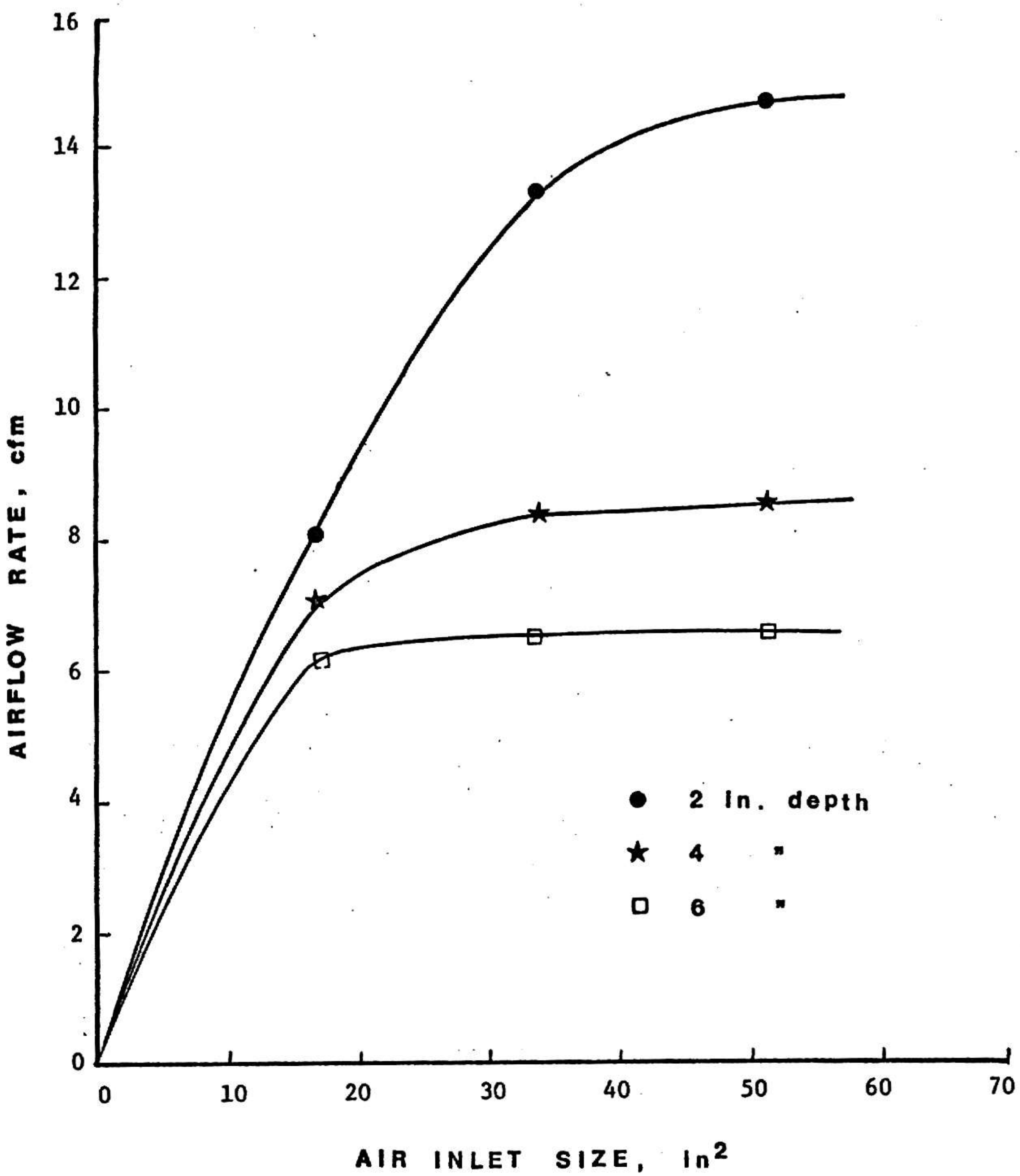

Figure 5. Airflow rate versus air inlet size at different depths of grain with a temperature rise of 40 °F and a floor height of 27.5 in.

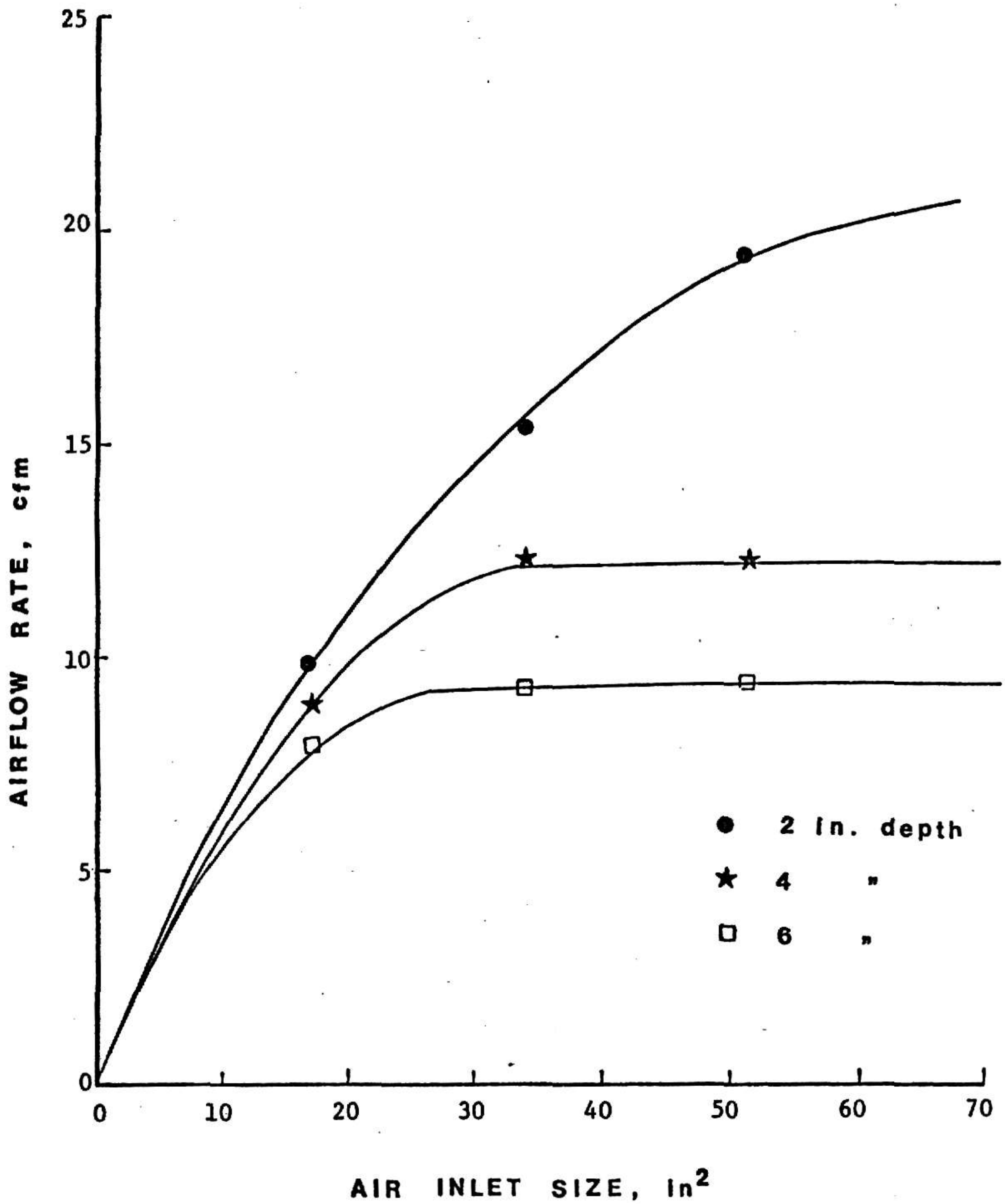

Figure 6. Airflow rate versus air inlet size at different depths of grain with a temperature rise of 60 °F and a floor height of 27.5 in.

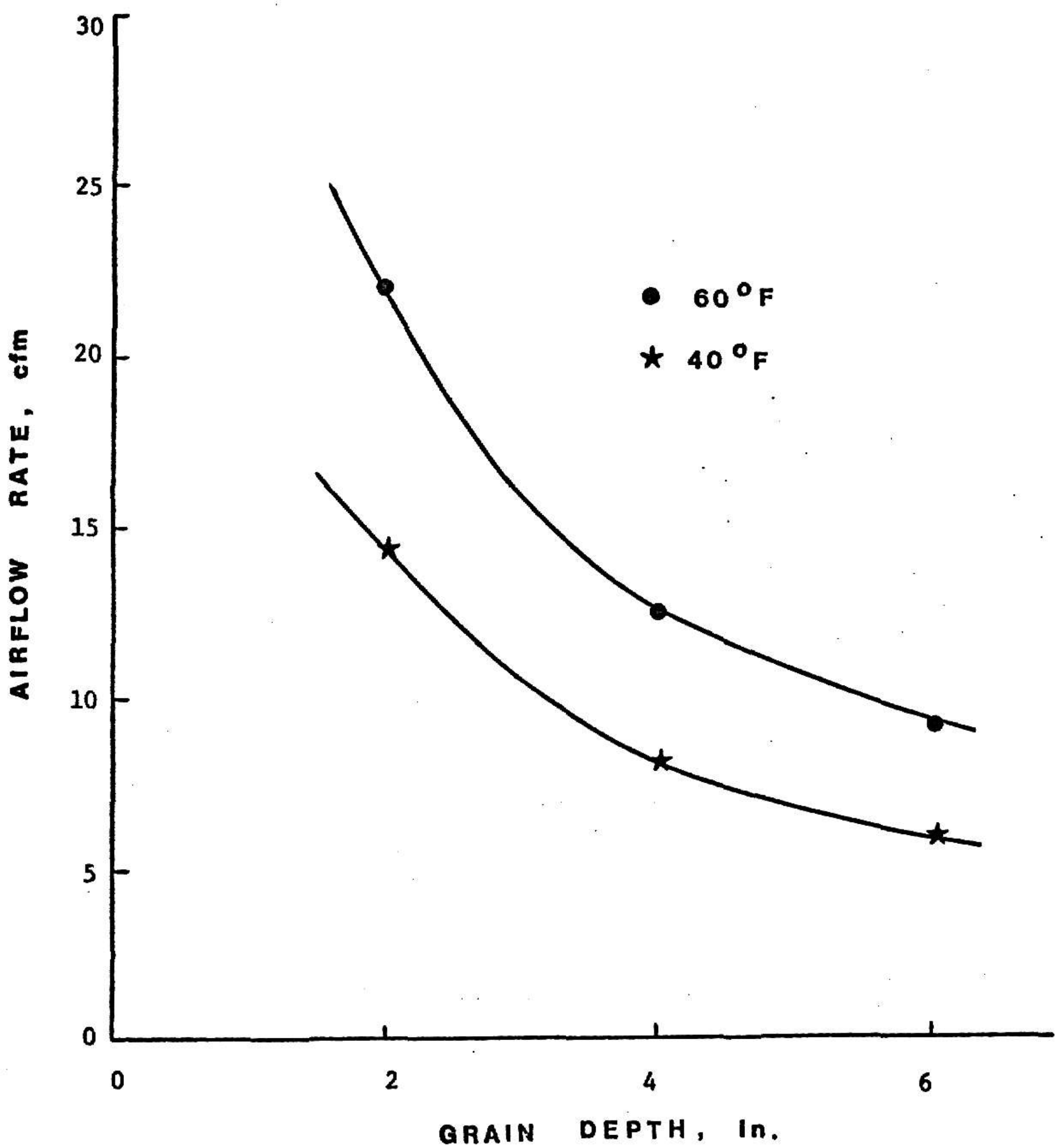

Figure 7. Airflow rate versus grain depth at different temperature rises with a floor height of 27.5 in.

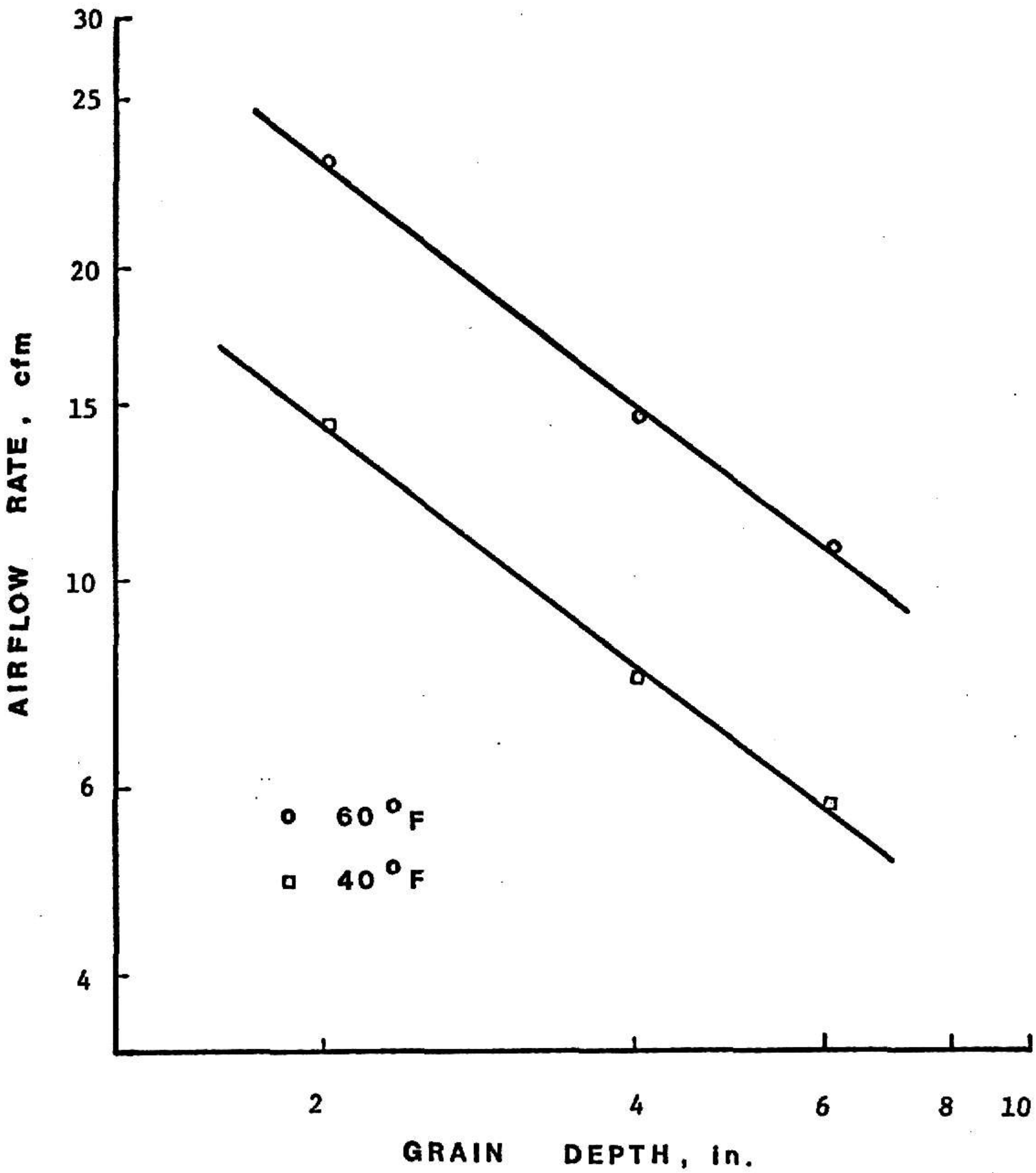

Figure 8. Airflow rate versus grain depth at different temperature rises with a floor height of 27.5 in on log-log paper.

$$q = 37.44\ D^{-0.785} \quad : \text{for temperature rise of } 60\ ^oF \qquad (9)$$

$$q = 24.27\ D^{-0.735} \quad : \text{for temperature rise of } 40\ ^oF \qquad (10)$$

where q : the rate of airflow rate (cfm)

D : the grain depth (in)

The above equations were approximated to :

$$q = C\ D^{-0.76} \qquad (11)$$

where C : constant for a given temperature rise and floor height.

Figure 9 shows that the heat loss through the walls and the grain has a linear relationship with the height of the drying floor. The overall thermal conductivity calculated from the results was 0.203 Btu/ft ^oF which was in good agreement with the calculated value of 0.211. Since the calculated overall thermal conductivity of 1 ft mud wall was 0.269 Btu/ft. ^oF, the heat loss through the wall in the conventional drier will be 27.5 % more than that of the model drier used in this study.

Table 10 shows the rate of airflow at the different heights of the drying floor with and without wind at the given temperature rise of 60 ^oF and the grain depth of 4 in. There is a tremendous effect of wind on the rate of airflow. A statistical analysis of the airflow data with 5 mph wind showed that there was no significant effect of the height of drying floor on the rate of airflow, as shown in Table 11.

Figure 10 shows that the rate of airflow without wind is a linear function of the drying floor height. The resulting equation is given by :

$$q = 0.443\ H + 0.378 \qquad (12)$$

where H : the height of drying floor, in.

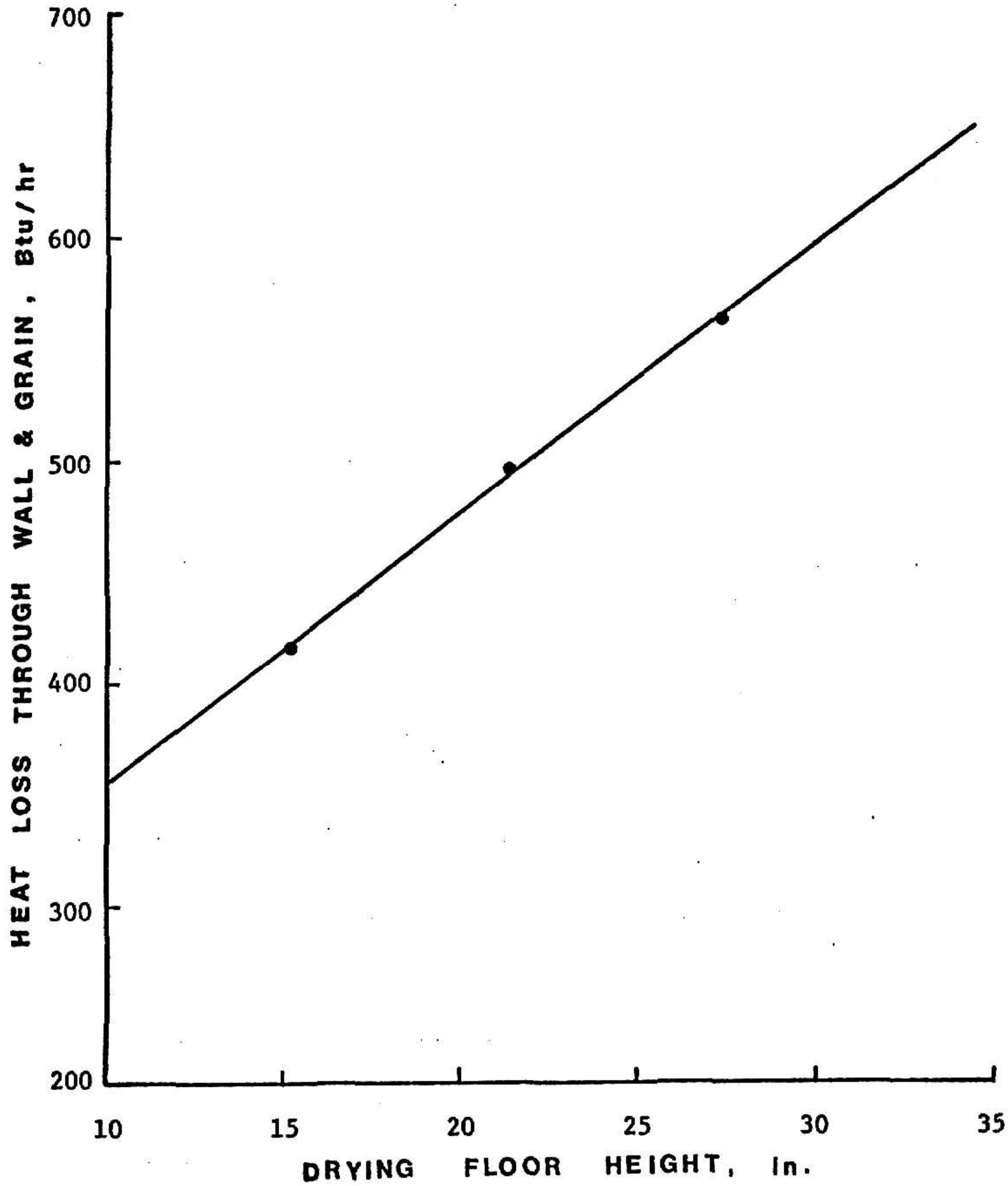

Figure 9. Heat loss through wall and grain by conduction heat transfer versus floor height with a temperature rise of 60 ^{o}F and a grain depth of 4 in.

Table 10. Airflow rate data for testing the effects of drying floor height with and without wind.

Unit : cfm

		Drying floor height (in)		
		15.5	21.5	27.5
Wind	0	7.27	10.20	12.95
		7.02	9.90	12.51
	5 mph	53.85	55.22	58.49
		57.83	57.64	56.96

Table 11. Analysis of variance for airflow rate data for testing the effects of drying floor height with 5 mph wind.

Source	Degrees of freedom	Sum of squares	Mean squares	F (calculated)
Floor height	2	3.7195	1.8598	0.4642
Error	3	12.0186	4.0062	
Total	5	15.7381		

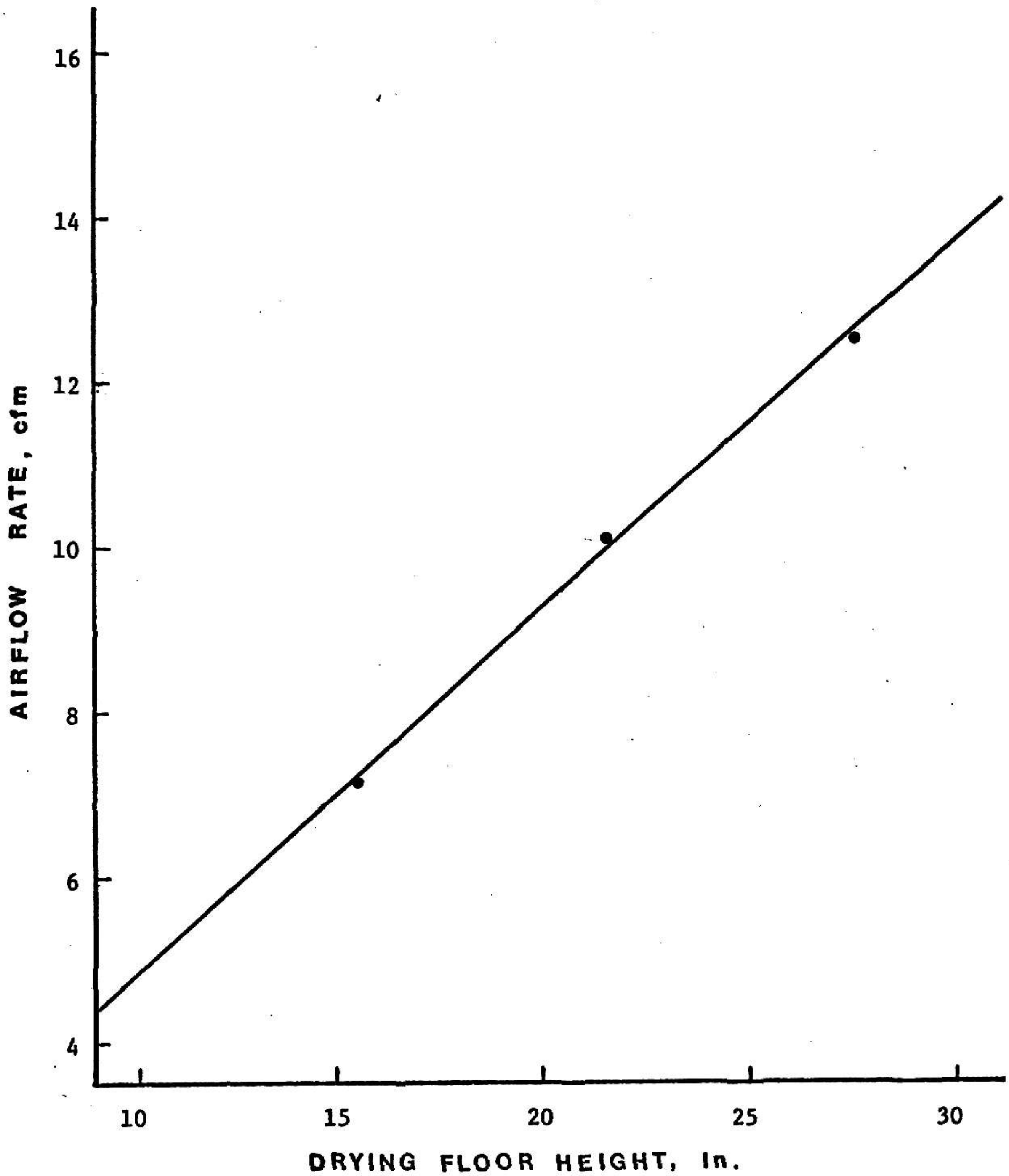

Figure 10. Airflow rate versus floor height with a temperature rise of 60 ^{o}F and a grain depth of 4 in.

The above equation was approximated to :

$$q = 0.443\ H \tag{13}$$

Statistical analysis for testing the temperature difference in the plenum chamber is given in Table 12. The results showed that there was no significant difference in drying temperature between the left and right side of the bed throughout the test. However, there was a significant difference in drying temperature between the front and back side of the bed. The mean temperature difference between the front and back side of the bed increased as the floor height decreased, more remarkably with 5 mph wind. In natural convection drying, the increase of the difference was relatively small above the height of 21.5 in. It is thought that the temperature difference under natural convection drying is due to the higher temperature of the front part of the heating unit. The difference in temperature with 5 mph wind results mostly from the higher static pressure of the back side of air duct inside the plenum chamber.

Figure 11 shows that the heat loss through the walls and the grain increases linearly as the temperature rise increases. As shown in Figure 12, the rate of airflow increased linearly with the temperature rise. The resulting equation is given by :

$$q = 0.202\ \Delta T + 0.384 \tag{14}$$

This equation was approximated to :

$$q = 0.202 \Delta T \tag{15}$$

where ΔT : the temperature rise, i.e., the difference between the drying air temperature and the temperature of inlet air, ^{o}F.

Three equations described previously can be combined to give the following

Table 12. Analysis of the drying temperature data for testing the temperature difference in the plenum chamber.

Wind	Height	Direction	$\bar{D}$	$S_{\bar{D}}$	t
0	15.5"	Left-Right	1.10	2.01	0.54
		Front-Back	3.98	0.48	8.35*
	21.5"	Left-Right	0.60	1.64	0.37
		Front-Back	2.92	0.84	3.45*
	27.5"	Left-Right	0.08	1.43	0.05
		Front-Back	2.52	0.73	3.43*
5 mph	15.5"	Left-Right	0.35	7.02	0.05
		Front-Back	18.23	1.46	12.50*
	21.5"	Left-Right	0.25	4.28	0.06
		Front-Back	11.42	1.25	9.14*
	27.5"	Left-Right	0.08	2.89	0.03
		Front-Back	7.93	1.13	7.02*

* : Significant at 0.05 level(one-tailed test)

$\bar{D}$: Mean difference

$S_{\bar{D}}$: Standard deviation

t : t-test value

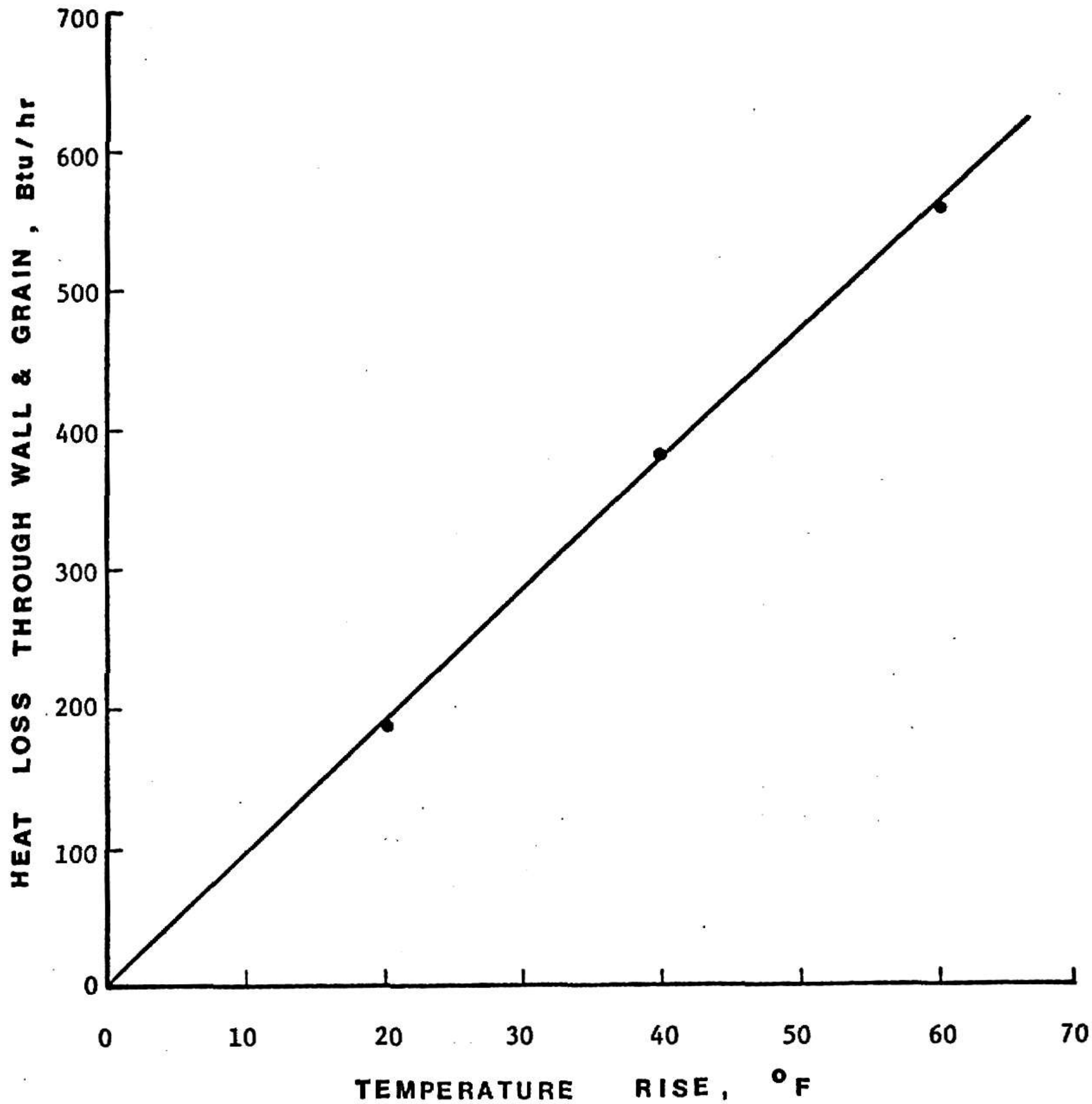

Figure 11. Heat loss through wall and grain by conduction heat trnsfer versus temperature rise with a floor height of 27.5 in and a grain depth of 4 in.

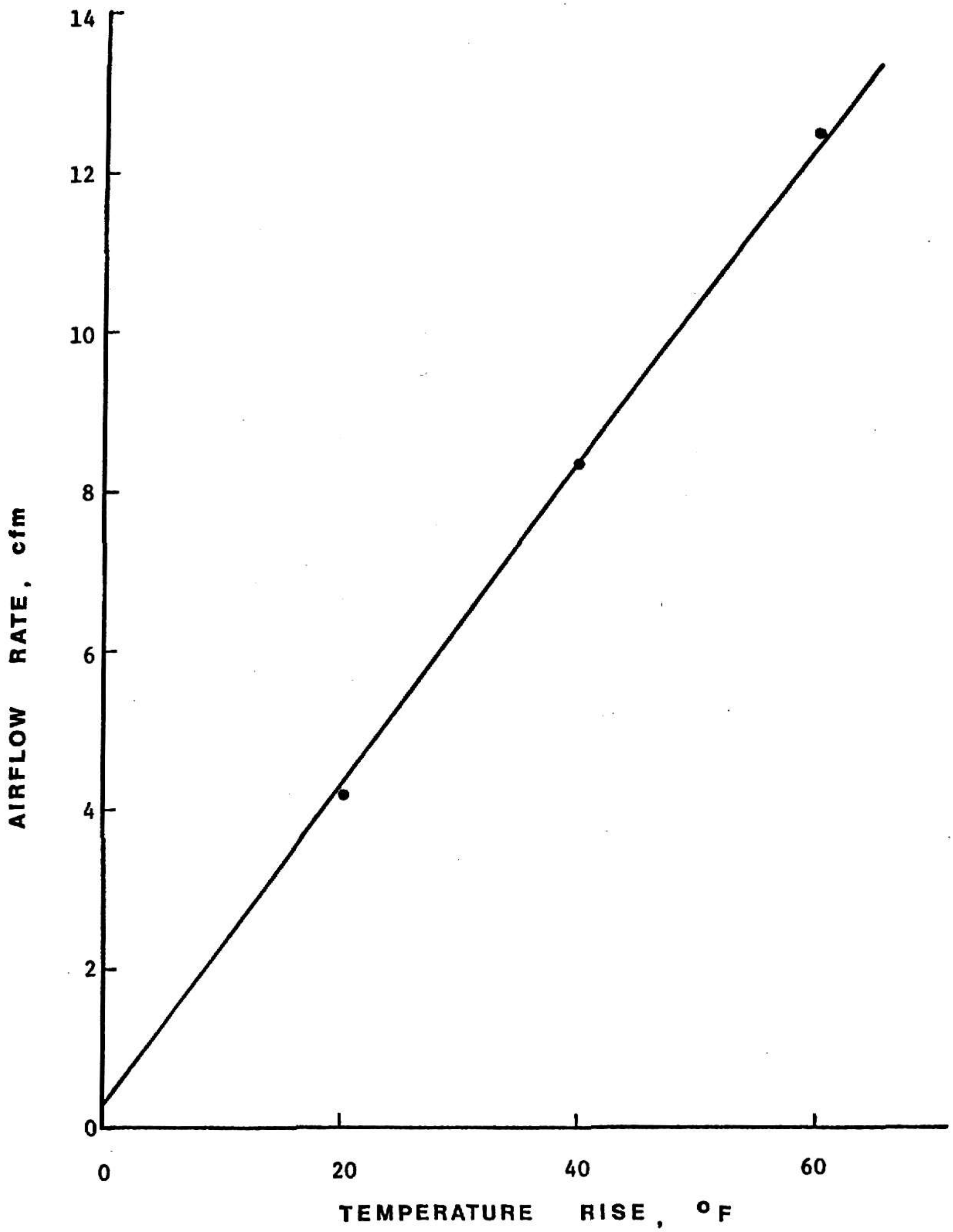

Figure 12. Airflow rate versus temperature rise with a grain depth of 4 in and a floor height of 27.5 in.

equation for approximating the airflow rate :

$$q = 0.0217\ H\Delta T\ D^{-0.76} \tag{16}$$

The general equation to determine the rate of airflow per unit bed area can be expressed by dividing the above equation by the bed area, 9 ft^2. The resulting equation is :

$$q = 0.0024\ H\Delta T\ D^{-0.76} \tag{17}$$

In Table 13 the values of airflow rate obtained from the experiment and those calculated by the equation(16) are given. The results show that there is a little difference, about 3.6 % in average, between the experimental and calculated values.

When Phase II experiment was set up, it was hoped that the temperature and humidity of the ambient air in the room could be kept constant in an effort to decrease the difference in drying performance due to the environmental conditions throughout the test. The room temperature was controlled by a room air conditioner to maintain 75 ^{o}F, but the relative humidity was left in natural condition because of difficulties in keeping it constant. Throughout the test the temperature was 77 $\pm$ 1.7 ^{o}F, and the relative humidity was 54 $\pm$ 4 % as shown in Table 19 in Appendix.

In natural convection drying the modified drier was changed to increase its height 50 percent above that of the unmodified drier. It was also changed to have a proper air inlet based on the results from Phase I.

In Table 14 the results from the drying test under natural convection are listed. The rate of airflow of the modified drier, 6.92 cfm/bu, was about 73 % more than that of the unmodified one, 3.99 cfm/bu. The increase of 23 %, out of 73 %, can be attributed to the proper size of air inlet according to the results

Table 13. The comparison of the values of airflow rate obtained from the experiments with those calculated by the predictive equation.

Grain depth (in)	Floor height (in)	Temperature rise (^{o}F)	Airflow rate(cfm) Experimental	Airflow rate(cfm) Calculated*	Difference (%)
2	27.5	40	14.67	14.05	4.23
4	15.5	60	7.14	6.99	2.10
4	21.5	60	10.05	9.70	3.48
4	27.5	20	4.45	4.14	6.97
4	27.5	40	8.46	8.27	2.24
4	27.5	60	12.52	12.41	0.88
6	27.5	40	6.44	6.07	5.74
6	27.5	60	9.36	9.10	2.78
Average					3.55

* : Calculated by the equation (16).

Table 14. Data for natural convection drying with a temperature rise of 60 °F and a grain depth of 4in.

Treatment	Drying time (hour)	Airflow rate (cfm/bu)	Grain moisture content(%,w.b.) Mean initial	Mean* final	Final at top	Final at bottom	Rate of evaporation (lb/hr.bu)	Utilization of heat (Btu/lb water)
Unmodified model	36.0	3.80	24.3	10.6	15.6	6.9	0.2246	1945(1485)**
	33.5	4.18	23.8	9.1	14.9	6.6	0.2537	1950(1544)
Modified model	22.0	6.70	24.8	12.0	16.8	7.9	0.3487	1939(1494)
	22.0	7.13	24.0	10.2	15.5	7.7	0.3675	1987(1565)
" mixed-1 hr	19.0	8.63	24.4	11.6	11.8	11.5	0.4038	2033(1649)
" mixed-2 hr	19.0	8.37	24.2	10.6	11.8	10.4	0.4256	1867(1502)
" mixed-2 hr	20.0	7.49	24.9	12.2	12.9	11.7	0.3836	1965(1560)
" mixed-4 hr	20.0	7.42	24.9	11.4	12.1	11.0	0.4043	1864(1480)

* : calculated from loss of weight.

** : excluded heat loss through walls.

of the Phase I experiments. Since the predicted rate of airflow by the equation (16) in Phase I is 5.75 cfm/bu for the modified drier, there is an increase of about 20.4 % in the rate of airflow obtained from the drying test over the predicted rate of airflow. It is thought that the increase is mostly due to the difference in corn used in each test. Henderson(1943) showed that there was a sizable difference in the resistance to airflow with different kinds of corn. And it is likely that there is an increase in airflow due to the decrease of grain depth during drying.

Figure 13 shows the experimental results on the rate of evaporation with respect to the airflow rate. In natural convection drying with the temperature rise of 60 ^{o}F and the grain depth of 4 in, the rate of evaporation of the modified drier, 0.36 lb/hr. bu, was about 50 % higher than that of the unmodified. In other words, there was a 50 % reduction in drying time with the modified drier compared to the unmodified. Since the researchers such as Clark (1968) and Woodforde(1965) stated that the rate of evaporation increased approximately linearly with the rate of airflow in drying wheat, the rate of evaporation with the modified drier should have been more than 50 % above the unmodified drier. The disagreement might be due to the contribution of the conduction heat transfer through the grain when drying with a low rate of airflow, which is almost negligible in conventional convection drying with higher airflow rate. It is shown in Figure 13 that the evaporation rate increased almost proportionally as the airflow rate increased.

There was practically no difference in the utilization of heat between two models as shown in Table 14. It agrees with the fact that the heat loss through the walls increases with the height of drying floor. It implies that the height of drying floor can be increased to improve drying rate without losing the utilization of heat.

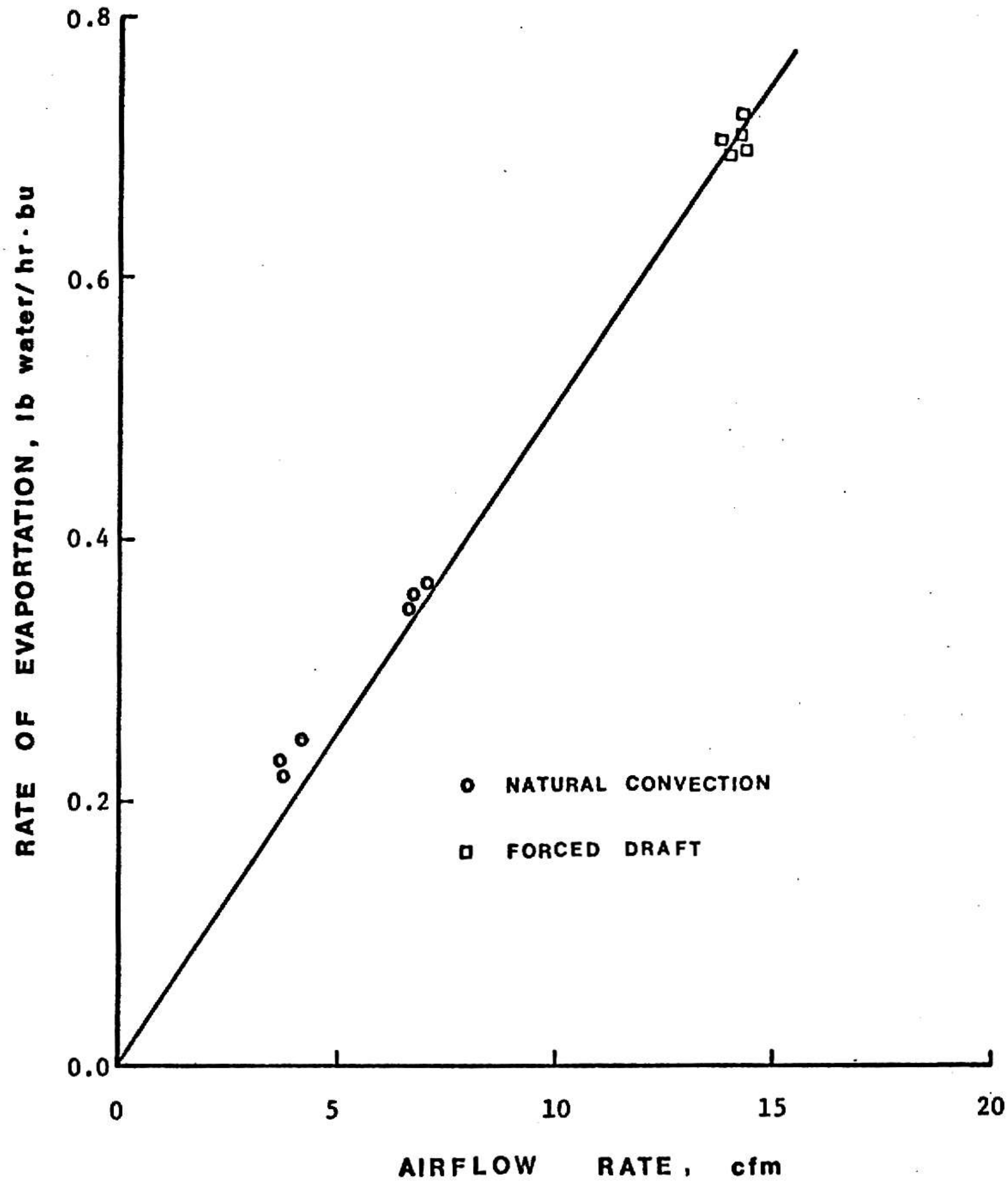

Figure 13. Airflow rate versus evaporation rate in drying a 4 in depth of corn from 25 % to 12 %(mean inlet air temperature of 76.5 °F and mean drying air temperature of 137.2 °F).

Figure 14 and 15 show the drying rate at different parts of the bed in natural convection drying with the modified and unmodified drier. They showed a typical curve of deep layer drying, which is characterized by overdrying at the bottom and distinct moisture gradient within the bed.

In Table 15 a statistical analysis of temperature data in the plenum chamber is listed to test the temperature difference between the locations in the bed. The results showed that there was no significant difference between the left and right side of the bed. But there was a significant difference between the front and back side of the bed. The mean difference for the modified drier was about 2.32 ^{o}F, which was much lower than that of the unmodified drier, 3.96 ^{o}F.

Table 16 shows a statistical analysis of the corn moisture content data to test the moisture gradient in the corn mass at the end of drying. The results show that there was a big difference in moisture content between the top and bottom of the bed for both driers although the mean difference in moisture content for the modified drier was slightly lower. The difference in moisture content between the front and back side of the bed showed a significance with the unmodified drier while no significance with the modified drier.

A number of tests were made to obtain an information on the results of mixing a bed of corn when drying with the modified drier. Figure 16 shows the drying rate of about 25 % initial moisture content corn when the grain was mixed during drying. As shown in Table 14, there was some improvement in the rate of evaporation compared with that of undisturbed drying. Even though there was no difference in the rate of evaporation between the intervals of mixing used in this experiment, it seemed that there was an improvement in the utilization of heat as the intervals increased. Mixing a bed at the interval of 2 or 4 hours seemed to be more efficient in the utilization of heat than undisturbed drying as shown in Table 14. It should be noted that too frequent mixing might result

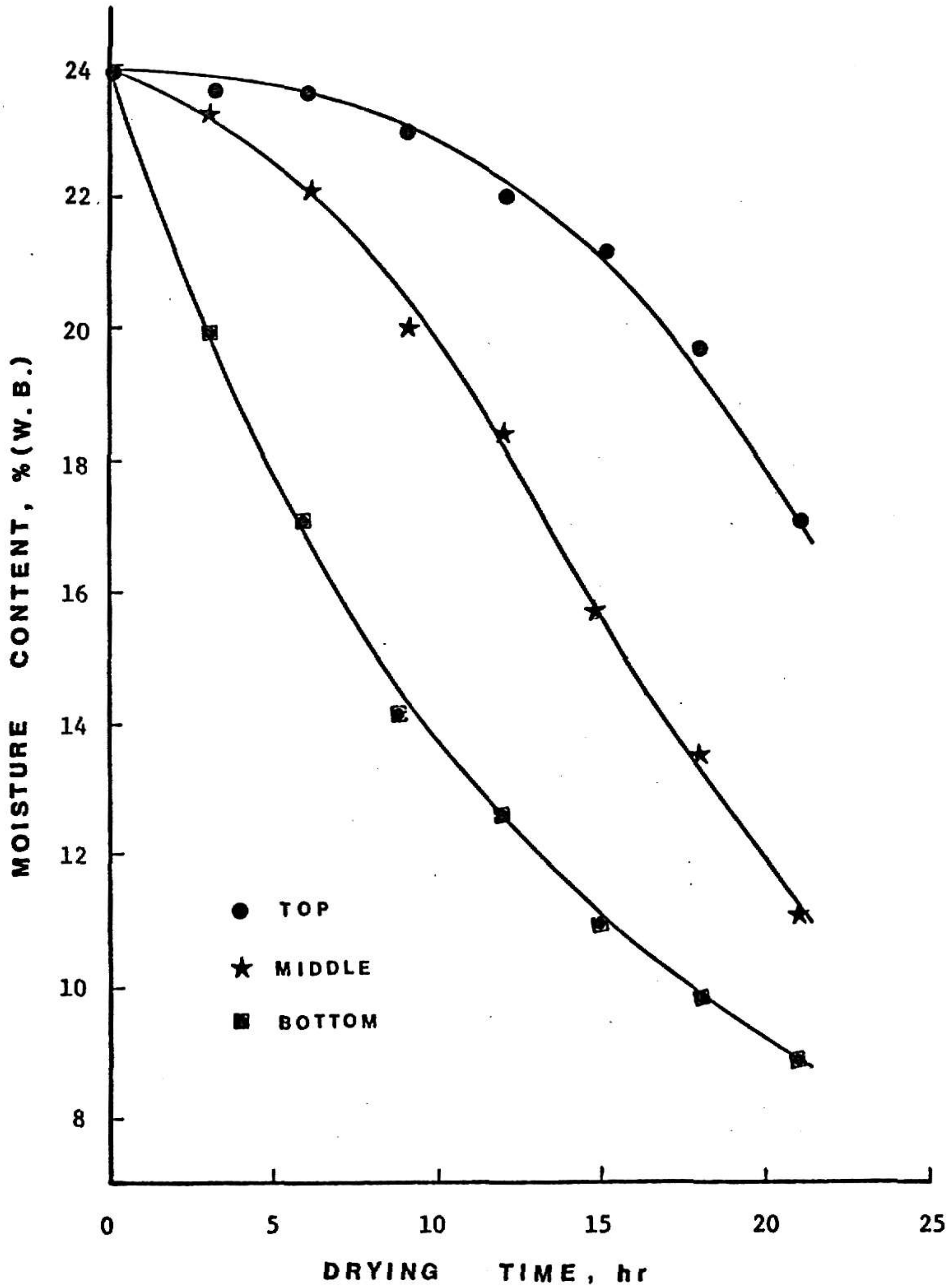

Figure 14. Moisture content versus drying time for drying with the modified drier(mean inlet air temperature of 76.2 °F and mean drying air temperature of 135.4 °F).

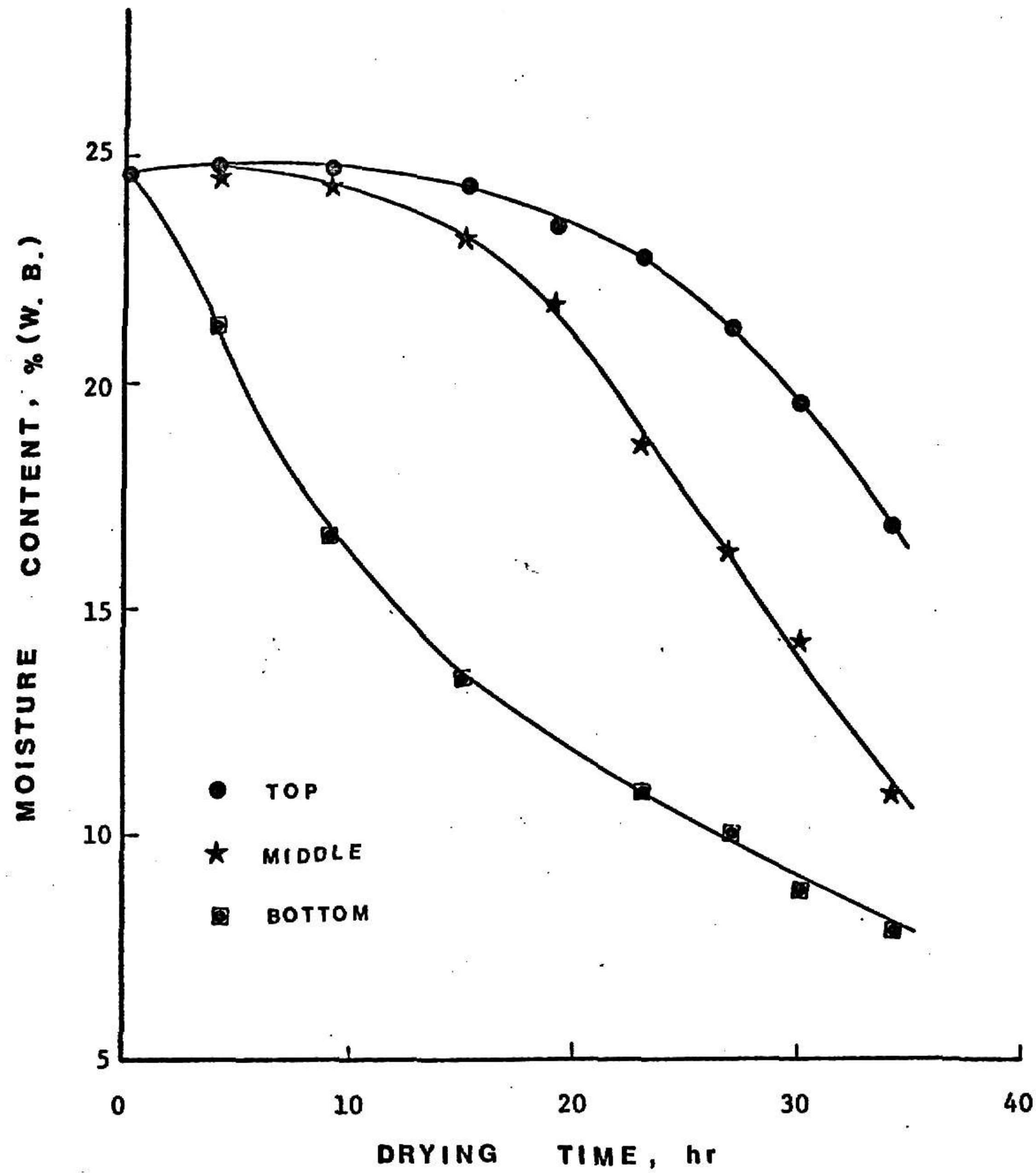

Figure 15. Moisture content versus drying time for drying with the unmodified drier(mean inlet air temperature of 76.0 ^{o}F and mean drying air temperature of 136.6 ^{o}F).

Table 15. Analysis of drying temperature data for testing the temperature difference in the plenum chamber in corn drying test.

Classification	Treatment	Direction	$\bar{D}$	$S_{\bar{D}}$	t
Natural convection	Unmodified drier (undisturbed)	Left-Right	0.63	1.21	0.52
		Front-Back	3.97	0.82	4.80*
	Modified drier (undisturbed)	Left-Right	0.05	1.14	0.04
		Front-Back	2.32	0.71	3.27*
	Modified drier (mixed - 2 hr)	Left-Right	0.02	0.72	0.03
		Front-Back	1.53	0.26	5.83*
Forced draft	4" depth	Left-Right	1.45	0.98	1.48
		Front-Back	2.52	1.02	2.45*
	6" depth	Left-Right	1.42	0.76	1.88
		Front-Back	2.62	1.12	2.32*

* ; Significant at 0.05 level(one-tailed test)

$\bar{D}$: Mean difference

$S_{\bar{D}}$: Standard deviation

t : t-test value

Table 16. Analysis of the corn moisture content data for testing the moisture gradient in the corn mass.

Classification	Treatment	Direction	$\overline{D}$	$S_{\overline{D}}$	t
Natural convection	Unmodified drier (undisturbed)	Top-Bottom	8.50	0.38	22.32*
		Left-Right	0.43	0.37	1.17
		Front-Back	0.97	0.25	3.86*
	Modified drier (undisturbed)	Top-Bottom	8.35	0.66	12.70*
		Left-Right	0.53	0.35	1.52
		Front-Back	0.63	0.44	1.44
	Modified drier (mixed-2 hr)	Top-Bottom	1.30	1.01	1.28
		Left-Right	0.67	0.62	1.08
		Front-Back	0.42	0.66	0.64
Forced draft	4" depth	Top-Bottom	6.35	0.05	127.00*
		Left-Right	0.25	0.31	0.81
		Front-Back	0.60	0.21	2.83*
	6" depth	Top-Bottom	6.90	0.07	97.60*
		Left-Right	0.18	0.63	0.28
		Front-Back	1.48	0.20	7.32*

* : Significant at 0.05 level(one-tailed test)

$\overline{D}$: Mean difference

$S_{\overline{D}}$: Standard deviation

t : t-test value

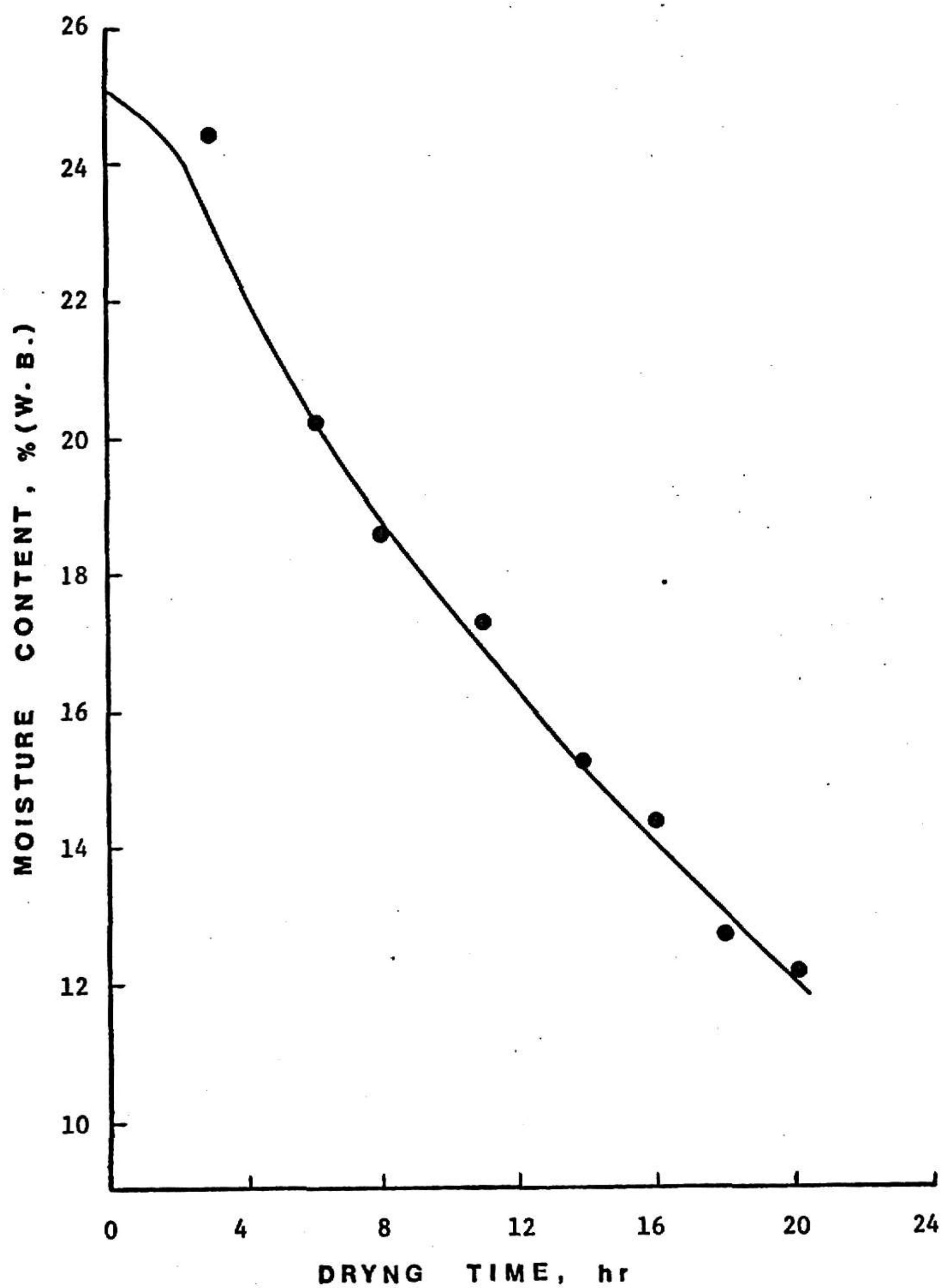

Figure 16. Moisture content versus drying time when mixed a bed at the intervals of two hours with the modified drier(mean inlet air temperature of 79.2 °F and mean drying air temperature of 138.9 °F).

in heat loss.

The effect of mixing on the final moisture content was a reduction in the moisture gradient between the top and bottom of the bed compared with unmixed grain as shown in Table 14. There was no practical difference in moisture gradient at any interval of mixing. A statistical analysis, as shown in Table 16, of the moisture data when the grain was mixed at the intervals of 2 hours after the start of drying showed that there was no significant gradient between the top and bottom of the bed. Therefore, the appropriate intervals of mixing can be assumed to be 2 to 4 hours, in other words, 5 to 10 times during the whole period required to dry from 25 to 12 % wet basis.

In forced draft drying with the airflow rate of 15 cfm/bu, the results as shown in Table 17 were obtained. The airflow rate calculated by heat input was about 4.5 % lower than the disired airflow rate of 15 cfm/bu. Figure 17 shows that there is no difference in the rate of evaporation between the different grain depths as long as the airflow rate per unit volume remains the same. The evaporation rate increased almost proportionally with the airflow rate compared to natural convection drying with the modified drier.

In Table 15, a statistical analysis of the drying temperature data obtained from the forced draft drying with a grain depth of 4 and 6 in is listed. The results show that there is a significant difference in drying temperature between the front and the back side of the bed. The mean temperature difference decreased greatly compared to the unmodified drier having the same height as the model for forced draft drying in spite of the higher airflow rate, about 4 times that of the unmodified drier. Therefore, it is possible to reduce the temperature difference inside the plenum chamber by modifying the shape of opening between the wall and the heating unit without increasing the height of drying floor. It should be noted that increasing the height of drying floor results in an increase

Table 17. Data for forced draft drying with the temperature rise of 60 ^{o}F and the airflow rate of 15 cfm/bu.

Grain depth (in)	Drying time (hour)	Grain moisture content(%, w.b.) Mean initial	Mean* final	Final at top	Final at bottom	Rate of evaporation (lb/hr.bu)	Utilization of heat (Btu/lb water)	Airflow*** rate (cfm/bu)
2	10.5	24.0	12.0	15.2	11.3	0.6872	1865(1565)**	14.52
4	11.0	23.6	11.5	15.3	9.0	0.6597	1702(1545)	14.60
4	10.5	24.1	11.7	15.4	9.0	0.6174	1603(1449)	14.02
6	12.0	24.0	10.8	15.7	8.9	0.6566	1558(1453)	14.10
6	12.0	25.4	11.3	15.8	8.8	0.7027	1490(1392)	14.40

* : calculated from loss of weight.
** : excluded heat loss through walls.
*** : calculated from heat input.

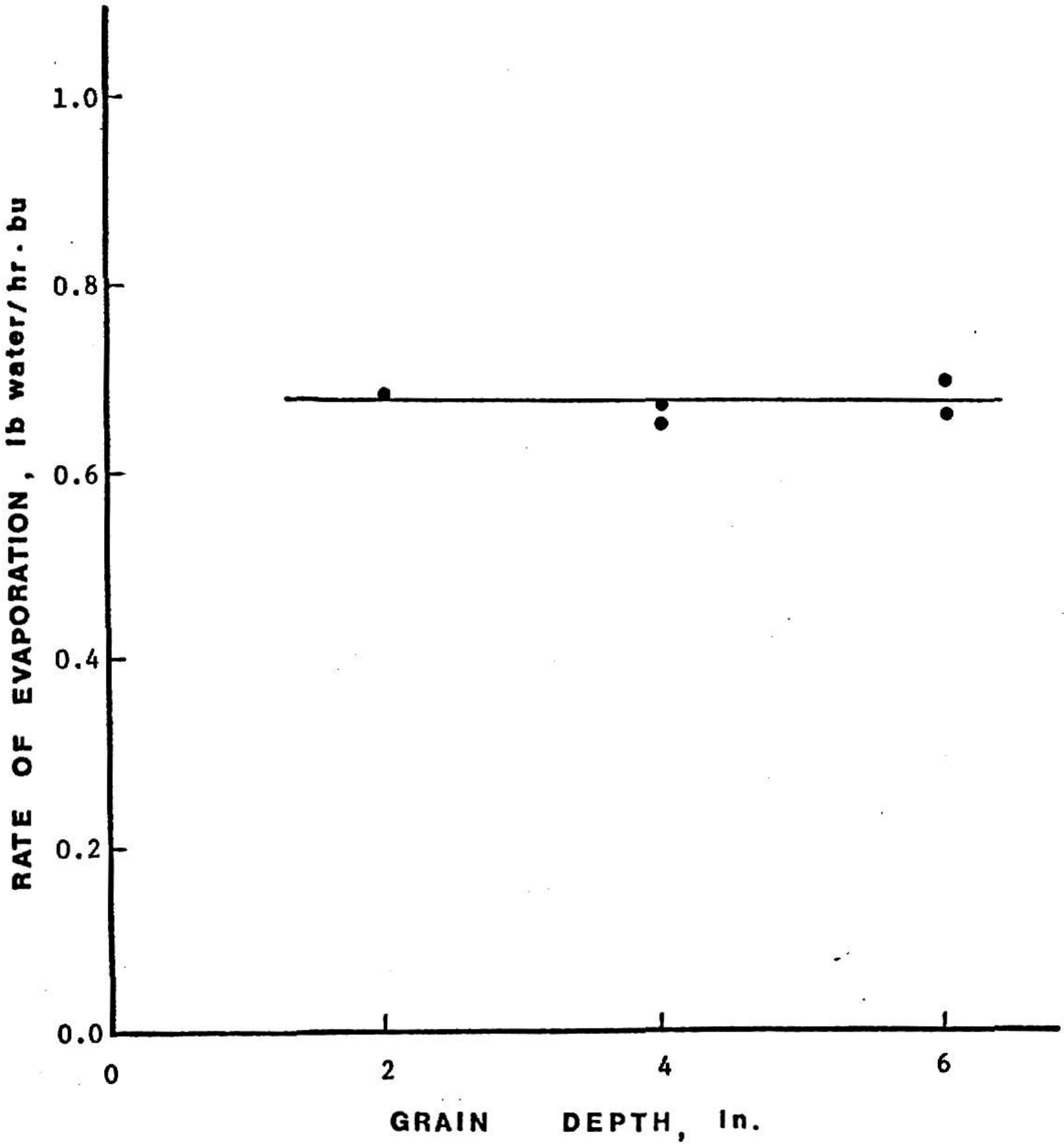

Figure 17. Rate of evaporation versus grain depth in forced drying with an airflow rate of 15 cfm/bu and a temperature rise of 60 °F.

of heat loss without any increase of airflow rate from the Phase I experiments with 5 mph wind.

In Table 16, a statistical analysis of the moisture content data is listed. The results indicated a significant difference in the moisture content between the top and bottom of the bed. As Woodforde(1965) stated, however, the mean difference in moisture content decreased compared to natural convection drying because of the higher airflow rate in forced draft drying.

Table 17 shows the utilization of heat increased with the grain depth. It can be explained by the fact that heat loss per unit volume through the wall decreases as the grain depth increases while the drying time remains the same. Similarly, the utilization of heat supplied into the grain, i.e., excluded the heat loss through the walls, increased as the grain depth increased since heat loss through the grain by conduction heat transfer decreases as the grain depth increases.

Summarizing the results, "Brook" drier can be modified to increase its drying capacity by modifying the air inlet, decreasing the grain depth, increasing the floor height and/or maintaining the drying air temperature as high as possible. For "Brook" drier with the drying floor of 8 ft x 8 ft, it is recommended that the floor height be 6.5 ft and the air inlet size be 4.7 ft^2 for the grain depth of 4 in. It will increase the drying capacity about 70 % over the conventional "Brook" drier. If the grain depth is decreased to 2 in, the drying capacity will increase about 50 % over that of the grain depth of 4 in. In this case the inlet size should be increased to 8 ft^2. Mixing or turning the bed during drying can improve drying rate and eliminate moisture gradient within the bed. During drying corn from 25 % to 12 it is recommended to mix or turn the grain bed thoroughly about 5 times.

CONCLUSIONS

From the results of this study the following conclusions were drawn :

I. For Phase I

(1) The size of air inlet has a significant effect on the rate of airflow. The air inlet should have the size which does not allow the air velocity through the inlet to be more than 53 ft/min.

(2) The rate of airflow decreased as the grain depth increased following the relationship given by :

$$q = C\ D^{-0.76}$$

where q : the airflow rate, cfm.

D : the grain depth, in.

C : constant for a given temperature rise and floor height.

(3) The rate of airflow increased linearly with the height of drying floor and the temperature rise from the inlet air temperature to the drying air temperature at the range tested.

(4) The rate of airflow can be predicted approximately in terms of the grain depth, the height of drying floor and the temperature rise following the equation given by :

$$q = 0.0024\ H \Delta T\ D^{-0.76}$$

where q : the rate of airflow per unit floor area, cfm/ft^2.

H : the height of drying floor from the center of the flue, in.

ΔT : the temperature rise from the inlet air temperature to the mean plenum temperature, ^{o}F.

(5) Wind has a tremendous effect on the airflow rate. The results showed that even a 5 mph wind increased the airflow rate as much as 5 times over natural convection without wind.

(6) The temperature difference between the front and back side of the bed increased as the height of drying floor decreased, more remarkably with 5 mph wind.

(7) The heat loss through the wall increased linearly with the height of drying floor and the temperature rise.

II. For Phase II

(1) The "Brook" drier, which had a modified air inlet and 50 % higher drying floor, showed an increase of 73 % in airflow over the conventional "Brook" drier, and of which 23 % was attributed to the improvement of inlet size in view of the results from Phase I.

(2) The evaporation rate of the modified "Brook" drier with the airflow rate of 6.9 cfm/bu was 0.24 lb water/hr.bu, about 50 % higher over the unmodified.

(3) There was no difference in the utilization of heat between the modified and unmodified drier. It agrees with the results from Phase I that the heat loss through the wall increases linearly with the height of drying floor.

(4) The temperature difference between the front and back side of drying floor was reduced considerably by increasing the height of drying floor. Consequently, there was a significant reduction in moisture gradient with the modified drier.

(5) Mixing or turning the bed during drying improved drying rate significantly. The final moisture gradient between the top and bottom of the bed was

eliminated by mixing the bed 5 times during the period required to dry corn from 25 % to 12 %.

(6) The evaporation rate in forced draft drying with the airflow rate of 15 cfm/bu was 0.66 lb water/hr. bu, which is about three times higher than that of the natural convection drying.

(7) Increasing the airflow rate by means of forced draft improved the utilization of heat by decreasing heat loss through the wall.

(8) In forced draft drying the temperature difference between the front and back side of the bed was reduced satisfactorily by modifying the shape of opening between the flue and wall without increasing the floor height.

(9) The evaporation rate increased almost proportionally with the airflow rate. Therefore, the drying capacity of "Brook" drier can be improved by modifying the air inlet size, decreasing the grain depth, increasing the floor height and/or maintaining the drying air temperature as high as possible.

SUGGESTIONS FOR FUTURE WORK

The following suggestions are recommended for future work :

1. Study the conventional flue using 50 GA.oil drum as a heat exchanger.
2. Develop a fire place for efficient combustion of fuel and for convenient disposal of combustion residue.
3. Conduct field tests to determine the optimum depth of grain for natural convection drying.
4. Study the use of manual fan to "Brook" drier to increase drying rate.
5. Repeat mixing experiments with field model.

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to the members of his graduate committee for their support and guidance in the completion of his work. Special thanks go to Dr. Do Sup Chung, the author's major professor, for his esteemed guidance and encouragement in the preparation of his master's thesis and through his graduate studies.

The author wishes to recognize the Food and Feed Grain Institute, Kansas State University, for financial assistance provided for this project. The author also expresses sincere appreciation to Mr. Dennis Kuhlman of Agricultural Engineering Department, who checked the English of this thesis.

The author is deeply indebted to his wife for her typing this thesis and sacrifice during this work.

REFERENCES

Allen,J.R. 1960. Application of grain drying theory of maize and rice. Journal of Agricultural Engineering Research 5(4) : 363.

Boyce, D.S. 1965. Grain moisture and temperature changes with position and time during thorough drying. Journal of Agricultural Engineering Research 10(4): 333-341.

Brook, J.A. 1964. A cheap crop drier for the farmer. Tropical Stored Products Information. (7) : 257-268.

__________ 1964. A cheap crop drier for the farmers : Results and recommended design. Tropical Stored Products Information. (8) : 301-307.

Chancellor, W.J. 1968. A simple grain drier using conducted heat. Transactions of the American Society of Agricultural Engineers. 11(6) : 857-862.

__________ 1971. Field testing a simple grain drier in Asia. Transactions of the American Society of Agricultural Engineers. 14(4) : 536-541.

Chung, D.S. and H.B. Pfost. 1967. Adsorption and desorption of water vapor by cereal grains and their products. Part II : Development of the general isotherm equation. Transactions of American Society of Agricultural Engineers. 10(4) : 553-556.

Clark, R.G. and W.J. Lamond. 1968. Drying wheat in two foot beds, I : Rate of drying. Journal of Agricultural Engineering Research. 13(2) : 141-148.

Corbett, G.G. 1973. Grain handling systems for the lowland tropics. Tropical Stored Products Information. (25) : 10-11.

Gallaher, G.L. 1951. A method of determining the latent heat of agricultural crops. Agricultural Engineering. St. Joseph, Michigan. 32(1) : 34

Henderson, S.M. 1943. Resistance of shelled corn and bin walls to airflow. Agricultural Engineering. St. Josept, Michigan.24(11) : 367.

__________ Pabis, S. 1961 Grain drying theory : I. Temperature effect on drying coefficient. Journal of Agricultural Engineering Research. 6(3) : 169.

__________ and R.L. Perry. 1966. Agricultural Process Engineering. Second edition. : 300.

Hustrulid, A and Flikke, A.M. 1959. Theorectical drying curve for shelled corn. Transactions of the American Society of Agricultural Engineers. 2(1) : 112.

Johnson, H.K. and Dale, A.C. 1954. Heat required to vaporize moisture. Agricultural Engineering. St. Joseph, Michigan, 35(10) : 705.

Kahn, A.U. 1973. Rice drying and processing equipment for Southeast Asia. Transactions of the American Society of Agricultural Engineers. 16(6) : 1131-1135.

Kutateladze, S.S. 1963. Fundamentals of heat transfer. Academic Press Inc., New York. : 21-22.

Lindblad, C., Newman, M. and Vinita, R. 1974. Construction manual for the mud-walled grain drier. Contonou, Dahomey.

Pabis, S. and Henderson, S.M. 1961. Grain drying theory : II. A critical analysis of the drying curve for shelled maize. Journal of Agricultural Engineering Research. 6(3) : 169.

Robinson, A. 1974. Food conservation at village level. West African Seminar on the Role of Volunteers in Grain Storage at Farm and Village Level. Contonou, Dahomey.

Simmonds, W.H.C., Ward, G.T. and McEwen, E. 1953. The drying of wheat grain. Part I : The Mechanism of Drying. Transactions of Institutions of Chemical Engineers, London. 31(3) : 265

Thorshaug, H. Construction and utilization of various farm and village level grain storage facilitities. Working paper No-2 for West African Seminar on the Volunteer Role in Farm and Village-Level Grain Storage, Contonou, Dahomey.

Webb, E.R. 1969. A crop drier and grain storage silo for the small farm. Ministry of Agriculture and Natural Resources, Ibadan, Nigeria.

Woodforde, J and P.J. Lawton. 1965. Drying cereal grain in beds six inches deep. Journal of Agricultural Engineering Research. 10(2) : 146-171.

APPENDIX

Table 18. Room conditions during the test for Phase I.

Date	Room temperature(^{o}F) Dry bulb	Wet bulb	Relative humidity(%)	Specific weight of air(lb/ft^3)
8.27	74.9	68.3	70	13.75
8.29	73.5	66.6	70	13.70
8.31	74.4	66.5	67	13.70
9.1	75.5	67.5	68	13.75
9.9	74.1	68.5	75	13.75
9.12	76.1	70.5	75	13.80
9.13	75.4	69 8	76	13.80
9.16	73.9	70.5	82	13.75
9.17	74.2	70.2	81	13.75
9.18	74.3	71.0	84	13.80
9.19	75.3	69.0	73	13.80
9.20	73.8	64.3	58	13.70
9.21	72.3	66.8	77	13.70
9.22	73.7	67.0	70	13.70
9.23	75.3	64.8	59	13.75
9.24	73.8	67.0	70	13.70
10.8	76.1	69.0	70	13.80
Average	74.5	68.1	72	13.75

Table 19. Room conditions during the drying test for Phase II.

Classification		Room temperature(^{o}F) Dry bulb	Wet bulb	Relative humidity(%)
Natural convection	Unmodified model	74.3	62.6	52
		75.8	63.6	51
		76.0	65.8	59
	Modified model	76.3	62.8	49
		77.0	63.9	50
		76.2	67.3	63
	Modified model (mixed-1 hr)	78.0	67.3	57
	Modified model (mixed-2 hr)	79.2	67.3	55
		77.5	65.5	53
	Modified model (mixed-4 hr)	78.2	65.5	52
Forced draft	2" depth	74.0	64.0	58
	4" depth	76.1	64.8	58
		80.4	68.7	56
	6" depth	77.5	66.2	56
		78.0	63.9	48
Average		77.0	65.3	54

Table 20. Test results for the effects of inlet size and grain depth on airflow rate with a height of 27.5 in and a temperature rise of 40 °F.

Depth (in)	Inlet size (in^2)	Inlet temp. (°F)	Plenum temp. (°F)	Leaving temp. (°F)	Temp. rise (°F)	Power (watt)	Plenum temperature(°F)* F-L	F-M	F-R	B-L	B-M	B-R
2	17	74.8	114.5	97.2	39.8	235.3	116.1	116.3	115.2	113.4	113.1	113.0
2	17	73.0	112.7	91.4	39.7	230.8	114.0	114.1	114.0	111.3	111.3	111.3
2	34	75.8	115.4	100.8	39.6	294.1	116.8	116.8	116.2	114.3	114.1	114.1
2	34	72.5	112.3	95.7	39.8	270.3	113.7	113.7	113.1	111.0	111.0	111.0
2	51	75.7	115.3	101.9	39.6	305.3	116.8	116.9	116.0	114.2	114.0	113.9
2	51	74.1	114.3	98.0	40.2	310.3	115.8	115.8	115.1	113.0	113.0	113.0
4	17	76.0	114.5	90.7	38.5	202.0	115.5	116.7	115.0	113.4	113.2	112.9
4	17	74.7	113.3	89.0	38.6	197.8	114.8	115.1	114.0	112.0	112.0	111.9
4	34	75.7	115.4	95.1	39.7	215.1	116.2	116.8	116.0	114.6	114.5	114.3
4	34	75.7	115.7	91.1	40.0	222.2	117.5	117.5	116.8	114.3	114.2	114.1
4	51	75.9	115.3	95.5	39.4	212.8	116.1	116.8	116.1	114.3	114.3	114.2
4	51	75.7	115.5	91.2	39.8	222.2	117.1	117.3	116.3	114.3	114.1	114.1
6	17	73.1	112.9	83.5	39.8	178.6	113.8	115.0	113.4	111.9	111.7	111.4
6	17	75.4	114.4	85.4	39.0	183.7	115.9	116.7	115.4	112.7	112.9	112.6
6	34	73.2	112.1	85.3	38.9	181.8	113.1	113.8	112.7	111.1	111.1	110.9
6	34	75.2	115.5	88.1	40.3	187.5	116.6	117.0	116.3	114.3	114.3	114.2
6	51	74.3	113.2	87.1	38.9	180.2	114.2	115.2	113.8	112.2	111.9	111.8
6	51	75.0	115.2	87.7	40.2	180.0	116.4	116.8	116.1	114.0	114.0	114.0

* : F-L : Front-Left F-M : Front-Middle F-R : Front-Right B-L : Back-Left B-M : Back-Middle
B-R : Back-Right

Table 21. Test results for the effects of inlet size and grain depth on airflow rate with a height of 27.5 in and a temperature rise of 60° F.

Depth (in)	Inlet size (in^2)	Inlet temp. (°F)	Plenum temp. (°F)	Leaving temp. (°F)	Temp. rise (°F)	Power (watt)	Plenum temperature (°F) F-L	F-M	F-R	B-L	B-M	B-R
2	17	75.8	135.8	103.6	60.0	384.6	137.2	137.3	136.9	134.7	134.7	134.0
2	17	76.4	136.1	106.2	59.7	381.0	137.6	137.7	137.5	134.6	134.5	134.4
2	34	73.1	134.2	105.2	61.1	487.8	135.5	136.6	135.1	133.0	133.0	132.2
2	34	73.8	134.3	108.2	60.5	483.2	135.7	136.1	135.9	132.8	132.7	132.4
2	51	72.7	134.2	107.0	61.5	555.6	136.4	135.6	134.6	132.9	132.8	132.6
2	51	73.1	134.2	110.3	61.1	562.5	136.0	135.6	135.0	132.8	132.8	132.8
4	17	75.2	134.5	102.9	59.3	327.9	135.7	136.4	135.7	133.0	133.0	132.9
4	17	74.7	134.5	100.4	59.8	330.3	135.8	136.1	136.0	133.2	133.1	133.0
4	34	75.3	134.4	106.0	59.1	392.2	135.7	136.0	135.5	133.0	133.0	132.9
4	34	74.5	134.4	101.7	59.9	395.6	135.7	135.7	135.7	133.1	133.0	133.0
4	51	75.0	134.0	107.1	59.0	388.3	135.5	135.7	135.2	133.0	132.9	132.8
4	51	74.4	134.0	101.7	59.6	400.0	135.3	135.5	135.2	132.6	132.6	132.6
6	17	72.7	135.1	104.6	62.4	307.7	136.1	137.0	136.2	133.8	133.8	133.7
6	17	75.6	135.8	91.3	60.2	298.5	137.6	137.9	136.9	134.2	134.2	133.9
6	34	73.7	135.1	104.0	61.4	342.9	136.1	137.0	136.3	133.7	133.7	133.7
6	34	76.0	136.2	92.1	60.2	322.6	138.0	138.1	137.4	134.7	134.7	134.5
6	51	73.2	134.8	104.7	61.6	346.2	135.4	136.8	136.1	133.5	133.4	133.4
6	51	75.2	136.2	92.3	61.0	322.6	137.8	138.0	137.5	134.7	134.7	134.5

Table 22. Test results for the effects of the floor height on airflow rate with a temperature rise of 60 ^oF and a grain depth of 4 in.

Wind (mph)	Height (in)	Inlet size (in^2)	Inlet temp. (^oF)	Plenum temp. (^oF)	Leaving temp (^oF)	Temp. rise (^oF)	Power (watt)	Plenum temperature(^oF) F-L	F-M	F-R	B-L	B-M	B-R
0	27.5	34	73.6	135.0	99.2	61.4	404.0	136.0	136.0	136.5	133.8	133.8	133.6
0	27.5	34	75.9	135.3	101.4	59.4	395.6	136.1	136.1	136.6	133.9	133.7	133.4
0	21.5	34	72.1	134.8	91.2	62.7	333.3	136.6	136.1	136.2	134.0	132.8	132.9
0	21.5	34	73.9	133.9	102.3	60.0	327.3	135.5	135.5	135.0	132.7	132.7	132.4
0	15.5	34	76.4	135.5	95.4	59.1	256.4	136.8	138.3	138.0	134.0	132.8	132.8
0	15.5	34	73.7	133.9	101.9	60.2	251.7	135.7	135.7	135.4	132.2	132.1	132.1
5	27.5	34	74.6	137.7	115.7	63.1	1242.4	142.6	141.8	141.7	135.8	129.4	135.0
5	27.5	34	73.0	134.6	116.9	61.6	1214.3	136.9	138.8	138.8	131.5	129.7	131.6
5	21.5	34	73.0	134.4	111.2	61.4	1162.3	140.8	138.9	138.9	131.0	126.6	130.4
5	21.5	34	75.4	134.7	121.0	59.3	1206.9	140.6	140.9	141.5	129.6	125.3	130.2
5	15.5	34	74.9	136.8	113.0	61.9	1114.3	145.2	145.4	145.5	130.4	125.3	129.0
5	15.5	34	71.4	130.2	117.9	58.8	1187.5	140.0	139.0	140.5	122.5	117.3	121.7

Table 23. Test results for the effects of the temperature rise on airflow rate with a floor height of 27.5 in and a grain depth of 4 in.

Temp. rise (°F)	Inlet size (in^2)	Inlet temp. (°F)	Plenum temp. (°F)	Leaving temp. (°F)	Temp. rise (°F)	Power (watt)	Plenum temperature(°F) F-L	F-M	F-R	B-L	B-M	B-R
60	34	73.6	135.0	99.2	61.4	404.0	136.0	136.0	136.5	133.8	133.8	133.6
60	34	75.9	135.3	101.4	59.4	395.6	136.1	136.1	136.6	133.9	133.7	133.4
40	34	75.7	115.4	95.1	39.7	215.0	116.2	116.8	116.0	114.6	114.5	114.3
40	34	75.7	115.7	91.1	40.0	215.6	117.5	117.5	116.6	114.3	114.2	114.1
20	34	75.9	96.7	82.0	20.8	82.6	97.3	97.1	97.1	96.6	96.1	96.0
20	34	75.8	95.7	81.4	19.9	83.3	96.1	96.1	96.1	95.4	95.3	95.2

Table 24. Heat loss through the wall and the grain bed by conduction heat transfer.

Floor height (in)	Temp. rise (°F)	Grain depth (°F)	Inlet temp. (°F)	Plenum* temp. (°F)	Surface temp. (°F)	Temp.** rise (°F)	Power (watt)	Plenum temperature (°F) F-L	F-M	F-R	B-L	B-M	B-R
27.5	40	2	74.3	112.3	83.1	38.0	129.9	114.1	115.9	112.1	111.1	110.3	110.1
27.5	40	2	73.7	112.0	83.5	38.3	127.7	114.8	115.1	113.8	109.9	109.2	109.2
27.5	40	4	73.2	111.6	81.5	38.4	114.3	112.8	114.4	111.8	110.4	110.2	109.9
27.5	40	4	72.7	112.1	81.0	39.4	110.4	114.8	115.5	113.3	109.9	109.8	109.7
27.5	40	6	74.0	113.4	79.4	39.3	107.5	114.9	116.3	113.1	112.0	111.9	111.4
27.5	40	6	73.1	112.1	81.3	39.0	101.1	113.8	114.9	113.0	110.3	110.4	110.1
27.5	60	2	73.9	133.2	91.4	59.3	199.4	135.4	137.5	133.1	131.5	130.9	130.7
27.5	60	2	74.7	134.5	90.7	59.8	204.5	138.6	138.7	135.8	131.8	130.9	131.1
27.5	60	4	75.9	134.9	89.6	59.0	166.7	136.8	136.3	136.6	133.4	133.1	133.1
27.5	60	4	74.5	134.5	93.8	60.0	163.6	136.7	137.4	135.5	132.6	132.6	132.1
27.5	60	6	73.3	134.4	91.1	61.1	160.0	135.7	137.3	134.9	132.9	132.9	132.5
27.5	60	6	76.1	134.9	84.2	58.8	151.3	138.4	139.2	136.5	132.0	131.8	131.5
21.5	60	4	73.5	134.6	86.7	61.6	147.1	135.9	135.8	136.5	133.4	132.9	132.9
21.5	60	4	72.8	132.8	89.1	60.0	143.4	134.8	136.5	133.9	130.4	130.4	130.6
15.5	60	4	73.7	132.3	95.4	58.6	118.7	133.1	137.5	133.2	130.1	130.1	130.0
15.5	60	4	72.2	132.2	84.4	60.3	125.9	135.0	138.8	133.1	129.5	129.4	129.4
27.5	20	4	74.1	95.2	81.6	21.1	54.6	95.8	96.3	95.3	94.8	94.8	94.4
27.5	20	4	78.5	98.5	84.3	20.0	56.5	99.3	98.9	98.8	98.5	97.7	97.7

* : mean plenum temperature.
** : mean temperature rise.

Table 25. Drying data from Phase II experiments.

Classification		Drying time (hour)	Initial m.c. (%)	Final m.c. (%)	Final m.c. at top(%) F-L	F-R	B-L	B-R	Average	Bottom final m.c.(%)	Total heat (Btu)
Natural convection	Unmodified model (undisturbed)	36.0	24.3	10.6	15.5	16.6	15.0	15.3	15.6	6.9	38908
		33.5	23.8	9.1	15.3	15.6	14.4	14.4	14.9	6.6	39591
		34.0	24.4	11.5	17.2	17.8	16.4	16.6	17.0	8.0	38556
	Modified model (undisturbed)	22.0	24.8	12.0	16.6	17.3	16.4	16.8	16.8	7.9	36860
		22.0	24.0	10.2	15.6	15.8	14.4	15.2	15.5	7.7	38555
		21.0	23.9	11.4	17.0	17.8	17.3	16.8	17.2	8.9	36508
	"(mixed-1 hr)	19.0	24.4	11.6	11.9	11.9	11.7	11.7	11.8	11.5	37543
	"(mixed-2 hr)	19.0	24.2	10.5	11.6	11.0	12.2	12.4	11.8	10.4	36860
	"(mixed-2 hr)	20.0	24.9	12.2	13.5	12.6	13.6	12.1	12.9	11.7	37202
	"(mixed-4 hr)	20.0	24.9	11.4	12.0	11.2	13.0	11.3	12.1	11.0	37202
Forced draft	2" depth	10.5	24.0	12.0	15.4	15.8	15.0	14.6	15.2	11.3	16719
	4" depth	11.0	23.6	11.5	15.6	15.9	14.6	15.0	15.3	9.0	30375
	4" depth	10.5	24.1	11.7	15.5	15.8	15.4	15.4	15.4	9.0	27645
	6" depth	12.0	24.0	10.8	16.7	16.2	14.8	15.3	15.7	8.9	45052
	6" depth	12.0	25.4	11.3	16.6	16.9	15.0	15.4	15.8	8.8	45905

Table 26. Drying conditions during the drying test for Phase II.

Classification		Initial grain temp. (°F)	Inlet temp. (°F)	Plenum temp. (°F)	Leaving temp. (°F)	Temp rise. (°F)	Heat input (Btu/hr)	Plenum temperature(°F) F-L	F-M	F-R	B-L	B-M	B-R
		62	74.3	134.9	80.4	60.6	1060	135.9	138.2	136.7	135.0	131.1	132.4
	Unmodified	83	75.8	139.3	84.0	63.5	1143	140.6	142.6	141.1	138.8	135.6	137.0
		61	76.0	136.6	78.5	60.6	1045	137.4	139.3	138.3	136.2	133.6	134.6
		62	76.3	136.1	80.1	59.8	1620	136.4	137.6	137.9	135.4	134.8	134.4
Natural	Modified	80	77.0	139.3	81.1	62.3	1741	140.3	141.0	140.9	138.1	137.8	137.6
convection		61	76.2	135.4	82.4	59.2	1634	135.9	136.3	136.4	134.9	134.7	134.1
	"mixed-1 hr	78	78.0	137.9	84.1	59.9	1907	137.8	138.8	139.1	138.2	136.5	136.6
	"mixed-2 hr	70	79.2	138.8	81.4	59.7	1867	139.6	139.6	140.2	138.2	138.1	137.6
	"mixed-2 hr	64	77.5	136.9	84.6	59.4	1728	137.0	137.8	137.9	136.9	136.0	136.0
	"mixed-4 hr	64	78.2	138.1	81.8	59.9	1738	138.4	138.7	139.0	137.6	137.6	137.3
	2" depth	62	74.0	135.2	87.4	61.2	1580	137.2	137.3	136.2	134.1	133.3	133.0
	4" depth	68	76.1	135.7	87.8	59.6	2696	137.3	139.5	133.7	134.2	134.8	134.9
Forced draft	4" depth	71	80.4	139.4	87.5	59.0	2586	141.2	143.2	138.2	137.9	137.9	138.3
	6" depth	67	77.5	137:9	87.6	60.4	3847	138.6	143.4	136.0	136.2	137.0	136.0
	6" depth	70	78.0	139.6	86.3	61.6	3754	139.8	145.0	137.6	138.6	139.0	137.9

FACTORS AFFECTING DRYING PERFORMANCE OF A NATURAL CONVECTION DRIER

FOR DEVELOPING COUNTRIES

by

KWAN HEE RYU

B. S., Seoul National University, 1967
M. S., Seoul National University, 1972

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

The broad objective of this study was to develop a simple and low-cost grain drier which can be used at farm and village levels in developing countries. The approach taken was to modify the "Brook" drier to increase its drying performance.

In Phase I experiments, "Brook" drier was evaluated in terms of airflow rate and its relationships with the air inlet size, the grain depth, the temperature rise and the height of drying floor. The results revealed that the airflow rate increased with the temperature rise and increased drying floor height, but decreased as the grain depth increased.

The air inlet size had a significant effect on the airflow rate. The maximum allowable velocity through the air inlet appeared to be 53 ft/min. The following equation which can be used to predict the airflow rate of the "Brook" drier was developed

$$q = 0.0024\ H \Delta T\ D^{-0.76}$$

where q : the rate of airflow per unit area of bed, cfm/ft^2

H : the height of drying floor from the center of the flue, in.

ΔT : the temperature rise from the inlet air temperature to the mean plenum temperature, ^{o}F.

D : the grain depth in bed, in.

Wind has a tremendous effect on the airflow rate. The test showed that even a 5 mph wind increased the airflow rate about 5 times over natural convection without wind.

In Phase II experiments, the study was conducted with yellow dent corn to evaluate the drying performance of the "Brook" drier. The modified air inlet size increased the airflow rate as much as 23 % over the conventional "Brook" drier. Drying capacity of "Brook" drier was increased proportionally by increasing the height of drying floor without reducing the utilization of heat. The evaporation rate of "Brook" drier with a modified air inlet and 50 % higher drying floor increased about 50 % over the unmodified.

The temperature difference between the front and back side of drying floor was reduced considerably by increasing the height of drying floor. Consequently, there was a significant reduction in moisture gradient with the modified drier. The final moisture gradient between the top and bottom of the bed was eliminated by mixing the bed 5 times during the period required to dry corn from 25 % to 12 %. There was also some improvement in drying rate by mixing or turning the bed.

Increasing the airflow rate by means of forced draft improved the utilization of heat. The evaporation rate in forced draft drying with the airflow rate of 15 cfm/bu was 0.66 lb water/hr. bu, which is about three times higher than that of the natural convection drying. The temperature difference between the front and back side of the bed was reduced satisfactorily by modifying the shape of opening between the flue and wall without increasing the height of drying floor.

This investigation showed several ways to improve the grain drying performance of "Brook" drier for developing countries.