DEHYDRATION CHARACTERISTICS OF GRAIN SORGHUM

by

BETZABE SULBARAN RODRIGUEZ

B.S., Universidad del Zulia, Venezuela, 1975

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

FOOD SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1979

Approved by:

Do Sup Chung

Major Professor

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A: Shape factor, constant

$\bar{A}$: Mean of A.

a: Area, ft^2

ANOVA: Analysis of variance test

B: Constant

bu: Bushels (1.25 cubic feet)

C: Constant

C.I.: Confidence interval

C_d: Discharge coefficient

c: Henderson Isotherm Equation constant

cfm: Cubic feet per minute

Cp: Specific heat, Btu lbs/°F

D: Pipe diameter, inch

d: Nozzle diameter, inch

D_v: Diffusion coefficient, ft^2/hr

d.b.: Dry basis

ERH: Equilibrium relative humidity, %

exp: Exponential

F: Statistical test

F^1: Velocity of approach factor

h_w: pressure drop, inch of water

K: Drying constant, hr^{-1}

$\bar{K}$: Mean drying constant, hr^{-1}

k: Thermal conductivity, Btu lb/°F

K_{11}, K_{12}, K_{13}: Phenomenological coefficients in Luikov's Equation

K_{21}, K_{31},...: Coupling coefficient in Luikov's Equation

LSD: Least significant difference in statistical analysis

M.: Moisture content, % d.b.

m: Moisture content, % w.b.

M.C.: Moisture content %

M(t): Moisture content at any time, %, d.b.

M_e: Equilibrium moisture content, %, d.b.

MR: Moisture ratio

n: Number of observation

P: Pressure, psia

P_a: Vapor pressure of water in grain, psia

P_o: Vapor pressure of water in air as it was saturated, psia

r^2: Coefficient of correlation

R_e: Reynold's number

RH: Relative humidity, %

S: Standard deviation

T: Temperature, °F

T_{abs}: Temperature, °R

t: Time, hr

V: Volume, ft^3

w.b.: Wet basis

W: Absolute humidity, lb of water/lb dry air

W_d: Dry matter, lb

W_h: Mass flow, lb/hr

W_m: Moisture, lb

Z: Airflow rate, cfm/bu

GREEK SYMBOLS

β: Diameter ratio

∂: Differential sign

∇^2: Laplacian operator

θ: Time, hr

π: 3.1416

∞ : Infinity

ρ: Density, lb/ft^3

INTRODUCTION

Grain sorghum has been used mostly for animal feed, although in recent years it has also been used as a source of starch in industries such as brewing. Since sorghum is usually harvested early and at high moisture content to reduce field losses, it is often necessary to dehydrate the grain to increase its shelf life and insure safe future storage. Dehydration lowers the availability of water to microorganisms which are the first and most dangerous limitation to shelf life. The growth of microorganisms is a function not only of the moisture content in the product but also of the temperature and humidity of the storage system.

Grains are hygroscopic materials which generally contain adsorbed moisture. The moisture exerts a vapor pressure in the grain that varies according to the moisture content of the grain. The equilibrium relative humidity of air in contact with the grain is determined by the ratio of moisture vapor pressure to the saturated vapor pressure of pure water at a specified temperature of the grain. When the relative humidity of the air in contact with the grain is higher than the equilibrium relative humidity of the grain at its moisture content, the grain will gain moisture, while for the reverse case the grain will lose moisture. Thus the equilibrium moisture properties of grain are very important in storage and drying.

Dehydration of grain is accomplished by three principal methods:

- Sun grain drying is a method that has been used widely in developing countries. The grain is scattered on a big surface and turned several times until dry.

- Artificial drying method uses high temperature air and high speed airflow. This is the most common drying method for food and grain.
- Natural air drying or air with supplemental heat. In this method the air is mildly heated to increase the drying potential. Airflow rate is low. It requires more time than artificial drying since the temperature is lower, but it is much less expensive due to the lower energy requirement.

Whereas the drying characteristics of other cereal grains such as corn and wheat are well known, the physical, thermal properties, and dehydration characteristics of grain sorghum under the natural air drying method have not been clearly determined. Such information is needed for developing grain sorghum drying and storage facilities. Therefore, the investigation was made to determine the drying characteristics of grain sorghum for the natural air and artificial drying methods and to study how they are affected by the different drying conditions.

LITERATURE REVIEWED

Grain Sorghum Generalities

Grain sorghum is one of the four classes of sorghum crops, the others being sweet sorghum, broom corn, and grass sorghum.

This cereal thrives in semi-arid and humid regions. It is an important crop in Asia and Africa. It is also grown in the United States, where it is the fourth major crop after corn, soybeans, and wheat, and in some areas of Argentina and Southern Europe.

Sorghum is the world's third most important food grain, being exceeded in utilization for food by only wheat and rice.

Before World War II, grain sorghum was used largely for feed, but since that time the crop has been improved with new varieties more resistant to damage by insects and diseases, offering higher yields and more economical to harvest and handle.

This grain is approximately equal to corn as a feed grain for most classes of livestock, although there are differences in contents of proteins, oil, and vitamin A that should be considered. It may be used directly as a feed grain, or it may be processed by the mixed feed industry into commercial feed preparation.

Grain sorghum has a pronounced flavor that has slowed the acceptance by persons not accustomed to consuming it from an early age.

Grain sorghum has an economical advantage over other cereals, which is why efforts are being made to use the flour as an ingredient of human foods. Some treatments have been applied to sorghum in order to reduce its characteristic strong flavor.

In many parts of Africa sorghum is the most important food grain and makes up a large part of the diet for the majority of the population.

Dry milling process yields grits very low in oil and fiber and thus suitable for production of flour of good quality which provides an excellent starting material for wet milling to starch. Grits can also be used in brewing, as corn and rice have been used. Sorghum grain flours have been converted to adhesives and sizings for various purposes, by Blank (1955), Matz (1959, 1969), and Pomeranz (1976).

Most grains of diverse crops are subject to drying. A grain is a living organism and can be defined as a colloidal capillary-porous body which contains a large amount of micro- and macro-capillaries, where moisture can move from the inside to the surface and vice versa.

Water is a vital component of grain; it is contained on its surface, in its capillaries, and also inside the cells of the various component parts of the grain. High moisture content in grain reduces its shelf life in storage since high moisture is a condition favorable to microorganisms and pests. Therefore, drying is attempted to increase the shelf life of the grain.

Drying Characteristics and Drying Theory

Information about drying characteristics of cereal grains is needed to insure efficient drying. This information has been determined for grains such as corn or wheat, but relatively few studies have been done for grain sorghum, particularly on the drying characteristics of this grain being dried in natural air conditions. Due to the nature of all cereal grains, it is assumed that the drying theory for other cereal grains is also applicable to grain sorghum.

The main reason there are few drying and storage studies of grains other than corn and wheat is the lack of basic physical and thermal property data. Sharma and Thompson (1973) found the thermal conductivity, Cp, and k, specific heat for sorghum as function of the moisture content as follows:

$$Cp = 0.337 + 0.007M \quad (1)$$

$$k = 0.0564 + 0.000858M \quad (2)$$

where M is moisture content expressed in percent, dry basis.

Drying characteristics of grain are being described as the changes occurring in the grain when subjected to drying air and are best represented by the rate of moisture removal as drying progresses. Principal parameters that affect drying process are initial moisture content, temperature and humidity of the drying air, airflow rate, and other variables.

Studies for describing the drying characteristics have been developed for a thin layer and a deep bed of grain. When the grain is theoretically fully exposed to the drying air a thin layer is considered, and when a series of layers are stacked on top of each other and the grain is not fully exposed to the drying air a deep bed is considered.

Drying is a process where simultaneous heat and moisture transfer occur. The heat is utilized to evaporate the moisture which is removed from the drying product surface by the air, by Brooker et al. (1974).

The drying of a column of grain can be considered an adiabatic process. This implies that the heat required for evaporation of the grain moisture is supplied solely by the drying air, without transfer of heat by conduction or radiation from the surroundings. As the air passes through the wet grain mass, a large part of the sensible heat of the air is transformed into latent heat as a result of the increasing amount of water held in the air as vapor. During the adiabatic drying process there is a decrease in the dry-bulb temperature, together with an increase in the humidity ratio, W, and relative humidity, the vapor pressure, and the dew point temperature. The enthalpy and the wet bulb temperature remain practically constant during the adiabatic drying process. In Figure 1 the process of grain drying can be seen, by Brooker et al. (1974).

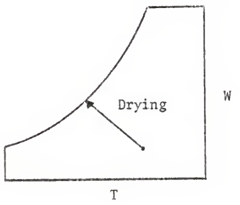

Figure 1. Representation on the psychrometric chart of the process of grain drying.

According to Henderson and Perry (1976), drying processes can be divided into two periods, the constant rate and the falling rate drying periods. In the first period moisture will evaporate as it will from an open-faced body of water, while in the falling rate period moisture evaporation comes from the available water in the grain. The falling rate drying mechanism involves movements of moisture within the material to the surface and removal of the moisture from the surface. Practically all agricultural drying takes place in the falling rate period, and the constant rate, if any, is often neglected because it represents a small part of the drying period when compared to the falling rate.

As the grain is being dried a moisture content gradient appears within the drying product, and the product temperature rises above the wet bulb temperature of the drying air. Since cereal grains usually dry solely during the falling rate period, the drying rate decreases continuously during the course of drying. Henderson and Pabis (1961), and others.

There are several mechanisms proposed for describing the transfer of moisture in capillary porous products such as cereal grains: capillary flow, liquid diffusion, surface diffusion, vapor diffusion, thermal diffusion, and hydrodynamic flow.

Luikov (1966) and his co-workers have developed a mathematical model for describing the drying of capillary porous products based on the physical mechanisms listed above. The model equations are a system of partial differential equations of the following form:

$$\begin{aligned} \frac{\partial M}{\partial t} &= \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P \\ \frac{\partial T}{\partial t} &= \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P \qquad (3) \\ \frac{\partial P}{\partial t} &= \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} P \end{aligned}$$

where K_{11}, K_{22}, and K_{33} are the phenomenological coefficients, while the other K-values represent the coupling coefficients, M is moisture content, T is temperature, P is pressure, and t is time. The coupling results from the combined effects of the moisture, temperature, and total pressure gradients on the moisture, energy, and total mass transfer.

The drying of cereal grains occurs under circumstances that allow simplifications of Luikov's drying equation.

The total pressure gradient is responsible for a moisture flow which is insignificant for the range of temperatures used in cereal grain drying. Therefore, the pressure terms can be dropped from the original equations. A second simplification is the elimination of the coupling effects of temperature and moisture, which are required in a very limited number of cereal grains. The latest simplification resulted when the temperature gradient in the kernel was ignored, since in practical analysis of cereal grain drying the temperature is assumed to be uniform throughout the kernel during the drying process. This has been also confirmed by Brooker et al. (1974), Chittenden et al. (1966), Henderson and Pabis (1961), and Hukill (1947).

Simplified Luikov's Equation:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \qquad (4)$$

The term K_{11} is then substituted by a D_v of diffusion coefficient since the moisture transfer inside the kernel is believed to be diffusion.

With appropriate initial and boundary conditions, the following solution of equation (4) was obtained for an infinite slab:

$$MR = A \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp[(-2n+1)^2 Kt] \qquad (5)$$

where MR is moisture ratio, A is the shape factor, and n is the number of observations. There are expressions with little variations for spheric and cylindrical shapes. The moisture ratio, MR, is found as follows:

$$MR = \frac{M_{(t)} - M_e}{M_o - M_e} \qquad (6)$$

For larger values of time the higher terms of Eq. (5) become negligible and can be expressed:

$$MR = A\ e^{-Kt} \qquad (7)$$

which has been used satisfactorily for most of the basic thin layer drying studies, such as Hukill (1947), Chittenden and Hustrulid (1966), and others.

Hukill (1947 and 1950) also developed a method to find the moisture content of grain at any given depth in a deep-bed drying system at any time after drying began. Paulsen and Thompson (1973) developed a drying simulation model to predict drying results in a deep bed.

Donald and Gordon (1960) developed a prediction equation for measuring the drying effect of air circulated through a bed of grain, in a batch or bed of grain of uniform depth and dried by forced circulation of heated or unheated air at a uniform rate.

Brooker, Bakker-Arkema, and Hall (1974) have described other theoretical models not only for thin and deep beds, but also for crossflow, concurrent flow, and counter current flow drying systems.

The drying constant, K, which is calculated from Equation (7) is temperature dependent. Fan et al. (1963), Henderson and Pabis (1961,

1962) and others have found that K and temperature follows an Arrhenius type Equation. Pabis and Henderson (1961) found an expression for corn:

$$K = 194.4\ e^{-5023/T_{abs}} \qquad (8)$$

where K is in hr^{-1}.

O'Callaghan et al. (1971) reported K value for wheat and barley using an equation similar to Equation (7), without constant A. They found:

$$K_{wheat} = 72 \times 10^5\ e^{-9179/T_{abs}} \qquad (9)$$

and

$$K_{barley} = 501480\ e^{-7976/T_{abs}} \qquad (10)$$

K in hr^{-1}.

Besides temperature, other conditions which affect the drying constant are airflow rate, initial moisture content, and bed depth. As the temperature of the drying process is increased, the drying constant increases; as the airflow rate increases, the K increases; and finally when either initial moisture content or depth is increased, the K value decreases. Those effects have been reported by Brooker et al. (1974).

Adsorption and Desorption

The term M_e on Equation (6) is called equilibrium moisture content. It is a function of the state characteristics of the drying air, and therefore it is constant if the air temperature and RH are constant. It is very important in the study of grain drying, because M_e determines the minimum moisture content to which grain can be dried under a given set of conditions. The M_e has been defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time, by Henderson and Pabis (1961) and Brooker et al. (1974).

Water in a hygroscopic material of a certain moisture content produces a water vapor pressure which is less than the saturated water vapor pressure of pure water at the same temperature as the material. The ratio of these pressures is the equilibrium relative humidity, ERH, for that particular moisture content and the temperature of the material, by Henderson (1952).

Equilibrium moisture curves have been described by a number of workers in the literature; one of the most widely used is the Isotherm Equation developed by Henderson (1952).

$$1 - RH = \exp(-cT\ M_e^{\ n}) \qquad (11)$$

where c and n are constant varying with material.

The equilibrium moisture properties of cereal grains are of great importance in storage and drying.

Grains can gain moisture when vapor pressure in the surroundings is greater than the water vapor pressure inside them; this process is called adsorption. They can lose moisture when the water vapor pressure inside them is greater than that of the surroundings; this process is called desorption. The amount of water that can be adsorbed by grains is studied by means of the isotherm. An isotherm is a curve describing the amount of water in a substance at a particular temperature as a function of the equilibrium vapor pressure, water activity or relative humidity.

The isotherms of adsorption and desorption of capillar porous bodies do not coincide, this phenomenon is called sorption hysteresis. In general terms, if a grain is moist after drying, lesser values of moisture content will be obtained with the same value of relative humidity, by Chung and Pfost (1967), and Gerzhoi and Samochetov (1958). Hysteresis phenomenon can be seen on Figure 2.

Drying Methods

Drying of grain can be accomplished in general in three principal methods. Sun drying uses the sun's rays and atmospheric air to dry the grain. This method has been widely used in developing countries. Grain is spread on flat surfaces and is turned occasionally until the moisture content is reduced to a desired level. The second method is natural air drying, or air with supplemental heat. Natural air is used to dry the grain according to its drying capacity. The air should have a relative humidity less than 75% and usually temperature less than 100°F. Under less favorable conditions supplemental heat is required. This method

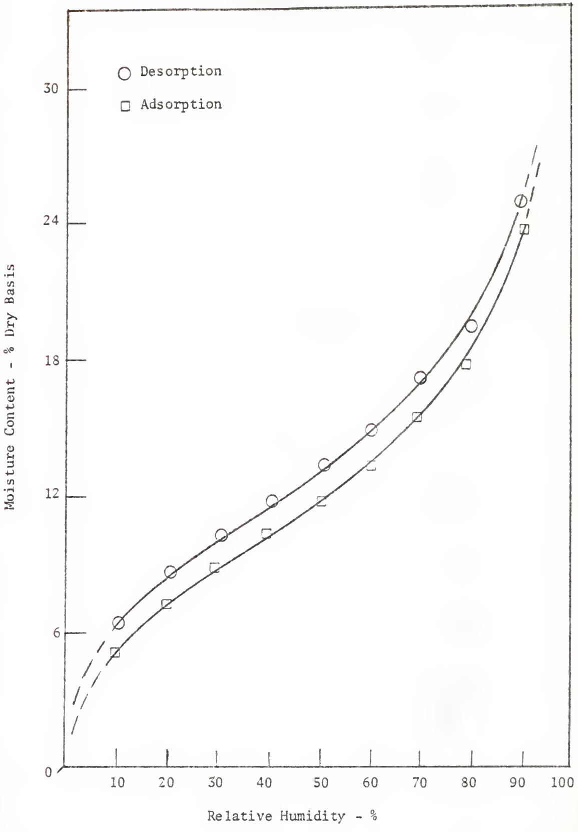

Figure 2. Adsorption-desorption isotherms for corn at 22°C showing hysteresis. Data from Chung and Pfost (1967).

is used with airflow of 1 to 5 cfm/bu, depending upon the moisture content and the kind of grain. It takes from five days to two or three weeks for drying, depending upon the initial moisture content of the grain, depth of grain, airflow rate, and weather conditions.

When heated air is forced by fans through a bed of grain until the desired moisture content is achieved, the grain at the intake site--frequently the bottom of the bin--dries most rapidly; that where the air leaves takes longer to dry. Therefore, drying takes place in a narrow layer called "zone of drying." This zone moves upwards in the direction of air movement until it finally has passed through all the grain.

In general, as the air passes through the grain, its wet bulb temperature remains unchanged, its dry bulb temperature drops as evaporation takes place, and its relative humidity increases, by Hukill (1947).

The third method, artificial drying, uses heated air and airflow from 10 to 100 cfm/bu for drying batches 1 1/2 ft deep or less. High air flow is necessary to prevent condensation in the grain or on the surface. Thin layer drying with this method is accomplished in two to three hours or a little more depending on the depth of grain, drying air temperature, and airflow rate. For methods using heated air, grain has to be cooled down after drying to prevent moisture migration.

The drying Equation that has been discussed is based on the thin-layer drying concept. The thin layer dries uniformly, and no gradients are assumed. This concept does not hold, however, for finite mass depth. The air temperature, humidity, relative humidity, and specific volume change as the air moves through a finite mass. The change in air state affects a progressive change in the drying rate because the temperature change affects the diffusivity, D_v; the relative humidity affects the equilibrium moisture content, M_e; and the changes in specific volume affect the air rate. Owing to the variables listed above, the top of the layer, Figure 3, would dry at a slower rate and have a higher moisture content after a period of time than the lower portion of the layer. The difference in moisture content between the top and bottom would increase progressively to a maximum and then decrease as drying progresses.

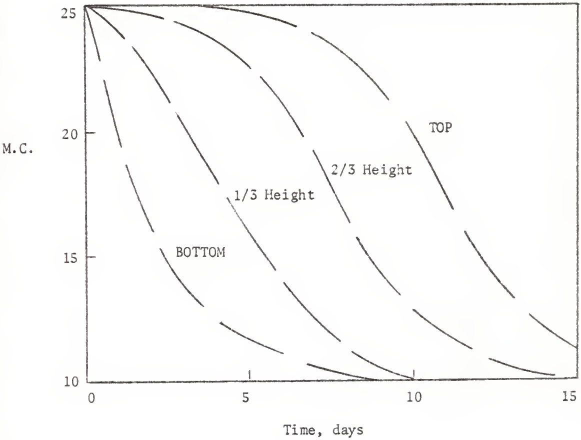

Figure 3. Schematic moisture pattern for dryers with air movements from bottom to top. (Henderson and Perry, 1976).

The moisture content curves, top and bottom, comes closer together as the bed height is reduced or as the air rate is increased. A decrease in air temperature brings the curves closer together but the drying time will be expanded. An increase in air temperature reduces the drying time but causes the curves to be farther apart (reported by Brooker et al. (1974), Henderson and Perry (1976), and Hukill (1947)).

Temperature of drying air must be kept below some maximum value depending on the intended use of the grain. 110°F is usually recommended as a maximum grain temperature for drying grain for seed; 125°F would damage the germ in most seeds. For milling, temperatures above 140°F should be avoided, and for feed grains, 190°F is often considered as the high temperature limit, although much higher temperatures are used.

Recommendations for temperature limitations to avoid harmful effects are usually stated on the basis of drying air temperatures, whereas the important consideration is the temperature of the grain. Furthermore, when high temperatures are used for long times, the effect on the grain is detrimental, but high temperature can be used for a short time without bad effects. Either high temperatures or high airflow may cause physical and chemical damage to the product.

To avoid product damage such as checking and cracking, recommended precautions are: low temperatures for drying, cooling heated grain slowly, removing a limited amount of moisture at a pass followed by a resting period.

Air is used in drying operations as a carrier element. It carries heat into the system to evaporate moisture and then carries the evaporated water out of the system.

When air is forced through a layer of grain, resistance to the flow, the so-called pressure drop, develops as a result of the energy lost through friction and turbulence. The pressure drop for airflow through any product depends on the rate of airflow, the surface and shape characteristics of the product, the number, size and configurations of the voids, the variability of particle size, and the depth of the product bed.

A common term used in designating specific airflow is cfm/bu. cfm/bu is defined as the total airflow to the bin divided by the number of bushels of grain in the bin. Most previous investigators have found that the single-kernel drying rate is not affected by changing the drying air velocity throughout the range generally used for drying packed beds. The airflow rate effect on the temperature differential is probably more significant than the surface moisture resistance factor, because of lowering the kernel temperature during drying, by Chittenden and Hustrulid (1966), and Henderson and Pabis (1962).

OBJECTIVES

The objectives of this research are:

1) To investigate the effects of temperature, airflow rate, initial moisture content, and depth of grain on the drying process.
2) To determine the drying constant, K, and to study its relationship with the drying conditions.

MATERIALS AND METHODS

Grain sorghum at 12% moisture content wet basis was used in this work to find the drying constant. Natural air drying method was used.

After receiving the grain it was cleaned with a clipper M-2B (A.T. Ferrell & Company). Since grain sorghum was to be used at 18% and 22% moisture content wet basis, the original (12% M.C. w.b.) was rewetted in a tumbling mixer until each specific moisture content was achieved. This work was performed for two grain bed depths, 6 inches and 12 inches; for the 6 inch depth 2.5 bushels of grain were rewetted, and for the 12 inch depth 5 bushels were used. The rewetting process lasted 20 hrs or less. The experimental design for natural air drying tests are tabulated in Table 1.

The drying process was carried out in two bins (Bin I, and Bin II) made of wood. Each had a 30 square inch bed. The walls contained glass fiber insulation and had a 3 inch wide styrofoam layer on the outside. The top consisted of two styrofoam sheets separated enough to permit ventilation. In each bin was an 8 inch plenum where a perforated drying floor, 35% open area, was placed. Bin I was used for experiments using 1 cfm/bu with the 6 inch and 12 inch depths, and for 2 cfm/bu with the 6 inch depth. Bin II was used for 2 cfm/bu with the 12 inch depth and for 3 cfm/bu for both depths. The specific use of each bin was determined by the exact amount of cfm through the pipe of the bins. Bin I had a 2 inch diameter pipe while Bin II had a 3 inch diameter pipe. Therefore, Bin I was used for smaller airflow rates than Bin II.

TABLE 1. Experimental Design for Natural Air Drying Tests.

Temperature (°F)	Airflow Rate (cfm/bu)	Initial Moisture Content (%, w.b.)	Depth (inch)
90	1	18	6
			12
	2	18	6
			12
		22	6
			12
	3	18	6
			12
		22	6
			12
100	1	18	6
			12
	2	18	6
			12
		22	6
			12
	3	18	6
			12
		22	6
			12
120	1	18	6
			12
	2	18	6
			12
		22	6
			12
	3	18	6
			12
		22	6
			12

Ambient air was taken by a fan (a Dayton blower Model ICI80 with intake damper to control the airflow for Bin I, and a Dayton Shunt Wound blower D C motor Model 6K357 with speed control for Bin II) and passed through a resistance type heater operated by a Honeywell thermistor in which the desired temperature was set. The heated air passed through a pipe to the bin, and finally through the grain bed, then leaving the bin with an increase in its absolute humidity. In order to measure the airflow rate, a nozzle was placed in the pipe connecting the heater and the bin (nozzle diameter, 0.5 inch for pipe on Bin I, and 1 inch for pipe in Bin II). The inlet and outlet pressure connections were connected to a manometer (The Merian Instruments Co. Model 34FB2) which measured the pressure drop in inches of water, regulating the amount of cfm passing through the pipe. A schematic diagram of experimental set-up is shown in Fig. 4.

Example of determination of airflow rate: for experiment No. 1.

T = 100°F

Airflow rate = 1 cfm/bu

M.C. = 18% w.b.

Depth = 6 inches

Volume of grain = 2.5 bushels

D, diameter of pipe = 2 inches

d, diameter of nozzle = 0.5 inches

$$W_h = 359\ C_d\ F^1\ d^2 \sqrt{h_w \rho} \qquad (12)$$

where, W_h is mass flow; C_d, discharge coefficient; F^1, velocity of approach factor; d, nozzle diameter; h_w, pressure drop; and ρ density.

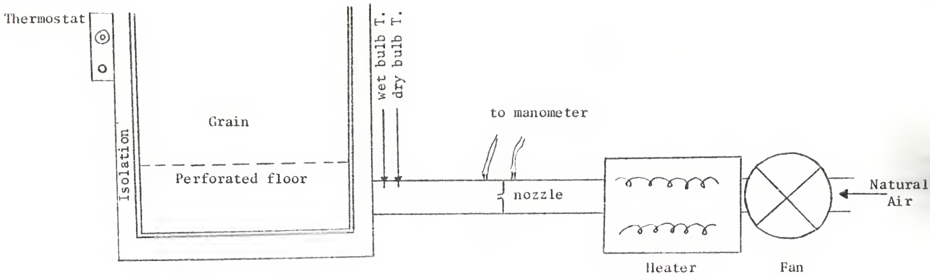

Figure 4. Sketch of the Dryer for the Natural Air Drying Conditions.

$$F = \frac{1}{\sqrt{1-\beta^4}} ; \qquad (13)$$

$$\beta = \frac{d}{D} \qquad (14)$$

where β is a diameter ratio.

C_d is evaluated with the Re and β.

Using Equation (13):

$$W_h = 359 \times 0.92 \times 1.002 \times (0.5)^2 \sqrt{0.233 \times 0.071} = 10.641 \text{ lb/hr}$$

$$\frac{10.641 \text{ lb/hr}}{\rho\ (60)} = \frac{10.641}{0.071 \times 60} = 2.498 \text{ cfm}$$

$$\frac{2.498 \text{ cfm}}{2.5 \text{ bu}} = 0.999 \text{ cfm/bu} \approx 1 \text{ cfm/bu}$$

Determinations were made by using the ASME Power Test Codes (1959).

To determine the relative humidity of the drying air entering the bins, two thermometers were placed in the pipe by the wall of the bins; the bulb of one was covered with a permanent wet cloth for reading the wet bulb temperature, and the second thermometer read the dry bulb temperature of the air.

As previously mentioned 2.5 bushels or approximately 140 lbs. were used for the 6 inch bed depth, and 5 bushels or approximately 280 lbs. for the 12 inch bed depth. For each experiment those specific weights of rewetted grain were placed in the bins, and then all the drying conditions were controlled; samples were taken to determine the initial moisture content of the grain. In addition, samples were taken every 8 hrs. for experiments at 100°F and 120°F, and every 12 hrs. for the 90°F temperatures. At each sampling time dry and wet bulb temperatures were read to further determine the relative humidity, and the flow rate was checked.

Representative and random samples for determining the moisture content were taken by using a tapered seed trier. The moisture content of the samples were found by two methods:

- First, using a steinlite automatic moisture tester (serial DM 125) in which 250 gr. samples are used. The moisture content of the sample in wet basis is given by the instrument.
- Second, using the Oven method, approximately 4 gr. samples were weighed in a Balance Meter DI200N and then placed in a Blue M Laboratory Oven (Model OV-500C-2) at 130°C for approximately 18 hrs. From Henderson and Perry (1976).

For the high temperature and high airflow dehydration conditions an Aeroglide Laboratory Tray Drier was used. The temperatures were set and controlled automatically, and the airflow was measured by installing a pipe with a nozzle in the air exit of the equipment. Dry and wet bulb temperatures were read before the air passed the grain. Samples were taken frequently every 2 or 3 hrs.

Conditions used were temperatures of 140°F and 180°F, airflow rates of 20 and 40 cfm/bu, and initial moisture content of 22% w.b. which were evaluated in the same way explained for the natural air drying conditions with heated air.

RESULTS AND DISCUSSION

The experimental results are tabulated in Table 13 in the Appendix. They show the variation of moisture content with time for all the different drying conditions of temperature, airflow rate, initial moisture content, and depth. Experiments for the higher temperatures have higher rates than the ones for the lower temperatures. For the high airflow rate experiments, Table 13 shows high drying rates. Variations due to different initial moisture content and depth of grain can also be noticed: the higher the initial moisture content, the lower the drying rate; the deeper the bed of grain, the lower the drying rate.

Experimental data in Table 13 was further studied by analytical means, and the discussion of results, based on statistical analysis, is presented later in this section.

Table 2 shows the drying conditions for each natural air drying experiment. From that table one can see that there were small fluctuations in temperature setting; the relative humidity was higher for lower temperatures as well as the equilibrium moisture content.

A typical dehydration curve for grain sorghum in this study is shown in Figure 5. Experiments were made for three different temperatures, 90°F, 100°F, and 120°F. For the 100°F temperature, one replication was made with all the other conditions but the 3 cfm/bu airflow rate and 18% initial moisture content (w.b.).

The following Graphs 6, 7, 8, and 9 were plotted in order to visualize individual effects of temperature, airflow rate, initial moisture content, and depth of grain on the drying rate: Figure 6 shows effect of

TABLE 2. Data on drying air conditions: wet bulb temperature, dry bulb temperature, RH, and M_e.

Temp (°F)	Air Flow (cfm/bu)	M.C. (% w.b.)	Depth (in.)	Dry bulb T. (°F)	Wet bulb T. (°F)	RH (%)	M_e (% d.b.)
90	1	18	6	91.52	73.85	44.28	12.01
			12	89.51	73.82	43.89	11.95
	2	18	6	89.38	74.38	50.00	12.95
			12	92.30	77.10	50.83	13.06
		22	6	90.65	75.65	50.83	13.07
			12	87.94	73.61	51.59	13.22
	3	18	6	89.90	74.12	48.59	12.72
			12	90.20	75.66	51.43	13.18
		22	6	90.14	75.33	50.83	13.08
			12	94.82	76.55	44.46	12.01
100	1	18	6	104.05	75.26	26.63	9.03
			12	104.00	79.27	34.49	10.34
	2	18	6	103.35	74.71	26.73	9.06
			12	108.34	77.90	26.15	8.92
		22	6	103.48	69.91	17.65	7.38
			12	104.88	70.92	17.65	7.38
	3	18	6	101.60	73.70	26.67	9.06
			12	101.30	73.80	27.67	9.23
		22	6	103.98	68.79	15.63	6.97
			12	103.01	72.30	22.72	8.35
100 Replication	1	18	6	103.04	74.02	25.79	8.90
			12	104.76	79.40	33.59	10.19
	2	18	6	102.74	73.53	26.94	9.10
			12	105.59	78.87	31.03	9.76
		22	6	102.60	69.80	18.69	7.60
			12	105.52	74.67	23.52	8.48
	3	18	6	-	-	-	-
			12	-	-	-	-
		22	6	103.49	68.00	15.00	6.84
			12	103.40	72.13	21.74	8.17

TABLE 2. (Contd.)

Temp (°F)	Air Flow (cfm/bu)	M.C. (% w.b.)	Depth (in.)	Dry bulb T. (°F)	Wet bulb T. (°F)	RH (%)	M_e (% d.b.)
120	1	18	6	120.28	81.17	19.18	7.59
			12	118.30	81.85	21.79	8.09
	2	18	6	118.74	80.60	19.44	7.65
			12	120.00	80.20	19.23	7.60
		22	6	119.38	81.20	20.00	7.75
			12	120.87	80.96	18.33	7.42
	3	18	6	121.00	80.09	17.50	7.26
			12	120.20	80.90	19.00	7.55
		22	6	117.23	80.42	20.71	7.89
			12	119.60	81.20	19.48	7.65

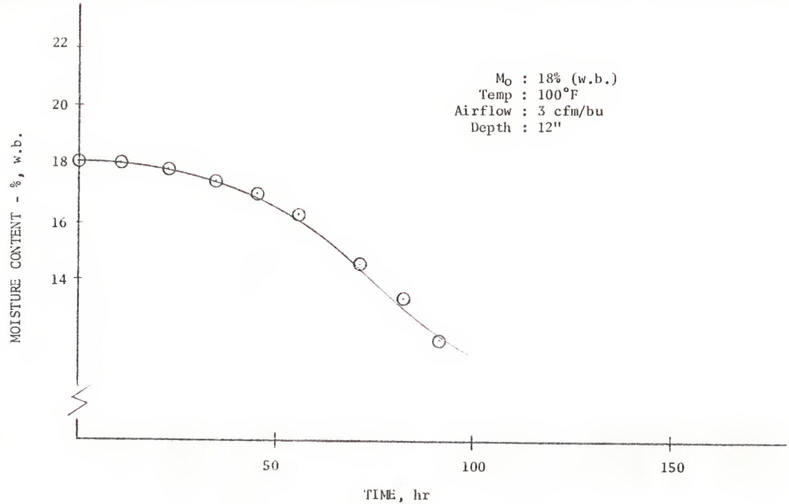

Figure 5. Typical dehydration curve of grain sorghum.

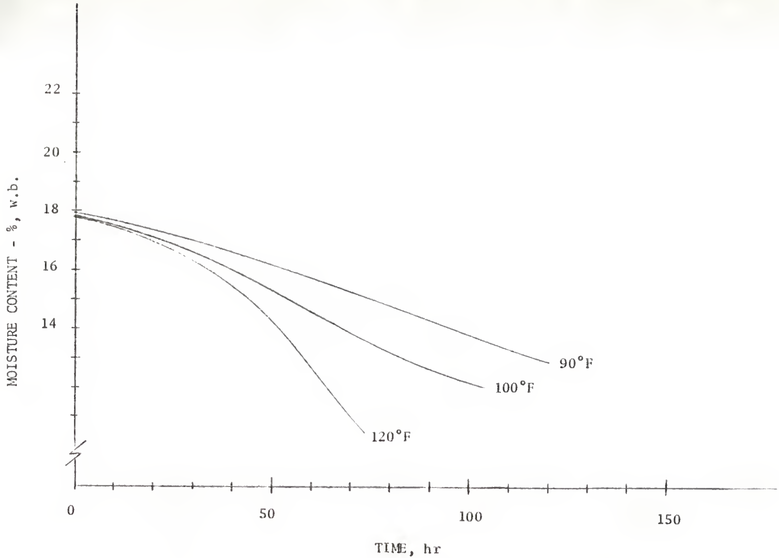

Figure 6. Effect of temperature on dehydration of grain sorghum at 3 cfm/bu, 18% initial moisture content (w.b.), and 6 inch depth.

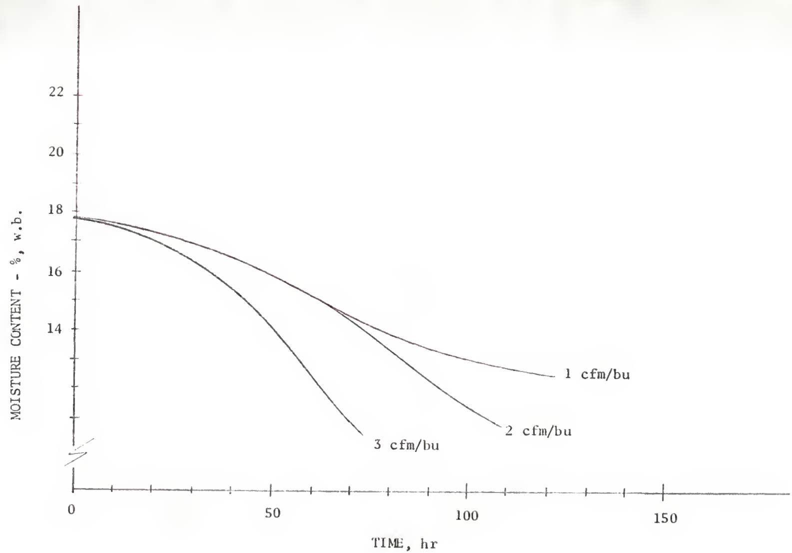

Figure 7. Effect of air flow rate on dehydration of grain sorghum at 120°F, 18% Mo (w.b.), and 6 inch depth.

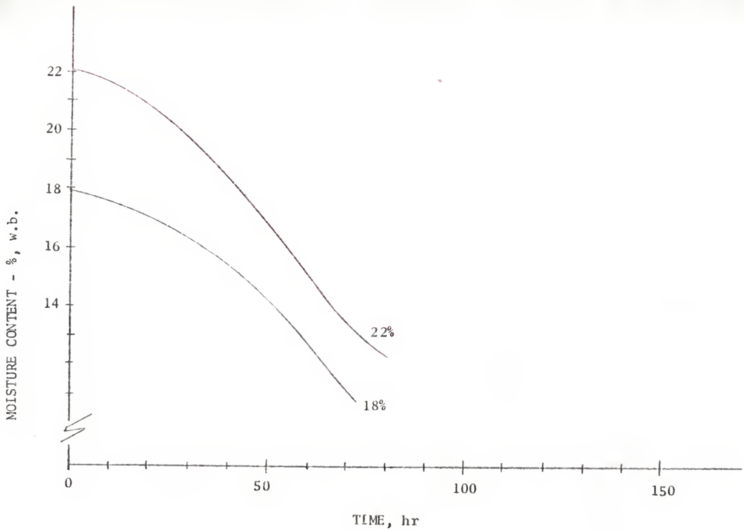

Figure 8. Effect of initial moisture content on dehydration of grain sorghum at 120°F, 3 cfm/bu and 6 inch depth.

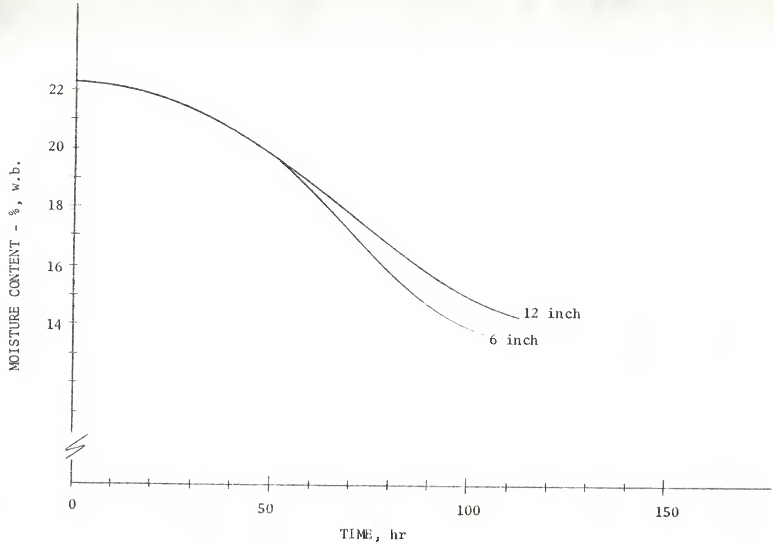

Figure 9. Effect of depth on dehydration of grain sorghum at 120°F, 2 cfm/bu, and 22% Mo (w.b.).

temperature; Figure 7 effect of airflow rate; Figure 8 effect of initial moisture content; and Figure 9 effect of depth. For each case, the other parameters were kept constant. For example, in Figure 6 the airflow, initial moisture content, and depth for the 90°F, 100°F, and 120°F temperatures are all kept constant.

From Figure 6 it can be seen that the 120°F temperature produced the highest rate of dehydration. Also, there seems to be more difference

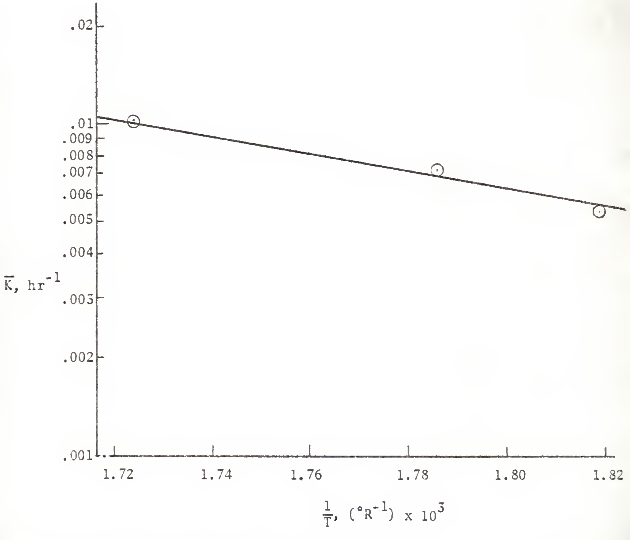

Figure 10. Effect of temperature on drying constant.

in the rate between the 120°F and 100°F temperatures than between the 100°F and 90°F temperatures. A relationship was found between the mean K and the temperature. Figure 10.

In Figure 10 the effect of temperature on the drying constant follows an Arrhenius type equation. This kind of relationship has been reported by other workers, such as Brooker et al. (1974), Fan et al. (1963), Henderson and Pabis (1962), and O'Callaghan et al. (1971), and has been confirmed with the data of this study based on 38 observations.

The Equation,

$$\bar{K}_{sorghum} = 241.4\ e^{-5844/T_{abs}} \qquad (15)$$

was found from the plot in Figure 10. It has a very good fit with a correlation coefficient of 0.99.

From Figure 7 can be noticed the highest effect of the 3 cfm/bu airflow on the dehydration rate compared to the 2 cfm/bu and 1 cfm/bu. 2 cfm/bu and 1 cfm/bu have only slightly different effects. Further analysis of the data showed an exponential function between airflow and drying constant, using the mean value of K from all the experiments with 1 cfm/bu, 2 cfm/bu, and 3 cfm/bu, for 18% and 22% M.C. w.b. Figure 11.

The relationship turned out to be:

$$\bar{K} = 1.003\ e^{.41\ z} \qquad (16)$$

where z is airflow rate in cfm/bu. The equation has a correlation coefficient of .997.

Initial moisture content effect is shown in Figure 8. The highest rate of drying corresponds to the 18% moisture content (w.b.).

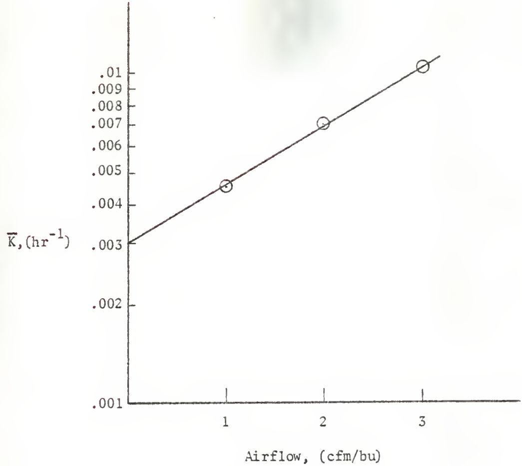

Figure 11. Effect of airflow rate on drying constant.

The effect of the depth on drying rate is shown in Figure 9. The highest rate of drying corresponds to the 6 inch depth.

Since the replication of the experiments at the 100°F temperature were not exactly the same for the K value, a statistical test "paired sample t test" was applied in order to check the replications, $t_7 = 0.207 < t_{7,5\%} = 2.365$, therefore, they showed a non-significant difference at the 5 percent level.

Determination of the drying constant, K, was made by using Equation 7. On a moisture ratio, MR, against time plot (Figure 12), K would be the slope, and A would be the intercept.

In order to find the constant A and K of Equation (7) the data of the 38 experiments was used in an SAS-76 computer program which performs a least squares estimation. The moisture ratio, MR, was plotted versus time. Figure 12 shows an example of an MR vs. Time plot.

Results from the SAS-76 computer program are tabulated in Table 3; where the values of A, K, and r^2 are evaluated for specific conditions of temperature, airflow, initial moisture content, and depth of grain.

Curves of MR versus Time resulted in a very good fit for most cases, with values of r^2 ranking from 0.80 to 0.99 for the 90°F temperature experiments; from 0.74 to 0.96 with an exception of a 0.64 in the 100°F temperature experiments and from 0.72 to 0.97 for their replications; and from 0.84 to 0.96 for the 120°F temperature experiments, as seen in Table 3. Therefore, it can be said that Equation (7) describes very well the drying process for grain sorghum.

Experimental values of the shape factor, A, were fairly constant throughout all the experiments, having a mean of 1.1013 with a standard deviation, s, of 0.067, and $1.2378 \leq A \leq 0.9648$, 95% C.I.. The theoretical value for this constant is 1.

From Table 3 it is important to notice the variation of the drying constant with each individual parameter. K values for the 120°F temperature experiments are higher than the values for the 100°F temperature experiments and therefore higher than the 90°F temperature experiments. In addition, the drying constant values corresponding to 3 cfm/bu airflow rate turned out to be the highest at each temperature for all experiments, being the second place for the 2 cfm/bu and so on. Furthermore, it can be noticed that as the initial moisture content is higher, the K values are smaller. Finally, the effect of depth is like the initial moisture content effect: as the depth of grain is increased, the drying constant is decreased.

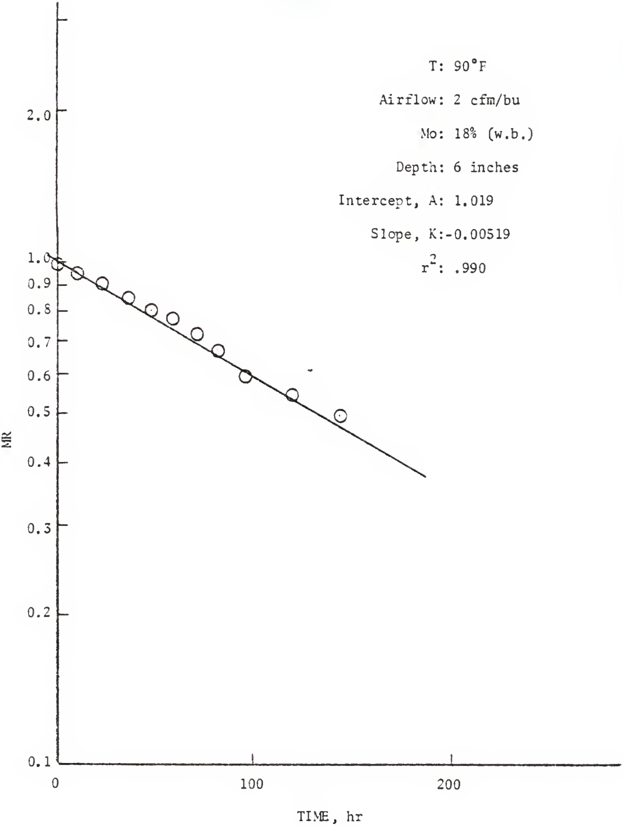

Figure 12. Semilog plot of MR vs. Time for finding the drying constant, K, and the shape factor A.

TABLE 3. Values of A, K, and r^2 from the MR vs. Time plot for the natural air drying experiments.*

Temp (°F)	Air Flow (cfm/bu)	Mo (%, w.b.)	Depth (in.)	A	K (hr^{-1})	r^2
90	1	18	6	1.072	0.00356	0.94
			12	0.897	0.00274	0.80
	2	18	6	1.019	0.00519	0.99
			12	0.953	0.00429	0.98
		22	6	1.157	0.00622	0.95
			12	1.010	0.00498	0.98
	3	18	6	0.999	0.00893	0.98
			12	1.051	0.00743	0.98
		22	6	1.134	0.00721	0.89
			12	1.062	0.00624	0.98
100	1	18	6	1.080	0.00472	0.95
			12	1.067	0.00309	0.89
	2	18	6	1.100	0.00719	0.92
			12	1.121	0.00577	0.74
		22	6	1.139	0.00887	0.93
			12	1.108	0.00512	0.64
	3	18	6	1.178	0.01088	0.93
			12	1.178	0.00908	0.83
		22	6	1.245	0.01074	0.79
			12	1.142	0.00981	0.85
100 replication	1	18	6	1.126	0.00572	0.94
			12	1.040	0.00402	0.97
	2	18	6	1.110	0.00876	0.93
			12	1.132	0.00651	0.72
		22	6	1.139	0.00777	0.92
			12	1.106	0.00639	0.80
	3	18	6	--	--	--
			12	--	--	--
		22	6	1.078	0.00935	0.95
			12	1.138	0.00789	0.88

TABLE 3. (Contd).

Temp (°F)	Air Flow (cfm/bu)	Mo (%, w.b.)	Depth (in.)	A	K (hr^{-1})	r^2
120	1	18	6	1.082	0.00667	0.96
			12	1.062	0.00528	0.97
	2	18	6	1.191	0.01028	0.90
			12	1.123	0.00808	0.91
		22	6	1.158	0.00900	0.89
			12	1.108	0.00741	0.96
	3	18	6	1.159	0.01461	0.84
			12	1.079	0.01345	0.94
		22	6	1.138	0.01330	0.93
			12	1.168	0.01241	0.85

*SAS-76 computer program output

Study of the experimental data was made by using an AARDVARK computer program which performed an analysis of variance, ANOVA, and an LSD test.

As seen in the experimental design (Table 1), the 1 cfm/bu was used only with 18% initial moisture content (w.b.) since the 22% Mo (w.b.) is not applicable for such a low airflow. Therefore, an ANOVA was made for the three air temperatures 90°F, 100°F, and 120°F, 2 depths, 6 inch and 12 inch, and three airflow rates, 1 cfm/bu, 2 cfm/bu, and 3 cfm/bu. Table 4.

TABLE 4. ANOVA table for the natural air drying conditions with 18% M.C. (w.b.)

Source of Variation	Degrees of Freedom	Mean Square	F
Temperature	2	0.000029	231.069
Airflow Rate	2	0.000056	447.558
Depth	1	0.000011	84.991
Error	12	0.00000012	
Total	17		

The ANOVA table shows that the highest mean square corresponds to the airflow rate. This means that the airflow rate has more effect on the dehydration rate than any other of the variables studied. Temperature is occupying the second place with a mean square lower than the one for airflow rate. Of the other two variables, the depth factor had the least effect.

A second ANOVA was made in order to see how the dehydration process is affected by the initial moisture content. It included both 18% and 22%

initial moisture contents (w.b.); the three temperatures, 90°F, 100°F, and 120°F; two airflow rates, 2 cfm/bu and 3 cfm/bu (since there is no data for 1 cfm/bu with 22% Mo (w.b.)), and the two depths of 6 inches and 12 inches. Table 5.

TABLE 5. ANOVA table for the natural air drying conditions with 18% and 22% initial moisture content (w.b.)

Source of Variation	Degrees of Freedom	Mean Square	F
Temperature	2	0.000046	861.308
Airflow Rate	1	0.000054	1013.902
Initial Moisture Content	1	0.000004	68.226
Depth	1	0.000013	
Error	18	0.000000053	
Total	23		

Results in Table 5 resemble the results in Table 4 for airflow rate, temperature, and depth. The temperature mean square went up when both 18% and 22% Mo (w.b.) were considered. The effect of initial moisture content on the drying rate was very small compared to the other variables.

Therefore, based on those results, one can say that it is more effective to increase the airflow rate than to increase the temperature in order to decrease the drying time.

The AARDVARK computer program performed an LSD test for knowing how each condition affects the drying coefficient, K. Table 6 shows the mean K value corresponding to the effect of each parameter.

In this table it can be noted that as the airflow rate increases the $\overline{K}$ increases; as the drying temperature increases the $\overline{K}$ also increases;

but when either the initial moisture content or the depth of grain gets higher the $\overline{K}$ values get lower.

TABLE 6. Mean value of the drying constant K corresponding to the effect of each parameter.

Parameter		$\overline{K}$ (hr^{-1})
Temperature (°F)	120	0.011061
	100	0.008327
	90	0.006311
Airflow (cfm/bu)	3	0.010064
	2	0.007073
Initial M.C. (%, w.b.)	18	0.008957
	22	0.008181
Depth (inch)	6	0.009292
	12	0.007846

From the original data, values of M_o and M_e were taken and subtracted out. The K values were plotted against (M_o - M_e) values for each airflow, at 18% Mo (w.b.).

The new variable (M_o - M_e) is depth independent since experiments were made for both depths at the same initial moisture content, and the equilibrium moisture content for experiments at the same temperature was kept fairly constant.

Values of (M_o - M_e) include variations due to both dry and wet bulb temperatures and relative humidity. Therefore, it was easier to relate (M_o - M_e) to K than each of the earlier mentioned variables to K. In addition, the relationship became simpler.

An empirical equation of the form:

$$K = B\ e^{C(M_o - M_e)} \qquad (17)$$

was found to satisfy the data. This equation gives a straight line as follows:

$$\ln K = \ln B + C(M_o - M_e) \qquad (18)$$

Figure 13 shows a plot of K against $(M_o - M_e)$ in a semilog paper for each airflow 1 cfm/bu, 2 cfm/bu, and 3 cfm/bu. Constants B and C are intercept and slope of the straight lines on that Figure, respectively. Those values appear tabulated in Table 7. The constants B and C can be expressed as a function of airflow as follows:

$$B = 0.000573\ z^{1.605} \qquad (19)$$

$$C = 0.1615\ z^{-0.517} \qquad (20)$$

where z is the airflow rate in cfm/bu.

Linear regression lines fitted to these Equations are shown in Figure 14. Table 8 shows the regression parameters. Applying log to both sides of Equations 19 and 20 a linear form is obtained:

$$\log B = \log (0.000573) + 1.605\ z \qquad (21)$$

and

$$\log C = \log (0.1615) - 0.517\ z \qquad (22)$$

TABLE 7. Values of constants B and C, and coefficients of correlation r^2, for Equation 18.

CFM (cfm/bu)	B	C	r^2
1	.00058	.162	.821
2	.00169	.112	.774
3	.00341	.092	.812

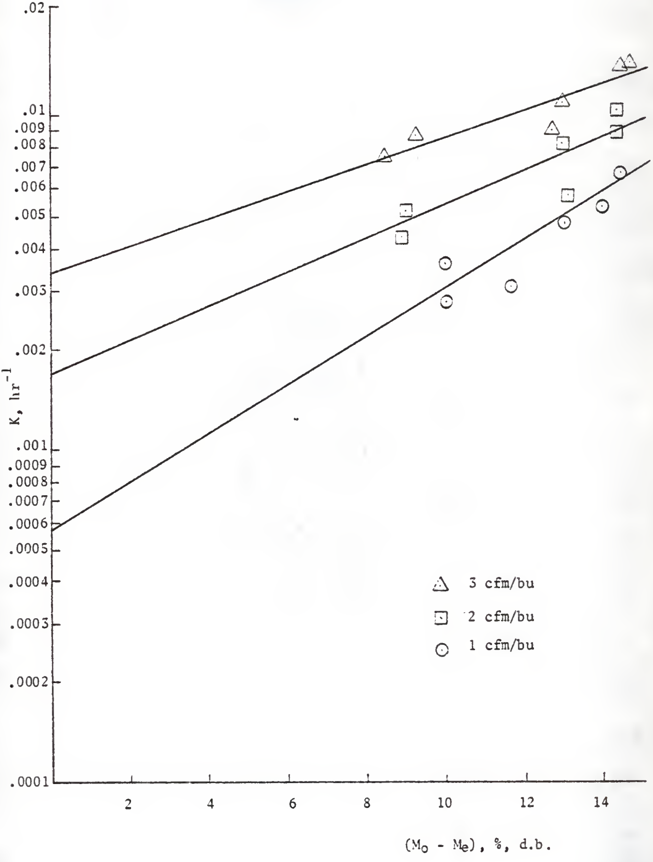

Figure 13. Plots of the drying constant, K, versus (M_o - M_e).

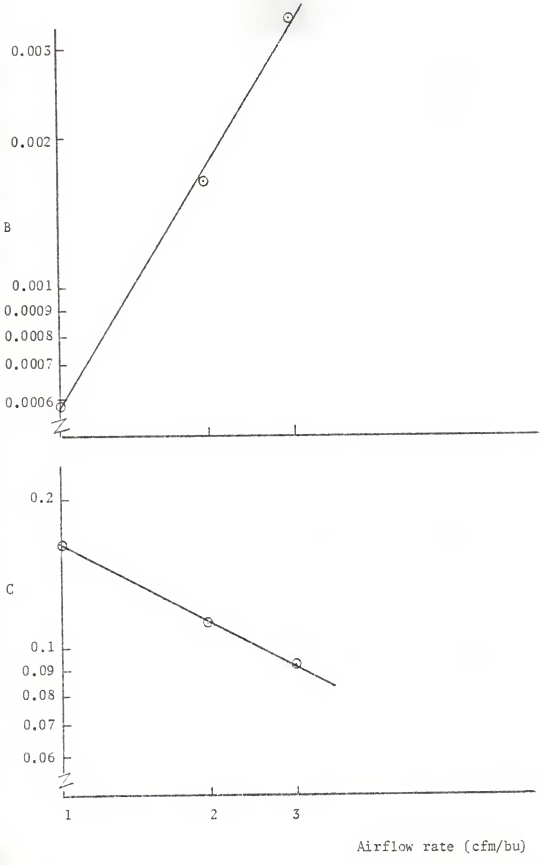

Figure 14. Value of the constant B and C of Equations 21 and 22 as a function of airflow.

TABLE 8. Regression parameters for Equations 21 and 22 in Figure 14.

Equation	Intercept	Slope	r^2
21	.000573	1.605	.999
22	.1615	-0.517	.999

Equation 19 shows that B increases as airflow increases, and therefore K increases as Equation 17 shows.

Equation 20 shows that C decreases as airflow increases, and makes the second term on the right side of Equation 18 lower. In other words, $(M_o - M_e)$ will have more influence on the drying rate at lower airflow.

Experimental results under the artificial air drying conditions are tabulated in Table 14 in the Appendix. There were four experiments at those conditions with two temperatures, 140°F, and 180°F, and two airflow rates, 20 cfm/bu and 40 cfm/bu. As seen in Table 14, experiments with the highest temperature or with the highest airflow rate turned out to be the highest drying rate.

Drying conditions for this method appear tabulated in Table 9. The temperature presents small variations from the value it should be, which can be attributed to experimental errors. As expected, the relative humidity and the equilibrium moisture content increase as the drying air temperature decreases.

Values of moisture content were plotted against time in Figure 15. From that it can be noticed that the main effect on the dehydration rate corresponds to the airflow rate. It should also be noted how the temperature effect is overtaken by the airflow rate effect.

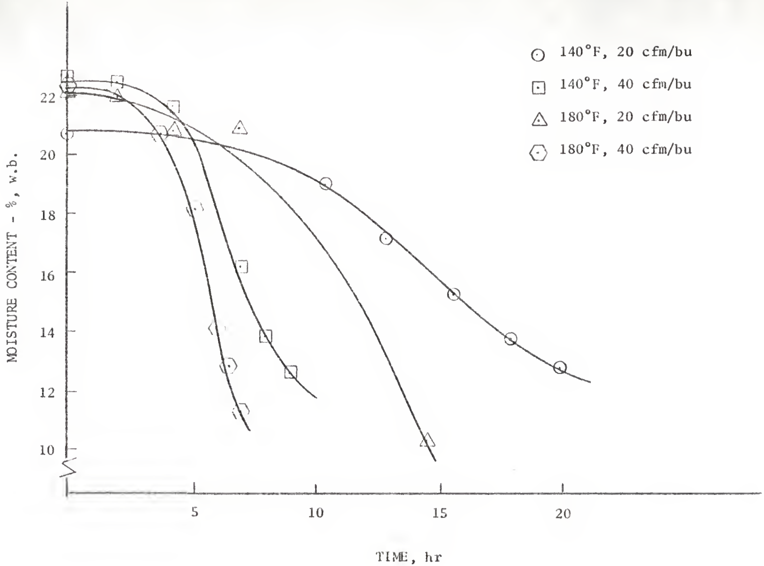

Figure 15. Moisture Content versus Time for the four artificial drying experiments.

TABLE 9. Data on drying air conditions: wet bulb temperature, dry bulb temperature, RH, and Me; at 22% M.C. (w.b.) and 12 inch depth. Artificial drying conditions.

Temp (°F)	Airflow (cfm/bu)	Dry bulb T. (°F)	Wet bulb T. (°F)	RH (%)	Me (% d.b.)
140	20	142.16	83.30	7.78	4.91
	40	143.60	81.28	6.35	4.54
180	20	178.25	95.00	5.36	4.05
	40	175.40	92.00	4.73	3.85

The SAS-76 computer program was used to determine the shape factor, A, and the drying constant, K, by applying the experimental data to Equation (7). The curves have values for the correlation coefficient around 0.80. Those values and the ones for A and K appear tabulated in Table 10. The values of the drying constant in this method were at least 10 fold higher than the K values under the natural air drying method.

In Table 10, as was seen in Figure 15, the dehydration constant increases with both airflow rate and temperature, and the K values corresponding to the 40 cfm/bu airflow rate are higher than the values corresponding to 20 cfm/bu independent of temperature.

That airflow rate has the greatest effect on the drying rate is also confirmed by its having the highest mean square in an analysis of variance table made for this data. Refer to Table 11.

An AARDVARK computer program was also applied to the artificial drying data and the results are in agreement with the ones for the natural air drying conditions; the higher the temperature, the higher the drying constant, K, and the higher the airflow the higher the K value (Table 12).

TABLE 10. Drying constant, K, and shape factor, A, for the artificial drying method tests. (22% M.C. (w.b.) and 12 inch depth).

Temperature (°F)	Airflow (cfm/bu)	A	K (hr^{-1})	r^2
140	20	1.222	0.04052	.86
	40	1.132	0.10169	.88
180	20	1.208	0.08576	.84
	40	1.187	0.14098	.79

TABLE 11. ANOVA table for the artificial drying tests.

Source of Variation	Degrees of Freedom	Mean Square	F
Temperature	1	0.001786	201.975
Airflow rate	1	0.003387	382.919
Error	1	0.000009	
Total	3		

TABLE 12. Mean values of the drying constant, K, corresponding to the effect of each parameter and their interactions for the artificial drying.

Parameter		$\overline{K}$, hr^{-1}
Temperature (°F)	180	0.113370
	140	0.071105
Airflow (cfm/bu)	40	0.121335
	20	0.063140

CONCLUSIONS

1 - Airflow rate shows higher influence than temperature, depth, and initial moisture content in increasing the drying rate.

2 - Equation (7), $MR = A\, e^{-Kt}$, describes very well the drying process for all experimental conditions in this study.

3 - Effects of depth of grain on the drying constant comes out to be inversely proportional. The deeper the bed, the lower the drying constant.

4 - Initial moisture content is also inversely proportional to the drying constant in most of the cases. The higher the initial moisture content, the lower the drying constant.

5 - Since the replication made for the 100°F temperature turned out to be non-significantly different, it is assumed that the overall results are consistent.

6 - The drying constant was found to be an exponential function of $(M_o - M_e)$ for all drying conditions at 18% moisture content (w.b.). The empirical Equation is:

$$K = B\, e^{C(M_o - M_e)}$$

where constants B and C are algebraic functions of airflow, z.

$$B = 0.000573\, z^{1.605}$$

$$C = 0.1615\, z^{-0.517}$$

7 - Results from the artificial drying method are in agreement with results from the natural air drying method in terms of curve

patterns, shape factor, and the effect of simple parameters on the drying constant.

8 - K values for the artificial drying conditions were at least 10 fold higher than the ones for the natural air drying conditions.

ACKNOWLEDGMENTS

The author wishes to dedicate this work to her husband for his support, help, and assistance in the completion of this work; to her family, in gratitude for their encouragement throughout her studies.

The author acknowledges CONICIT for financing her studies.

The author wishes to express her gratitude to CIEPE for their encouragement and support throughout her studies.

Special thanks and sincere appreciation to her major professor, Dr. Do Sup Chung, for his guidance and excellent advice in the course of this work.

The author is thankful to her committee members, Dr. Larry E. Erickson, and Dr. Richard Bassette.

REFERENCES

Agricultural Engineers' Handbook. C. B. Richey, Ed. McGraw-Hill, 1961.

ASME Power Test Codes. Supplemental on Instruments and Apparatus. 1959.

Blank, F. C. 1955. Handbook of Food and Agriculture. Reinhold Publishing Corporation. New York.

Brooker, D. B., Bakker-Arkema, F. W., and Hall, C. W. 1974. Drying Cereal grains. The Avi Publishing Co. Inc., Westport, Connecticut.

Chemical Engineers' Handbook. 1950. 3rd ed. McGraw-Hill Book Co. Inc. New York.

Chittenden, D. H. and Hustrulid, A. 1966. Transaction of the ASAE. Determining Drying Constant for Shelled Corn. 9 (1):52-55.

Chung, D. S. and Pfost, H. B. 1967. Adsorption and Desorption of Water Vapor by Cereal Grains and their Products. Parts I, II, III. Trans. ASAE. 10(4):549-557.

Donald, L. D., and Gordon, L. N. 1960. Effects of Basic Parameters in Drying Grain Sorghum. Tech. Bull. Okla. Agr. Exp. Sta. T-85, 19 p.

Fan, L. T., Chu, P. S., and Shellenberger, J. A. 1963. Diffusion of Water in Kernels of Corn and Sorghum. Cereal Chemistry. Vol. 40:303.

Fenton, F. C. 1941. Storage of Grain Sorghum. Agricultural Engineering. 22(5):185-188.

Gerzhoi, A. P. and Samochetov, V. F. 1958. Grain Drying and Grain Dryers. 3rd ed. Published for the National Science Foundation. Moscow.

Henderson, S. M. and Pabis, S. 1962. Grain Drying Theory: IV. The Effect of Air flow Rate on the Drying Index. 7(2):85-89.

Henderson, S. M. and Perry, R. L. 1976. Agricultural Process Engineering. 3rd ed. The Avi Publishing Co., Inc. Westport, Connecticut.

Henderson, S. M. and Pabis, S. 1961. Grain Drying Theory:I. Temperature Effect on Drying Coefficient. J. Agric. Engng. Res. 6(3):169.

Henderson, S. M. 1952. A Basic Concept of Equilibrium Moisture Content. Agriculatural Engineering 33(1):29-33.

Hukill, W. V. 1947. Basic Principles in Drying Corn and Grain Sorghum. Agricultural Engineering. 28(8):335-338-340.

Hukill, W. V. 1965. Moisture in Grain, in Humidity and Moisture, Measurement and Control in Science and Industry. A. Wexler. Vol. 2, Reinhold Publishing Corporation. New York.

Hustrulid, A. and Flikke, A. M. 1959. Teoretical Drying Curve for Shelled Corn. Transaction of the ASAE. (2)1:112-114.

Kazariam, E. A. and Hall, C. W. 1965. Thermal Properties of Grain. Transaction of the ASAE. 33-48.

Matz, S. A. 1969. Cereal Science. The Avi Publishing Co. Inc. Westport, Connecticut.

Matz, S. A. 1959. The Chemistry and Technology of Cereals as Food and Feed. The Avi Publishing Co. Inc. Westport, Connecticut.

Moncada, L. F. 1978. Hygroscopic Properties of Corn Cobs and their Applications for Small On-form Grain Conditioning. Unpublished M.S. Thesis. Kansas State University. Manhattan, Kansas.

O'Callaghan, J. R., Menzies, D. J. and Bailey, P. H. 1971. Digital Simulation of Agricultural Dryer Performance.

Pabis, S. and Henderson, S. M. 1962. Grain Drying Theory: II. A Critical Analysis of the Drying Cereal Shelled Maize. J. Agric. Eng. Res. 6, 272-277.

Pabis, S. and Henderson, S. M. 1962. Grain Drying Theory: III. The Air/Grain Temperature Relationship. J. Agric. Eng. Res. 7(1):21.

Paulsen, M. R. 1972. Thin Layer and Deep-Bed Drying Characteristics of Grain Sorghum. Unpublished M.S. Thesis. University of Nebraska. Lincoln, Nebraska.

Paulsen, M. R. and Thompson, T. L. 1973. Drying Analysis of Grain Sorghum. Transaction of the ASAE. (16)3:537.

Pomeranz, Y. 1976. Advances in Cereal Science and Technology. Published by American Association of Cereal Chemists, Inc. St. Paul, Minnesota.

Sharma, D. K., Thompson, T. L. 1973. Specific Heat and Thermal Conductivity of Sorghum. Transactions of the ASAE. 16 (1):114:117.

APPENDIX

TABLE 13. Data on Moisture Content and Time for the Natural Air Drying Conditions.

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
91.52	44.28	1	18	6	0	18.21
					12	18.10
					25	17.88
					40	17.74
					60	17.55
					74	17.48
					90	17.26
					110	17.00
					135	16.25
					156	15.54
					175	15.25
					182	15.02
					194	14.94
89.51	43.89	1	18	12	0	18.00
					10.00	17.60
					22.00	17.31
					30.00	16.76

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
89.51	43.89	1	18	12	41.50	16.26
					52.00	16.35
					65.50	16.28
					76.50	16.10
					88.50	14.93
					101.00	15.13
					112.50	15.94
					123.75	15.83
					135.50	15.79
					148.00	15.65
					160.00	15.59
					171.00	15.48
					183.00	15.50
					196.00	15.35
					207.25	15.32
					217.50	14.96
					229.50	14.95

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
89.51	43.89	1	18	12	242.50	14.61
					254.00	14.22
					266.25	14.02
					272.00	13.52
89.38	50.00	2	18	6	0	17.30
					11.5	17.03
					23.5	16.76
					35.5	16.47
					47.5	16.18
					59.5	16.05
					71.5	15.81
					83.5	15.48
					95.5	15.01
					119.5	14.73
					132.0	14.49
					143.5	14.44

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
92.30	50.83	2	18	12	0	17.00
					6.00	16.59
					11.50	16.29
					22.75	16.35
					34.00	16.11
					46.50	15.87
					58.00	15.68
					70.33	15.52
					82.00	15.21
					94.00	14.84
					105.00	14.77
					150.00	14.38
					175.00	14.12
90.65	50.83	2	22	6	0	21.97
					23	21.69
					35	21.53

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
90.65	50.83	2	22	6	47	20.95
					59	20.29
					71	19.37
					83	19.42
					95	19.08
					109	18.38
					119	17.88
					131	17.98
					143	16.99
					155	16.16
					167	15.75
					179	15.38
87.94	51.59	2	22	12	10.5	20.18
					23.0	19.62
					34.5	19.08
					46.5	18.84

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
87.94	51.59	2	22	12	70.5	18.58
					82.5	18.32
					94.5	18.08
					106.5	17.41
					118.5	16.81
					130.5	16.28
					142.5	16.39
					155.0	16.15
					166.5	15.77
					178.5	15.51
					190.5	15.41
89.90	48.59	3	18	6	11.75	17.43
					22.25	17.34
					28.25	16.56
					47.75	15.32
					60.75	15.13

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
89.90	48.59	3	18	6	71.25	14.85
					84.75	14.66
					95.75	14.19
					107.75	13.98
					120.25	13.80
90.20	51.43	3	18	12	0	17.80
					8.00	17.59
					12.00	17.52
					29.75	17.09
					36.50	16.89
					44.00	16.36
					52.75	16.17
					60.00	15.84
					70.25	15.45
					78.00	15.32
					84.50	15.15

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
90.20	51.43	3	18	12	92.00	14.85
					104.00	14.63
90.14	50.83	3	22	6	0	21.21
					11.75	21.06
					23.75	20.83
					35.75	20.20
					47.75	19.69
					59.75	19.39
					71.75	19.11
					85.75	18.58
					95.75	18.11
					107.75	17.05
					119.75	16.34
					131.75	19.19
94.82	44.46	3	22	12	0	21.53
					18.00	20.89

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
94.82	44.46	3	22	12	25.00	20.68
					32.50	20.42
					42.50	20.12
					48.00	19.74
					73.00	18.69
					84.00	18.22
					94.00	17.87
					104.75	16.91
					114.50	16.67
					121.25	16.46
					137.00	16.02
104.05	26.63	1	18	6	0	17.86
					5.00	17.95
					18.00	17.71
					38.00	17.24
					49.00	16.46

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
104.05	26.63	1	18	6	58.50	16.35
					66.00	16.24
					73.00	16.01
					82.25	15.98
					97.50	15.33
					107.00	15.20
					114.00	14.87
					121.00	14.58
					132.75	13.94
					138.17	13.65
					145.33	13.37
					157.33	13.16
103.04	25.79	1	18	6	0	17.81
					12.25	17.48
					23.25	17.19
					36.50	17.03

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
103.04	25.79	1	18	6	47.75	16.83
					60.25	16.68
					72.25	16.10
					84.00	15.71
					97.50	15.07
					107.50	14.71
					118.50	14.41
					131.50	13.68
					142.25	13.30
					155.75	12.72
					167.25	12.04
104.00	34.49	1	18	12	0	17.91
					12.83	17.62
					24.00	17.42
					29.75	17.26
					36.50	17.40

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
104.00	34.49	1	18	12	48.00	17.25
					53.50	17.09
					61.75	17.27
					72.25	17.07
					78.00	16.92
					97.00	17.03
					103.25	16.63
					111.25	16.22
					120.50	16.41
					126.75	15.63
					142.75	15.71
					149.50	15.71
					157.00	15.89
					167.00	15.53
					173.00	14.59
					191.00	14.47
					199.00	14.16

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
104.00	34.49	1	18	12	206.50	14.30
					216.50	13.52
104.76	33.59	1	18	12	0	17.91
					6.00	17.68
					11.50	17.55
					23.25	17.30
					35.00	17.08
					47.50	17.03
					59.00	16.97
					71.30	16.21
					83.00	16.01
					95.00	15.92
					106.00	15.76
					118.00	15.70
					129.00	15.09
					141.50	14.89
					153.00	14.31

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
104.76	33.59	1	18	12	164.50	14.16
					176.00	13.83
					190.00	13.64
					206.00	13.33
103.35	26.73	2	18	6	0	18.36
					11.00	18.11
					21.50	17.80
					28.00	17.78
					36.00	17.74
					45.75	17.05
					52.67	15.92
					59.50	15.66
					69.83	15.59
					84.00	14.75
					100.50	13.44
102.74	26.94	2	18	6	0	18.32
					5.25	18.05

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
102.74	26.94	2	18	6	22.00	18.03
					29.00	17.80
					37.00	16.79
					46.00	16.77
					53.00	15.36
					61.50	15.63
					74.33	14.14
					85.60	13.58
					96.66	13.11
108.34	26.15	2	18	12	0	18.23
					7.00	18.13
					23.25	18.00
					31.50	17.93
					41.00	17.81
					48.00	17.39
					66.75	17.27
					72.17	16.20

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
108.34	26.15	2	18	12	80.00	16.34
					92.00	14.85
					104.00	13.25
105.59	31.03	2	18	12	0	17.45
					6.00	17.31
					14.00	17.14
					23.75	17.09
					30.67	16.96
					37.50	16.81
					47.83	16.57
					54.00	16.29
					62.00	16.28
					71.75	15.91
					78.50	15.92
					85.50	15.28
					96.16	14.59

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
105.59	31.03	2	18	12	101.50	13.96
					114.50	12.07
103.48	17.65	2	22	6	0	22.45
					10.3	21.6
					22.0	21.36
					28.0	21.12
					37.0	20.82
					46.5	20.43
					54.5	19.47
					58.3	18.59
					66.0	18.47
					83.0	16.73
					89.0	15.33
					97.0	14.59
					104.5	13.96
					115.0	13.48

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
102.60	18.69	2	22	6	0	22.35
					12.0	21.52
					24.5	21.16
					34.25	21.02
					46.5	20.11
					59.0	19.32
					70.0	18.86
					82.5	17.22
					95.0	15.99
					106.5	14.79
					118.5	13.53
104.88	17.63	2	22	12	0	21.08
					7.50	20.49
					17.75	20.60
					24.17	20.50
					31.25	20.09
					46.00	19.95

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
104.88	17.63	2	22	12	53.50	19.92
					62.75	19.67
					69.83	19.62
					88.75	19.61
					94.50	19.52
					101.25	17.88
					112.00	16.82
					118.25	15.44
					124.25	14.60
105.52	23.54	2	22	12	0	21.40
					6.75	21.12
					18.25	20.86
					23.75	20.78
					42.50	20.58
					48.25	20.28
					55.25	20.19
					61.50	18.96

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
105.52	23.54	2	22	12	69.42	18.90
					78.75	16.84
					83.00	16.59
					99.00	15.09
101.60	26.67	3	18	6	0	17.60
					8.0	17.40
					16.0	16.80
					24.0	16.47
					32.5	16.27
					45.5	15.85
					55.5	14.91
					69.0	13.55
					80.0	13.04
					91.0	12.14
101.30	27.67	3	18	12	0	18.40
					11.50	18.29
					24.50	18.06

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
101.30	27.67	3	18	12	36.25	17.80
					46.50	17.46
					58.50	16.73
					71.50	15.16
					83.00	13.93
					95.25	12.71
103.98	15.63	3	22	6	0	22.16
					14.50	21.85
					23.50	21.89
					32.00	21.46
					38.00	21.60
					45.50	20.85
					53.50	19.82
					61.50	18.31
					72.50	16.16
					78.33	14.83
					84.75	13.25

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
103.49	15.00	3	22	6	0	22.38
					8.0	22.06
					16.0	21.10
					24.0	20.24
					32.5	20.74
					45.5	19.58
					55.5	17.91
					69.0	15.73
					80.0	15.01
					91.0	14.13
103.01	22.72	3	22	12	0	21.24
					6.0	20.70
					15.0	20.67
					24.5	20.50
					32.5	20.27
					48.3	19.14
					56.0	19.15

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
103.01	22.72	3	22	12	73.0	16.59
					79.0	15.59
					87.0	14.12
					94.5	13.02
103.40	21.74	3	22	12	0	21.18
					5.25	20.91
					22.00	20.64
					29.00	20.37
					37.00	20.20
					46.00	19.52
					53.00	18.95
					61.50	18.65
					74.33	17.38
					85.66	16.34
					96.75	14.78
					108.50	13.52

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
120	19.18	1	18	6	0	18.03
					12	17.67
					21	17.51
					28	17.11
					36	16.92
					46	16.57
					51	16.08
					60	15.49
					76	14.24
					84	13.81
					93	13.35
					100	13.28
					107	13.22
					118	12.84
118.30	21.79	1	18	12	0	17.25
					15.0	17.11
					29.0	16.98

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
118.30	21.79	1	18	12	53.5	15.67
					61.0	15.32
					69.8	14.97
					77.0	14.57
					85.3	14.27
					95.0	13.81
					101.5	13.60
					109.0	13.17
					121.0	13.05
					132.5	12.96
					143.0	12.84
118.74	19.44	2	18	6	0	18.38
					12	17.90
					18	17.57
					32	17.32
					38	16.90
					45	16.88

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
118.74	19.44	2	18	6	53	16.14
					62	15.62
					69	14.66
					77	13.96
					86	13.31
					93	12.38
					101	11.90
					110	10.13
120.00	19.23	2	18	12	0	17.29
					9	17.15
					16	17.06
					26	16.92
					34	16.45
					39	16.08
					48	15.65
					57	15.14
					64	14.46

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
120.00	19.23	2	18	12	72	13.76
					81	13.06
					88	12.22
119.38	20.00	2	22	6	0	22.28
					9.5	22.02
					17.75	22.17
					24.25	21.95
					33.25	21.68
					40.25	21.40
					57.25	19.25
					64.42	17.54
					72.25	17.18
					81.25	15.33
					96.25	14.62
120.87	18.33	2	22	12	0	22.22
					14.25	21.77
					23.75	21.60

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
120.87	18.33	2	22	12	32.0	20.93
					38.5	20.28
					47.5	19.83
					54.5	19.02
					71.5	17.90
					78.5	17.35
					86.5	16.68
					95.5	15.47
					110.5	14.54
121.00	17.50	3	18	6	0	17.91
					5.75	17.40
					19.25	16.84
					25.50	16.55
					31.50	16.20
					39.50	15.61
					48.50	15.37
					55.50	13.19

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
121.00	17.50	3	18	6	64.25	11.32
					72.50	11.00
120.20	19.00	3	18	12	0	17.92
					11	17.15
					18	16.55
					30	15.83
					38	14.60
					46	14.15
					51	13.12
					60	12.08
117.23	20.71	3	22	6	0	22.37
					5.75	22.18
					19.25	20.98
					25.50	20.60
					31.50	20.15
					39.50	18.81
					48.50	17.62

TABLE 13. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
117.23	20.71	3	22	6	55.50	16.18
					64.25	14.60
					72.50	13.55
119.60	19.48	3	22	12	0	21.94
					6.5	21.75
					16.5	21.64
					28.0	20.51
					37.5	20.29
					49.5	18.90
					60.0	16.94
					71.0	14.12
					77.5	13.13

TABLE 14. Data on Moisture Content and Time for the Artificial Drying Conditions.

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
142.16	7.78	20	22	12	0	20.65
					10.50	18.87
					13.00	16.97
					15.67	15.04
					18.00	13.50
					20.00	12.53
143.60	6.35	40	22	12	0	22.52
					1.00	21.67
					2.00	22.36
					4.25	21.53
					7.25	16.08
					8.25	13.60
					9.25	12.32
178.25	5.36	20	22	12	0	22.17
					2.00	21.84
					4.33	20.74

TABLE 14. (Contd.)

T (°F)	RH (%)	Airflow (cfm/bu)	M.C. (%, w.b.)	Depth (inch)	Time (hr)	Moisture Content (%, w.b.)
178.25	5.36	20	22	12	7.0	20.82
					14.5	10.08
175.4	4.73	40	22	12	0	22.45
					3.67	20.61
					5.25	18.01
					6.25	13.99
					6.75	12.64
					7.25	11.08

DEHYDRATION CHARACTERISTICS OF
GRAIN SORGHUM

by

BETZABE SULBARAN RODRIGUEZ

B.S., Universidad del Zulia, Venezuela, 1975

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

FOOD SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1979

The principal purpose of this work is to determine the drying characteristics of grain sorghum under the natural air drying method and to study how these characteristics are affected by different drying conditions. Four experiments were made under the artificial drying conditions for comparison.

Grain sorghum was dried under various conditions of temperature, airflow rate, initial moisture content, and depth of grain bed. The experimental conditions tested are:

- natural air drying: three temperatures--90°F, 100°F, and 120°F; three airflow rates--1 cfm/bu, 2 cfm/bu, and 3 cfm/bu; two initial moisture contents--18% and 22% (w.b.); and two depths of grain--6 inches and 12 inches.
- artificial drying: two temperatures--140°F and 180°F; two airflow rates--20 cfm/bu and 40 cfm/bu; one initial moisture content--22% (w.b.); one depth--12 inches.

Statistical analysis of experimental data showed effects of the parameters studied on the dehydration rate. As drying temperature or airflow rate is increased, the dehydration rate increases; as depth of grain is higher, the dehydration rate decreases; and finally as initial moisture content is higher the dehydration rate decreases, in most of the cases.

The Equation,

$$\frac{M_{(t)} - M_e}{M_o - M_e} = A\ e^{-Kt}$$

described the drying data, and the constant A, shape factor, and K drying constant, were determined by fitting a straight line by the least square method. Range of K values was: from 0.00274 hr^{-1} to 0.01461 hr^{-1} for the natural air drying tests; and from 0.1410 to 0.0405 for the artificial drying tests.

The mean drying constant, $\overline{K}$, varies in an exponential function with airflow rate for the natural air drying conditions studied. Airflow rate was the most effective parameter on the drying rate in this study.

An Arrhenius type equation was found to describe the variation of the mean drying constant with temperature.

An Equation of the form:

$$K = B\ e^{C(M_o - M_e)}$$

was found to satisfy the data. The constants B and C can be expressed as a function of airflow:

$$B = 0.000573\ z^{1.605}$$

and

$$C = 0.1615\ z^{-0.517}$$

Linear regressions applied to those equations gave high correlation coefficients.