AN ABSTRACT OF THE THESIS OF

WICHAI LAKSANAKORN for the M. S. in Agricultural Engineering
(Name) (Degree) (Major)

Date thesis is presented ____________

Title RELATION OF THE DRYING RATE OF GRAIN IN A CONTINUOUS COUNTERFLOW COLUMN TO THE EXPOSED DRYING RATE

Abstract approved Redacted for Privacy
(Major professor)

The drying characteristic of shelled corn in a pilot model continuous counterflow dryer was investigated. An attempt was made to establish an empirical equation which could be used for predicting the design and operating conditions of the counterflow dryer. Entering air temperatures from 120 to 180°F with a relative humidity of 10.5% and lower were employed. It was found that after the steady state had been reached, the drying rate of each kernel was nearly constant while passing through the drying zone. The assumption was made that it was constant and represented by $(dM/d\theta)_c$. It was observed that the value of $(dM/d\theta)_c$ increases as the entering air temperature increased.

If the value of $(dM/d\theta)_c$ is known for a particular entering air condition, the kernel travel time within the drying zone, θ_t, necessary to remove the moisture of ΔM could be determined from

$$\theta_t = \frac{\Delta M}{\left(\frac{dM}{d\theta}\right)_c}$$

If the value of $(dM/d\theta)_c$ could be expressed in terms of the drying rate of fully exposed grain under the condition of the entering air, it could be determined from the more readily available exposed drying rate data. The time of one-half response, $\theta_{\frac{1}{2}}$, was selected as the index to indicate the exposed drying rate and determination of the following expression was attempted.

$$\left(\frac{dM}{d\theta}\right)_c = f(\theta_{\frac{1}{2}})$$

The value of $(dM/d\theta)_c$ obtained experimentally was correlated with the time of one-half response observed by exposing a single layer of kernels to the same air condition as the air entering the counterflow column.

The empirical relation obtained was:

$$\left(\frac{dM}{d\theta}\right)_c = 10\ \theta_{\frac{1}{2}}^{-0.61}$$

Knowing the value of $\theta_{\frac{1}{2}}$ under the entering air condition, the value of $(dM/d\theta)_c$ could be determined and could be used in the proper design and adjustment of the continuous counterflow column dryer.

RELATION OF THE DRYING RATE OF GRAIN IN A CONTINUOUS COUNTERFLOW COLUMN TO THE EXPOSED DRYING RATE

by

WICHAI LAKSANAKORN

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

August 1964

APPROVED:

Redacted for Privacy

Professor of Agricultural Engineering

In Charge of Major

Redacted for Privacy

Head of Department of Agricultural Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented ____________________

Typed by Lucinda Nyberg

ACKNOWLEDGEMENT

The author wishes to express his deep gratitude to Professor Dale E. Kirk for his helpful guidance, suggestion, and assistance throughout this course of study.

Appreciation is also extended to Clary L. Campbell, mechanician for the Department of Agricultural Engineering, for his help when two men were needed at the time the runs were performed; to fellow graduate students, William A. Mannion and John G. Little IV for their original proof reading of this thesis; and to Ronald L. Zeiler for his help on typing the rough draft.

Thankfulness is given to the Department of Farm Crops and Dr. R. E. Fore for the supply of shelled corn needed in this investigation.

The completion of this thesis was made possible with the cooperation of Oregon Agricultural Experiment Station under Project No. 529 which is headed by Professor Dale E. Kirk. This cooperation is sincerely appreciated.

The credit must also be given to the Preserved Food Organization, Thailand, for the financial support during my stay at Oregon State University.

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NOMENCLATURE

β = diameter ratio, dimensionless

γ_m = density of manometer fluid, lb./ft.^{3}

Δ = the change

θ = time, hr.

$\theta_{\frac{1}{2}}$ = time of one-half response, hr.

θ_t = kernel travel time, min. or hr.

π = 3.1416

a = regression coefficient

b = intercept

C = discharge coefficient, dimensionless

d = a constant

d. a. = dry air

D = zone depth, in.

D_o = inside pipe diameter, ft.

e = natural logarithm base

f( ) = function of

ft. = foot (feet)

^oF = degree Fahrenheit

g = acceleration due to gravity, ft./sec.^{2}

h = manometer differential, ft.

hr. = hour(s)

H_d = exhaust air humidity, lb. water/lb. d. a.

H_o = entering air humidity, lb. water/lb. d. a.

in. = inch(es)

k = a constant

K_1, K_2, K_3 = constants

K_o = flow coefficient, dimensionless

lb. = pound(s)

log = common logarithm

m = a constant

min. = minute(s)

M = moisture content, % db.

M_o = initial moisture content, % db.

M_d = discharge moisture content, % db.

M_e = equilibrium moisture content, % db.

M_s = dynamic equilibrium moisture content, % db.

n = a constant

N = number of data points

N_o = a constant

p_1 = upstream pressure, lb. /ft.^{2}

p_2 = downstream pressure, lb. /ft.^{2}

p_a = partial vapor pressure of the entering air, lb. /in.^{2}

p_b = barometric pressure, lb. /in.^{2}

p_g = vapor pressure of moisture within the kernel

p_w = saturation vapor pressure corresponding to the entering air temperature, lb. /in.^{2}

% db. = percent dry basis

% wb. = percent wet basis

Q_a = air flow rate, lb. d. a. /hr. -ft.^{2}

Q_g = grain flow rate, lb. bone dry/hr. -ft.^{2}

r = correlation coefficient

rh = relative humidity, a decimal or percent

^oR = degree Rankine

R_D = Reynolds Number, dimensionless

R_t = kernel travel speed, in. /hr.

sec. = second(s)

T = time units

T_o = temperature, ^oR

v_1 = specific volume of fluid, ft.^{3}/lb.

w = weight rate of flow, lb. /sec.

X, X_o = value in X axis

Y, Y_o = value in Y axis

RELATION OF THE DRYING RATE OF GRAIN IN A CONTINUOUS COUNTERFLOW COLUMN TO THE EXPOSED DRYING RATE

INTRODUCTION

The counterflow method of grain drying, is a system in which the grain flows in one direction and the drying air flows in the opposite direction. This can be achieved by allowing the grain to flow downward by gravity within a column with the drying air forced upward. By doing so, it is possible that all grain kernels would receive the same treatment throughout the drying process. This result can not be obtained in the conventional batch drying systems. In batch drying the drying zone would continuously move upward as the drying progresses and by the time the bottom part is adequately dried, the top part might still be at or near the initial moisture content. This results in non-uniformity of the final moisture content of the dried grain. In a continuous counterflow drying system with a proper setting, the drying zone could be kept at a standstill within the column indefinitely, and the same treatment of all kernels would result. Consequently, a uniform final moisture content could be obtained. The exhaust air could also be kept continuously at nearly saturation throughout the drying process. This indicates that the maximum thermal efficiency would be obtained. Furthermore, the hot air temperature limit for drying grain without damage is related to the grain moisture content

(1, p. 144-145). The higher the moisture content, the lower will be the air temperature limit. With the counterflow system, the coolest air would meet the wettest grain and the hottest air would meet the driest grain. This characteristic of the counterflow method could make it one of the fastest drying systems possible with minimum damage to the product.

DRYING RATE IN THE CONTINUOUS COUNTERFLOW COLUMN

Within the column, as the air is forced upward and the kernels flow downward, the air picks up moisture as it flows through the layers of grain. An amount of energy is required to evaporate moisture from the kernels. The drying with heated air is considered as an adiabatic process (20, p. 24, 118; 8, p. 335; 7, p. 285), for which the heat losses through the wall of the dryer are neglected. The energy for the moisture evaporation is supplied by the reduction in dry-bulb temperature of the heated air. Thus, as the drying takes place a drop of the air dry-bulb temperature occurs along the drying zone. The wet kernels travel from the top of the drying zone downward to the discharge box and the moisture content decreases enroute. With this system, there are gradients of air temperature, air humidity, average kernel moisture, and average kernel temperature across the drying zone in the direction of air flow and grain flow. After steady state is reached, these gradients, if plotted against zone depth, would be constant in shape and position. In the counterflow drying system, the dryer could be operated at steady state conditions continuously for a long period of time. The unsteady or transient state would occur for only a short time at the beginning of the drying process. For this reason the latter would be ignored and only the drying phenomena at steady state conditions would be of interest.

Ives, Hukill and Black (11) investigated the continuous counterflow drying system at steady state using wheat in a laboratory model dryer. The continuous counterflow system was simulated by placing the grain in a stack of trays. The air was forced upward through the trays and the bottom tray was removed periodically. At the same time a tray of wet grain was placed at the top of the stack. Dimensional analysis was employed in planning and analyzing the data. The kernel travel time in minutes through the drying zone was given (11, p. 19) for wheat as follows:

$$\theta_t = \left(1.08 \log \frac{M_o}{14}\right)\left(\frac{4400}{M_d^{1.41}} - 30\right)\left(\frac{0.608}{\left[(p_w - p_a)/p_b\right]^{.74}}\right)\left(\frac{0.311}{(p_a/p_b)^{.247}}\right)$$

where θ_t = kernel travel time, minutes

M_o = initial moisture content, % dry basis

M_d = discharge moisture content, % dry basis

p_w = saturation vapor pressure corresponding to the entering air temperature, lb./in.^{2}

p_a = partial vapor pressure of the entering air, lb. / in.^{2}

p_b = barometric pressure, lb. /in.^{2}

The interesting phenomena within the counterflow column were the typical zone gradients. It was found that the typical air temperature and grain moisture gradients at steady state were similar to an s-shaped curve. The curve was composed of upper and lower asymptotes

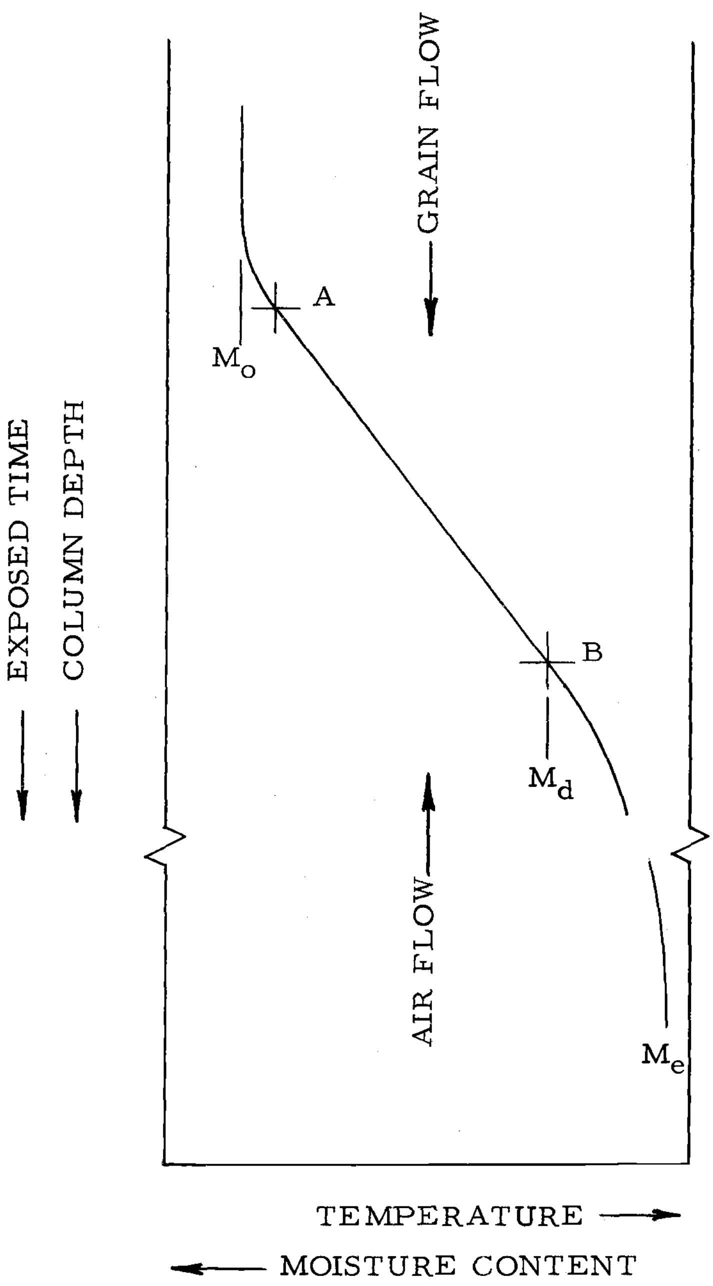

Figure 1. Typical zone gradient.

with the portion between them nearly a straight line as shown in Figure 1 (11, p. 9). The upper asymptote is the curve above the plus mark A, and represents the region in which air is in equilibrium with the wet grain and no drying occurs. The lower asymptote is the curve below the plus mark B. This region, if allowed to form completely, would be extremely long because the grain approaches equilibrium with the drying air very slowly at this stage of drying.

The air temperature and grain moisture gradients, if properly plotted with an adjusted scale, form identical curves (11, p. 2). This can be seen from the fact that the lowering of the air temperature is the result of evaporation of moisture from the grain to the air. Therefore, the air temperature drop is proportional to the lowering of the moisture content of the grain (20, p. 119). Ives, Hukill, and Black also illustrated this fact experimentally by determining the air temperature gradients from thermocouples placed in the air stream along the zone depth. The moisture gradients were determined by weighing each tray in the stack immediately upon the completion of the run. These two observed gradients were plotted on the same graph with correctly oriented and adjusted scales. They appeared to form almost identical curves (11, p. 12). The slight departures were accounted for by the non-uniformity of air flow through the column. Thus, it could be concluded that the typical zone gradient in Figure 1 represented both the air temperature and grain moisture gradients.

The difference in the vapor pressure of the moisture within the kernel and the partial vapor pressure of the air, $(p_g - p_a)$ is considered as the driving force in drying. The vapor pressure of the moisture within the kernel, p_g, is dependent upon the kernel temperature. The partial vapor pressure of the moisture in the air, p_a, varies with the absolute humidity.

The highest air temperature and the highest kernel temperature would be at the lowest part of the column. As the air progresses upward, the absolute humidity rises, the wet-bulb temperature remains approximately constant and the dry-bulb temperature drops until the air reaches equilibrium with wet grain at the upper asymptote. This results in the highest vapor pressure difference at the lower part of the column and the value decreases as the air flows upward. Therefore, it can be seen that, as each kernel travels down through the drying zone, the most available moisture in the kernel is evaporated to the air that has the lowest driving force. As it flows down the column and progressively loses moisture, the temperatures of both the air and the kernel itself are increased and the kernel with the lowest moisture content is exposed to air providing the highest driving force near the bottom of the drying zone. With these phenomena combined, the typical zone gradient results, as observed by Ives, Hukill, and Black.

If the general shape of this typical zone gradient holds true under various environmental conditions which would be employed in industrial counterflow drying systems, it is seen that, if the upper and lower asymptotes were not allowed to form by exhausting the air at point A and discharging the dried grain at point B, the zone gradient would be nearly a straight line. This straight line is represented by line AB.

It is evident that the slope of this gradient at any point represents the instantaneous drying rate of the grain at that particular zone depth (11, p. 3). This may be seen more clearly by reorienting the gradient using moisture content and exposed time as the axes, as shown in Figure 2. The exposed time could be determined from the distance traveled by the kernel within the column, provided that the kernel travel speed, which would be practically constant in this system, is known. Figure 2 represents the typical drying curve of each kernel in the continuous counterflow system. The different conditions between this drying curve and the general exposed drying rate curve must be realized. For the former curve the kernel continuously moves to the higher air temperature and lower air humidity as the drying takes place, while the latter curve is obtained by exposing a single layer of kernels to constant air conditions.

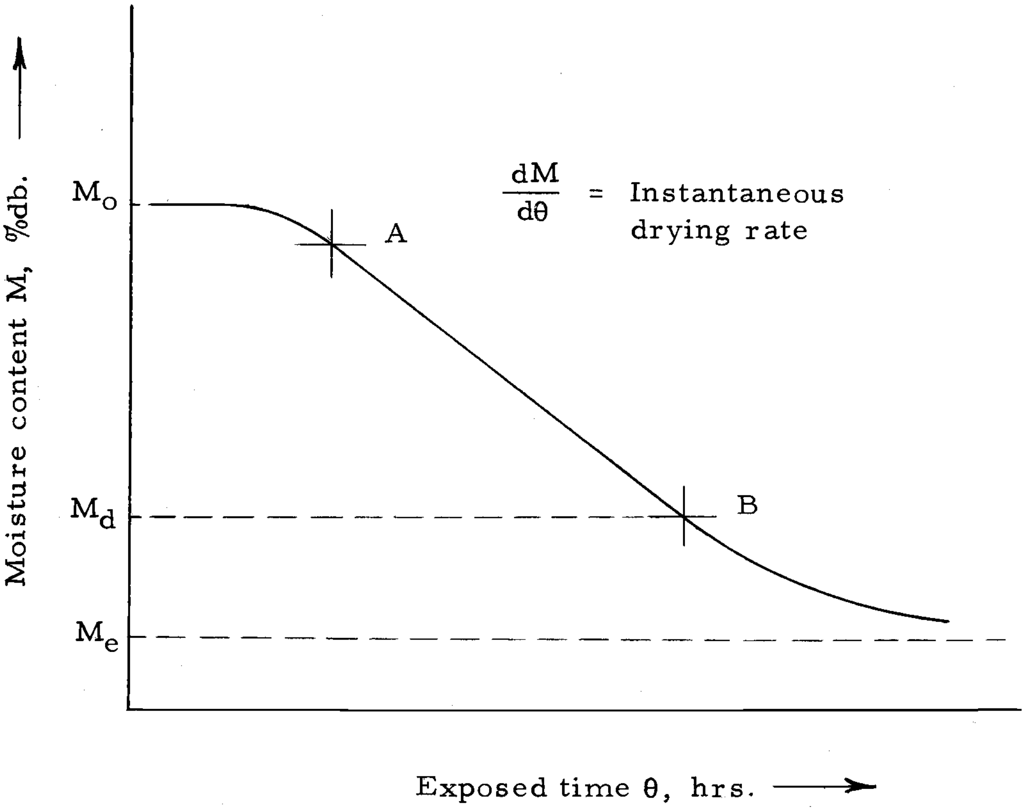

Figure 2. Typical drying curve of the kernel within the counterflow system.

STATEMENT OF PROBLEM

A pilot model experimental counterflow dryer was designed and built at the Oregon Agricultural Experiment Station. The preliminary runs were performed in December 1962 with shelled corn. The air temperature gradients obtained from these tests showed that, within the practical operating range for the drying of shelled corn, the typical zone gradient on Figure 1 was also applicable to the pilot model counterflow dryer in which the grain was held in a column instead of on trays. Whether the asymptotes existed or not, the portion AB always occurred. This led to the conclusion that, if the counterflow dryer were adjusted so that the upper asymptote did not exist and the grain was discharged at point B, the zone gradient could be approximated by a straight line. Under this approximation, it can be seen from Figure 2 that, the drying rate of each kernel is constant within this linear portion, AB. Thus, if the counterflow dryer was operated under conditions adjusted as above, each kernel would have had nearly constant drying rate from the time it entered at the top until it left the drying zone at the bottom. The kernel travel time required to remove a given amount of moisture out of the kernel within counterflow column can then be obtained from the relation;

$$\left(\frac{dM}{d\theta}\right)_c = \frac{\Delta M}{\Delta\theta} = \frac{\Delta M}{\theta_t} \qquad (1)$$

where $\left(\frac{dM}{d\theta}\right)_c$ = counterflow constant drying rate, % dry basis/hour

M = grain moisture content, % dry basis

$\Delta \theta = \theta_t$ = kernel travel time, hours.

It has been observed by several investigators that air velocity has no significant effect on drying rate within the practical drying range. This was observed on shelled corn and grain sorghum by Hukill (8, p. 337) and on wheat by Simmond, Ward and McEwen (19, p. 268) within the velocity range of 42-163 feet per minute. Ives, Hukill and Black (11, p. 15) also found that the kernel travel time in counterflow drying for wheat was not significantly affected by air velocity. Therefore, if the air velocity within the column was doubled by doubling the air flow rate, the zone depth also would be doubled. In order to maintain the same kernel travel time, θ_t, the kernel travel speed must be doubled. This leads to the relation

$$\theta_t = \frac{R_t}{D} \qquad (2)$$

where R_t = kernel travel speed, inches/hour

D = zone depth, inches

Where the effect of air velocity on drying rate is negligible, the above changes in air flow rate, zone depth and kernel travel speed should not affect the value of grain discharge moisture content as long as the exposure time is held constant.

Combination of equation (1) and (2), obtained

$$\frac{R_t}{D} = \frac{\Delta M}{\left(\frac{dM}{d\theta}\right)_c} \qquad (3)$$

The value of ΔM is usually predetermined from the initial moisture content and the level of dryness desired. If the value of $(dM/d\theta)_c$ is known under a particular set of running conditions, then the value of either R_t or D may be determined by taking an appropriate value for the other.

The problem now is the determination of the counterflow constant drying rate, $(dM/d\theta)_c$, for a given entering air condition. At steady state, the value of $(dM/d\theta)_c$ is dependent on those same factors which control the drying rate of fully exposed grain under constant air conditions. They are, in order of importance, air temperature, initial grain moisture content, and air humidity (4, p. 279). The higher the air temperature and initial moisture content, the faster will be the drying rate. Higher air humidities will result in slower drying rates. However, the effect of air humidity is small compared to that of the air temperature (19, p. 269; 4, p. 279-280).

If the entering air conditions of a counterflow dryer are changed, the new value of $(dM/d\theta)_c$ would be obtained after the new steady state is reached. This change of $(dM/d\theta)_c$ should be proportional to the change of the drying rate of grain which has been fully exposed to the air of the same conditions as entering air. The study of drying characteristics of grains is usually performed under conditions in which each kernel is fully exposed to the air so that the factors other than the air conditions and the grain itself are not encountered. These data are then used as a guide for the design and operation of practical dryers.

If the value of $(dM/d\theta)_c$ could be expressed in terms of the drying rate of fully exposed grain under the conditions of the entering air, the former could be determined by knowing the latter, for which more data is available. Thus, it was decided in this investigation to correlate the $(dM/d\theta)_c$ with a parameter representing the drying rate of fully exposed grain under the above conditions.

SELECTION OF PARAMETER FOR THE EXPOSED DRYING RATE

The drying rate of a single layer of grain with each kernel fully exposed to the drying air is generally referred to as the exposed drying rate. The study of drying characteristics of various materials is usually performed under this condition. Sherwood (18, p. 151-162) postulated three possible drying rate periods in the drying of solids. These are the constant-rate period and the first and second falling-rate periods. The constant-rate period occurs on material containing so much moisture that the surface is completely wet and the drying takes place similar to the evaporation of moisture from a free water surface with constant area in which the surroundings control the rate. The first falling-rate period is the period when the surface is partially wet and the drying rate varies with the proportion of the surface which is still wet. The second falling-rate period is the period in which the drying rate is controlled largely by the moisture movement within the material. The moisture content at the end of the constant-rate period when the drying rate begins to fall is termed critical moisture content. However, it has now been observed that the drying of most agricultural products takes place in the falling-rate periods (7, p. 282; 3, p. 246), and almost entirely in the second falling-rate period (4, p. 276). The constant rate period may occur at the beginning with grain having high initial moisture content, but it lasts such a short period compared to the complete drying process that it is generally ignored in the calculation by investigators.

Moisture movement within the drying solids has been studied by several investigators. The possible mechanisms which may occur, depending upon the structure of the solid and the certain time of drying, were summarized by Perry (15, p. 801) as;

1. Diffusion as liquid, vapor, or both, in a continuous homogeneous solid.
2. Capillary flow in granular interstices and porous solids.
3. Flow caused by shrinkage and pressure gradients.
4. Flow caused by gravity.
5. Flow caused by vaporization-condensation sequence.

However, the studies of internal mechanisms have been done mostly on materials other than agricultural products and using certain assumptions. For agricultural products, it would be far more complicated, since their structures are generally more complex and their properties change during the drying process. Van Arsdel (20, p. 59) pointed out that the study of these massive and difficult internal mechanisms has shown less immediate practical usefulness than the studies of the effects of external environment conditions on the drying rate. It appears that knowledge of the external factors on drying rate is immediately applicable to the design and operation of dryers. Due to these facts, most investigation on drying of agricultural products has been done on an empirical basis and based on the effects of external variables. These variables generally are taken to be air temperature, humidity, and air flow.

The drying relationship is often represented by the following equation which is analogous to Newton's law of cooling (3, p. 254):

$$\frac{M - M_e}{M_o - M_e} = e^{-K_1\theta} \qquad (4)$$

where M = moisture content at time θ, % dry basis

M_o = initial moisture content, % dry basis

M_e = equilibrium moisture content, % dry basis

K_1 = drying constant

θ = drying time, hours

The term $\frac{M - M_e}{M_o - M_e}$ is generally called the free moisture ratio. The numerator represents the amount of free moisture present at any time; the denominator is the initial free moisture that could be taken out of the material at the prevailing environmental conditions.

If the experimental data obeys the above relation, the plot of the free moisture ratio against the drying time on semi-logarithmic paper would yield a straight line, and the value of K_1 could be determined directly from the slope of the line. Drying data obtained by

Marshall and Hougen (13, p. 113-114) showed that the drying of some materials follows this relation while that of several others does not.

Simmonds, Ward and McEwen (19, p. 268) investigated the drying of wheat one grain deep and obtained experimental data that agrees well with the above relation under a wide range of environmental conditions of air temperature 70 to 170^{o}F and air velocities 32 to 163 ft./sec.

Hall and Rodriguez-Arias (4, p. 277-279) found that the drying of fully exposed shelled corn could be described by this relation but with different values of K_1 for different intervals throughout the drying process. This relation was established because their drying curves when plotted on semi-logarithmic paper were composed of several continuous straight lines, each with definite slope. Each slope is the K_1 - value for that particular portion.

Page (14) studied the effect of the air temperature, relative humidity and the initial moisture content on the drying rate of thin layer shelled corn about a half inch deep. A similar relation was given to represent the drying relationship.

$$\frac{M - M_e}{M_o - M_e} = e^{-K_2 T^{N_o}} \qquad (5)$$

where T = time units

= hours/hours to reach moisture ratio of 0.5

K_2 = experimental constant

N_o = experimental constant

The N_o - value was found to vary with the relative humidity of the drying air. The values obtained at 35%, 50% and 70% relative humidity were 0.60, 0.65 and 0.83 respectively and the value of K_2 was 0.68. The initial moisture content and the air temperature has no effect on the form of this equation but does affect the time unit. A decrease in either one of them increases the time unit.

Hustrulid and Flikke (10, p. 112-114) stated that their experimental data on drying of shelled corn did not show any definite break nor any straight line portion as observed by Hall and Rodriguez-Arias. They made an attempt to apply the diffusion equation for spheres to describe the experimental drying curve. The equation was given as:

$$\frac{M - M_s}{M_o - M_s} = \frac{6}{\pi^2} \sum_{n_o=1}^{\infty} \frac{1}{n_o^2} e^{-n_o^2 K_3 \theta} \qquad (6)$$

where M = moisture content at time θ, % dry basis

M_o = initial uniform moisture content, % dry basis

M_s = dynamic equilibrium moisture content, % dry basis

K_3 = drying rate constant

The number of terms needed in the series depends on the value of $K_3\theta$ (10, p. 112). They were able to fit the experimental drying curves of shelled corn to the above theoretical equation reasonably well by assuming values of M_s and obtaining different values of K_3 for different air conditions. However, it was also pointed out that values of K_3 as a function of temperature, shape, and size of kernels, and the effect of temperature and relative humidity on M_s, should be found to extend the usefulness of this equation (10, p. 114).

Time of One-Half Response

The time of one-half response is defined as the time in hours required for fully exposed grain under constant drying air conditions to attain the free moisture ratio, $\frac{M - M_e}{M_o - M_e}$, equal to one-half. It is sometimes used as an indication of the drying rate for grains under constant environmental conditions (8, p. 338). The same factors that control the drying rate also affect the time of one-half response (4, p. 279-280). The higher the air temperature and grain initial moisture content, the greater will be the drying rate and the shorter the time of one-half response. Lowering the air relative humidity also reduces the time of one-half response.

The intention of this investigation was to correlate the parameter representing the drying rate within the counterflow column with the exposed drying rate at the same air conditions used in the counterflow system. Therefore, one or more parameters must be selected to represent the exposed drying rate. The drying constant K_1, in equation (4) may be chosen. However, only the drying of some materials can be described by this equation. The data obtained for this experiment on shelled corn did not appear to be describable by this relation, because the drying curves when plotted on semi-logarithmic paper did not show any straight line or any portions with definite breaks as observed by Hall and Rodriguez-Arias. The drying constants in equations (5) and (6) which were developed for the drying of shelled corn may be used as the parameters. However, it was realized that the value of these constants have not been given for a wide range of environmental conditions. In the application of the correlation obtained here to the operation of the counterflow dryer, the drying air conditions would be chosen and then the value of the exposed rate parameter for that type of grain with that initial moisture content and under the particular air conditions must be known. If the exposed drying rate parameter is not available, it must be determined by performing an exposed rate test under similar environmental conditions and carrying out the involved method of determining the value of these constants. Due to these facts, the time of one-half response seemed the best one to use. It can be determined from the exposed drying curve of any kind of material whether or not that curve could be described by any form of equation. If the exposed drying rate test at selected air condition must be performed due to the lack of existing data, which is generally the case, the time of one-half response would be more easily determined by the operator of the counterflow dryer than trying to describe the drying curve by an equation and finding the value of the drying constant concerned. On the other hand, if the existing data is available, the time of one-half response could also be determined conveniently by equating the free moisture ratio in one of equations (4) or (6) to be one-half and solving for time. Hustrulid (9, p. 66) used the time of one-half response as an indicator to compare the drying rates of naturally moist, remoisted, and frozen shelled corn instead of the drying constant K_3 in equation (6), which he developed. It was done so because there was much less labor involved determining the former rather than the latter, and the same relative results were still obtained.

Thus, it was decided to use the time of one-half response as the parameter representing the exposed drying rate in this investigation for the reasons discussed above.

EQUIPMENT AND PROCEDURE

The pilot model counterflow dryer used is shown in Figure 3. The size of the column is two feet on each side. The column was placed above a plenum chamber into which the heated air was blown by a centrifugal fan. An automatically controlled heat exchanger was used to control the air temperature within the accuracy of $\pm 1^{o}F$ for all runs. The relative humidity of the heated air was left uncontrolled and depended upon the outside air conditions. The effect of the relative humidity on the drying rate was minor compared to the effect of air temperature.[1] Also, the outside air conditions varied very little during each run being performed.

The front side of the grain column was made visible by using clear plastic panels instead of plywood. The grain discharge was regulated by tilt baffle boxes as seen in Figure 7. They were linked together and all had the same movement. The position shown is the halt position in which no grain is discharged. When the baffle boxes were tilted to the opposite halt position, a constant amount of grain was discharged to the vibrating conveyor trough beneath. The tilting was done

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[1]Data obtained by Simmond, Ward and McEwen (19, p. 269) showed that at $150^{o}F$ the increase in relative humidity from 5 to 20% caused only a slight decrease in the value of drying constant from 2.29 to 2.06, while the decrease in temperature from 150 to $120^{o}F$ caused the decrease approximately from 2.10 to 1.00.

Figure 3. The continuous counterflow dryer.

Figure 4. Zone gradient measuring instrument.

Figure 5. Exposed drying rate chamber.

Figure 6. Exposed drying rate measurement.

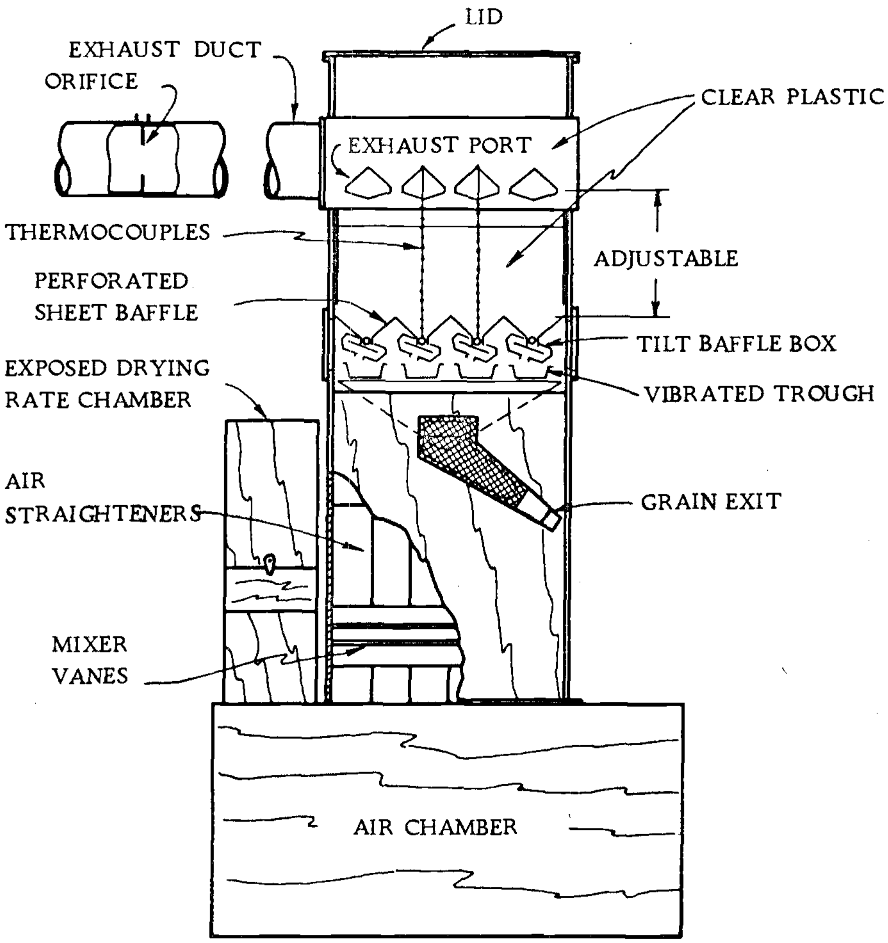


Figure 7. Front view of the continuous counterflow dryer.

periodically and the intervals were adjusted to allow for the difference of grain flow rate. The timing and tilting mechanisms were attached to the back of the column. The grain within the column was supported by perforated sheet metal baffles above the tilt baffle boxes.

A grain cooler was connected to the grain exit as shown in Figure 3. It was composed of an inclined aluminum pipe, turned slowly so that the grain could slowly flow down the slope. A small fan was installed at the lower end and cool air was blown through the pipe in the opposite direction to the flow of grain.

The upper part of the column, including the exhaust ports and exhaust ducts, could be moved up and down along the column with telescopic action to adjust the column depth. There were four exhaust ports on front and four on back of the column. Four air escape channels made of sheet steel bent to fit the upper part of the exhaust ports were attached to each pair of ports. The wet air escaped out of the column through the channels and the grain flowed down to the adjustable drying zone through the spaces between the channels. Air straighteners were provided at the lower part of the column to straighten the air flow and achieve a uniform velocity profile. The air straightener was composed of 36 small square ducts with mixer vanes in between as shown in Figure 7.

To measure the air temperature gradient, the copper-constantan thermocouple wires were suspended from the two middle air escape channels. There was one thermocouple at every inch depth down to the baffle in the tilt baffle box as seen in Figure 7. The assumption was made that the air temperature at any certain depth was uniform along the cross section. This assumption was checked by hanging four thermocouples to the same depth and at different locations in the cross section. It was found the temperature differences were less than 3^{o}F either at the upper or lower part of the drying zone. All thermocouple wires were connected to selector switches which could connect each thermocouple separately to the potentiometer used for the temperature reading. The potentiometer used was a manual-balance type equipped with automatic reference-junction compensation. It is shown with the selector switches in Figure 4.

The air flow rate was measured by orifices installed in the exhaust ducts. Both ducts were eight inches in diameter and were 20 feet long. This provided 25 diameters of duct length ahead of each orifice and 5 diameters downstream from each orifice. The pressure difference was measured by an inclined manometer. The relation of air flow rate in pounds dry air per hour, to the pressure difference is shown in Figure 14. In addition, a manometer was also used to measure the pressure drop through the column. It was connected to measure the pressure difference between the exhaust port and the point under the perforated sheet. This would probably be a practical means of determining the air flow rate for an industrial dryer after the relationship of the heated air flow rate to the pressure drop per unit depth for a specific grain was determined.

The exposed drying rate chamber was placed on the main air chamber beside the column so that the air which went through the chamber was at the same condition as that passing through the counterflow column. The tray for the exposed sample was removed through a small opening in front of the chamber as seen in Figure 5.

The grain used in this investigation was shelled yellow dent corn grown at the Hyslop Agronomy Farm by the Department of Farm Crops. It was freshly harvested usually on the day before the run was to be made and was stored under a shed in the field until the run was started. The column was filled with shelled corn from the top by a screw conveyor seen in Figure 3. Four entering air temperatures of 120, 140, 160 and 180°F and three different column depths of 16, 20 and 32 inches were used. The runs were performed between November 21, 1963 and February 21, 1964. The moisture content of the wet corn was determined and operating adjustments set for drying to a predicted final moisture of about 15.6%db. or 13.5%wb. which is the moisture content for safe storage for one year (16, p. 660). In each run with a certain air temperature and column depth, the corn flow and air flow rates were adjusted so that the exhaust air came out at near saturation. This adjustment was predicted by the use of moisture balance computations based on the air flow rate, the corn flow rate, and the amount of moisture to be removed. The corn flow rate was regulated by the time interval of the tilting baffle boxes. An infinite variable type speed reducer on a constant speed motor was used as the timing device. The air flow rate was controlled by a sliding gate at the entrance to the plenum chamber. The sliding gate was adjusted so that the pressure difference across the orifices met the desired value for the air flow rate. This value was obtained from Figure 14. The lid at the top of the column was kept closed except for the brief time when the corn was added to the column.

The steady state condition was determined by observation. After the adjustments were completed, the zone gradient was observed by reading the potentiometer for each thermocouple every half hour. When the temperature at each point in the column was constant, it was assumed that the steady state had been reached, and the zone gradient was then recorded. It was observed that the time for the zone gradient to reach the steady state ranged from 5 to 8 hours depending upon the entering air temperature. The runs with the higher temperatures tended to reach equilibrium sooner.

To determine the corn travel speed, groups of kernels coated with red paint were put into the column immediately below the exhaust ports. They were placed at 3 to 5 locations in the front of the column and could be seen through the clear plastic front panel. Their position was measured at one-half hour intervals until they reached the perforated sheet. The average position of all the colored kernals was used to plot against time to determine the corn travel speed.

The exposed drying rate data was collected while the counterflow dryer was running. A one hundred gram sample of wet corn was picked from different sacks and placed in the exposed rate chamber on the tray seen in Figure 5. The tray was removed and quickly weighed at selected time intervals as seen in Figure 6.

The moisture content samples of both wet and dried corn were placed in air-tight cans. They were weighed and put into a hot air oven and the lids removed. The samples were left in the oven at 212° F for 96 hours. The lids were then closed within the oven, and the cans were brought out and weighed. The remaining weight of the samples was assumed to be the weight of bone dry material for computing the moisture content of each sample.

RESULTS AND DISCUSSION

Counterflow Constant Drying Rate

The air temperature gradients along the zone depth of each run were plotted on rectangular coordinates as shown in Figure 8. From these plots it was found that the upper asymptotes formed on run numbers 3, 10, 11, 12, 13, 14, 16, but not on the others. In each run, an attempt was made to adjust the corn and air flow rates so that the exhaust air would come out of the column just before it was saturated. In the actual runs, if both rates turned out exactly equal to the values desired for that particular column depth, the air would have been exhausted when barely saturated. The principle difficulty was the adjustment of corn flow rate. The time interval for the tilt of the baffle box for the desired corn flow rate was estimated from the preliminary data that was obtained in December 1962. It was observed that even though the tilt time intervals were equal on different runs, there were some differences in corn flow rate depending upon the column height, and probably the final kernel size due to the shrinkage of the dried corn. These variations made the corn flow rate somewhat higher or lower than the desired values and affected the position of the upper asymptote. The faster the corn flow at constant air flow rate, the lower would be the upper asymptote in the column. In other words, the air becomes saturated sooner.

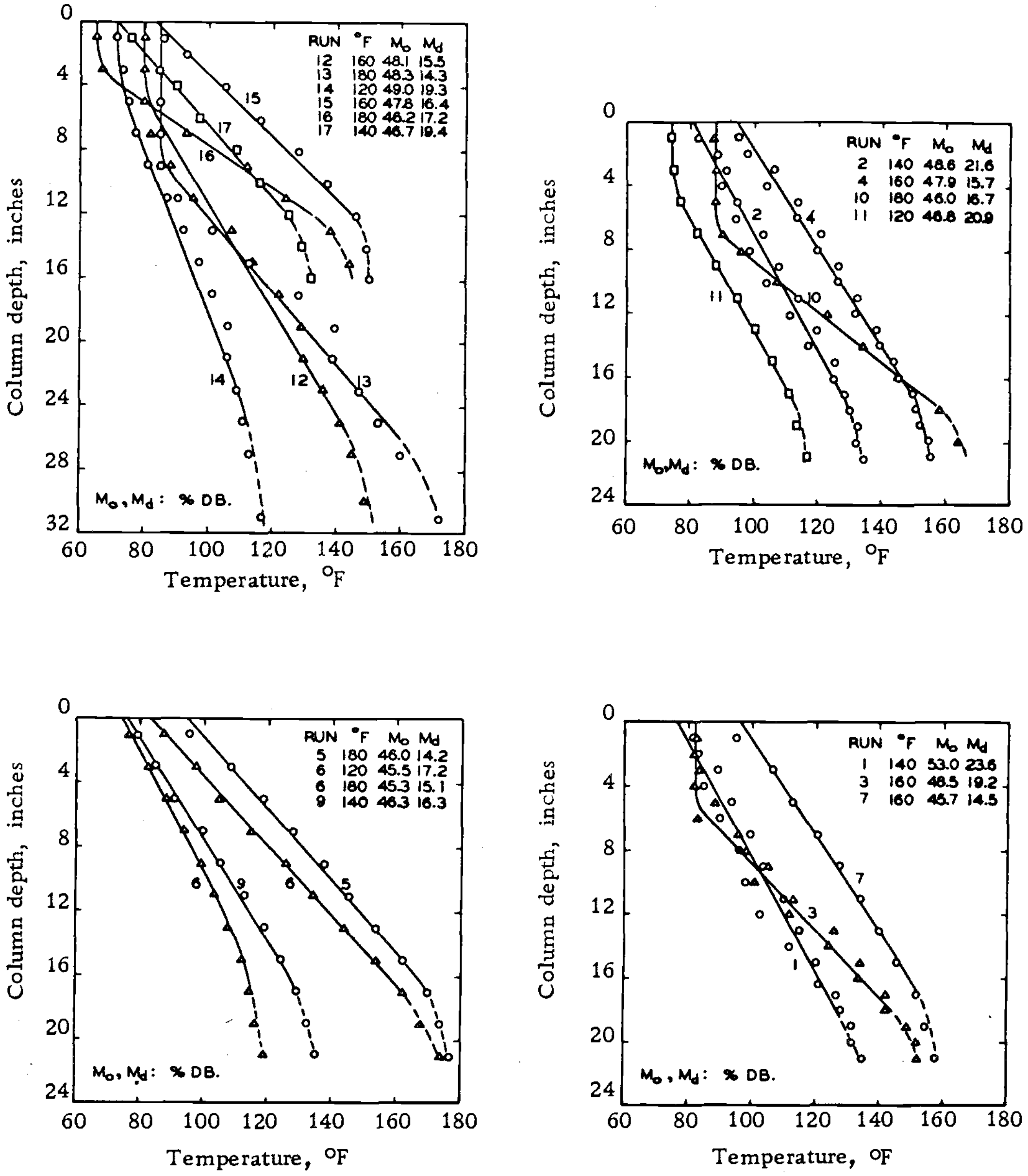


Figure 8. Temperature and moisture gradients

The assumed linear portion of the gradients were selected by observation from the plots. For the runs in which the air was saturated within the column, the linear portion began just under the upper asymptote and extended downward toward the bottom of the column. For those runs in which the upper asymptote did not form, the gradient appeared to be within the linear portion of the typical zone gradient.

An attempt was made to draw the best fitted line to those points in the selected linear portion. The method of least-squares with one variable precisely known and the other subjected to error is usually used for this purpose. The general equation for a straight line through the data points can be written as:

$$Y = aX + b \qquad (7)$$

where a = slope or regression coefficient of the line

b = intercept on Y at X = O.

The values of a and b for the least squares line through a set of scattered data points on XY plane are given (17, p. 173) as:

$$a = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2} \qquad (8)$$

$$b = \frac{\Sigma X^2 \Sigma Y - \Sigma X \Sigma XY}{N\Sigma X^2 - (\Sigma X)^2} \qquad (9)$$

where N = number of data points.

The closeness of fit of the data points to the least squares line may be illustrated by the correlation coefficient which is defined as (12, p. 265):

$$r = \frac{\Sigma(X - \overline{X})(Y - \overline{Y})}{\sqrt{\Sigma(X - \overline{X})^2 \Sigma(Y - \overline{Y})^2}}$$

where r = correlation coefficient between X and Y.

By substituting $\overline{X}$ with $\Sigma X/N$ and $\overline{Y}$ with $\Sigma Y/N$ this relation can be rewritten in the following form for the convenience of programming:

$$r = \frac{N\Sigma XY - \Sigma X \Sigma Y}{\sqrt{\left[N\Sigma X^2 - (\Sigma X)^2\right]\left[N\Sigma Y^2 - (\Sigma Y)^2\right]}} \qquad (10)$$

The value of r ranges from $\pm$ 1 to 0. As the absolute value of r approaches 1, the more closely will the point fit the least squares line. If the absolute value of r equals 1, every point will be on the line. If it is equal to 0, the points are completely random and X, Y would be completely lacking in correlation. The plus and minus sign indicate whether the line has a positive or negative slope.

The data points within the linear portion of each run were punched into cards. The value of a, b, and r were computed according to equations (8), (9) and (10) by processing the data cards through an IBM 1620 Digital Computor along with FORTRAN Programming. The results are shown in Table I. The program is shown in Appendix IV.

TABLE I. LEAST SQUARES LINES OF AIR TEMPERATURE GRADIENT AT THE LINEAR PORTION.

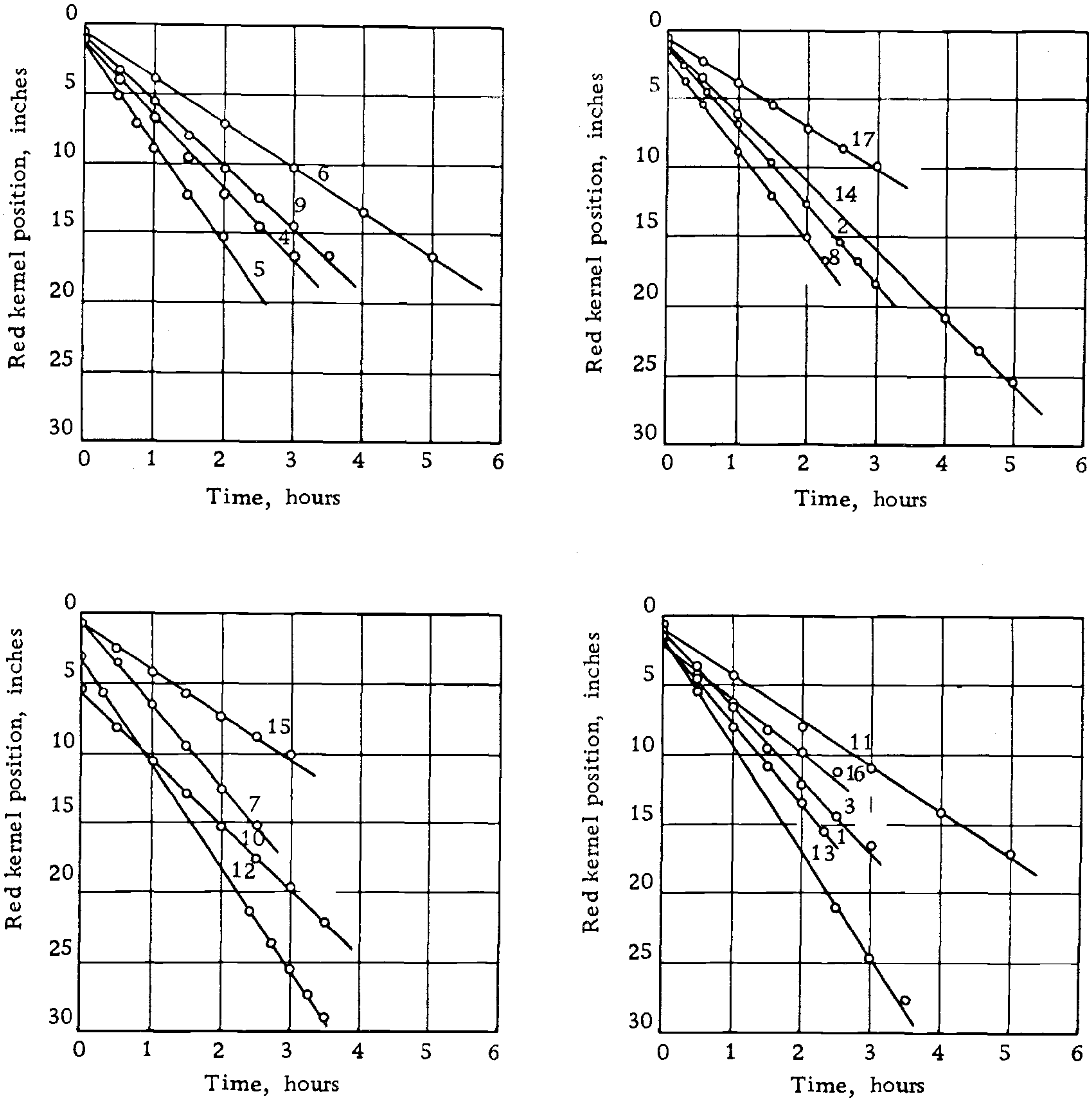
Run no.	Intercept on Y at X = o ^{o}F	Regression coefficient	Correlation coefficient	Number of data points
1	76.411	2.798	0.972	18
2	80.915	2.739	0.986	18
3	57.408	4.815	0.971	14
4	94.633	3.237	0.990	18
5	94.209	4.533	0.996	18
6	74.530	2.751	0.993	12
7	96.320	3.375	0.989	18
8	83.366	4.657	0.997	18
9	75.594	3.206	0.994	18
10	45.495	6.293	0.998	12
11	64.620	2.719	0.995	13
12	67.726	2.952	0.977	20
13	46.547	4.362	0.959	18
14	63.937	2.035	0.969	21
15	83.807	5.115	0.992	13
16	62.709	7.445	0.993	11
17	71.576	4.434	0.997	13

The least square lines were drawn to the linear portions in Figure 8 according to the values of the intercepts and regression coefficients shown in Table I. The upper and lower asymptotes, where existent, were extended from the least squares line through the data points by eye.

The dotted curve of each zone gradient is not the lower asymptote. Since the thermocouple wires were hung down to the bottom of the tapered cross section as shown in Figure 7, the dotted region in the zone gradient is the region within the tapered shape. The flow speed of each corn kernel above this region was constant, but after it reached this region, the speed was accelerated due to the tapered shape of the discharge exit. The kernel would take less time to travel the same distance within this region than it would take above this region. From this fact, it is seen that dotted portion of the curve is not necessarily the lower asymptote as it appears. This part of the distorted curve was also plotted in Figure 8 for the purpose of fitting the moisture content scale to the curve. The moisture content samples of the dried corn were taken from the corn that came out of the drier. Therefore, the value of M_d from these samples would be best assumed to be at the end of the distorted curve or at the discharge exit to the tilt baffle box because drying still occured within this region.

The initial moisture content, M_o, and discharge moisture content, M_d, of each run are the average of the four wet corn and four dried corn samples respectively. They are expressed in percent dry basis and shown in Table II. The moisture content scale was fitted to the zone gradient curve by assuming the value of M_o to be at the upper end of the zone gradient and the value of M_d to be at the lower end. Knowing these two points, the moisture content scale was calibrated graphically for each curve.

The linear change in moisture content along the depth of the drying zone or the value of ΔM/inch could then be determined from Figure 8. This was done graphically by determining the slope of the



Number at each curve is run number

Figure 9. Kernel travel curves.

linear portion in %db./inch. The value of ΔM/inch of each run is shown in Table II. Knowing the value of ΔM/inch in %db./inch and the kernel travel speed, R_t, in inches/hr. which was obtained from the plot of red kernels position against time shown in Figure 9, the counterflow constant drying rate, $(dM/d\theta)_c$, was calculated with the results shown in Table II. It is seen from this table that, the initial moisture content of all runs varies from 45.3 to 49.0 %db. except on Run Number 1 which is slightly higher at 53.0 %db. Each value is the average of four samples taken from larger amounts of corn varying from four to eight sacks on each run. The relative humidities of the heated air for the various runs was low, approximately 10% or under. Since it had only a slight effect on the drying rate compared to air temperature, and since the grain initial moisture content variation was quite low with the one exception of Run Number 1, strong consideration was given only to the effect of air temperature. From Table II it is seen that the average value of $(dM/d\theta)_c$ increases as the air temperature increases. The difference in value among the runs of the same air temperature could be the result of differences in air relative humidities and initial moisture contents, along with experimental error.

Exposed Drying Rate

The exposed drying rate samples were taken at the initial net weight of 100 grams. The samples were exposed to the drying air within the exposed drying column. The tray with the single layer of kernels was removed and weighed periodically to determine the weight lost due to the evaporation of the moisture. The samples, after exposure to the drying air long enough to give adequate information for determining the exposed drying rate (which was estimated with the experience learned from the preliminary run in the 1962 season) were put into the hot air oven at 212^{o}F for 96 hours to determine the bone dry weight in the same way as was done on the wet and dried corn samples.

Knowing the moisture weight and the bone dry weight which would not change during the process, the moisture content, M, in percent dry basis was calculated.

The equilibrium moisture content, M_e, was calculated from the data shown in appendix II.

The dimensionless moisture ratio $\frac{M - M_e}{M_o - M_e}$ at a particular exposure time was determined. To find the time of one-half response and to illustrate the exposed drying rate data, the moisture ratios were plotted as the ordinate against time of exposure as abscissa on semi-logarithmic paper shown in Figure 10. The time was expressed in minutes. The time of one-half response was determined from these curves. It was the time corresponding to the moisture ratio equal to 0.5. This value in minutes was converted to hours and the time of

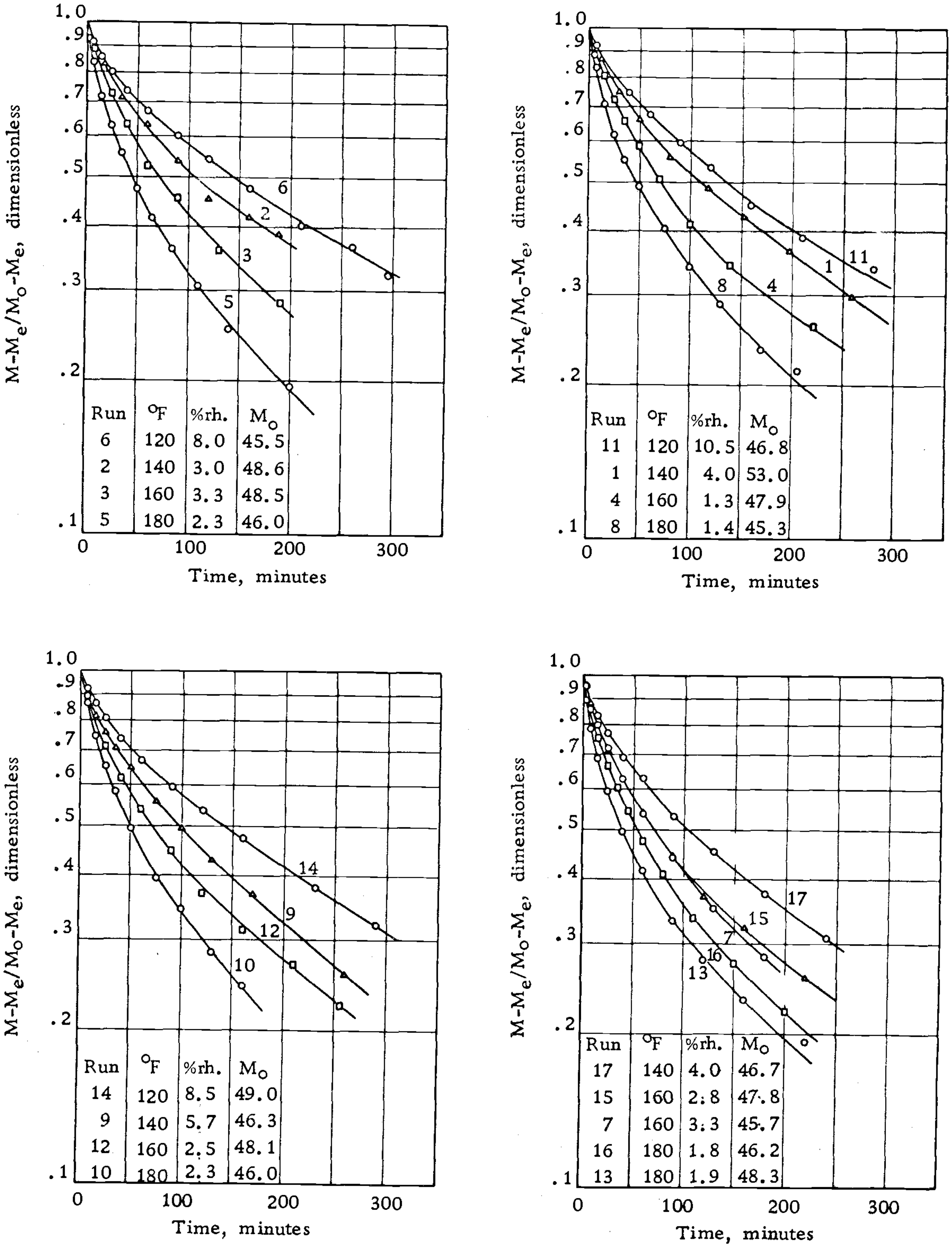


Figure 10. Exposed drying curves.

TABLE II. RESULTS

Run no.	Air temp. °F	Air rh. %	M_o %db.	M_d %db.	M_e %db.	Column depth in.	Air flow lb. d.a. /hr.-ft.^{2}	Corn flow lb. bone dry /hr.-ft.^{2}	$\triangle M$ per inch %db/in.	R_t in./hr.	$\left(\frac{dM}{d\theta}\right)_c$ %db./hr.	$\theta_{\frac{1}{2}}$ min.	$\theta_{\frac{1}{2}}$ hr.
10	180	2.3	46.0	16.7	1.6	20	246	13.95	2.325	5.83	13.56	49	0.817
13	180	1.9	48.3	14.3	1.5	32	403	20.20	1.626	7.65	12.44	40	0.667
5	180	1.0	46.0	14.2	1.2	20	358	17.85	1.720	7.14	12.27	45	0.750
16	180	1.8	46.2	17.2	1.5	14	184	10.15	2.735	3.89	10.64	54	0.900
8	180	1.4	45.3	15.1	1.3	20	313	18.00	1.556	6.58	10.25	47.5	0.792
3	160	3.3	48.5	19.2	2.0	20	263	12.47	2.050	5.28	10.83	72	1.200
12	160	2.5	48.1	15.5	1.8	32	383	20.50	1.264	7.39	9.34	71	1.183
4	160	1.3	47.9	15.7	1.4	20	277	12.77	1.731	5.23	9.05	72	1.200
7	160	3.3	45.7	14.5	2.0	20	326	14.56	1.669	4.71	7.86	71	1.183
15	160	2.8	47.8	16.4	1.8	14	199	9.23	2.380	3.25	7.74	71	1.183
1	140	4.0	53.0	23.6	2.4	20	-	14.90	1.414	5.91	8.35	110	1.834
2	140	3.0	48.6	21.8	2.1	20	349	14.71	1.389	5.71	7.92	107	1.784
9	140	5.7	46.3	18.3	2.9	20	271	11.82	1.534	4.54	6.98	97	1.616
17	140	4.0	46.7	19.4	2.4	14	171	8.23	1.979	3.13	6.19	105	1.750
14	120	8.5	49.0	19.3	3.9	32	416	13.00	1.269	4.92	6.24	142	2.367
6	120	8.0	45.5	17.2	3.8	20	263	9.66	1.791	3.22	5.77	144	2.400
11	120	10.5	46.8	20.9	4.3	20	240	8.26	1.681	3.29	5.53	135	2.250

one-half response in hours for each run is shown in Table II. It is seen that, the higher the air temperature, the shorter the time of one-half response. This result agrees with those obtained by Hall and Rodriguez-Arias (4, p. 277-280).

The Correlation

To correlate the counterflow constant drying rate, $(dM/d\theta)_c$, with the time of one-half response, $\theta_{\frac{1}{2}}$ they were plotted with the former as the ordinate and the latter as abcissa on rectangular graph paper as shown in Figure 11. An attempt was made to determine the functional relationship between these two variables so that it could be readily available for determining the suitable running conditions in counterflow drying of shelled corn for various heated air conditions. When plotted on log-log paper, the curve appeared to describe a good straight line as seen in Figure 12. This implied the relation (17, p. 183):

$$\left(\frac{dM}{d\theta}\right)_c = k\theta_{\frac{1}{2}}^{n} \qquad (11)$$

where k and n are fitting constants.

To apply the method of least-squares so that the best fitted curve could be determined, equation (11) was transformed by taking logarithms

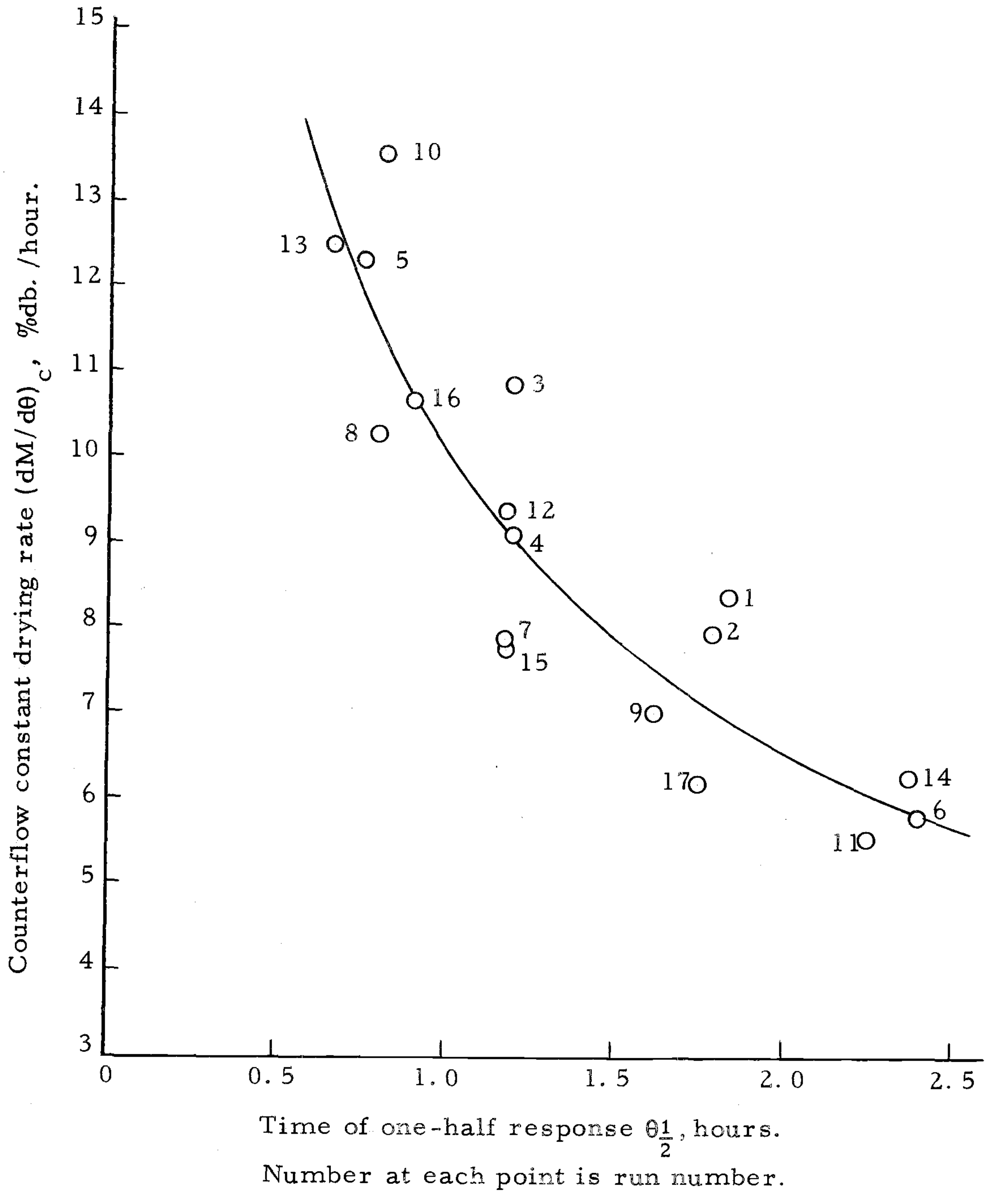


Figure 11. Relation of counterflow constant drying rate to the time of one-half response.

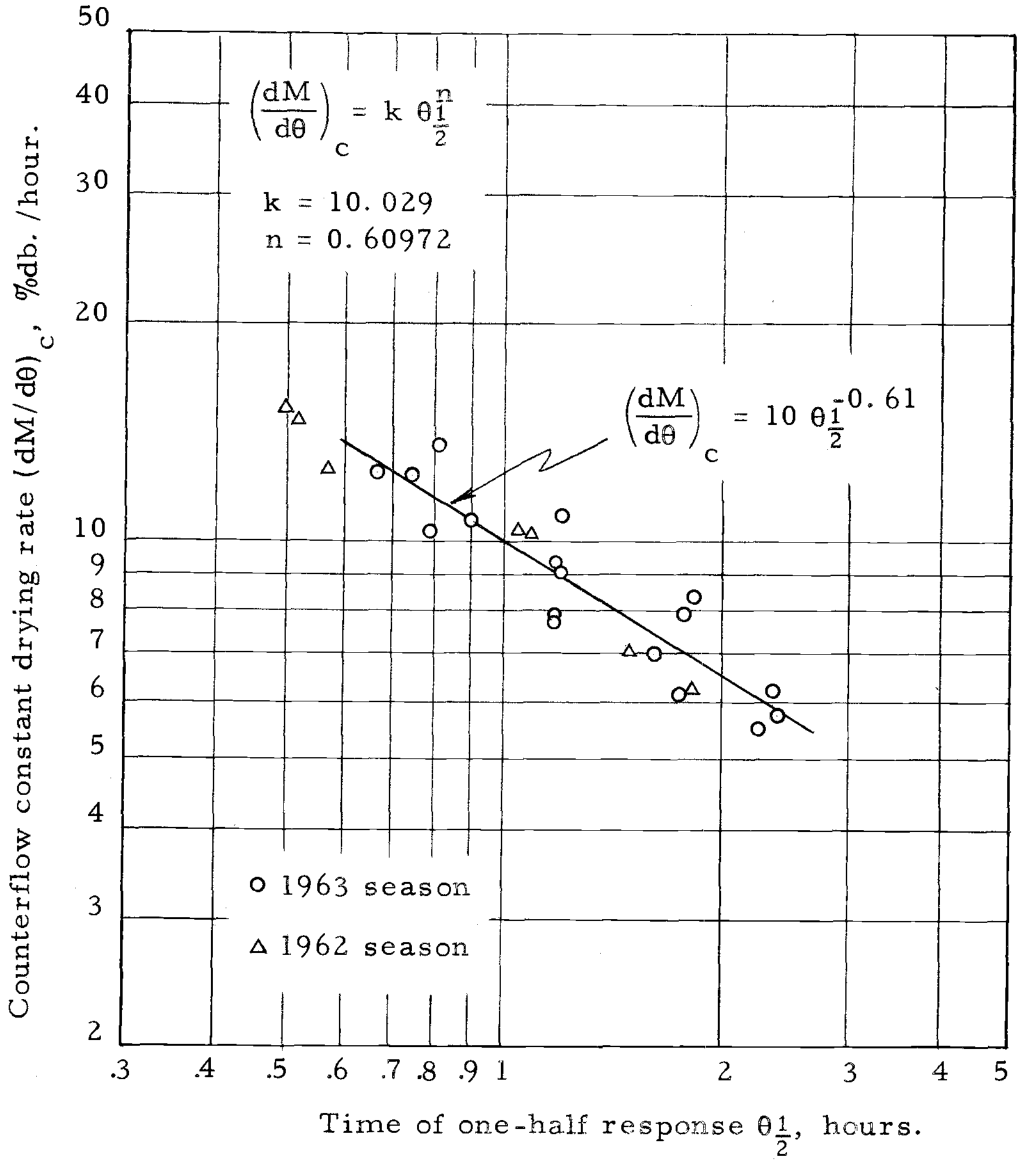


Figure 12. Relation of counterflow constant drying rate to the time of one-half response.

to be

$$\log \left(\frac{dM}{d\theta}\right)_c = \log k + n \log \theta_{\frac{1}{2}}$$

which is linear on rectangular coordinate with $\log (dM/d\theta)_c$ as the ordinate and $\log \theta_{\frac{1}{2}}$ as the abcissa. This form of equation is analogous to equation (7). Therefore the least-squares line was determined by taking the log of both $(dM/d\theta)_c$ and $\theta_{\frac{1}{2}}$ values and applying equation (8), (9) and (10). The values of constants k and n were found to be k = 10. 029, and n =-0. 60972. The correlation coefficient was found to be r = -0. 91043. The calculation is shown in Appendix III.

Equation (11) becomes

$$\left(\frac{dM}{d\theta}\right)_c = 10.029 \theta_{\frac{1}{2}}^{-0.60972}$$

and could be approximated by

$$\left(\frac{dM}{d\theta}\right)_c = 10\, \theta_{\frac{1}{2}}^{-0.61} \qquad (12)$$

The line in Figure 12 was fitted to the data points according to this relation. Equation (12) is then the empirical equation describing the relation between $(dM/d\theta)_c$ and $\theta_{\frac{1}{2}}$.

By substituting the $(dM/d\theta)_c$ in equation (3) with equation (12), the ΔM with $(M_o - M_d)$ and rearranging, obtains

$$D(M_o - M_d) = 10 R_t\, \theta_{\frac{1}{2}}^{-0.61} \qquad (13)$$

Equation (13) can be used to find the zone depth, D, and the kernel travel rate, R_t, for the drying of shelled corn in continuous counterflow dryer within the range tested. One would predetermine the value of M_o and take the desired value of M_d and substitute these values including the time of one-half response, $\theta_{\frac{1}{2}}$, for shelled corn at the air condition used into equation (13). The value of either D or R_t could be found by giving the appropriate value for the other. The proper column depth and the corn flow rate would be adjusted according to the value of D and R_t obtained.

The next step is to find the suitable air flow rate so that the air would come out of the drying zone almost saturated. This could be found by the moisture balance:

$$Q_a (H_d - H_o) = Q_g (M_o - M_d)$$

where Q_a = air flow rate, lb. d. a. /hr. -ft.^{2}

Q_g = grain flow rate, lb. d. a. /hr. -ft.^{2}

H_d = exhaust air humidity, lb. water/lb. d. a.

H_o = entering air humidity, lb. water/lb. d. a.

Knowing the kernel travel speed, R_t, the grain flow rate, Q_g, for shelled corn could be determined from Figure 13. The value of H_d and H_o could be obtained from psychrometric chart.

The preliminary runs in December 1962 were made at three entering air temperatures of 120, 150 and 180°F. The average

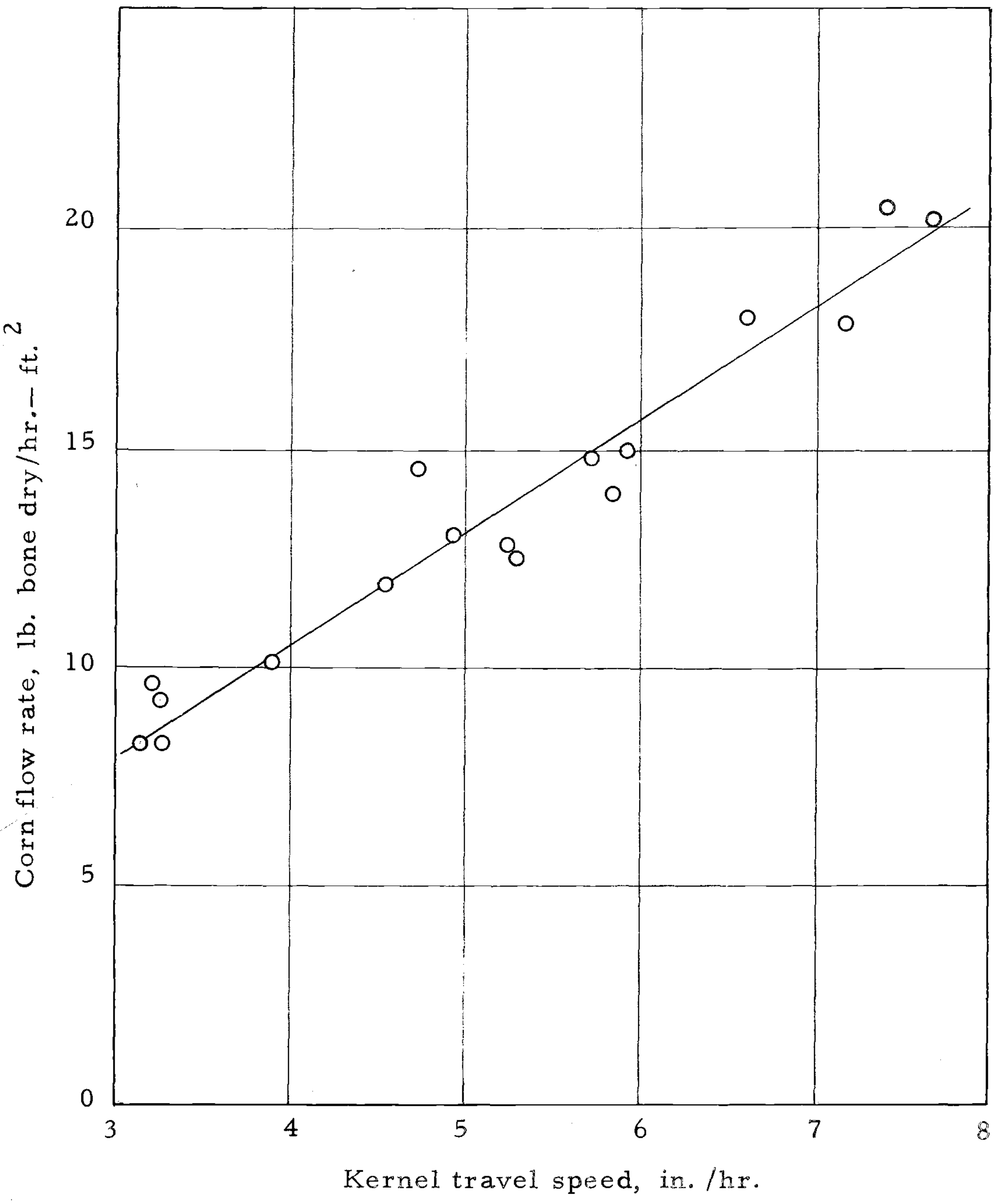


Figure 13. Relation of corn flow rate to the kernel travel speed.

initial moisture content was higher than for those runs in the 1963 season. They varied from 56.4 to 62.6%db. on the runs in 1962. To check whether equation (12) could be applied to shelled corn at other initial moisture contents, the data obtained from some of the 1962 runs was used to plot the counterflow constant drying rate against time of one-half response as shown in Figure 12. It is seen that the points can be described by equation (12) reasonably well even though the initial moisture content was higher. This led to the conclusion that equation (12) is valid for shelled corn at least for the initial moisture content range from 45.3 to 62.6%db.

SUMMARY AND CONCLUSIONS

The drying of grain in a continuous counterflow column dryer was investigated. The runs were performed under various conditions. Entering air temperatures of 120, 140, 160 and 180°F were used with column depths of 16, 20 and 32 inches. The air relative humidities were 10.5% and lower for all runs. Freshly harvested shelled corn with an initial moisture content range from 45.3 to 53.0 %db. was dried within the counterflow column. At a particular entering air temperature and column depth, the corn flow and air flow rate were adjusted so that the air would be exhausted near saturation. The air temperature gradient along the zone depth was measured by thermocouples after the steady state had been reached. The adiabatic exchange was assumed in the drying zone and the corn moisture content was fit to the curve so that the curve would also represent the moisture gradient within the drying zone. It was found that the drying rate of each kernel was almost constant from the point where it entered the drying zone to the point where it was discharged from the column, under the controlled conditions tested. The constant drying rate was assumed and termed the counterflow constant drying rate. The counterflow constant drying rate of each run was determined. The exposed drying rate of shelled corn was also tested on each run under the same air condition as the entering air. The time of one-half response was selected as the index to indicate the exposed drying rate and was determined from each test. The counterflow constant drying rate was correlated with the time of one-half response and a functional relationship was obtained. From this relationship the counterflow constant drying rate of shelled corn for an entering air condition could be determined by knowing the time of one-half response under the same air condition. The counterflow constant drying rate could be used to determine the feed rates, column depths, and air requirements necessary in the design and operation of a continuous counterflow dryer for certain agricultural products.

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APPENDICES

APPENDIX I

Determination of the Air Flow Rate

The sizes of the exhaust ducts and the orifices were designed to operate within the range of 0 to 1 inch of water pressure drop across the orifice for the flow rates desired. Two eight-inch diameter ducts were each fitted with 4 inch diameter square edged orifices. Pressure taps were at 1 inch from each side of the orifices.

The ratio of the downstream to the upstream pressure employed in these tests would be higher than 0.99, therefore the following equation could be used with less than 0.6% error (2, p. 272-273):

$$w = \frac{\pi \beta^2 D_o^2}{4} \frac{C}{\sqrt{1 - \beta^4}} \sqrt{\frac{2g (p_1 - p_2)}{v_1}}$$

where w = weight rate of flow, lb/sec.

β = diameter ratio, dimensionless

D_o = inside pipe diameter, ft.

C = discharge coefficient, dimensionless

g = acceleration due to gravity, ft./sec.^{2}

p_1 = upstream pressure, lb./ft.^{2}

p_2 = downstream pressure, lb./ft.^{2}

v_1 = specific volume of fluid, ft.^{3}/lb.

with $K_o = C/\sqrt{1 - \beta^4}$ and $\gamma_m h = (p_1 - p_2)$, the above equation becomes:

$$w = \frac{\pi}{4} \beta^2 D_o^2 \sqrt{2 g \gamma_m} K_o \sqrt{\frac{h}{v_1}}$$

where K_o = flow coefficient, dimensionless

γ_m = density of manometer fluid, lb. /ft.^{3}

h = manometer differential, ft.

By substituting $\beta = 0.509$, $D_o = 0.655$, $g = 32.2$ and $\gamma_m = 62.4$ obtain

$$w = \frac{\pi}{4} (0.509)^2 (0.655)^2 \sqrt{2 (32.2) (62.4)} K_o \sqrt{\frac{h}{v_1}}$$

$$= 5.975 K_o \sqrt{\frac{h}{v_1}}$$

If;

350 lb. d. a. /hr. < air flow rate < 800 lb. d. a./hr.

The Reynolds Number would be:

$$30,000 < R_D < 70,000$$

From the table for the value of K_o (2, p. 381):

$$0.639 < K_o < 0.631$$

The approximate value of $K_o = 0.634$ was used.

From above equation:

$$w = 5.975\ (0.634) \sqrt{\frac{h}{v_1}}$$

$$h = 0.0697\ v_1\ w^2$$

The relation of h and w was calculated from this equation and shown in Table III. The curves of this relation were plotted in Figure 14, so that it could be used as a guide for the air flow rate.

TABLE III. RELATION OF AIR FLOW RATE TO THE MANOMETER READING

Air flow rate		w lb. air/sec.		$h = 0.0697\, v_1\, w^2$			
				70°F		90°F	
lb. d. a./hr.	lb. d. a./sec.	70°F	90°F	ft. water	in. water	ft. water	in. water
800	0.2222	0.2260	0.2290	0.04830	0.580	0.05160	0.619
700	0.1944	0.1976	0.2004	0.03695	0.443	0.03955	0.475
600	0.1667	0.1693	0.1720	0.02716	0.326	0.02910	0.349
500	0.1390	0.1414	0.1434	0.01895	0.2274	0.02025	0.243
450	0.1250	0.1270	0.1289	0.01525	0.183	0.01633	0.196
350	0.0972	0.0987	0.1003	0.0923	0.1107	0.00990	0.119

Taken from psychrometric chart with air at near saturation:

At 70°F: 1 lb. d. a. = 1.016 lb. air; obtain v_1 = 13.58 $ft.^3$/lb. air.

At 90°F: 1 lb. d. a. = 1.031 lb. air; obtain v_1 = 14.11 $ft.^3$/lb. air.

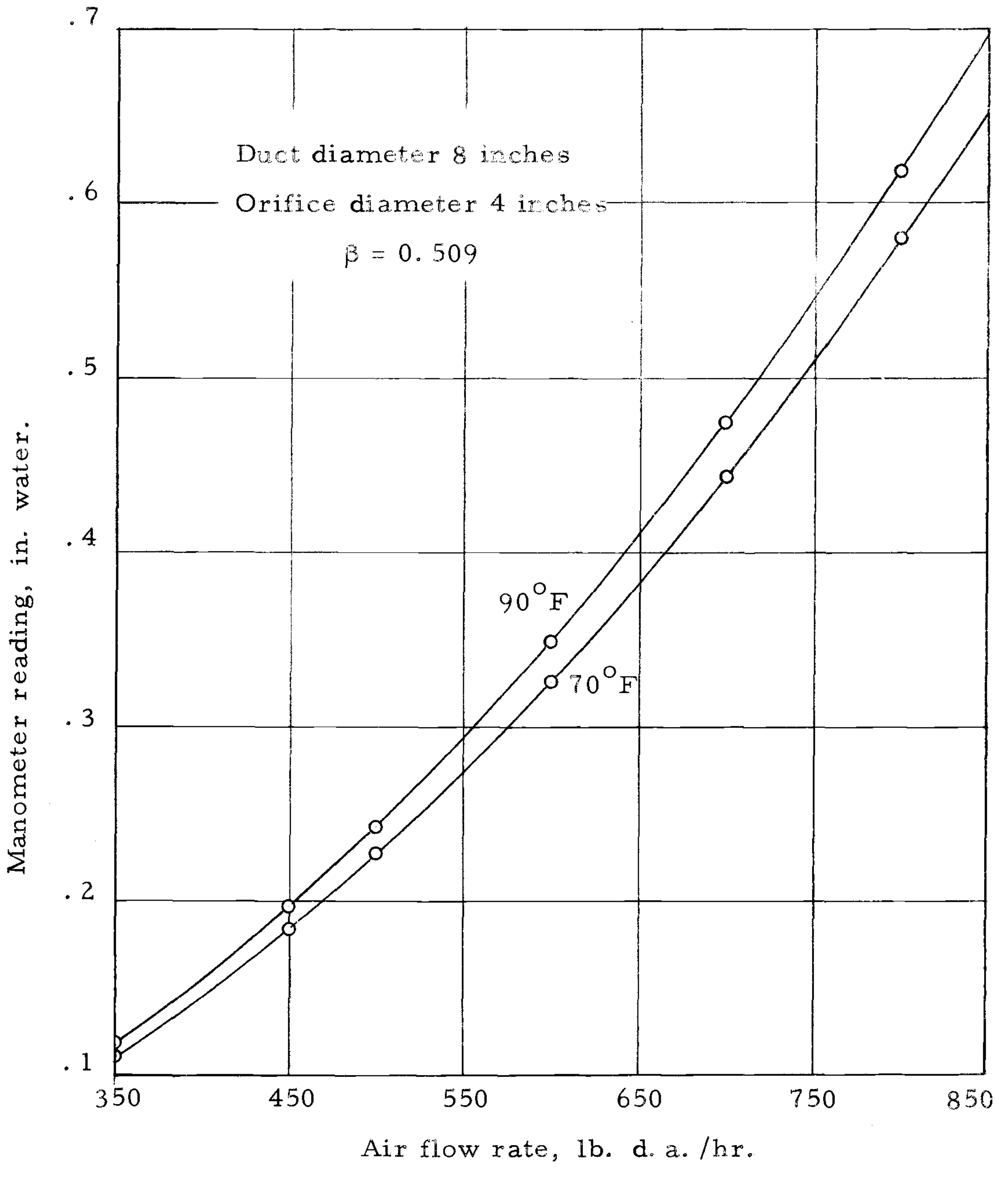


Figure 14. Relation of the flow rate of air at near saturation to manometer reading.

APPENDIX II

Determination of Equilibrium Moisture Content

It was not convenient to keep the exposed drying rate samples long enough within the chamber to reach the equilibrium moisture content. Equilibrium values were calculated using the equation derived by Henderson (6, p. 31) for describing the relationship of M_e for hygroscopic materials with given air conditions.

$$1 - rh = e^{-dT_o M_e^m}$$

where rh = relative humidity, a decimal.

M_e = equilibrium moisture content, % dry basis.

T_o = temperature, ^oR.

d, m = constants dependent upon the materials.

Hall and Rodriguez-Arias (5, p. 466-470) checked the validity of the above equation for shelled corn at a wide air temperature range. They found that the above equation successfully agreed with experimental data within the range of relative humidities from 10% to 60% and the values of d and m were temperature dependent. However, their curves showed that the deviation of the experimental curve from the calculated curve at the region below 10% relative humidity which was employed in this work was small. Therefore, it was decided to use this equation for determining the value of M_e.

The values of constants d and m for shelled corn, as a function of temperature were found from 40 to 140°F (5, p. 469). Since the values at 160 and 180°F were also needed in this investigation, the curves were extended as seen in Figure 15, and the extrapolated values for these two temperatures were used.

The values of drying air relative humidity, rh, were determined by recording the outside air dry bulb and wet bulb temperatures during the running period. The average values were assumed as the outside air conditions before it went through the heat exchanger. The outside air condition was considered heated with constant humidity to the final dry bulb temperature of each individual run as measured by the thermocouple in the plenum chamber. The relative humidity at this point was read from a psychrometric chart and used to represent the drying air relative humidity.

Sample of calculation

Run Number 1

$$T = 600^{\circ}R \qquad m = 2.2$$

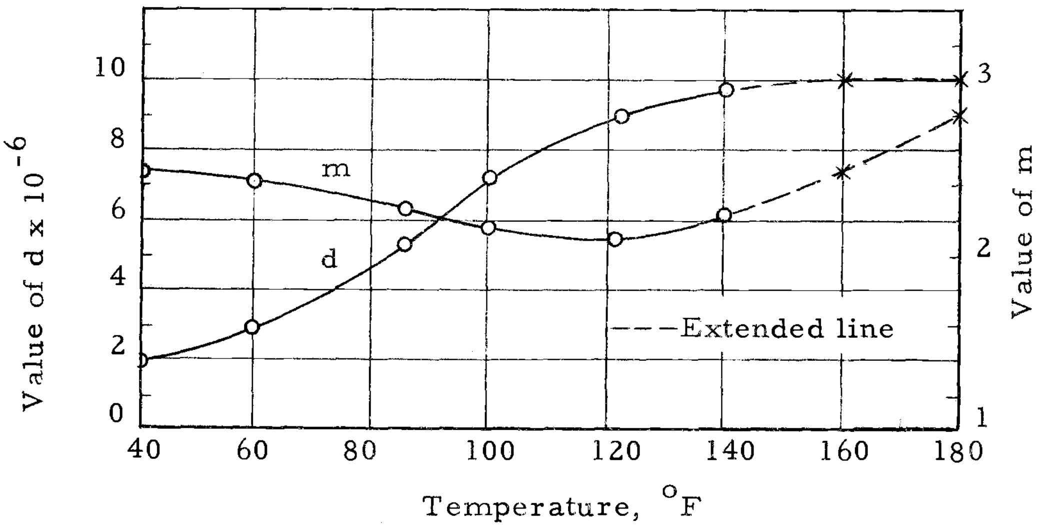
$$d = 9.7 \times 10^{-6} \qquad rh = 0.04$$

$$1 - 0.04 = e^{-(9.7 \times 10^{-6})(600)\, M_e^{2.2}}$$

$$0.96 = e^{-0.00582\, M_e^{2.2}}$$

$$M_e^{2.2} = \frac{-0.0409}{-0.00582} = 7.025$$

$$M_e = 2.43 \text{ \%db.}$$



°F	d	m
120	8.8×10^{-6}	2.1
140	9.7×10^{-6}	2.2
160	9.8×10^{-6}	2.5
180	10.0×10^{-6}	2.8

Figure 15. The constant d and m as a function of temperature.

APPENDIX III

Determination of Constants k and n

Equation (11)

$$\left(\frac{dM}{d\theta}\right)_c = k\ \theta_{\frac{1}{2}}^{n}$$

$$\log \left(\frac{dM}{d\theta}\right)_c = \log k + n \log \theta_{\frac{1}{2}}$$

If $Y_o = \log \left(\frac{dM}{d\theta}\right)_c$ and $X_o = \log \theta_{\frac{1}{2}}$, the above equation become

$$Y_o = \log k + n\ X_o$$

By taking logarithm of each value of $\left(\frac{dM}{d\theta}\right)_c$ and $\theta_{\frac{1}{2}}$ in Table II,

and computed:

$$\Sigma X_o = 1.911 \qquad \Sigma X_o^2 = 0.73705$$

$$\Sigma Y_o = 15.856 \qquad \Sigma Y_o^2 = 15.0232$$

$$\Sigma X_o Y_o = 1.46399 \qquad \overline{X}_o = 0.11241$$

$$\overline{Y}_o = 0.93270$$

By application of equation (8), (9) and (10) with X_o as X and Y_o as Y obtained: From equation (8);

$$n = \frac{17\ (1.46399) - (1.911)\ (15.856)}{17\ (0.737047) - (1.911)^2}$$

$$= -0.60972$$

From equation (9);

$$\log k = \frac{(0.73705)(15.856) - (1.911)(1.46399)}{17(0.737047) - (1.911)^2}$$

$$= 1.00125$$

$$k = 10.029$$

From equation (10);

$$r = \frac{17(1.46399) - (1.911)(15.856)}{\sqrt{(8.87788)\left[17(15.0232) - (15.856)^2\right]}}$$

$$= -0.91043$$

APPENDIX IV

FORTRAN PROGRAM

```
      DIMENSION C(17), SX(17), SY(17), SXY(17), SXX(17), SYY(17), A(17), B(17),
     1          R(17)
      DO11 I=1,17
      C(I)=0.
      SX(I)=0.
      SY(I)=0.
      SXY(I)=0.
      SXX(I)=0.
   11 SYY(I)=0.
   50 READ12,I,X,Y
   12 FORMAT(I2,F3.0,F4.0)
      C(I)=C(I)+1.
      SX(I)=SX(I)+X
      SY(I)=SY(I)+Y
      SXY(I)=SXY(I)+(X*Y)
      SXX(I)=SXX(I)+(X**2)
      SYY(I)=SYY(I)+(Y**2)
      IF(SENSE SWITCH 9)13,50
   13 DO14 I=1,17
      B(I)=((SXX(I)*SY(I))-(SX(I)*SXY(I)))/((C(I)*SXX(I))-(SX(I)**2))
      A(I)=((C(I)*SXY(I))-(SX(I)*SY(I)))/((C(I)*SXX(I))-(SX(I)**2))
   14 R(I)=((C(I)*SXY(I))-(SX(I)*SY(I)))
     1     /SQRTF(((C(I)*SXX(I))-(SX(I)**2))*((C(I)*SYY(I))-(SY(I)**2)))
      PUNCH17
   17 FORMAT(8X,6HRUN NO,6X,9HINTERCEPT,9X,5HSLOPE,7X,9HCORR COEF,
     1        4X,9HNO OF PTS//)
      DO15 I=1,17
   15 PUNCH16,I,B(I),A(I),R(I),C(I)
   16 FORMAT(I12,F16.3,F15.3,F13.3,F13.0)
      STOP
      END
```