DESIGN OF A SMALL SAMPLE LABORATORY GRAIN DRYER

by 1264

IBRAHIM MOHAMED SHAFIE TAHA

B. Sc., Mechanical Engineering,
University of Cairo, Cairo, U.A.R., 1964

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1970

Approved by:

J O Hodges

Major Professor

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

THIS IS AS RECEIVED FROM THE CUSTOMER.

TABLE OF CONTENTS

Page

INTRODUCTION 1

REVIEW OF LITERATURE 4

Heated Air Drying of Grain. 4

Thin Layer Drying 4

Thick Layer 27

Some Notes Involved in Drying Studies 39

DISCUSSION OF SIMMONDS, WARD, AND McEWEN STATEMENT 44

DESIGN OF LABORATORY GRAIN DRYER 47

1. General Description. 47

2. Detail Design. 50

2.a. Heaters 53

2.a.1. Heating Capacity Calculations. 53

2.a.1.1. Air Washer Heater 53

2.a.1.2. Second Heater 54

2.a.2. Heater Design. 54

2.b. Temperature Controller. 57

2.c. Air Washer. 57

2.d. Air Humidity Ratio Measurement. 64

2.e. Air Velocity Measuring Device 66

2.e.2. Manometers 73

2.e.2.1. Small Inclination Manometer Specification 73

2.e.2.2. Second Inclined Manometer 76

2.e.3. Calibration. 76

2.f. Bin Structure and Moisture Loss Measuring Device. 76

2.f.1. Calculations 77

2.f.1.1. Calculations for grain depths from 1 inch to 4 inches 78

2.f.1.2. Calculations for grain depths from 5 inches to 12 inches 80

2.f.2. The Weight-Measuring Instrumentation 81

2.f.2.1. Instruments to be Used 81

2.f.2.2. Calculations of Circuit Sensitivity 82

2.f.3. Bin Structure Assembly 84

2.g. Insulation of Bin and Ducts 84

2.g.1. Bin Insulation 89

2.g.2. Branch Duct Insulation 90

2.g.3. Pipe Insulation 90

2.h. Fan 90

2.h.1. Estimation of Static Pressure Loss 91

2.h.1.1. Calculation of Pressure Drop in Heaters 93

2.h.2. Fan Specifications 93

ACKNOWLEDGMENTS 95

REFERENCES 96

LIST OF PLATES

Plate		Page
I	Fan and One Branch Duct Assembly.	49
II	Processes on Psychrometric Chart.	52
III	Heater.	56
IV	Temperature Controller Circuit.	59
V	Air Washer.	61
VI	Details of Air Washer	63
VII	Butterfly Valves Mechanism.	70
VIII	Sample Bin Assembly	86
IX	Details of Levers and Spherical Segment	88

LIST OF FIGURES

Figure		Page
1	Rate of drying vs. moisture content for different depths in a grain bed.	37
2	Porous tube psychrometer	65
3	Herschel venturimeter.	67
4	Inclined manometer (small inclination)	74
5	Inclined manometer	75
6	Weight measuring circuit	83
7	Assumed dimensions of heating elements	92

INTRODUCTION

Storage of grain has always been one of the important problems facing mankind. Since grain harvest is seasonal, proper storage is necessary in order to maintain product quality to meet daily requirements for cereal grain.

In early times man delayed harvesting time and exposed the grain to the sun for drying. He then stored the grain in mud-made silos in layers with openings in the silo for aeration. With this early method of storage, a loss of about 30% of the crop occurred due to birds' attack; besides, leaving the unharvested grain in the field till it dries requires favorable weather conditions.

Heated air drying has become widely used to decrease this harvest loss. The grain is harvested earlier at a relatively high moisture content. However, grain damage during heated air drying remains a point in need of thorough investigation, especially at high temperatures and high air velocities. This point is very important since many commercial dryers work at air temperatures higher than 200°F and at high air velocities.

Most research work has been devoted to the effect of various variables on the rate of drying; that is, air temperature, air velocity, depth of grain, grain initial condition, etc. Much work has been published on the effect of air temperature up to 170°F. Although the effect of air velocity and air humidity ratio on drying rates is accepted by most investigators, only limited data are published on their effect on the quality of the grain as measured by mechanical damage, insect attack, and nutritive value of the grain after drying.

A valuable study would be to study the effects of all variables of drying on grain quality. These factors are thought of to be as follows:

1. Air temperature up to 300°F.
2. Air velocity - the study may lead to a compromise between drying time and capital and operating costs.
3. Air humidity - the study here may include both drying rate and quality of the grains.
4. Remoistening the grain to different moisture contents.
5. Time of drying.
6. Final moisture content of grain after drying with respect to depth of grain.
7. All these factors may be summed up as a moisture-time study and its effect on the quality of the grain.

To accomplish this research work, a design for an apparatus is proposed here. This apparatus is capable of changing, controlling, and measuring air properties in a wide range. The design has the following features:

1. Six samples can be tested at the same time at different air conditions and/or different grain conditions.
2. The air temperature can be changed, controlled, and measured in a range from 100°F up to 300°F.
3. The air humidity can be changed, controlled, and measured from nearly zero up to 0.04 lb water/lb dry air.
4. The air velocity can be changed, controlled, and measured from 5 feet/min up to 80 feet/min. Lower velocities could be obtained, but could not be accurately measured. Higher velocities can be attained and accurately measured, but at lower temperatures than the maximum suggested here.
5. Grain depth can be changed from 1 inch up to 12 inches.
6. Grain weight for each sample can be measured almost continuously.

This measurement, plus measuring the initial moisture content using scales and oven, will lead to continuous determination of moisture content of the grain.

It was thought that a design of a six-sample apparatus would offer the needed capability to perform research during the harvesting season with the same grain properties as in practical conditions. This design is planned to satisfy minimum initial and running cost for six samples at a time.

REVIEW OF LITERATURE

Heated Air Drying of Grain

Although many early investigators were interested in artificial drying of grain using heated air from the beginning of this century, most of these investigations provided only limited experimental data with little generalized theoretical basis until 1947 when Hukill (20) published his half-response-time theory of drying.

All investigators found that both air properties and grain properties affect the drying performance characterized by rate of drying or time needed for drying, and that for bulk grain, as the air passes the grain its properties (temperature and humidity) change with depth and time which affect the rate of drying for different layers of grain. Thus, it was essential to study the exposed (or thin) layer performance to thoroughly investigate the different factors influencing the behavior of particles of air passing individual kernels of grain.

Thin Layer Drying

Hukill (20), in 1947, mentioned that the rate of drying is proportional to the grain moisture content and the dry basis equilibrium moisture content. The formula of this statement was used widely from this date on. Simmonds, Ward, and McEwen (38), 1953, used a formula based on this statement which was based on Fick's law of diffusion as reported by McEwen and O'Calaghan (31).

$$\frac{\partial W}{\partial t} = -2.303\ m\ (W - W_E) \qquad (1)$$

which when integrated will form

$$\log \frac{W - W_E}{W_o - W_E} = -mt \qquad (2)$$

where

W = moisture content, dry basis, of grain at time t, lb_w/lb dry grain.

W_o = initial moisture content, dry basis, lb_w/lb dry grain.

W_E = equilibrium moisture content, dry basis, lb_w/lb dry grain.

m = a constant, hr^{-1}, expressing the slope of plotted line $\frac{W - W_E}{W_o - W_E}$ against t on a semilogarithmic paper.

t = time, hr.

This theory is based on the assumption that all resistance to mass transfer is a thin layer of solid material (6). McEwen, Simmonds, and Ward in a following paper in 1954 (29) studied the nature of the resistance to drying in wheat grain and stated that the results of other investigators' work suggested that the rate of drying depends on the resistance of the aleurone layer in the grain surface. This layer lies at the base of the pericarp or skin. They stated further that the resistance to movement of water in the interior of the grain is negligible in comparison, and concluded that these results lead to the semilogarithmic law represented by equation (1). They gave the theoretical mathematical derivation of the law. However, many investigators showed deficiencies in this law. Hukill humself (22), in 1954, stated that this formula is only an approximation and that the semilogarithmic plot in some cases did not fit a straight line and that the constant m which is dependent on air conditions (temperature, humidity, and velocity) should be formulated in terms of these variables for generalized drying application in predicting drying for any grain and air conditions. Babbit (1949), as reported by Chittenden and Hustrulid (6) in 1966, compared the drying rates of normal wheat kernels with wheat kernels whose aleurone layers had been removed and no difference was found except that due to kernel size, indicating that the aleurone layer has no special resistance to water movement. In 1955, McEwen and O'Callaghan (31) found that the equilibrium moisture content to which drying tends at any time is in itself a function of the moisture content at that time. They concluded that the semilogarithmic law is not really true; however, they stated that nevertheless it is conveniently and adequately represented by the data for the purpose of designing a grain dryer provided that dynamic equilibrium moisture content is used in the equation. In 1961, Henderson and Pabis (15) showed that plotting $\frac{W - W_E}{W_o - W_E}$ against time on semilogarithmic paper departed from a straight line during the first 1½ hours of drying. This was due to a higher rate of drying initially when the material was adjusting itself to air temperature. They stated that if drying is accomplished for a long time, a departure from straight line will be noticed due to an increase in energy of desorption.

In 1966, Rest and Isaacs (36) reported that G. E. Page, in 1949, added an imperical constant to the equation to produce

$$MR = e^{-Kt^n} \quad (K,n \text{ constants}) \tag{3}$$

where MR is the moisture ratio $\frac{W - W_E}{W_o - W_E}$. They used data obtained by various investigators at Purdue University for shelled corn, wheat, and oats to examine the closeness of fit of data to both the semilogarithmic law and the modified one represented by Page. Closeness of fit was measured by the mean square deviation and the fit was considered favorable for 2.2% moisture content variation. Page's equation was found to fit a larger percentage of the data than the semilogarithmic one, which resulted in an inadequate fit in all cases except for some data on wheat. However, they stated that for both equations different constants were obtained for two samples differing only in original moisture content, which suggested that using the parameter moisture ratio may be encouraging a false conception of the way grain dries. The data seemed to show that the rate of drying is not only a function of the excess of moisture over the equilibrium condition but also is dependent on original moisture content. They suggested an equation, calling it "half-response equation freed". They called the semilogarithmic law the half-response after Hukill. It is in the form $MR = 10^{a+bt}$ where a and b are constants. However, they stated that it has only a practical value in predicting drying rates of exposed layers by properly selecting the constants a and b.

Hustrulid and Flikke (23), in 1959, reported that it appears that Babbit, in 1949, was the first research worker to apply the diffusinn equation to data for an agricultural crop. They developed and applied the equation for the adsorption of water by wheat and to the rate of drying as well. They used the principle of diffusion, assuming the wheat kernel as a sphere, and obtained an equation in the form

$$\frac{M - M_s}{M_o - M_s} = \frac{6}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{n^2} e^{-n^2Kt} \quad (4)$$

where

M = average moisture content, dry basis, at time t, lb_w/lb dry grain.

M_o = initial uniform moisture content, dry basis, lb_w/lb dry grain.

M_s = effective surface moisture content, dry basis, lb_w/lb dry grain.

$K = \frac{D\pi^2}{a^2}$

D = diffusion coefficient.

a = radius of sphere

t = time, hr.

They, Hustrulid and Flikke, presented justification for their equation and provided a method of checking it against experimental data. They assumed a reasonable value of M_s according to air temperature and humidity. Adjusting data of drying experiments, the value of K was obtained by introducing an experimental value of M at a certain t and calculating the value of K. The theoretical drying curve was then plotted and compared with experimental plots. The results showed satisfactory coincidence. They compared their results with those of Simmonds, Ward, and McEwen for high moisture contents. The results obtained by Simmonds, Ward, and McEwen did not fit for high moistures, while those obtained by Hustrulid and Flikke showed good agreement of experimental and theoretical data. Hustrulid and Flikke discussed the modified suggestion of Rodriguez-Arias using different values of m for the semilogarithmic law as represented by breaks in the semilogarithmic plot of the drying curve. The Rodriguez-Arias data gave a poor fit. Hustrulid and Flikke also discussed disadvantages of their equation caused by assuming the kernel was a sphere and stated that it is a gross approximation. However, if moisture is lost through all surfaces of the kernels, an expression could be derived which is in the same form as that of the sphere assumption. They said that the usefulness of this approach could be to extend K as a function of temperature, and size and shape of the kernel. Also, M_s must be determined as a function of temperature and relative humidity. The principle of this law was based on the assumption that diffusional resistance is uniformly distributed throughout the grain kernel (6). This principle was revealed experimentally by Babbit (reported by (2)) as mentioned before.

Chittenden and Hustulid (6) used data from previous work (24) on shelled corn for a wide range of initial moisture contents, air temperature, and relative humidity and they got very accurate results for the first nine hours of drying. They also stated that this equation is superior to the semilogarithmic law for the first four hours and for larger values of time when the higher terms are neglected and the equation reduces to

$$\frac{\bar{M} - M_s}{M_o - M_s} = \frac{6}{\pi^2} e^{-Kt} \tag{5}$$

This reduced equation (5) is in the semilogarithmic form. In 1963, Hustrulid (24) used the same equation and he defined M_s as the dynamic equilibrium moisture content. He used a value of M_s, found by trial and error, such that the semilog plot of $M - M_s$ versus t is a straight line and found that the experimental and theoretical plots compare closely. He also used a value of K obtained by substituting a value of experimentally determined moisture content at a certain time.

Pabis and Henderson (33) in 1961, used the same principle of diffusion used by Hustrulid and Flikke (23), but they assumed the diffusion in grain kernel to be in three dimensions. They used a brick as a mathematical model representing the maize (corn) kernel. They obtained two mathematical solutions, one considering the value of D or K is constant and the other considering D as a function of temperature of grain kernels which they showed to be a function of time of drying. The equations they obtained are, respectively, in the form

$$\frac{W(t) - W_E}{W_o - W_E} = \frac{512}{\pi^6} \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \mu_{l,m,n} e^{-t\alpha_{l,m,n}} \tag{6}$$

$$\frac{W(\phi) - W_E}{W_o - W_E} = \frac{512}{\pi^6} \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \beta_{l,m,n} e^{-\phi\mu_{l,m,n}} \tag{7}$$

where

$$\beta_{l,m,n} = \frac{1}{(2l + 1)^2(2m + 1)^2(2n + 1)^2}$$

$$\alpha_{l,m,n} = \frac{\pi^2 D}{4} \left(\frac{2l + 1}{S^2} + \frac{2m + 1}{W^2} + \frac{(2n + 1)^2}{L^2}\right)$$

$$\phi = \int_0^t D(t)\, dt$$

$$\mu_{l,m,n} = \frac{\pi^2}{4} \left(\frac{(2l + 1)^2}{S^2} + \frac{(2m + 1)^2}{W^2} + \frac{(2n + 1)^2}{L^2}\right)$$

2S,2W,2L = equivalent dimensions of grain kernel

l,m,n = indices for x,y,z coordinates and S,W,L respectively.

They (33) stated that if the value Dxt is greater than 1.2, the temperature of the grain will change only very slightly and will be very close to that of drying air and for practical purposes only the first term will be significant and both equations will reduce to

$$\frac{W(t) - W_E}{W_o - W_E} = \frac{512}{\pi^6} e^{-\frac{\pi^2}{4} t D\left(\frac{1}{S^2} + \frac{1}{W^2} + \frac{1}{L^2}\right)} \qquad (8)$$

and

$$K = \frac{\pi^2 D}{4} \left(\frac{1}{S^2} + \frac{1}{W^2} + \frac{1}{L^2}\right) \qquad (9)$$

They showed in a previous paper (15) that

$$D = D_o\, e^{-\frac{E}{RT}} \qquad (10)$$

where

R = gas constant

T = absolute temperature, ^oR

D_o,E = energy terms to be obtained experimentally. (They were determined by Fan, et al, (10) in 1961.)

In a following paper (34) Pabis and Henderson obtained an equation for the temperature of the grain kernel at any time of drying and provided experimental verification using data of grain and grain-air properties for maize suggested by other investigators. This equation is in the form

$$\frac{t - t_o}{t_a - t_o} = 1 + \frac{\alpha(e^{-K\Theta} - e^{-K\Theta})}{(t_a - t_o)(P - K)} - e^{-P\Theta} \tag{11}$$

where

$\alpha = -\frac{512}{\pi^6}\frac{\gamma_o KL}{C\gamma}(M_0 - M_E)\, e^{-K\Theta}$

$P = \frac{hA}{C\gamma V}$

t, t_a, t_o = grain, air, and atmospheric temperatures respectively, ^oF.

γ_o = specific gravity of bone dry kernel

= 1.28 gm/cm^3.

γ = specific weight of moist kernel

= $0.9\gamma_o(1 - \frac{M(d.b.)}{100})$, gm/cm^3.

C_o = specific heat of bone dry kernel

= 0.27 cal/gm ^oF.

C = specific heat of moist kernel

= $0.555\,(0.48 + \frac{M}{100})$, cal/gm ^oF.

A = equivalent surface area of kernel, cm^2.

V = equivalent volume of kernel, cm^3.

h = convective coefficient of heat transfer

= 1.76 $cal/cm^2hr\ ^oF$.

Θ = time, hr.

They (34) stated that for $K\Theta$ greater than 0.25 the error in their equation is less than 2%, while for $K\Theta$ greater than 1.2 the error is negligible. Pabis and Henderson (33) stated that though equations (6) and (7) fit their data very well, the consideration of the kernel as a sphere also fit the data satisfactorily and even better when considering the diffusion coefficient as a constant (for Dt > 1.2). They recommended the spherical procedure for its simplicity.

The definitions of equilibrium moisture content given by Hustrulid and Flikke (23) and Hustrulid (24) were argued by Chittenden and Hustrulid (6). They stated that since air velocity does not affect the rate of drying for exposed layer grains, as confirmed experimentally for velocities above a critical value, it could be concluded that all mass transfer resistance resides within the kernel.

Experiments designed to determine the equilibrium moisture content of grain usually require several days before a final moisture content value is obtained. If it is theorized that this is the time required for the moisture to diffuse from the interior of the kernel, and this is not influenced by the rate of some reaction through which water is released from a physical or chemical bond to the solid, then it may be argued that the exterior of the single kernel during drying will instantaneously assume a moisture content in equilibrium with the passing airstream. However, it is often found that the dynamic equilibrium moisture content, or surface moisture content, thus defined is greater than the final equilibrium moisture content and tends towards that latter value at long times (6).

McEwen, Simmonds, and Ward (29), in 1954, defined the static and dynamic equilibrium moisture content based on the way of measuring it. The static method of measuring, they stated, is done by exposing samples of grain for a long time to an atmosphere of controlled humidity, maintained usually by sulpheric acid of different strengths, or more rapidly by circulating the air through the acid solution and past the sample. Other acids or salts are used also. The dynamic moisture content was determined from the asymptotic value of the drying curve measured on a small sample using air of controlled temperature and humidity. They also stated that the rate of approach to equilibrium should also be determined. The straight line semi-log plot was achieved only when this asymptotic value is used. When drying was continued below the time needed for this value, dynamic moisture content was decreased slightly and the curve was no longer linear. They proposed an explanation of the performance of the process. If the grain remains exposed to the drying conditions after free moisture content, $(W - W_E)$, is given off during drying, it adjusts its life to the new environment by physical changes in the colloidal materials in the cells, or by chemical reactions, to reduce the loss of moisture. Hence, two processes are occurring simultaneously within the grain but with different rates; a relatively rapid drying process and a much slower adjustment of the life of the grain to the new conditions. They stated that engineering calculations are concerned with that part during the drying period and that they used the dynamic equilibrium moisture content. If the static method is used, W_E will be decreased, apparently increasing the drying force term, $W - W_E$, in the drying equation. Predicted drying time would then be less than actual.

In 1967, Thompson, Foster, and Peart (42, 43) represented the exposed thin layer for a wide range of high temperatures (120 - 340 ^{o}F) by the following equation

$$t = A \ln MR + B(\ln MR)^2 \qquad (12)$$

where

$A = -1.862 + 0.00488T.$

$B = 427.4\, e^{-0.033T}.$

t = time to dry to MR with drying temperature T, hr.

MR = moisture ratio, $\dfrac{W - W_E}{W_o - W_E}$ (all terms as defined before).

They based this equation on a series of thin layer drying tests performed at Purdue University on Yellow dent shelled corn during the fall of 1963. With air temperature as the main variable investigated, they found that semilogarithmic law did not adequately represent their experimental results. When using their equation of the second order exponential curve (parabola on semi-log paper), the plot shows a reasonable representation of the experimental results for the wide range of temperature used.

All the investigators stated that increasing the air temperature will increase the rate of drying, all other variables remaining the same, and that the air temperature is the main factor affecting the drying rate.

Simmonds, Ward, and McEwen (38) worked on wheat grain, in 1953, for a temperature range (70 - 170 ^{o}F) and found that the rate of drying increases with increasing temperature and that the effect decreases as the temperature increases. They found also that temperature will correspondingly decrease the equilibrium moisture content. In a following paper (39), 1953, they correlated the results of the constant m of the semilogarithmic law (equation (1)). Neglecting the effect of air humidity and air velocity, they found

$$\log_{10} m = \frac{t_a - 154.4}{84.4} \qquad (13)$$

where

t_a = air temperature, ^{o}F.

McEwen and O'Callaghan (30), in 1955, discussed the effect of air temperature on the rate constant m and found that a better correlation is given by

$$\log_{10} m = \frac{t_a - 159}{87} \qquad (14)$$

as a mean value for different kinds of grains. Their runs over a large range of humidity show that for air relative humidites not exceeding 70% the rate constant is unaffected by humidity. McEwen, Simmonds, and Ward (29), 1954, reported that Stansfield and Cook suggested that the rate of drying is not significantly increased when air temperature was raised to 180 °F - 270 °F. However, investigators discussed the maximum temperature to which the grain can be subjected without injury. Hukill (20), 1948, stated that this maximum temperature depends on type of grain and the use expected from it. Generally for grains used as seeds, a limiting temperature is 110 °F. For grains used as feed there is little information about drying temperature. Livestock can eat grains heated up to 200 °F, the temperature at which commercial grain dryers usually operate. Corn dried at a temperature above 120 - 130 °F is difficult to mill. MacMasters, et al, in 1954 and 1959, (27,28) studied the effect of drying parameters on ear corn and shelled corn respectively. They found processing the corn with respect to quality and starch recovery was acceptable for temperatures 140 °F or below for ear corn and 160 °F or below for shelled corn.

In 1951, Cramer (8) worked on rice and stated that for good milling quality, air temperature of 130 °F with air relative humidity exceeding 60% and lower velocity are used and for good germination a limit of air temperature is 110 °F.

Thompson, Foster, and Peart (43), 1967, studied the effect of high air temperature, 200 - 400 °F, on quality of corn for a concurrent dryer. The results obtained showed that the millability score of grains decreased as temperatures increased and only the 200 °F resulted in millability score above the minimum acceptable. They also showed that there was no appreciable difference in the amount of breakage due to the drying air temperature. Opposite from expected, the higher the drying temperature, the lower the percentage of checked kernels in the stress crack test.

Pickett and co-workers (35), in 1963, investigated accelerated drying at very high air temperatures ranging from 300 ^{o}F up to 900 ^{o}F for a very small time of exposure to show the effect on quality of grain. They found no apparent decrease in the nutritive value of the corn occurred due to exposure to high temperature air. However, they found that the germination percent was zero for all temperatures except for 300 ^{o}F which showed 14%. All temperatures except the 300 ^{o}F level caused damage to the starch birefringence of kernels and grain would not be suitable for wet milling.

Simmonds, Ward, and McEwen (38), in 1953, studied the effect of air velocity on drying rate of wheat grain and found that it has negligible effect in the range of 32 ft/min. up to 163 ft/min. They stated that a fourfold variation in air velocity produced little or no change in the rate of drying as measured by the slope of the semilogarithmic plot. McEwen and O'Callaghan (31), 1955, found that a fourfold increase of mass air flow from 0.055 to 0.22 lb/ft^{2}sec did not alter either the equilibrium moisture content or the rate constant. This confirmed the previous findings that the main resistance to moisture loss is inside the grain layers and not at the surface of the kernel. Thompson, Foster, and Peart (43), 1967, studied the effect of air velocity on the millability of corn and concluded that the millability score was decreased slightly with higher air flow rates and there was essentially no change in the number of stress cracks or the breakage observed.

Simmonds, Ward, and McEwen (38), 1953, studied the effect of air humidity on wheat grain and their results show that increasing the humidity of the air decreases the rate of drying slightly. The effect is much smaller than the effect of temperature changes. A three- to four-fold increase in the humidity is roughly equivalent to a drop in temperature of 50 °F.*

Hustrulid (24), 1961, stated that most investigators use remoistened or frozen samples of grains when studying the drying process since the availability of naturally moist samples is limited to a short time during harvesting and also because it is impossible to have freshly harvested grain of uniform quality throughout the year. He used naturally moistened (kept at temperature 35 - 40 °F), frozen (at 0 - 10 °F), and remoistened samples from the same ears, working with temperatures in the range of 60 - 190 °F and relative humidities of 10 to 90%. He found that the drying rates of the naturally moist and frozen samples were nearly the same while the remoistened samples dried at slightly higher average rates than the naturally moist. He stated that his results were less different than other investigators found for wheat. He found that it was difficult to prepare samples of the same initial moisture content; however, as stated in the other investigations, the small difference in initial moisture content will not affect the results too much. Simmonds, Ward, and McEwen (38), 1953, soaked wheat grain in water at room temperature of 60 °F and provided an imperical equation of moisture content with time Θ in the form

$$\log_{10} (81.5 - W) = -0.02335\,\Theta + 1.7745 \qquad (15)$$

This equation, as expected, changes with room temperature. They used a standard time for soaking of 24 hours to obtain a moisture content of 39.5% w.b. (or 66% d.b.). McEwen and O'Callaghan (31), 1955, noted that for remoistened grain there were scatter points at the initial part of drying. They stated that this is partly due to evaporation of free water remaining

*See discussion at end of the Literature Review.

on the surface. They also showed that the value of the rate constant, m, at a certain temperature is not seriously different for rewetted Scandia and freshly harvested King II wheat for relative humidity of air greater than 70%.

Carey (5), in 1955, in a discussion of papers by Simmonds, Ward, and McEwen in 1953, showed that the sum of effects due to growing location, variety, species, grain damage, and repeated soaking (rewetting) on drying rate constants for wheat and oats caused variations no greater than caused by changing temperature ± 7 ^{o}F.

Many investigators studied the equilibrium moisture content in relation to corresponding relative humidity at different temperatures.

In 1958, Hall and Rodriguez-Arias (12), investigated the applicability to equilibrium moisture content data expressed as desorption isotherm equations and theories in an attempt to explain the nature of water binding in shelled corn. Desorption is the removing of water from the grain appoaching equilibrium. Isotherms refer to the curves resulting from plotting the equilibrium moisture content on the ordinate and the respective relative humidities on the abscissa at a constant specified temperature. As reported by them, Brunauer and his co-workers proposed a classification of five types of isotherms according to shape and characteristics. Type II isotherm, called the s-shaped or sigmoid shape, has been generally attributed to multimolecular adsorption and is of considerable importance for cereal grains. The B-E-T theory due to them is based on the assumption that the same forces that produce condensation are also responsible for the binding energy of multimolecular adsorption. The first attempt to present a unified theory of physical adsorption, the B-E-T equation is in the form

$$M = \frac{V_m CP}{(P_s - P)\ (1 + C^{-P/P_s})} \qquad (16)$$

where

V_m,C = constants, dependent on temperature.

P = partial pressure of water vapor, in. of air.

P_s = saturation partial pressure of water vapor at the air temperature.

M = moisture content of material, dry basis.

Hall, et al, stated that this equation was found to conform very closely for many adsorbants over the range of relative humidities between 5 and 10% up to at least 35% and sometimes to 50%. Outside this range the equation usually breaks down. Hall and Rodriguez-Arias discussed this equation and stated that beyond 50% relative humidity the amount of water adsorbed increases more and more slowly than indicated by the equation. This may be discussed according to the assumption of adsorption on a free surface assumed in the B-E-T theory. It is evident that the internal surface of grain is by no means a free surface. Within the range of relative pressures for which the equation holds the factors which restrict the number of molecular layers have generally not yet become strong enough to make themselves noticeable. They discussed a modified B-E-T equation with three constants. The third constant introduced is the maximum number of layers that can be adsorbed on each wall of the capillaries which characterize the surface of the grain. This method needs trial and error in fitting the experimental points since this number is changed according to the range of relative humidity beyond 50%. It is noted that their plot is approximate for certain ranges of relative humidity when fitting the experimental values to the theoretical ones. Becker and Sallans obtained excellent correlation for wheat at 25 °C (77 °F) up to a relative humidity about 35%. Hagon and Karon obtained reasonably good plots over a range of relative humidity between 10 and 40% for rice. These results confirm the validity of multimolecular adsorption hypothesis as postulated by the B-E-T theory.

Harkins and Jura, 1944, (as reported by (12)) provided a simple method for determining the surface area involved in adsorption. Good linear plots have been obtained in the range from 50 to 95% relative humidity when applied to water-protein adsorption. This procedure provided a method for finding equilibrium values at the high relative humidity values with great accuracy. The equation is in the form

$$\mathrm{Ln}\ \frac{P_g}{P_s} = B - \frac{A}{M^2} \qquad (17)$$

where

A and B are given for various temperatures ranging between 40 and 140 ^{o}F.

P_g = P as defined before.

P_s,M = as defined before.

Hall and Rodrigues-Arias (12) stated that excellent correlation between the experimental and theoretical calculation based on this equation was obtained for moisture contents down to 10% dry basis and for relative humidities from 40 to 45%. According to their theory, these results indicated that in these ranges the adsorbed water occurs as a condensed film.

Smith, 1947, reported by (12), developed an equation which yields a straight line if moisture content is plotted against Ln (1 - P_g/P_s) for relative humidities between 50 and 95% (same range as Harkins and Jura). The equation was justified for wheat. Smith's equation and the B-E-T equation compliment each other over their respective ranges of validity. Smith's equation is in the form

$$\frac{M}{M + 100} = W'\mathrm{Ln}\ (\frac{1}{1 - P/P_s} + W_P) \qquad (18)$$

where

W', W_p depend on temperature and all other terms are as stated before.

This agreement of B-E-T and Smith's equations was noted by Becker and Sallan (2), 1956, and suggested an interesting and valuable method of defining the intermediate linear region characteristics of the S-shaped isotherm. This is done by plotting the data according to both equations on the same graph and drawing a line tangent to the Smith curve and intersecting the B-E-T curve at its point of inflection. This procedure results in an excellent fit of the experimental data and gives a smooth, unbroken transmission into the curved regions described by both equations. They provided a table for constants of the three parts of this best fit isotherm at two temperatures, 25 and 50 ^{o}C, for wheat. They also proved that the B-E-T equation is not applicable below about 4% grain moisture content and that Smith's equation fit well for high moisture content values.

All preceding equations have temperature-dependent constants which need to be stated for a wide range of temperatures. Henderson (14), 1952, was the first investigator to derive a formula which includes the temperature effect upon the equilibrium relative humidity-moisture content relationship in the form

$$1 - rh = e^{-KTM_e^n} \qquad (19)$$

where

rh = relative humidity P/P_s, decimal

T = absolute temperature, ^{o}R

M_e = equilibrium moisture content, dry basis

K,n = constants depending on the hygroscopic material used and range of temperatures.

Henderson correlated the results of many investigators and the value of K and n were given in a table corresponding to a variety of grain but for a small range of temperature, 77 to 90 ^{o}F. as derived from the table provided by him. He stated that certain assumptions were made in his derivation, one of which has never been completely substantiated. This was Gibb's adsorption theory and that experimental confirmation of its validity is advisable before urging the general use, although the observed and calculated points are remarkably coincident.

Simmonds, Ward, and McEwen (39), 1953, used this equation due to Henderson for other values of the constants given in his table. They doubted if this equation will fit at high and low relative humidities. They stated that it appeared that Henderson's is less satisfactory at higher humidities and the form of the equation itself is very sensitive for low relative humitieies. If the equation is put in the form

$$\text{Ln } (1 - rh) = -KTM_e^n$$

then

$$\text{Ln } (1 - rh) \rightarrow rh$$

since rh is small compared to unity.

Hall and Rodriguez-Arias (12), 1958, found excellent agreement with Henderson's equation between 20 and 60% relative humidity. Beyond that range, the experimental isotherms generally deviate markedly in an upward direction from the calculated curve. The equation failed to account correctly for the temperature dependence of the isotherms for corn, wheat, rice, pea beans, and sugar beet seeds. For all these crops the actual equilibrium moisture contents at a given relative humidity and temperature were below the theoretically calculated moisture content determined on the basis the data obtained at the lower temperature (as derived from his table). In 1967, Thompson, Peart, and Foster (44) used Henderson's equation but varied the constants which were determined by a computer analysis of data due to Rodriguez-Arias. They replaced the temperature factor T by (t = 50) (where t = ^{o}F) to fit the experimental data for shelled corn.

Shelef and Mohsenin (37), 1966, gave an experimental explanation to the invalidity of Henderson's equation for high values of relative humidity. They investigated the isotherms for the whole corn kernel, the germ, and the endosperm at 74 ^{o}F and relative humidities ranging from 11% up to 97%. They prepared the germ and endosperm samples by hand dissection. They found that the equilibrium moisture content for the germ was lower than that for the endosperm up to 88% relative humidity. Above this level, the germ took up water much more rapidly. At 97% relative humidity, the equilibrium moisture content of the germ was as high as 40% d.b. compared to about 28% for the endosperm. They also made a check for the effect which respiration of the living germ might have influenced the results at the high relative humidities. They used dead germ kernels and they obtained slightly lower values but the same pattern was obtained. They checked Henderson's equation and found coincidence for the endosperm for most of the relative humidity range. For the germ, no coincidence occurred which explained the lack of coincidence for the results obtained for the whole kernels at high relative humidities.

Strohman and Yoerger (40), 1967, provided an equation which has correct temperature dependence based on Othmer lines which are physically correct for all values of M. This equation is

$$\frac{P}{P_s} = \exp\left(ae^{bM} \ln P_s + ce^{dM}\right). \qquad (20)$$

where

a,b,c,d are constants depending on the kind of grain and can be directly obtained from experimental data using a digital computer program.

They introduced values for corn as follows

a = - 0.8953

b = -0.1232

c = -5.482

d = -0.1917

Thompson, Peart, and Foster (44), 1967, reported that this equation is valid in the whole range of moisture, relative humidities, and temperatures. However, Strohman and Yoerger (40), stated that these isotherms do not pass by zero moisture content, but actually zero moisture content is hard to define and when a heated-air oven is used another equilibrium moisture content is determined. The zero percent moisture content could be plotted when relative humidity of air in the oven is 3% at 200 °F drying temperature.

Thompson and Shedd (42), 1954, used duplicate samples of ear corn, shelled corn, and wheat, pretreated to obtain different initial moisture contents (high and low values), one above and the other lower than the expected equilibrium moisture content. Temperatures were 20, 32, 50, and 70 °F and relative humidities were 35 and 82%. Their results showed that a 7% increase in relative humidity will raise the moisture content about 1%, a 50 °F drop in temperature will increase the equilibrium moisture content about 2% and pre-drying to 8% moisture will decrease the equilibrium moisture content from 0.5 to 0.8% in comparison with samples pre-moistened to 16% wet bulb. The initially high moisture sample had a higher equilibrium moisture content than the initially dry samples.

Many investigators (2,3,4,13,19,26,37,47) found that the value of the equilibrium moisture content is different at the same relative humidity and temperature of air depending upon whether the grain is reaching hygroscopic equilibrium by desorption or adsorption. The difference between the moisture contents of desorption and adsorption at the same relative humidity was denoted by them as the hysteresis effect.

Hubbard, et al, (19) worked on wheat and corn and showed that both adsorption and desorption isotherms at 25, 30, and 35 ^{o}C were sigmoid in shape, with a maximum hysteresis effect for a relative humidity range between 12 and 44%. This amounted to 1.6% moisture content. The hysteresis effect was only 0.2% at 92% relative humidity. They stated that temperature had no effect on hysteresis but the isotherms are displaced towards the relative humidity axis as temperature increases. Breese (3), 1955, obtained similar results for rice. Hart (13), 1964, also studied the effect of air temperature on the hysteresis effect. He found that the hysteresis decreased from 0.76% to 0.37% by increasing the temperature from 76 ^{o}F to 90 ^{o}F. He also investigated the effect of increasing the pressure by 9 lb/in^2, which is equivalent to that exerted by a depth of 60 ft for a 40 ft dia. bin, and found that the effect was small. Juliano (26), 1964, worked on rough rice and concluded that in areas with relative humidities higher than 75%, drying of rough rice with unheated air may be used only on wet grain and final supplemental heating is required. Otherwise, the equilibrium moisture content of rice will be more than 14%, the safe moisture content for storage.

Bushuk and Hlynka (4), 1960, obtained volume isotherms similar to that of the weight isotherms, but the hysteresis effect was more noticeable in volume than in weight. Also, they found that after a complete cycle of adsorption and desorption a net increase in the volume resulted which they attributed to the micro-crack formation in wheat.

Young and Nelson (47), 1967, explained hysteresis effects as follows: When dry biological material is subjected to a wetting environment, moisture first adheres to the surface of the cells forming a unimolecular layer. The surface molecules of the cells exert binding forces on water molecules preventing them from moving inward. As more and more molecules adhere to the surface, the diffusional forces exceed the binding forces and allow some moisture to move inside the cell. Then on desorption there is no force to pull the moisture out of the cells until all the moisture has been removed from the surface. At this time, diffusional forces caused by the concentration gradients cause the absorbed moisture to move out of the surface. They (47) also provided equations for both the desorption and adsorption isotherms which were not available before. They used Hubbard, et al, data at 30 ^{o}F to find good agreement between theoretical and experimental work.

Chung and Pfost (7), 1967, hypothesized that more sorption sites, which pass the adsorption potential on the surface of the adsorbent, are available to water vapor during the desorption process than during adsorption. They justified their hypothesis by investigating the difference between heat of adsorption and heat of desorption. They found the differences to be statistically greater than zero. They explained the effect of increased sites to cause the hysteresis effect as due to crack formation caused by wetting the grain before desorption is carried out.

Simmonds, Ward, and McEwen (38) studied the effect of grain size and its change with drying on rate of drying. They found that the rate of drying is inversely proportional to the grain size and the product md_e, where m is a rate constant and d_e is the mean diameter of grain, is a constant. They derived a value of $md_e = 0.305$ for wheat at air temperature 150 ^{o}F, and for this temperature the semilogarithmic equation could be rewritten in the form

$$\frac{\partial W}{\partial t} = 0.305\ (W - W_e)/d_c. \qquad (21)$$

Also, they concluded that during drying most of the shrinkage occurs between moisture contents of 60% and 20% dry basis, and they stated that since the important practical range of drying is from 20% dry basis downwards, the shrinkage can usually be neglected. They showed that beds of four grain kernels deep provided the same constants of drying and hence could be considered as thin layer.

Thick Layer

Hukill (20), 1947, was the first investigator to compute bulk drying rates from exposed layer drying rates for wide ranges of grain depth, moisture content, air volume, temperature, and humidity. His approach was the first theoretical one made. He constructed a chart of dimensionless moisture ratio, expressed in percentage, as ordinate against dimensionless time units as abscissa, representing the ratio of time of drying to the time needed for drying the fully exposed layer to half its free moisture content, i.e. MR = 0.5. The family of lines represented on this chart represent the bottom layer (considered fully exposed) depth factor 0 and depths represented by depth factors 1,2,3,...etc. These curves show the moisture content of layers of grain at successive depth increments (units). The depth unit for a given set of conditions depends upon the number of pounds of grain (dry weight) traversed by air. The depth unit is defined on this basis: if all heat theoretically available could be used, it would all dry to equilibrium in the time taken to dry fully exposed grain half way to equilibrium. The number of pounds of grain contained in each depth unit is

$$G = \frac{Q \times 60 \times T \times S_A \times H}{0.01 \times M \times V} \qquad (22)$$

where

G = pounds of dry matter in a layer one unit deep

Q = volume of air, lbs/min

T = the maximum temperature drop that may occur in the air, ^{o}F

S_A = specific heat of air at constant pressure (taken as 0.24) btu/lb ^{o}F

H = time required for fully exposed layer of grain to reach half way to equilibrium, hrs

M = the total possible change in moisture content of grain

= (initial moisture - equilibrium moisture corresponding to entering air condition), % dry basis

V = latent heat of drying, btu/lb.

The maximum temperature drop that may occur is equal to the difference between the dry bulb temperature at inlet and the dry bulb temperature of air corresponding to the same initial wet bulb and the equilibrium relative humidity at the moisture content of wet grain (assuming adiabatic saturation process). For very moist grain, this temperature approaches the wbt. Hukill stated that the work of investigators show values of latent heat of drying differ from those of heat of vaporization of free water at the same temperature by the amount of heat of wetting. He used a value of $V = 1050 + 120$ btu/lb at 75 ^{o}F assuming the 120 btu/lb value is required in wetting grain from 10% to 16% moisture content. He stated that only limited data are available. Other investigators studied the latent heat of drying. Johnson and Dale (25), 1954, stated that there was little information on the matter in which the energy requirement is dependent on the type of grain, moisture content, drying rate, and drying temperature. They stated that since the grain is a hygroscopic material and exhibits a vapor pressure less than that of free water at the same temperature, it would be expected that the heat requirement would be somewhat above that of free water and that there would be an increase in this quantity as drying is carried to lower moisture levels. They used an equation predicted by Othmer in the form

$$\log p = \frac{L}{L'} \log p' + C \text{ (constant)} \tag{23}$$

(based on equilibrium vapor pressure data).

where

L = latent heat of vaporization of water in grain and the dash refers to another liquid usually taken as free water.

They conducted a series of drying tests to provide data on heat required to vaporize grain moisture for shelled corn and wheat and found that the moisture content had the greatest effect on heat requirement. Drying temperature and initial moisture content were of minor significance over the range of temperatures 110 to 150 ^{o}F, and initial moisture contents of 8 to 22%. They also showed that over the range of moistures encountered in most actual drying systems for wheat and shelled corn, above 14% wet basis, the heat required for vaporization is between 1.00 and 1.06 times that of vaporization of free water. At lower moisture content (say 10%) it is about 1.15 to 1.2 times that of free water. The same conclusion was made by Johnson and Shedd (42) with values of L/L' changed from 1.16 at 11% moisture content to 1.03 at 15%. They expected this value to reach 1 for higher moisture contents. Thompson, Peart, and Foster (44), 1967, assumed latent heat of water in corn is represented by the equation

$$L' = (1094 - 0.57\ T)(1.0 + 4.35\ e^{-28.25\ M}). \tag{24}$$

Equation (24) was obtained by fitting the data of Thompson and Shedd to the equation ($L/L' = 1 + ae^{-bM}$). The data were obtained in the moisture range of 10 to 15% wet basis but the authors stated that they felt extrapolation of this equation is justified.

Hukill (20,22) identified the main factors affecting the change in moisture content for a given layer at a given time as the initial grain moisture content and grain temperature (small effect), exposed drying rate which depends on grain and air conditions, relation between air humidity and grain moisture at equilibrium, latent heat of drying, the initial air dry bulb and wet bulb temperature, the depth of grain through which the air passes to reach the given layer and the volume of air passing through the grain, $ft.^3/min.ft^2$ of floor area. He showed that the last two factors could be combined in a single factor of pounds of air per minute per unit weight of dry grain which could be handled independently of grain depth or air velocity. This means that if air is passed through grain at the same mass rate, pounds of air per minute per unit weight of dry grain, the moisture changes in the bottom layer, intermediate layers, and top layer will be the same whether the grain is in a deep column of small cross section or in shallow depth of large cross section. Experimental results of Hukill gave slower rates than theoretical which showed that the assumptions need to be modified to give a more accurate representation of the general relation between moisture content, time of drying, and depth of grain. As shown for thin layers, the effect of initial moisture content on equilibrium moisture content affects the validity of the semilogarithmic law, which in turn affects the validity of Hukill's analysis for the time of half response of an exposed layer.

Simmonds, Ward, and McEwen (39), 1953, worked on beds ranging from shallow to 12 inches. Their results agreed with the description given by other investigators that a zone of vaporization or drying propagates through the bed depending on the bed thickness, air conditions, and properties of material. Their results were due to the average moisture content of bed for a certain depth they worked on. Their results with air at 111 ^{o}F, 32 ft/min, average air humidity of 0.009 lbs_w/lbs air showed the shallow bed and 1" thick bed gave no constant rate of drying period and drying occurred in the falling rate period. Constant rate of drying period increases as bed depth increases proportionally. They also found that for a 6" bed and air temperature of 111 ^{o}F the change in air velocity did not change the constant rate of drying. They concluded that for this period the rate of drying is dependent solely on the moisture capacity of air passing through the bed. To study the distribution of moisture content within the bed, they developed a system for sampling lasting for 2 minutes, which would be reasonably accurate for lower moisture content and found that up to 8" of bed the average moisture content of bed lied above the value at the middle. At 8" they are practically coincident and over 8" the average lies just below the middle value, which means that the zone of vaporization extends throughout the bed of the grain and the bottom is never completely dry. For the same average moisture content, the spread of moisture throughout the bed increases with the depth of the bed, but it is rapidly reduced as the average moisture content falls. They suggested the same equation of drying they used for shallow beds (38) based on average value of the rate of drying as follows

$$\log_{10} \frac{W_{av} - W_e}{W_o - W_e} = m' \theta. \qquad (25)$$

$$\log_{10} m' = \frac{t_{a\ mean} - 154.4}{84.4} \qquad (26)$$

They stated that these equations could be used, choosing the mean air temperature to be used as the logarithmic mean temperature between the air dry bulb temperature and its adiabatic saturation temperature at the inlet to the actual drying section. They used the value of W_e from results obtained for shallow bed (38) at different temperatures, using the logarithmic mean temperature. They claimed very satisfactory results. Poor quality wheat drying was performed slightly slower than good quality wheat.

Woodforde and Osborne (45), 1961, studied the effect of temperature and air flow rate on drying curves expressed as average loss in weight against time for beds of wheat 1 ft and 2 ft deep. Air humidity ratio was fixed at 59 grains of water/lb dry air and runs were performed at temperatures of 100, 120, and 140 ^{o}F and air flow rates ranging from 63 down to 31 $ft^3/ft.^2 min$. Their data showed that for the same air velocity and average initial and final moisture contents the time needed for drying decreased by increasing air temperature and increased by increasing the grain depth. The effect of lowering air velocity is to increase drying time. At 1 ft depth the effect on drying time of lowering the air velocity from 75 ft/min down to 30 ft/min was slightly less than lowering air temperature from 140 to 100 ^{o}F. For 2 ft depth, the effect of decreasing air velocity from 60 ft/min to 30 ft/min had higher effect than lowering the air temperature from 140 to 100 ^{o}F. They made an interesting comparison between the results of their experimental trays and data with large area trays (52.3 ft^2) and found the rate of drying was about 6.2% slower with small scale apparatus than with large. They also found that the rate of vaporization was higher by about 2.5% for remoistened samples than for naturally moist samples.

Thompson (41), 1962, studied the effect of air flow rate and temperature on drying rate of wheat in 6-inch deep layers. It can be noticed from his plotted curves of air rate against time in drying from 26.6 to 17.6%, dry basis, at air temperatures from 62.5 to 157.5 ^{o}F that the effect of increasing the air rate is to decrease time of drying. He obtained the following emperical equation for the effect of air temperature and air rate of flow on drying rate

$$R = \frac{\frac{9nP_s}{2.3}}{\log\left(\frac{h_1 - h_e}{h_2 - h_e}\right)} \tag{27}$$

$$\log_{10} (R_a G_M^{0.414}) = 0.0112\ (t - 57.5) - 0.413 \tag{28}$$

where

n = constant of the drying equation $\left(\frac{\partial W}{\partial \theta}\right)_{G_{M,t}} = -n(P - P_s)$

P, P_s = vapor and saturation partial pressures

h_1, h_2, h_e = initial, final, and equilibrium relative humidities

t = air temperature, ^oF

G_M = air mean rate of flow, $lb_{air}/lb_{dry\ grain}hr$.

R = rate of drying, hr^{-1}

Subscript "a" refers to artificially moistened grain.

He (41) stated that equation (27) cannot be used for temperatures higher than atmospheric temperature by less than 10 ^oF and for air flow rate below a critical value depending on air temperature. Below this critical value the air would be delivered from the drying bin saturated and in this case R and G_M will have direct proportionality.

Similar results on the effect of air velocity and temperature were obtained by Woodforde and Lawton (46), 1965. However, no conclusions were derived by Thomason (41) or Woodforde (45) on the effect of air flow rate on drying time as a function of temperature. It seemed that the effect of air rate is nearly independent on the air temperature. On the other hand, Woodforde and Lawton (46) showed higher effect of rate of flow on evaporation rate for a simple reduction in moisture content as temperature increases.

In 1967 Thompson, Peart, and Foster (44) provided a new approach based on simulation. The basic simulation approach was to calculate the drying performed on a thin layer of grain and then to combine many thin layers to form the grain bed. This approach permits complete simulation of less conventional drying methods such as concurrent (parallel) and counterflow continuous beds, as well as the cross flow drying method. Prediction of the amount of drying that occurs in a thin layer of corn could be made by considering the initial air and grain conditions, using a thin layer drying equation, and complete heat balance to predict the final air and grain conditions. The equations of drying they used were interpretated in the preceding review of thin layer drying as follows

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

$$A = -1.862 + 0.00488T$$

$$B = 427.4 \exp(-0.033T)$$

$$1 - RH = \exp(-c\,(T + 50)\,M_e^n)$$

$$c = 3.82 \times 10^{-5}$$

$$n = 2$$

$$L' = (1o94 - 0.57T)(1 + 4.35\,e^{-28.2M})$$

They used an equation by Kazarin and Hall for the specific heat of corn

$$c = 0.35 + 0.00851\,M_W \qquad (29)$$

where

M_W = moisture content, % wet basis.

The method depends on the assumption that the kernel temperature of the corn was equal to the air surrounding the kernels after accounting for the cooling effect of moisture evaporation and different initial corn and air temperatures. This was based on very rapid heat transfer between a corn kernel and the surrounding air. They called this temperature of the drying air at a certain layer and certain time, T_e where

$$T_e = \frac{(0.24 + 0.45\ H_o)\ T_o + CG_o}{0.24 + 0.45\ H_o + C} \tag{30}$$

as obtained by a sensible heat balance. Subscript o refers to original value.

G = grain temperature

H = air humidity

C = specific heat of grain in btu/lb air ^oF

$= c \times \frac{m\ grain}{m\ air}$

M_e was calculated using T_e as the air temperature. In a deep bed drying process T_e at one location in the bed usually changes as drying progresses. A new drying curve is specified as T_e changes, and the amount of drying in the old curve has to be transformed to the new one. The transformation was done by calculating an equivalent drying time using the drying equation and substituting using new values of A, B, and M_e with the same value of M. The equivalent time calculated is the time needed on the new curve to dry the present moisture content. The final moisture content at the end of a new drying time, t, will be obtained by substituting the value of $t_{eq} + t$ in the new drying equation (44). When applied to a cross flow batch drying, each layer was dried for a short time interval, t, using the exhaust air from one layer as the input drying air to the next. The process was then repeated with the second, third, etc., drying time intervals until the average final was as desired (44). For this they applied heat and mass balances between the equilibrium condition of air and grain to the final condition.

$$H_f = H_o + H = H_o + \frac{(M_o - M_f)}{100} \times \frac{M\ grain}{M\ air} \quad (31)$$

$$T_f = \frac{(0.24 + 0.45\ H_o)\ T_e - H(1060.8 + \Delta L + 32 - G_e) + CG_e}{0.24 + 0.45\ H_f + C}$$

T_f = the final air and grain temperature for the layer

($T_e = G_e$ as assumed)

$\Delta L = L' - L$

Thompson, Peart, and Foster (44) proposed a method to calculate for infeasible state points which give mathematically a value of relative humidity greater than 100% and also a method of application to concurrent and counterflow continuous dryers. However, their results have not yet checked practically for bulk drying. For thin layers, their experimental results fit satisfactorily for a wide range of temperatures with an upper limit of 300 ^oF.

In 1968, Myklested (32) published a theoretical analysis to calculate moisture content for any depth at any time in a bulk batch drying process for granular materials exhibiting four drying stages (constant rate, increasing rate, first falling rate, and second falling rate). The importance of his work in this analysis is that it was applied to very wet wheat grain (75% dry basis initial moisture content) and the results showed that the assumptions were not far from actual (32). He stated that his equation will help in calculating changes in moisture during large scale drying of grain with warm air on the basis of small scale laboratory experiments. The behavior of the drying rate drawn against the moisture content was assumed to be as represented by Fig. 1.

(CR) = constant rate

(IR) = increasing rate

(FR) = falling rate

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

THIS IS AS RECEIVED FROM CUSTOMER.

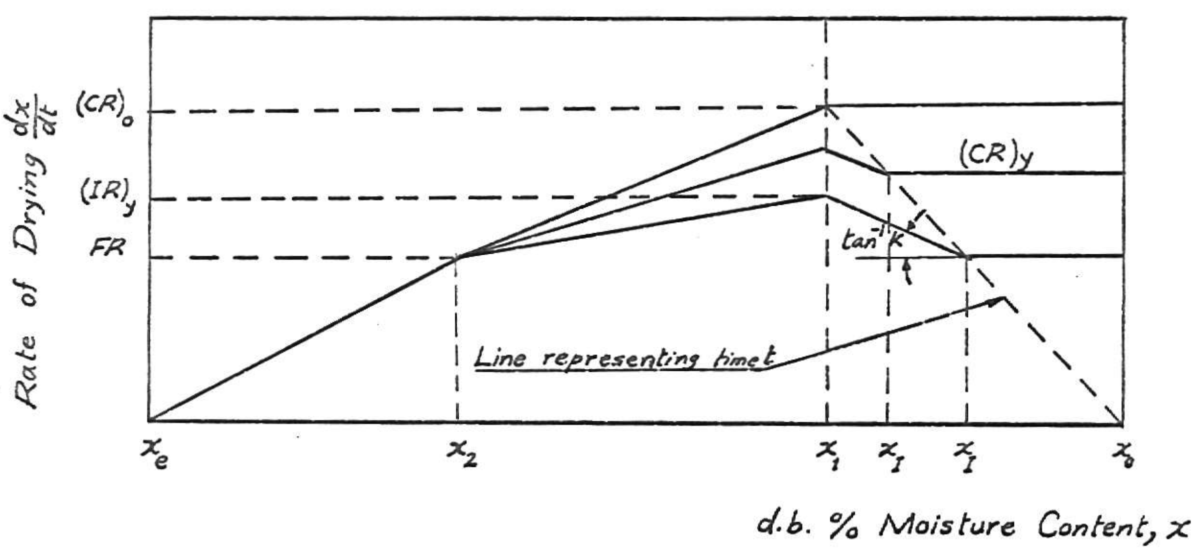


Fig. 1: Rate of drying vs. moisture content for different depths in a grain bed.

The equation of moisture content for different rates are as follows

Constant rate: $X = X_o - Bt\ e^{-\beta y}$ (32)

Limits: $X_o > X > X_I$

Increasing Rate: $X = X_o + \frac{B}{K} e^{-\beta y} (D - \exp (k(t - t_I))$

Limits: $X_I > X > X_I$

1st Falling Rate: $X = X_2 + \frac{FR}{u_b} + v_b^{u_b/k} (X_1 - X_2 - \frac{FR}{u_b}) \cdot \exp(-u_b (t - t_I))$

Limits: $X_1 > X > X_2$

2nd Falling Rate: $X = X_e + (X_2 - X_e)\ v_b^{-M/k} \cdot (1 - \frac{u_b (X_1 - X_2)}{(FR)})^{-\frac{M}{u_b}} x$

$\exp (M(t - t_I))$

where

X_o = initial moisture content

$\beta = \frac{K}{G}$ K = volumetric coefficient of mass transfer,

Kg H_2O/hr m^3 Kg H_2O/Kg dry air.

$= -(\frac{dx}{dt})\ cr\ \frac{\rho s}{H_c - H_i}$

G = mass velocity of gas, Kg dry gas/hr m^3

$B = \frac{K}{s} (H_c - H_i)$

ρ_s = bulk density of dry material Kg/m^3

H_c = nearly constant saturation humidity near the surface of the solid (at wbt of air)

H_i = initial humidity

$t_I = (X_o - X_1)/B$

$X_I = X_o - Bt_I e^{-\beta y}$

k = slope of increasing rate line, nearly the same for all lines at different depths, or taken as the mean value at the middle

$$D = 1 - kt_I$$

$$u_b = \frac{BDe^{-\beta y} + E}{X_1 - X_2}, \quad E = k(X_o - X_1) + (FR)$$

$$v_b = \frac{L}{B} e^{\beta y} + D, \quad L = k(X_o - X_1)$$

$$M = \frac{(FR)}{X_2 - X_e}$$

Values of X_o, X_1, X_2, X_e, k, H_i, (FR), $(\frac{dx}{dt})_{cr}$ are obtained from experiments on small scale laboratory dryers.

Myklestad (32) stated that these equations could be modified to be of wider applicability according to the drying rate stages observed (major assumption made is encountered in the graph of $\frac{dx}{dt}$ against x). He derived also equations of humidity and temperature during drying.

Some Notes Involved in Drying Studies

Hukill (21), 1948, discussed the disadvantages of batch dryers and stated that the main disadvantage is the nonuniformity of grain moisture content after drying. He also stated that this nonuniformity could be decreased if the drying time is increased. The increase of drying time will be at the expense of the efficiency of heat energy applied to the air. As the time of drying increases, the amount of moisture liberated will be small and the air leaves the dryer carrying a considerable quantity of available energy. This discussion was supported by Simmonds, et al (38). Hukill described a modification of the simple batch process. Air is passed through the batch for a certain period in one direction and then is reversed for completing drying. He stated that little information is given about its effectiveness since it is not generally used.

Woodforde and Lawton (46), 1965, conducted test runs on 6" beds of wheat. They used mixing of wheat after each interval of 10 minutes from the start of drying to investigate mixing effect on the average, top, and bottom moisture contents. They stated that there appears to be a distinct reduction in the weight of water evaporated at the same time of drying, when the grain was mixed. In general, the amount, as a percentage, was small but the effect of mixing on the final moisture content was a reduction in the gradient between the top and bottom of the bed.

McEwen, Simmonds, and Ward (30) studied the pressure drop in a deep bed 1-12" to relate it to air flow rate. For insuring the reproducibility of their results the manner in which the bed was prepared was the same for all beds. The material was poured in a slow thin stream into the container from a fixed height and then disturbed as little as possible. They found that the main factors influencing the pressure drop for a certain air flow is the porosity of bed, the grain size, and the depth of bed. The effect of depth of bed (1" - 12") agreed generally with the other investigators' work, although they got less effect. Rate of increase of pressure drop falls off very slightly as the bed depth increases (30). For the same surface roughness with approximately the same particle shape and at the same bed porosity, they found that reduction in diameter of the grain does produce a drop both for wheat and for oats. The parallel nature of plots of pressure drop vs. particle diameter for wheat and oats suggests that the diameter effect is similar for both of them. A decrease in porosity has the effect of increasing pressure drop. They stated that the effect of porosity is the major influence of these factors. They provided curves for the pressure drop for the different factors influencing it. They pointed out that if clean grain, which has higher porosity, is used, there will be lower pressure difference than if dusty grains are used.

Drying experiments were performed by the author, unpublished, on Egyptian Wheat grain Giza 155 (48). Tests were performed in Assiut University, Egypt, during the late spring and summer, 1968. Main parameters investigated were air temperature and air velocity. Different experiments, at air temperatures of 99.4, 108.4, 118.4, 129.2, and 138 ^{o}F and at air velocities of 80 ft^3/ft^2min, 40 ft^3/ft^2min, 30 ft^3/ft^2min, and 23 ft^3/ft^2min, were performed. The absolute humidity of air varied slightly and ranged between 0.007 lb_s/lb dry air and 0.009 lb_w/ lb dry air. The effect of this change was neglected according to previous work (38). Actually, there was no need for controlling the air humidity since its variation was small during the period of performing the experiments. The weather in Assiut, Egypt, is dry during this period.

The investigation results at the same air velocity and air temperatures in the range of 99.4 to 138 ^{o}F confirm the previous investigations submitted by Simmonds, Wards, and McEwen (38) on other kinds of wheat grain. The semi-logarithmic plot fits a straight line, taking the value of equilibrium moisture content from the drying curve at the end of a prolonged period of drying of 9 to 11 hours. The time of drying for each experiment ranged between 9 hours for high air temperatures to 11 hours for lower air temperatures to obtain an accurate value for dynamic equilibrium moisture content.

A series of experiments were performed at constant air temperature, for temperatures mentioned, and varying air velocities from 80 ft/min to 23 ft/min. No significant change of drying rate was observed for the range from 80 ft/min down to 30 ft/min. However, for 23 ft/min velocity the rate of drying was decreased. Its effect was approximately equivalent to the effect of a drop in air temperature of 5 ^{o}F. The results of these experiments confirms the other investigations (31,38) and is extended to verify the expectation of lowering drying rate by lowering the air velocity.

On the other hand, Henderson and Pabis (16), 1962, worked on wheat and predicted higher drying rates at lower velocities than at higher velocities for the thin layer drying; however, the effect was small. This shows that the effect of air velocity on drying rate should be investigated further.

Since naturally moist wheat was not available for this series of experiments at Assuit, naturally dried, clean, good quality samples of wheat stored for six months were moistened by soaking in water and kept in a dark closet for an interval of time ranging from 20 to 24 hours. Extra water was stripped from the grain. The grain was left fully exposed to air for one hour to remove the surface moisture and dried for about five minutes at the specific air conditions of the experiment before readings were recorded.

To compare the drying curves obtained by this method of remoistening and those obtained by naturally moist grain, fresh samples of harvested wheat at 27.3% d.b. moisture content were brought directly to the laboratory and a test was performed at air temperature 118.0 ^{o}F and air velocity 30 ft/min. For each drying time two samples of grain were taken from different positions of the drying bin and the average moisture content was estimated. After drying to equilibrium moisture content, the dried grain was remoistened by soaking in water for 20 hours as mentioned before and a new drying curve was obtained. The two curves were compared by shifting the coordinate representing moisture content of remoistened grains so that the initial moisture content was the same as for naturally moist grain. The comparison indicated that the same drying curve was obtained for both naturally moist and remoistened grain. The only difference was a maximum deviation of drying points up or down of

± 0.6% d.b. moisture content. These deviations seemed to be due to the non-homogeneous initial moisture content of naturally moist wheat. The result of this investigation seems to disagree with the work of Hustrulid (24) on shelled corn and other investigations reported by him on wheat. Their results indicate that remoistened grains dry at a rate higher than naturally moist grains. It seems that the method of preparing remoistened grain needs more investigation.

Another set of drying experiments was performed at an air velocity of 80 ft/min at air temperatures of 99.4 ^{o}F, 108.4 ^{o}F, 118.4 ^{o}F, 129.2 ^{o}F, and 138 ^{o}F for a thin layer laid on predried thick layer, 6" thick. The thick layer was not remoistened and was exposed to the same specific drying conditions for 8 hours. The air temperature was checked the same just below and over the thick layer before laying the remoistened thin layer over it. The obtained drying curves were approximately the same as obtained for fully exposed grain layers at the same air and grain conditions. It could be concluded from this set of experiments that a thin layer in the bulk of grain will act the same as the fully exposed layer for the same conditions of air and grain. This conclusion may be helpful for the simulation work proposed by Thompson, Peart, and Foster (44) and any other investigations using mathematical simulation of thin layer to obtain the performance of thick layer dryers.

DISCUSSION OF SIMMONDS, WARD, AND McEWEN STATEMENT

Simmonds, Ward, and McEwen (38) stated "The results show that increasing humidity of the air decreases the rate of drying slightly, but the effect is very much smaller than the effect of temperature changes, a three-to-four fold increase in the humidity being roughly equivalent to a drop in temperature of 50 ^{o}F."

This statement is important since most of the investigators did not discuss it and to my knowledge no other researches were published discussing the effect of air humidity in a wide range. The first part of the statement seems to be true and reasonable, but a thorough look to the last specific part and to the data of experiments obtained and published by them throws a shadow of doubt on this part of the statement. A trial is made to show my point of view in that a three-to-fourfold increase in humidity may be equivalent to a much less effect of temperature drop of 50 ^{o}F. The data chosen from Simmonds and the others to show my point of view are listed below:

Air Temperature	Humidity	W_1	W_e	2.303m
120 ^{o}F	0.00079	0.401	0.105	1.18
120 ^{o}F	0.0273	0.498	0.110	0.92
150 ^{o}F	0.0078	0.402	0.087	2.29

The discussion is based on the drying time for a certain decrease in moisture content. The same initial moisture content is used. The equilibrium moisture content and the rate constant (m) values were substituted from the data obtained by Simmonds, Ward, and McEwen (38), which is listed in this discussion.

For the same temperature (120 ^{o}F), and changing the humidity from 0.0079 to 0.0273, the time of drying for each drying process could be computed using the semilogarithmic law.

For 0.0079 absolute humidity (T = 120 °F):

$$\ln \frac{W_1 - W_E}{W_o - W_E} = -2.303m\ t$$

$W_o = 0.401$ $W_1 = 0.2$ $W_E = 0.105$ $2.303m = 1.18$

$$\ln \frac{(0.2 - 0.105)}{0.401 - 0.105} = 1.18t$$

$$\ln \frac{0.095}{0.296} = 1.18t$$

$$t = \frac{\ln 0.321}{-1.18} = \frac{-1.104}{-1.18} = 0.935 \text{ hours}$$

For humidity 0.0273 (T = 120 °F):

$W_o = 0.401$ $W_1 = 0.2$ $W_E = 0.110$ $2.303m = 0.92$

$$\ln \frac{0.200 - 0.110}{0.401 - 0.110} = -0.92t$$

$$\ln \frac{0.09}{0.291} = -0.92t$$

$$t = \frac{\ln 0.3095}{-0.92} = \frac{-1.175}{-0.92} = 1.278 \text{ hours}$$

The inverse ratio of time of drying for the same temperature, 120 °F, and increasing the absolute humidity from 0.0079 to 0.0273, which is 3.45 the initial value,

$$= \frac{1/1.278}{1/0.935} = \frac{0.935}{1.278} = 0.732$$

For nearly the same lower humidity 0.0078 and temperature 150 °F:

$W_o = 0.401$ $W_1 = 0.2$ $W_E = 0.087$ $2.303m = 2.29$

$$\ln \frac{0.20 - 0.087}{0.401 - 0.087} = -2.303m\ t = -2.29t$$

$$\ln \frac{0.113}{0.314} = -2.29t$$

$$t = \frac{\ln 0.36}{-2.29} = \frac{-1.022}{-2.29} = 0.4455 \text{ hours}$$

The inverse ratio of time of drying for the same humidity, 0.0079, when temperature is decreased from 150 ^{o}F to

$$120\ ^{o}\text{F} = \frac{1/0.935}{1/0.4455} = \frac{0.4455}{0.9350} = 0.477.$$

If the rate of drying for a certain decrease in moisture content would be proportional to the inverse ratio of time of drying, as would be expected, it is concluded that the rate of drying was decreased (1 - 0.732) × 100% or 26.8% when the humidity is increased between three-to-fourfold at the same temperature, while the rate of drying was decreased (1 - 0.477) × 100% or 52.3% when the temperature is decreased 30 ^{o}F at the same humidity. This leads to doubts about the precision of the statement of Simmonds, Ward, and McEwen (38).

Note: Nearly the same results were obtained when the comparison was based on decrease in temperature for the same high humidity instead of same low humidity.

DESIGN OF LABORATORY GRAIN DRYER

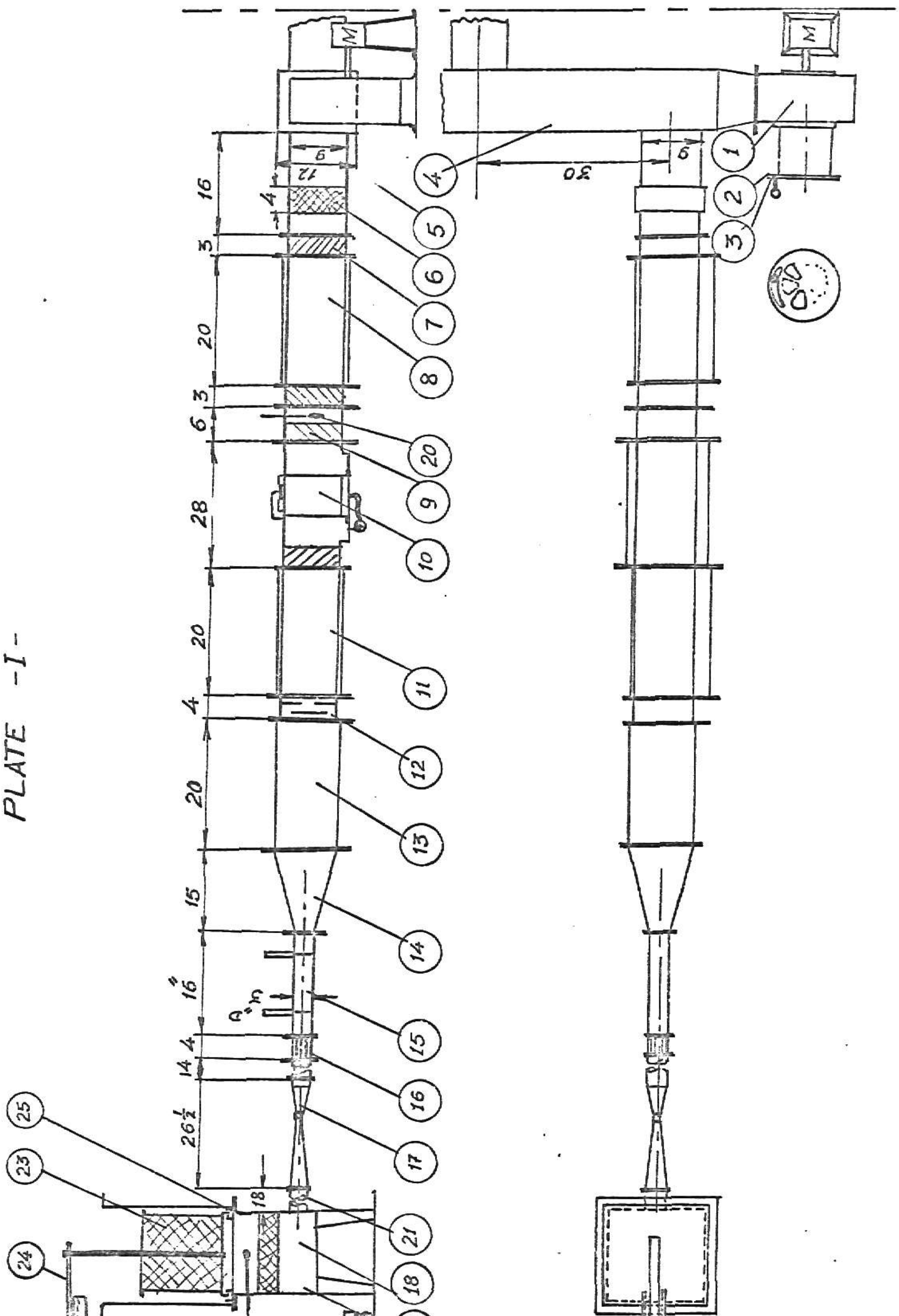
1. General Description (see Plate I). In the following discussion, numbers in parentheses refer to numbered parts shown on the plates.

Air is delivered to the 12" × 9" main duct (4) through the 0.9 H.P., 570 cfm forced draft fan (1). The volume rate of air is controlled by restricting the flow through different relative positions of the manually rotating (2), and stationary (3) slotted discs mounted on the inlet duct of the fan. Six 9" × 9" similar ducts (5) are branched from the main duct. The air delivered to each branch is controlled by two butterfly valves in series (15). The branch ducts are distributed three on each side of the main duct. The distance between the centers of two successive ducts is 30". The air delivered to each branch duct passes through a silica-gel (6) perforated box 4" thick. The dehumidified air passes through the 7750-watt divided initial heater (8) with an inclined louvered box on each side (7). This initial heater is used to heat the air to increase its ability to absorb water in the air washer which is down stream from the heater. The inclined louvered boxes are added to minimize the effect of radiation on the sensing element of the heater controller (20) used to control the temperature of air leaving the heater. The deflector (12) is used to mix the air. The sensing element is a dry bulb thermistor immersed in the duct downstream from the second louvered box. The hot dehumidified air passes through the air washer (10) with two water eliminators (9) at its sides. The humid air is delivered from the air washer to the second heater (11). The sensing element of the controller of this heater is just below the sample bin. The humid heated air then passes through a deflector for mixing the air, then through the humidity ratio measuring devices duct (13), then through the connection duct (14) to change gradually the

EXPLANATION OF PLATE I

The diagram shows the fan and one branch duct assembly. A Sectional Elevation (top) and a Sectional Plan (bottom) are given.

PLATE -I-



9" × 9" duct into 3" diameter pipe (15). Two butterfly valves (15) are inserted in the 16" long pipe, 8" apart. The valves are manually set through a slow motion controlling mechanism. Air then passes through the 4" long straightener (16) to the standard Herschel venturimeter tube (17) where the air rate of flow is measured. Air leaving the venturi tube flows through the 18" long 3" diameter pipe (21) from which it is delivered to the sample bin (18). The air flows in the bin through a layer of glass wool (22) to accomplish uniform flow, then through the free hanging sample tray (23). The sample tray is hung from the free end of a cantilever beam (24) which is fixed at the other end to a housing structure (19) suspended on rollers. Air leakage from the bin is prevented by the oil seal annulus (25). The overall dimension of the set-up is approximately 40' × 19'.

The sample bin is insulated by 9.5" thick cork; the 3" tubes and the venturimeter are insulated by 6.5" thick cork; and the 9" × 9" duct and the connection duct are insulated by 9" thick cork.

Dry bulb thermocouples are inserted in the branch ducts after the second heater and after the ventri tube. Pressure taps are mounted at the beginning of each branch duct and in the bin below and above the sample tray.

2. Detail Design:

The main items which will be given in detail here are

a. heaters and accessories

b. temperature controllers

c. air washer and accessories

d. air velocity measuring device

e. bin structure and moisture loss measuring device

f. fan

EXPLANATION OF PLATE II

The ideal processes in the heaters and the air washer are drawn on the Psychrometric Chart. The solid line a-b-c-d- represents the following processes:

a-b dehumidification in silica-gel box

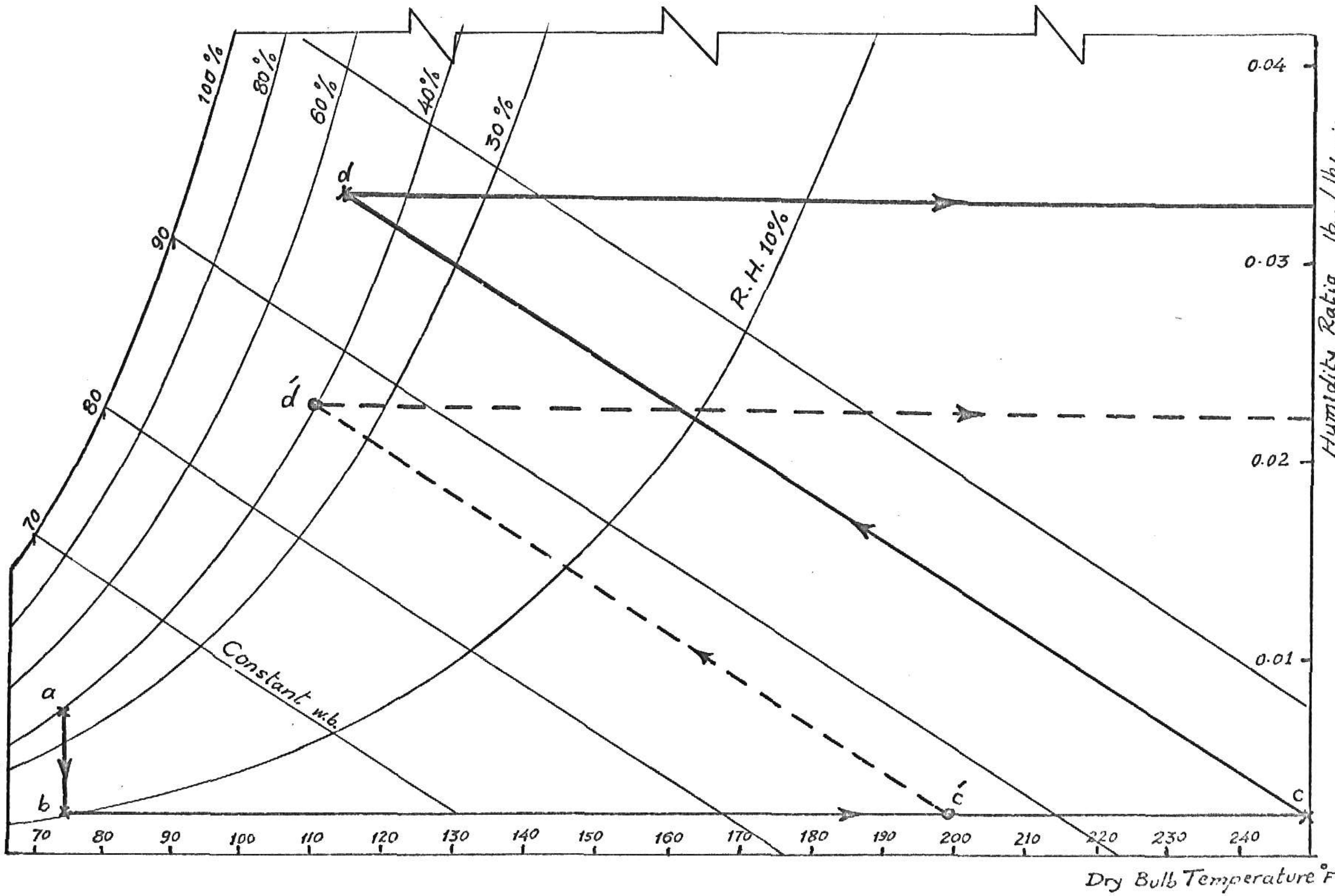
b-c heating of air in first heater

c-d humidification in the air washer

d- heating of air in second heater

The dotted line a-b-c'-d'- shows that the higher the temperature of the air leaving the first heater the higher the humidity ratio attained in the air washer.

PLATE -II-


100 %
80%
60 %
40%
30 %
R.H. 10%
90
80
70
Constant w.b.
a
b
c
c'
d
d'
0.04
0.03
0.02
0.01
Humidity Ratio lb_w / lb_dry air
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
Dry Bulb Temperature °F

2.a. Heaters

Two similar heaters are used, one prior to the air washer and the other following the air washer. The air washer heater is used to widen the humidity ratio range of air attained at the air washer, to provide a method of controlling this humidity ratio and as an initial stage of raising air temperature. The widening of the air humidity ratio range could be seen directly from the psychrometric chart (Plate II). The humidity ratio controlling is done through controlling the inlet air temperature to the air washer which will be discussed later. The last item of raising air temperature, however, is not large, especially if the room temperature is high and/or the humidity ratio is not chosen high (Plate II).

2.a.1. Heating Capacity Calculations

2.a.1.1. Air Washer Heater

Assumptions:

Inlet air condition

inlet dry bulb temperature $t_{d.b.1} = 75^{o}F$

inlet air relative humidity $\phi_1 = 10\%$

Outlet air condition for maximum heat requirement

outlet dry bulb temperature $t_{d.b.2} = 300^{o}F$

outlet air humidity ratio = inlet air humidity ratio

air mass rate of flow = $\dot{m}_1 = 3.9$ lb/min

(based on air conditions of 80 cu ft/min, $300^{o}F$, and 0.045 lb_w/lb dry air).

Outlet air condition for minimum heat requirement

outlet dry bulb temperature $t_{d.b.2\ min.} = 100^{o}F$

outlet air humidity ratio = inlet air humidity ratio air mass rate of flow = $\dot{m}_2$ = 0.34 lb/min

(based on air conditions at bin of 5 ft^3/min, 100^oF, and 60% R.H.)

Using psychrometric chart:

Enthalpy of inlet air h_1 = 19.70 btu/lb

Maximum enthalpy of outlet air = $h_{2\ max.}$ = 75.5 btu/lb

Minimum enthalpy of outlet air = $h_{2\ min.}$ = 26.3 btu/lb

Maximum heat required = $\dot{m}\ (h_{w\ max.} - h_1)$

$= 3.9\ (75.5 - 19.7)$

$= 217.6$ btu/min

Maximum watts required = $\dfrac{217.6 \text{ btu/min} \times 60 \text{ min/hr}}{3.400 \text{ btu/watt hr}}$

$= 3840$ watts

Minimum heat required = $\dot{m}_2(h_{2\ min.} - h_1)$

$= 0.34\ (26.3 - 19.7) = 2.245$ btu/min

Minimum watts required = $\dfrac{2.245 \times 60}{3.400} = 39.6$ watts

2.a.1.2. Second Heater

Nearly the same loads resulted as from the calculation of the first heater and for ease of operation it was decided to use two similar heaters.

2.a.2. Heater Design (Plate III)

The heating elements for each heater are divided into nine units. Seven units are 1000 watts each; one unit 500 watts; and one unit 250 watts. The units are connected in parallel and their power is controlled. Each unit has its own switch. The total heating capacity of the seven units is 7750 watts which was chosen to compensate for heat loss in the heater, to not overload the heating units, to allow for higher velocities, and better performance of the controlling device. The minimum heat unit is 250 watts, which was so

EXPLANATION OF PLATE III

Fig. 1: Shows the dimensions of the heater

Fig. 2: A diagrammatic representation of the split heater circuit

PLATE-III-

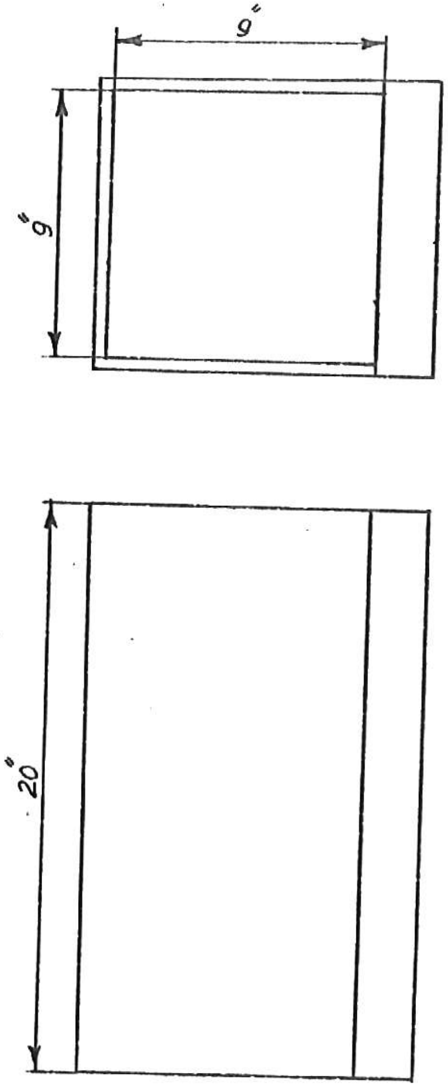


Fig. 1

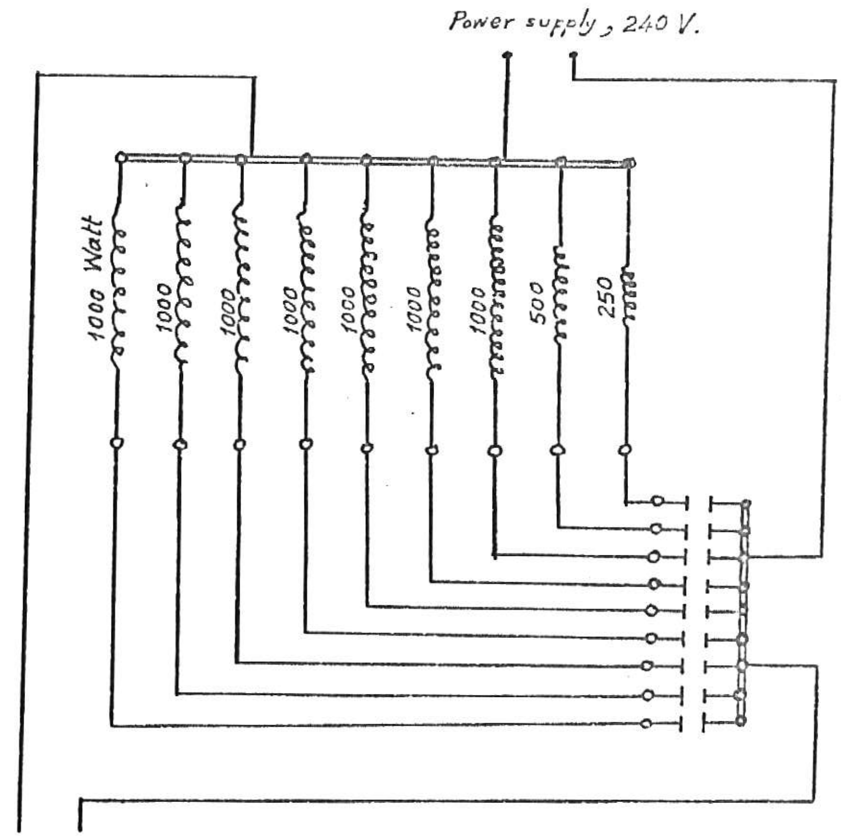


Fig. 2

chosen that the minimum required heat capacity is always higher than 10% of the heater capacity for more stable performance of the controlling device. The inside faces of the duct at the heater sections are coated with 1/8 inch teflon sheets. Teflon was used here as an electric insulator since it does not fail at high temperatures. This design of heaters was approved by H. W. Tuttle & Company to be done in their factory.

2.b. Temperature Controller

The temperature controlling system presented here was designed partially based upon an interview with a representative of Honeywell, Inc.

The controlling system is accomplished through a potentiometric temperature controller with an output that fires a silicon controlled recrifier modulating the power to resistive heating elements of the heater (Plate IV). The input of the instrument is a thermistor inserted in the duct down stream from the heater before the air washer heater and below the sample tray in the second heater. The instrument has a proportional control plus automatic reset.

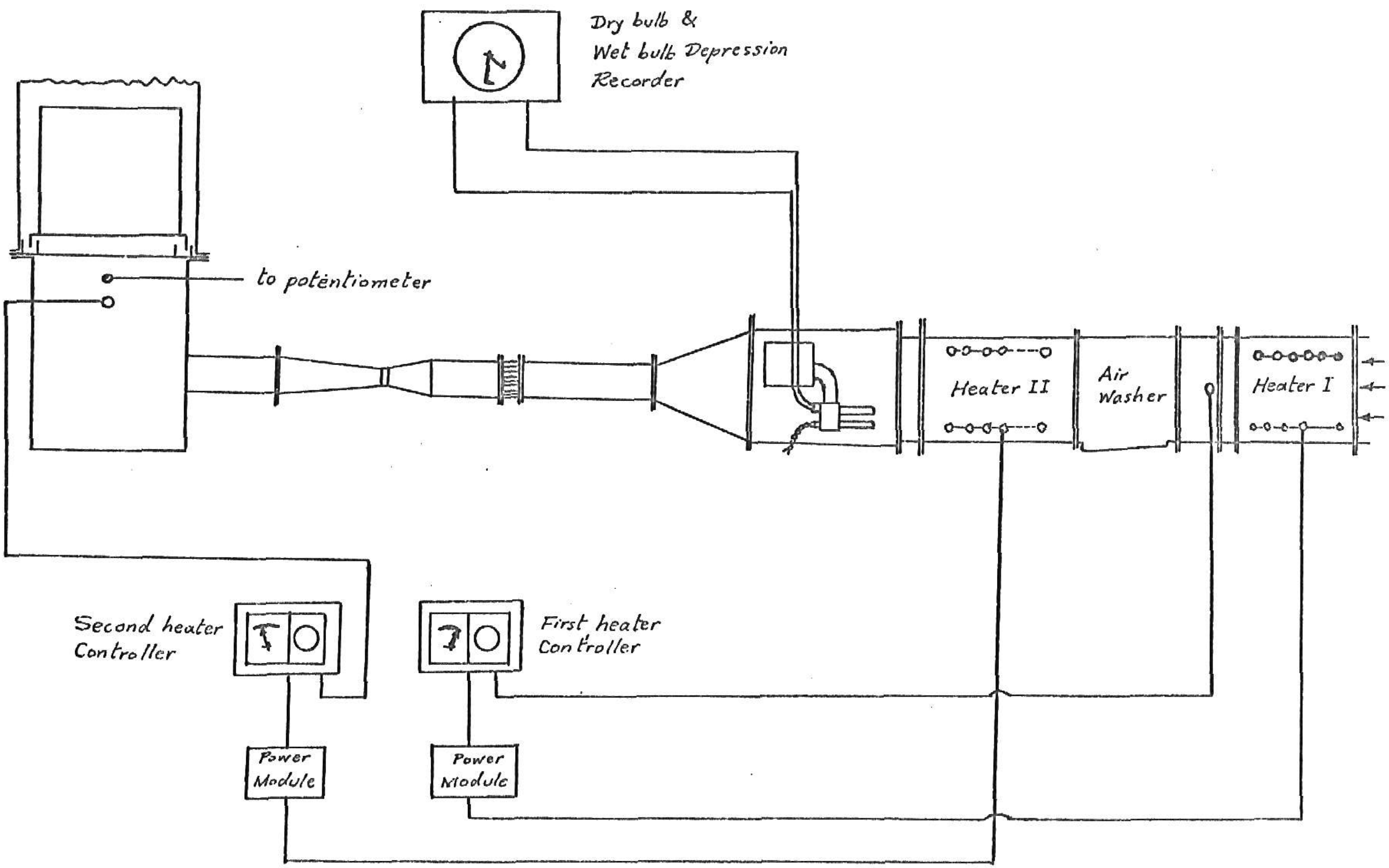
2.c. Air Washer

The air washer is used to humidify the air. The main features of the air washer (Plates V and VI) are the water pump, the orificed brass pipe, and the perforated box which is full of excelsior fibers. The 1/3 HP water pump sucks the water from the one inch water level in the slightly sloped bottom of the air washer structure. The pump delivers the water through rubber tubing to the two orificed brass pipes at the top of the air washer. The atomized water through the orifices of the tubes is showered on the excelsior perforated box, wetting it continuously. The other components of the air washer are the overflow vertical pipe to drain and the compensating water pipe from the main, fitted at the bottom of the air washer. A perforated

EXPLANATION OF PLATE IV

A diagram showing the temperature controller circuit of the two heaters and the psychrometer circuit.

PLATE -IV-


Dry bulb &
Wet bulb Depression
Recorder
to potentiometer
Heater II
Air
Washer
Heater I
Second heater
Controller
First heater
Controller
Power
Module
Power
Module

EXPLANATION OF PLATE V

Views showing the air washer assembly

1- body

2- cover

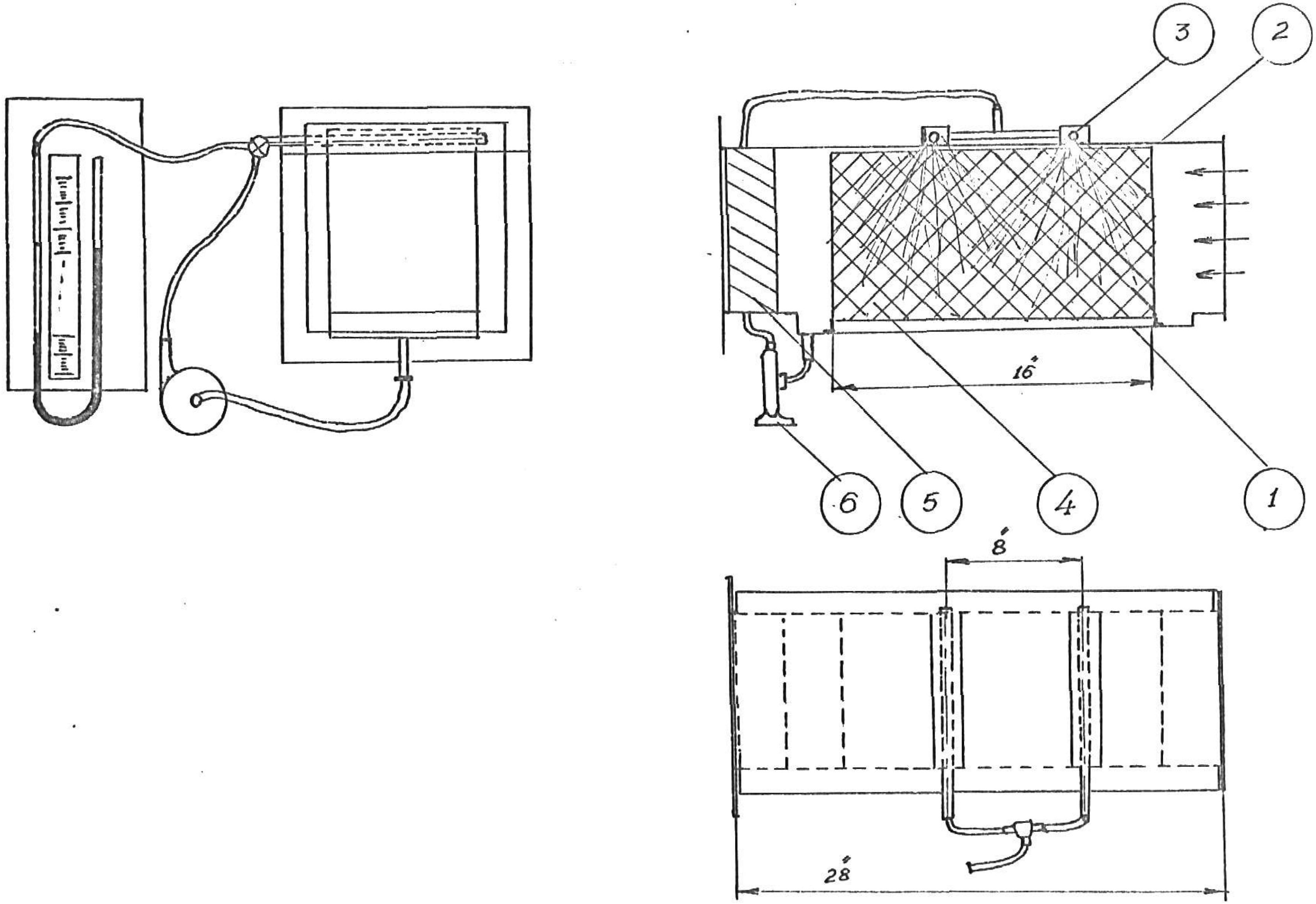
3- orificed tube

4- excelsior wire box

5- water eliminator

6- water pump

PLATE -V-



EXPLANATION OF PLATE VI

Fig. 1: Shows detail views of the air washer cover.

Fig. 2: Shows detail views of the air washer body.

PLATE -VI-

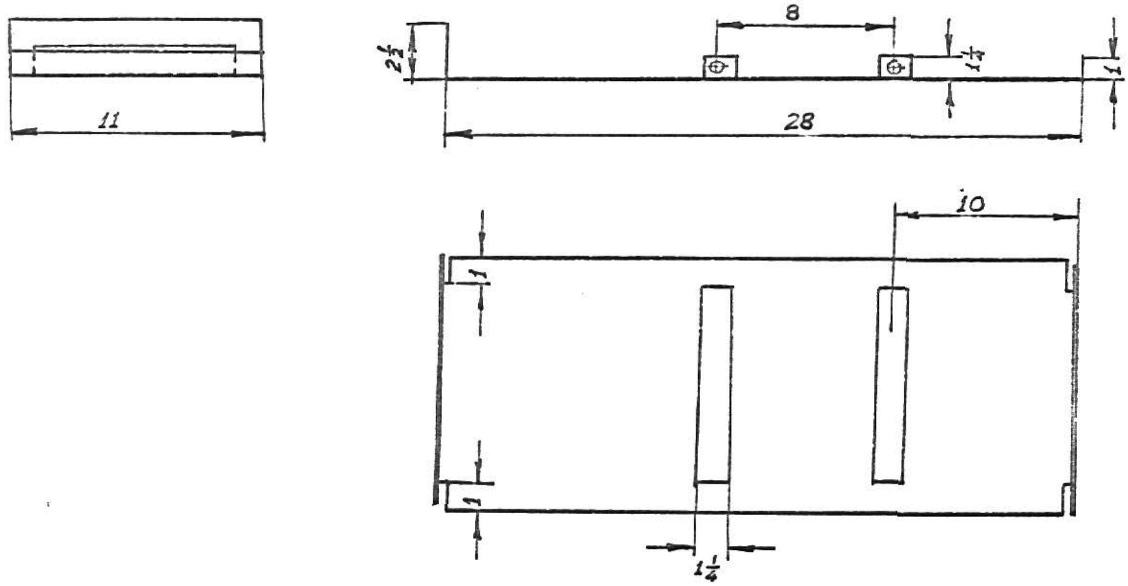


Fig. 1

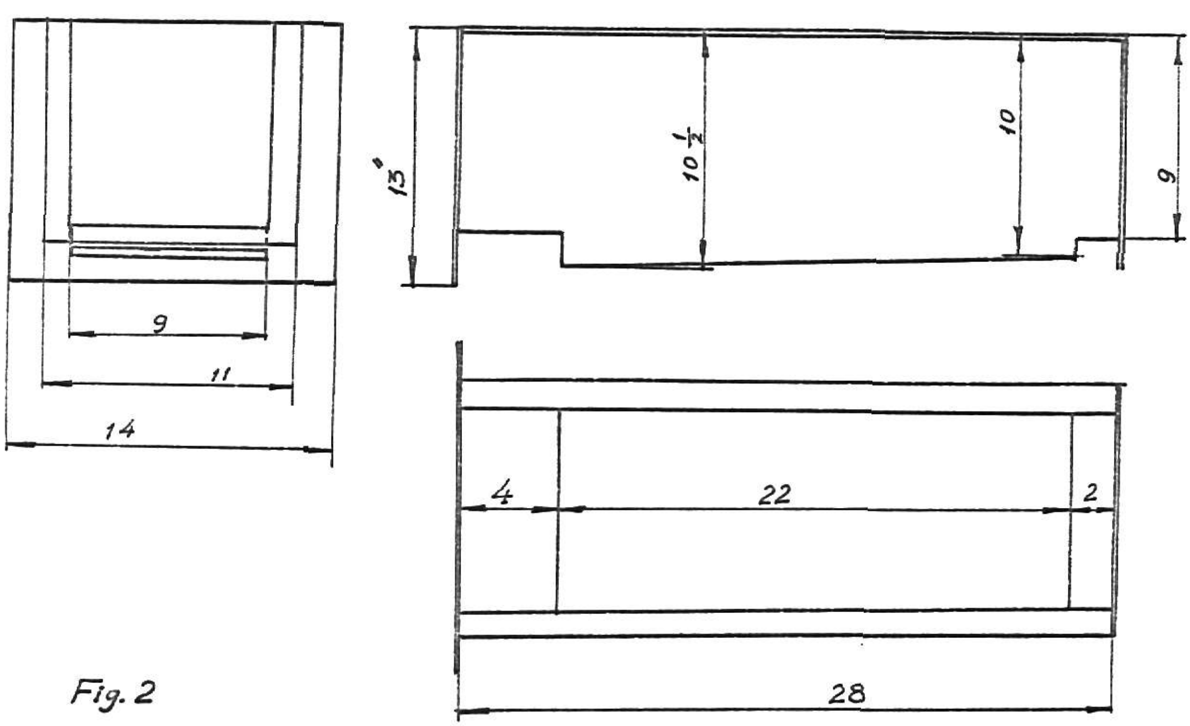


Fig. 2

box full of silica gel is fitted in the branch duct upstream from the air washer heater. The dehumidified heated air which has already passed the silica gel box and the air washer heater passes through the wetted excelsior box and leaves it at a high humidity ratio at the same wet bulb temperature of the inlet air.

The stable performance of the air washer is dependent on the stability of the operating conditions. These are the rate of water flow, the thickness of the excelsior box, and the inlet air condition. The rate of flow of water is controlled by the water head on the pump. The procedure is to insert a valve in the delivery pipe to the pump and to mount an inclined water manometer at the T-joint in the rubber tubing upstream from the water flowing to the orificed brass tubes. The inlet air condition is initially controlled through the temperature controller and the silica gel box which delivers nearly dry air.

The water eliminators on both sides of the air washer prevent water from escaping from the inlet side and water drops from being carried by air at the discharge side.

2.d. Air Humidity Ratio Measurement

The humidity ratio of the air is measured by recording the dry bulb temperature and the wet bulb temperature of air entering the sample tray. The difficulty of measuring the wet bulb temperature at the high temperature, for which the apparatus was designed, arises from the evaporation of water at 212^{o}F for atmospheric pressure and somewhat higher for the working pressure. However, this difficulty can be overcome by using a continuously regulated supply of water to a porous (ceramic) tube-type psychrometric assembly which is used in this design (Fig. 2). The porosity of the ceramic tube has the

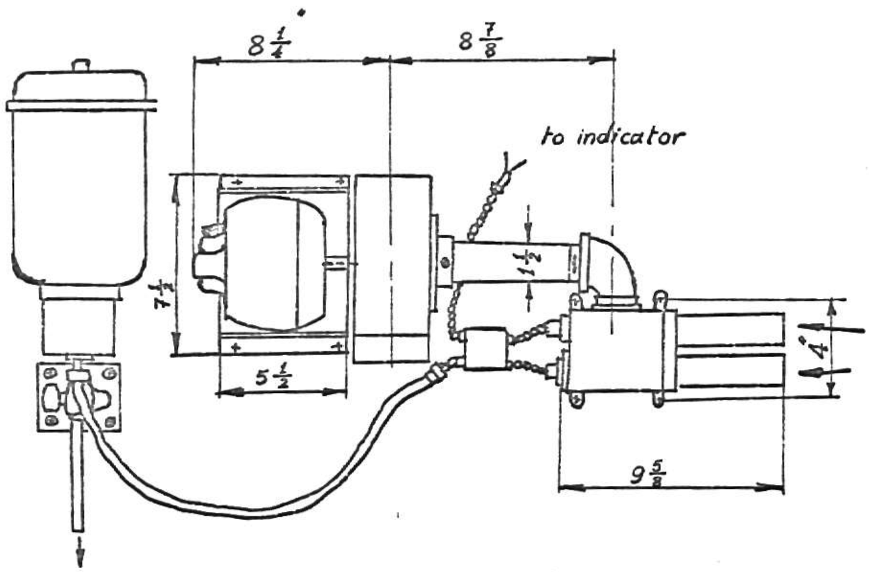


Fig. 2 : Porous tube Psychrometer

capacity to keep a continuous film of water at the surface of the tube and the bulb of the wet bulb thermometer. Experiments performed in Honeywell Laboratories showed that the error in measuring relative humidity is as low as 0.14% at a temperature of 300°F using this psychrometer. It is nearly 0% at 275°F or lower. This error, of course, is under laboratory conditions which may be different from field conditions. The main factors that would change the accuracy of the wet bulb measurements, as reported by Honeywell, are as follows:

1. The velocity of air which should be at least 15 ft/sec.
2. Temperature of water which should be at or slightly higher than the air wet bulb temperature.
3. Water purity.
4. Radiant heat and stem conduction heat.
5. Experience of operator in taking the readings.

The psychrometer should be fitted with its own small forced fan to accomplish an air velocity higher than 15 ft/sec. The temperature of water, which is at room temperature, can be heated to nearly the wet bulb temperature of air by immersing the water reservoir of the psychrometer in a water or sand path before recording the reading. Distilled water is used to assure water purity.

The dry bulb and wet bulb thermometers are connected to a two-pen recording potentiometer (Plate IV). It records the dry bulb temperature and the wet bulb depression, from which the air humidity ratio can be obtained from a psychrometric chart.

2.e. Air Velocity Measuring Device

A standard Herschel venturimeter tube (Fig. 3) is selected for its availability for measuring the low air velocity with considerable accuracy

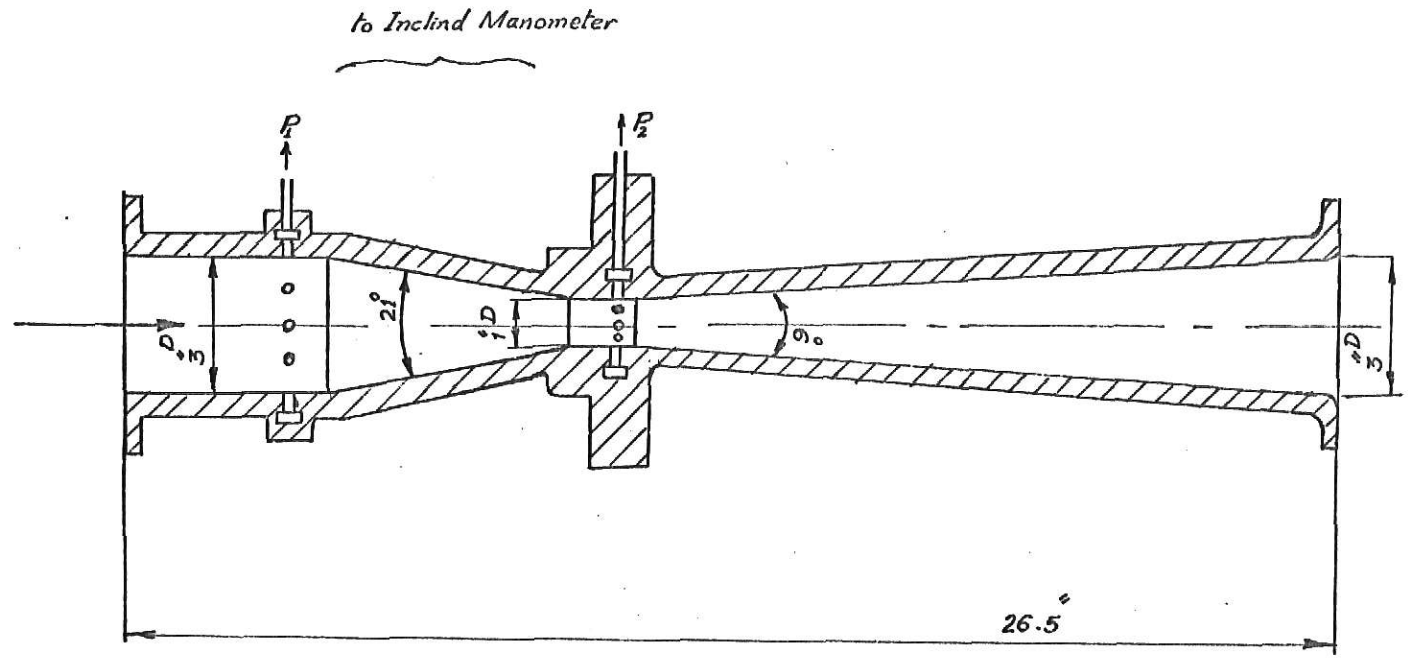


Fig. 3 : Herschel Venturimeter

and with small pressure loss compared with any other air velocity measuring device. It can be calibrated at room temperature. Laws of thermodynamics and emperical formulas are used to correct readings for the actual working temperatures and pressures. One disadvantage of using the venturimeter in this design is that it cannot be mounted in the bin just below the sample tray. However, it can be mounted in the duct, discharging the air to the bin. Nonuniformity of air distribution to the sample bin can be overcome by using three inches of glass wool fitted at the bottom of the bin. A second disadvantage may result from the instability of the reading at low air velocities. This is overcome by using screw-adjustable butterfly valves (Plate VII), and by increasing air velocity by decreasing the size of the duct to a 3" diameter tube before delivery to the venturimeter. The length of pipes before and after the tube and the dimensions of the air straightener before the venturitube were designed according to standards for Herschel tubes.

These initial calculations are based on the expected minimum and maximum differential pressures between the inlet and the throat of the venturimeter.

Let

Throat diameter of venturimeter = d inches

Air velocity at throat of venturimeter = v ft/sec

Air velocity at bin = V ft/min

Air volume rate of flow at bin = Q ft^3/sec

Dynamic viscosity of air at throat = μlb/ft-sec

Density of air at throat = ρ_a lb/ft^3

Density of water = ρ_w = 62.4 lb/ft^3

Coefficient of discharge of venturimeter = C

Differential head of air in venturimeter = h_f ft air

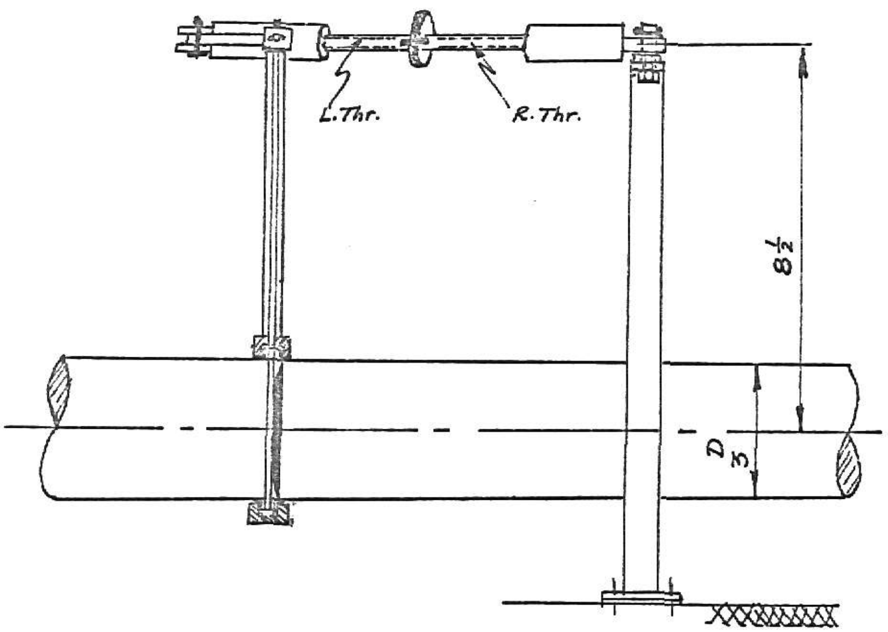
Differential head of air in inches of water = h_w

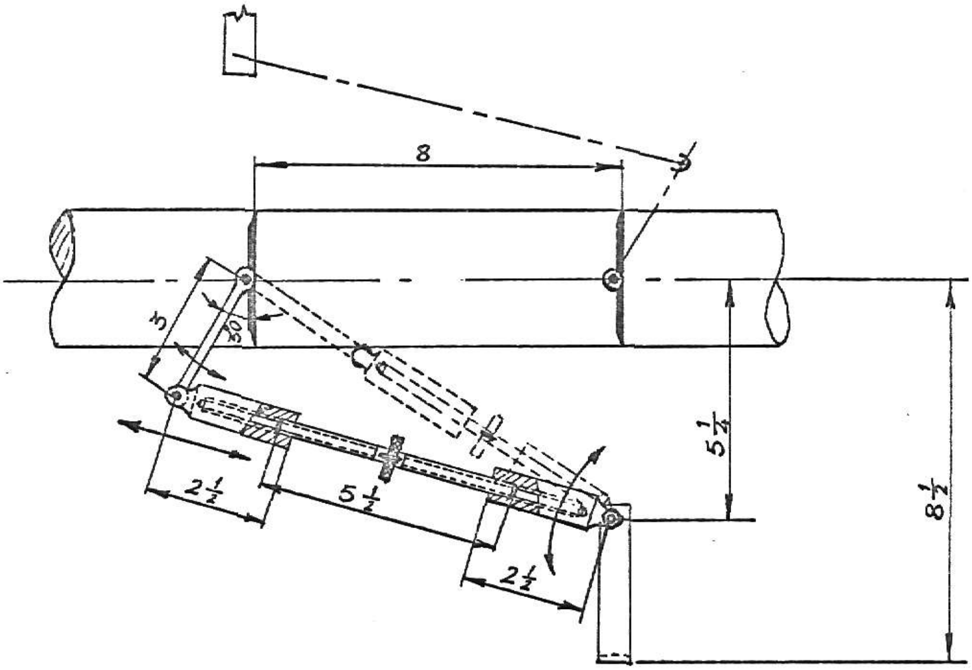
EXPLANATION OF PLATE VII

Section elevation and plan view of the screw-adjustable butterfly valve mechanism.

The solid drawing represents the closed position, and the dotted drawing shows the full-open position.

PLATE -VII-





Gravitational constant = g ft/sec^2

Assuming the cross section of the bin at the entrance to the sample tray is 1 ft × 1 ft, the volume rate of flow at the venturimeter is the same as at the bin, and neglecting the approach kinetic energy

$$Q = C \frac{\pi}{4} \left(\frac{d}{12}\right)^2 (2gh_a)^{\frac{1}{2}}$$

$$h_a = \frac{Q^2}{C^2 \left(\frac{\pi}{4}\right)^2 \left(\frac{d}{12}\right)^4 2g} \text{ ft of air}$$

$$Q = \left(\frac{V}{60}\right) \times (1 \times 1) = \frac{V}{60}$$

$$h_a = \frac{V^2}{(60)^2 \left(\frac{\pi}{4}\right)^4 2g \left(\frac{d}{12}\right)^4 C^2} \text{ ft of air}$$

$$h_w = h_a \frac{\rho_a}{\rho_w}$$

Assuming maximum air density ($\rho_{a\ max.}$) at air conditions of 100°F and atmospheric pressure and minimum air density ($\rho_{a\ min.}$) at air conditions of 300°F and atmospheric pressure,

$$\rho_{a\ max.} = \frac{P_a}{RT_a} = \frac{14.7 \quad 144}{53.3 \times (100 + 460)} = 0.0707 \text{ lb/ft}^3$$

$$\rho_{a\ min.} = \frac{14.7 \times 144}{53.3 \times (300 + 460)} = 0.0521 \text{ lb/ft}^3$$

$$\text{maximum } h_w = h_{a(\text{at } 100^\circ\text{F})} \times \frac{\rho_{a\ max.}}{\rho_w} \times 12 \text{ in/ft}$$

$$= h_{a(\text{at } 100^\circ\text{F})} \text{ ft air} \times \frac{0.0707}{62.4} \times 12$$

$$= \frac{0.001974\ V^2}{C^2_{(\text{at } 100^\circ\text{F})}\ d^4} \qquad (1\text{-a})$$

$$\text{minimum } h_w = h_{a(\text{at } 100^\circ\text{F})} \times \frac{\rho_{a\ min.}}{\rho_w} \times 12 \text{ in/ft}$$

$$= \frac{V^2 \times 0.0521 \times 12}{60^2 (\frac{\pi}{4})^2 \times 2 \times 32.2 \times (\frac{d}{12})^4 \times C^2_{(at\ 300^oF)} \times 12}$$

$$= \frac{0.001454\, V^2}{C^2_{(at\ 300^0F)}\, d^4} \tag{1-b}$$

The value of C is a function of Reynolds' Number (Re) at the throat of the venturimeter, and the venturi geometry and could be obtained from emperical graphs for Herschel type venturimeters.

$$Re = \frac{(\frac{d}{12})\ v\ \rho}{\mu}$$

$$v = \frac{Q}{(\frac{\pi}{4})(\frac{d}{12})^2} = \frac{(\frac{V}{60})}{(\frac{\pi}{4})(\frac{d}{12})^2}$$

$$Re = \frac{(\frac{d}{12})(\frac{V}{60})}{(\frac{\pi}{4})(\frac{d}{12})} = \frac{(\frac{V}{60})}{(\frac{\pi}{4})(\frac{d}{12})}$$

at 100^oF = 0.00001249 lb/ft sec

at 300^oF = 0.00001586 lb/ft sec

$$\text{at } 100^oF,\ Re = \frac{(\frac{V}{60})\quad 0.0707}{(\frac{\pi}{4})(\frac{d}{12})\quad 0.00001249} = \frac{1455\ V}{d} \tag{2-a}$$

$$\text{at } 300^oF,\ Re = \frac{(\frac{V}{60})\quad 0.0521}{(\frac{\pi}{4})(\frac{d}{12})\quad 0.00001586} = \frac{840.9\ V}{d} \tag{2-b}$$

The venturimeter selected as the 1" throat diameter and 3" inlet diameter. The selection is based on the minimum and maximum water differential head which can be measured accurately using suitable manometers.

Using 1 and 2, the following table could be constructed for different values of throat diameter d:

d inches	1"	1.5"	2"	2.5"
Re V = 80, t = 100	116,400	77,600	58,200	46,560
Re V = 5, t = 300	4,204	2,803	2,102	1,682
C V = 80, t = 100	0.979	0.971	0.965	0.960
C V = 5, t = 300	0.910	0.898	0.890	0.878*
h_w in.w.g. max.	13.190	2.650	0.850	0.350
h_w min.	0.0439	0.00891	0.00287	0.00121

*Values obtained from ASHRAE Guide, 1963, by extrapolation.

2.e.2. Manometers

Two inclined water manometers are used: one has a very small inclination with a fine screw adjustment (Fig. 4) and the other's inclination is varied from horizontal to vertical (Fig. 5). The specifications for the two manometers are as follows:

2.e.2.1. Small Inclination Manometer Specification

Rotating disc	100 divisions
Pitch of screw	0.1 inch
Vertical scale range	1 inch
Vertical scale division	0.1 inch
Inclined scale range	25 inches
Inclined scale division	0.1 inch
Fluid used	water

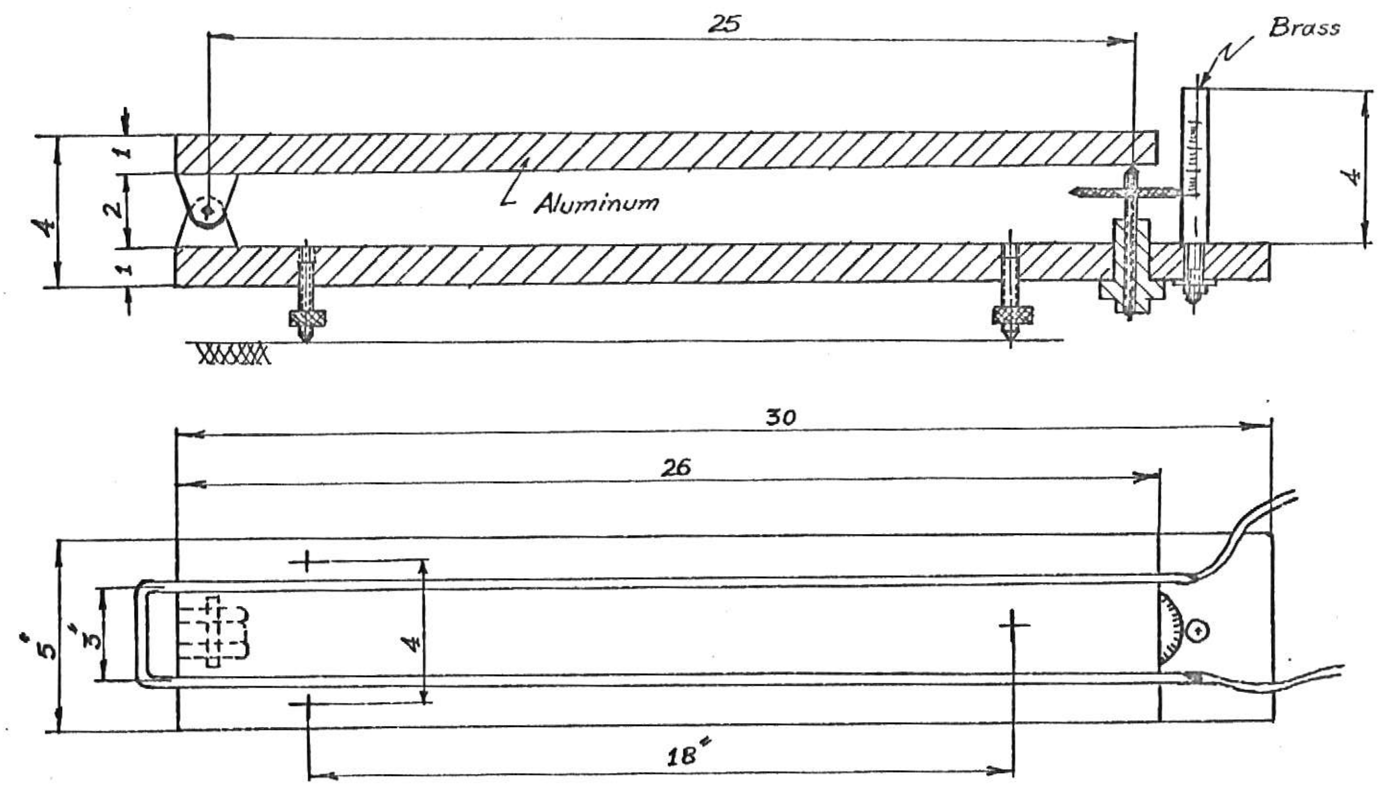


Fig. 4 : Inclined Manometer (small inclination)

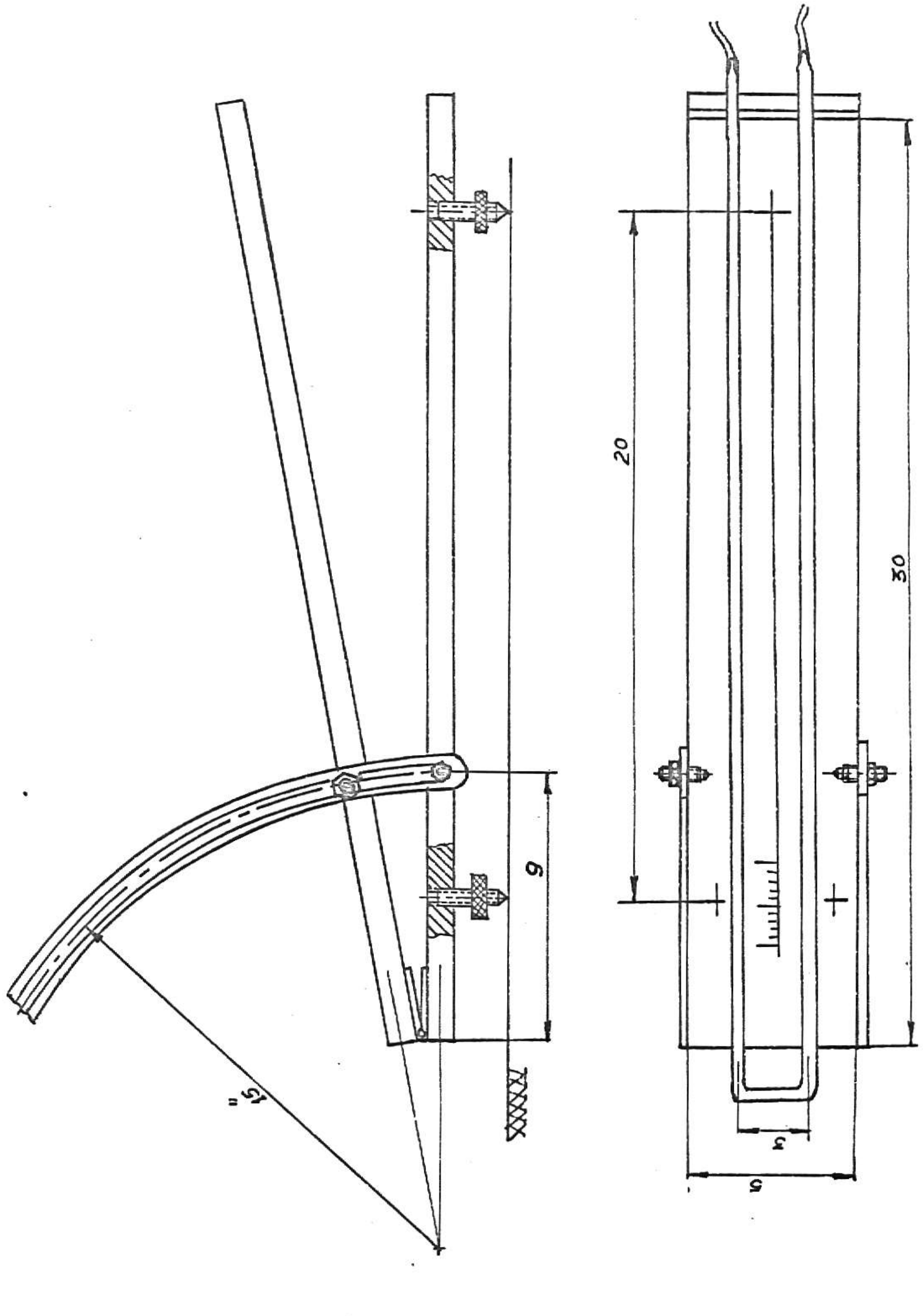


Fig. 5 : Inclined Manometer

2.e.2.2. Second Inclined Manometer

Inclined scale range	25 inches
Inclined scale division	0.05 inch

2.e.3. Calibration

It will be assumed that air is imcompressible for the range of pressures obtained by the fan. The venturitube is checked in the laboratory using a standard nozzle at laboratory temperature and pressure. It may not be possible to calibrate the venturitube at the high level of temperature, which is a function of the proposed setup, depending on facilities in the laboratory. For each test run the Reynold's number will be calculated, and C will be obtained from standard codes accompanying the device. The effect of the temperature on the coefficient of discharge is reported by ASHRAE to be 1% at 500°F and this will be neglected. The air discharge calculated at the venturitube will be corrected to the actual conditions at the bin. This procedure is made advantageously prior to test runs.

2.f. Bin Structure and Moisture Loss Measuring Device

The bin structure is composed of the bin, the sample tray, the oil seal, the cantilever beams, and the housing structure.

There are many methods that could be used to measure the moisture loss of the grain in the sample tray; among them are the following:

a. Using sensitive balance and replacing one of its panels by the free hanging sample tray;

b. Using an air oven or other standard methods to determine moisture contents of grain samples from the test trays;

c. Using strain gages mounted on a beam and continuously measuring the strain caused by the weight of the sample and its tray.

The method which is selected here is the strain gage method since it has many advantages over the other methods. These advantages are

1. Sensitivity to small load changes;
2. Readings are taken in a very short time compared to other methods;
3. The output strain can easily be calibrated to obtain the moisture loss;
4. Taking the reading does not disturb the grain bed in any way;
5. Accuracy of the measurement can be made high be selecting suitable instruments.

However, this method is not yet widely used and needs more trials and perfections. Some of the drawbacks encountered in this method are the following:

1. The accuracy of reading is affected by the accuracy and skill of mounting the gages on the beam;
2. The device needs recalibration before using it due to drift and hysteresis in the strain gages;
3. The accuracy and sensitivity are so related that a very low sensitivity cannot be accompanied with very high accuracy. However, if high accuracy is required, more costly instruments are used; that is, a high input voltage wheatstone bridge should be used coupled with a high ratio amplifier.

2.f.1. Calculations

Calculations are based on a cantilever beam fixed at one end and loaded by the sample tray at its free end. The considerations are the following

1. The strain output due to a loss in moisture equivalent to 1% decrease in dry basis moisture content;
2. The bending stresses developed in the cantilever beam and the strength of the material of the beam to withstand the stresses;

3. The deflection of the cantilever beam at its free end which in turn represents the deflection of the sample tray in the bin.

The calculations are based on corn of initial moisture content from 35%, wet basis, to 15%, wet basis. The corn is dried to equilibrium moisture content or to bone dry depending on the air temperature in the bin. The strain output due to 1% loss in dry moisture content is based on the minimum expected bone dry weight. This is the bone dry weight of a one-inch thick sample of corn in a 1 ft × 1 ft tray cross section. This weight is calculated to be 3.17 lb of corn. The bending stress and the deflection of the free end are based on maximum expected weight of grain, which is the weight of maximum thickness of a layer of corn at 35% moisture content. This weight is calculated to be 58.5 lb for a thickness of 12".

After some trials to compromise between the three preceeding factors, it was decided to use two cantilever beams; one will be used for depths from 1 inch up to 4 inches of grain and the other for depths from 5 inches up to 12 inches.

2.f.1.1. <u>Calculations for grain depths from 1 inch to 4 inches</u>

The material of the cantilever beam is suggested to be Aluminum Alloy 17 ST with the following specifications

Yield Strength	56×10^3 psi
Young's Modulus, E	10.3×10^6 psi

or Aluminum Alloy 51 ST with specifications as follows

Yield Strength	48×10^3 psi
Young's Modulus, E	10.3×10^6 psi

Assumptions

1. The cross section of the beam is rectangular, 1 inch wide and 3/16 inch thick.
2. No transverse stresses will occur in the beam.
3. Four strain gages will be mounted on the beam, two on the upper surface and two on the lower surface. All gages are mounted at a distance of 6 inches from the free end of the beam.
4. The fixed end of the beam is at a distance of 6.5 inches from the free end.
5. The weight of the sample tray with its central rod is assumed to be 9 lbs.

The strain decrease caused by moisture loss due to 1% in percent moisture content is given by

$$\varepsilon = \frac{P_m \times L \times C/2}{I\ E} \times 4 \times 10^6,$$

where

ε = strain decrease caused by moisture release due to 1% dry basis decrease in percent moisture content, μin/in.;

P_m = moisture release due to 1% decrease in percent dry basis moisture content = 3.17 × 0.01 = 0.0317 lb.;

L = the distance between the strain gage mounting position and the free end = 6 inches;

C = the thickness of the beam = 3/16 inch;

I = area moment of inertia = $1/12\ W\ C^3$, in^4;

W = width of beam = 1 inch;

E = Young's modulus of elasticity of beam = 10.3×10^6 psi

The constants 4 and 10^6 are four strain gages and for converting the units to micro inch/inch, and give

$$\varepsilon = \frac{0.0317 \times 6 \times 3/12 \times 4 \times 10^6}{1/12 \times 1 \times (3/16)^3 \times 10.3 \times 10^6} = 12.57 \mu in/in.$$

To check the maximum bending stress and the deflection at the free end, the following relationships are used

$$\sigma = \frac{PL' \times C/2}{I}$$

$$\delta = PL'^3/3\ EI$$

where

σ = maximum bending stress in the beam, psi

L'= distance from free end of the beam to its fixed point, inches

P = weight of a four-inch depth of corn at 35% w.b. plus the sample tray weight $= \frac{58.5}{3} + 9 = 28.5$ lb

δ = deflection of the free end of the beam, in

$$\sigma = \frac{28.5 \times 6.5 \times 3/32}{(1/12) \times 1 \times (3/16)^3} = 31{,}620 \text{ psi}$$

$$\delta = \frac{28.5 \times (6.5)^3}{3 \times 10.3 \times 10^6 \times (1/12) \times 1 \times (3/16)^3} = 0.46 \text{ in.}$$

2.f.1.2. Calculations for grain depths from 5 inches to 12 inches

The material of the cantilever beam is suggested to be steel, SAE 4340, annealed with specifications as follows:

Yield Strength	80×10^3 psi
Young's Modulus, E	30×10^6 psi

Assumptions are the same as for the previous beam, but the cross section of the beam is 1" × ¼".

$Pm = 3.17 \times 5 \times 0.01 = 0.1585$ lb

$P = 58.5 + 9 = 67.5$ lb

$$\varepsilon = \frac{0.1585 \times 6 \times 1/8 \times 4 \times 10^6}{1/12 \times 1 \times (\frac{1}{4})^3 \times 30 \times 10^6} = 12.2\,\mu in/in$$

$$\sigma = \frac{67.5 \times 6.5 \times 1/8}{1/12 \times 1 \times (\frac{1}{4})^3} = 42{,}185 \text{ psi}$$

$$\delta = \frac{67.5 \times (6.5)^3}{3 \times 30 \times 10^6 \times 1/12 \times 1 \times (\frac{1}{4})^3} = 0.158 \text{ in}$$

Keeping in mind that the error of the measuring instruments will be ±3 micro inch/inch, the accuracy of the percent moisture content is recommended to be within ±0.25% dry basis. Even if the instrument error is doubled, the accuracy will be within ±0.5%. Before the assembly is made, the strength of the beam should be checked to verify the given specifications. If the beam fails, the width of the beams in this design may be increased by 0.25 inch. The effect of deflection is absorbed as will be seen when discussing the bin structure assembly.

2.f.2. The Weight-Measuring Instrumentation

2.f.2.1. Instruments to be used

1. Four strain gages/sample, type Beam BAE - xx - 031CC - 350

Resistance	350 ohm
Gage overall length	0.075"
Gage width	0.062"

2. Power supply 10 volt D.C.
3. Wheatstone bridge circuit with balance switch and four active arms.
4. Amplifier of ratio 250:1.
5. Voltage readout apparatus of range 30 V and sensitivity 0.005 volt (or calibrated range and sensitivity of 6000 μin/in and 2 μin/in respectively).

2.f.2.2. Calculations of circuit sensitivity

$$S_c = V\frac{r}{(1+r)^2} S_g \times 4$$

where

S_c = circuit sensitivity for bridge, volt/in/in;

V = input voltage, volt;

r = resistance ratio R_1/R_2 (Fig. 6), dimensionless;

S_g = gage factor for the strain gages, $\frac{\Delta R/R}{\varepsilon}$, dimensionless;

The constant of multiplication, 4, is used for four active gages. The value of r is 1 since $R_1 = R_2 = 350$ ohm. The value of S_g is assumed to be 2.

$$S_c = 10 \times 1/4 \times 2 \times 4 = 20 \text{ volt/in/in.}$$

Using an amplifier with a ratio of 250 will increase the circuit sensitivity 250 times. The total circuit sensitivity is as follows

S'_c = total circuit sensitivity

$= 20 \times 250 = 5000$ volt/in/in

$$S'_c \text{ micron/in} = \frac{5000}{10^6} = 0.005 \text{ volt/}\mu\text{in/in}$$

To check the current in the bridge circuit, the following is used

$$I = \frac{V}{2R} = \frac{10}{2 \times 350} = 0.0143 \text{ amps.}$$

A check for the maximum voltage to be read on the readout indicator is given by

$$\varepsilon_{max.} = \frac{\text{max. weight} \times L \times C/2 \times 4 \times 10^6}{I\ E}$$

$$= \frac{67.5 \times 6 \times 1/8 \times 4 \times 10^6}{1/12 \times 1 \times (\frac{1}{4})^3 \times 30 \times 10^6} = 5200\ \mu\text{in/in.}$$

Maximum voltage output = 0.005 × 5200 = 26 volts.

Instruments available can read 0.01 volt which means a sensitivity of 2 micro inch/inch. The safe current for no overheating of gages is reported

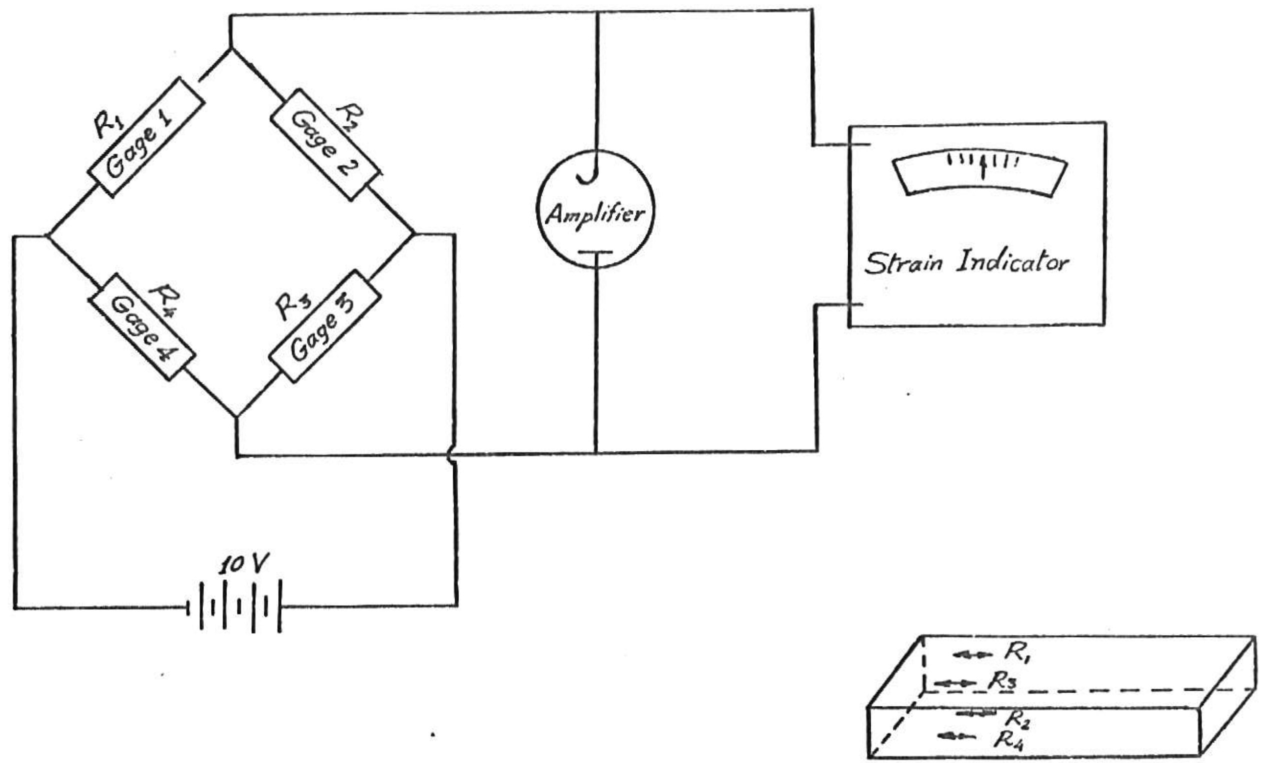


Fig. 6 : Weight Measuring Circuit

to be 0.030 amperes which is double the value of the current presented in the calculations.

2.f.3. Bin Structure Assembly

The rectangular bin is composed of two parts, the bottom part and top part. The bottom part is 13" × 13" in cross section and is fitted with a rectangular ring of one inch width, just above the opening of the inlet duct. A 3-inch layer of woolglass will be above the inlet opening to make the air flow to the test samples uniformly. The top part is 14" × 14" in cross section. The flanges of the two parts and the flange of the rectangular annulus oil seal are bolted together (Plate VIII). The sample tray is 12.5" high and has a central rod, the end of which is bolted on a spherical segment. The spherical piece is seated in a spherical groove in the free end of the cantilever beam. The bottom of the sample tray has a vertical stand. When the sample tray is deflected under its weight, the spherical piece and spherical seat will adjust themselves such that the sample tray will remain vertical. The dimensions of the vertical stand and the oil seal are so designed to fit the calculated deflection of the tray. The vertical stand will sink in the oil seal and it will not tough any fixed part of the bin structure nor will it leave the oil to permit air leakage. The other end of the cantilever beam is fixed to the housing structure through supporting beams and bolts. The lever and the supporting beams are slotted to allow adjusting of the lever to suit the sample tray position. The housing structure is composed of linked channels and moves on rollers for adjusting the sample tray in the bin.

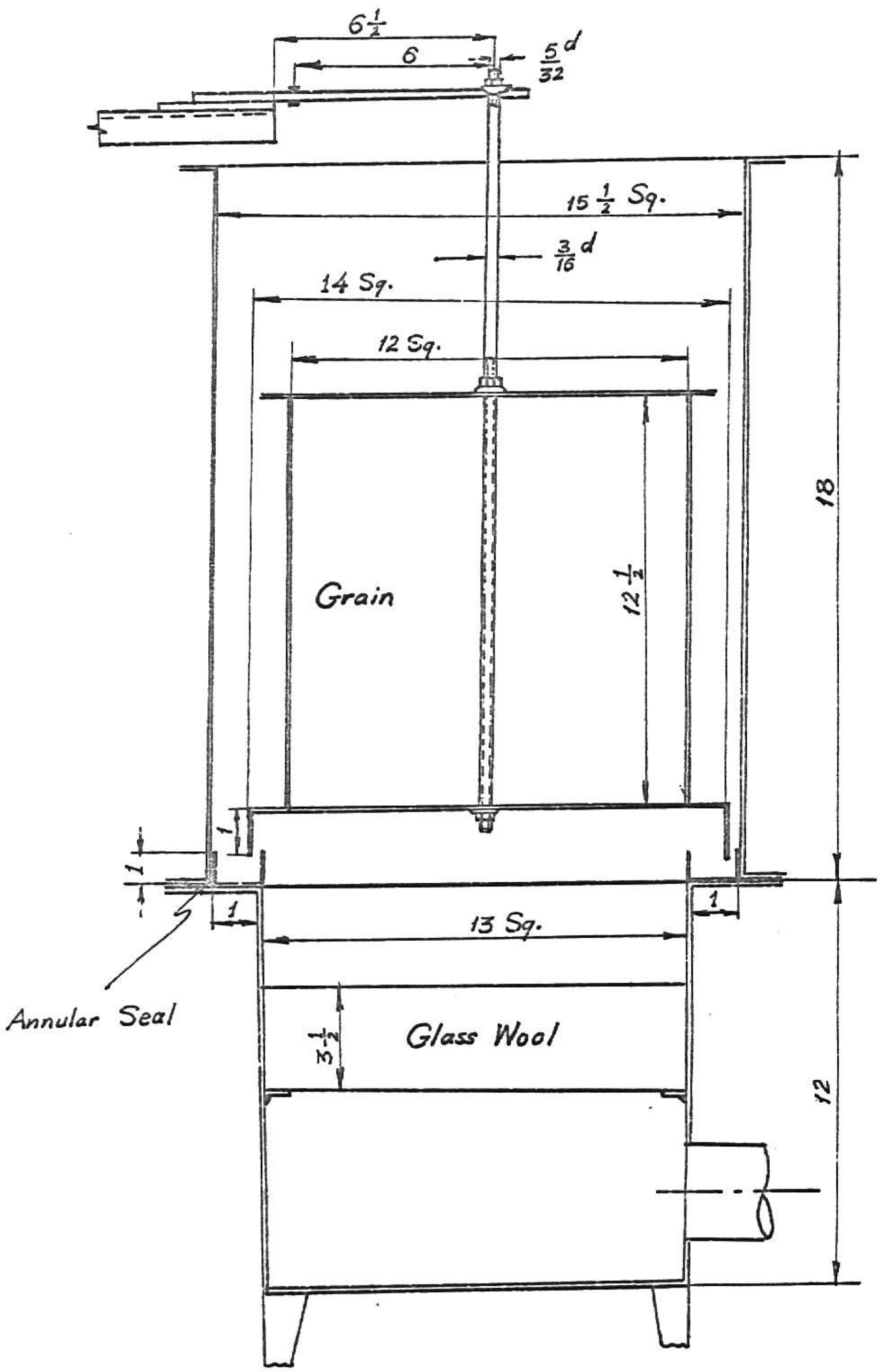
2.g. Insulation of Bin and Ducts

Cork insulation will be used because of its rigidity and its ability to resist high temperatures. The insulation calculations are estimated for

EXPLANATION OF PLATE VIII

Section elevation in the sample bin showing the position of sample tray when unloaded.

PLATE -VIII-



6 1/2
6
5/32 d
15 1/2 Sq.
3/16 d
14 Sq.
12 Sq.
18
Grain
12 1/2
1
1
1
1
13 Sq.
Annular Seal
3 1/2
Glass Wool
12

EXPLANATION OF PLATE IX

Fig. 1: Elevation and plan views of the aluminum lever.

Fig. 2: Elevation and plan views of the steel lever.

Fig. 3: Section elevation and plan views of the spherical piece.

PLATE -IX-

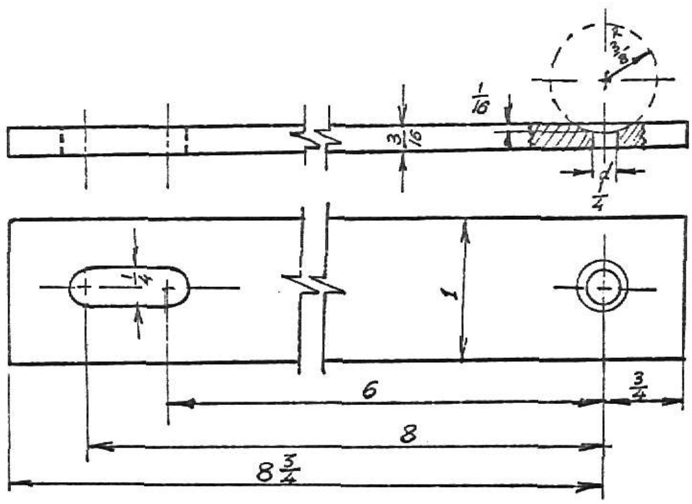


Fig. 1

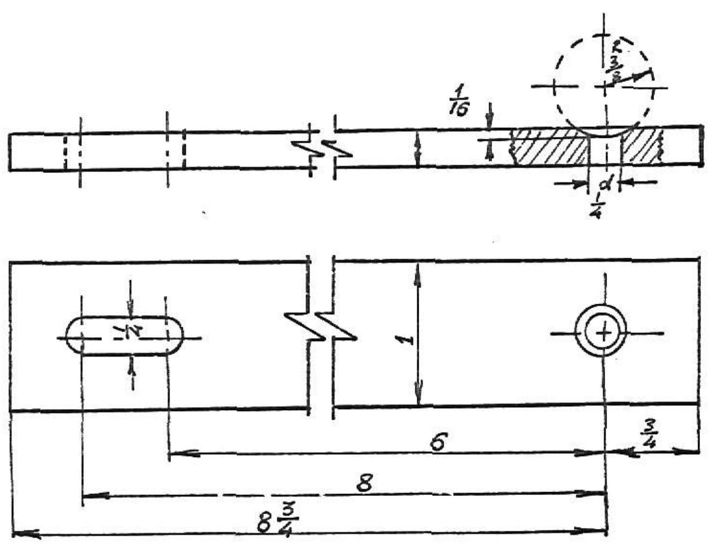


Fig. 2

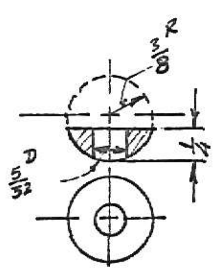


Fig. 3

three cross sections; namely, the top part of the bin, 14.5" × 14.5", the main branch duct, 9" × 9", and the 3" diameter pipe.

Assumptions

1. The temperature of the inner surfaces, t_{is}, is 300°F. This neglects the thermal resistance of air in the ducts.
2. The room temperature, t_R, is 70°F.
3. The insulator surface temperature, t_{os}, is 75°F.
4. The outside surface thermal conductance, h_o, is 1.65 btu/hr °F ft^2.
5. Ther thermal conductivity of cork, K_c, is 0.04 btu/hr °F ft^2/ft.
6. For the square duct, the area at half the thickness is considered the constant heat transfer area.
7. The conductance of duct material is neglected.

2.g.1. Bin Insulation

The heat, q, transferred per unit length of bin through the thickness, X inches, of bin insulation is given by

$$q = K_c \times 4 \times \frac{14.5 \times X_1}{12} \times \frac{t_{is} - t_{os}}{(X_1/12)} \qquad (1)$$

For steady state condition, this quantity will be equal to the convective heat transfer from the outer surface of the insulator to the room; hence,

$$q = h_o \times \frac{4(14.5 + 2X_1)}{12} \times (t_{os} - t_R) \qquad (2)$$

From (1) and (2)

$$K_c \times \frac{4(14.5 + X_1)(t_{is} - t_{os})}{12 \times (X_1/12)} = h_o \frac{4(14.5 + 2X_1)(t_{os} - t_R)}{12}$$

$$0.04 \frac{4(14.5 + X_1)(300 - 75)}{12(X_1/12)} = 1.65 \frac{4(14.5 + 2X_1)(75 - 70)}{12}$$

This yields $X_1 = 9.40''$.

2.g.2. Branch Duct Insulation

For a thickness of insulation, X_2 inches,

$$0.04 \times \frac{4(9 + X_2)(300 - 75)}{12 \quad (X_2/12)} = 1.65 \times \frac{4(9 + 2X_2)(75 - 70)}{12}$$

This yields

$X_2 = 8.77$ inches.

2.g.3. Pipe Insulation

For insulation thickness X_3,

$$q = h_o \times \frac{(3 + 2X_3)(75 - 70)}{12}$$

$$= K_c \times \frac{2(300 - 75)}{\mathrm{Ln}\frac{(3/2 + X_3)}{3/2}}$$

or $$\frac{1.65(3 + 2X_3)(75 - 70)}{12} = \frac{0.04 \times 2 \times (300 - 75)}{\mathrm{Ln}(1 + \frac{X_3}{1.5})}$$

By trial calculation this yields

$X_3 = 6.40$ inches.

With these levels of insulation, the calculated bin heat loss is 92 btu/hr ft length or 27 watts/ft. It can be predicted from this loss that the heat loss will be approximately 5%.

2.h. Fan

The fan selection is based on the air volume rate of flow and the static pressure loss. An estimation of the static pressure loss based on total air volume rate of flow of 500 cfm in the main duct and the maximum volume rate of flow of 80 cfm in the branch ducts is as given here.

2.h.1. Estimation of Static Pressure Loss

Pressure loss in main duct (12" × 9" = 11.3" diam.)

$$= \frac{0.08 \text{ in.w./ft} \times 10}{100} = 0.008 \text{ in.w.g.}$$

Pressure loss in branch duct (9" × 9" = 9.9" diam.)

$$= \frac{0.005 \text{ in.w./ft} \times 10}{100} = 0.0005 \text{ in.w.g.}$$

These values are taken from reference (1).

Pressure drop in the gradual contraction to the 3" pipe from the branch duct is assumed to equal 0.1 in.w.g.

Pressure drop in sudden enlargement of air entering the bin and in the fibre glass bed is assumed to equal 0.25 in.w.g.

Pressure drop in silica gel box, eliminators, and deflector is assumed to equal 0.40 in.w.g.

Pressure drop in air washer and humidity measurement duct is assumed to equal 0.60 in.w.g.

Pressure drop in the two heaters (calculated) = 0.3 in.w.g.

Pressure drop in the venturimeter = 20% of entering head (from ASME power test code).

Pressure drop in 12" clean corn bed at 12.4% m.c. = 1.75 in.w.g.

Total pressure drop after venturimeter = 1.75 + 0.25 = 2" w.g.

Total pressure drop before venturimeter = 1.41 in.w.g.

Static pressure before venturimeter should be at least

$$= 2 \times \frac{100}{80} = 2.5 \text{ in.w.g.}$$

Total static pressure needed = 2.5 + 1.41 = 3.91 inw.g.

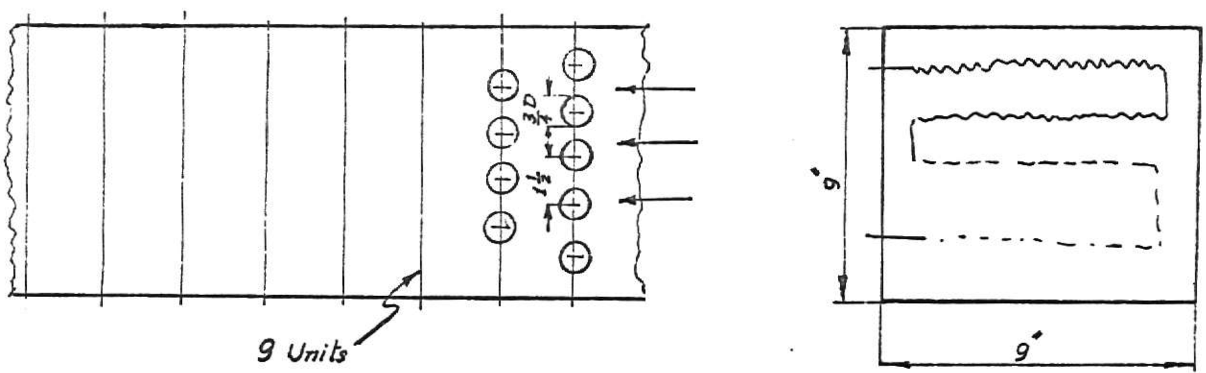


Fig. 7: Assumed Dimensions of Heating Elements.

2.h.1.1. Calculation of pressure drop in heaters

The pressure drop in heaters is calculated assuming dimensions of heating elements and their space clearance as shown in Fig. 7. Equation used is reported by Henderson and Perry (17) for fluid passing rows of tubes.

$$\Delta P = \frac{4 f E \gamma V^2}{2g}$$

where

E = number of rows of tubes normal to fluid stream = 9

γ = fluid specific weight = 0.0707 lb/ft^3 at 100°F

V = maximum velocity through minimum cross section = 7.12 ft/sec

C = clearance between tubes = 1/24 ft

μ = fluid viscosity = 0.00001249 lb/ft sec at 100°F

$$f = 0.75 \left(\frac{cv\gamma}{\mu}\right)^{-0.2} \text{ for turbulent flow (Re > 40)}$$

$$v = \frac{80 \text{ cfm} \quad 1 \text{ min}}{(9/12)(1/24) \times 6 \text{ spaces}} = 7.12 \text{ fps}$$

$$Re = \frac{(1/24) \times 7.12 \times 0.0707}{0.00001249} = 1679.3 > 40$$

hence the flow is turbulent.

$$f = 0.75 \times \left(\frac{1}{24} \times \frac{7.12 \times 0.0707}{0.00001249}\right)^{-0.2}$$

$$= 0.75\ (1679.3)^{-0.2} = 0.75 \times 0.2265 = 0.170$$

$$P = \frac{4 \times 0.17 \times 9 \times 0.0707 \times (7.12)}{2 \times 32.2} = 0.34 \text{ lb/ft}^2$$

$$= 0.34 \text{ lb/ft}^2 \times 0.18825 \text{ in.w./lb/ft}^2 = 0.064 \text{ in.w.g.}$$

Pressure drop in the two heaters = 0.064 × 2 = 0.128 in.w.g.

The pressure drop in the two heaters is taken as 0.3 in.w.g.

2.h.2. Fan Specifications

Based on rate of flow of about 600 cfm to account for leakage of air and total static pressure drop of 6 inches of water to make possible the drying of wheat in 12" beds, a 17MW Buffalo industrial fan is selected as follows:

Capacity	570 cfm
Static Pressure	6 in.w.g.
Speed	2742 r.p.m.
Brake Horsepower	0.9 H.P.
Wheel Diameter	12½ in.
Exit Area	7¼" × 6"
Inlet Outer Diameter	17"

The higher air volume rate chosen is designed to make possible blocking the flow down to increase the static head if the resistance is exceeded due to any factor such as using unclean wheat in the experiments and to make the design flexible if any part is added to the system.

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude and thanks to Prof. T. O. Hodges, Professor of Agricultural Engineering at Kansas State University, for his guidance and advice throughout conducting this study.

Gratitude and thanks are also extended to Prof. G. H. Larson, Head of the Department of Agricultural Engineering, and the staff of the Department and U.S.D.A. personnel for their assistance.

The author can not forget the help of the people of his own country, who qualified him for graduate study.

REFERENCES

1. ASHRAE Guide and Data Book (1963).

2. Becker, H. A. and Sallans, H. R.

   "A Study of the Desorption Isotherms of Wheat at 25°C and 50°C."

   Cereal Chem., V 33 : 79 - 91 (1956).

3. Breese, M. H.

   "Hysteresis in the Hygroscopic Equilibria of Rough Rice at 25°C."

   Cereal Chem., V 32 : 481 - 487 (1955).

4. Bushuk, W. and Hlynka, I.

   "Weight and Volume Changes in Wheat During Sorption of Moisture."

   Cereal Chem., V 37 : 390 - 398 (1960).

5. Carey, W. F.

   "Discussion to Simmonds, Ward and McEwen Results."

   Trans. Chem. Engg., V 33 : 138 - 146 (1955).

6. Chittenden, D. H. and Hustrulid, A.

   "Determining Drying Constants for Shelled Corn."

   Trans. of ASAE, V 9 : 52 - 55 (1966).

7. Chung, D. S. and Pfost, H. B.

   "Adsorption and Desorption of Water Vapor by Cereal Grains and Their Products." Part III "A Hypothesis for Explaining the Hysteresis Effect."

   Trans. of ASAE, V 10 : 556 - 557 (1967).

8. Cramer, H. A.

   "Engineering Aspects of Rice Drying."

   Agric. Engg., V 32 : 44 - 45, 50 (1950).

9. Dally, J. W. and Riley, W. F.

"Experimental Stress Analysis."

McGraw-Hill, Inc. (1965).

10. Fan, L. T., Chung, D. S., and Shellenberger, J. A.

"Diffusion Coefficients of Water in Wheat Kernels."

Cereal Chem., V 38 : 540 - 548 (1961).

11. Hall, C. W.

"Drying Farm Crops." Chapter vi

Edwards Brothers, Inc. (1957).

12. Hall, C. W. and Rodriguez-Arias, J. H.

"Equilibrium Moisture Content of Shelled Corn."

Agric. Engg., V 39 : 466 - 470 (1958).

13. Hart, J. R.

"Hysteresis Effect in Mixtures of Wheat Taken from the Same Sample but Having Different Moisture Contents."

Cereal Chem., V 41 : 340 - 350 (1964).

14. Henderson, S. M.

"A Basic Concept of Equilibrium Moisture."

Agric. Engg., V 33 : 29 - 32 (1952).

15. Henderson, S. M. and Pabis, S.

"Grain Drying Theory I: Temperature Effect on Drying Coefficient."

Journal of Ag. Engg. Res., V 6 : 169 - 174 (1961).

16. Henderson, S. M. and Pabis, S.

"Grain Drying Theory IV: The Effect of Airflow Rate on the Drying Index."

Journal of Ag. Engg. Res., V 7 : 85 - 89 (1962).

17. Henderson, S. M. and Perry, R. L.

Agricultural Process Engineering, Chapter II,

Library of Congress Catalog Card Number 54-12684 (1966).

18. Honeywell, Inc.

Bulletin titled "How Humidity Is Measured."

19. Hubbard, J. E.; Earle, F. R.; and Senti, F. R.

"Moisture Relations in Wheat and Corn."

Cereal Chem., V 34 : 422 - 433 (1957).

20. Hukill, W. V.

"Basic Principles in the Drying of Corn and Grain Sorghum."

Agric. Engg., V 28 : 335 - 338, 340 (1947).

21. Hukill, W. V.

"Types and Performance of Farm Grain Dryers."

Agric. Engg., V 29 : 53 - 54, 59 (1958)

22. Hukill, W. V.

"Drying of Grain"

Storage of Cereal Grains and Their Products, Chapter IX.

23. Hustrulid, A. and Flikke, A. M.

"Theoretical Drying Curve for Shelled Corn."

Trans. of ASAE, V. 2 : 112 - 114 (1959).

24. Hustrulid, A.

"Comparative Drying Rates of Naturally Moist, Remoistened, and Frozen Shelled Corn."

Trans. of ASAE, V 5 : 64 - 67 (1962).

25. Johnson, H. K. and Dale, A. C.

"Heat Required to Vaporize Moisture."

Agric. Engg., V 35 : 705 - 709 (1954).

26. Juliano, O. B.

"Hygroscopic Equilibria of Rough Rice."

Cereal Chem., V 41 : 191 - 197 (1964).

27. MacMasters, M. M., Earle, F. R., Finkner, M. D., Holzapfel, M. M., Ramser, J. H., and Dungan, G. H.

"Studies on the Effect of Drying Conditions Upon the Composition and Suitability for Wet Milling of Artificially Dried Corn."

Cereal Chem., V 31 : 451 - 461 (1954).

28. MacMasters, M. M., Finkner, M. D., Holsapfel, M. M., Ramser, J. H., and Dungan, G. H.

"A Study of the Effect of Drying Conditions on the Suitability for Starch Production of Corn Artificially Dried After Shelling."

Cereal Chem., V 36 : 247 - 260 (1959).

29. McEwen, E., Simmonds, W. H., and Ward, G. T.

"Drying of Wheat-Grain, Part III": "Interpretation in Terms of Biological Structure."

Trans. Instn, Chem, Engrs., V 32 : 115 - 120 (1954).

30. McEwen, E., Simmonds, W. H., and Ward, G. T.

"The Drying of Wheat-Grain, Part IV": "The Resistance to Air Flow of Beds of Agricultural Products, Experimental Work."

Trans. Instn. Chem. Engrs., V 32 : 121 - 129 (1954).

31. McEwen, E. and O'Callaghan, J. R.

"The Effect of Air Humidity on Thorough Drying of Wheat Grain."

Trans. Instn. Chem. Engrs., V 33 : 135 - 154 (1955).

32. Myklestad, V.

"An Analysis of Transient Flow of Heat and Moisture During Drying of Granular Beds."

International Journal of Heat and Mass Transfer, V 11 : 675 - 687 (1968).

33. Pabis, S. and Henderson, S. M.

"Grain Drying Theory II": " "A Critical Analysis of the Drying Curve for Shelled Maize."

Journal Ag. Engg. Res., V 6 : 272 - 277 (1961).

34. Pabis, S. and Henderson, S. M.

"Grain Drying Theory III": "The Air/Grain Temperature Relationship."

Journal Ag. Engg. Res., V 7 : 21 - 26 (1962).

35. Picket, L. K., Pinkerton, J. W., Younger, R. R., and Jensen, A. H.

"Accelerated Drying of Corn."

Trans. of ASAE, V 6 : 151 - 157 (1963).

36. Rest, D. V. and Isaacs, G. W.

"Exposed Layer Drying Rates of Small Grains."

Trans. of ASAE, V 9 : 688 - 689 (1966).

37. Shelef, L. and Mohsenin, N.

"Moisture Relations in Germ, Endosperm, and Whole Corn Kernel."

Cereal Chem., V 43 : 347 - 353 (1963).

38. Simmonds, W. H., Ward, G. T., and McEwen, E.

"The Drying of Wheat-Grain, Part I": "The Mechanism of Drying."

Trans. Instn. Chem. Engrs., V 31 : 265 - 278 (1953).

39. Simmonds, W. H., Ward, G. T., and McEwen, E.

"The Drying of Wheat Grain, Part II": "Thorough Drying of Deep Bed."

Trans. Instn. Chem. Engrs., V 31 : 279 - 288 (1953).

40. Strohman, R. D. and Yoerger, R. R.

"A New Equilibrium Moisture Content Equation."

Trans. of ASAE, V 10 : 675 - 677 (1967).

41. Thomas, A. M.

"Grain Drying by Through - Circulation."

Journal Ag. Engg. Res., V 6 : 300 - 309 (1961).

42. Thompson, H. J. and Shedd, C. K.

"Equilibrium Moisture Content and Heat of Vaporization of Shelled Corn and Wheat."

Agric. Engg., V 35 : 786 - 788 (1954).

43. Thompson, T. L., Foster, G. H., and Peart, R. M.

"Comparative Performance of Concurrent Flow, Cross Flow, and Counter Flow Drying Methods."

USDA - ARS, Transportation and Facilities Division, Submitted January (1967).

44. Thompson, T. L., Peart, R. M., and Foster, G. H.

"Mathematical Simulation of Corn Drying - A New Model."

Special Paper Presented Before ASAE Meeting, June 27 - 30 (1967).

45. Woodforde, J. and Osborne, L. E.

"The Drying of Wheat in Beds One and Two Feet Deep."

Journal Ag. Engg. Res., V 6 : 300 - 309 (1961).

46. Woodforde, J. and Lawton, P. J.

"Drying Cereal Grain in Beds Six Inches Deep."

Journal Ag. Engg. Res., V 10 : 146 - 171 (1965).

47. Young, J. H. and Nelson, G. L.

"Theory of Hysteresis Between Sorption and Desorption Isotherms in Biological Materials."

Trans. of ASAE, V 10 : 260 - 263 (1967).

48. Taha, Ibrahim Shafie

Unpublished Research Report, Mechanical Engineering Department, University of Assiut, Assiut, U.A.R.

DESIGN OF A SMALL SAMPLE LABORATORY
GRAIN DRYER

by

IBRAHIM MOHAMED SHAFIE TAHA

B. Sc., Mechanical Engineering,
University of Cairo, Cairo, U.A.R., 1964

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1970

ABSTRACT

The purpose of this study was to design a heated air grain drier capable of performing laboratory experiments for a wide range of drying variables. Variables controlled and measured are air temperature, air velocity, humidity ratio, and a wide range of grain moisture contents for grain depths of 1 to 12 inches.

To fulfill this purpose a design is given which provides different air conditions to six samples of grain at a time. The temperature of air can be changed and controlled in a range of $100^{o}F$ to $300^{o}F$, the air velocity can be changed and controlled in a range of 5 fpm up to 80 fpm, and the air humidity ratio can be varied and controlled in a range of nearly zero to 0.045 $lb_{w}/lb_{dry\ air}$.

A single fan provides air to a main duct from which six ducts are branched. Air is processed in these ducts and supplied to sample trays suspended in the sample bins from cantilever beams provided with strain gages to measure moisture loss of the grain. In the branched duct the air passes through silica gel and the exit dry air passes through two split 7750 watt-heaters separated by an air washer. The hot humid air then passes through two successive butterfly valves to a venturimeter where it is delivered to the sample bin.

The air temperature is controlled by a potentiometric temperature controller whose output fires a silicon controlled rectifier, modulating the power to resistive heating elements of the heaters.

The air humidity ratio is controlled by introducing dry air to an air washer at a controlled dry bulb temperature. The humidity ratio is measured by a porous tube psychrometer.

The air velocity is controlled through two successive screw-adjustable butterfly valves and measured by the venturimeter.

Grain moisture loss is measured by the change in strain of the cantilever beam due to the change in sample tray weight. A calibrated 4-active arm wheatstone bridge coupled with an amplifier and a readout apparatus is used for the moisture loss measurement. Two levers of different materials and cross sections are proposed, one for grain depths up to four inches and the other for grain depths from 5 inches up to 12 inches. This procedure will provide better sensitivity and accuracy of the measuring device.

This design is thought to be helpful for further studies on drying, especially for a study involving the effect of moisture-time history during drying on the quality of grain.