

第二減速 乾燥期에 있어서의 假濕球溫도의 普偏性

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The Universality of the Pseudo Wet Bulb Temperature During the Second Falling Rate Period

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Abstract The universality of the pseudo wet bulb temperature has been established in the drying of macroporous inerts, microporous inerts, and microporous swellable materials using water and methyl alcohol as the liquids.

The pseudo wet bulb temperature is a new constant temperature intermediate between the wet bulb and dry bulb temperatures of the air during the second falling rate period. This temperature is calculated from consideration of the heat transfer to, and vapor diffusion from, liquid evaporating at the liquid-air boundary. The experimental results agree with that calculated from the equation proposed by Nissan, Bolles and George.

요 약 물 및 Methyl Alcohol 과 같은 液體에 젖은 巨大孔 不活性 微少孔 不活性 및 微少孔 濕潤性 物質을 乾燥할때 假濕球 溫度가 普偏의으로 形成되며 假濕球 溫度는 空氣乾燥의 第2減速期中 乾球溫도와 濕球溫度間에 나타난 하나의 새로운 一定溫度이다.

이 溫度는 液體 空氣 境界에서의 熱傳達, 蒸氣擴散, 液體蒸發 現象을 考慮한 式으로 計算되며 Nissan Bolles 및 George 가 誘導한 式에 依하여 計算된 數値는 實驗結果値와 一致한다.

Introduction

The manner in which moisture moves through a solid and then out into the air during the drying process is termed the mechanism of drying¹⁶. This mechanism is of considerable practical interest in industrial drying operations because it determines the particular variables under the control of the designer and operator

that govern the rate of drying and the quality of the product.

Air drying involves vaporization of the water contained in the solid and removal of the vapor by an air stream. The heat requirement is great due to the large latent heat of vaporization. In all drying processes vaporization is an essential factor in the removal of water from the material to be dried. Generally air drying is used since it is convenient and relatively inexpensive.

Water vaporizes from a very wet solid into

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the air in the same way as it evaporates from a free water surface. This phenomenon is one of diffusion; the diffusional resistance is concentrated in an air "film" adjoining the liquid surface²⁰.

There are several distinct stages in the process of drying by evaporation from an exposed surface into a moving stream of air. These stages are characterized by differences in the conditions of the surface exposed to the gaseous drying medium. Fig. 1 shows a typical drying curve and drying rate curve. **The Constant Rate Period**-During constant rate period (A-B in Fig 1), it is generally accepted that drying takes place at the exposed surface by diffusion of vapor through the stationary air film. **The Falling Rate Period**-At the critical moisture content (B in Fig. 1), the rate of evaporation begins to decrease as drying continues. The falling rate period can be divided into two distinct period. The first falling rate period (B-C in Fig. 1) is linear with moisture content, while the second falling rate period (C-D in Fig. 1) decreases exponentially with moisture content¹⁰.

Nissan, Bolles and George^{4,6,12} have recently determined that during the second falling rate period a new temperature equilibrium is established throughout the wet material. This new constant temperature has been called the "Pseudo Wet Bulb Temperature"¹¹.

The object of this work is to establish further the universality of the pseudo wet bulb temperature during the second falling rate period of hygroscopic and non-hygroscopic material (macroporous inerts, microporous inerts, and microporous wellable) drying, and the scope of this work is empirical determination of the pseudo wet bulb temperature and comparison of it with the theoretical value calculated from the equation proposed by Nissan, Bolles and

George.

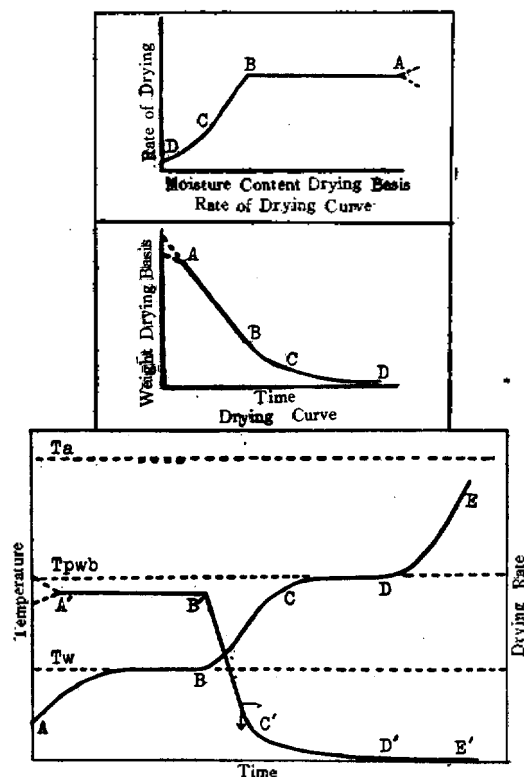


Figure 1. Generalized drying rate and drying curve

Theory

The pseudo wet bulb temperature It is not intended to rederive the equations here as they have been fully discussed by Nissan, Bolles and George, but in order that this section is self-sufficient the principal equations will be enumerated.

It has been shown experimentally that when the falling rate period proceeds and the water surface retreats the wet region maintains a constant temperature.

The balance of heat and mass transfer across the dry layer of material will now be considered in order to explain this temperature equilibrium. The limiting water surface of the wet material is considered to have proceeded well within the

bed. Since a coordinately symmetrical distribution of liquid has been assumed, the liquid surface is at a distance x from the bottom of the bed. Then the heat is transferred through the thin dry layer material dx , adjoining the liquid surface, is available to supply the latent heat of evaporation and so produce the mass transfer outward through the layer. Thus

$$q = \frac{dw}{d\theta} \lambda_{pwb} \quad (1)$$

where q is the rate of heat flow, w is the liquid content and λ_{pwb} is the latent heat of vaporization at the liquid surface.

Therefore, if one assumes the rate of evaporation to be governed by vapor diffusion

$$q = KA_m \left(\frac{dc}{dx} \right) = -(\epsilon D_{pwb}) A_m \left(\frac{dc}{dx} \right) \lambda_{pwb} \quad (2)$$

where K is the effective thermal conductivity of the dry bed, and A_m is the mean area, t and c the temperature and vapor concentration, respectively. (ϵD_{pwb}) is the appropriate vapor diffusion coefficient at the temperature of the liquid surface corrected with the void fraction of bed.

The temperature gradient across the layer and the concentration gradient are unknown but the shapes of the temperature and concentration gradients are usually similar; hence it will be assumed that,

$$\frac{\frac{dt}{dx}}{T_a - T_{pwb}} = \frac{\frac{dc}{dx}}{C_a - C_{pwb}} \quad (3)$$

where suffixes a and pwb refer to the air stream and liquid surface, and X is the a maximum depth of the bed. X should strictly include the upper boundary layer. The concentration boundary layer is not exactly same as the thermal boundary layer under all conditions, but when the layer through which diffusion takes place is

large, $(X \cdot x)$ s in the both side of equation (3) can be cancelled each other. Substituting equation (2) into equation (3), we obtain

$$(T_a - T_{pwb}) = (\epsilon D_{pwb}) \lambda_{pwb} (C_{pwb} - C_a) \quad (4)$$

From the ideal gas equation we have

$$C = \frac{MP}{RT} \quad (5)$$

Then

$$K(T_a - T_{pwb}) = 1.285 \times 10^{-3} (\epsilon D_{pwb})$$

$$\lambda_{pwb} \frac{M}{R} \left(\frac{P_{pwb}}{T_{pwb}} - \frac{P_a}{T_a} \right) \quad (6)$$

where the constant is for English units and R is the gas constant 1.98 B. T. U. / (lb-mole)(°R)

By using dimensional analysis with the variables from equation (6), the following equation was derived to give the ratio the air temperature to the pseudo wet bulb temperature as a function of three dimensional groups:

$$\frac{T_a}{T_{pwb}} = 1 + 1.285 \times 10^{-3} \left[\frac{\epsilon D_{pwb}}{K} \left(\frac{P_{pwb}}{T_{pwb}} - \frac{P_a}{T_a} \right) \right] \left[\frac{M \lambda_{pwb}}{R T_{pwb}} \right] \quad (7)$$

Using equation (7), the pseudo wet bulb temperatures were calculated for runs in which wool, terylene(British form of polyester fiber), and dry sand by trial and error technique because the right hand side of equation (7) is a complex function of the pseudo wet bulb temperature.

Experimental

In this work experimental drying were performed on a loop dryer which was consisted of the air blower, temperature controller, electrical heaters, and temperature recorder. A bed, where the material to be dried was packed in, was even with the bottom of a loop dryer. Temperature through various depths and places of

the bed and in the loop dryer were read with electrical thermocouple junction circuits, and the vaporized liquid surface and liquid in the bed weight were measured by a pan balance.

A. The loop dryer and specimen bed. The main structure of the loop dryer (Fig. 2) was constructed 8 inches by 12 inches, 21 gage galvanized steel duct covered with 1 inch asbestos insulation sheets. The detail of the specimen bed is shown in Fig. 4 and 5. The bed was constructed of $\frac{1}{4}$ inches plywood (outside) and lined with $\frac{1}{8}$ inches polyethylene plastic sheet (inside) and coated around the edge of the inside bed for waterproofing with plastic cement.

For minimizing the fluctuations of the balance itself and bed due to atmospheric air stream and down drafts, the bed and balance were enclosed in air tight case which was fitted

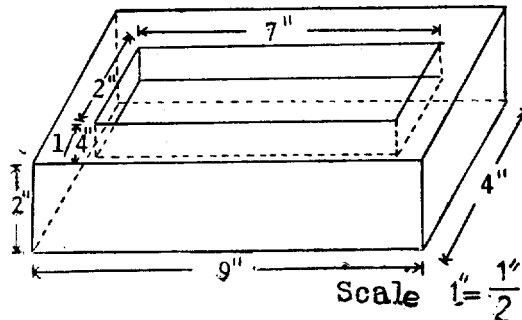


Figure 4 Sketch of experimental dry bed

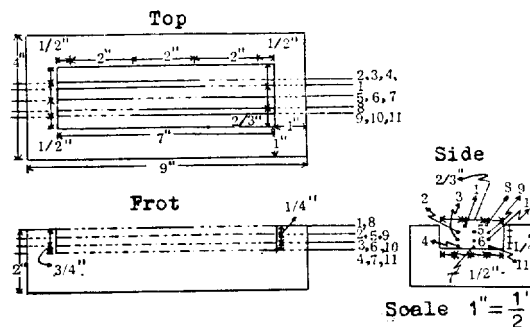


Figure 5 Thermocouple arrangement in bed

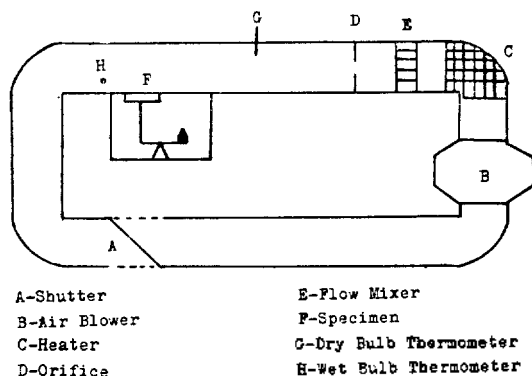


Figure 2 Sketch of experimental loop dryer

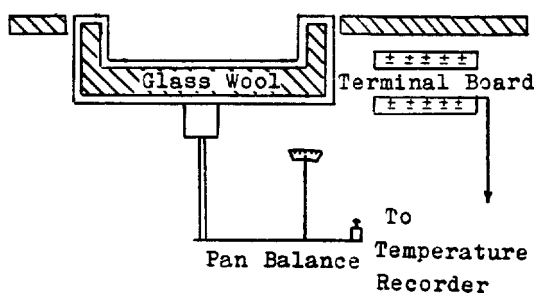


Figure 3 Sketch of specimen bed in drying

made of polyethylene plastic sheets. A movable copper arm was through into the front surface of the polyethylene plastic case to remove the weights from the pan balance at outside.

B. Thermocouple circuits. The thermocouple circuits were made with #26 B. & #S. gage ironconstantan wire and were placed in a horizontal position at four different depths and three different places throughout the bed. To determine the eleven different positions in the bed and air stream temperatures, the thermocouple circuit in the bed was arranged as shown in Fig. 7. The thermocouple wire passed through both sides of inside bed and came out from the bottom of the bed, and then connected to a terminal board which was placed on the wall of the tight plastic case. The thermocouple extension wires include one in air stream went from the terminal board to a Brown Recording potentiometer (Model No. 153×64pin-X41,

Series No. 533846).

C. **Materials.** The hygroscopic and non-hygroscopic materials which were used as a sample of drying for this experiment were macroporous inerts-sand, glass bead, microporous inerts-kaoline, microporous swellable-rice powder,

pulp. Table I shows the specific description of samples for each separate run. Water and methyl alcohol were used as liquid and the amount of liquid used (weight before drying) shows in Table II.

Table I Description of samples

Run	Name of sample	Size mash	Apparent density gm./cu. cm.	Amount used gm.	Void volume cu. cm.	Void fraction
1	Sand-A	20	2.560	142	120.5	0.685
2	Sand-B	8	2.540	285	64	0.364
3	Pulp	—	0.580	67	60.4	0.343
4	Rice-powder	28	1.525	175	61.0	0.3463
5	Kaoline-Clay	65	2.560	213.7	92.0	0.523
6	Glass bead-#10-a	48	2.651	276.0	72.0	0.41
7	Glass bead-#9	24	2.55	270.0	70.0	0.3988
8	Glass bead-#10a	48	2.651	258.0	78.6	0.445
9	Glass bead-#13	100	12.667	246.0	83.8	0.475
10	Pulp	—	0.580	50.0	89.7	0.509
11	Sand-A	20	2.560	255.0	76.5	0.435
12	Sand-B	8	2.540	262.0	73.0	0.415
13	Glass bead-#9	24	2.550	273.0	68.91	0.391
14	Glass bead-#10a	48	2.651	210.0	96.6	0.549
15	Glass bead-#13	100	2.667	249.0	82.7	0.470
16	Ksoline-Clay	65	2.560	266.0	75.6	0.430
17	Rice-powder	28	1.525	147.0	79.6	0.452
18	Pulp	—	0.58	59.4	73.8	0.420

Total volume of the bed=170 cu. cm.

Table II Description of liquids

Run	Name of liquid	Amount used gm.	Run	Name of liquid	Amount used gm.
1	water	160	10	water	180.0
2	water	61.0	11	methyl alcohol	40.5
3	water	162.5	12	methyl alcohol	40.0
4	water	60.5	13	methyl alcohol	45.0
5	water	114.0	14	methyl alcohol	49.0
6	water	68.7	15	methyl alcohol	49.0
7	water	698	16	methyl alcohol	87.0
8	water	61.0	17	methyl alcohol	47.0
9	water	56.0	18	methyl alcohol	91.0

In preparing each drying experiment, the weight of the dry sample and the wet sample was recorded step by step. When making a drying run, a enough amount of dry sample was placed in 500c.c. beaker and the liquid was sprayed over the sample untile a liquid film appeared over the surface of wet sample and the beaker was covered with a glass sheet. The covered beaker was left to stand over night so as to allow all the voids to be saturated with the liquid. The next day, the saturated sample was packed into the bed and more liquid was sprayed over the bed until the liquid film reappeared, and then the bed was covered with a sheet of polyethylene plastic. The blower, heaters and temperature recorder were turned on. After the air temperature had become constant the section of polyethylene sheet was removed, and removed weights and time were recorded.

Results

The temperature variation within the bed for 18 runs is shown in Fig. 7. The general shape of the temperature variation curve at various depths in the bed is shown in Fig. 6. In Fig. 6, region A'B' represents the heating of wet sample from room temperature to the wet bulb temperature and this region agrees with the constant rate AB; region B'C' represents (first falling rate) the rising of the temperature of the sample from wet bulb temperature to the pseudo wet bulb temperature. Equilibrium region C'D' between heat and mass transfer in the wet sample at the pseudo wet bulb temperature is represented as second falling rate and remains at this temperature untile the sample is at the equilibrium moisture constant. As the different layers of sample become dry, the temperature leaves the pseudo wet bulb and approaches the air temperature. When the

sample is dry, the temperature curves show a break with a more rapid approach to the air temperature. The pseudo wet bulb temperature for each run was calculated by using equation⁷.

The effective thermal conductivities were evaluated from the data of Bolles⁴ and Scottes,¹⁵ equation and Deissler-Dian's correlation graph. The diffusion coefficients were determined by the theoretical equation based on the kinetic theory¹⁹. The results of calculation were shown in Table III, and in Fig. 8 for the pseudo wet bulb temperature. Also the results of Nissan⁷ and Bolles⁴ were shown in the Fig. 8. In Fig. 8, the dashed line is straight line fitted by the least square method to the data. The equation of this line^(4,6) is:

$$\frac{T_a}{T_{pwb}} = 1.018 + 1.111 \times 10^{-3} \left[\frac{cD_{pwb}}{K} \left(\frac{P_{pwb}}{T_{pwb}} - \frac{P_a}{T_a} \right) \right] \left[\frac{M\lambda_{pwb}}{RT_{pwb}} \right] \quad (8)$$

For solving the pseudo wet bulb temperatures from equations (7) and (8), the trial and error method was used because the unknown temperature value appears on the both sides of the equation. However, the liquid and sample properties at air temperature helped the first trial value since the air temperature and the property values are known, and the both sides were dimensionless. The ratio of air temperature to

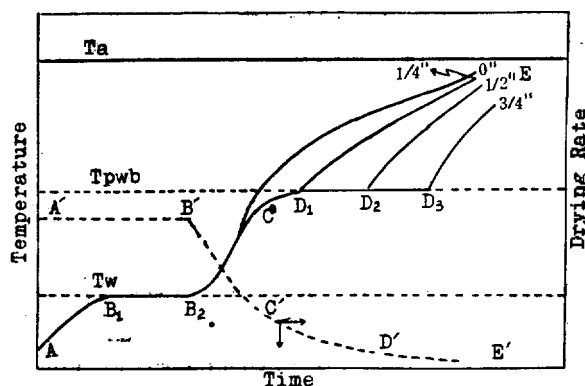


Figure 6 Generalized temperature variation

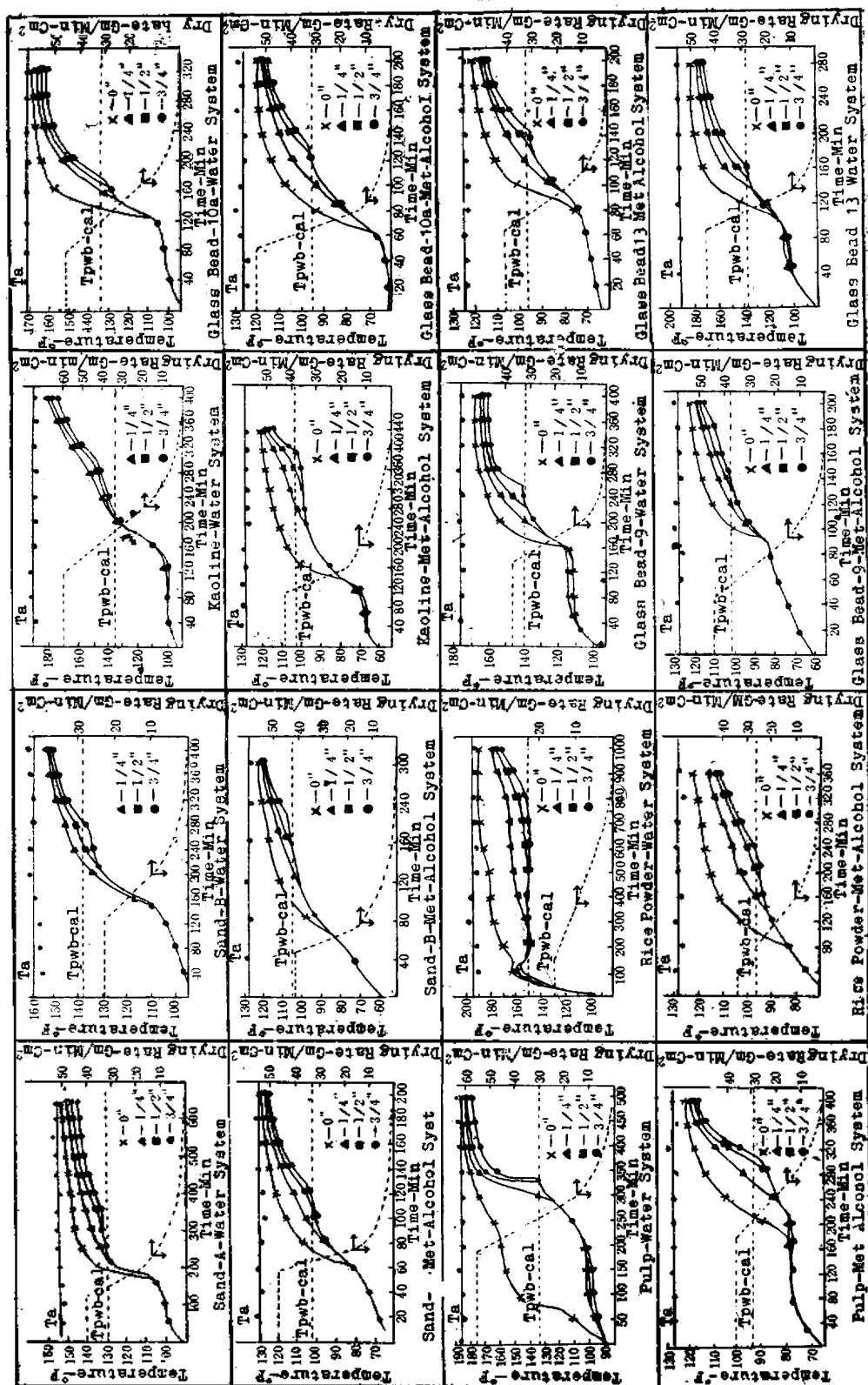


Table III The results of calculation for the resudo wet bulb temperature

Run	T_a	P_a/T_a	Flow rate	D_{pwb}	K	T_{pwb}
1	155	0.118	250	1.20	0.16	130.0
2	159	0.094	250	1.23	0.14	138.6
3	185	0.1183	265	1.21	0.043	133.3
4	193	0.138	265	1.267	0.081	148.5
5	191	0.126	265	1.22	0.06025	136.0
6	172	0.116	200	1.215	0.0813	134.7
7	175	0.130	200	1.236	0.0875	139.95
8	176	0.130	200	1.210	0.0175	134.5
9	191	0.1435	200	1.217	0.0655	138.0
10	147	0.118	140	1.120	0.0352	109.8
11	127	0.398	86	0.523	0.0940	105.8
12	127	0.356	86	0.522	0.0985	105.5
13	127	0.466	86	0.517	0.0705	102.6
14	127	0.3858	86	0.500	0.0486	94.0
15	126	0.370	86	0.506	0.0567	97.0
16	128	0.356	86	0.5173	0.0764	103.0
17	128.5	0.371	86	0.506	0.0534	97.0
18	127	0.396	86	0.496	0.0406	95.3

Flow rate dimension: ft./min.

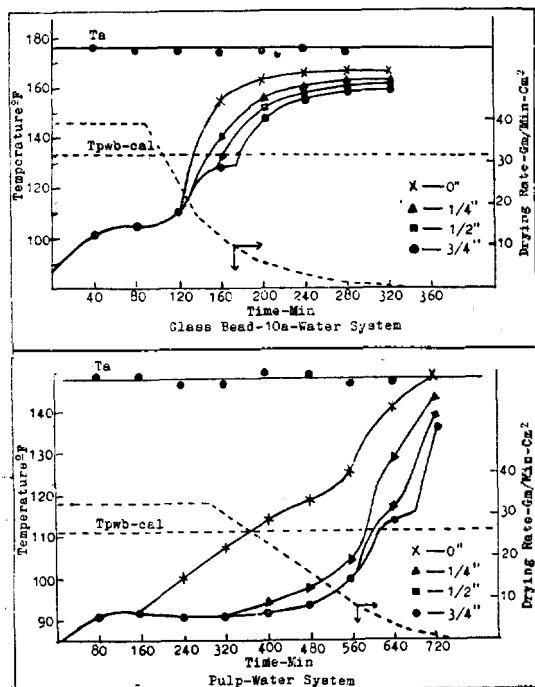


Figure 7 Temperature variation in bed

the pseudo wet bulb temperature was shown in Fig. 9.

Discussion of Results

Fig. 7 show temperature measured by thermocouples at various depths in the bed as a function of time for water-solid and methyl alcohol-solid systems. The temperature profile measured by the upper one or two thermocouples (positioned surface and 1/4 inch depth) remained at the wet bulb temperature during the constant rate period and increased to the air temperature during the falling rate period. The temperatures measured by the lower two or three thermocouples (1/4", 1/2", and 3/4" depth) also started at the wet bulb temperature. These temperatures, however, were found to increase and reach a temporary equilibrium at the pseudo

wet bulb temperature. Possibly due to the difficulty of absorbed liquid homogeneous distribution in the bed and air penetration the liquid surface recedes them before the new equilibrium conditions are established or maintain with the conditions for a moment. These period of equilibrium were found to range between twenty and eighty minutes. At the end of the equilibrium period the temperatures were found to be raised to the air temperature. This rise was due to the fact that the interface had receded beyond the thermocouple.

The reason why the upper one or two thermocouples did not attain equilibrium at the pseudo wet bulb temperature was the interface passed them before the start of the second falling rate period.

The lower two or three thermocouples, however, were sufficiently deep to facilitate the establishment of an equilibrium between mass diffusing outward through an increasing depth of dry sample and heat transfer into the bed by conduction. Thus the tendency was to attain the pseudo wet bulb temperature before the liquid surface passed through them.

The pseudo wet bulb temperature was calculated from the consideration of the heat transfer to, and vapor diffusion from, liquid evaporating at the water or methyl alcohol boundaries. Difficulties were encountered in the evaluation of the term involving the pressure to temperature ratio in the pseudo wet bulb temperature equation. This was due to the extreme sensitivity of this ratio to small temperature variations.

Calculations show that the experimental determinations of the pseudo wet bulb temperature agree with the theoretical equation within 0 to 3.9 degrees *F.* for all experimental systems. Table IV presents a comparison between the theoretical and experimental results. The differences of 0 to 3.9 degrees *F.* are believed to be due to calculation and experimental error.

Conclusion

When wet materials are drying, the rate of evaporation falls off as heat and liquid vapor

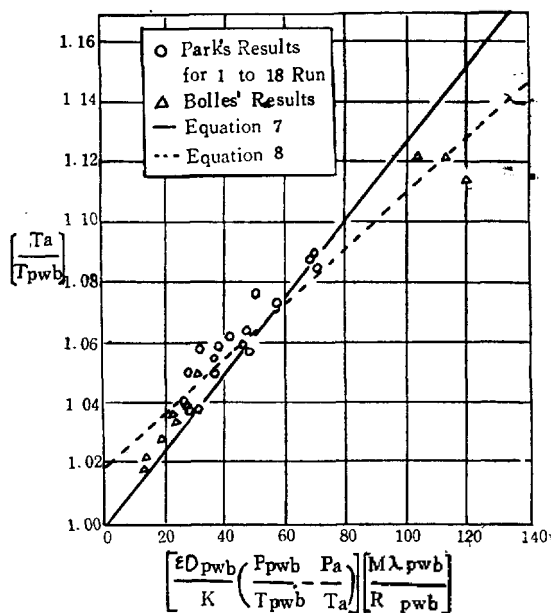


Figure 8 Pseudo wet bulb temperature as function of dimensionless groups

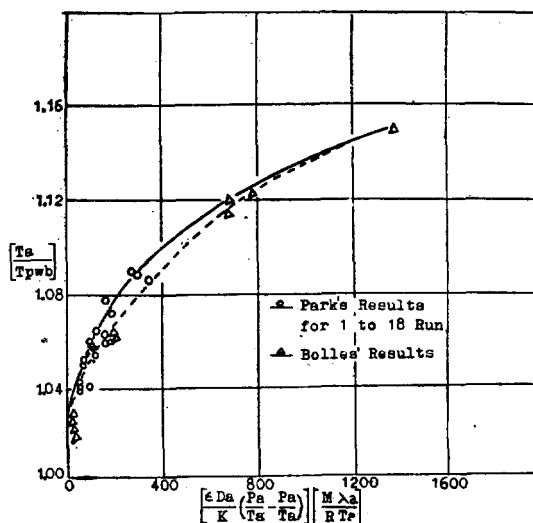


Figure 9 Pseudo wet bulb temperature as function of air temperature

Table IV Comparison of the Results

Run	Sample	Liquid	T_a	T_{pwb} (Exp)	T_{pwb} (Cal)	Difference of Results
1	Sand-A	water	155.0	132.0	130.0	-2.0
2	Sand-B	water	159.0	135.5	138.6	+3.1
3	Pulp	water	185.0	132.1	133.3	+1.2
4	Rice-powder	water	193.0	148.3	148.5	+0.2
5	Kaoline	water	191.0	139.6	136.0	-3.6
6	G. bead 10a	water	172.0	134.0	134.7	+0.7
7	G. bead 9	water	175.0	140.4	139.9	-0.45
8	G. bead 10a	water	176.0	130.6	134.5	+3.9
9	G. bead 13	water	191.0	138.0	138.0	0.00
10	Pulp	water	147.0	118.7	109.8	-3.9
11	sand-A	methyl alcohol	127.0	103.2	105.8	+3.6
12	Sand-B	methyl alcohol	127.0	105.5	105.5	0.0
13	G. bead 9	methyl alcohol	127.0	99.5	102.6	+3.1
14	G. bead 10a	methyl alcohol	127.0		94.0	-0.3
15	G. bead 13	methyl alcohol	126.0	95.5	97.0	+1.5
16	Kaoline	methyl alcohol	128.0	100.0	103.0	+3.0
17	Rice-powder	methyl alcohol	128.6	95.7	97.0	+1.3
18	Pulp	methyl alcohol	127.0	92.3	95.3	+3.0

The temperature unit is in degree F.

have to pass through an increasing layer of dry material left by receding liquid surface. While this is occurring, a temperature equilibrium is maintained within the wet portion and this temperature, so called "Pseudo Wet Bulb Temperature", appears to be well established.

With the combined results of this work and that of Nissan, Bolles and George, a pseudo wet bulb temperature during the second falling rate period has been shown to be established in the drying of microporous, macroporous and microporous swellable materials.

K	Effective thermal conductivity	B. T. U. /hr-ft ² -F.
M	Molecular weight	lb. /mole
P	Vapor pressure at surface temperature	m. m. Hg lb. /ft ² .
P	Partial pressure of vapor in air	m. m. Hg lb. /ft ² .
q	Rate of heat flow	B. T. U. /hr.
R	Universal gas constant	B. T. U. /lb-mole ^o R
T	Temperature	°R., °K.
X	Depth of bed	cm., ft.
W	Weight of liquid content	gm., lb.

Nomenclature

A_m	Mean area	ft. ²
C	Concentration of vapor	lb. /ft. ³
C_a	Concentration of vapor in air	lb. /ft. ³
C_{pwb}	Concentration of vapor at evaporation surface.	lb. /ft. ³
D	Volumetric diffusion coefficient	cm. ² /hr. ft. ² /hr.

Greek

ϵ	void fraction	
θ	Time	hr.
λ	Latent heat of vaporization	B. T. U. /lb.

Subscripts

a	property evaluated at air temperature
pwb	property evaluated at the pseudo wet bulb

temperature in English unit.

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