PRODUCTION OF UNIFORM
CONDENSATION FROM SATURATED AIR
FLOW IN COOLED POROUS MEDIA

by

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DEFINITION OF SYMBOLS

A = Total cross sectional area of test section, ft^2.

B = Heat of wetting of soil, btu/ft^3.

C = Velocity of fluid based on entire area, A, ft/hr.

$G = \rho_m C$, mass flow rate of mixture, lb/ft^2-hr.

$G_a = \rho_a C$, mass flow rate of air, lb/ft^2-hr.

$G_v = \rho_v C$, mass flow rate of vapor, lb/ft^2-hr.

K = Thermal conductivity of porous medium, btu/ft-hr-^oF.

K_e = Mean effective thermal conductivity of porous bed, btu/ft-hr-^oF. $K_{e\ particles}$ = Mean effective thermal conductivity of compacted bed of particles only. $K_{e\ pins}$ = Mean effective thermal conductivity of metal pins embedded in the porous medium.

L = Length of test bed in the direction of fluid flow, ft.

M_a = Molecular weight of air.

M_w = Molecular weight of water.

P_a = Pressure of the air, psia.

P_v = Pressure of the water vapor, psia.

S = Specific surface area of porous bed, ft^2/ft^3.

T_g = Temperature of the fluid stream, ^oF.

$$a = \frac{jS}{G_a c_{pm}}$$

$$b = \frac{jS}{K_e}$$

c_{pa} = Mean specific heat of air, btu/lb-^oF.

c_{pv} = Mean specific heat of vapor, btu/lb-°F.

$\bar{c}_{pm}$ = Mean specific heat of air and water vapor mixture, btu/lb-°F.

h_f = Enthalpy of water liquid, btu/lb.

h_g = Enthalpy of water vapor, btu/lb.

h_{fg} = Enthalpy of condensation of water, btu/lb.

h_m = Enthalpy of air-water vapor mixture, btu/lb.

j = Convection heat transfer coefficient, btu/ft²-hr-°F.

t_s = Temperature of porous medium, °F.

u_f = Internal energy of water liquid, btu/lb.

u = Internal energy of porous medium and liquid, btu/lb.

$w = \frac{\rho_v}{\rho_a}$, specific humidity, lb_v/lb_a.

$\dot{w}_c$ = Condensation rate per unit of time per unit of volume, lb/ft³-hr.

$\dot{w}_R$ = Moisture removal rate of a plant, lb/ft³-hr.

x = Distance along the path of flow in porous bed, ft.

$$\gamma = -\frac{\dot{w}_c \, \bar{h}_{fg}}{G_a \, c_{pm}} = \frac{\Delta w \, \bar{h}_{fg}}{L \, c_{pm}}$$

ρ = Density of porous medium including condensate.

ρ_a = Density of air.

ρ_f = Density of water as a liquid.

ρ_v = Density of water vapor.

ρ_m = Density of air-water vapor mixture.

θ = Time, hrs.

PRODUCTION OF UNIFORM CONDENSATION FROM SATURATED AIR FLOW IN COOLED POROUS MEDIA

INTRODUCTION

This is a study of heat and mass transfer from a saturated water vapor-air mixture flowing through a cooled porous medium to the particles of this medium. A method for predicting the conditions required for achieving uniform condensation in a given porous medium is developed, and experimental verification of the theory is presented.

The primary purpose of the testing program is to develop methods which will deposit moisture uniformly throughout a porous bed from a saturated water vapor-air mixture flowing through the bed. The secondary purpose of these tests is to investigate the possibility of increasing the uniform condensation rates within the porous medium by increasing the effective thermal conductivity of the bed.

During the fluid flow through the porous bed, heat is transferred from the fluid to the particles of the bed because of a temperature difference between the fluid and the porous material. This heat is then transferred through these particles to a heat sink at the flow outlet end of the bed because of a temperature gradient in the bed. If the fluid stream contains saturated water vapor, some of this vapor will condense on the particles of the bed as it is cooled during its flow through the porous medium. It is assumed that some of this liquid may be adsorbed by the surface of these particles, if the material is hydroscopic, and the remaining moisture will be deposited as a liquid film around each particle in the bed (2, p. 34-43).

A uniform condensation process requires that the liquid which is condensed be uniformly deposited throughout the porous medium. To produce this condition, a particular distribution of dewpoint temperatures and their corresponding saturation pressures must be maintained within the porous system so that an equal amount of liquid will be condensed from the saturated vapor-air stream at each point along its flow path.

The governing conditions used in this study were chosen to correspond to the limitations imposed by the physiological characteristics of several plants that might be grown in such a porous medium and irrigated with this uniform condensation process. These conditions include a maximum moisture content of 10 per cent by weight-dry, temperature limits of from 55° to 85° F; and a condensation rate sufficient to supply a plant's needs of at least 2 grams per hour (4, p. 4-10).

The first published work concerning the use of an air stream saturated with water vapor as a supply for a vapor irrigation process was the Ph.D thesis of John Wolfe (20, p. 1-4). In his thesis, Wolfe tried to develop and maintain uniform moisture content of the soil in which a plant was growing. The moisture was added to the soil by condensing water from a cooled, saturated water vapor-air mixture flowing through the pore space in the soil. To cool the soil bed, Wolfe used five horizontal grills equally spaced along the flow path in a column of soil, 4 inches deep by 3 inches square. The air-water vapor mixture was passed vertically up through the soil. In his analysis, Wolfe used a required temperature distribution based on an overall linear pressure distribution and a constant rate of change of specific humidity with distance along the flow path. He assumed that a linear temperature distribution between each grill would be a satisfactory approximation to the required temperatures for uniform condensation. Wolfe measured the moisture content at the end of a test by weighing samples of the soil. The best distribution of moisture content reported was from a maximum of 2.85 per cent to a minimum of 1.63 per cent over the length of the soil column. Wolfe indicated that the main factors which affect the uniformity of the moisture distribution are the compaction of the soil, the fluctuations in the temperature of the grills and the air-vapor stream, and the moisture extraction pattern of the plant.

The porous materials used in the present study are: fine spherical glass beads; chromium powder; and a sandy soil of the same type as was used by Wolfe.

Chen (3, p. 1-51) used the equipment and procedure developed by Wolfe to irrigate a sunflower plant growing in a sandy soil. His experimental results indicated that the transpiration rate of this plant decreased with increasing soil moisture tension. The distribution of the moisture content for the soil bed at the end of the test ranged from 1.9 to 4.3 per cent over the length of the bed. Chen did not consider that the moisture distribution achieved during his work was satisfactory for a condition of uniform moisture.

A discussion of how moisture is removed by a plant and what the desirable conditions for this process should be are presented by Chen in his study of moisture tension (3, p. 1-4).

The work of Shen (18), a general solution to the problem of saturated water vapor-air flow through porous media, is being prepared concurrently with this study.

THEORETICAL ANALYSIS

The system to be analyzed consists of particulate matter compacted into a bed with condensed liquid and a mixture of air and saturated water vapor filling the pore spaces. The bed is contained within an insulated circular cylinder and is fixed in place at the flow inlet and outlet faces by fine mesh wire screens. In the analysis, the flow will be considered one dimensional in the direction of the cylindrical axis. The bed is assumed to have a uniform porosity and it is assumed that there is no variation in the properties of the fluid in a plane normal to the direction of the flow. The flow of the fluid through the pore volume of the bed will be assumed laminar (13, p. 64-65).

The thermodynamics of the system may be stated in terms of the energy equation for a flow system. The fluids, air and water vapor, will be described by the equation of state of a perfect gas (12, p. 23-24).

For purposes of analysis a control volume will be considered which is composed of two parts within a parallelepiped of dimensions Δx, Δy, Δz. The first part of the control volume will consist of the pore volume which contains the air and water vapor. If the porosity, f, is defined as the ratio of the pore volume to the total volume of the system, then the volume of the gas-vapor part of the control volume will be $f\Delta x\,\Delta y\,\Delta z$. The second part of the control volume will consist of the solid particles and the condensed liquid, and will occupy a volume of $(1-f)\Delta x\Delta y\Delta z$.

The principle of the conservation of mass, as applied to the gas in the control volume, requires that

$$\left[\rho_m C + \frac{\partial}{\partial x}(\rho_m C)\Delta x\right]\Delta y\Delta z_{\text{out}} - \rho_m C\Delta y\Delta z_{\text{in}} + \dot{w}_c\Delta x\Delta y\Delta z$$

$$= -\frac{\partial}{\partial\theta}(f\rho_m)\Delta x\Delta y\Delta z_{\text{control volume}}.$$

Upon cancelling equal terms and dividing by $\Delta x\Delta y\Delta z$ this becomes

$$\frac{\partial}{\partial x}(\rho_m C) + \dot{w}_c = -\frac{\partial}{\partial\theta}(f\rho_m), \qquad (1)$$

where the term $\dot{w}_c$ represents the rate at which vapor is condensing per unit of volume.

Since the flow is a mixture of air and water vapor, equation 1 can be written as

$$\frac{\partial}{\partial x}(\rho_a C + \rho_v C) + w_c = -\frac{\partial}{\partial\theta}(f\rho_m). \qquad (2)$$

If $\rho_a C = G_a$ and $\rho_v C = G_v$ are substituted in equation 2 and a condition of steady flow with small fluctuations is considered, then the terms $-\frac{\partial}{\partial\theta}(f\rho_m)$ and $\frac{\partial}{\partial x}(\rho_a C)$ will be negligible, and $-\dot{w}_c = \frac{d}{dx}G_v$. (3)

The theory of psychrometry defines the specific humidity, w, as the ratio of the density of the water vapor to the density of the air in a given volume of the mixture. For an ideal gas, w may be stated in terms of the molecular weights and partial pressure of the gases in the system (12, p. 371) as

$$w = \frac{\rho_v}{\rho_a} = \frac{M_v}{M_a}\frac{P_v}{P_a} = 0.622\frac{P_v}{P_a}.$$

Using the above relations equation 3 becomes

$$-\dot{w}_c = \frac{d}{dx}\left(G_a\frac{\rho_v}{\rho_a}\right) = G_a\frac{dw}{dx} = 0.622\,G\frac{d}{dx}\left(\frac{P_v}{P_a}\right) \tag{4}$$

The production of uniform condensation requires that $\frac{dw}{dx}$ be a constant. Integration of equation 4 over the length of flow, L, between the inlet and outlet yields,

$$-\dot{w}_c = \frac{G_a(w_{in} - w_{out})}{L}.$$

wrong (+)

The continuity equation for the solid-liquid part of the control volume involves only the transfer of the condensate. If the rate of water removal by a plant is $\dot{w}_R\,\Delta x\Delta y\Delta z$, the conservation of mass for the solid-liquid control volume requires that

$$\dot{w}_R\Delta x\Delta y\Delta z - \dot{w}_c\Delta x\Delta y\Delta z = -\Delta x\Delta y\Delta z\,\frac{d}{de}(1-f)\rho$$

and upon dividing by $\Delta x\Delta y\Delta z$ is

$$\dot{w}_R - \dot{w}_c = -\frac{d}{de}(1-f)\rho. \tag{6}$$

An accounting of the energy transfer rates for the air-vapor part of the control volume of figure (1) is

$$\left[G\, h_m + \frac{\partial}{\partial x}(G\, h_m)\Delta x\right]\Delta y \Delta z + jS(T_g - t_s)\Delta x \Delta y \Delta z + \dot{w}_c h_f \Delta x \Delta y \Delta z$$

$$-G\, h_m \Delta x \Delta y \Delta z = -\frac{\partial}{\partial \theta}(f\rho_m u_m)\Delta x \Delta y \Delta z. \qquad (7)$$

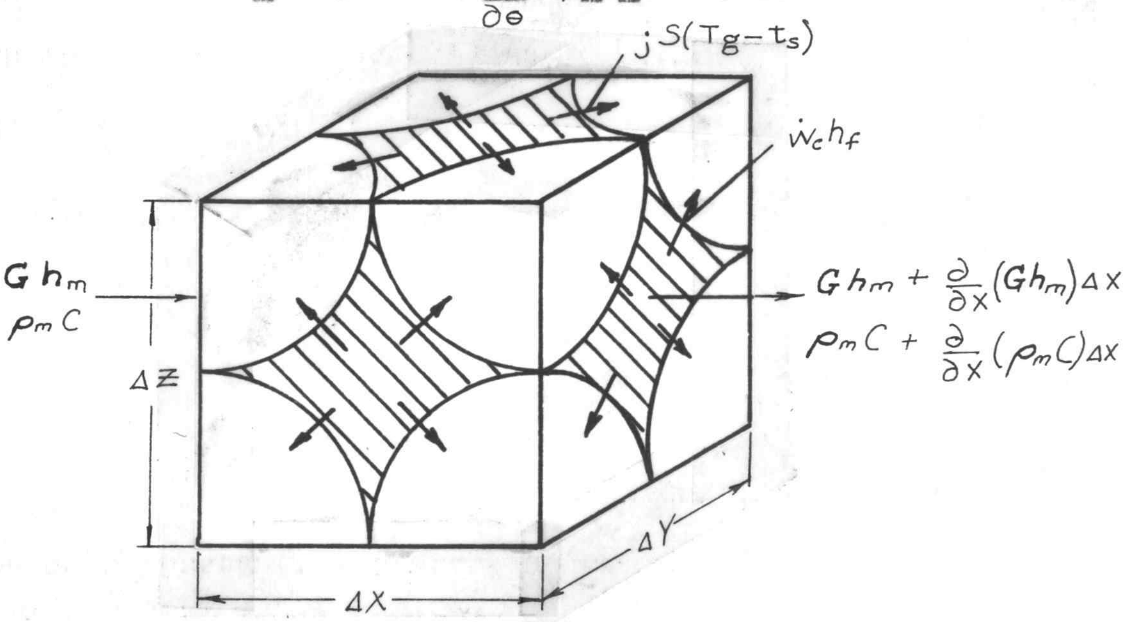

Figure 1 Air vapor control volume

Cancelling equal terms and dividing by the volume $\Delta x \Delta y \Delta z$ yields

$$\frac{\partial}{\partial x}(Gh_m) + jS(T_g - t_s) + \dot{w}_c h_f = -\frac{\partial}{\partial \theta}(f\rho_m u_f). \qquad (8)$$

The first term in equation 8 is the net rate of change of enthalpy of the fluid stream between the inlet and outlet control surfaces of the control volume. The second term is the convection heat transfer rate to the solid-liquid part of the control volume. The letter j is the convection heat transfer film coefficient; S is the surface area between the two parts of the control volume per unit of volume;

and T_g and t_s are the temperatures of the gas and solid parts of the control volume respectively. The term $\dot{w}_c h_f$ is the enthalpy of the condensed liquid leaving the air-vapor part of the control volume per unit of volume. In the case of steady flow or of small changes in the properties of the fluid, the time rate of change of internal energy within the air-vapor control volume will be negligible.

Further simplification of equation 8 results from expanding the first term,

$$\frac{d}{dx}(Gh_m) = G_a\bar{C}_{pa}\frac{dT_g}{dx} + G_v\bar{C}_{pv}\frac{dT_g}{dx} + \bar{h}_g\frac{dG_v}{dx}$$

$$= G_a(\bar{C}_{pa} + \bar{w}\,\bar{C}_{pv})\frac{dT_g}{dx} - h_g\dot{w}_c$$

$$= G_a\bar{C}_{pm}\frac{dT_g}{dx} - \bar{h}_g\dot{w}_c \tag{9}$$

where the specific heat, $\bar{C}_p$, specific humidity, $\bar{w}$, and specific enthalpy of the vapor, $\bar{h}_g$, will be considered as constant mean values for the process. Substituting the relation of equation 9 into equation 8 and combining the terms $(\bar{h}_f - \bar{h}_g)\dot{w}_c = -\bar{h}_{fg}\,\dot{w}_c$ yields

$$G_a\bar{C}_{pm}\frac{dT_g}{dx} + jS(Tg - t_s) - \bar{h}_{fg}\,\dot{w}_c = 0. \tag{10}$$

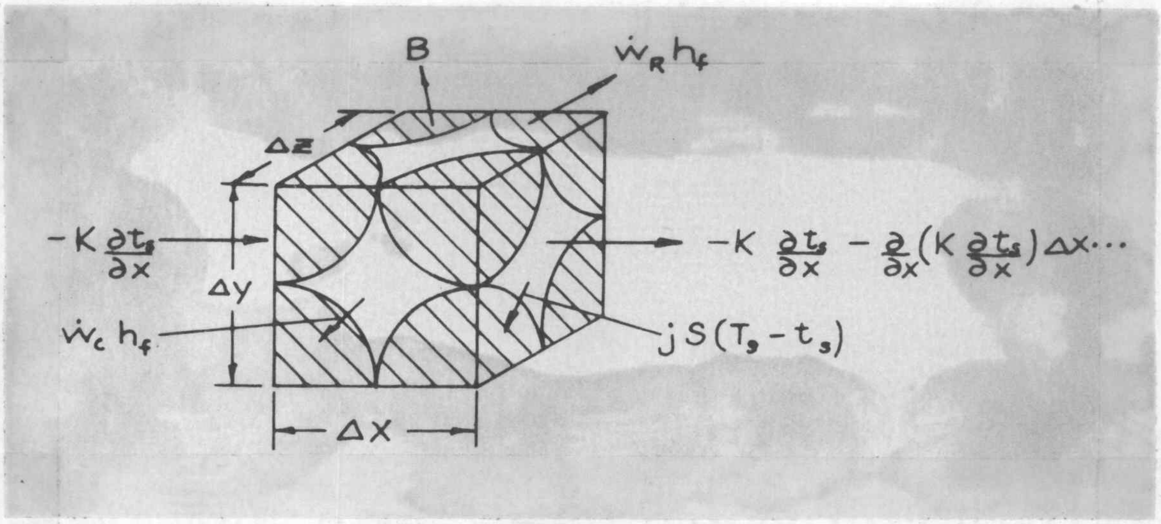

Figure 2 Solid liquid control volume.

An accounting of the energy rates for the solid-liquid control volume of figure 2 is

$$\left[K \frac{\partial t_s}{\partial x} + \frac{\partial}{\partial x}\left(K \frac{\partial t_s}{\partial x}\right)\Delta x\right] \Delta y \Delta z - K \frac{\partial t_s}{\partial x} \Delta y \Delta z + jS(T_g - t_s)\Delta x \Delta y \Delta z$$

$$+ B \Delta x \Delta y \Delta z + \dot{w}_c h_f \Delta x \Delta y \Delta z - \dot{w}_R h_f \Delta x \Delta y \Delta z = \Delta x \Delta y \Delta z \frac{\partial}{\partial \theta}\left[(1-f)\rho u_f\right]. \tag{11}$$

The term $\dot{w}_R h_f$ represents the energy removed by a plant as it consumes water. $B \Delta x \Delta y \Delta z$ is the energy released in the adsorption of liquid by porous particles (2, p. 40-45). This "heat of wetting" term will be considered negligible since it is very small for materials such as sandy soils, glass beads, and powdered chromium.

If the temperatures within the bed are maintained constant during the uniform condensation process, the internal energy of the liquid in equation 11 is not a function of time and can be expanded, by using equation 6, as $\frac{d}{d\theta}\left[(1-f)\ \bar{u}_f\right] = -(\dot{w}_R - \dot{w}_c)\bar{u}_f$.

Simplifying equation 11, replacing K by K_e, the mean effective thermal conductivity of the bed, and substituting the preceding relations yields

$$K_e\frac{d^2t_s}{dx^2} + jS(T_g - t_s)+(\dot{w}_c - \dot{w}_R)\bar{h}_f = (\dot{w}_c - \dot{w}_R)\bar{u}_f. \quad (12)$$

Equation 12 can be simplified by assuming that the enthalpy of the liquid, $\bar{h}_f$, is equal to the internal energy, $\bar{u}_f$, to yield

$$K_e\ \frac{d^2t_s}{dx^2} + jS(T_g - t_s) = 0. \quad (13)$$

The preceding analysis of the uniform condensation process has considered that either a steady state condition exists for which there are no time variations in the properties of the system, or a quasi-steady state condition exists for which there is either a slow change in the properties of the system with time or a negligible change. The significant difference between the two conditions is that the relatively small increase in the moisture content of the porous bed with time for the quasi-steady state causes the thermal conductivity of the bed to increase (3, p. 375), while the thermal conductivity of the bed for the steady state condition is constant. To maintain an energy balance for the quasi-steady state condition, it will be shown that the mass flow rate of the fluid must be increased by an amount corresponding to the increase in the thermal conductivity of the bed. Equations 10 and 13, which are formulations of the energy transfer rates within the bed, are presented in terms of total derivatives. This implies that the variables do not change with time. These equations represent the steady state condition, in which a plant is assumed to be removing water at the same rate as it is condensed from the vapor. These same equations can also represent a quasi-steady state condition in which the process is carried out without a plant if the thermal conductivity, K_e, of the bed and the convection heat transfer coefficient j are considered functions of moisture content and time.

The substitution of the relations

$\frac{G_a(W_{in} - W_{out})}{L}$

$a = \frac{jS}{G_a\bar{C}_{pm}}$, $b = \frac{jS}{K_e}$, $\gamma = -\frac{\dot{w}_c\bar{h}_{fg}}{G_a\bar{C}_{pm}}$, where a, b, and γ

are assumed constants, into equations 10 and 13 yields

$$\frac{dT_g}{dx} + a(T_g - t_s) + \gamma = 0, \tag{14}$$

$$\frac{d^2t_s}{dx^2} + b(T_g - t_s) = 0. \tag{15}$$

Combining equations 14 and 15 in terms of T_g yields

$$\frac{d^3T_g}{dx^3} + a\frac{d^2T_g}{dx^2} - b\frac{dT_g}{dx} = b\gamma \tag{16}$$

The solution of this nonhomogeneous linear differential equation is found by the use of operators. The general solution for T_g is the sum of the complimentary function, T_{gc}, and the particular integral, T_{gp}.

Integrating equation 16 yields

$(D^2 + aD - b)\, T_g = b\gamma x + C_3$ which has a solution of the form

$T_{gc} = C_1 e^{m_1 x} + C_2\, e^{m_2 x}$ for the complimentary function

where

$$m_1 = \frac{-a - \sqrt{a^2 + 4b}}{2}, \text{ and } m_2 = \frac{-a + \sqrt{a^2 + 4b}}{2} \qquad (17)$$

$T_{gp} = -\gamma x - \frac{a\gamma}{b} - \frac{C_3}{b}$ for the particular integral.

$T_g = T_{gc} + T_{gp}$

$$T_g = C_1\, e^{m_1 x} + C_2\, e^{m_2 x} - \gamma x - \frac{a\gamma}{b} - \frac{C_3}{b} \qquad (18)$$

The following assumptions are made to establish boundary conditions for the evaluation of the constants C_1, C_2, and C_3 in equation 18. At the flow inlet to the bed, the temperature of the fluid, T_g, and the temperature of the bed, t_s, are constant but not the same value. At the flow outlet end of the bed the temperature of the fluid is a constant and is equal to the temperature of the bed.

The general solution to equation 18, which satisfies both the steady state and the quasi-steady conditions for uniform condensation, with the constants evaluated, is

$$T_x = T_{in} - (T_{in} - T_{out} + \gamma L) \frac{1-e^{m_2 x}}{1-e^{m_2 L}} + \gamma x. \qquad (19)$$

For a given uniform condensation process, the constant γ can be evaluated by determining w_c from equation 5.

To maintain constant uniform condensation within a porous bed, m_2 must remain constant. The evaluation of m_2 for a particular process in which the mass flow rate G_a and the condensation rate w_c are known, requires a knowledge of the specific surface area, S, the heat transfer coefficient, j, and the mean specific heat c_{pm}.

An accurate determination of the surface area of granular and powdered materials is a very complicated process. This calculation requires a knowledge of the number of particles and their size and shape distribution. A discussion of the effects of particle size and shape on the surface area may be found in reference (2, p. 10-18). Spherical materials such as 3-M "superbrite" glass beads, of a controlled size will provide surface areas of a smaller uncertainty than will soils, if the bulk density or compaction of the bed is maintained at a known constant.

The calculation of the convection heat transfer coefficient, j, depends upon a knowledge of the effects of the saturated air mixture and the condensing process. The data of heat transfer coefficients available at the present time are for dry air flow in packed porous materials (4, p. 57-63) and for the evaporation of water from packed porous materials (5, p. 1003-1006) and (22, p. 445-451). These data, however, were determined at Reynolds numbers above 5.0 while the present study is concerned with Reynolds numbers less than 0.5. Coppage and London correlate their results with those of others for values of the heat transfer coefficient from dry air flowing over wire screens, or over spherical packings at Reynolds numbers from 5 to 50,000. Evaporation heat transfer studies for flow through porous beds were presented by DeAletis and Thodos and Wilke and Hougen for Reynolds numbers above 13. No known work has been published for heat transfer coefficients between saturated air with condensation and small particles in packed porous beds.

Equation 17 defines m_2 as

$$m_2 = -\frac{a}{2} + \frac{\sqrt{a^2 + 4b}}{2}$$

If m_2 is represented by its binomial expansion as

$$m_2 = -\frac{a}{2} + \left(\frac{a}{2} + \frac{b}{a} - \frac{b^2}{a^3} + \frac{b^3}{2a^5} - \cdots\cdot\right), \tag{20}$$

and if all but the first three terms are neglected, then the result is a simple but useful approximation for m_2. Substitution of the values for "a" and "b" into this approximation yields

$$m_2 \simeq \frac{b}{a} = \frac{G_a C_{pm}}{K_e} \text{ .} \qquad (21)$$

The present study uses equation 21 to approximate the value of m_2 because its definition by equation 17 requires that the convection heat transfer coefficient for uniform condensation and the surface area of the porous bed be evaluated, while this is not necessary in using equation 21. The error introduced in approximating m_2 by equation 21 as compared to its evaluation by equation 17 for the conditions of this study is less than 0.1 per cent.

In equation 21, m_2 and c_{pm} are constants for a uniform condensation process, therefore the ratio $\frac{G_a}{K_e}$ must also be constant. For the quasi-steady state process with which this paper is concerned, equation 21 requires that the mass flow rate, G_a, be controlled so that the ratio $\frac{G_a}{K_e}$ will remain a constant for any changes in the effective thermal conductivity of the bed.

Equation 19 represents the physical relationship between the properties of a porous system in which liquid is being condensed uniformly from a saturated vapor-air stream. In order that this relation be applied to a specific uniform condensation process, the following data must be determined:

1. The inlet and outlet fluid stream temperatures and pressures;

2. The required dewpoint temperature distribution;

3. The effective thermal conductivity of the porous bed as a function of moisture content;

4. The mass flow rate required for a uniform condensation process as a function of the thermal conductivity of the porous bed.

In determining the required dewpoint temperature distribution, a linear pressure gradient is assumed for the particular mass flow rate required for uniform condensation. The calculation of these required dewpoint temperatures also utilizes equations 4 and 5, the boundary conditions of temperature for the fluid at the inlet and outlet of the bed, and the steam tables.

Harrison E. Patten of the U. S. Bureau of Soils performed the first significant experiments studying the effect of moisture content on the thermal conductivity and thermal diffusivity of soils (14, p. 36-40). Figure 3 shows some of Patten's results for quartz sands. This is a graph of per cent thermal conductivity of a dry porous bed vs. per cent moisture content by weight-dry. The experimental results of Shaw and Baver on the use of heat flow as a measure of soil moisture indicates that all soils show the same tendencies with respect to the change in thermal conductivity with moisture (16, p. 886-891). It can be noted from figure 3 that the effective thermal conductivity of the bed increases with moisture content and that the greatest change in thermal conductivity occurs at the lower moisture contents. This relation between the thermal conductivity and the moisture content of sands and soils as porous beds was verified in the work of Robins (15, p. 127-130). Since the moisture content of a porous bed is described in figure 3 on a weight basis for quartz sands, a correction must be applied to account for the difference in specific gravities between other materials and the quartz sand. In order to use figure 3 to determine the change in the thermal conductivity of a specific porous bed with moisture content, the per cent moisture content of the test bed must be corrected to correspond to an equivalent per cent moisture content for a quartz sand bed as follows; the equivalent per cent moisture content of quartz sand bed equals

$$\frac{(\text{specific gravity of test bed})(\text{per cent moisture content of test bed})}{(1.6,\ \text{the average specific gravity of quartz sand bed})}. \qquad (22)$$

This correction is made on the basis that for small particle sizes (0.008 to 0.002 inches) the amount of water in a unit volume of a porous bed is the significant factor

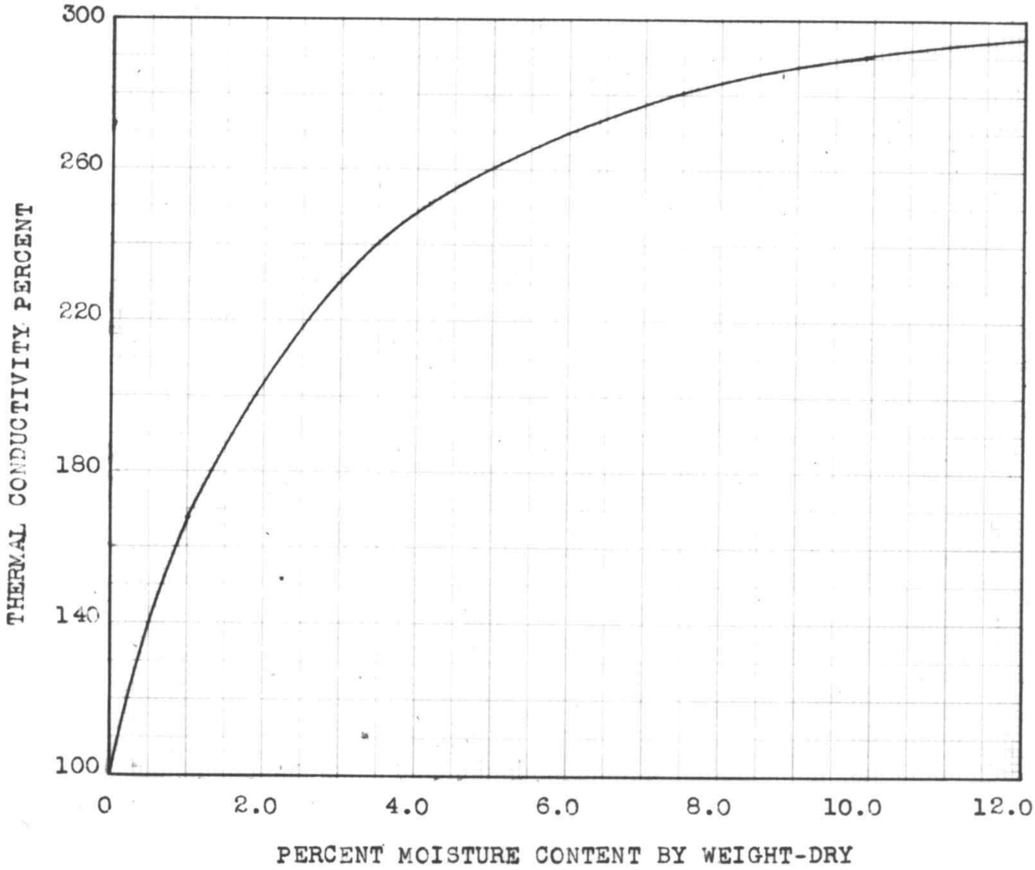

Figure 3. Percent of dry thermal conductivity of packed beds of quartz sands with increasing moisture content. Patten (1909). Average specific gravity of quartz sand bed is 1.6.

and not the percentage of water by weight. The assumption is made that all of the moisture condensed on the materials considered will be deposited as a film about each particle and will form a fillet at the points of contact between the particles. It is further assumed that the increase in thermal conductivity occurs because of an increase in the area of contact between the particles of the bed as water is added to the bed.

The condensation rate for a uniform condensation process, with specific conditions of temperature and pressure in a given porous bed, is fixed by the required mass flow rate, G_a, as given by equation 21.

If the uniform condensation rate could be increased above the values obtained by Chen and Wolfe, then the equipment could be made more useful. Greater uniform condensation rates could irrigate plants with higher moisture usage requirements than were previously considered. One method for obtaining greater rates of uniform condensation is to produce a porous bed of relatively high thermal conductivity and therefore cause a corresponding increase in the required flow rate for uniform condensation. A method of increasing the effective thermal conductivity of the bed is to place metal pins, with a thermal conductivity that is higher than that of the bed, in the porous bed with the long axis of the pins oriented parallel to the axis of the gas flow through the bed. It is assumed that the effective thermal conductivity of the metal pins embedded in a porous medium, $K_{e,pins}$, is different from the thermal conductivity of the metal from which the pins are made. To further analyze the problem, the effect of the metal pins on the thermal conductivity of a porous bed must be determined. This effect can be measured by determining the thermal conductivity of the porous bed with the pins and without the pins for dry air flow through the bed. Equation 19 may be used to calculate the values of the effective thermal conductivity of the bed from measurements with dry air flow. The effective thermal conductivity of the metal pins, $K_{e\ pin}$, is then calculated on a per cent by volume basis from the following relation.

$$K_e = K_{e,pins}(\text{per cent volume that is pins}) + K_{e,particles}(\text{per cent volume that is particles}) \quad (23)$$

After the value $K_{e,pins}$ is determined, then the variation in thermal conductivity of the system, with moisture content, can be calculated by assuming that only the thermal conductivity of the packed porous particles changes with moisture content during the uniform condensation process.

A number of relatively simple correlations have been reported for predicting the thermal conductivity of porous beds with stagnant gas in the pore volume. Although the conduction process through such systems appears to be complex, these correlations have been quite successful. Generally, the thermal conductivity of the packed bed is expressed as a function of the thermal conductivity of the solid, the thermal conductivity of the gas, and the void fraction of the porous medium. Figure 4 is a graphical correlation for predicting the effective thermal conductivity of a porous bed from the work of Deissler and Eian (6, p. 17-29). They have also determined the effect of pressure on the porous bed and found that there is a "break away pressure" below which the thermal conductivity of the packed bed will decrease with a reduction in pressure. A correlation to predict the thermal conductivity of packed porous beds considering variations in pressure below the break away pressure, and variations in particle size was developed by Shotte (19, p. 63).

Kunii and Smith present a method for predicting the effective thermal conductivities of consolidated and unconsolidated porous beds in stagnant fluids if the thermal conductivity of the solid material can be determined (10, p. 71).

Extensive equations for predicting the effective thermal conductivity of a bed with a flowing fluid are presented by Kunii and Smith (11, p. 29-34). This study

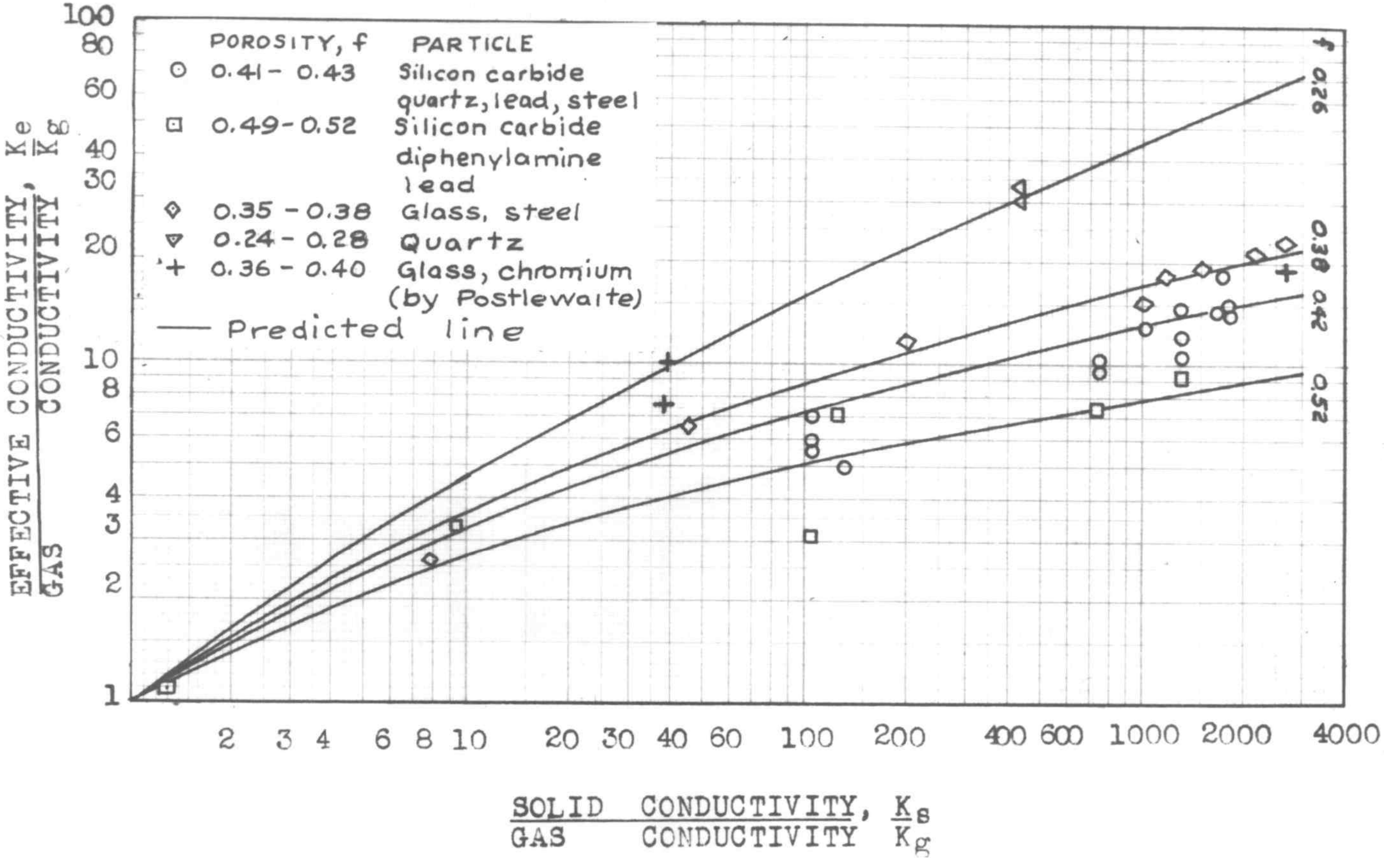

Figure 4

EFFECTIVE THERMAL CONDUCTIVITY
OF PACKED POROUS BEDS
THEORETICAL ANALYSIS BY R.G. DEISSLER AND B.S.EIAN
EXPERIMENTAL RESULTS BY R.G. WILHELM, et. al. (21. p.105).
JUNE 1952 NACA RM52C05

is a theoretical analysis requiring some knowledge of the packing arrangements of the particles, effective thickness of the fluid film adjacent to the surface of two solid particles, and the effective length between centers of the neighboring solid particles in the direction of heat flow. Kunii and Smith's work indicates an increasing trend in the effective thermal conductivity of the porous bed with increasing Reynolds number. This measure of the heat transfer within the porous bed is called the apparent effective thermal conductivity of the bed by Kunii and Smith because it includes the effects of radiation and convection heat transfer as well as conduction. There is not enough information available at the present time to apply this work of Kunii and Smith to the present study.

Kasansky, Lutsick, and Oleynikov used a gamma ray absorption method called gammascopy to determine moisture inside porous beds without breaking the integrity of the porous structure (8, p. 231-239). This work studied the mechanism of non-stationary temperature and moisture content fields in unconsolidated porous beds. Further work in this field and possible application of the gammascopy method should be of great benefit to the subject of the present paper.

APPARATUS

The test section consists of an acrylic plastic tube which has a 5.5-inch inside diameter, a $\frac{1}{4}$-inch wall thickness, and a 9-inch length. The tube has flanges for bolting to the cooling plate and the bubble column, figure 5. The test sample is held in place by two 150-mesh inconel screens. The plastic tubing, chosen for its low thermal conductivity, is easy to modify and has the useful property of transparency.

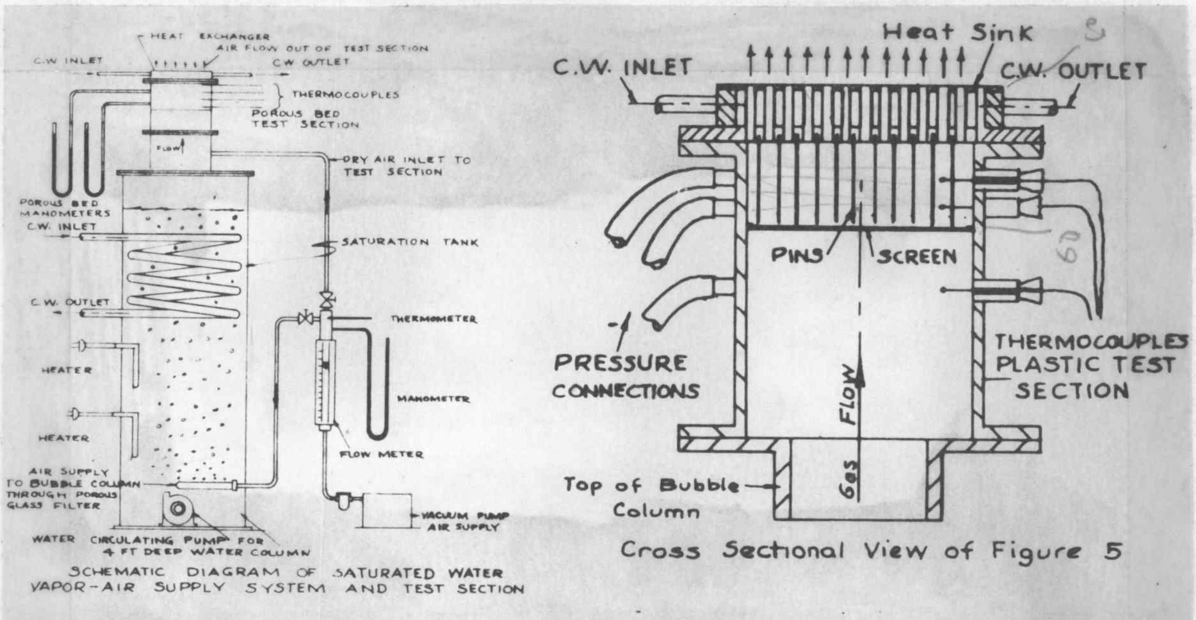

Figure 5. Test apparatus with plastic test section mounted on top.

The porous bed is cooled by a copper, water cooled heat sink of the type pictured in figure 6. Gas flowing through the porous column leaves through the inside of the tubes in the heat exchanger. The cooling water is circulated inside the heat exchanger around the tubes. The heat exchanger cools the porous medium by conduction heat transfer through contact with the particles of the bed. Figure 6 shows the two types of heat exchangers used in the tests. The significant difference between these heat exchangers is that heat exchanger No. 2 has pin type fins pressed into the tube sheet while heat exchanger No. 1 does not have pins. The purpose of the pins is to increase the effective thermal conductivity of the porous bed so that higher uniform condensation rates can be realized. There are 103 pins, each 0.093 inches in diameter made of 18- 8 stainless steel or of brass of 60 per cent copper and 40 per cent zinc by weight.

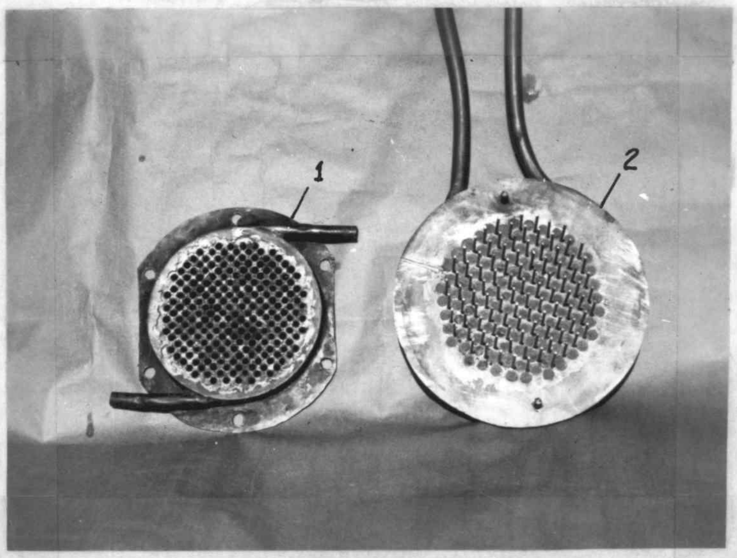

Figure 6. The two water cooled heat exchangers for cooling the porous bed are shown above.
No. 1 Copper heat exchanger.
No. 2 Brass heat exchanger with pin fins.

Air is supplied for the tests by a $\frac{1}{6}$-HP vacuum pump and is metered by a Shutte Koerting Co. flow meter with capacity of 0.02 to 0.80 CFM in 0.02 CFM graduations. Air is supplied to the porous column either as low humidity room air, or as air saturated with water vapor. For those runs in which condensation is not required, the low humidity air is passed through a copper tempering coil in the bubble column, figures 7 and 8. When condensation is required, the air flow is passed through a 9-inch by

$1\frac{1}{4}$-inch diameter porous glass filter at the bottom of a four foot column of water, figure 7. The purpose of the glass filter is to disperse the air into the bottom of the water column in the form of very small bubbles. Water vapor is mixed with these air bubbles as they rise up through the water column. It is assumed that the air-water vapor mixture leaving the top surface of the water column is saturated.

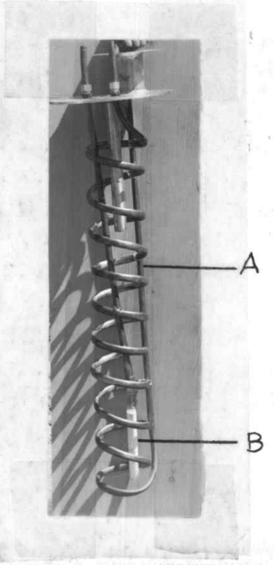

Figure 7. A. Tempering coil for room air supply. B. Porous filter for saturated air supply.

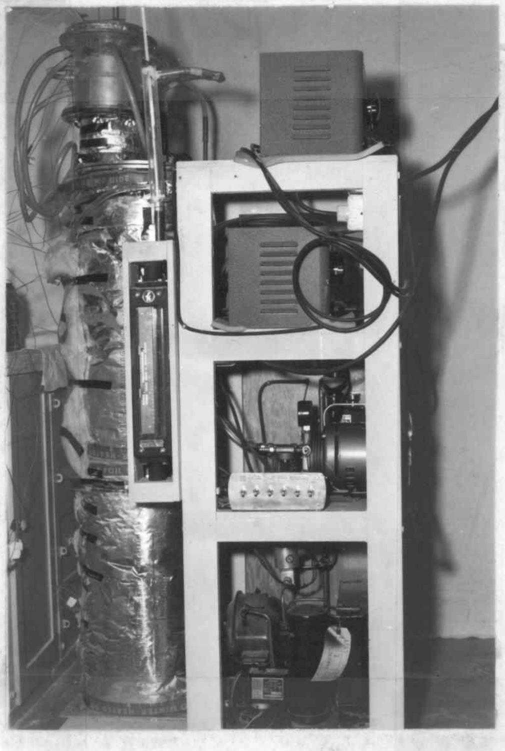

Figure 8. End view of test apparatus, showing bubble column insulated with aluminum foil and fiberglass blanket with the test section mounted on top at the left, the flow meter near the center, and the instruments on the right.

Cooling water is supplied to the heat sink and to the bubble column from the constant temperature tank, figure 9. The temperature of the cooling water supply tank and the bubble column can be controlled to $\pm$ 0.1°F by two Electron-O-Therm Sr. Temperature Controllers, figure 9. Each temperature controller consists of a variac, an electronic circuit, and a resistance thermometer probe. The variac controls a 750-watt submersed heater. The electronic circuit controls a 250-watt submersed heater and can vary the amount of input energy up to 250-watts depending upon the instrument setting and the temperature sensed by the probe.

Figure 9. Front view of test apparatus. The two instruments in the upper left hand corner are the Electron-O-Therm temperature controllers. The cooling water supply tank is shown on the right.

Temperatures of the cooling water and the metered air are measured with calibrated mercury thermometers having 0.01°C graduations. Temperatures of the bubble tank and test section are measured with copper-constantan thermocouples and a K-3 Leeds and Northup Universal potentiometer. The calibration curve (see appendix A) for all of the thermocouples agrees with published values to the accuracy of the values listed in the standard table (17, p. 80-83). Pressures at the flow meter and in the test section are measured with mercury and water manometers, figure 10.

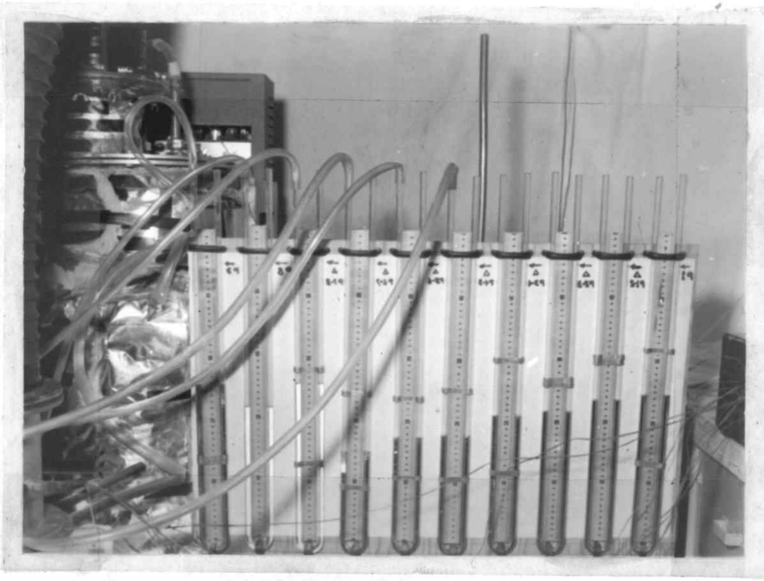

Figure 10. Manometer board mounted on back of the test apparatus.

The total electrical load for the test apparatus was 4-KW. A two-ton cooling load was used to maintain the room temperature within $\pm$ 2°F of the room temperature indicated on the data sheets (appendix C).

PROCEDURE

In preparation for a test, thermocouples are located in the test section along the flow path with an accuracy of $\pm \frac{1}{32}$-inch. The test sample is oven dried at 220°F for eight hours, air cooled, and poured into the test section through a funnel in even one-quarter inch deep layers. Each layer is compacted by vibrating the test section for 30 seconds with a vibrator fastened to the bottom flange.

Before the uniform condensation process is started, the uniformity of compaction within the test bed must be observed from the pressure distribution in the bed, and the thermal conductivity of the dry porous bed must be established. If the pressure distribution is nearly linear for dry air flow, then the compacted bed is accepted for a test. The temperatures and the pressure gradients are observed for several different flow rates with low humidity air flowing through the porous medium. Two of these conditions of flow are chosen so that the graph of temperature vs. length has a large change in slope as in curves (a) and (b) of figure 11. From these conditions, the effective thermal conductivity of the packed porous bed is calculated by using equation 19. A third flow rate is established to produce a temperature gradient with small change in curvature so that at the mid-point of the flow length, L, the temperature has a value between 0.50 and 0.58 of the normalized temperature distribution, figure 11 curve (c). This condition of flow then will be approximately the same as the required conditions for a uniform condensation process in this bed. The required dewpoint temperatures are then calculated for the points along the flow path where the thermocouples are located. The required mass flow rate is then calculated for these required values of dewpoint temperature and for the calculated value of the effective thermal conductivity of the bed. Adjustments are then made in the flow rate until the required temperature distribution and flow rate are developed and maintained within the bed. This procedure of establishing the required dewpoint temperature distribution within the porous bed before the saturated air flow is passed through it reduces the possibility of a non-uniform condensation condition within the bed while the required dewpoint temperature distribution is being established. With the required conditions for the uniform condensation process established, the air flow is then directed through the bubble column to provide saturated air to the test section. A mass flow rate schedule is calculated so that the uniform condensation process can be maintained as the thermal conductivity of the bed increases with the moisture content. For the tests in which the

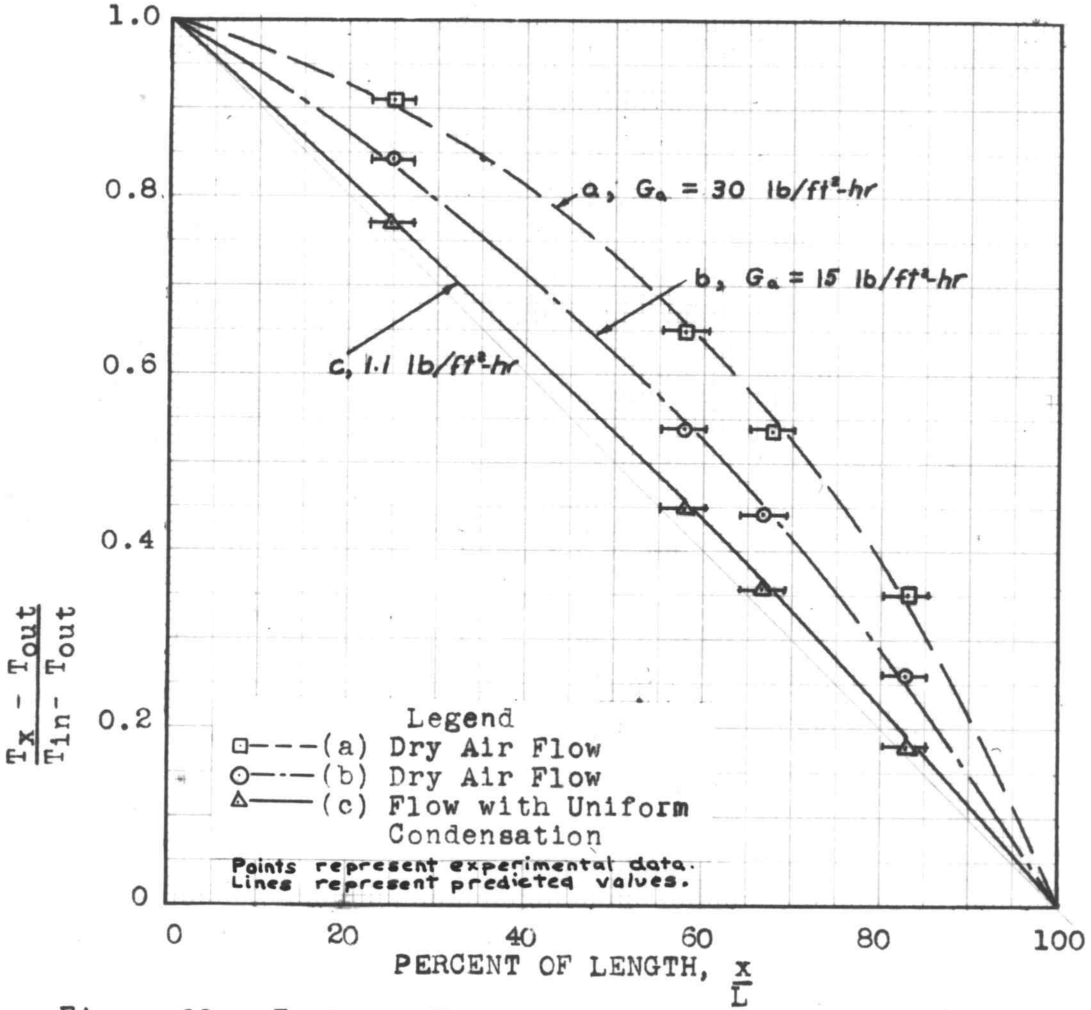

Figure 11. Test A. Temperature distribution for air flow through a 1.5 inch bed depth of chromium powder with 0.004 mean particle size.

porous bed consists only of compacted particles, equation 21 and figure 3 are used to determine the required mass flow rate. If pins are embedded in the porous medium, then the calculation to determine the mass flow rates with time requires the use of equation 23 in addition to the preceding method. When the test has been operated for a long enough period of time to condense the desired amount of moisture within the bed, then the test is terminated. The moisture content is determined by dividing the bed into four sectors, subdividing each sector into one quarter inch thick layers, placing each of these layers in a sampling can, and weighing the samples in the moist condition and then again after drying.

A discussion of the procedure used to determine the thermal conductivity of compacted porous beds with still air in the pore volume is presented in appendix B.

RESULTS AND DISCUSSION

Six tests were conducted with a saturated vapor-air mixture flowing through a cooled porous bed in an attempt to produce a condition of uniform condensation.

Tests A, C, and F were performed with the fluid flow up through the porous bed. A condition of free convection heat transfer from the fluid flow in the entrance region of the test section and to the bottom surface of the porous bed was encountered during these tests which prevented the establishment of a uniform condensation process. Tests B, D, and E were conducted with the test section inverted so that the fluid flow was down through the porous bed. The effects of the natural convection heat transfer in the entrance to the test section were greatly reduced and a satisfactory uniform condensation process was produced in each of these tests.

Test runs B, C, D, and E were performed with metal pins embedded in the porous medium in order to achieve higher uniform condensation rates than for the beds of lower thermal conductivity. It may be seen from figure 20 that as the effective thermal conductivity of the porous bed was increased by adding metal pins to the bed, a corresponding increase in the required mass flow rate was produced.

The variations of moisture content within the porous beds, with the exception of a one quarter inch thick layer at the flow inlet to the bed, may be attributed to: (a) the non-uniformity of compaction of the particles in the bed causing differences in porosity and variations of the pressure gradient from the values required for uniform condensation, (b) the degree with which the thermocouples within the porous medium were indicating the fluid temperature, the porous bed temperature, or some intermediate temperature; (c) the uncertainty as to the location of a thermocouple within the porous medium after the bed was compacted with a vibrator (d) the uncertainty in the reading of the flow rate due to slight fluctuations in the flow meter. The estimated uncertainty interval for the measured indications of flow rate and temperature was $\pm$ 4 per cent.

The packed porous beds of tests A, C, and F consisted of chromium powder for test A, sandy soil with embedded stainless steel pins for test C, and spherical "superbrite" glass beads for test F. The saturated air flowed up through a 1.5-inch deep bed for each test.

Examination of figures 12, 13, and 14 shows that the moisture content for each of these tests was greatest at the flow inlet end of the bed. The temperature of the bottom surface of the bed decreased with time for each of these tests. Although a dewpoint temperature distribution appeared to have been maintained during these tests, the coefficient of variation (the per cent variation from the mean) moisture content of each bed for tests A, C, and F was greater than the values for tests B, D, and E for which the dewpoint temperatures remained relatively constant. The coefficient of variation of the moisture content for each test is the standard deviation divided by the mean and is a comparative measure of the uniformity of moisture content within the porous bed. The values of the coefficient of variation in moisture content for these tests are listed in table 1 and range from 19.4 to 5.2 per cent for tests A, C, and F and from 4.4 per cent to 2.6 per cent for tests B, D, and E.

Heat transfer studies by Eckert and Diagula have shown that for conditions of flow with large Grashof numbers and small Reynolds numbers the flow may be predominantly that of free convection (7, p. 331-332). For test A, a typical value of the Grashof number in the entrance of the test section was 2.5×10^6 and the corresponding Reynolds number was 13.5. These parameters define a condition described by Eckert and Diagula (7, p. 332) as laminar free convection with mixed flow. The occurrence of more moisture in the beds of tests A, C, and D than could be condensed from a saturated flow

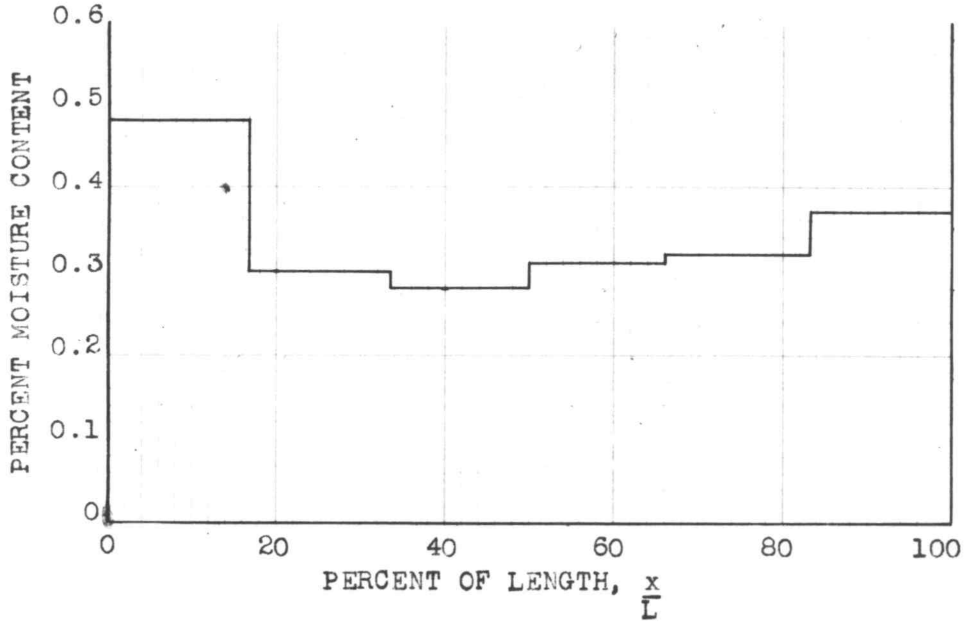

Figure 12. Test A. Percent moisture content by weight-dry is for a 1.5 inch bed depth of 0.004 inch mean particle size chromium powder.

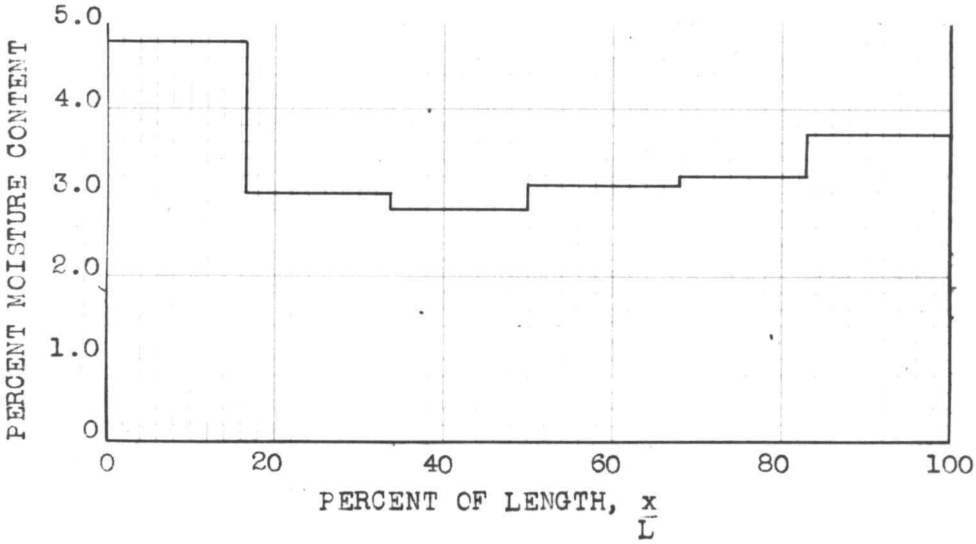

Figure 13. Test C. Percent moisture content by weight-dry is for a 1.5 inch bed depth with 1.5 inch stainless steel pins in a sandy soil of 0.003 inch mean particle size.

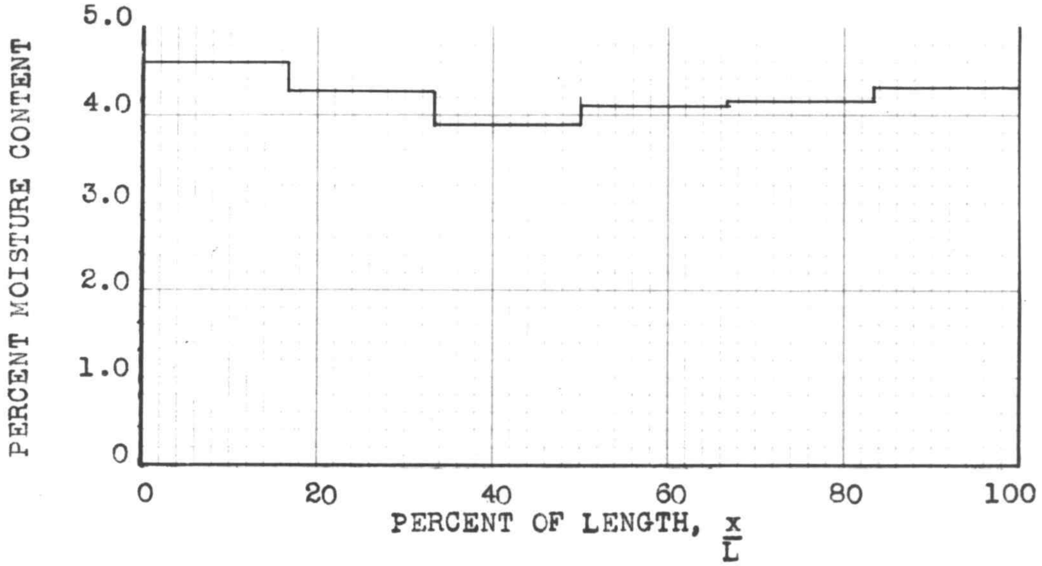

Figure 14. Test F. Percent moisture content by weight-dry is for a 1.5 inch bed of 0.008 inch mean diameter glass beads.

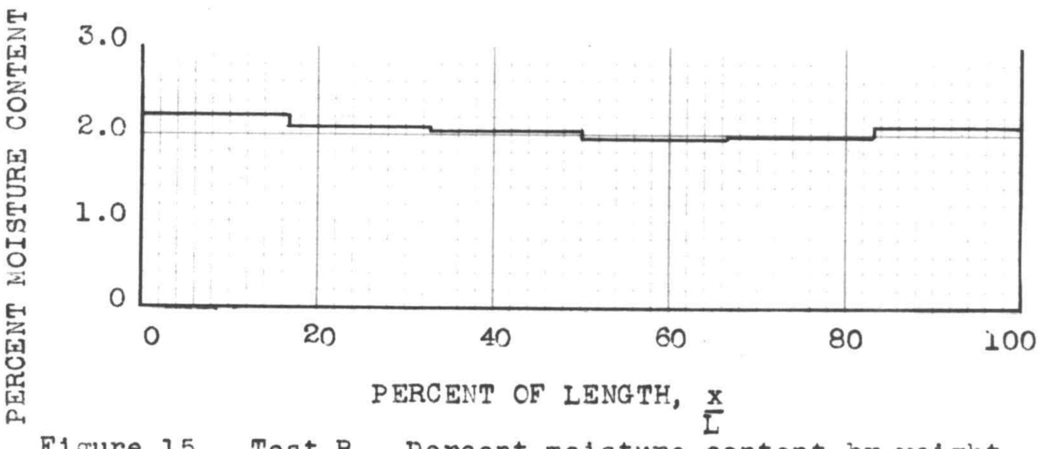

Figure 15. Test B. Percent moisture content by weight-dry is for a 3 inch bed with 3 inch brass pins in sandy soil of 0.003 inch mean particle size.

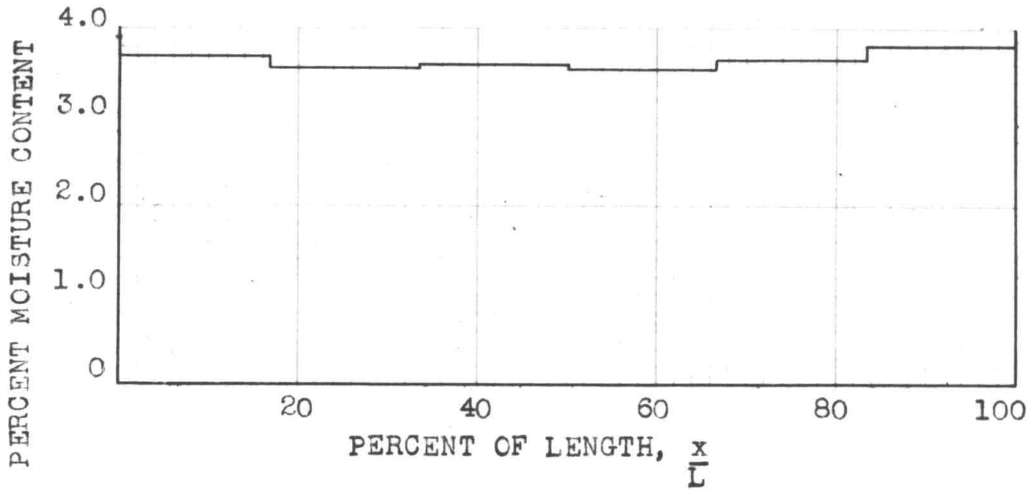

Figure 16. Test D. Percent moisture content by weight-dry is for a 1.5 inch bed depth with 1.5 inch stainless steel pins in a sandy soil of 0.003 inch mean particle size.

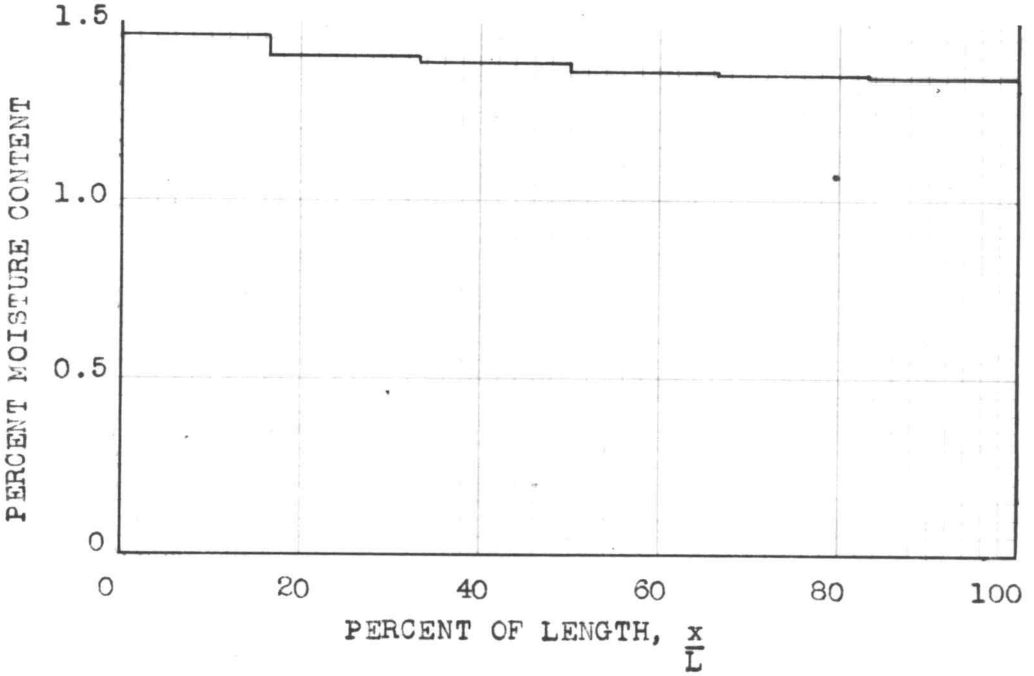

Figure 17. Test E. Percent moisture content by weight-dry is for 1.5 inch bed depth with 1.5 inch stainless steel pins in a sandy soil of 0.003 inch mean particle size.

Table 1 Summary of test results for uniform condensation in cooled porous beds

Test	Porous Bed Material	Mean Particle size inch	K_e of Bed	Saturated Air Flow Rate, G	N_R $\left(\frac{D_p G_a}{\mu}\right)$	w 10^{-3}	Condensation Time, Hr.	Mean Temp Bed, °F	Mean Percent Moisture Content	Coef. var. Moisture Content
A	Chromium 1.5-inch bed Flow up through bed	0.004	0.29	1.3	0.009	3.9	8.0	55.7	0.35	± 19.4
B	Sandy Soil 3.0-inch bed brass pins Flow down Through bed	0.003	7.2	26.7	0.152	2.9	6.0	62.5	2.06	± 4.4
C	Sandy Soil 1.5-inch bed St. pins Flow up Through bed	0.003	2.1	8.4	0.048	5.3	16.0	61.5	5.60	± 5.2
D	Sandy Soil 1.5-inch bed St. pins Flow down through bed	0.003	2.1	8.0	0.045	5.5	10.0	63.0	3.65	± 2.6
E	Sandy Soil 1.5-inch bed St. pins Flow down through bed	0.003	2.1	7.9	0.045	4.2	5.5	60.8	1.38	± 3.0
F	Glass beads 1.5-inch bed Flow up through bed	0.008	0.16	1.1	0.017	6.1	16.0	63.0	0.86	± 5.5

with the same inlet and outlet temperatures and pressures indicates that the water vapor must have been supersaturated. The large value of the moisture content at the inlet or bottom layer of these test beds, compared to the mean value for each bed, might be resulting from the excess moisture which is condensing from a supersaturated fluid as it approaches the saturated condition corresponding to its temperature at that point in the flow. The difference between the temperature of the bed at the inlet and the temperature of the fluid leaving the surface of the water in the bubble tank increased 4.4°F during test A, 3.4°F during test C, and 1°F during test F. To reduce the free convection effects in the entrance region of the test section for tests C and F, a 5-inch thick layer of fiber glass wool was packed into the entrance region. The water level in the bubble column was raised until the top of the bubbling surface just touched the bottom of this fiber glass layer. Since small amounts of moisture were observed throughout the glass wool packing at the end of tests C and F, it is assumed that some of the water in the rising fluid stream was deposited on the glass wool rather than in the bottom end of the porous bed. This would account, in part, for the smaller variations in the moisture contents of tests C and F as compared to test A.

A sandy soil was used in the porous beds of tests B, D, and E. The bed in test B was three inches in depth with three inch brass pins embedded in the porous medium. The beds in tests D and E were each 1.5-inches in depth with 1.5-inch stainless steel pins within the porous medium. Test B was designed to reduce the free convection heat transfer effects encountered in test A and to study the effects of the brass pins upon the effective thermal conductivity of the bed. The test section was connected to the bubble column with a 6-inch diameter flexible rubber tube so that the bed could be turned upside down and cause the fluid flow to be directed down through the bed. The coefficient of variation in moisture content for test B was 4.4 per cent. Some of this variation in moisture content was caused by the large amount of moisture deposited at the flow inlet end of the bed. The high moisture content at the inlet end of test bed B may be attributed to conduction through the inflowing fluid from the surface of the bed causing additional moisture to be deposited in the bed. The temperature difference from a point 3-inches above the bed and the inlet surface to the bed was measured to be 2.6°F. For tests D and E, fiber glass wool was placed in the entrance region of the test section with an air space of about 1/8-inch provided between the bed inlet surface and the surface of the packing. The purpose of the air space was to eliminate conduction heat transfer between the bed and the fiber glass wool. Smaller temperature differences were observed between the fluid leaving the bubble column and the inlet surface of the porous bed for tests D and E than for test B. During these tests, the temperatures of a pin, and a point in the porous bed between several pins, were measured at different locations along the flow path. The difference between these measurements, which were made in the same horizontal plane of the bed, was consistently between 0.4° and 0.5°F. This difference in the temperature of the porous bed and the pins surrounded by the particles of the bed indicates conduction heat transfer in the radial direction through the porous bed to the pins.

The uniform condensation rates for the six tests were: 5.8 grams per hour for test B with brass pins; 3.4, 3.3, and 2.5 grams per hour for tests C, D, and E respectively with stainless steel pins; 0.5 grams per hour for test A with chromium powder; and 0.37 grams per hour for test F with glass beads. These uniform condensation rates indicate that the uniform condensation process can be significantly increased by increasing the effective thermal conductivity of the bed.

Figure 18 is a graph of soil column pressure for test B for the beginning and for the end of the condensation process. These results are typical of all of the tests

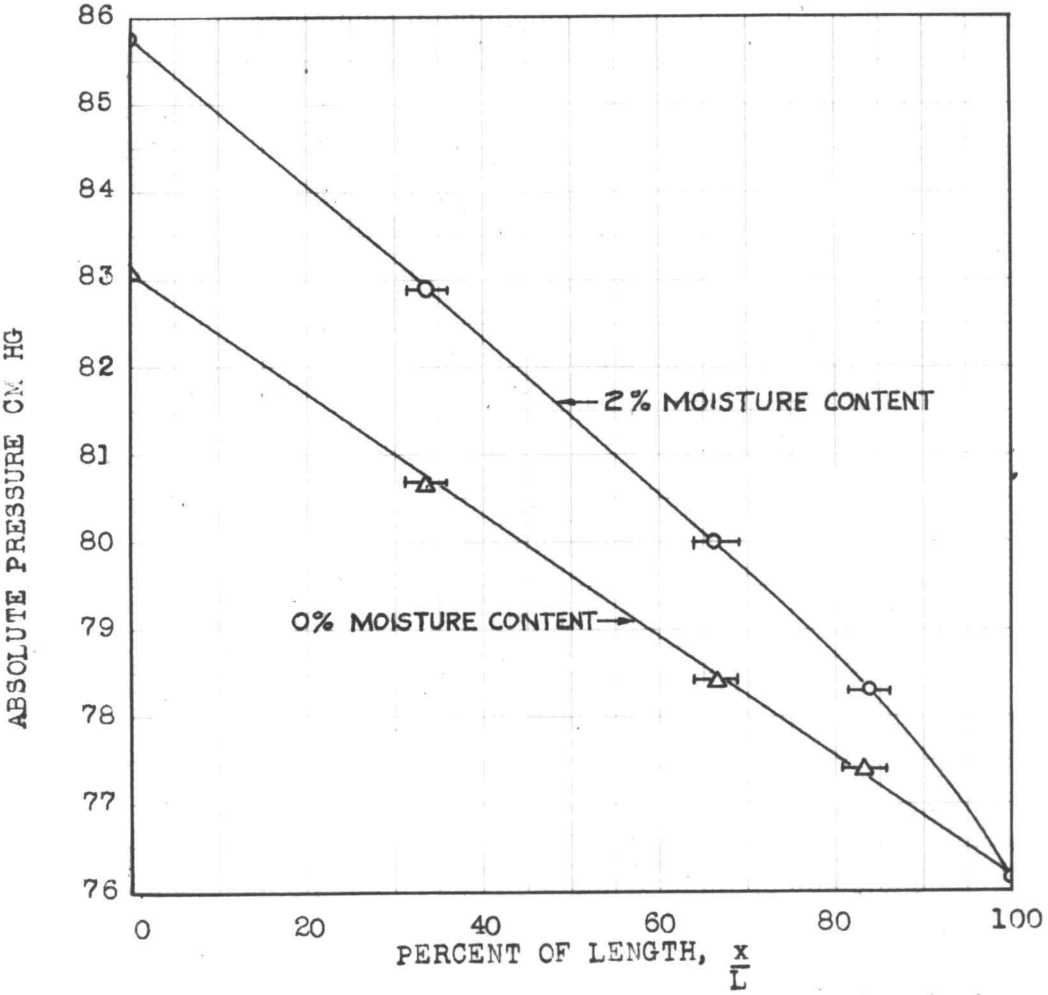

Figure 18. Test B. Pressure distribution in a 3.0 inch bed depth of sandy soil with 3.0 inch brass pins for uniform condensation at (a) beginning and (b) end of test.

and substantiate the assumption of a linear pressure distribution used in equations 4 and 5 to calculate the required dewpoint temperatures.

Figure 19 represents the temperature distribution required for uniform condensation and the measured temperature distribution for test C. This example is typical for all of the test runs.

In order to satisfy the condition of uniform condensation, the ratio $\frac{G_a}{K_e}$ was found to have values between 3.65 and 3.75 Lb-^{o}F/Ft-Btu for all of the tests. This result may be observed by the linear relation of this ratio on figure 20.

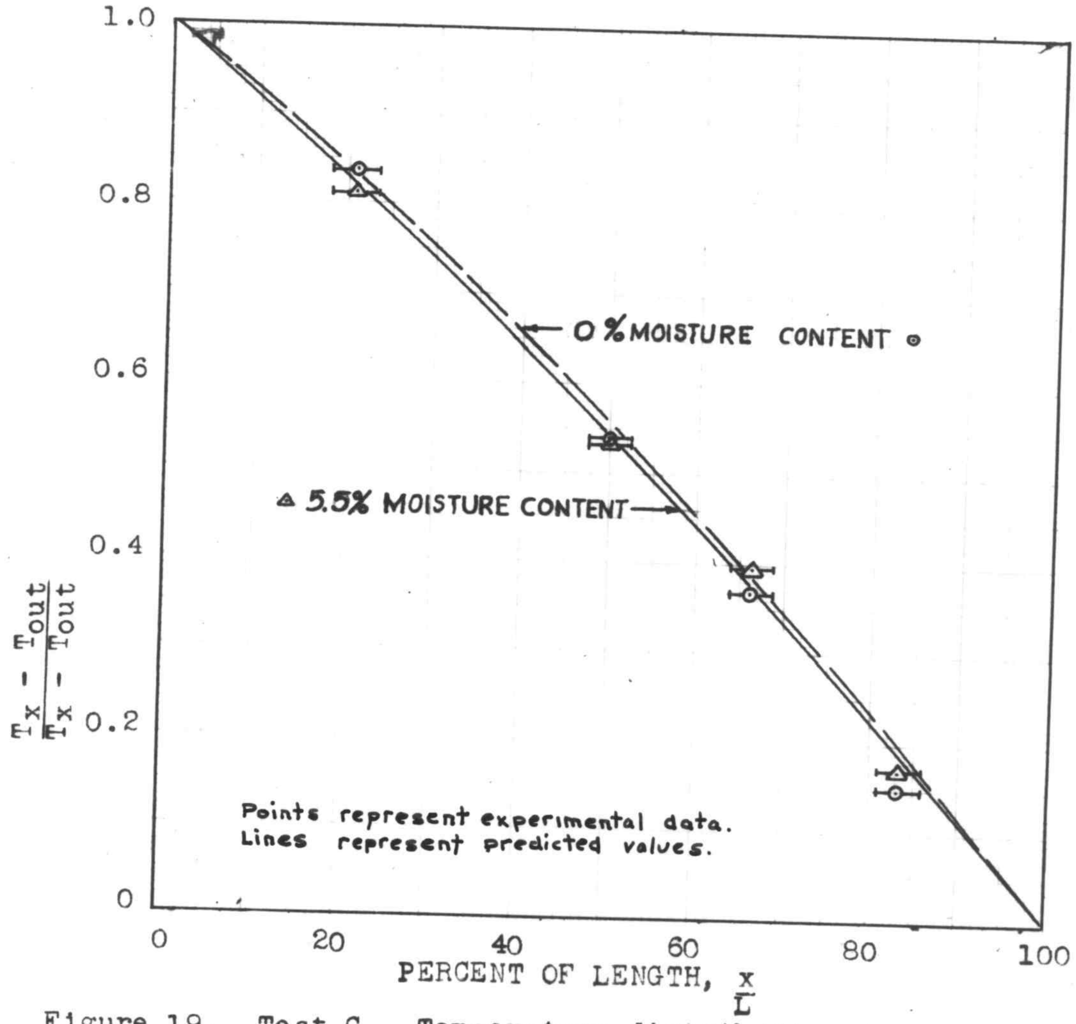

Figure 19. Test C. Temperature distribution for saturated air flow with uniform condensation in a 1.5 inch bed depth of sandy soil with 1.5 inch pins.

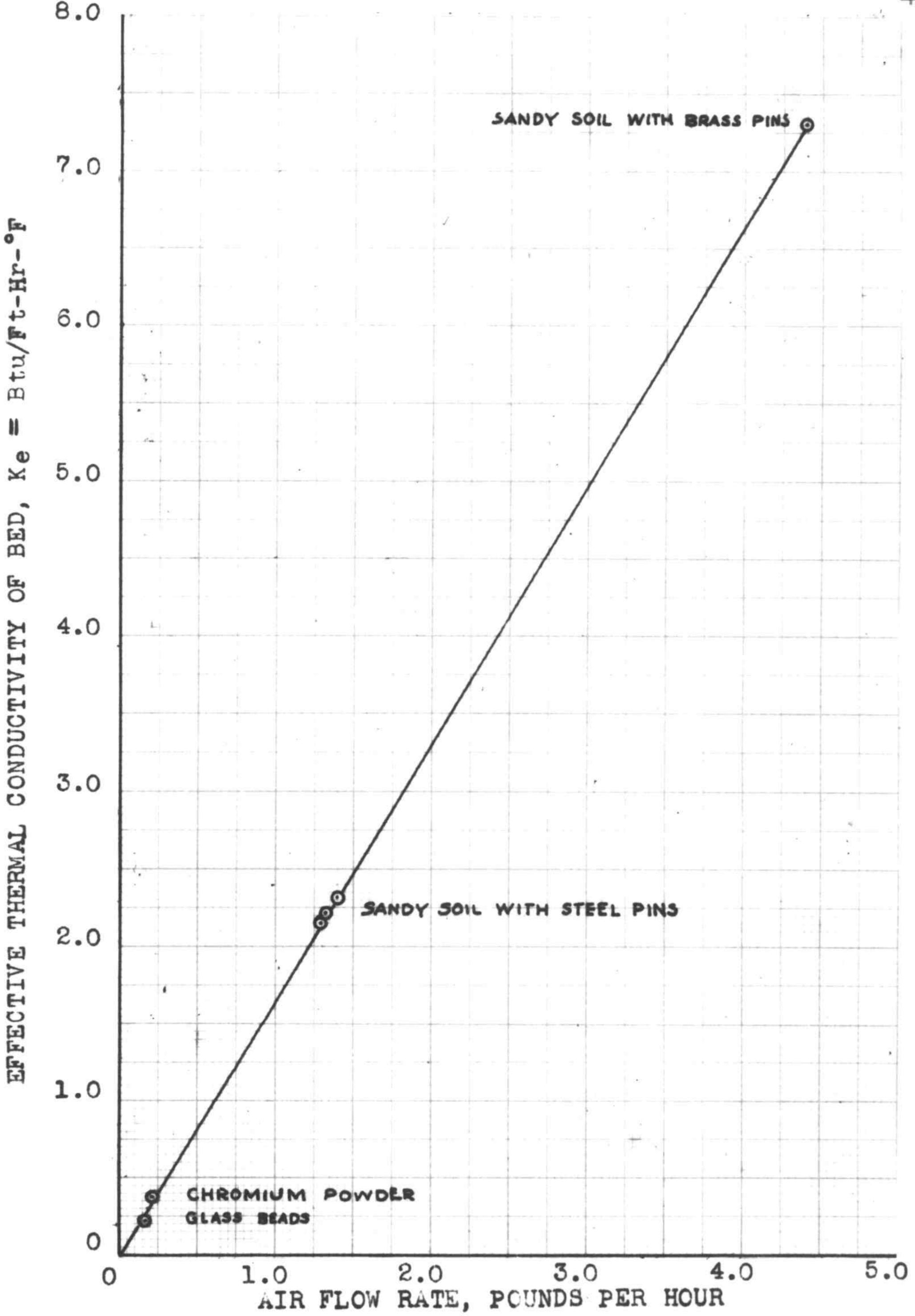

Figure 20. Mass flow rate for uniform condensation and effective thermal conductivity of packed porous bed.

Values of the effective thermal conductivities of the porous beds considered in the present study may be found in table 2 (see appendix C). The thermal conductivities of porous beds consisting of sandy soil, glass beads, and chromium powder were measured for the condition of still air in the pore volume of the bed and for the condition of air flow through the bed. These two values of the thermal conductivity for each bed are compared in figure 21, showing a maximum difference of 2 per cent. It is concluded from this comparison that the effective thermal conductivity of the porous beds in these tests is independent of the air flow.

The measured results for the thermal conductivities of porous beds of glass beads and of chromium powder are shown in figure 4 for comparison with the work of others. These values are 30 per cent higher than the predicted thermal conductivities of the glass beads and are 3 per cent higher than the predicted thermal conductivities of the chromium powder. Since the correlation in figure 21 is made for different porosities, the variation in the compaction of these beds could account for some of the difference between the measured and the predicted values of the thermal conductivity.

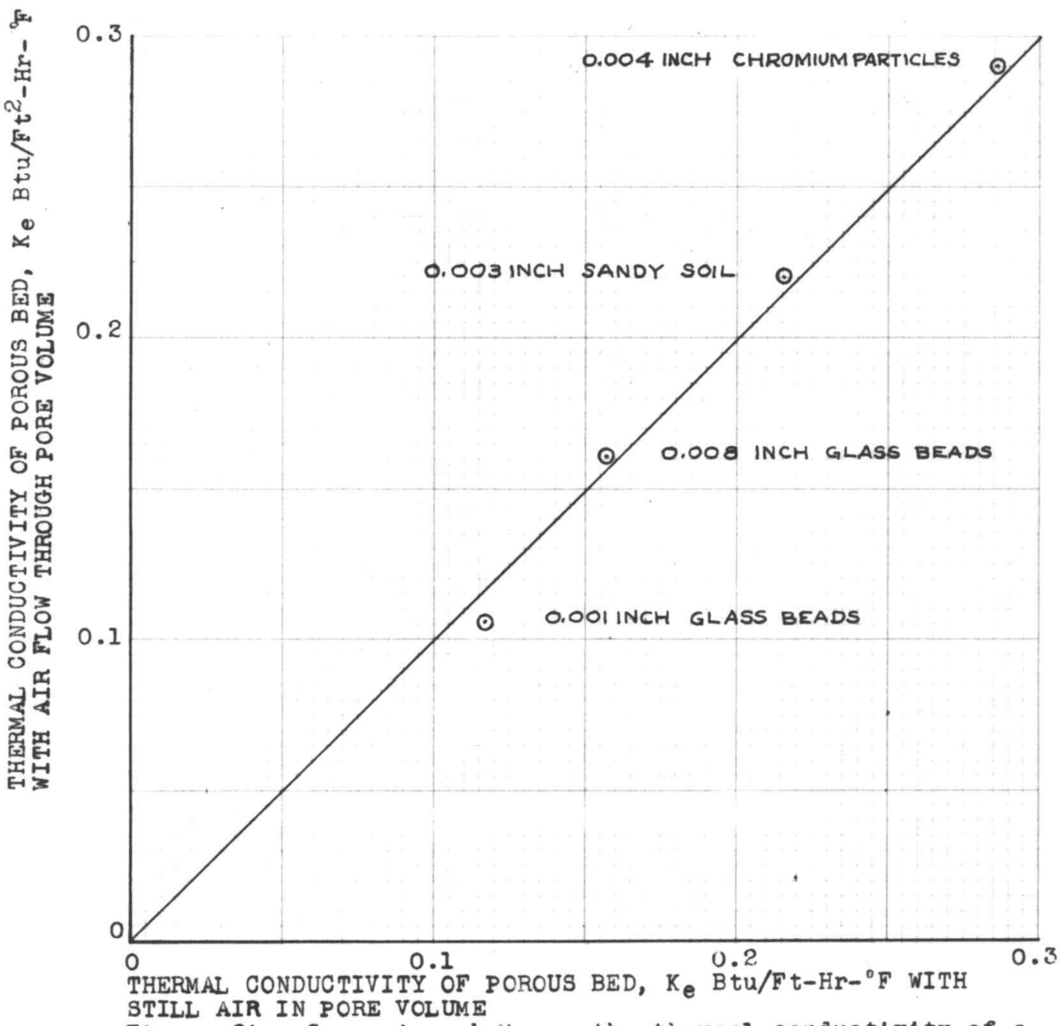

Figure 21. Comparison between the thermal conductivity of a porous bed with air flow in pore volume and the thermal conductivity of a porous bed with still air in pore volume.

The findings of Kunii and Smith indicate a definite increase in the "apparent effective thermal conductivity" of the bed with a corresponding increase in Reynolds number. No change was observed in the effective thermal conductivity of the porous bed with different Reynolds numbers in the present work. The difference in these results is that the definition of the apparent effective thermal conductivity of the porous bed given by Kunii and Smith includes convection heat transfer as well as conduction, while the definition of the effective thermal conductivity of the porous bed in this paper does not include convection.

CONCLUSIONS

The analysis of the problem of uniform condensation from a saturated water vapor-air mixture flowing through a cooled porous bed shows that to provide uniform condensation, the ratio of the mass flow rate of the fluid to the effective thermal conductivity of the bed must be maintained constant. This result has been verified experimentally with beds of glass beads, chromium powder, and sandy soil in which uniform condensation was obtained with coefficients of variation from $\pm$ 2.6 per cent to $\pm$ 19.4 per cent for the moisture content of these beds. The uniform condensation rates achieved range from 0.37 to 5.8 gram per hr. To achieve the more uniform condensation condition, it was necessary to invert the porous bed and cause the saturated water vapor-air mixture to flow down through the porous bed to reduce the natural convection effect. The higher uniform condensation rates were produced in a given porous medium by embedding metal pins of stainless steel or brass in the medium. Higher uniform condensation rates should be possible by adding metal pins of aluminum or copper to the porous bed.

To satisfy the condition of uniform condensation, the ratio of the mass flow rate to the effective thermal conductivity of the bed was found to have nearly the same value for all of the tests. This ratio had a variation of only 2.6 per cent for all of the test runs. Using the average value of this ratio, the temperature of the fluid in a porous bed for a uniform condensation process may be given by the equation

$$T_x = T_{in} + \gamma x - (T_{in} - T_{out} + \gamma L) \frac{1 - e^{0.91x}}{1 - e^{0.91L}} .$$

RECOMMENDATIONS

The determination of the moisture content of the bed by some method which would not disturb the integrity of the bed during the uniform condensation process should be invaluable in the study and application of this method to irrigate plants growing in a porous medium of constant moisture content. One method used by Kasansky, et. al. (8, p. 231-239) to study moisture content fields in porous bodies is called gammascopy and appears promising.

It has been the custom to use an overall heat transfer coefficient to describe the situation in which an analysis has been made combining several modes of heat transfer. The appearance in recent publications of terminology, such as, "the apparent effective thermal conductivity of a porous bed" to describe the combined heat transfer capability of a porous bed causes unnecessary confusion.

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APPENDIX A

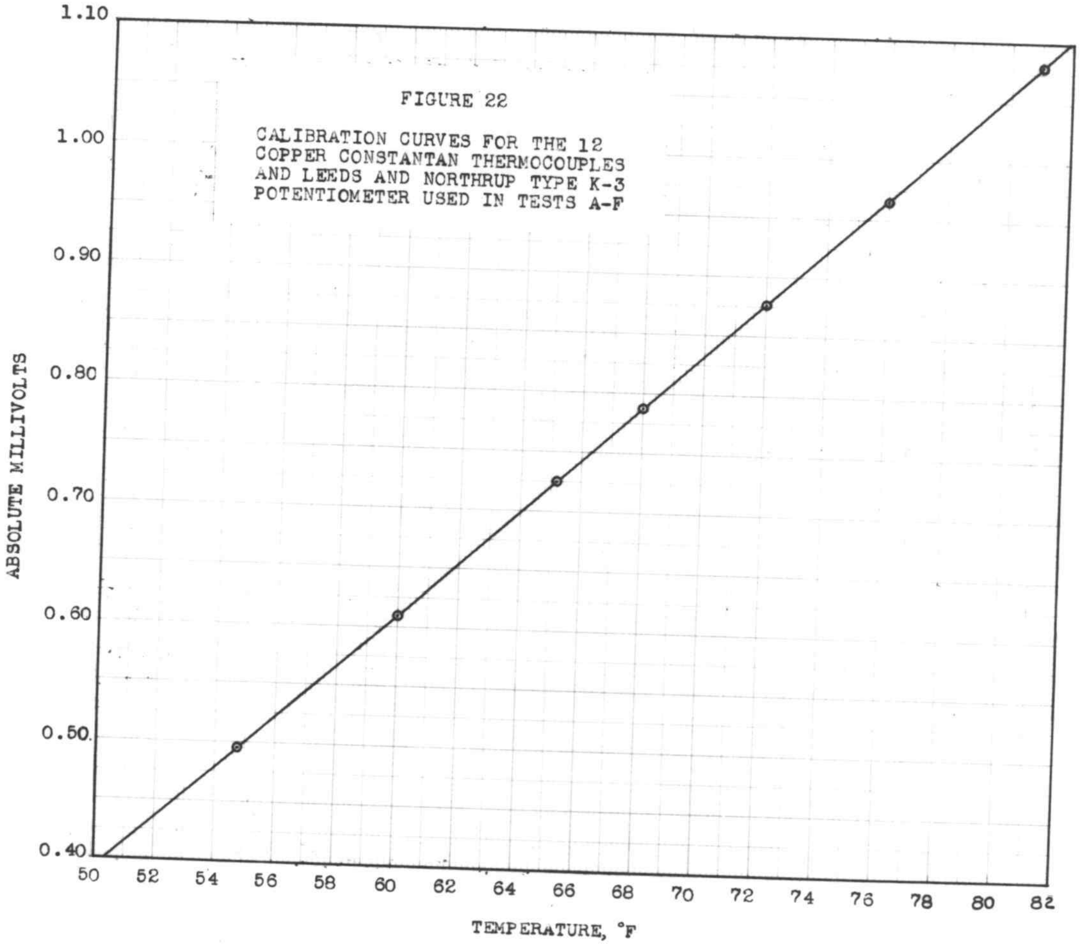
FIGURE 22
CALIBRATION CURVES FOR THE 12
COPPER CONSTANTAN THERMOCOUPLES
AND LEEDS AND NORTHRUP TYPE K-3
POTENTIOMETER USED IN TESTS A-F
ABSOLUTE MILLIVOLTS
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
TEMPERATURE, °F

APPENDIX B

THE THERMAL CONDUCTIVITY OF POROUS BEDS IN STILL AIR

The thermal conductivities of the glass beads, the chromium powder, and the sandy soil used in the uniform condensation process were measured as compacted beds with still air in the pore volume as a check on the values determined from the flow process. The thermal conductivities of these porous materials as packed beds in still air were determined from Fouriers' conduction equation for steady state tests. The test sample was packed into a water jacketed cylindrical pipe with heating elements located along the cylindrical axis. The electrical energy input to the center heater and the temperature difference across the bed in the radial direction were measured. Guard heaters on either end of the center heater were maintained at the constant temperature of the center heater. Constant temperature cooling water was supplied to the water jacket from the constant temperature tank. The preceding method for measuring the thermal conductivities of porous beds with a stagnant gas was the same as that used by Deissler and Eian (6, p. 17-29) in the determination of the thermal conductivities of powders.

A P P E N D I X C

Table 2 Thermal Conductivity of Porous Beds in Air, K_e, Btu/Ft-Hr-°F

Porous Bed Material	Mean Particle Size	Mean Temp °F	K_e Measured Still Air	K_e Predicted Deissler Eian Still Air	K_e Predicted Kunii Smith Still Air	K_e Predicted Kunii Smith Air Flow	K_e Measured Air Flow Dry	N_R $\left(\frac{D_p G_a}{\mu}\right)$	K_s Solid
Sand	0.0043	77	--	0.162	0.12	0.21	--	0.15	2.7
Sandy Soil	0.003	76	0.218	--	--	--	0.22	0.01	--
Glass Beads	0.0011	71	--	0.096	--	--	0.11	0.05	0.6
Glass Beads	0.0011	98	0.117	0.098	--	--	--	0.01	0.6
Glass Beads	0.0043	77	--	0.091	0.07	0.23	--	0.33	0.47
Glass Beads	0.008	92	0.157	0.100	--	--	--	0.01	0.6
Glass Beads	0.008	71	--	0.097	--	--	0.16	0.33	0.6
Chromium Powder	0.004	76	0.287	0.280	--	--	0.29	0.01	38.7

Table 3 SUMMARY DATA SHEET FOR TEST RUN A
CONDENSATION PROCESS WITH SATURATED AIR FLOW

	MEASURED			CALCULATED	
Time Hours	0	4	8	0	8
FLOW METER					
FLOW CFM	0.035	0.036	0.038		
TEMPERATURE °C	23.5	23.5	23.2		
PRESSURE CM HG	12.3	12.4	12.6		
MASS FLOW G	1.1	1.2	1.5		
X/L PRESSURE IN BED CM HG					
0	0.15	0.25	0.40	.15	0.40
.33	0.10	0.18	0.30	.10	0.27
.67	0.07	0.09	0.15	.05	0.13
.91	0.02	0.04	0.05	.01	0.04
1.00 A	0.00	0.00	0.00	.00	0.00
X/L TEMPERATURE IN BED °F					
0	64.1	60.3	60.0	64.1	60.0
0.25	61.2	58.6	58.1	61.2	58.1
0.50	--	--	--	58.1	56.0
0.58	57.1	55.3	55.2	--	--
0.67	55.9	54.5	54.4	--	--
0.75	--	--	--	54.8	53.8
0.83	53.8	53.2	53.0	--	--
1.00	51.4	51.4	51.4	51.4	51.4
BUBBLE TANK TEMP °F	68.5	68.5	68.5	--	--
ROOM TEMP °F	72	72	72		
ROOM RELATIVE HUMIDITY	28%	25%	25%		

SAMPLE LOCATION X/L	0-.167	.167-.333	.333-.500	.500-.667
PERCENT MOISTURE CONTENT	0.48	0.30	.28	0.31
SAMPLE LOCATION X/L			.667-.833	.867-1.00
PERCENT MOISTURE CONTENT			0.32	0.37

BED DEPTH 1.5 inches
CHROMIUM POWDER CONTROLLED PARTICLE SIZE 0.004 inch
K = 38.7 BTU/FT^2-HR-°F FOR SOLID CHROMIUM:ASM HANDBOOK
CONDENSATION TIME 8 HOURS
Specific Gravity = 3.7 for compacted bed

Table 4 Summary Data Sheet for Test Run B
Condensation Process with Saturated Air Flow

	MEASURED			CALCULATED	
TIME HOURS	0	3	6	0	6
FLOW METER					
FLOW CFM	0.72	0.74	0.76		
TEMPERATURE °C	27.4°	27.4°	27.4°		
PRESSURE CM HG	26.1	26.8	27.6		
MASS FLOW G	26.0	26.6	27.5	26.0	27.5
X/L PRESSURE IN BED CM HG-GAUGE					
0	9.2	9.6	10.0	9.2	10.0
.33	6.1	6.3	6.8	6.1	6.7
.67	3.4	3.6	3.9	3.1	3.3
.83	2.0	2.1	2.2	1.6	1.7
1.00	0.0	0.0	0.0	0.0	0.0
X/L TEMPERATURE IN BED °F					
0 INLET	67.8	67.7	67.7	67.8	67.7
0.21	66.0	65.7	65.6		
0.25	--	--	--		
0.42	64.7	64.3	64.3	65.4	65.3
0.50	63.6	63.4	63.3	63.2	63.1
0.63	62.7	62.4	62.0		
0.75	--	--	--	60.3	60.2
0.79	60.3	60.2	59.9		
0.92	59.0	58.8	58.6		
1.00 EXIT	57.4	57.4	57.4	57.4	57.4
BUBBLE TANK TEMP °F	70.4	70.4	70.4		
ROOM TEMP	71.0	70.0	71.0		
ROOM RELATIVE HUMIDITY	28.0	24.0	26.0		

SAMPLE LOCATION X/L	0-.167	.167-.333	.33-.500	.50-.667
PERCENT MOISTURE AVERAGE	2.23	2.06	2.05	1.94

SAMPLE LOCATION X/L	.67-.834	.83-1.00
PERCENT MOISTURE AVERAGE	1.99	2.07

BED DEPTH 3.0 inches. Bed inverted with flow down through sandy soil with mean particle size of 0.003 inch with 103 brass fins, 0.093 inch dia., composition of pins 60% copper and 40% zinc. Thermal conductivity of pins K = 61BFU/Ft - HR-°F (Reference ASM Handbook)

Condensation time 6 hours.

Specific Gravity = 1.55 for compacted bed.

B,D,E

Table 5 SUMMARY DATA SHEET TEST RUN C
CONDENSATION PROCESS WITH SATURATED AIR FLOW

	MEASURED			CALCULATED	
	0	6	16	0	16
FLOW METER					
FLOW CFM	0.24	0.25	0.27		
TEMP °C	25.3	24.6	24.0		
PRESSURE CM HG	16.1	17.3	18.2		
MASS FLOW G	7.8	8.2	8.9	7.8	8.9
X/L PRESSURE IN BED CM HG GAUGE					
0	1.6	1.9	2.6	1.6	2.6
.33	1.0	1.3	1.7	1.1	1.7
.83	0.4	0.6	0.7	0.3	0.7
1.00	0	0	0	0	0
X/L TEMPERATURE IN BED °F					
0	70.2	68.6	67.6	70.2	67.6
.21	67.4	66.3	65.6	--	--
.25	--	--	--	67.0	64.9
.50	63.4	62.5	62.0	63.6	62.0
.67	61.3	60.0	59.8	--	--
.75	--	--	--	59.7	58.8
.83	58.0	57.6	57.3	--	--
1.00	55.5	55.5	55.5	55.5	55.5
BUBBLE TANK °F	73.2	73.4	73.3	--	--
ROOM TEMP °F	74	74	74		
ROOM RELATIVE HUMIDITY	30%	28%	26%		

SAMPLE LOCATION X/L	.167	.333	.500	.667	.834	1.00
PERCENT MOISTURE AVERAGE	6.2	5.7	5.5	5.3	5.4	5.6

BED DEPTH 1.5 inches. GAS FLOW UP THROUGH THE SANDY SOIL WITH MEAN PARTICLE SIZE OF 0.003 INCH 103 STAINLESS STEEL PINS 0.093 Dia., COMPOSITION ASTM 18-8 THERMAL CONDUCTIVITY OF PINS, K = 9 Btu/Ft-Hr-°F(REFERENCE ASM HANDBOOK)
CONDENSATION TIME 16 HOURS
Specific Gravity = 1.55 for compacted bed

Table 6 SUMMARY DATA SHEET TEST RUN D
CONDENSATION PROCESS WITH SATURATED AIR FLOW

	MEASURED			CALCULATED	
TIME HOURS	0	6	10	0	10
FLOW METER					
FLOW CFM	0.23	0.25	0.26		
TEMP °C	25.8	25.9	25.6		
PRESSURE CH HG GAGE	15.7	17.0	17.8		
MASS FLOW G	7.5	8.1	8.7	7.5	
X/L PRESSURE IN BED CM HG GAGE					
0	1.20	1.25	1.30	1.20	1.30
.67	0.40	0.44	0.45	0.40	0.43
.92	0.10	0.10	0.10	0.09	0.10
1.00	0	0	0	0	0
X/L TEMP IN BED °F					
0 INLET-SOIL	69.7	69.5	69.3	69.7	69.3
0 INLET-PIN	69.2	69.1	68.9		
0.25	--	--	--	66.8	66.5
.33	66.3	66.3	66.2		
.50	--	--	--	63.7	63.4
.67	61.7	61.5	61.4		
.75	--	--	--	60.3	60.1
.88	58.2	58.1	58.1		
1.00 OUTLET	56.4	56.4	56.7	56.4	56.4
BUBBLE TANK TEMP°F	76.1	75.8	76.1		
ROOM TEMP °F	76	75	76		
ROOM RELATIVE HUMIDITY	30	27	28		

SAMPLE LOCATION X/L	-.167	-.333	-.500	.667	.834	1.00
PERCENT MOISTURE AVERAGE CONTENT	3.71	3.56	3.59	3.56	3.64	3.82

BED DEPTH 1.5 INCHES. BED INVERTED WITH FLOW DOWN THROUGH SANDY SOIL WITH MEAN PARTICLE SIZE 0.003 INCH WITH 103 STAINLESS STEEL PINS 0.093 INCH DIA - COMPOSITION ASTM 18-8 - THERMAL CONDUCTIVITY OF PINS K = 9 Btu/Ft-HR-°F (REFERENCE ASM HANDBOOK.)

CONDENSATION TIME 10 HOURS.

Specific Gravity = 1.55 for Compacted Bed.

Table 7 SUMMARY DATA SHEET TEST RUN E
CONDENSATION PROCESS WITH SATURATED AIR FLOW

	MEASURED			CALCULATED	
TIME HOURS	0	3	5.5	0	5.5
FLOW METER					
FLOW CFM	0.23	0.24	0.25		
TEMP °C	25.0	25.0	25.1		
PRESSURE CM HG GAGE	15.3	16.1	16.5		
MASS FLOW G	7.5	7.8	8.2	7.5	8.2
X/L PRESSURE IN BED CM HG GAGE					
0	1.50	1.60	1.70	1.50	1.70
.33	1.05	1.10	1.20	1.00	1.13
.83	0.30	0.35	0.40	0.26	0.29
1.0	0	0	0	0	0
X/L TEMPERATURE IN BED °F					
0 SOIL - INLET	66.4	66.1	65.7	66.4	65.7
0 PIN	66.0	65.6	65.2		
.25 SOIL	--	--	--	63.9	63.4
.33 SOIL	64.0	63.7	63.1		
.50 SOIL	62.6	61.6	61.2	61.3	60.9
.67 SOIL	60.0	60.0	59.8		
.67 PIN	59.7	59.6	59.2		
.75 SOIL	--	--	--	58.4	58.2
.83 SOIL	57.3	56.9	56.7		
1.00 EXIT	55.2	55.2	55.2	55.2	55.2
BUBBLE TANK TEMP °F	72.7	72.6	72.7		
ROOM TEMP °F	73	74	73		
ROOM RELATIVE HUMIDITY	20%	15%	15%		

SAMPLE LOCATION X/L	0.167	.167-333	.33-.500	.50-667
PERCENT MOISTURE AVERAGE CONTENT	1.45	1.40	1.38	1.36

SAMPLE LOCATION X/L	.67-834	.83-1.00
PERCENT MOISTURE AVERAGE CONTENT	1.34	1.34

BED DEPTH 1.5 INCHES. BED INVERTED WITH FLOW DOWN THROUGH SANDY SOIL - WITH MEAN PARTICLE SIZE 0.003 INCH. WITH 103 STAINLESS STEEL PINS 0.093 INCHES DIA. - COMPOSITION ASTM 18-8, THERMAL CONDUCTIVITY OF PINS K = 9Btu/Ft-HR-°F (REFERENCE ASM HANDBOOK.)

CONDENSATION TIME 5.5 HOURS.

Specific Gravity = 1.55 for Compacted Bed.

Table 8 SUMMARY DATA SHEET FOR TEST RUN F
CONDENSATION PROCESS WITH SATURATED AIR FLOW

	MEASURED			CALCULATED	
TIME HOURS	0	8	16	0	16
FLOW METER					
FLOW CFM	0.02	0.04	0.05	--	--
TEMP °C	29.4	29.0	29.0		
PRESSURE CM HG GAGE	13.0	13.3	13.5		
MASS FLOW G	0.62	1.24	1.56	0.62	1.56
X/L PRESSURE IN BED CM HG GAGE					
0	0.10	0.13	0.15	0.100	0.150
.33	0.07	0.09	0.11	0.067	0.100
.83	0.02	0.03	0.04	0.016	0.025
.92	0.01	0.01	0.01	0.08	0.014
1.00	0	0	0	0	0
X/L TEMPERATURE IN BED °F					
0 INLET	70.0	68.8	69.0	70.0	69.0
.25	--	--	--	67.0	
.33	65.8	66.0	65.4		
.50	63.4	64.0	63.2	63.8	
.67	61.6	61.7	61.2		
.75	--	--	--	60.1	
.83	58.6	58.7	58.4		
1.00 EXIT	56.1	56.0	56.0	56.1	56.0
BUBBLE TANK	79.8	79.6	79.8		
ROOM TEMP °F	80	79	79		
ROOM RELATIVE HUMIDITY	22%	21%	18%		

SAMPLE LOCATION X/L	0.167	.167-.33	.33-.50	.50-.667
PERCENT MOISTURE AVERAGE CONTENT	0.92	0.85	0.77	0.82
SAMPLE LOCATION X/L			.67-.83	.83-1.0
PERCENT MOISTURE AVERAGE CONTENT			0.83	0.86

BED DEPTH 1.5 INCHES. GAS FLOW UP THROUGH SPHERICAL GLASS BEADS WITH MEAN DIA. 0.008 INCH. THERMAL CONDUCTIVITY OF SOLID GLASS 0.6 Btu/Ft-HR-°F

CONDENSATION TIME 16 HOURS.

Specific Gravity = 1.55 for Compacted Bed.