

# INTERACTION OF A MOIST CAPILLARY-POROUS SOLID WITH A HOT GAS FLOW

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An experimental investigation of the temperature distribution in the boundary layer of air above a capillary-porous solid from which a liquid is evaporating is described. An analysis of the experimental results confirms Lykov's hypothesis of the presence of a bulk evaporation source in the boundary layer of air above a capillary-porous solid. This source increases the rate of heat and mass transfer from the solid to the air flow.

Heat and mass transfer between a moist capillary-porous solid and its surroundings is a complicated, interrelated process. Its main feature is that in this case effects taking place within the solid determine the nature of the interaction of the solid and its surroundings. Although such processes are complex, their investigation is of great importance, since similar effects are a feature of such technological processes as drying, evaporative cooling, molecular distillation, etc. In this case evaporation takes place at some depth within the solid and not at its surface. Because of the presence of a dry interlayer of material the heat and mass transfer cannot be calculated from the usual heat transfer formulas. Hence, there is a need to investigate the effect of submersion of the evaporation surface on heat- and mass-transfer coefficients.

This paper gives the results of an experimental investigation of heat and mass transfer from a capillary-porous solid to a gas flow with the evaporation surface inside the solid. The experiments were carried out on the apparatus described in [1]. The test specimen was a model capillary-porous solid made of clear plastic in the form of a  $0.2 \times 0.1 \text{ m}^2$  flat plate and filled either with quartz sand or  $\text{Al}_2\text{O}_3$  powder. The parameters of the external flow in the experiments were  $t_\infty = 50^\circ\text{C}$ ,  $w_\infty = 5 \text{ m/sec}$ ,  $\varphi = 7\%$ , and the depths of the evaporation front were 0, 2, 4, 6, and 8 mm. We investigated the velocity and temperature distribution in the air boundary layer, the temperature gradient in the dry interlayer of the capillary-porous solid, the temperature gradient on the solid surface in the direction of the flow, and the amount of vapor removed from the solid by evaporation. As was shown in [2], the transverse mass flow has no significant effect on the hydrodynamics of the process. When a liquid evaporates from the pores of a solid a laminar boundary layer is formed at the "solid-air" interface (see Fig. 1). The evaporation of water from the specimen surface was an almost adiabatic process. The process became markedly nonadiabatic when the evaporation front moved into the solid. Significant heat loss from the sides of the experimental solid was prevented by thorough heat insulation. Check measurements showed that heat loss from the sides of the solid and radiative heat transfer between the black walls of the working chamber and experimental solid could be neglected (these two components did not constitute more than 5% of the total heat balance).

Figure 2 shows the temperature distribution in the air boundary layer for quartz sand and alumina powder. The graphs show that the gradient of the curves increases with reduction of the depth of the evaporation surface. At large depths the relationship is almost linear, i.e., it is similar to the case of "pure" heat transfer. The curve has maximum gradient when evaporation takes place at the surface. The temperature of the solid surface increases with increase in the depth of the front and, hence, the temperature difference  $t_\infty - t_w$  is reduced.

The evaporation rate decreases with increase in  $\xi$ . A qualitative assessment of the water evaporation rate indicated that evaporation is much more rapid from the pores of  $\text{Al}_2\text{O}_3$  powder (see Table 1). This fact can be explained in the following way. The quartz sand used had a strictly defined particle size obtained

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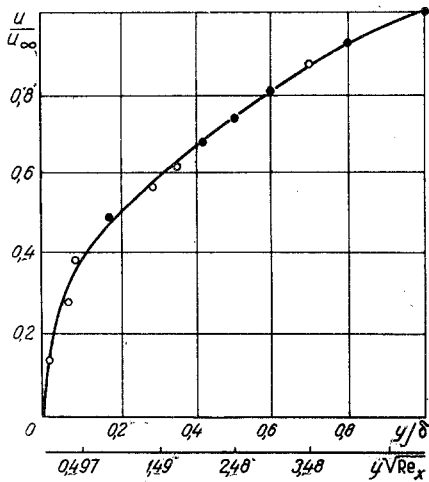


Fig. 1. Profile of velocity distribution  $u_x(y)$  in air boundary layer [circles) experiment; dots) calculation].

by passage through chemical sieves. It would presumably have a fairly uniform structure and there would be no great variation in the size of the capillaries. The situation was quite different in the case of  $Al_2O_3$  powder. The mean diameter of the alumina particles were approximately  $0.15 \mu$ . A powder with such fine pores should have very high porosity (up to 90%). It is known, however, that any disperse material can have a porosity of 46.7%, corresponding to cubic packing, or 26%, corresponding to hexagonal packing. This indicates that in such a capillary-porous substance some  $Al_2O_3$  particles form solid inclusions. This produces a highly inhomogeneous system with capillaries ( $r < 10^{-5}$  cm) and large cavities (this can be seen by using a microscope with a binocular attachment). In a capillary-porous solid of this structure the moisture distribution is altered. The capillaries extract water from the large pores and the pressure drop in the dry interlayer will depend considerably on its capillary-porous structure. This leads to an increase in the flow rate of the evaporated liquid.

We will give an account of the method of calculating the heat fluxes and heat-transfer coefficient. The amount of heat passing from the hot air flow into the capillary-porous solid was calculated in two ways. The first method involved the temperature profile in the air boundary layer

$$q = -\lambda_a \left( \frac{\partial t}{\partial y} \right)_{y \rightarrow 0}; \quad (1)$$

while the second method used the amount of heat passing through the dry interlayer of the capillary-porous solid due to its heat conduction

$$q = -\lambda_i \frac{t_w - t_s}{\xi}. \quad (2)$$

The good agreement of the results obtained by the two methods indicates that they are equally applicable to the described process (see Table 2).

It is of interest to note that the method of heat flux calculation used in the case of evaporation of liquid from a solid surface

$$q = jr + q_h \quad (3)$$

(in adiabatic conditions the second term is omitted from the equation) is quite unsuitable in the case of evaporation of a liquid from within a capillary-porous solid. The heat which can pass through the dry interlayer of the solid is not sufficient for evaporation of the amount of water which is converted to vapor. A saturated vapor-air mixture moves through the pores in the solid. Since the matrix of a capillary-porous

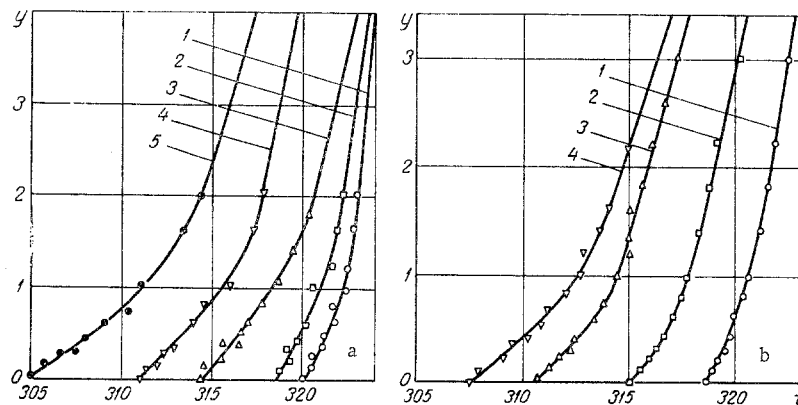


Fig. 2. Temperature distribution over quartz sand (a) and over  $Al_2O_3$  powder (b) ( $y$ , mm;  $t$ , °K): 1, 2, 3, 4, 5) thickness of dry interlayer 8, 6, 4, 2, and 0 mm, respectively.

TABLE 1. Flow Rate of Evaporated Water  $j$  ( $\text{kg}/\text{m}^2 \cdot \text{h}$ )

Material	$\xi$ , mm				
	0	2	4	6	8
Quartz sand	2,1	1,1	0,85	0,70	0,52
$\text{Al}_2\text{O}_3$ powder	—	2,2	2,1	1,8	1,2

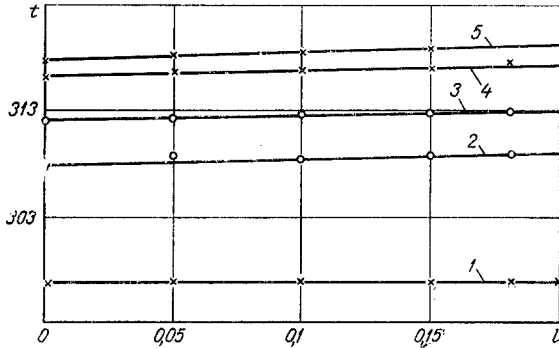


Fig. 3. Plate surface temperature distribution along  $x$ -axis ( $t$ ,  $^{\circ}\text{K}$ ;  $l$ ,  $\text{m}$ ): 1, 2, 3, 4, 5) thickness of dry interlayer 0, 2, 4, 6, and 8 mm, respectively.

in  $q$  and  $t_w$  are not directly related. Both the heat flux and the solid surface temperature depend on the thermal resistance of the dry interlayer and the thermal resistance of the air boundary layer. Because of the complex structure of the capillary-porous solid in which evaporation occurs the heat flux decreases more slowly than the surface temperature increases, which leads to an increase in the heat-transfer coefficient. This again confirms the fact that a rigorous formulation of the problem of heat transfer between a damp capillary-porous solid and its surroundings will necessitate the joint consideration of the heat transfer inside the solid and the interrelated heat and mass transfer in the boundary layer close to its surface. Neglect of particular factors (flow temperature, velocity, humidity, porosity of solid, thermal conductivity of solid, thickness of dry interlayer) can lead to quantitatively and qualitatively contradictory results.

To find out if the heat-transfer coefficient is increased or reduced when liquid evaporates from a solid in comparison with "pure" heat transfer, we experimentally measured the temperature profile in the air boundary layer and determined the heat-transfer coefficient, uncomplicated by mass transfer, by the method described above. The ratio  $\alpha_{\xi}/\alpha_0$  or  $\text{Nu}_{\xi}/\text{Nu}_0$ , denoted by the dimensionless complex  $N$ , was greater than unity. This indicates that in the case of low-rate processes the transverse mass flow leads to an increase in the heat-transfer coefficient. This was confirmed by the temperature distribution along the solid surface. In the case of adiabatic evaporation  $t_w$  will be constant and equal to the temperature of a wet-bulb thermometer in the flow, and the temperature head  $\Delta t$  will be  $t_{\infty} - t_w$ . If the process is non-adiabatic the solid surface temperature will differ from the reading of a wet-bulb thermometer. Figure 3 shows the solid surface temperature profile along the flow for quartz sand and an external flow with  $t_{\infty} = 50^{\circ}\text{C}$  and  $w_{\infty} = 5 \text{ m}/\text{sec}$ . Figure 3 shows that the temperature head increases in the direction of the gas flow. Since the flow velocity and temperature differences in the experiments were small the temperature head along the plate was 1–3 $^{\circ}\text{C}$ . A higher temperature head can be expected at higher temperatures and velocities.

It was also noted that with increase in the interlayer thickness the temperature difference between the beginning and end of the plate increased. It is known from heat-transfer theory that if the temperature head in the direction of the heat flow on the surface of a solid is increased, the heat-transfer coefficient is greater than at constant surface temperature. Hence, with increase in the thickness of the dry interlayer the heat-transfer coefficient between the flow and the solid surface will increase.

solid offers a fairly high hydraulic resistance to mass transfer, there will be no flow of moisture unless there is a pressure difference in the pores. The greater the thickness of the dry interlayer, the greater the pressure gradient. The moist vapor air mixture will be expelled and will subsequently evaporate in the air flow over the plate surface. Hence, we can postulate the presence of an additional heat sink ("bulk" evaporation) over a capillary-porous solid.

Table 2 gives the values of the heat-transfer coefficient between the solid surface and the gas flow.

The tabulated data indicate that the heat transfer coefficient increases with increase in the depth of the evaporation front. This is due to the fact that an increase in  $\xi$  causes an increase in the temperature of the solid surface and a reduction of the heat flux. The changes

TABLE 2. Heat Characteristics in Relation to Thickness of Dry Interlayer of Material

$\varepsilon$	$q_1$	$q_2$	$q_3$	$\alpha$	Nu	$N = \frac{Nu_e}{Nu_0}$	H	K	$N^*$
Quartz sand									
0	212	202	1180	10,1	72	1,23	—	—	—
2	156	148	985	10,34	74	1,27	524	0,427	1,26
4	122,9	117,5	890	11,0	79,2	1,35	262	0,2135	1,32
6	78,0	70,8	602	11,28	80,5	1,37	175	0,1428	1,40
8	62,5	57,5	553	11,5	82,1	1,4	131	0,107	1,46
Alumina powder									
2	162	156	1627	9,32	66,7	1,14	1430	1,165	1,15
4	150	135	1590	10,2	73,2	1,25	715	0,582	1,20
6	106	119	1440	10,5	76,3	1,30	477	0,389	1,25
8	70,8	102	1057	10,9	78,5	1,33	358	0,292	1,30

Note:  $N^*$  is calculated from Eq. (3).

The obtained experimental data were also correlated by general relationships obtained from a solution of the differential transport equation in a boundary layer with allowance for the effect of submersion of the evaporation surface [2, 3].

The dimensionless variable  $K = Hx/\sqrt{Pe}$  (where  $H = \lambda_a/\lambda_s \xi$ ) characterizes the effect of submersion of the evaporation surface on the heat-transfer coefficient;  $B = (w_y/w_x)Re_x^{0.5}Pr^{0.5}$  is a dimensionless parameter characterizing mass transfer in the transverse direction. If we assume a parabolic velocity distribution  $w_x(y)$  along the plate on the  $y$  axis, then  $B = 0.21$  (see [3]). The quantity  $N$  characterizes the relative increase in the local Nusselt Number due to evaporation of water from a capillary-porous solid

$$N(K, B) = \frac{\sqrt{\pi Nu_x}}{\sqrt{Pe_x}} = \frac{\varphi(K, B) - \frac{1}{2} \sqrt{\pi B} \operatorname{erfc} \frac{1}{2} B}{\left(1 - \frac{B}{K}\right) - \frac{1}{KV\pi} \varphi(K, B) + \frac{1}{2} \frac{B}{K} \operatorname{erfc} \frac{1}{2} B}, \quad (4)$$

where

$$\varphi(K, B) = \left(1 - \frac{1}{2} \frac{B}{K}\right) \sqrt{\pi K} \exp(K^2 - BK) \operatorname{erfc} \left(K - \frac{1}{2} B\right). \quad (5)$$

The values of  $H$  and  $K$  were determined for quartz sand and  $Al_2O_3$  powder and the values of  $N$  were calculated from formulas (4) and (5). Table 2 gives the results of the calculations, which also confirm the conclusion that the heat-transfer coefficient is higher in the case of evaporation from capillary-porous solids than in the case of a dry solid.

The experimental measurements of the thermal boundary layer in the case of evaporation of water from  $Al_2O_3$  powder and quartz sand into a flow of hot air lead to the following conclusions:

1. The thermal boundary layer associated with evaporation of a liquid depends on the depth of the evaporation surface.
2. The heat flux on the wall  $q = -\lambda_a (\partial t / \partial y)_{y \rightarrow 0}$  is many times greater than the heat flux given by Eq. (3), which indicates that vapor-gas mixture is expelled from the pores and subsequently evaporates in the air flow and its boundary layer.
3. Evaporation of water from the pores of alumina powder is more rapid than from quartz sand. This can be attributed to the complex structure of  $Al_2O_3$  powder. Its high porosity (about 90%) is due to the fact that there are large cavities between particle conglomerates, in addition to micropores ( $r < 10^{-5}$  cm).
4. When a dry interlayer is present the heat flux depends on the thermal resistance of the boundary layer and the dry interlayer. The surface temperature increases and the heat flux decreases with increase in  $\xi$ . There is no direct relation between the change in these quantities. In view of the complex structure of the capillary-porous solid in which evaporation occurs the heat flux decreases

more slowly than the surface temperature increases, and, hence, since  $q = \alpha (t_\infty - t_w)$ , there is an increase in the rate of emission of vapor-water mixture from the pores with increase in  $\xi$  and, hence, an increase in the heat-transfer coefficient.

#### NOTATION

t	is the temperature;
w	is the velocity;
$\varphi$	is the moisture content;
$\xi$	is the thickness of dry interlayer of solid;
r	is the pore radius;
q	is the specific heat flux;
x, y	are the coordinates;
$\lambda$	is the thermal conductivity;
j	is the mass flow density;
$\alpha$	is the heat-transfer coefficient;
a	is the thermal diffusivity;
Nu	is the Nusselt number;
Pr	is the Prandtl number;
$Re_x$	is the local Reynolds number;
$Pe_x$	is the local Peclet number referred to mean integral velocity in boundary layer ( $\overline{Pe}_x = \overline{w}_x x / a$ ).

#### Subscripts

$\infty$	denotes the flow;
w	denotes the wall;
0	denotes the dry solid.

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