HEAT TRANSFER IN A DYNAMIC TWO-PHASE BED AT REDUCED PRESSURES

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The design of plants for the chemical and petroleum industries, heat exchangers for transport equipment, and several other problems necessitates a knowledge of the variation of the coefficient of heat transfer from surfaces situated in a dynamic two-phase bed at reduced pressures.

The results of the investigations given in [1-4] relate to atmospheric pressure and their treatment was based on simplifying assumptions. The present paper is devoted to an investigation of heat transfer on a cylindrical calorimeter under the following conditions: reduced velocity of light phase $W_0'' = (0.5 + 3.5)$ m/sec, specific heat flux $q = (20\text{-}120)$ kW/m^2, and initial air temperature $t_1'' = 15\text{-}90°\text{C}$ and pressure range (0.8-0.1) bar. The light phase was air and the heavy phase water.

It should be noted that at reduced pressures the air flow rate per kWh power consumption is greatly reduced and its vapor content increases. At $p = 1.0$ bar the velocity W_0'' of the liquid phase is determined solely by the air volume flow rate, whereas at reduced pressure the vapor volume flow rate must also be taken into account.

Figure 1 shows a diagram of the experimental apparatus. The clear plastic tower 1 was connected through a valve 11 and trap 14 to a VN-4G vacuum pump. A slit separator 12 was mounted at the top of the column to reduce entrainment of the liquid. The calorimeter 2 ($d = 8$ mm, $l = 80$ mm) was powered through an autotransformer 18. The air was heated by an electric heater 26, which was powered through an autotransformer 25. The air flow rate was measured by a calorimetric flowmeter 27. The flowmeter was powered through an autotransformer 20. At low air flow rates the volumetric method employing a gasholder 19 was used. The water was delivered to the tower through valve 3 and was drawn off through the drain cock 29 into tank 28.

To measure the moisture content of the vapor–air mixture at the outlet from the tower we used a psychrometric probe 4 [5]. The velocity of the air flowing through the probe was measured with a rheometer 8. A mercury vacuum gauge 13 was used to measure the pressure in the tower. A barometer 17 and an Assmann psychrometer 16 were used to measure the parameters of the surrounding atmosphere.

A stable foam layer was observed in experiments in the considered temperature range. At $p < 0.1$ bar, $W_0'' > 2.0$ m/sec, and low heat fluxes, however, there was local ice formation below and above the gas-distributing grid. When the heat flux was increased and the velocity W_0'' was reduced, the ice disappeared.

As an example, Fig. 2 shows some relationships, which confirm the conclusions obtained at atmospheric pressure: a and b are plots of the heat-transfer coefficient α against foam temperature t^* and air temperature t_1'', respectively, at $p = 0.2$ bar, $W_0'' = 1.5$ m/sec, $q = 100$ kW/m^2; c is a plot of t^* against the specific heat flux q at $p = 0.1$ bar and $W_0'' = 1.5$, 1.0, and 0.5 m/sec (curves 1, 2, 3). In our investigation, proceeding from the assumption of insignificant heat flux due to evaporation of the liquid film covering the heat-exchange surface and the negligibly small heat resistance of the dynamic two-phase bed (owing to the greatly increased interphase surface), and using the well-known methods [6], we obtained the following dimensionless relationship:

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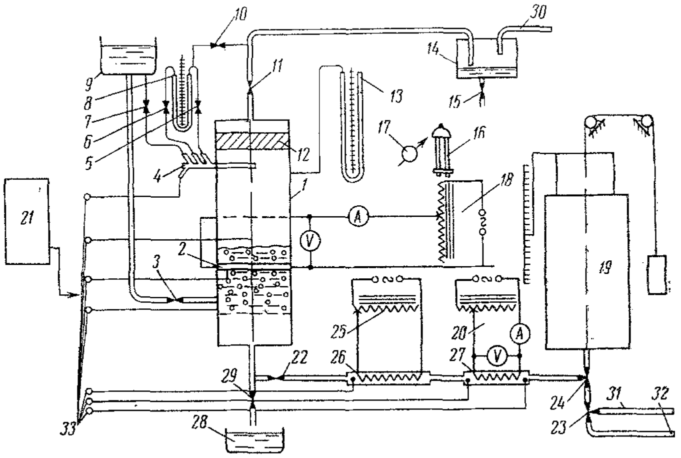

Fig. 1. 5,6,7,10,15,22,23,24) Regulating valves; 9) tank for liquid; 21) potentiometer; 30) pipe to vacuum pump; 31) air from atmosphere; 32) air from compressor; 33) thermocouples.

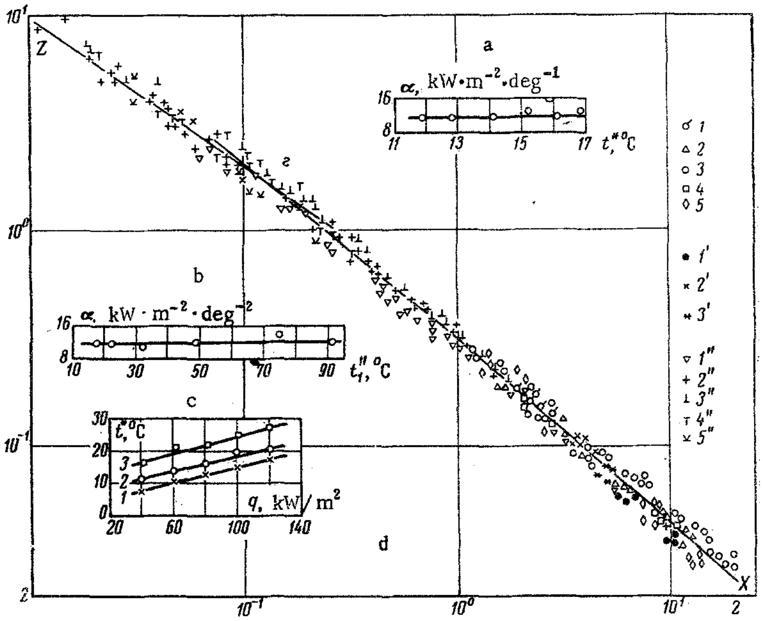

Fig. 2. 1-4) Data obtained in [1-4] for air–water system: (d = 4, 8, 13, and 18 mm, respectively); 5) data obtained in this investigation for air–water system, p = 0.1-0.8 bar; 1',2',3') data obtained in [1-4] for systems composed of air and aqueous solutions of Na oleate, glycerol, and ethyl alcohol, respectively; 1'',2'',3'',4'',5'') data taken from [8, 9, 10, 11, 12, 13], respectively.

$$S^* = f\left(K,\ R^*,\ W,\ (\rho' - \rho'')/\rho'',\ \mu''/\mu',\ P'\right) \tag{1}$$

Here S* is the Stanton number referred to the light phase; K is the hydrodynamic stability number of the two-phase flow [7]; R* is the Reynolds number referred to the kinematic viscosity of the heavy phase; W is the Weber number; P' is the Prandtl number

$$S^* \equiv \frac{\alpha}{W_0'' C_p' \rho'},\quad K \equiv \frac{W_0'' \sqrt{\rho''}}{[\sigma g (\rho' - \rho'')]^{1/4}},\quad R^* \equiv \frac{W_0'' d}{\nu'},\quad W \equiv \frac{\sigma}{g(\rho' - \rho'') d^2},\quad P' \equiv \frac{\nu'}{a'}$$

Figure 2d shows the correlation of the experimental heat transfer results in the form

$$Z = f(X),\ X = (K^2R^*)^{1/3}$$

$$Z = S^* P'^{0.56} W^{0.07} ((\rho' - \rho'')/\rho'')^{0.35} \tag{2}$$

The value of $(K^2R^*)^{1/3}$ at which the nature of the illustrated functional relationship changes can easily be determined from Fig. 2. This value is approximately 0.1-0.2 and for air–water and air–alcohol systems corresponds to the changeover from the nucleate regime to the bubbling regime.

Thus, for bubbling and well-developed bubbling (foam) regimes we have

$$S^* = 0.31 K^{-0.56} R^{*-0.28} P^{-0.56} ((\rho' - \rho'')/\rho'')^{-0.35} W^{-0.07} \tag{3}$$

Similarly, for the nucleate regime we obtain

$$S^* = 0.37 K^{-0.48} R^{*-0.24} P'^{-0.56} ((\rho' - \rho'')/\rho'')^{-0.35} W^{\ 0.07} \tag{4}$$

Relationship (3) is of most interest for practical problems. The differences between the experimental data and the data obtained from (3) and (4) do not exceed ±10% in the vast majority of experiments.

Formula (3) can also be put in the form

$$S^* = 0.31 R^{*-0.28} F''^{-0.28} P'^{-0.56} ((\rho' - \rho'')/\rho'')^{-0.35} W^{-0.07} \tag{5}$$

Here F" is the Foude number

$$F'' \equiv W_0''^2 / gd$$

It is easy to establish from (5) that α increases insignificantly with increase in σ ($\alpha \sim \sigma^{0.07}$), decreases with increase in diameter d of the heat exchanger ($\alpha \sim d^{0.14}$), and decreases slightly with reduction of the gas phase density ρ'' ($\alpha \sim \rho''^{0.07}$). Hence, we can neglect the effect of the last two complexes. Replacing them by the mean values from the experiments we obtain after correction of the constant C,

$$S^* = 0.15 R^{*-0.28} F''^{-0.28} P'^{-0.56} \tag{6}$$

The values of α obtained from Eq. (6) agree satisfactorily with the experimental data; the differences do not exceed ± (15 + 18%).

In [1,2] we obtain the relationship

$$S^* = 0.108 R^{*-0.26} F''^{-0.26} P'^{-0.52} \tag{7}$$

The differences between the constant C and the indices of the powers in the complexes in (7) and (6) can be attributed to the fact that Eq. (7) was derived by correlating experimental data for heat transfer from the surface of a tower wall, which proceeds at a lower rate than the heat transfer of cylinders and spheres, which were used to obtain relationships (3) and (5).

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