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BOILING OF REFRIGERANTS ON DIFFERENTLY ORIENTED TUBES PLACED IN GRANULAR BEDS

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Experimental investigation of the boiling heat transfer of refrigerants R12 and R227 on inclined tubes placed in granular beds has been carried out. The plots show the reduced coefficient of heat transfer as a function of the reduced specific heat flux for various positions of a tube placed in different granular beds.

Investigations of boiling heat transfer in granular and porous media are being given much attention at present. The publications of the last ten years have been reviewed in [1]. As has been found, the main factors that have an effect on the intensity of heat transfer are the porosity and the pore size, the velocity of a liquid, the diameter of the particles of a granular bed, absorption conditions, and the position of heat-transfer surfaces. But the existing works devoted to investigation of the influence of the orientation of tubes are too few.

We have carried out experimental investigations of the boiling heat transfer on tubes of different orientation (horizontal, vertical) for refrigerants R12 and R227 and additionally on inclined tubes for refrigerant R227. A laboratory setup (Fig. 1) was used.

The main units of the stand were boiler 1 and condenser 2 combined in one vessel. Two copper tubes 4 and 5 with a diameter of 8 mm were installed in the boiler. One of them was placed in a granular bed. Glass spheres of d = 0.8 and 1.1 mm and metal spheres of d = 1.3 mm were used as the particles of granular materials.

During the experiments, we supplied hot water from thermostat 3 to one tube of the boiler; the liquid boiled up on the tube surface, and the vapor formed rose to the condenser 2 and was condensed on the tubes of a coil pipe at which cold water arrived. Using a joint we changed the position of the stand from the horizontal position to a vertical one through intermediate angles of inclination of the tube to the horizon which were measured with a cathetometer.

In the course of the experiments, we determined the saturation pressure in the boiler by a Sapfir 22DT pressure transducer 6, the surface temperature of the wall of the working tube by Chromel–Copel thermocouples 8 chalked into it, the flow rate of the hot water in the tube by rotameter 7, and the water temperature at the inlet and the outlet of the tube by thermocouples. The liquid temperature was determined using thermocouples installed in the neighboring unheated tube. The measurements were carried out in an automated regime with the use of an IBM PC computer.

From the data obtained we calculated the parameters that determine boiling heat transfer, i.e., saturation temperature T_s for the corresponding refrigerants from the P–T dependence, average temperature of the tube wall T_w as the mean arithmetic temperature of the tube wall at eight points, density of the heat flux q through the surface of the working tube from the difference of the enthalpies of the water at the inlet and the outlet, temperature head wall–liquid ΔT, and coefficient of heat transfer from the wall to the liquid α.

As is known, in the process of boiling of a liquid, one singles out two main regimes, i.e., the nucleate regime and the film regime [2]. With a certain heat flux, called first critical, the nucleate regime of boiling

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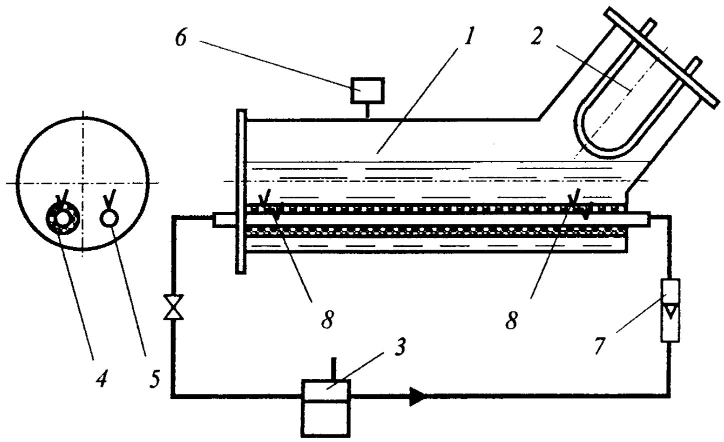

Fig. 1. Scheme of the experimental setup for investigation of boiling heat transfer on differently oriented tubes placed in granular beds.

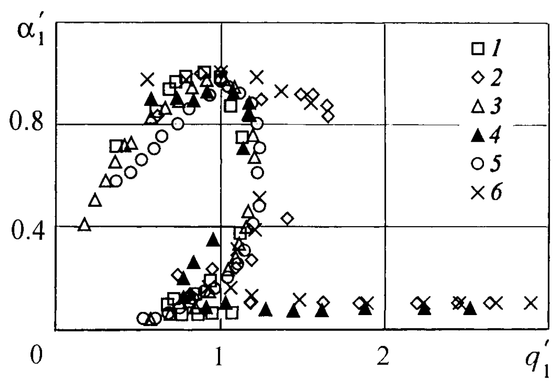

Fig. 2. Heat-transfer coefficient vs. heat flux in boiling of refrigerant R12: 1) d = 0.8 mm, horizontal orientation, 2) vertical orientation, 3) d = 1.1 mm, horizontal orientation, 4) vertical orientation, 5) d = 1.3 mm, horizontal orientation, and 6) vertical orientation.

is replaced by a film regime, which causes the coefficient of heat transfer to decrease significantly. The reverse transition from the film regime of boiling to a nucleate one is realized with a heat flux severalfold smaller than the first critical flux. This heat flux is called second critical.

In boiling of liquids on surfaces placed in a granular bed, the picture is different. One observes no change of boiling regimes, i.e., no rapid transition from the nucleate regime to a film one. Conversely, the transition observed is rather long and smooth; it is accompanied by a gradual decrease in the heat-transfer coefficient with increase in the heat-flux density, i.e., the region of a transient regime exists, which we observed in the course of the experiment. Obviously, in this region of the transient regime, the two types of boiling replace each other both with time and over the surface until complete steaming occurs, in which the entire surface of the tube is covered with a vapor film and the heat-transfer coefficient is constant.

The authors consider it necessary to refine the terminology of definition of the critical heat fluxes in boiling of liquids on surfaces placed in a granular bed unlike the case of boiling on smooth surfaces, since there is no sharp transition from the nucleate boiling to film boiling. The values of the heat flux for which the heat-transfer coefficient attains its maximum value α_{cr1} and thus, at $q = q_{cr1}$, the regime of transition from nucleate boiling to film boiling occurs will be assumed to be the first critical heat flux q_{cr1}. The value of the heat flux for which the heat-transfer coefficient becomes constant (α = const) and the minimum value $\alpha_{cr2} = \alpha_{min}$ occurs and thus the film regime of boiling is realized for $q > q_{cr2}$ will be assumed to be the second

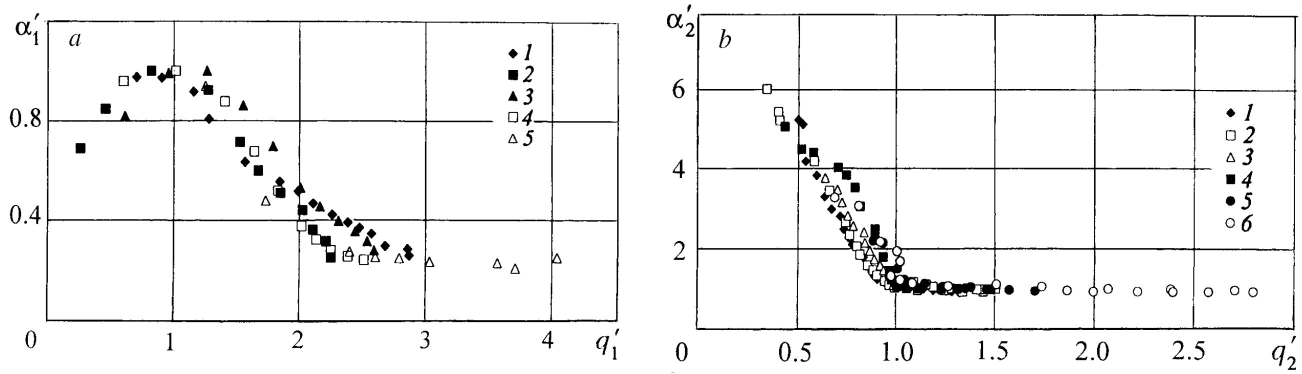

Fig. 3. Reduced coefficient of heat transfer vs. reduced heat flux in boiling of refrigerant R227 (d = 1.1 mm) (a) and 0.8 mm (b)): (a) 1) $\varphi = 0^o$, 2) 10^o, 3) 50^o, 4) 70^o, and 5) 90^o; (b) 1) $\varphi = 0^o$, 2) 5^o, 3) 35^o, 4) 50^o, 5) 70^o, and 6) 90^o.

critical heat flux q_{cr2}. When $q_{cr1} < q < q_{cr2}$ the region of the transient regime of boiling appears; in this regime, the steaming is local, unlike the case of the film regime where the steaming is complete.

With the aim of generalizing experimental data on the boiling of refrigerants on variously oriented tubes placed in different granular beds we introduce the generalized coordinates $\alpha'_1 = f(q'_1)$ and $\alpha'_2 = f(q'_2)$, where $\alpha'_1 = \alpha/\alpha_{cr1}$ and $\alpha'_2 = \alpha/\alpha_{cr2}$ are the reduced coefficients of heat transfer and $q'_1 = q/q_{cr1}$ and $q'_2 = q/q_{cr2}$ are the reduced specific heat fluxes.

Figure 2 shows results of processing of experimental data for refrigerant R12 in reduced coordinates. It follows from the figure that the profiles of the curves $\alpha'_1 = f(q'_1)$ for the horizontal and vertical positions of the tube are of the same character. In the experiments, we were able to obtain rather extended regions of the nucleate and transient regimes of boiling and small regions of film boiling for the horizontal position of the tube and a more extended region of film boiling than in the cases of nucleate and transient boiling for the vertical position of the tube. Thus, the experimental data in reduced coordinates can be generalized with a certain degree of approximation by a single curve $\alpha'_1 = f(q'_1)$. Furthermore, one can clearly recognize three different regularities of heat exchange on the plot which correspond to dissimilar regimes: nucleate, transient, and film boilings.

Figure 3a shows results of processing of experimental data for refrigerant R227 in reduced coordinates. As is seen from the figure, the profiles of the curves $\alpha'_1 = f(q'_1)$ for a charge with 1.1-mm spheres for all the angles of inclination of the tube are of the same character: on all the curves, one observes an extended region of the transient regime, and only for the vertical position of the tube ($\varphi = 90^o$) do we have a stable region of film boiling when $q'_1 > 2$. An analogous picture is seen in Fig. 3b, i.e., the profiles of the curves $\alpha'_2 = f(q'_2)$ for a charge with 0.8-mm spheres are the same; there is an extended region of the transient regime. Stable film boiling is also observed for the vertical position of the tube ($\varphi = 90^o$). The plots show a rather good generalization of the experimental data in reduced coordinates.

Thus, as a result of processing the experimental data of the investigation of the process of boiling of refrigerants R12 and R227 in granular media we have detected the presence of a stable region of the regime of transition from the nucleate boiling to film boiling; in reduced coordinates, we have been able to generalize the experimental data obtained by a single plot, which is independent of the angle of inclination of the tube.

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NOTATION

d, particle diameter, mm; *T*, temperature, ^oC; *q*, heat-flux density, W/m^2; α, heat-transfer coefficient, $W/(m^2 \cdot K)$; φ, angle of inclination of the tube, deg. Subscripts: s, saturation; w, wall.

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