HEAT TRANSFER CHARACTERISTICS OF TUBE BUNDLES DURING BOILING IN VACUUM

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Heat transfer during boiling in vacuum was compared experimentally for single tubes, rows of tube, and tube bundles to analyze characteristic properties of vaporization under such conditions. Relations for calculating heat transfer coefficients are proposed.

Physical heat transfer properties during the boiling of liquids in vacuum with the use of tube bundles as the heating surfaces, which are used in commercial heat exchangers in food, power, and ship-building industries, have been insufficiently studied [1-5].

In order to evaluate the heat transfer process during the boiling on tube bundles in vacuum, we compared the vaporization on a single tube, a single-row heat exchanger consisting of six horizontal vertically-stacked tubes, and a horizontal in-line bundle of three tube rows.

The pressures took the values of 100, 60, 40, 20, and 6 kPa; heat fluxes were between 22 and 132 kW/m^2; and the geometrical sizes of the tubes were $d = 18/2$ mm and $l = 400$ mm. The relative longitudinal s_1/d and transverse s_2/d spacings were set at 1.25, 1.5, and 2.0.

Visual observations and the filming of the evaporation process on a single tube between atmospheric pressure and 6 kPa indicated substantial qualitative changes on its surface caused by the operating pressure.

At $p = 100$-60 kPa and low heat fluxes ($q = 22$ kW/m^2), the distance between adjacent nucleation sites was much larger than the size of vapor bubbles. The number of active nucleation sites on a tube surface increased, and the distance between them decreased, as the heat flux ($q = 44$ kW/m^2) increased.

An assessment of the process for $q = 22$-66 kW/m^2 suggests that vapor bubble formation and growth almost coincide with vaporization on flat horizontal surfaces [6-8]. For the maximum heat flux ($q = 132$ kW/m^2), boiling visually corresponded to the process at atmospheric pressure with $q = 88$ kW/m^2. According to the results of our studies, features in the vaporization on a single tube begin to appear at $p \leq 20$ kPa. This pressure level was mentioned in [8, 9] as a transition boundary for unstable boiling.

The departure diameters of vapor bubbles reached 6-10 mm at $p = 20$ kPa for large-volume developed boiling generated by a heat flux of $q = 132$ kW/m^2. According to the data of [8], at a pressure of 20 kPa, the unstable boiling mode on electrically heated surfaces corresponds to q between 22 and 110 kW/m^2.

The heat load decrease was accompanied by an insignificant decrease of the departure rate and of the number of nucleation sites, as well as by the growth of departure diameters to 10-15 mm. After $q \leq 44$ kW/m^2, vaporization became irregular with a limited number of nucleation sites and intermittent vapor generation. Higher heat loads (up to 100 kW/m^2) resulted in bubbles of 20-25 mm.

Boiling was most unstable at a pressure of 6 kPa. Under these conditions, 6-8 sec intervals were observed between the generation of single bubbles at $q = 66$ kW/m^2, and their diameter reached 70 mm.

Representing the data as $\alpha_2 = Aq^n$ suggests that the decreasing pressure relative to atmospheric pressure changes n from 0.7 to 1.0. The pressure drop during boiling causes a significant decrease in the heat transfer coefficient and its stronger dependence on q.

An analysis of the data obtained by the authors and in [9, 10] on the basis of D.A.Labuntsov's equation has shown (Fig. 1) that its primary form satisfactorily describes atmospheric and low pressure boiling results:

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$$Nu = 0{,}15\, Re_*^{0{,}56} Pr^{1/3}. \tag{1}$$

An examination of vaporization conditions for tube rows has shown that vapor bubbles are generated over the whole surface of tubes whose diameters in the bottom part are larger than at the top. Similar to atmospheric and lower pressure conditions, at $p \leq 20$ kPa boiling on the tubes of a row at the inlet started on the upper tubes. For underheated boiling, when the temperature in the volume of the liquid was below the saturation point, surface boiling started as nucleation on the lower tubes. When sliding over a tube surface, the bubbles increased their sizes and, reaching a diameter of about 10 mm on the upper tube, they condensed. This was especially distinct at a pressure of 6 KPa. In this case, the bubble diameters reached 1.5-2 tube diameters. As seen from the film, for 20 kPa, the mechanism was very complex and different along the row height and along the tubes (Fig. 2). For $p \leq 10$ kPa, the number of nucleation sites is very limited, and the vaporization rate is less than at 20 and 40 kPa.

In spite of its unstable character over tube rows, vaporization on the whole had no long intervals even at 6 kPa and had minimal heat fluxes. The departure bubbles for rows had smaller sizes than for a single tube under similar conditions.

Stable vaporization on rows was essentially determined by the vaporization rate on a lower tube. Here, vaporization had a lower rate. However, the development and growth of a vapor phase on this tube appreciably changed vaporization across the whole row. The bubbles which originated on a lower row tube and then rose up were in contact with the wall layer of the whole row. As a result, their sizes and velocity increased sharply. An analysis of the boiling data (Fig. 3) shows that the heat transfer rate over the row tubes decreases as pressure is lowered, and the rate of the decrease is different for different pressures and heat fluxes. At atmospheric and lowered pressures ($p \geq 40$ kPa), the tube row effect on the heat transfer rate for low q is more significant than for $p \leq 20$ kPa. For pressures consistent with vacuum conditions, at all heat fluxes, α_2 coefficients are determined by tube arrangement in a row. This dependence becomes stronger as the heat load increases along the row height, especially for $p \leq 10$ kPa.

An analysis of our observations and films of the process on horizontal tube bundles suggest that the influence of adjacent vertical rows on the heat transfer rate is most distinct for $p \leq 10$ kPa.

Stable boiling was observed on all three tube rows at $p = 20$ kPa. Under these conditions, the number of large bubbles was smaller as compared to vaporization on rows. Bubbles were formed around lower tubes and departed from side walls, the bubble sizes (3-5) mm being considerably smaller than those in row boiling. Further vapor phase development proceeded in bundle passages where, at a lower tube level, the bubbles in a liquid flow were smaller. During the rise of growing bubbles in passages, the bubbles partially fused and a uniform vapor phase in the center of a vapor-water flow filled up individual sections of vertical passages. The rate of formation of such zones increased with growing q.

The stability of vaporization throughout the bundle should be considered a fundamental feature of vacuum boiling for $p \leq 10$ kPa. Characteristically, vaporization was not observed on the outer surface of outer sides of vertical rows. The vapor phase rose inside vertical passages. Nucleation was rather steady on the side surfaces of lower bundle tubes. The bubbles grew and fused when departing from tubes. Here, over the entire passage height, a uniform vapor wedge with insignificant liquid strips was established in the center of the passage. Heat removal into the vapor wedge enhanced heat transfer as compared to row processes under the same conditions. The general boiling behavior on tube bundles is illustrated in Fig. 4.

The influence of side bundle rows on the heat transfer of the tubes in the central vertical row is most significant at low q and low pressures. This effect decreased appreciably with growing heat flux. For example, at $p = 60$ kPa, in comparison to a similar tube row, α_2 for the densest bundle, $s/d = 1.25$, increased by 6% for $q = 22$ kW/m^2, while for $q = 132$ kW/m^2 heat transfer coefficients were identical. As pressure increased, the effect of side tube rows on the vaporization rate was less significant. However, their effect on boiling was substantial for dense and loose bundles. A comparison of average heat transfer coefficients for a single tube, tube rows, and bundles suggests that the value of n in the equation $\alpha_2 = Aq^n$ for all q adopted is smaller for tube bundles and rows than for a single tube. The change of longitudinal and transverse spacings for tube rows and bundles under different heat loads indicates the possibility of achieving greater heat transfer coefficients than for a single tube. The calculated α_2 values obtained for denser bundles and rows at below atmospheric pressures are higher for surfaces with large relative spacings, as was shown in [4].

Experimental data show that heat transfer conditions on tube bundles and rows are determined by heat flux, pressure, relative spacing, and the number of horizontal tube rows. This is expressed by the relation

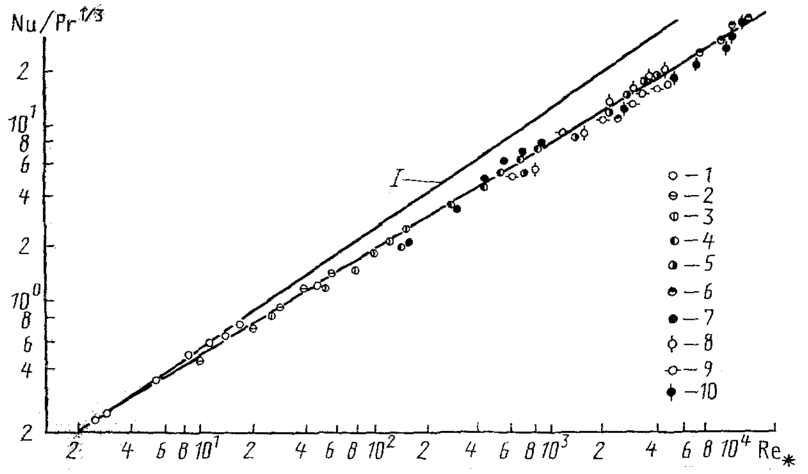

Fig. 1. Generalization of D. A. Labuntsov equation data: I) D. A. Labuntsov equation; 1) p = 100 kPa; 2) 60; 3) 40; 4) 20; 5) 10; 6) 6; 7) 20 [10]; 8) 11 [10]; 9) 10 [8]; 10) 6 kPa [8].

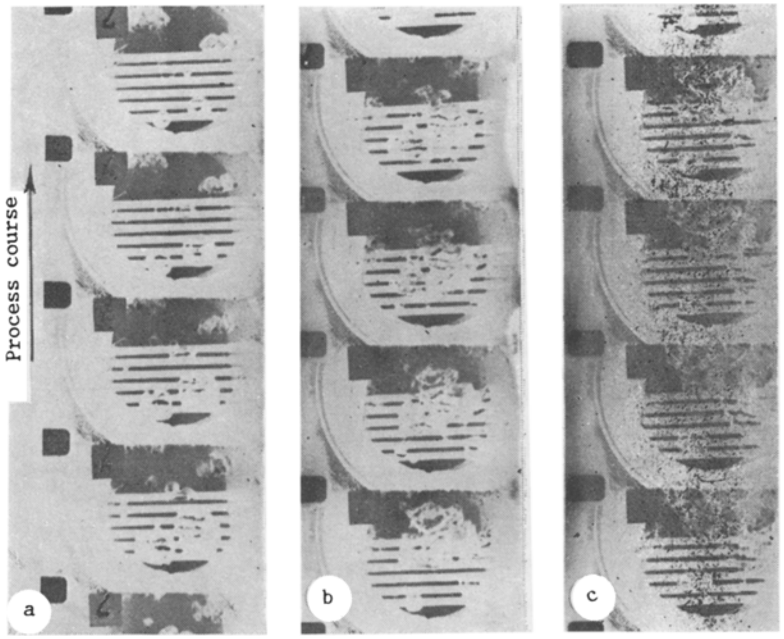

Fig. 2. Boiling on a tube row at p = 20 kPa; q = 110 kW/m^2; s_2/d = 1.25: a) incipient vaporization; b) intermediate mode; c) developed boiling.

$$\mathrm{Nu} = f\,[\mathrm{Re}_*(m+1),\ \mathrm{Pr},\ s_2/d], \qquad (2)$$

where

$$\mathrm{Re}_* = \frac{ql}{r\rho''\nu};\quad l = \frac{C_p\rho'\sigma T_s}{(r\rho'')^2};$$

and m is the number of tube rows.

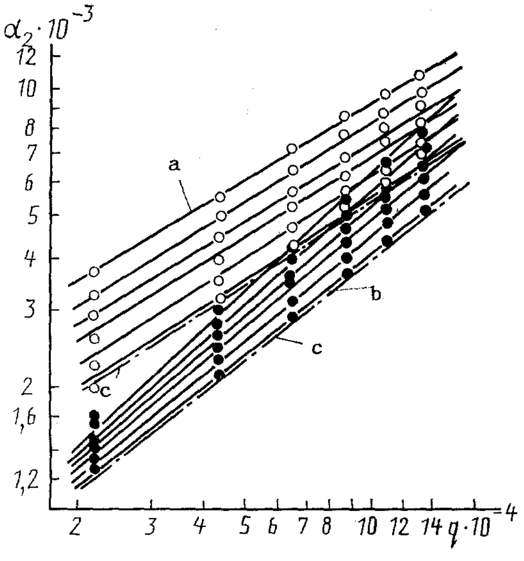

Fig. 3. Heat transfer coefficient variation for row tubes: a) p = 20 kPa; b) p = 6 kPa; c) single tube.

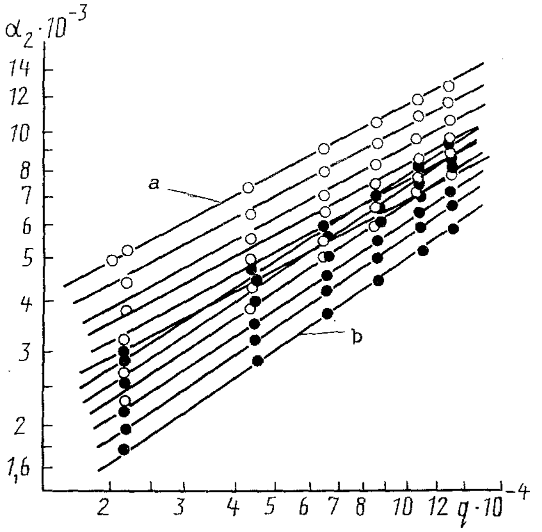

Fig. 4. Coefficient α_2 vs. heat flux for tubes of a central vertical bundle row at p = 20 kPa (a) and 6 kPa (b); $s_1/d = s_2/d = 1.25$.

Analyzing the data by using the equation $Nu/Pr^{1/3} = f[Re_*(m+1)]$ for boiling on tube rows leads to the equation

$$Nu = 0{,}06\,Pr^{1/3}\,[Re_*\,(m+1)]^{0{,}61}\,(s_2/d)^{-0{,}28}. \tag{3}$$

In Fig. 5, combined data for boiling on tube bundles are given for comparison. These results allow estimation of such conditions in the form

$$Nu = 0{,}09\,Pr^{1/3}\,[Re_*\,(m+1)]^{0{,}58}\,(s_2/d)^{-0{,}12}\,(s_1/d)^{-0{,}11}. \tag{4}$$

Both relations hold for the parameter ranges cited above.

Experimental data and their generalization show a higher heat transfer rate for upper tubes for tube rows and bundles than for a single tube, which is determined by heat flux, pressure, number of tubes over the surface height, and relative

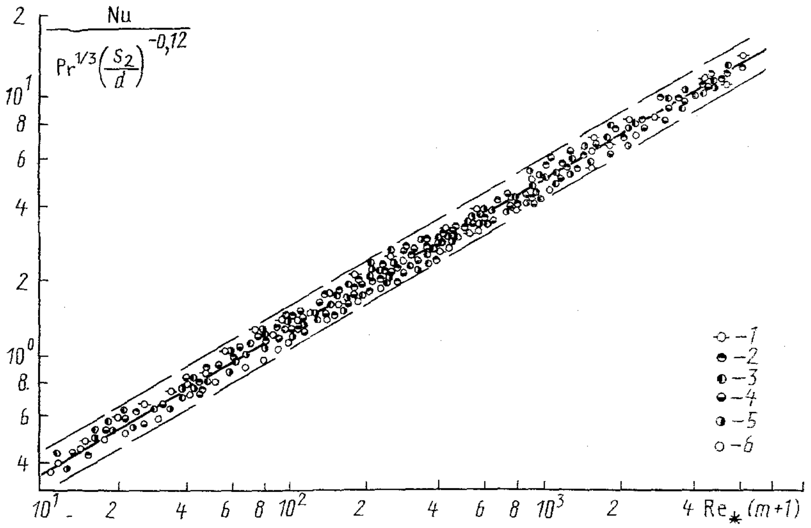

Fig. 5. Generalization of boiling data for tube bundles at p = 100-20 kPa: 1) 6th row; 2) 5th row; 3) 4th row; 4) 3rd row; 5) 2nd row; 6) 1st row.

spacing. Under such conditions, at p = 4-100 kPa, the average heat transfer coefficient is a weaker function of q than for a single tube, whereas its value coincides with that for a single tube at a pressure below 20 kPa. Vaporization on tube bundles in high vacuum is stable even at low heat loads. Tube bundle geometry exerts a critical effect on heat transfer.

NOTATION

T_s, saturation temperature, °C; q, heat flux, kW/m^2; p, pressure, kPa; α_2, boiling heat transfer coefficient, $kW/(m^2 \cdot {}^\circ C)$; r, heat of vaporization, J/kg; C_p, heat capacity, $J(kg \cdot {}^\circ C)$; ρ', ρ'' water and vapor density, kg/m^3; σ, surface tension coefficient, N/m.

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