

AN EXPERIMENTAL STUDY OF HEAT TRANSFER
DURING BOILING OF n-BUTANE IN VERTICAL TUBES

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This article presents the results of an experimental investigation of heat transfer during boiling of n-butane in tubes. We isolated the zones in which the principal parameters (heat flux density and effective liquid velocity) affect the heat transfer rate. Appropriate equations are recommended for calculating the heat transfer constant.

At present, the literature contains very few publications devoted to research on heat transfer during boiling in compressed hydrocarbons. There are only a few experimental data on the boiling of heptane and pentane in vertical tubes under natural-convection conditions [1]. Study of heat transfer during boiling of compressed hydrocarbons in tubes under forced-convection conditions is of great interest.

The experiments were conducted in an ac-heated vertical tube with pressures of 145 and 330 kN/m², circulation rates $w_0 = 0.2-1.2$ m/sec, heat flux densities $q = 5000-136,000$ W/m², and flow mass vapor contents x of up to 0.91. Preliminarily purified n-butane was used; its residual impurity content did not exceed 3 vol. %.

The working section consisted of a vertical tube fabricated from OKh18N10T stainless steel with an inside diameter of $7.75 \cdot 10^{-3}$ m and a heated length of 0.99 m. Fifteen copper - constantan thermocouples were installed in order to measure the temperature of the outer tube wall at ten cross-sections (0.1 m apart). The temperature of the liquid at the tube inlet and the vapor - liquid mixture inside the tube was measured with four thermocouples centered along the channel axis. The thermocouples were calibrated to within 0.1°C. The thermocouple emf was measured with a potentiometric circuit that included a low-resistance R-306 potentiometer (class 0,015), a normal element (class 2), and an M 17/1 mirror galvanometer. The pressure at the inlet and outlet of the experimental apparatus was measured with standard manometers (class 0,35).

The voltage drop in the working section of the tube was measured with an É-59 voltmeter (class 0.5), while the current was measured with an ÉLA ammeter (class 0.2) connected in through a UTT-5 transformer. Hydrodynamic stabilization sections with a length of 35 d were provided at the inlet and outlet of the working section. The liquid was supplied to the experimental section in an almost saturated state during the experiments. The circulating-liquid flow rate was determined by the volumetric method to within $\pm 3-5\%$. In order to verify the experimental method, we first conducted experiments to determine the heat transfer constant between the wall and nonboiling n-butane; these showed the reliability of the basic measurements.

The procedure employed made it possible to determine the local heat transfer constant α during boiling of n-butane in the tube.

The maximum possible error in the determination of α was $\pm 20\%$.

In most of our studies, the circulation rate w_0 was used as the parameter for evaluating the influence of forced liquid convection on heat transfer during boiling.

However, the circulation rate could be utilized to appraise this effect only in the region of low vapor contents. The convective heat transfer at high vapor contents is determined by the true flow velocity of the liquid in the channel ([2], Appendix).

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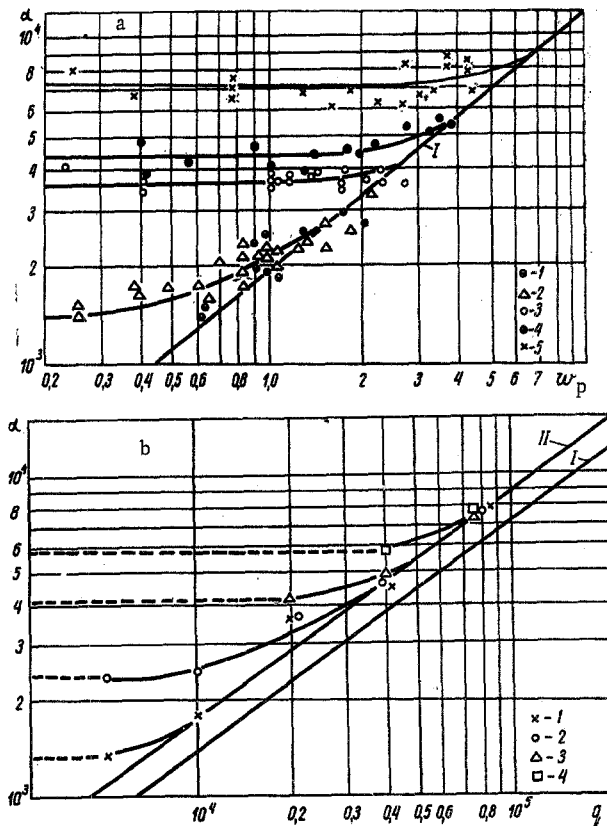


Fig. 1. Local heat transfer constant α as a function of true liquid velocity w_t (a) and heat flux density q (b) at $p = 145 \text{ kn/m}^2$: a] 1) $q = 5250 \text{ W/m}^2$; 2) 10,100; 3) 20,200; 4) 39,000; 5) 79,500; I) from Eq. (4); b] 1) $w_t = 0.6 \text{ m/sec}$; 2) 1.2; 3) 2.4; 4) 3.7; I) from data in [5]; II) from authors' data.

The proportion of the cross section φ occupied by the moving vapor flow was evaluated on the basis of Armand's data [3], as processed by Mamaev and Odishariya [4]. The volume vapor content was determined from the equation

$$\beta = \frac{x\rho'}{x\rho' + \rho''(1-x)} \quad (1)$$

In conformity with [4], we used the equation

$$\varphi = 0.81\beta [1 - \exp(-2.2\sqrt{Fr_c})] \quad (2)$$

for $\beta \leq 0.9$ and the averaged curve $\varphi = f(\beta)$ given by Armand [3] for $\beta > 0.9$. The true liquid velocity w_t was calculated from the equation

$$w_t = \frac{w_0(1-x)}{1-\varphi} \quad (3)$$

The experimental data were represented in the form of the dependence of α on w_t with $q = \text{const}$ and of α on q with $w_t = \text{const}$ (for $p = 145 \text{ kn/m}^2$, Fig. 1).

It can be seen from Fig. 1a that the influence of the true velocity on the heat transfer constant gradually decreased with increasing q and became almost independent of the velocity at certain heat fluxes. In these instances, α was wholly determined by the value of q , as can be seen especially clearly in Fig. 1b.

The dependence of α on the true velocity became more pronounced as w_t increased and q decreased. At certain velocities, α was wholly governed by the forced convection and can be calculated from the equation

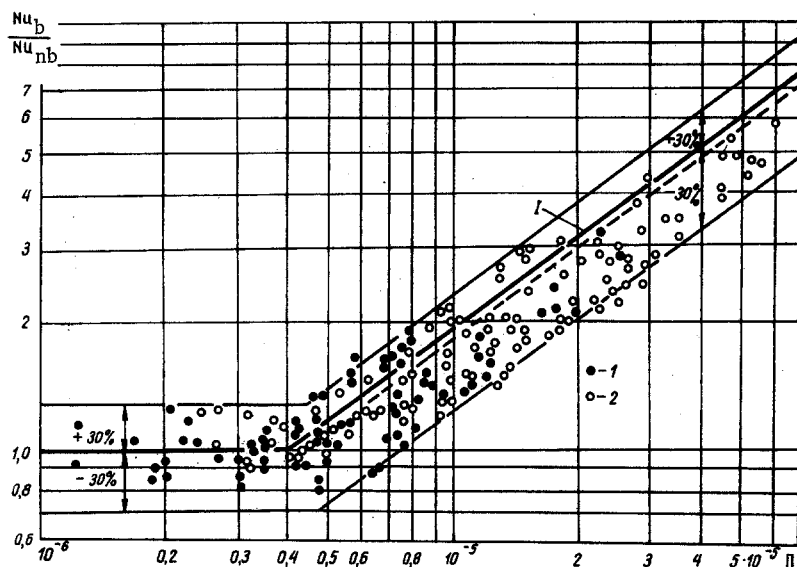


Fig. 2. Processing of experimental data with Sterman's equations: 1) $p = 145 \text{ kN/m}^2$; 2) $p = 330 \text{ kN/m}^2$; I) from Sterman's equations.

$$\alpha = \frac{\lambda}{d} 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \quad (4)$$

introducing the true liquid-phase velocity w_t into the Reynolds number Re .

Figure 1a also shows the calculated curve for convective heat transfer from a nonboiling liquid, determined from Eq. (4); Fig. 1b (curve I) gives the corresponding graph for n-butane boiling in a large volume, based on the data of Klimenko and Kozitskii [5].

Curve II in Fig. 1b was plotted from the data in the present article for the zone in which the heat transfer constant depends solely on q ($\alpha \sim q^{0.7}$). The dash lines in Fig. 1b correspond to extrapolation of our experimental data to the region where α is determined from Eq. (4).

Similar relationships were obtained at a pressure $p = 330 \text{ kN/m}^2$. In the region where the influence of the velocity was slight and $\alpha \sim q^{0.7}$, an increase in the pressure led to a rise in α of about 40%.

The influence of the pressure on the heat transfer rate was small in the region where α was governed principally by forced convection.

As can be seen from Fig. 1b, our experimental data for the region where $\alpha \sim q^{0.7}$ at $p = 145 \text{ kN/m}^2$ (curve II) lay above those of Klimenko and Kozitskii [5] (curve I) by an average of 18%.

The observed discrepancies reached 37% at a pressure $p = 330 \text{ kN/m}^2$.

In our opinion, these differences were due to the difference in the heat transfer conditions during boiling of a liquid in a large container and full boiling in tubes, even in the region where the influence of the liquid velocity was slight. In our experiments, this region was characterized by high values of β ($\beta > 0.7$) and boiling probably occurred under an annular or dispersed-annular regime with a higher heat transfer rate than for boiling in a large volume.

Similar conclusions were drawn by other authors [6, 7]. They have been confirmed by experimental data [8].

According to the results of a number of other experimental studies, however, particularly those by Miropol'skii and Shitsman [10] and Alekseev [9], vapor content was not found to have any influence and the values obtained for the heat transfer constants α during boiling in tubes did not exceed those for boiling in a large container.

We therefore cannot preclude the possibility that the discrepancies we found may also be due to the fact that Klimenko and Kozitskii [5] used technical-grade n-butane, in which the possible impurity content

(up to 10%) is very important from the standpoint of its effect on heat transfer, while the n-butane in our experiments was subjected to additional purification. The heat transfer constant for a mixture boiling in a large container is known to be lower than for the pure mixture components. In this connection, further research is required to resolve the question of the manner in which the vapor content affects the process during boiling in tubes.

The experimental data we obtained were processed in the form of the criterial relationship proposed by Sterman and in Collier's foreword [11, 2] (Fig. 2).

It can be seen from Fig. 2 that the experimental data are generalized by the relationship

$$\frac{Nu_b}{Nu_{nb}} = f(\Pi) \quad (5)$$

to within $\pm 30\%$. The average dash line in Fig. 2 is approximated by the equation

$$\frac{Nu_b}{Nu_{nb}} = 5540\Pi^{0.7}, \quad (6)$$

where the coefficient 5540 differs from that adopted by Sterman (6150) by 10%.

Equation (6) is valid when $\pi > 0.45 \cdot 10^{-5}$. When $\pi < 0.45 \cdot 10^{-5}$, $Nu_b = Nu_{nb}$ and α is calculated from Eq. (4).

Equations (4) and (6) can be used to determine the heat transfer constant during boiling of compressed hydrocarbons in vertical tubes.

In conclusion, the authors wish to thank L. S. Sterman for his interest in this work and his helpful comments.

NOTATION

w_0	is the circulation rate (m/sec);
q	is the heat flux density (W/m^2);
d	is the inside diameter of tube (m);
w_t	is the true liquid-phase velocity (m/sec);
α	is the heat transfer constant ($W/m^2 \cdot ^\circ C$);
λ	is the coefficient of thermal conductivity of liquid ($W/m \cdot ^\circ C$);
Re	is the Reynolds number;
Pr	is the Prandtl number;
ρ^n, ρ^l	are the densities of vapor and liquid (kg/m^3);
r	is the heat of vaporization (J/kg);
c_p	is the heat capacity of liquid ($J/kg \cdot ^\circ C$);
T_s	is the saturation temperature ($^\circ K$);
β	is the volumetric flow vapor content;
φ	is the true volumetric vapor content;
x	is the mass flow vapor content;
Fr _c	is the Frude number of mixture;
Nu_b	is the Nusselt number for liquid boiling in tube;
Nu_{nb}	is the Nusselt number for nonboiling liquid, determined from Eq. (4);
Π	is the complex, $\Pi = q/r\rho^n w_t (\rho^n/\rho^l)^{1.45} (r/c_p T_s)^{0.33}$.

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