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FILM CONDENSATION OF A MOVING VAPOR ON A HORIZONTAL CYLINDER

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The computation of heat transfer during film condensation of a moving vapor on a horizontal cylinder is possible at this time for a whole series of simplifying hypotheses. The problem of an experimental confirmation of the dependences proposed [1-3] in order to refine further the mechanism of moving vapor condensation is urgent. There is a limited quantity of data in the literature which could be used for this purpose [4-8]. Their significant discrepancy under comparable conditions as well as the lack of systematic measurements on such important dependences for analysis as the dependence of the coefficient of heat transmission on the temperature head, the condensation pressure, and the geometric parameters should be noted.

This paper is a continuation of investigations on the condensation of the moving vapor Freon-21 (F-21, $CHFCl_2$) on horizontal cylinders. The tests were conducted on a test stand by the methodology of [8].

The tests were conducted on horizontally arranged nickel tubes of D = 16 mm outer diameter and L = 580 mm length, placed in a condenser with 400-mm inner diameter. The wall temperature t_W of the experimental sections was measured by six thermocouples calked around the perimeter of the tube at the middle of the section, and whose readings were averaged. The saturated vapor temperature t" was measured by a thermocouple and was determined by means of the $\bar{p}-T$ data for Freon-21 by measuring the saturated vapor pressure with a standard manometer of the class 0.35.

The heat flux q on the outer surface of the experimental section was determined by the change in enthalpy of the cooling water which came in from a constant-level tank. The change in temperature head $\Delta t = t'' - t_W$ was achieved by adding hot water to the cooling water.

The ranges of variation of the main condensation parameters were $q = (3\text{-}150) \cdot 10^3$ W/m², $\Delta t = 1\text{-}30$°C, $t'' =$ 60-90°C. The accuracy of determining the heat transmission coefficient $\alpha = q/\Delta t$ at $\Delta t \geq 2$°C is estimated at 10%.

In the tests on moving vapor condensation the experimental sections were located in a channel whose geometry could be changed. The schemes for locating the experimental sections which were realized in the experiment are shown in Fig. 1a-c. In the case illustrated in Fig. 1a, the experimental section 2 is 170 mm from the vapor input to the channel. The spacing between the channel walls 1 was b = 26, 46, and 66 mm in the different test series. The vapor was smoothly introduced into the channel and three damper grids 4 were also set up. The spacing between the channel walls was 66 mm for the disposition of the experimental sections according to the scheme shown in Fig. 1b, and the tests were conducted serially in the 1, 4 and 9 tubes of a ten-set unstaggered bundle. In the case shown in Fig. 1c, the spacing between the walls was 26 mm and the inserts 3 simulating a checkerboard bundle with $s_1/D = 1.87$, $s_2/D = 0.81$ were additionally mounted in the channel. The tests were conducted in each tube of the bundle without feeding cooling water to those located above.

The experiment showed that despite the great diversity in conditions under which the test was conducted, the magnitude of the heat transmission coefficient had the same value upon referring the vapor velocity to the channel through-section. Part of the test results is presented in Fig. 2 for the vapor motion velocities w = 0.57 m/sec (points 1-3) and w = 1.1 m/sec (points 4 and 5) at t" = 60°C. Points 1 and 4 correspond to the section arrangement shown in Fig. 1a, 2 to Fig. 1b, and 3, 5 to Fig. 1c. Tests conducted on different tubes of the bundle along its height at the same vapor velocity and saturation temperature showed that the coefficient of heat transmission has the identical value (within the limits of experimental error).

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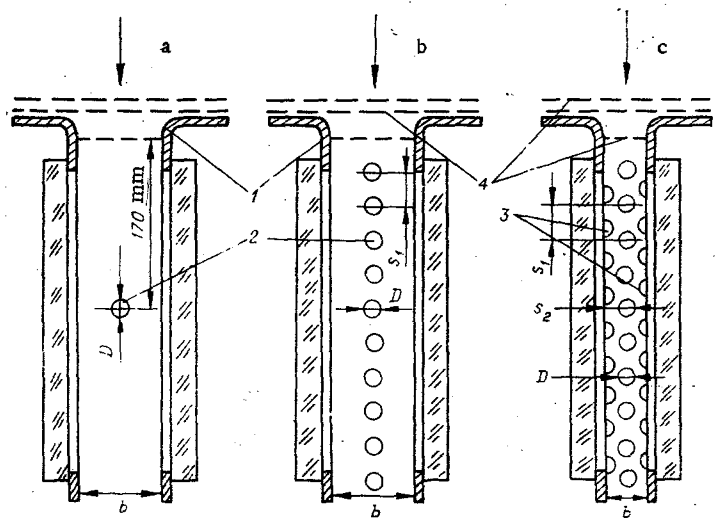

Fig. 1

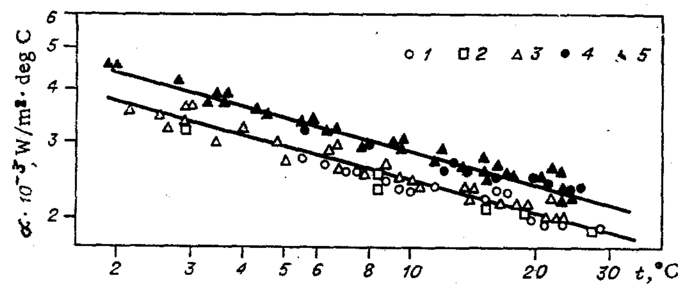

Fig. 2

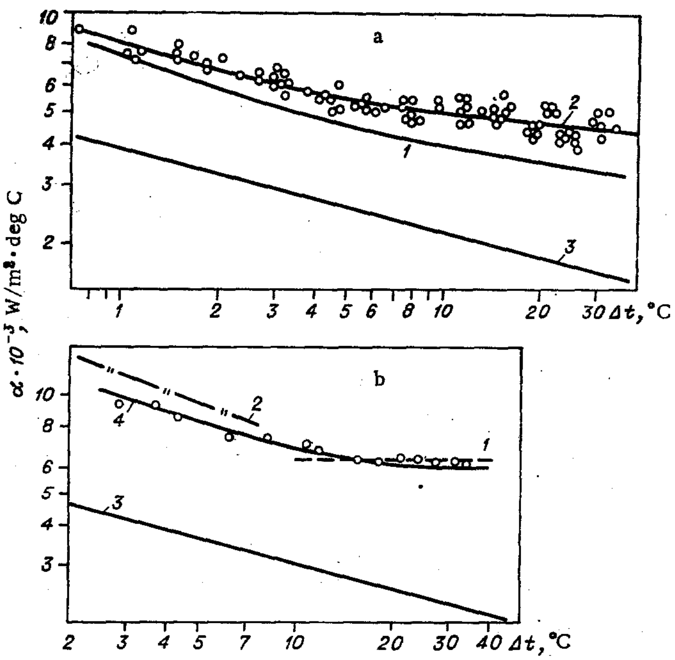

Fig. 3

Therefore, the magnitude of the mean heat transmission coefficient for condensation of the moving vapor in the velocity range investigated is determined just by the mean velocity of the vapor flux and is independent of its aerodynamics ($\Delta t = \text{idem}$).

Special attention was turned in the tests presented on moving vapor condensation to a possibly more accurate determination of the nature of the dependence of the heat transmission coefficient α on the temperature head Δt. To this end, the accuracy of determining α in a moderate range of temperatures heads ($\Delta t \leq 5°C$) was raised as compared to results published earlier [8].

Data on the dependence of the heat transmission coefficient on the temperature head are presented in Fig. 3a for $t'' = 60°C$ and $w = 4.3$ m/sec during vapor condensation on a tube of diameter 16 mm (line 1 is a computation using (3), 2 is a line taking the average of the test data, and 3 is a computation according to [11]), and in Fig. 3b on a tube of 2.5 mm diameter for $w = 3.81$ m/sec (line 1 is a computation using (5), 2 is a computation using (6), 3 is a computation according to [11], and 4 is the line taking the average of the test data). An analogous form of the $\alpha-\Delta t$ dependence is obtained for a tube with $D = 2.5$ mm and $w = 5.0$ m/sec at $t'' = 40°C$. It is seen from Figs. 3a and b that at large temperature heads α is practically independent of Δt.

A change in the law of interaction on the phase interface, vapor-condensate film, determined by the friction coefficient c_f should be considered the reason causing a change in the nature of the $\alpha-\Delta t$ dependence under conditions of laminar runoff of the condensate film. In particular, the great influence of the crossflow of material on the quantity c_f should be noted.

Thus, if c_f is determined completely by the momentum transported by the vapor crossflow [9], then

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} = \text{const.} \tag{1}$$

It follows from (1) that the coefficient of heat transmission is independent of the temperature head as well as of the physical properties of the vapor.

If the vapor velocity is sufficiently high so that the influence of the vapor crossflow on the quantity c_f can be neglected, then the corresponding heat transfer law has the form

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} \sim (\mathrm{Pr}\,\mathrm{K}/R)^{1/3}, \tag{2}$$

where $\mathrm{Nu} = \alpha D/\lambda$, $\mathrm{Re} = wD/\nu$, $\mathrm{Pr} = \nu/a$, $\mathrm{K} = r/c\Delta t$ are the Nusselt, Reynolds, Prandtl, and Kutateladze criteria; $R = (\rho\mu/\rho''\mu'')^{1/2}$; ρ, ρ'', μ, μ'' are the density and dynamic viscosity of the fluid and vapor; λ, ν, a, c are the heat conduction, kinematic viscosity, thermal diffusivity and specific heat of the fluid. From (2) there follows $\alpha \sim \Delta t^{-1/3}$. The pressure dependence of the heat transmission coefficient is taken into account by the complex R. Formulas (1) and (2) have been obtained in [9] by solving the motion and energy equations for a condensate film on a horizontal plane, and the equation of vapor phase motion in the absence of gravity. In a complete formulation, the problem of condensation of a moving vapor was first examined in [10]. The numerical solution of the problem of moving vapor condensation on a cylinder and its analytical approximation were performed in [3]. The approximate expression proposed by the authors has the form

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} = \chi(1 + 0.276\,\mathrm{Pr}\,\mathrm{K}/\chi^4\,\mathrm{Fr})^{1/4}, \tag{3}$$

where

$$\chi = 0.9(1 + \mathrm{Pr}\,\mathrm{K}/R)^{1/3}.$$

Or in another form

$$\alpha/\alpha_0 = (1 + 3.62\chi^4\,\mathrm{Fr}/\mathrm{Pr}\,\mathrm{K})^{1/4}, \tag{4}$$

where α_0 is the heat transmission coefficient during condensation of a fixed vapor [11], and $\mathrm{Fr} = w^2/gD$ is the Froude criterion. According to (4), the relative change in heat transmission depends on a complex criterion $\chi^4\mathrm{Fr}/\mathrm{PrK}$. The dependence (3) satisfies the limit relationships obtained in [9]. Thus, for large Δt (small K) $\chi \to$ const and (3) goes over into

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} = 0.9. \tag{5}$$

For small Δt there follows from (3)

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} = 0.9(1 + \mathrm{PrK}/R)^{1/3}. \tag{6}$$

Let us also note that

$$\alpha/\alpha_0 = f(\mathrm{Fr}/\mathrm{PrK}) \tag{7}$$

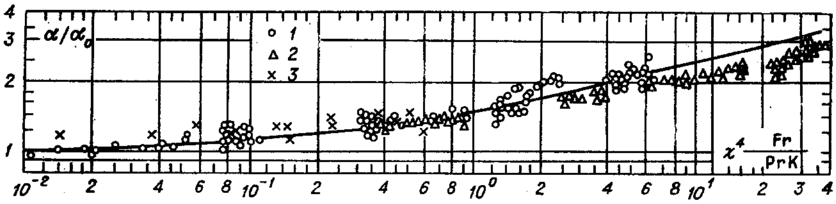

Fig. 4

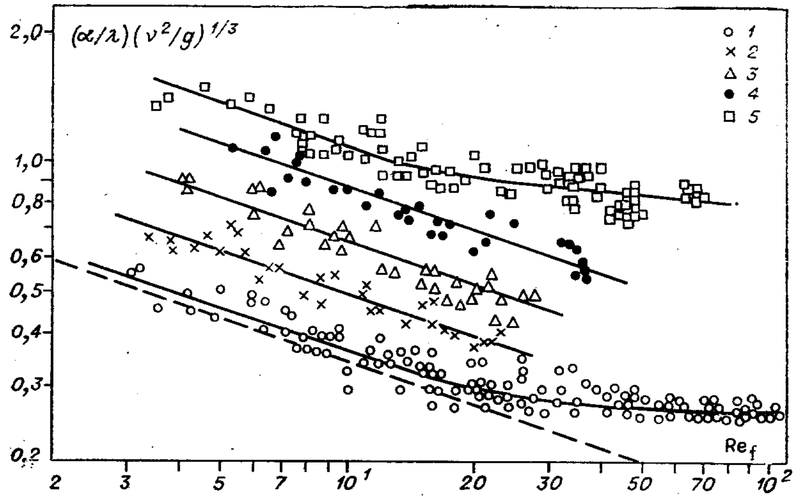

Fig. 5

can be obtained from (4) for large temperature heads. The relationship (7) was used in extending the test data in [8]. However, such a representation is ambiguous and possible only in a limited range of temperature head variation when $\chi \to$ const.

Experimental results on the condensation of a moving vapor at the maximum velocities are presented in Figs. 3a and b. The computational dependences (3), (5), and (6) and the computation by the Nusselt formula for a fixed vapor are superimposed here.

Experimental results on the condensation of freon-21 at $t'' = 40$, 60 and 90°C and vapor velocities 0.2-5 m/sec on cylinders of 16 mm diameter (points 1) and 2.5 mm diameter (points 2) [8], as well as results on the condensation of water vapor (points 3) [6] are processed in Fig. 4 in the coordinates (4) (the solid line). The vapor velocity is referred to the channel through section.

As is seen from Figs. 3a and b and 4, there is satisfactory agreement between the computed and experimental dependences.

Results of experiment with the vapor velocities $w = 0.57$, 1.1, 2.3, 4.3 m/sec (points 2-5, $D = 16$ mm, $t'' = 60$°C) have been processed in the coordinates

$$\mathrm{Nu}^* = f(\mathrm{Re}_f), \tag{8}$$

where

$$\mathrm{Nu}^* = (\alpha/\lambda)(\nu^2/g)^{1/3};\ \mathrm{Re}_f = (\pi D/2)\cdot q/\mu r.$$

Data on the condensation of a fixed vapor are represented in Fig. 5 in a broad range of Reynolds numbers of the condensate film [12] (points 1). In the case of fixed vapor condensation at high temperature heads a change in the nature of the α–Δt dependence also occurs. In this case, wave formation in the condensate film is the reason causing this change. Tests on the condensation of a moving vapor on a 2.5-mm-diameter cylinder (see Fig. 3b) indicate that the inflection on the α–Δt dependence during moving vapor condensation is due to a change in the phase interaction law but not the flow mode of the condensate film. In this case the film Reynolds number did not exceed $\mathrm{Re}_f = 15$.

Therefore, both the condensate film flow mode and the change in the friction law on the vapor-condensate film phase interface exert influence on the nature of the experimentally determined α–Δt dependences.

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LOW-TEMPERATURE POLYMERIZATION CONDITIONS IN A FLOW-THROUGH REACTOR

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In the literature of the last few years investigations are frequently encountered devoted to the process of polymerization in a flow-through reactor. However, the amount of work in which account is taken of the dependence of the viscosity of the reaction mixture on the degree of polymerization of the substance is extremely small, although this dependence has a considerable effect on the profiles of the temperature and the degree of polymerization, the pressure drop, and other characteristics of the process. We note [1], which considered adiabatic conditions of the course of the polymerization and a weak dependence of the viscosity on the degree of polymerization was taken, [2], in which, with a number of simplifying assumptions, an analytical investigation was made of isothermal polymerization, and [3], in which an experimental investigation was made of the course of the process. The present authors have earlier investigated the process of polymerization in a flow-through continuous reactor, with a viscosity depending exponentially on the degree of polymerization η and the temperature T, and postulated averaging of these values over the cross section of the reactor [4, 5]. Such an approach is justified as a first approximation with calculation of the pressure drop and the distribution of the mean temperatures along the length of the reactor. However, within the framework of this approach it is impossible to establish the true distribution of the temperature, the degree of polymerization, and the velocities of the flow of the liquid over the cross section of the reactor. All these characteristics of the process are considerably affected by the dependence of the viscosity on the degree of polymerization, particularly when the polymerization takes place in the mass. With the aim of a study of the effect of the distribution of all these quantities on the course of the process, the present article considers the problem of polymerization in a tubular reactor in a two-dimensional unsteady-state statement, taking account of the dependence of the viscosity on the temperature and the degree of polymerization.

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