EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER WITH THE CONDENSATION OF THE MOVING VAPOR OF FREON-21 ON HORIZONTAL CYLINDERS

I. I. Gogonin and A. R. Dorokhov

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The article gives experimental data on heat transfer with the condensation of the moving vapor of Freon-21 (F-21) in a wide range of velocities, specific weights of the vapor, transverse dimensions of the experimental section, and heat fluxes. The points obtained are compared with the experiments of other authors and with existing theoretical dependences.

The problem of the condensation of a moving vapor, posed in 1916 by Nusselt [1] for the laminar flow of a film of condensate, has not been solved for many other conditions up to the present time, and is attracting more and more attention on the part of investigators, both in our country [2-12] and abroad [13-16]. The experimental data for a quantitative evaluation of the effect of the velocity of the vapor on heat transfer with condensation are still insufficient.

The present work is a continuation of [12] and has the aim of broadening the range of change in the principal parameters of the condensation, i.e., the velocities of the vapor, its specific weights, the heat fluxes and temperature heads, and the geometric dimensions of the experimental sections. The experiments were made with Freon-21 ($CHFCl_2$), whose condensation can be studied with an excess pressure, which eliminates noncondensing gases from the vapor volume, the main source of errors in experiments on the investigation of heat transfer with condensation. A schematic diagram of the test stand in which the experiments on the condensation of F-21 were made is shown in Fig. 1a, b.

The Freon was fed by the pump 1 to the heater 2, where it was heated up to the saturation temperature. It then entered the vaporizer 3, where it was vaporized using the heater 4 (power $N \leq 200$ kW). From the vaporizer, the Freon vapor passed through a separator, arranged in the upper part of the housing of the vaporizer, and then entered the condenser 5, where it condensed on the tube bundle 14. The condensed liquid flowed off to the supercooler 6, and then to the reservoir 7. The experimental section 9 was arranged in the slit 13 inside the tube bundle of the condenser. The maximal width between the walls of the slit was 46 mm, and the length 560 mm. The experimental section was installed at a distance of 130 mm from the inlet of the

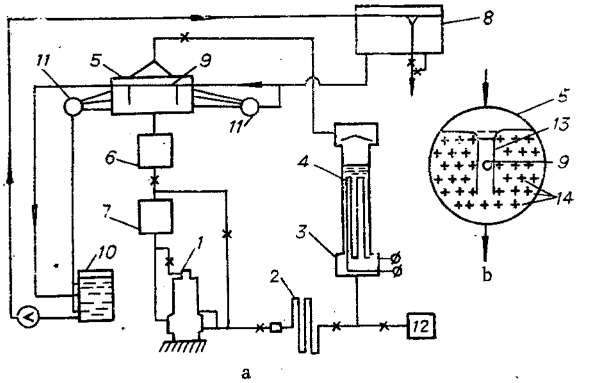

Fig. 1

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TABLE 1

Number of tube	D, mm	l, mm	δ, mm	Material	W, m/sec	t_s, °C
1	17	565	1,2	Nickel	8,0	40; 60
2	17	547	1.0	Titanium	1,3	40; 60
3	6	528	0,25	Nickel	3,0	40; 60; 90
4	2,5	548	0,15	Nickel	5,0	40; 60

vapor into the slit.

The tube bundle of the condenser was cooled by water, which entered from the constant-head tank 8 through the distributing receivers 11. The overflow receiver 10 was used as a volumetric flowmeter for measuring the total mass flow rate of water through the tube bundle of the condenser and the experimental section. Filling of the unit with Freon was carried out after its preliminary evacuation with the forevacuum pump 12.

All the parts of the unit were made of stainless steel and were designed for a pressure of 50 atm. The main subassemblies of the unit were heat-insulated with asbestos and were provided with compensating heaters.

In the experiment, a determination was made of the heat-transfer coefficient α, W/(m^2 · °C), at the external surface of the experimental section

$$\alpha = q/\Delta t. \tag{1}$$

The heat flux q, W/m^2, was determined by the generally accepted method, measuring the mass flow rate and the heating of the water used for cooling the experimental section. The mass flow rate of the water was measured with a pneumatic rotameter, and the heating with a differential thermocouple, calibrated with an accuracy of ±0.02°C.

In determination of the temperature head $\Delta t = t_s - t_w$, °C, the temperature of the saturated vapor t_s, ° C, was measured with a Chromel–Copel thermocouple, and was monitored with respect to the pressure. The temperature of the wall of the experimental section t_w, °C, was determined from the change in its resistance; here, a correction was introduced for its thickness. The accuracy in determination of α with $\Delta t \geq$ 5°C was within the limits of 7%.

The velocity of the vapor in the slit ahead of the experimental section w, m/sec, was determined from the power generated by the heater. To monitor the heat balance, measurements were made of the amount of heat removed from the condenser, and the mass flow rate of Freon entering the vaporizer. Under steady-state conditions, these three methods gave close results (not worse than 5%).

The temperature in different parts of the loop was measured with thermocouples, led out to multipoint potentiometers. Exact measurements of the readings of the thermocouples were made with a semiautomatic R-368 potentiometer. The thermocouples in the experimental section were calibrated using a U-10 ultrathermostat (product of East Germany) with reference to laboratory mercury thermocouples with a graduation of 0.1°C.

The heat-transfer coefficient with the condensation of F-21 in the experimental sections was determined under steady-state conditions of operation of the unit. With a given velocity of the vapor ahead of the experimental section, and with a determined temperature of the vapor in the condenser, a series of measurements was made of the heat-transfer coefficient as a function of the value of the temperature head, a change in which was achieved mainly by a change in the temperature of the water used to cool the experimental section.

The experiments were made with high-purity Freon. During the course of the experiment, repeated analyses were made of samples of the liquid and vapor phases, which showed that the main impurity in the vapor was air, but that its concentration did not exceed 0.1%. Experiments on the condensation of the motionless vapor of F-21 with an air impurity showed that a concentration of air up to 0.1% has no appreciable effect on the heat transfer; therefore, its diffusional resistance may be left out of consideration.

The physical characteristics of F-21 in the calculations were taken from handbooks [17, 18]. The experimental sections, on whose outer surface the condensation of the Freon vapor took place, were smooth thin-walled tubes, whose geometric characteristics (D is the diameter, l is the length of the tube, δ is the thickness of the wall) are given in Table 1. The same table gives the values of the condensation temperatures

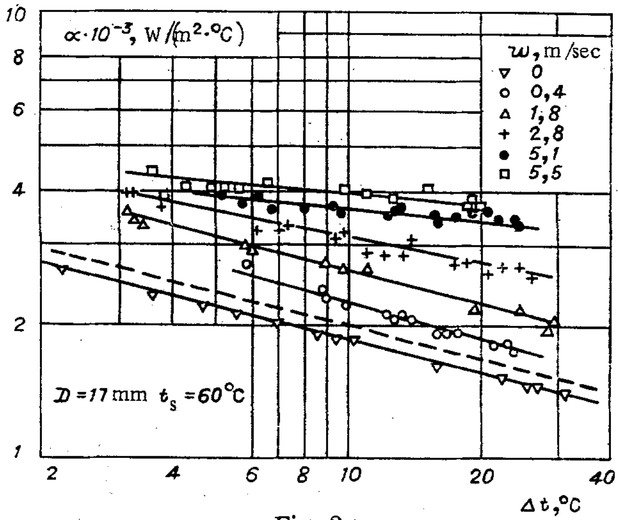

Fig. 2

at which the experiments were made and the maximal velocities of the motion of the vapor attainable in the experiments.

In all, 200 experiments were made on the condensation of motionless, and 470 on the condensation of moving vapor. Part of the experimental data obtained on the condensation of F-21 on tubes Nos. 1, 3, and 4 is shown in Figs. 2-4 in the form of the dependence of the heat-transfer coefficient $\alpha \cdot 10^{-3}$ W(m$^2 \cdot$°C) on the vapor–wall temperature head Δt, °C.

As follows from the figures, for motionless vapor on all the tubes the Nusselt dependence $\alpha \sim \Delta t^{-0.25}$ is satisfactorily fulfilled. The experimental dependence of the heat-transfer coefficient differs from the calculated [1] for tubes of different diameters. While, for a tube with $D = 17$ mm, the points lie below the calculated by approximately 10%, for a tube with $D = 2.5$ mm, they are higher by 15%. Specially set-up experiments on the condensation of motionless vapor in tubes with $D = 1.5, 3.6, 7,$ and 45 mm in the unit, in accordance with the method of [12], confirmed the measurements obtained. The reason for the deviation of the experimental data from the theoretical in the case of the condensation of motionless vapor is obviously the effect of the surface tension forces which were not taken into consideration in the calculation of [1]. The heat-transfer coefficient for motionless vapor in our experiments does not depend on the change in the pressure (the condensation temperature), which is in agreement with the correlation of [19].

The form of the dependences of the coefficient of heat transfer on the temperature head obtained with the condensation of moving vapor is in qualitative agreement with the experiments of other authors on water and Freon vapor [3, 5, 8, 11, 12]. The power exponent n in the dependence $\alpha \sim \Delta t^{-n}$ decreases with a rise in the velocity and reaches values of $n = 0.08$ in experiments on tube No. 1 (see Fig. 2), i.e., the heat-transfer coefficient is practically independent of the heat flux.

The effect of the inlet conditions has been verified in experiments on tubes Nos. 1 and 2. Tube No. 1 was arranged in the second row of a checkerboard bundle with a spacing of $s_1/D = 1.6$ and a distance between neighboring tubes of the bundle equal to 10 mm, as in the experiments of [12], and tube No. 2 in a slit formed by smooth walls, with a distance between them of 46 mm. The experiment showed that the dependences of the heat-transfer coefficient on the velocity of the vapor coincide in the case where the velocity of the vapor is referred to the flow-through cross section of the slit ahead of the experimental section (which held if the width of the slit was taken as 10 and 46 mm, respectively). Tubes Nos. 3 and 4 were installed in a slit formed by smooth walls, with a distance between them of 26 and 10 mm.

The dependence of α on Δt for tube No. 4 (see Fig. 4) is fundamentally different in that, with small temperature heads ($\Delta t \leq 10$°C), the power exponent n does not change its value and is equal to 0.25, independently of the rate of motion of the vapor. With large temperature heads, with a rise in the velocity there is a decrease in the power exponent from $n = 0.25$ to a value of n practically equal to zero, as in the experiments on tubes Nos. 1, 3.

Experimental data on the condensation of moving water [5] and Freon vapor were correlated in [12] by the dependence

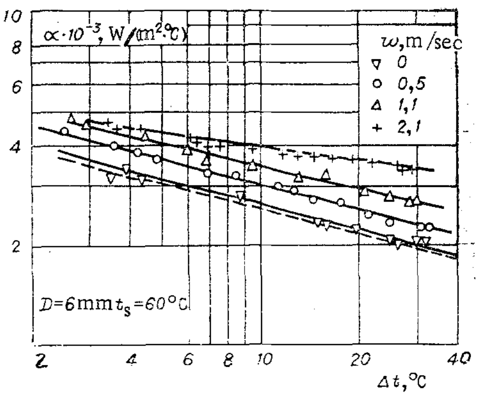

Fig. 3

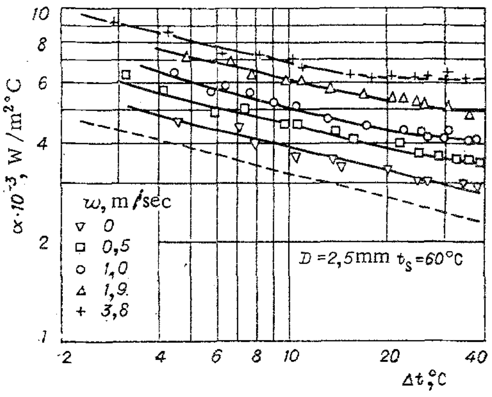

Fig. 4

$$\alpha/\alpha_0 = f(\pi_1\pi_2), \tag{2}$$

$$\pi_1 = q/r\rho''w,\ \pi_2 = w^2\alpha_0\rho''/\rho'g\lambda,$$

where α and α_0 are the heat-transfer coefficients of moving and motionless vapor, W/(m^2·°C); λ is the coefficient of thermal conductivity of the liquid, W/(m·°C); g is the acceleration due to gravity, m/sec^2; ρ'' is the density of the liquid and the vapor, kg/m^3.

With boundary conditions given with respect to the temperature head Δt, from (2) we can obtain

$$\alpha/\alpha_0 = f[\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K})]. \tag{3}$$

where $\mathrm{Fr} = w^2/gD$, $\mathrm{Pr} = \nu/a$, $\mathrm{K} = r/c\Delta t$ are the well-known Froude, Prandtl, and Kutateladze numbers; ν is the kinematic viscosity, m^2/sec; a is the thermal diffusivity, m^2/sec; c is the specific heat capacity of the liquid, J/(kg·°C).

An analytical form of dependence (3) was obtained in the theoretical communications [4, 9, 10, 15]. According to [4, 9], with an increase in the velocity of the vapor, the dependence of the heat-transfer coefficient on the temperature head becomes weaker and, at the limit, vanishes altogether, which was also observed in experiments on tubes Nos. 1, 3, and 4 (with $\Delta t \geq 10$°C).

A correlation of the experimental data on the condensation of moving Freon-21 vapor on tubes 1-4 is shown in Fig. 5 [lines 1, 2, and 3 – average experimental data in tubes with D = 17.6 and 2.5 mm, respectively; line 4 was calculated using formula (4)]. With the condensation of motionless vapor, the experimental value of the heat-transfer coefficient and the theoretical value do not coincide for tubes of different diameter, as a result of the effect of the surface tension forces; therefore, a correlation in the coordinates α/α_0, Fr(Pr·K) is not single-valued and depends on the choice of α_0. This indeterminacy can be eliminated if we consider the limiting cases of large and small rates of motion of the vapor.

It can be seen on Fig. 5a that, with the condensation of slowly moving vapor [$\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K}) < 1$], the data correlate better if we take the experimental value of the heat-transfer coefficient with the condensation of motionless vapor α_{0e}; under these circumstances, the effect of the forces of surface tension is taken into consideration automatically. In the case of the condensation of rapidly moving vapor [$\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K}) > 1$], where the hydrodynamics of the film of condensate are completely determined by the forces of interphase friction and the viscosity of the liquid, the effect of the surface tension forces degenerates: the experimental data correlate better if we take the theoretical value of the heat-transfer coefficient $\alpha_{0\mathrm{T}}$ (Fig. 5b). The experimental data on the condensation of moving F-21 vapor are in satisfactory agreement with the data of [5] on the condensation of water vapor, up to values $\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K}) \sim 1$. With large values of the determining complex, the data of [5] lie below ours. A probable reason for this divergence is the effect of noncondensing gases (air), whose concentration, according to the data of [5], rose considerably with a decrease in the condensation pressure.

The data obtained are compared on Fig. 6 with calculated dependences from the literature [4, 9, 15]. Calculation using the formula of [4] (Fig. 6, curve 1), over the whole range of change in the determining complex, gives low values of the heat-transfer coefficient. The experimental data [curve 5, value of α_0 with $\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K}) < 1$ taken with consideration of the surface tension] are in satisfactory agreement with the formula of [9] (curve 3). With values of $\mathrm{Fr}/(\mathrm{Pr}\cdot\mathrm{K}) \rightarrow 10$, the experimental data move to the asymptote (curve 4)

$$\mathrm{Nu}/\sqrt{\mathrm{Re}} \rightarrow 0.9, \tag{4}$$

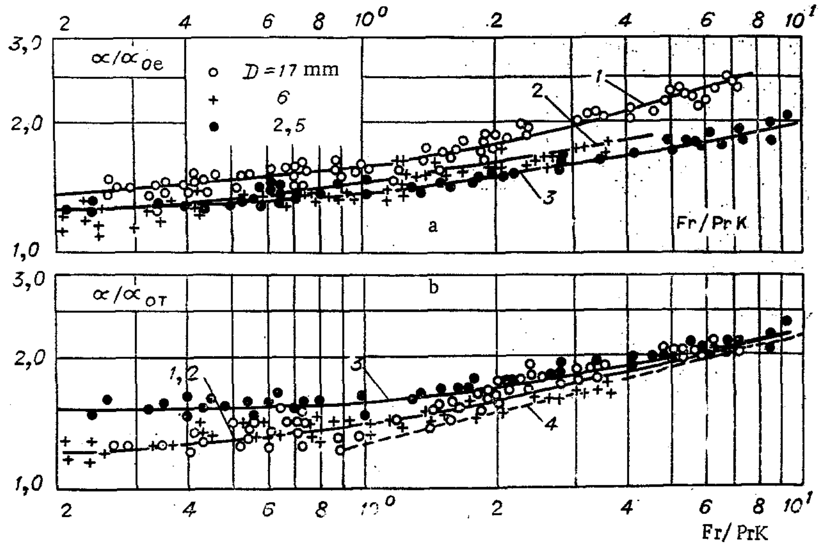

Fig. 5

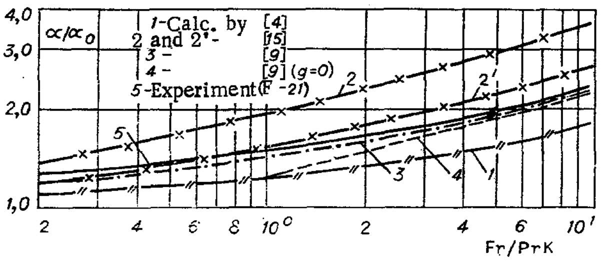

Fig. 6

where Nu $= \alpha D/\lambda$ and Re $= wD/\nu$ are the Nusselt and Reynolds numbers, constructed from the physical properties of the liquid. Dependence (4) is valid for rapidly moving vapor.

A calculation using the formula of the authors of [15] was made for two temperature heads $\Delta t = 5$ and 20°C ($Pr \cdot K = 140$ and 35 with $t_s = 40°C$). In Fig. 6, curve 2 was calculated for $Pr \cdot K = 140$, curve 2' for $Pr \cdot K = 35$. A comparison of the data obtained with the formula given in [15] shows that a calculation with small temperature heads gives high values of the heat-transfer coefficient. The dependence of α on Δt, which follows from the calculation, coincides qualitatively with the experiments on tube No. 4. This is obviously explained by the fact that, on tube No. 4 with $\Delta t \leq 10°C$, "dry" friction must also be taken into consideration. Under these circumstances, in accordance with [15], the heat-transfer coefficient depends not only on the complex $Fr/(Pr \cdot K)$, but also on the product $Pr \cdot K$ and the properties of the liquid and the vapor, determined by the complex $R = (\rho'\mu'/\rho''\mu'')^{1/2}$, where μ' and μ'' are the dynamic viscosities of the liquid and the vapor, respectively.

On the basis of the data obtained, it can be assumed that a one-parameter representation of the relative heat-transfer coefficient, in accordance with (3), in the investigated range of temperature heads is possible up to values of $Fr/(Pr \cdot K) \approx 5.0$.

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