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EXPERIMENTAL STUDY OF THE PROCESS OF FILM CONDENSATION OF NITROGEN VAPOR FROM A MIXTURE WITH HELIUM

V. K. Orlov, A. I. Smorodin,
and L. D. Marchenko

UDC 536.423.4

On the basis of an experimental study of the process of film condensation of nitrogen vapor from a mixture with helium and of the hydrodynamics of the film, data are obtained which make it possible to calculate counterflow condensers for cryogenic installations.

In apparatuses for the obtainment and enrichment of a neon—helium mixture through the fractionation of air, for the purification of helium from admixtures of neon, hydrogen, nitrogen, and oxygen, and for the low-temperature fractionation of hydrocarbons, the process of vapor condensation is complicated by the presence of a component with a small molecular mass, this presence having an important effect on the intensity of heat and mass exchange. The heat and mass exchanges in these apparatuses take place, as a rule, at increased pressures and low temperatures, which prevents the reliable use of experimental data on heat and mass exchange during the condensation of water vapor from mixtures with different gases [1-2]. Under the conditions of increased pressures, vapor—gas mixtures display the properties of physicochemical solutions, and their thermophysical properties do not obey laws of additivity.

The results of an experimental study of the process of condensation of nitrogen vapor from a nitrogen—helium mixture moving inside vertical pipes are presented in the report. The tests were performed on a stand which was created with allowance for the special features of the process of condensation of cryogenic substances. A shield cooled by liquid nitrogen was placed between the experimental model and the thermal chamber to reduce the heat influxes (Fig. 1). The thermal chamber had powder-vacuum insulation. A vacuum (1.33 Pa) was maintained in the space between the shield and the experimental model. The gas mixture of the required composition was made up in a gas holder; the pressure was produced with a membrane compressor. The preliminary cooling of the mixture was accomplished in a coil placed in a vessel containing boiling nitrogen. The pipeline from the heat exchanger to the experimental model had vacuum-shield insulation, which made it possible to obtain a vapor—gas mixture with a temperature exceeding the saturation temperature by 2-3°. Under these conditions the vapor—gas mixture was in the saturated state along almost the entire length of the zone of mass exchange.

The experimental model (Fig. 1) consisted of five copper pipes with an inner diameter of 8 mm, a wall thickness of 2 mm, and a length of 3000 mm, soldered to pipe grids. The height variation in the composition of the moving vapor—gas mixture was determined by sampling the mixture from the centers of the pipes through

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 32, No. 1, pp. 24-29, January, 1977. Original article submitted December 31, 1975.

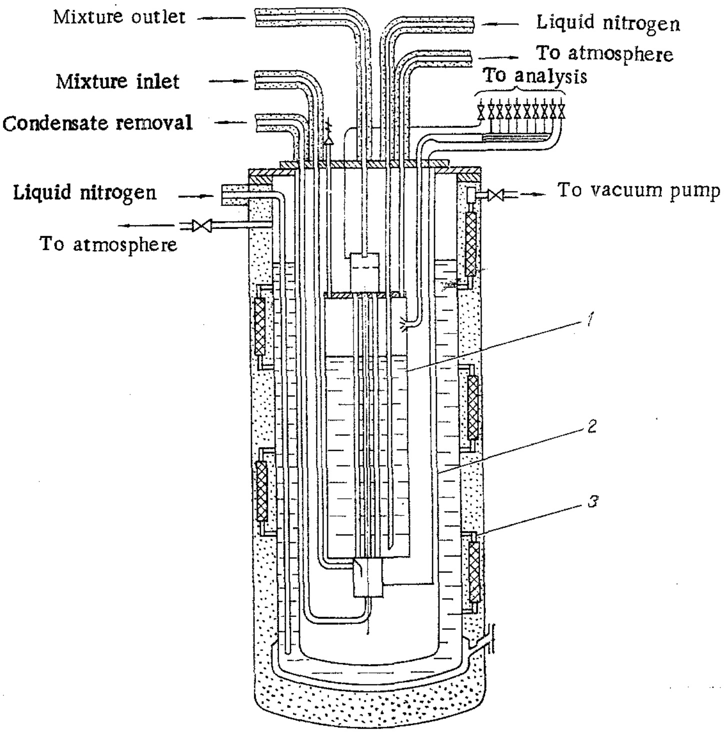

Fig. 1. Diagram of experimental model: 1) experimental model; 2) shield; 3) thermal chamber.

samplers mounted at heights of 130, 210, 410, 600, 800, 1000, 1200, and 1400 mm measured from the lower pipe grid, respectively. Liquid nitrogen was used as the cooling liquid. The level of the cooling liquid was kept constant in the tests and comprised 2.0 m. The pipe temperature along the height of the wall was measured with a multijunction copper—Constantan thermocouple. The mounting points of the thermocouple junctions coincided with the points of sampling of the mixture for analysis.

The determination of reliable data on the thermophysical properties of vapor—gas mixtures at increased pressures and low temperatures, when one component is in a saturated state while the other component is a gas of low molecular mass (helium or hydrogen), is hindered in connection with the absence of literature data. The calculation of the thermophysical properties of the nitrogen—helium mixture in the investigated range of temperatures, pressures, and concentrations through the analysis of the experimental data was carried out on the basis of empirical functions valid at pressures of $0.2\text{-}1 \cdot 10^5$ Pa and temperatures of from 273 to 373°K in which the effect of the component with the low molecular mass is taken into account [3, 4]. The dependence of the Prandtl number of the nitrogen—helium mixture on the temperature and pressure is presented in Fig. 2. The complicated nature of the dependence of the Prandtl number is determined by the fact that the thermal conductivity, viscosity, and heat capacity of the vapor—gas mixture vary to different degrees as functions of the temperature and pressure and of the composition of the mixture.

The temperature at the phase interface was determined by calculation using the Nusselt function [5]. The theory of film condensation of a pure vapor at a vertical surface was worked out by Nusselt using a number of assumptions, including the fact that the condensate film moves under the effect of the force of gravity and that friction at the phase interface is negligibly small. To extend this premise to the real process of counterflow condensation of vapor from a vapor—gas mixture in a vertical channel one needs exact data on the conditions of existence of the film mode of flow of the condensate film without its retardation by the vapor—gas stream.

The stable separation of the vapor—gas mixture can take place only at a velocity corresponding to the film mode of motion of the phases. An increase in the velocity of the vapor—gas stream to the critical velocity at the entrance to the apparatus leads to the "choking" phenomenon in which the condensate film flowing down along the walls and the vapor—gas stream begin to move upward in company. The composition of the vapor—gas mixture becomes the same at the entrance and exit, i.e., the separation process ceases to take place.

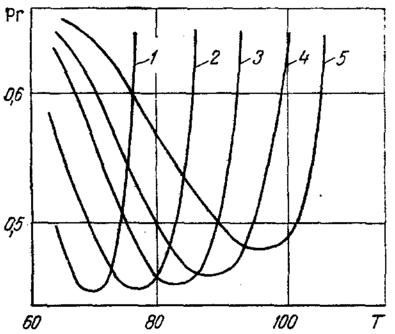

Fig. 2

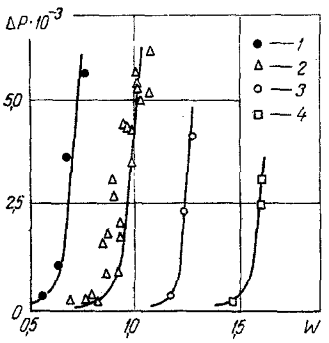

Fig. 3

Fig. 2. Dependence of Prandtl number of nitrogen—helium vapor—gas mixture on temperature at different pressures: 1) $2.0 \cdot 10^5$ Pa; 2) $4.0 \cdot 10^5$; 3) $6.0 \cdot 10^5$; 4) $1.2 \cdot 10^6$; 5) $3.0 \cdot 10^6$ Pa. T, °K.

Fig. 3. Dependence of pressure drop in experimental section on velocity of vapor—gas mixture at entrance at different pressures: 1) $2.0 \cdot 10^5$ Pa; 2) $4.0 \cdot 10^5$; 3) $6.0 \cdot 10^5$; 4) $1.2 \cdot 10^6$ Pa. W, m/sec; ΔP, Pa.

An experimental study was conducted to determine the conditions of the transition from the film mode to the mode characterized by retardation of the liquid by the gas stream and by a sharp increase in the pressure drop in the experimental section.

The dependence of the pressure drop in the experimental section on the velocity of the vapor—gas mixture at the entrance at different pressures is presented in Fig. 3. The character of these functions is qualitatively retained with a variation in pressure from $2 \cdot 10^5$ to $12 \cdot 10^5$ Pa.

The experimental data on the critical velocity were analyzed in the form of the dependence [6]

$$\frac{(W_{\mathrm{ex}}^{\mathrm{cr}})^2}{gd} \cdot \frac{\rho_{\mathrm{mi}}}{\rho_l} \mu_l^{0.16} = f\left[\left(\frac{L}{G}\right)^{0.25} \left(\frac{\rho_{\mathrm{mi}}}{\rho_l}\right)^{0.125}\right] \tag{1}$$

and are presented in [7].

The results of the studies of the critical velocity of vapor under the conditions of condensation showed that Fradkov's equation [6], obtained for irrigated pipes, gives vapor velocities which are overstated by about two times. At the same time, Eq. (1) in general form is valid for these two cases of the counterflow of the vapor and liquid film.

The studies of heat and mass exchange during the condensation of nitrogen vapor from a mixture with helium were conducted in the film mode of motion of the phases.

The pressure of the vapor—gas mixture in the tests was varied from $2 \cdot 10^5$ to $30 \cdot 10^5$ Pa, the initial concentration of nitrogen vapor was varied from 10 to 40% by volume, and the Reynolds number was varied from $0.8 \cdot 10^3$ to $10 \cdot 10^3$. The results of measurements of the distributions of the concentration of nitrogen vapor and of the wall temperature along the height of the experimental model were used as the initial data for the determination of the coefficients of heat and mass transfer.

Theoretical and experimental studies [2, 8, 9] have shown that the physical pattern of the process of condensation of vapor from a vapor—gas mixture can be described using the analogy of the processes of heat and mass exchange during condensation with the process of heat exchange during the suction of gas from a boundary layer.

In this case the relative intensity of mass exchange during condensation

$$\Psi_D' = \frac{j_{\mathrm{wa}}(1 - c_{\mathrm{wa}})}{\rho_0 u_0 (c_{\mathrm{wa}} - c_0)\,\mathrm{St}_{D_0}} \tag{2}$$

is connected with the relative permeability

$$b_D' = \frac{j_{\mathrm{wa}}}{\rho_0 u_0} \cdot \frac{1}{\mathrm{St}_{D_0}} \tag{3}$$

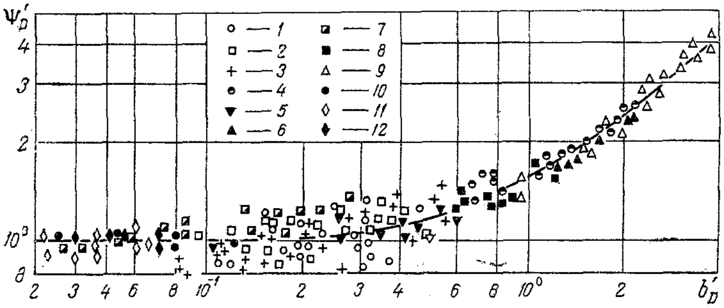

Fig. 4. Generalization of experimental data on mass exchange during condensation of vapor from vapor—gas mixtures: 1) $6.0 \cdot 10^5$ Pa; 2) $1.2 \cdot 10^6$; 3) $3.0 \cdot 10^6$. Data: 4, 5) [10]; 6) [11]; 7, 8) [12]; 9) [13]; 10, 11) [14]; 12) [2]; Ψ'_D, b'_D: dimensionless complexes.

by the relation obtained by Kutateladze and Leont'ev [8]:

$$\Psi'_D = f(b'_D). \tag{4}$$

The results of an analysis of the experimental data of the present study and the data of [2, 10-14] in the form of the dependence (4) are presented in Fig. 4. The relative intensity of mass exchange Ψ'_D is constructed from the diffusional mass flux, which is taken into account by the introduction of the factor $(1 = c_{wa})$; the quantity St'_{D_0} is a property of the hydrodynamic environment in the concrete case.

The satisfactory agreement of the results of our work and the results of [2, 10-14] with the theoretical solution of Kutateladze and Leont'ev should be noted.

The satisfactory agreement of the experimental data of the present work with the dependence (4) makes it possible to use the theoretical solution of [8] to analyze a wider circle of problems of condensation and to make qualitative and quantitative allowance for the effect of the transverse flow of material and the type of gas on the intensity of the process of mass exchange. The results of the experimental study made it possible to develop a method for calculating counterflow devices for cryogenic installations.

NOTATION

W_{ex}^{cr}, critical velocity of mixture at inlet based on experimental data; d, inner diameter of pipe; ρ, density of mixture; μ, coefficient of dynamic viscosity; L, amount of vapor condensing in the experimental section; G, amount of mixture at inlet to experimental section; ρ_0, density at outer limit of boundary layer; u_0, velocity at outer limit of boundary layer; j_{wa}, transverse flow of substance at heat-exchange surface; c_{wa}, mass concentration of component at wall; c_0, mass concentration of component at outer limit of boundary layer; St, Stanton number.

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CRITICAL DISCHARGE OF A SPONTANEOUSLY EVAPORATING LIQUID FROM CYLINDRICAL CHANNELS

V. A. Zysin, É. L. Kitanin,
and F. R. Latypov

UDC 532.542:536.423.1

A method is proposed for the calculated determination of the critical pressure in the discharge of a spontaneously evaporating saturated liquid through cylindrical channels. The results of the calculation are compared with experimental data.

The discharge of adiabatically effervescing streams through channels of constant cross section at large longitudinal pressure gradients is of considerable practical interest for a wide circle of problems of modern technology. In this case, as a rule, the pressure drop exceeds the critical value. The relationships of the crisis phenomena in spontaneously evaporating streams are very complicated. Depending on the geometrical characteristics and the initial parameters of the liquid the true flow rates vary within wide limits: from a value corresponding to isentropic discharge to flow rates corresponding to the case of the discharge of a non-effervescing liquid. As a result, all the design recommendations have a particular nature, as a rule, and are not subject to generalization [1, 2].

Below we propose a method for calculating the critical state of a spontaneously evaporating stream during discharge from cylindrical channels based on the simplified thermodynamic model of [3], the essence of which comes down to the following.

1. The effervescence of the stream takes place only at the channel walls and the penetration of the vapor into the core of the stream takes place only through the movement of bubbles formed in the boundary layer.

2. The peripheral (boundary) stream is in equilibrium and mechanical and thermal phase slippage is absent from it.

3. A jet of superheated (metastable) liquid whose temperature is taken as constant moves in the center. Thus, the motion of two one-dimensional concurrent streams is analyzed.

If one neglects the effect of frictional forces at the channel walls, a stream in a channel of constant cross section is described by the system

$$\rho_1 W_1 f_1 + \rho_2 W_2 f_2 = \Phi_0, \tag{1}$$

$$P_0 + \rho_0 W_0^2 = P + \frac{1}{\rho_1}(\rho_1 W_1)^2 f_1 + \frac{1}{\rho_2}(\rho_2 W_2)^2 f_2, \tag{2}$$

$$\left(h_0 + \frac{W_0^2}{2}\right)\Phi_0 = \left(h_1 + rx + \frac{W_1^2}{2}\right)\Phi_1 f_1 + \left(h_2 + \frac{W_2^2}{2}\right)\Phi_2 f_2. \tag{3}$$

As shown in [2], the velocity of the central metastable stream is determined by the equation

$$W_2 = \sqrt{\frac{2(P_0^* - P)}{\rho'}}, \tag{4}$$

while the mass velocity Φ_2 is equal to $\rho_2 W_2$.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 32, No. 1, pp. 30-33, January, 1977. Original article submitted December 16, 1975.