of the profiles of the liquid velocity and the intensity of the turbulent pulsations is now being conducted for a future investigation of the flow in the indicated range of the parameters.

NOTATION

τ, wall shear stress; τ_0, wall shear stress in one-phase flow; β, bulk flow-rate gas content; φ, local true gas content; R, pipe radius; y, distance from wall; Re, Reynolds number, constructed from reduced velocity and viscosity of the liquid.

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HEAT EXCHANGE IN FILM CONDENSATION OF STATIONARY VAPOR ON A VERTICAL SURFACE

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UDC 536.248.2

New experimental data are presented on the condensation of chladone-21 on vertical tubes over a wide range of Reynolds numbers and are compared with theoretical results.

The heat exchange when a pure stationary saturated vapor condenses on a vertical surface was first considered by Nusselt [1] in the case of laminar flow of a film of condensate. He obtained the following relation for the mean heat-transfer coefficient α for condensation on a vertical plate of height L:

$$\alpha = 0.943 \sqrt[4]{\lambda^3 \rho' (\rho' - \rho'') rg/\mu \Delta t L}\,. \tag{1}$$

In dimensionless form Eq. (1) can be written as

$$(\alpha/\lambda)(\nu^2/g)^{1/3} = 0.925 \mathrm{Re}^{-1/3}. \tag{2}$$

Nusselt made a number of assumptions in deriving Eq. (1), the correctness of which was confirmed by later investigations. A review of the work on this question can be found in [2]. It has been established that for laminar flow of a film of condensate there is no need to introduce any additional corrections to (1) when $\mathrm{Pr} \geq 1$, and $K \geq 5$, since they lie within the limits of experimental accuracy. Here $\mathrm{Pr} = \nu/a$, $K = (r/c)\Delta t$ are the Prandtl and Kutateladze criteria.

However, Eq. (1) has an extremely limited area of application since purely laminar flow of a film of condensate only occurs for very small Reynolds numbers of the film $\mathrm{Re} = qL/\mu r = G/\nu$.

For Re ~ 5 waves are formed in the flowing film which intensify the heat transfer. Attention was first drawn to this in [3]. In [4] for Reynolds numbers of the film characterizing the beginning of wave formation, the following relationship was proposed:

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TABLE 1. Theoretical Relations for Calculating the Heat Transfer When a Fixed Vapor Condenses on Vertical Surfaces

Lit. source	Equation	Re, Re_{cr}	Eq. No.
Kirkbride [10]	$(\alpha/\lambda)(\nu^2/g)^{1/2}=0{,}0076Re^{0,4}$	$Re=4G/\nu$, $Re_{cr}=1600$	(6)
Colburn [7]	$(\alpha/\lambda)(\nu^2/g)^{1/3}=Re/[22Pr^{-1/3}\times$ $\times(Re^{0,8}-364)+12800]$	$Re=4G/\nu$, $Re_{cr}=1600$	(7)
Kutateladze [9]	$(\alpha/\lambda)(\nu^2/g)^{1/3}=0{,}054Pr^{0,4}Re/$ $(Re^{5/6}-47+21Pr^{0,4})$	$Re=G/\nu$, $Re_{cr}=100$	(8)
Labuntsov [6]	$(\alpha/\lambda)(\nu^2/g)^{1/3}=Re/[2300+$ $+41Pr^{-0,5}(Re^{3/4}-89)(Pr/Pr_{st})^{0,25}]$	$Re=G/\nu$, $Re_{cr}=400$	(9)

$$Re_{\upsilon}=0.607\,(\sigma^3/\rho^3\nu^4g)^{1/11}, \tag{3}$$

which was obtained assuming that the occurrence of the waves had a capillary origin. According to the data from recent investigations [5], gravitational waves are formed on the surface of the flowing film which accompany capillary waves.

When introducing a correction to take into account the wave formation, Eq. (2) takes the form [30]

$$(\alpha/\lambda)(\nu^2/g)^{1/3}=1.18Re^{-1/3}. \tag{4}$$

When calculating the heat exchange for Reynolds numbers of the film of condensate $5 < Re < 100$ in [6] the following empirical correction to Eq. (2) was recommended:

$$\varepsilon_{\upsilon}=Re^{0.04}. \tag{4a}$$

When the Reynolds number of the film is increased further, the wave mode of flow of the condensate becomes turbulent. The heat transfer in condensation in the case of turbulent flow of the film of condensate has been investigated in [6-10, 33, etc.].

Table 1 shows some of the theoretical relations most often encountered in practice, representing to some degree the following functional relationship:

$$(\alpha/\lambda)(\nu^2/g)^{1/3}=f(Re,\ Pr). \tag{5}$$

Experimental investigations of the condensation of stationary vapor of different liquids in vertical tubes have been made by many workers. Table 2 gives information on some of the experimental work. It is seen from Table 2 that the greatest amount of work has been carried out on the condensation of water vapor. Figure 1 shows experimental data obtained by different workers in experiments with water vapor. The large spread in the points, particularly in the range $10^2 < Re < 10^3$, corresponding to the transition mode, is noteworthy. The experiments carried out by each worker were over a narrow range of Reynolds numbers.

Figure 2 shows experimental data on the condensation of the vapor of different materials. Here the spread between the experimental points is somewhat less but, as in the experiments with water vapor, the data given in the various papers were obtained over a narrow range of Reynolds numbers.

In Figs. 1 and 2 we compare the experimental results with the theoretical equations from Table 1 for Pr = 2 and Pr = 5, respectively.* It is seen from the figures that in the range of laminar and laminar-wave

* In constructing the Kutateladze curve, the values of the heat-transfer coefficient in the turbulent mode were found from (10).

TABLE 2. Experimental Data on the Condensation of Different Substances

Lit. source	Substance	Exper. part	Range of main parameters
Badger et al. [11]	Diphenyl	D = 22.2 mm L = 3.6 m	Re = 300-5500 Pr ≃ 5
Meisenburg [12]	Water	D = 25.4 mm L = 3.6 m	Re = 100-1000 Pr ~ 1.75
Kutateladze, Shrentsel [13]	Water	D = 19 mm L = 1 m and 4 m	Re = 25-2200 Pr ~ 1.1-1.75
Gudemchuk [14]	Water	D = 35 mm L = 950 mm	Re = 300-2500 Pr ~ 1.75
Masynkevich [15]	Chladone-12	D = 16 mm L = 276 mm	Re = 20-100 Pr = 3.7
Burov [16]	Water	D = 20 mm L = 275; 550; 1000 mm	Re = 25-175 Pr ~ 1.75
Zozulya [17]	Glycerine	D = 24 mm L = 972 and 1947 mm	Re = 0.25-2.5 Re = 25-500
	Water	The same	Pr ~ 1.75
Zozulya [18]	Water	Generalization of the data from 12 publications	Re = 10-2000
Pimenova [19]	CO_2	D = 25 mm L = 1 m	Re = 200-850
Ratiani, Shekriladze [20]	Water	D = 21.5 mm L = 217 mm	Re = 2.5-45 Pr ~ 1.75
Zozulya, Khorunzhii [21]	CCl_4	D = 16 mm L = 980 mm	Re = 7.5-620 Pr = 4.55
Kozitskii [22]	Chladone-12	D = 40 mm L = 500 mm	Re = 70.0-200 Pr = 3.9
	Chladone-22	The same	Re = 46-138 Pr = 3.6
Sato, Ogata [23]	Helium	D = 14 mm L = 32 mm	Re = 1-95.0 Pr = 0.59
Ivanov, Elukhin [24]	Oxygen Nitrogen Argon	D = 8 mm L = 2.4 m D = 16 mm L = 0.2 m	Re = 1-75.0 {Pr = 1.74 Pr = 2.26 Pr = 2.0
Chernobyl'skii, Gorodinskaya [25]	Ammonia	L = 0.5; 2 m D = 17 mm, 22 mm	Re = 4-240
Butuzov et al. [26]	Water	D = 18 mm L = 1.27 m	Re = 11-44 Pr = 1.75
Baker, Hipkin [27]	Benzine Ethanol Acetone, heptane mixture	D = 25.4 mm L = 1.12 m	Re = 38-500

flows of the film of condensate the experimental data are satisfactorily described by the Nusselt relation (2) with a correction for the wave flow of the film ε_V.

Equations (6)-(10) for the turbulent mode differ considerably from one another in the range of Reynolds numbers corresponding to the transition from laminar-wave flow to turbulent flow. From the experimental data it is not possible to draw any conclusions regarding the correctness of any particular theoretical equation because of the large spread in the experimental points.

The purpose of the present paper is to make an experimental investigation of the heat exchange in the condensation of a fixed vapor on vertical tubes over a wide range of Reynolds numbers. We chose chladone-21 ($CHFCl_2$) as the working substance since it is a convenient simulating substance and is a promising working material in low-temperature power engineering [31].

The experiments were carried out using the arrangement shown in Fig. 3. The body of the condenser consisted of a cylinder of internal diameter 50 mm and length 1200 mm. A distributed supply of vapor was provided from the sides of the cylinder. All the parts of the equipment were made of stainless steel and were thermally insulated with asbestos. The experimental parts were fastened with packing on the upper and lower

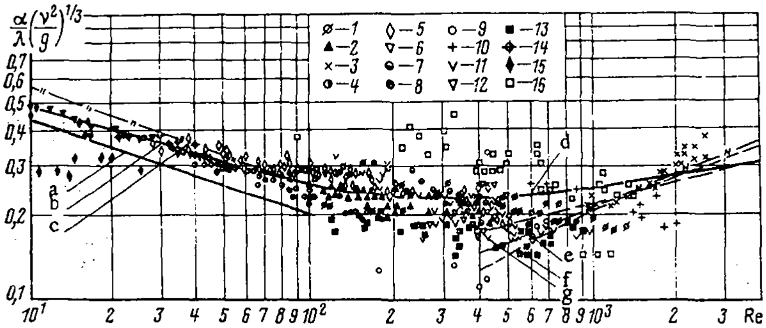

Fig. 1. Condensation of water vapor on vertical tubes: 1) Meisenburg [12]; 2) Kutateladze, Shrentsel [13]; 3) Gudemchuk [14]; 4) Burov [16]; 5) Zozulya [17]; 6) Ratiani, Shekriladze [20]; 7) Butuzov et al. [26]. The data obtained by the following authors are taken from [10, 18]: 8) Calender and Nicholson; 9) Jordan; 10) Jakob, Erk, Ek; 11) Gebbard and Badger; 12) Lozhkin and Kanaev; 13) Baker and Strobe; 14) Shi and Kraze; 15) English and Donkin; 16) Fredzhen. a) (2); b) theoretical from (2) with the correction (4a); c) (4); d) (10); e) (6); f) (7); g) (9). Curves (7), (9), and (10) are drawn for Pr = 2.

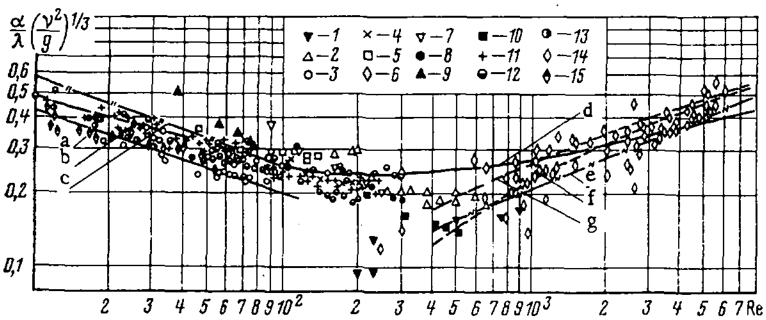

Fig. 2. Film condensation of different liquids on vertical tubes: 1) CO_2 [19]; 2) CCl_4 [21]; 3) X-12 [15]; 4) X-12 [22]; 5) X-22 [22]; 6) diphenyl [11]; 7) acetone [27]; 8) benzine [27]; 9) ethanol [27]; 10) heptane mixture [27]; 11) ammonia [25]; 12) oxygen [24]; 13) nitrogen [24]; 14) argon [24]; 15) ammonia [15]. The remaining notation is the same as in Fig. 1. Curves (7), (9), and (10) are drawn for Pr = 5.

flanges of the condenser along their center. The characteristics of the experimental parts are given in Table 3.

We used fairly pure chladone in the experiments. According to a factory analysis, its composition was as follows: $CHFCl_2$ 99.8%, moisture 0.12% (by weight), CF_2Cl_2 0.08%.

Before the experiment the chladone was purified of water and after filling the equipment the latter was blown through many times. In the calculations the properties of X-21 were taken from [28].

In the experiment we determined the heat-transfer coefficient α at the external surface of the experimental part $\alpha = q/\Delta t$. The heat flux density q, W/m^2, was found from measurements of the flow rate and heating of the water, and also from the flow rate of the condensate. When determining the temperature head $\Delta t = t'' - t_w$, °C, we measured the temperature of the saturated vapor t'' using a thermocouple. In the experiments the correspondence between the measured temperature of the vapor and the dependence of X-21 determined from P, T was maintained. The pressure in the condenser was measured with a class 0.35 manometer. The temperature of the wall of the experimental parts was measured by two methods. In the experiments on parts No. 2, 3, and 4 of the tube we used resistance thermometers. The temperature of the wall of tubes No. 1 and 5 was found as the average of the readings of six thermocouples stamped with an interval increasing uniformly from the vertex to the bottom of the tube.

TABLE 3. Experimental Parts

No.	External diameter D, mm	Tube length L, mm	Material
1	15	1130	Brass
2	15	260	Nickel
3	2,5	1140	"
4	5	1120	"
5	16	290	"

TABLE 4. Experimental Data on the Condensation of Chladone-21 on Vertical Tubes

$q \cdot 10^{-3}$, W/m²	Δt, °C
Tube No. 1	
t'' = 40 °C	
5,2	2,9
4,8	2,5
5,0	2,8
3,8	2,1
7,1	4,6
8,3	5,7
10,2	7,7
11,2	8,5
11,8	9,5
22,0	16,5
20,6	18,5
20,9	19,7
20,8	18,7
11,8	8,5
11,7	8,8
2,8	1,5
t'' = 60 °C	
24,7	22,5
21,6	18,2
19,4	14,9
17,6	14,9
17,1	14,4
9,6	8,1
9,9	8,5
8,2	5,7
7,9	6,5
6,6	5,3
19,4	14,1
16,6	11,8
13,9	11,6
6,5	4,8
4,5	3,2
3,9	2,6
3,3	2,0
3,2	2,1
2,8	1,6
36,6	35,1
27,1	26,5
13,2	9,6
12,2	9,2
7,6	4,7
2,8	1,7
t'' = 90 °C	
49,1	43,8
64,4	62,7
58,4	54,5
53,8	49,6
19,8	16,7
38,8	34,7
33,4	28,6
13,4	10,3
75,0	64,9
17,7	13,6
22,4	15,9
25,6	19,9
31,6	25,9
t'' = 125 °C	
96,5	89,3
96,0	87,7
33,7	76,1
67,1	63,8
54,0	48,9
53,2	47,5
67,5	63,8
54,6	49,1
82,1	77,1
111	94,9
Tube No. 2	
t'' = 40 °C	
2,8	1,0
6,4	2,8
7,5	3,5
9,6	5,1
11,9	6,6
15,0	9,0
18,4	11,5
t'' = 60 °C	
27,3	19,5
39,5	33,5
Tube No. 3	
t'' = 40 °C	
31,1	30,3
38,4	33,0
30,2	30,8
26,1	24,6
18,0	15,1
10,9	8,3
9,9	8,3
t'' = 90 °C	
80,0	67,4
76,0	64,0
70,0	59,4
66,6	57,7
56,3	49,1
58,7	49,2
35,2	28,0
28,8	24,7
Tube No. 4	
t'' = 40 °C	
20,7	19,3
21,3	18,7
22,0	19,1
14,6	12,2
11,1	10,1
7,8	5,8
7,5	5,4
7,3	5,7
8,7	7,2
9,3	7,2
10,7	8,4
10,6	8,4
12,0	10,2
12,4	10,2
12,8	11,1
16,3	13,5
t'' = 60 °C	
39,5	37,8
39,1	37,1
36,7	33,6
33,0	30,6
35,2	33,9
34,1	30,9
31,6	28,5
28,0	24,7
27,6	23,6
21,9	19,5
18,6	17,2
17,7	16,8
18,2	15,9
15,8	13,7
13,0	10,9
t'' = 90 °C	
71,5	63,8
71,7	64,1
68,4	61,0
60,5	54,3
59,6	53,5
52,7	47,5
46,1	41,4
46,0	41,4
48,5	43,7
38,1	35,6
36,6	34,9
25,9	24,7
19,8	19,5
27,4	26,1
26,6	25,8
42,6	39,0
52,7	47,2
t'' = 125 °C	
118,0	93,1
115,0	92,3
104,0	86,8
88,7	71,6
95,9	81,1
94,7	80,1
93,0	78,3
85,1	69,7
Tube No. 5	
t'' = 40 °C	
23,8	16,3
10,9	5,7
7,7	3,7
4,9	2,2
3,1	1,4
3,3	1,3
6,0	2,9
5,4	2,7
4,0	2,0
2,3	0,8
4,0	1,8
5,4	2,7
23,0	15,3
20,0	12,8
17,2	9,9
8,9	5,1
7,0	3,6
9,0	4,3
11,8	6,6
t'' = 60 °C	
42,0	36,0
42,9	35,6
26,9	20,3
29,0	23,4
20,3	14,6
t'' = 90 °C	
60,5	62,7
56,2	56,9
43,5	43,1

The accuracy in determining the heat-transfer coefficient was not less than 10%.

We investigated the dependence of the heat-transfer coefficient on the temperature head and on the physical properties of the condensates (the saturation temperature). The vapor-wall temperature head was changed by varying the temperature of the water which cool the experimental part. About 200 measurements in all were taken of the heat-transfer coefficient. Part of the data obtained is shown in Table 4.

We found in the experiment that for a change in the condensation temperature from 40°C to 125°C there is no differentiation of the experimental data with respect to the pressures, in agreement with the results obtained in [29].

The experimental data obtained were processed in $(\alpha/\lambda)(\nu^2/g)^{1/3}$—Re coordinates (Fig. 4). As is seen from the figure, the Reynolds numbers varied over the range $10 \leq Re \leq 4300$, which enabled us to cover laminar-wave flow, transitional flow, and turbulent flow of the film. Here we also present data on the condensation of other chladones [15, 22].

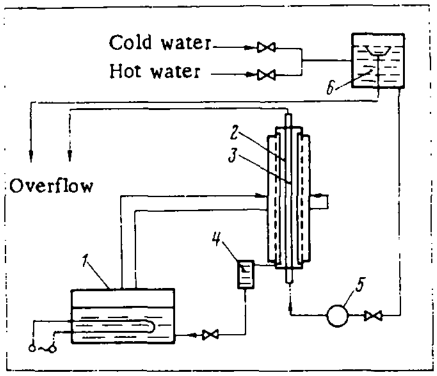

Fig. 3. Experimental arrangement: 1) vapor generator; 2) condenser; 3) experimental part; 4) condensate volume flowmeter; 5) water flowmeter; 6) constant-head tank.

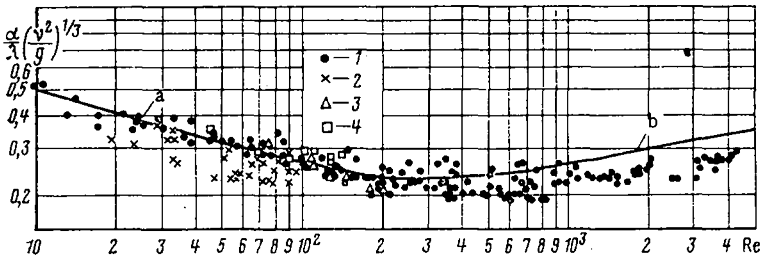

Fig. 4. Film condensation of chladones on vertical surfaces (Re = G/ν): 1) obtained by the authors, X-21; 2) X-12 [15]; 3) X-12 [22]; 4) X-22 [22]. a) Calculated from Eq. (2) with the correction (4a); b) calculated using (10) with Pr = 3.

Experimental data obtained on tubes of different length and diameter, for different condensation temperatures, can be satisfactorily generalized in these coordinates, and agree with condensation data for other chladones.

A comparison with the theoretical relations showed that up to Re ~ 100 the results of the experiment are in satisfactory agreement with the calculations using Eq. (2) with a correction for the wave motion ε_V [6] (line 2). For Re > 100 best agreement with experiment is obtained by a numerical calculation of the heat transfer for a mixed flow mode of the condensate film, when the local value of the heat-transfer coefficient in the region of turbulent flow is calculated using Kutateladze's equation [30] (line 4). In this case the critical Reynolds number was taken as $Re_{cr} = 100$

$$(\alpha_x/\lambda)(\nu^2/g)^{1/3} = 0.4\Pr\eta_\delta^{1/3}\delta\left\{\ln\left[\left(\sqrt{\eta_\delta}+\sqrt{\eta_\delta-11.6}\right)/\left(\sqrt{\eta_\delta}-\sqrt{\eta_\delta-11.6}\right)\right]+4.65\Pr\right\}^{-1}, \qquad (10)$$

where $\eta_\delta = v_w^*\delta/\tau$ is the dimensionless thickness of the film, and $v_w^* = \sqrt{\tau_w/\rho} = \sqrt{g\delta(1-\rho''/\rho')}$ is the velocity of the tangential stress.

At the same time it is well known that the critical Reynolds number of the film for gravitational flow is equal to 400 [30, 32].

Kutateladze explained this disagreement by assuming that the waves on the external surface of the film of condensate increase the contact surface and increase the effective value of its thermal conductivity. The latter can be considered as the occurrence of quasiturbulent heat conduction and one can extend Eq. (10) into the region of Reynolds numbers beginning with Re ≃ 100.

A calculation using the approximate relation (8) in the region of Reynolds numbers $100 \le Re \le 1000$ gives a somewhat increased value (by ≈ 10%) of the heat-transfer coefficient compared with the numerical calculation.

It is noteworthy that over a wide range of variation of Reynolds numbers the experimentally determined heat-transfer coefficient had a practically constant value, which disagrees with calculations using the theoretical relations (6)-(9) if we take $Re_{cr} = 400$. Note that these relations were obtained for a mixed flow mode for the condensate film, i.e., taking into account the laminar part.

It follows from an analysis of the data obtained and also of the data obtained by other workers that:

a) up to the present time heat exchange in condensation has been investigated over a wide range of Reynolds numbers only for two materials, viz., water and chladone-21;

b) for Re < 5, according to [17, 20, 25], the heat exchange can be calculated using Eq. (2);

c) in the range of values $5 \leq Re \leq 100$ satisfactory results are obtained using Eq. (2) with the correction $\varepsilon_V = Re^{0.04}$;

d) for values of Re = 100-1000 best agreement with experiment is obtained using Eq. (10);

e) for Re > 1000 calculations using Eqs. (6)-(10) give practically the same results and agree with the data obtained for the condensation of X-21, and also the data on the condensation of diphenyl [11], in the region of high Reynolds numbers with an accuracy of ±15%.

NOTATION

ν, kinematic viscosity, m^2/sec; c, specific heat, J/kg·deg C; g, acceleration due to gravity, m/sec^2; L, length of the experimental part, m; D, diameter of the experimental part, m; τ_W, tangential stress on the wall, N/m^2; q, specific heat flux, W/m^2; α_X, local heat-transfer coefficient, $W/m^2 \cdot deg\ C$; λ, thermal conductivity of the liquid, W/m·deg C; ρ' and ρ'', densities of the liquid and vapor, kg/m^3; r, latent heat of vaporization, kJ/kg; μ, dynamic viscosity of the liquid, $N \cdot sec/m^2$; $\Delta t = t'' - t_W$, temperature difference between the saturated vapor and the wall, °C; σ, surface tension, N/m; δ, film thickness, m; and a, thermal diffusivity, m^2/sec.

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EFFECT OF THE DEGREE OF DISPERSION, THE DROP CONCENTRATION AND THEIR FINE SUBDIVISION ON THE ENERGY AND FLOW CHARACTERISTICS OF VAPOR-DROP FLOWS

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The degree of dispersion of the condensed phase and its concentration are the most important parameters of high-speed two-phase flows, which determine, in particular, their energy and discharge characteristics.

Numerous investigations have been made of two-phase flows in nozzles. A generalization of the results of these investigations is given in [1-3, etc.]. A theoretical analysis of the effect of the particle size on the flow of a mixture of gas and particles in nozzles was first given in [4] using the solution of a simplified system of differential equations. It was shown that when the slip coefficient $\nu = u_2/u_1$ increases (in the case considered this corresponded to a reduction in the particle size) the flow of a two-phase mixture through a nozzle is reduced, other things being equal. In [2, 4] an analysis is given of experimental investigations of the effect of the concentration of condensed phase y_0 when a highly disperse vapor-drop medium flows in nozzles over a wide range of values of y_0. A numerical investigation of the effect of the particle size D_0 on the characteristics of two-phase flows is given in [5]. The strong effect of D_0 and y_0 on the energy loss and the flow characteristics of nozzles in the case of the flow of two-phase mixtures was qualitatively confirmed.

It should be noted that in these investigations the fine subdivision of the particles was ignored. At the same time, in actual vapor-drop high-speed flows (particularly in the flowing parts of moist-vapor turbines) the deformation and subdivision of the liquid drops are extremely intense. This in turn leads to a considerable difference between the theoretical results obtained ignoring these processes, and experimental data. In practice, there have also been no investigations in developing methods for the artificial control of the degree of dispersion of high-speed vapor-drop flows due to intensification of the subdivision or coagulation of the particles and the energy and flow characteristics of such flows as a result of this. The development of methods of reducing the particle sizes is of considerable practical importance, particularly from the point of view of increasing the economic efficiency of moist-vapor turbines and for reducing the erosion of their components.

The main purpose of this paper is to make a numerical and experimental investigation of the effect of fine subdivision of the drops on the characteristics of vapor-drop flows, and also to study methods for the effective control of their dispersion structure. One of these methods is by introducing small quantities of surface-active materials into the flow. The surface-active material, when it interacts with the liquid phase, changes the surface tension of the drops, and, consequently, the location, mechanism, and intensity of their subdivision. In this investigation we added octadecylamine to the flow to obtain a different dispersion structure at the input to the nozzle. At the same time, the assumption that octadecylamine only affects the surface tension of the drops (i.e., the Weber number) enables us, to a first approximation, to estimate the effect of the surface-active material on the characteristics of two-phase flows.

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