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JETS OF INCIPIENT LIQUIDS

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Jets of incipient water escaping into the atmosphere through a short channel are photographed. In some experiments, complete disintegration of the jet is observed. The relationship of this phenomenon with intense volume incipience is considered. The role of the Coanda effect upon complete opening of the jet is revealed. Measurement results of the recoil force R of the jets of incipient liquids are presented. Cases of negative thrust caused by the Coanda effect are noted. Generalization of experimental data is proposed.

Introduction. Jets of incipient liquids can arise in emergency situations in various thermoenergetic, cryogenic, and chemical devices. The consequences of an accident with local depressurization of a high-pressure pipeline (tank) are determined by various factors, for example, the flow rate of the heat-carrying agent, the shape of the jet, and its dynamic response to constructural elements.

In previous publications [1–7], the main focus was on the regime of explosive incipience of the liquid on vapor-formation sites of a fluctuating nature. This regime is reached if the initial temperature of the liquid is $T_0 \geqslant 0.9T_{\rm cr}$ ($T_{\rm cr}$ is the temperature at the critical point) [8]. Short cylindrical channels with sharp edges were used in the experiments. The flow in such channels is close to that arising when cracks appear in pipelines. The main results of these investigations are as follows. A thermodynamically nonequilibrium flow of an incipient liquid is formed in a short channel. Because of the delay in incipience and the small residence time of the superheated liquid in the channel (about 10^{-5} sec), the mass flow rate upon exhaustion into the atmosphere can be twice as high as the equilibrium flow rate [2, 3]. Under conditions of intense homogeneous nucleation ($T_0/T_{\rm cr} \geqslant 0.9$), critical choking of the channel occurs. In other words, a decrease in counterpressure does not affect the flow rate of the liquid [4]. The shape of the jet behind the probe exit varies significantly depending on the magnitude of liquid superheating relative to the saturation line under conditions of adiabatic expansion. The rodlike shape of the jet changes gradually to conical, parabolic (with a large angle of expansion at the exit), and gaseous (at $T_0/T_{\rm cr} > 1$). In the case of high superheating of the liquid, flow instability is observed. The jet can be "captured" by the solid wall of a pressure flange and spread in the plane perpendicular to the direction of its motion [6] (the Coanda effect [9]). The recoil force of the jet R acting on the chamber with the liquid increases with increasing saturation pressure in the chamber. However, as the conditions of explosive incipience and complete disintegration of the jet (spreading of the jet along the surface of the test chamber) are reached, the value of R decreases. Jet "adhesion" to the wall and its spreading on the latter strongly alter the pressure diagram, and the recoil force decreases by several times and can even change its sign [7].

The above results of the previous test series demonstrate the necessity of a more careful inspection of the jets of an incipient liquid, in particular, the interaction of the jet with a closely located solid wall. It is clear that there are no conditions for "capturing" of the jet by the wall in special nozzle devices, but this

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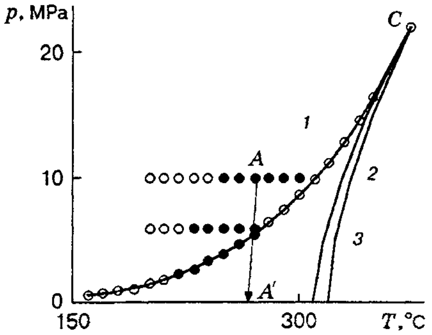

Fig. 1. Phase diagram of water (C is the critical point of water): 1) saturation line; 2) spinodal: 3) superheated water for $J = 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{sec}^{-1}$: AA' is an isentrope; the points indicate the initial states (the dark points show the initial states for which complete disintegration of the jet is observed).

effect may be important for kinematics and dynamics of an accident in emergency violation of the continuity of pipes or reservoirs.

In the present work, a series of tests with jets of water, n-pentane, and Freon-11 was performed using short cylindrical channels and replaceable flanges affecting the jet shape. Tests with water are necessary, since the conditions of explosive incipience of water have some special features different from those for other liquids. Intense formation of vapor sites in water begins at lower relative values of superheating [10]. In addition, water is the most frequent heat-carrying medium and working body. In the present experiments, the recoil force was measured for jets of n-pentane and Freon-11 for an initial saturation pressure varying up to the pressure at the critical point. The data of Vinogradov et al. [11] for water were used. The results were treated using the technique of thermodynamic similarity.

Jets of Incipient Water. The shapes of the jets of incipient water were experimentally studied on a short-term laboratory setup, which ensured a steady regime of exhaustion into the atmosphere for 5–10 sec. The working chamber was a cylindrical glass of volume 350 cm^3 made of stainless steel [6]. The initial state (p_0, T_0) of water in the chamber varied along the saturation line within the interval $200°\mathrm{C} \leqslant T_0 \leqslant 350°\mathrm{C}$ and along the isobars $p_0 = 6$ and 10 MPa (Fig. 1). Significant superheating was ensured by the use of short channels with high rates of pressure decrease (about 10^6 MPa/sec). The region between lines 2 and 3 corresponds to the conditions of explosive incipience of the liquid in the flow characterized by high intensity and spatial and temporal concentration. For $p > p_s(T)$, the initial conditions were ensured by pressing the liquid by gaseous nitrogen.

The shape of the jets of incipient water escaping through a cylindrical channel of diameter $d = 0.5$ mm and length $l = 0.7$ mm was observed visually and photographed. The photographing was performed in reflected light. Exhaustion of the liquid was initiated by removing a valve closing the channel inside the chamber and proceeded horizontally. The initial conditions corresponded to the parameters at the saturation line (T_0, p_{0s}). We note the main features of the jets studied. For $T_0 = 150°\mathrm{C}$ (superheating at the exit is 50°C), the jet does not differ from a jet of a non-incipient (cool) liquid. For $T_0 = 170°\mathrm{C}$, the influence of individual vapor bubbles and surface effects on the jet shape is noted. [Pavlov and Isaev [12] analyzed the jet processes for superheatings from 35 to 70°C and revealed the determining role of intense evaporation from the jet surface (mechanism of barocapillary instability) on its disintegration.] Beginning from the temperature $T_0 \approx 190°\mathrm{C}$, the main factor affecting the jet shape is intense volume incipience. The jet acquires the shape of a hollow cone. At $T_0 = 200°\mathrm{C}$, the apex angle of the cone is $\alpha \approx 90°$. The major part of the vapor-liquid medium is concentrated near the cone generatrix. Complete disintegration of the jet ($\alpha \approx 180°$) at $T_0 = 230°\mathrm{C}$ is shown in Fig. 2. Figure 2a shows the jet spreading in the radial direction over the surface

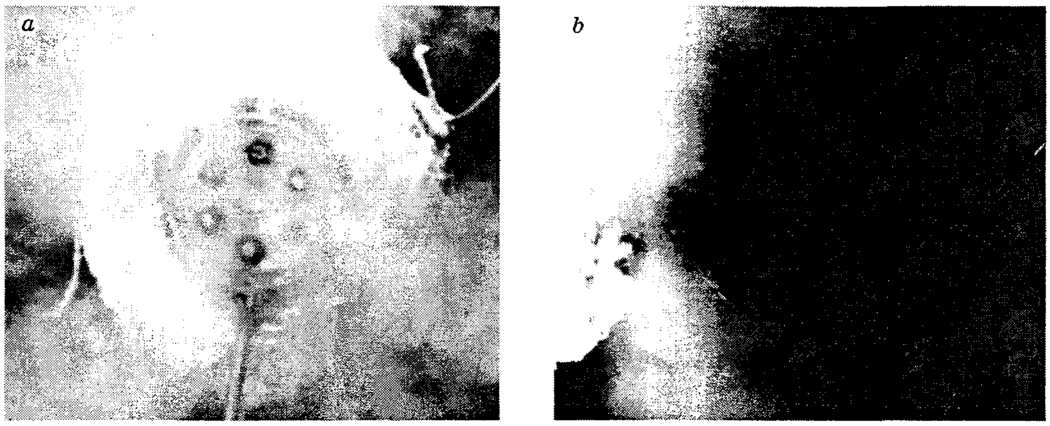

Fig. 2. Complete disintegration of the jet of incipient water for $T_0 = 230°C$: front view (a) and side view (b).

of a pressure flange (fan-shaped jet). Complete opening of the jet of incipient water in this test series was observed in the temperature range $T_0 = 215$–$275°C$. For $280°C \leqslant T_0 \leqslant 330°C$, the jet again is not opened completely and has a form close to parabolic. For $T_0 \geqslant 330°C$, the flow acquires the shape of gas jets with an expansion angle $\alpha \approx 25°$.

The discussion of experimental data is primarily based on the analysis of the thermodynamic state of the medium in the channel. Since this state is metastable, it is determined by three physical parameters T, p, and J (J is the number of viable vapor sites that can appear in 1 cm^3 during 1 sec). Instead of J, one can also use the mean waiting time of the critical bubble $\langle\tau\rangle$, since these quantities are related as

$$JV\langle\tau\rangle = 1,$$

where V is the volume of the liquid in a superheated state. The effectiveness of this approach was demonstrated by studying the flow rates of an incipient liquid [1–4]. By comparing the values of $\langle\tau\rangle$ and the residence time of the superheated liquid in the channel t_{ch}, we can conclude that the liquid in the channel remains practically in a single-phase state (for $t_{\text{ch}} < \langle\tau\rangle$) in a wide range of superheated states $T \leqslant 0.9T_{\text{cr}}$ and $0 < p < p_s$. Hence, the exhaustion can be described using the approximation of a perfect incompressible liquid, and the flow rate can be calculated using the Bernoulli formula

$$g = \mu\sqrt{2(p_0 - p_a)\rho_0}, \tag{1}$$

where g is the specific mass flow rate, μ is the flow-rate coefficient, p_a is the atmospheric pressure, and ρ_0 is the density of the liquid in the initial state. As a result, good agreement of the calculated values of g and experimental data was obtained. The measurement of the flow rates of incipient water escaping through short channels demonstrated the validity of this approach for water [13], though anomalously high frequencies of nucleation [10] are typical of water for $T/T_{\text{cr}} < 0.9$ as compared to most organic liquids. The difference in the nucleation rate affected the jet shape significantly. Thus, complete disintegration of the jet of incipient n-pentane was observed only for $T/T_{\text{cr}} \approx 0.9$, i.e., near the region of explosive incipience [5]. In our experiments with water, complete opening of the jet occurred already at $T/T_{\text{cr}} \approx 0.75$, which is associated with water-incipience kinetics.

The effect of jet disintegration found extensive applications in engineering. It was established [14] that, for complete opening of an air jet, it should have the shape of a hollow cone (this is ensured by preliminary swirling of the flow or by placing a conical body in the jet behind the channel exit). In addition, there was a plane perpendicular to the jet axis behind the channel exit.

In experiments with incipient liquids escaping through a short channel, a hollow cone of the jet was observed as a result of intense volume incipience, and the exit flange served as a plane normal to the jet axis. Several test series were conducted to study the effect of geometric parameters on the jet shape. In particular,

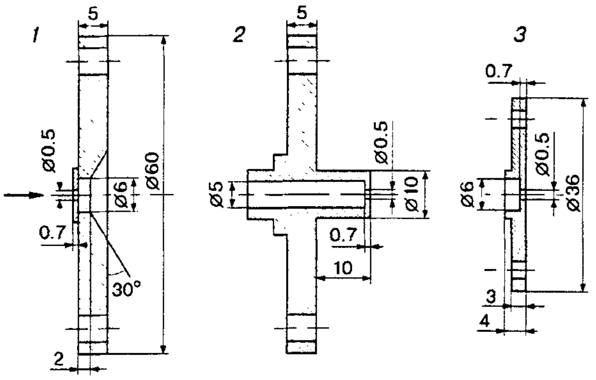

Fig. 3. Geometry of exit flanges.

the effect of the relative length of the channel ($l/d = 1.4$, 7, and 12) was studied for $d = 0.5$ mm. As the channel length increases, the phase nonequilibrium in the adiabatic flow within the channel decreases. For a rather high value of l/d, the phase transition is completed, and we obtain a thermodynamically equilibrium two-phase flow at the channel exit. The results of tests with the main channel ($l/d = 1.4$) plotted in Fig. 2 can be characterized as those obtained in the regime of a thermodynamically strongly nonequilibrium flow of incipient water. For $l/d = 7$, the jet shapes observed coincided with those obtained in the main channel, i.e., the exhaustion regime remained the same. The exhaustion pattern changed dramatically in experiments with $l/d = 12$. Here the jet shape within the entire field of initial thermodynamic states shown in Fig. 1 remained almost constant and similar to the shape of the gas jet. This indicated that the vapor–water flow at the channel exit acquired an almost completely thermodynamically equilibrium state.

Figure 3 shows the geometric characteristics of the exit flanges. The photographs in Fig. 2 were obtained for flange configuration 1. As T_0 and J increase, the external surface of a conical annular jet approaches the exit-flange surface and is "captured" by it due to the Coanda effect. Then the jet is spread on the walls of external structures (see Fig. 2). The filled points in Fig. 1 correspond to the initial parameters of water for which complete disintegration of the jet was observed for the geometry of flange 1. For flange configuration 2, which does not have a plane behind the channel exit, complete disintegration of the jet was not registered in the entire temperature range under study. The conic and parabolic shapes of the jet were retained. The geometry of flange 3 occupies an intermediate position. The plane of the channel exit here coincides with the plane of the flange, which hinders effective interaction between the jet and the flange. Only accidental short-term disintegrations of the jet were observed in experiments at $T_0 = 250$–300°C. The conical profile of the jet was much more stable.

Experiments with *n*-Pentane and Freon-11. Isaev et al. [7], who studied the recoil force of a jet of incipient *n*-pentane, did not clarify the questions related to the effect of geometric parameters on the magnitude of the recoil force of the jet, in particular, they did not discuss the Coanda effect. Therefore, an additional experimental study of the dynamic action of a jet of an incipient liquid was performed.

The experiments were conducted in a laboratory facility whose layout can be found in [7]. It is a pendulum in a gravity field. The exhaustion was performed in the horizontal direction, and the force acting on the pendulum was determined by its deviation from the equilibrium position. The load on the working chamber is determined by two components:

$$R = \int\limits_{\Omega_k} U_n g \, d\omega + \int\limits_{\Omega} \Delta p \, d\omega. \qquad (2)$$

Here Ω_k is the surface of the "hemisphere" bounding the jet, U_n is the projection of velocity onto the direction of the jet axis, and Ω is the total surface of the chamber accepting the changes in static pressure. The second term in (2) is small except for the cases of jet spreading over the surface of the pressure flange. This is

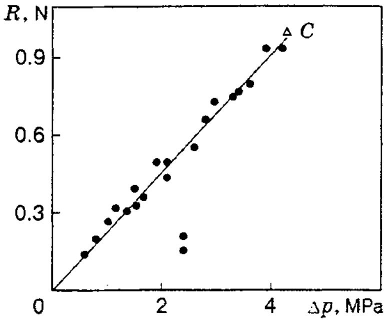

Fig. 4. Recoil force R for Freon-11 versus the pressure difference $\Delta p = p_0 - p_a$ (the points refer to experimental data and the straight line to calculation by formula (3): C is the critical point).

supported by the estimate obtained by measuring the static pressure difference Δp near the front and back walls of the working chamber by a differential manometer. Thus, the recoil of the jet was measured directly in experiments without jet spreading.

Figure 4 shows the measurement results for the recoil force of the jet of incipient Freon-11 (p_c = 4.37 MPa and $T_{\rm cr}$ = 198°C) for the initial parameters of the liquid corresponding to the saturation line. Eliminating the second term, we can write formula (2) in the form

$$R = G\langle U_n \rangle,$$

where G is the mass flow rate of the substance and $\langle U_n \rangle$ is the mean component of velocity of the medium in the cross section where the pressure in the jet is equal to the atmospheric pressure. Using Bernoulli formula (1), we obtain the formula for a small expansion angle of the jet in the hydraulic approximation

$$R = 2\mu(p_0 - p_a)S, \tag{3}$$

where S is the cross-sectional area of the channel. The solid curve in Fig. 4 shows the calculation by formula (3) for initial parameters corresponding to the saturation line of Freon-11. Except for two points, the experimental data are close to the calculated line. To establish a relationship between the measured values of the recoil force and the shape of the jet of incipient Freon-11, the jet was monitored and photographed. For a rather high temperature $T_0/T_{\rm cr} \geqslant 0.84$, the shape of the jet differs from the jet of a non-incipient liquid and acquires conicity. For $T_0/T_{\rm cr} \geqslant 0.9$, the cone expansion angle increases approximately to 100°. A further increase in temperature and initiation of the mechanism of explosive incipience cause a change in the jet shape from hollow conical to hollow parabolic; at T_0 = 155 and 157°C ($T_0/T_{\rm cr} \approx 0.91$), complete disintegration of the jet is observed. In Fig. 4, these conditions correspond to points lying outside the general dependence (Δp = 2.4 MPa). The experiments with Freon-11 were conducted with exit flange 3 shown in Fig. 3.

The same approach (observation, photographing, and recoil-force measurement) was used in an experimental study of the jet of incipient n-pentane (p_c = 3.37 MPa and $T_{\rm cr}$ = 197°C). Test series were conducted with changing of the exit flanges (configurations 2 and 3 in Fig. 3). It was found that a jet of n-pentane for the same initial temperatures as in experiments with Freon-11 acquires similar shapes: conical, parabolic, and completely opened. In the case of flange 2, complete disintegration of the jet was not observed within the entire temperature range of the saturation line up to $T_{\rm cr}$. The magnitude of the recoil force did not experience any nonmonotonic changes, and its values agreed with the hydraulic calculation. Concerning the experiments with flange 3, the behavior of the jet shape and the dynamic response almost completely repeat the results of experiments with Freon-11. The difference is that the complete disintegration was more stable and covered a greater region of the parameters of state. This may be related to the lower value of p_0 in the region of jet disintegration than for Freon-11 and, hence, with the lower exhaustion velocity. Note that the critical temperatures are little different for Freon-11 and n-pentane, whereas the ratio of their critical pressures is 1.3.

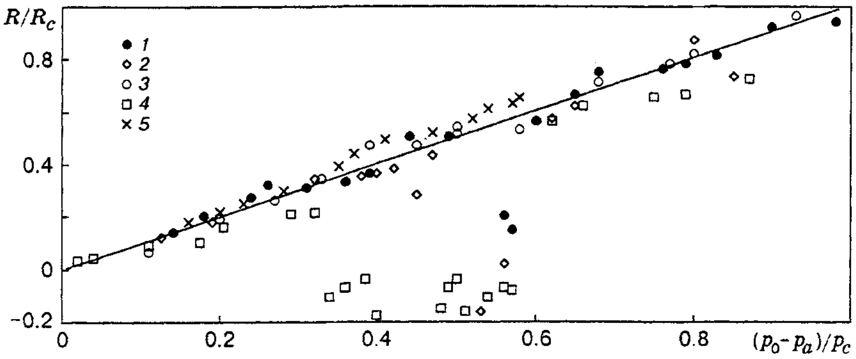

Fig. 5. Relative recoil force of the jets of incipient liquids escaping into the atmosphere through a short channel for different configurations of exit flanges shown in Fig. 3: 1) Freon-11 (flange 3): 2) *n*-pentane (flange 3): 3) *n*-pentane (flange 2): 4) *n*-pentane [16] (flange 1): 5) water [11] (flange 2): the solid line shows the calculation by formula (3).

To generalize the experimental data on the measurement of the recoil force of incipient liquid jets escaping from a short channel into the atmosphere, it is reasonable to use the method of thermodynamic similarity. This approach was used for the flow rate of incipient liquids in [3, 15]. Since the flow rate in the exhaustion regime with strong phase nonequilibrium is significantly affected only by the thermodynamically determined explosive process of incipience, the use of this method turned out to be rather effective. The results of experiments on recoil-force measurements are presented in dimensionless coordinates in Fig. 5. The pressure at the thermodynamical critical point p_c is used as the pressure scale, and the value of R_c in the approximation of the hydraulic regime of exhaustion [see (3)] for the initial pressure $p_0 = p_c$ is chosen as the recoil-force scale. The majority of the measured recoil forces for different substances are close to the straight line calculated by formula (3). The data for water are taken from [11], where experiments with the exit-flange geometry similar to that of flange 2 in Fig. 3 are described. In the absence of the plane near the channel exit section, disintegration of the water jet was not observed in experiments [11]. A similar monotonic form of the dependence $R(\Delta p)$ close to the calculated line was obtained in experiments with *n*-pentane for flange 2. For flange 1, we used the data of experiments with *n*-pentane reported in [16]. In this case, the negative values of the recoil force are within the interval of relative pressures from 0.4 to 0.6 (see Fig. 5), which corresponds to the temperature range from 140 to 165°C. Isaev et al. [16] indicated that a dramatic decrease in R is caused by complete disintegration of the jet. Because of the Coanda effect, which leads to significant changes in the flow near the working chamber, the second term in (2) becomes comparable with the recoil force of the jet and even greater than that. As a result, the total force acting on the device has a negative value. In experiments with flange 3 [see Fig. (3)], the data for *n*-pentane and Freon-11 are close to each other.

Conclusions. The recoil force of a jet of an incipient liquid in a thermodynamically strongly nonequilibrium regime of exhaustion was measured. The thermodynamic determinacy of explosive incipience allowed generalization of experimental data. Visual observations made it possible to relate the dramatic decrease in the recoil force of the jet with complete disintegration of the latter, which, in turn, is caused by intense volume incipience and interaction of the jet with the plane behind the channel exit. For jets of incipient water, the Coanda effect, which favors complete opening of the jet, is manifested already at $T_0/T_{\rm cr} \approx 0.75$ [17]. This is related to the high volume density of easily activated vapor sites in water. This fact distinguishes water from most examined liquids for which the conditions of intense incipience upon exhaustion through short channels into the atmosphere are satisfied for $T_0/T_{\rm cr} \approx 0.9$ in accordance with the classical model of homogeneous nucleation.

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