BREAKAWAY OF A LIQUID BY A GAS STREAM AT AN INTERFACE CONTAINING A GRID

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It is shown that in a system comprised of a gas stream, a liquid, and a grid, breakaway of a drop of liquid by the gas stream occurs under certain conditions. This paper determines the characteristic and dimensions at which drop breakaway will begin for a given gas velocity.

The interaction of gas streams with a liquid having a free surface is of practical interest in the design of equipment used in chemical and power engineering. In particular, in calculating limiting dimensions of future heat transfer evaporator—condenser equipment (heat pipes) it is necessary in some cases [1] to have numerical data on the breakaway of a liquid drop from a surface of capillary form by a stream of vapor moving under a positive pressure gradient.

The results of [2], where the velocity of a gas required to cause breakaway of a liquid drop from the surface of models of various capillary-type heat pipes was measured, indicate that there is no drop breakaway when the surface is an exposed fine grid. In our opinion, this result is due primarily to the absence of modeling of recovery pressure, typical for this class of heat pipe, in which one examines the limitations associated with liquid-drop breakaway. At present this conclusion of reference [2] is sometimes used without justification to criticize the existing theory of limiting parameters of heat pipes and should therefore be revised.

This paper presents results of an experimental investigation showing, in particular, that drop breakaway does occur for a positive pressure gradient in a stream which entirely floods the cavity above a grid and with excess of liquid present, and this contradicts the results presented in [2].

The problem of determining the gas velocity at the start of drop breakaway from a liquid surface belongs to a class of problems concerning instability of the interface. Available theoretical results [3] mainly describe processes at the stage of surface perturbation. The instability of the system is usually investigated by means of the theory of small oscillations, and an arbitrarily small oscillation is represented in the form of a linear superposition of elementary wave solutions. It is easy to show that, from the classical Kelvin solution which considered the simplest problem of Helmholtz instability at the perturbation stage, one can derive the well-known surface interface instability condition, i.e., that the Weber number should be unity:

$$\frac{\rho w^2}{\sigma k} = 1, \tag{1}$$

where the wave number $k = 2\pi/\lambda$ on the free surface may take various values, depending on the characteristic wavelength λ. The oscillations of the interface near the solid surface of the grid are not free, and one naturally assumes that the geometric dimensions of the grid determine a characteristic first-order wavelength λ_c (which is critical), and a corresponding wave number k_c. When this hypothesis is valid one can determine a value of λ_c experimentally for a specific grid, and then, using Eq. (1), one can determine the velocity at which the liquid drop breaks away from the interface from the relation

$$w = \left(\frac{2\pi\sigma}{\rho\lambda_c} \right)^{1/2}. \tag{2}$$

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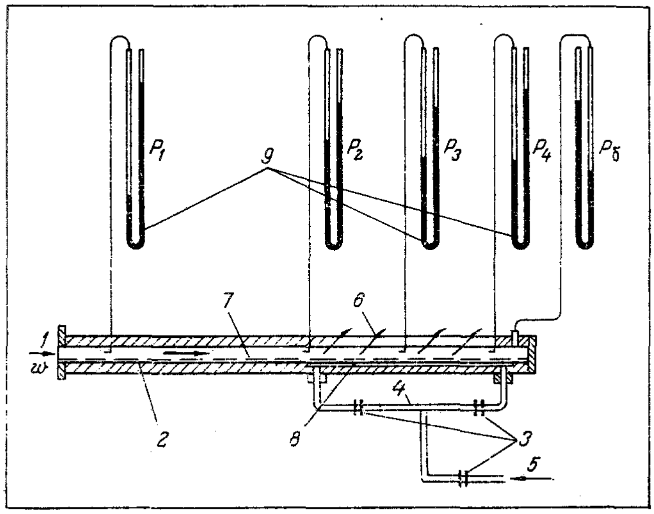

Fig. 1. Diagram of the experimental equipment: 1) gas supply; 2) two-dimensional channel; 3) pinched area; 4) bypass; 5) water supply; 6) exit of gas through a slit in the top cover; 7) grid; 8) gaps in the lower channel wall; 9) piezometer.

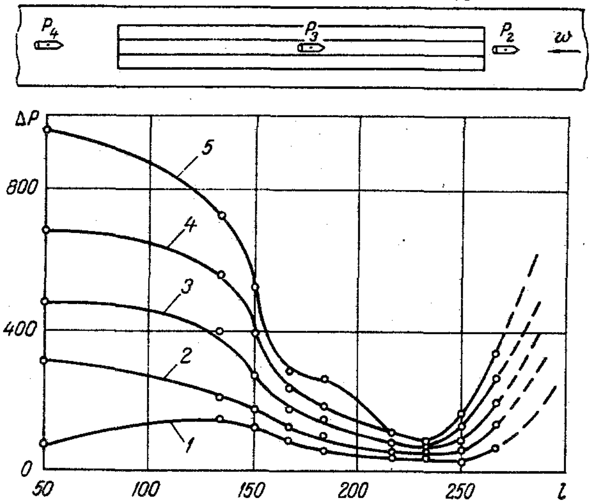

Fig. 2. Typical pressure distribution along the channel (for different values of pressure drop): 1) 100; 2) 196; 3) 287; 4) 388; 5) 488 mm H_2O. Δp, Pa; l, mm.

To check the correctness of this postulate and to determine the characteristic dimensions λ_c of various grids, we conducted tests on the experimental equipment shown schematically in Fig. 1. The working element is a transparent two-dimensional channel of cross section 46 × 4 mm, total length 805 mm, made of lucite and located horizontally. The removable top cover of the element is fastened to the base by means of coupling pins and has four longitudinal gaps of width 1 mm, cut to a length of 180 mm. In the lower plate there is a shaped cutout of depth 2 mm, to which the liquid is supplied from the supply tank. Above the lower plate of the base there is a single layer of mesh along the channel axis, which is pressed against the lower plate by the side walls of the channel and sealed along the perimeter by a rubber strip. This construction makes it possible to replace the grid while operating.

Air is supplied to the working element through the left end (see Fig. 1) of the channel, passes above the bath containing the liquid, and exits upward through the milled gaps. The static air pressure distribution along the channel is measured by means of four probes and recorded from the readings of water piezometers. A measuring section with an orifice plate and an array of multijunction thermocouples allows one to measure the air mass flow rate, with an accuracy of better than 2%, and its temperature.

Immediately before the experiment the liquid level is set in the bath below the grid (the liquid should wet the entire grid; this is monitored visually). The bath is filled until the liquid menisci occupy the interstices of the grid, and then the supply line is detached and the fan supplying air to the channel is opened up smoothly. A typical static pressure distribution along the channel is shown in Fig. 2. At the place where the slots begin in the top cover of the channel, there is a minimum of air pressure, close to atmospheric. Above the liquid-filled bath, the static pressure with the air blowing increases continuously due to stagnation of air and the establishment of a velocity head. The result obtained is evidence that one obtains an air flow with a positive pressure gradient in the working part of the experimental model.

As the air flow rate is gradually increased one obtains a visual picture of the process of interaction of the gas and the liquid within the channel. A typical picture of this interaction can be described as follows. At a certain value of the air flow rate the liquid is squeezed out onto the top surface of the mesh in the minimum gas static pressure region, i.e., at the leading edge of the bath and liquid (in the middle part of the experimental equipment). Here there is circulation of liquid, due to the positive pressure gradient and the interaction of the gas and liquid at the free boundary of the interface. As the air flow rate increases well-marked waves appear on the liquid surface, resulting from interaction of the gas with the liquid and the liquid with the gas and the grid surface.

With further increase in the air flow rate there is liquid-drop breakaway from the perturbed interface, at a certain "critical" value of the gas velocity. The drops are carried away by the air stream and fall onto the top transparent cover of the channel, where they can easily be observed by eye. At this gas velocity value we recorded the pressures along the channel, the pressure drop at the measurement orifice plate, and the air temperature.

As test specimens we used pieces of woven steel filter mesh. The main geometric parameters of these grids, from our measurements, are given in Table 1. It should be noted that the actual grid parameters can differ substantially from the values given in the appropriate standards, and, therefore, in specific cases one must measure the warp and weft diameters and pitches of the grids. The diameters are easily determined by ordinary measurement instruments, e.g., with a micrometer. The pitch of the warp and the weft were determined from photographs of the grid surface, with ×200 magnification. In the experimental model the threads of the warp were placed parallel to the main channel axis. As the working liquids we used water and kerosene. Special steps were taken to ensure good wetting of the grid by the liquid, when water was used.

From the experiment, as was noted above, we obtained a qualitative picture of the development of instability of the liquid–gas interface surface in a system with a positive pressure gradient; it was found that the gas velocity for which drop breakaway begins is higher, the finer the grid separating the liquid and the gas.

It should be noted that if the grid does not lie on the surface of the liquid, i.e., if the bath is not completely full of liquid, no drop breakaway is observed, even for very high gas velocities. This is the reason why it is impossible to force liquid above the grid if there is a gap between the grid and the free surface of the liquid. The fact that there is a definite gas velocity for the start of drop breakaway corresponding to each grid number is evidence that the characteristic linear dimension (the wavelength) of the perturbation at the gas–liquid interface in the system examined is the primary parameter governed by the geometric dimensions of the grid.

TABLE 1. Geometrical Parameters of Woven Stainless-Steel Filter Mesh

Mesh		Warp diameter, d_{wa}, mm	Weft diameter, d_{we}, mm	Warp pitch, h_{wa}, mm	Weft pitch, h_{we}, mm	Thickness, mm	$\frac{h_{we}}{d_{we}}$
One-sided, No.	56	0,400	0,280	1,89	0,573	0,890	2,05
"	80	0,280	0,190	1,39	0,481	0,640	2,24
Double-sided, No.	90	0,800	0,190	1,08	0,427	0,725	2,25
One-sided, No.	160	0,190	0,125	0,698	0,278	0,410	2,72
Double-sided, No.	450	0,085	0,050	0,240	0,115	0,205	2,30
"	685	0,060	0,030	0,158	0,067	0,130	2,25

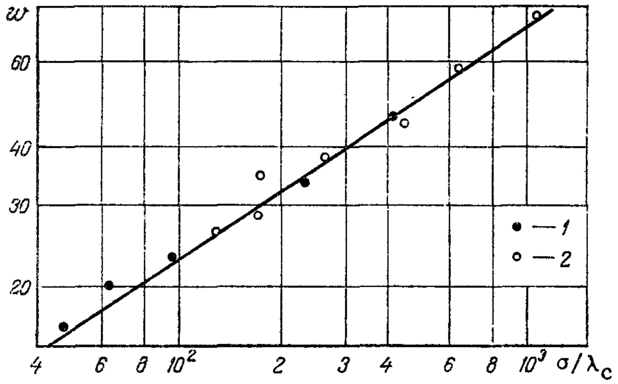

Fig. 3. The gas flow velocity at the start of drop breakaway as a function of the analog of capillary pressure at the interface boundary: 1) kerosene; 2) water: w, m/sec; σ/λ_c, Pa.

The experimentally obtained results allow us to check our model for calculating the gas velocity at the onset of drop breakaway, the basic postulate of which is the statement that the characteristic dimension λ_c governing the start of removal of the liquid drop is equal to the roughness step size of the grid surface along the flow at the liquid–gas interface. If this model is valid, then one can calculate the gas velocity at the start of drop breakaway from a simple formula obtained from Eq. (2) by replacing the quantity h_{we} by λ_c:

$$w = \left(\frac{2\pi}{\rho}\right)^{1/2}\left(\frac{\sigma}{h_{we}}\right)^{1/2}. \tag{3}$$

Figure 3 shows the results of comparing the velocity calculated from Eq. (3) with the test data obtained in the grid experiments. Each experimental point on the graph is a result of a statistical processing of a relatively large number of measurements (up to 150 points).

The need for statistical processing of the experiment stems from the subjective visual determination of the time for the start of drop breakaway, the presence of air pressure oscillations during the recording of one point, and the possibility of arbitrary variation in the cross-section area of the channel during the tests with fine grids. The systematic error in determining the velocity did not exceed 10-13%. In the statistical processing a confidence interval is chosen with a probability of 0.9 and it is one-tenth of the systematic error.

The data of Fig. 3 indicate that there is satisfactory agreement, within the limits of experimental error, between the values of w calculated from Eq. (3) and values of w obtained experimentally.

The results obtained allow the following conclusions to be drawn.

1. The results of [2], that liquid is not carried away from the grid surface, are confirmed only when the bath under the grid is only partially filled with liquid. With the bath fully filled and when a positive pressure gradient is present, one sees drop breakaway even at moderate gas flow velocity.

2. For the existing conditions in the range of variation of the governing parameters examined, in particular of the quantity σ/h_{we}, which is the analog of the capillary pressure at the boundary of a perturbed surface, the gas velocity at the start of drop breakaway can be determined by a computation based on a simple model which accounts only for the inertial force and the surface tension; in the model one must take the characteristic linear dimensions in the Weber number to be the pitch of the regular surface longitudinal roughness of the grid, which is equal, for a woven mesh, to the weft pitch, when the warp is positioned along the channel axis.

NOTATION

d_{wa}, diameter of warp threads; d_{we}, diameter of weft threads; h_w, pitch of the grid warp; h_{we}, pitch of the grid weft; k, wave number; k_c, "critical" value of k; w, gas velocity at the channel entrance; λ, characteristic wavelength; λ_c, "critical" value of λ; ρ, gas density; σ, surface tension of the liquid.

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INSTANTANEOUS VELOCITY PROFILE IN A WAVY FLUID FILM

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Results of measuring the instantaneous velocity profiles in a laminar fluid film in the presence of stationary waves of different shape on its surface are presented.

It is known [1] that the velocity profile in the flow of a smooth laminar fluid film along a vertical wall is subject to a parabolic law

$$\frac{u}{U}=2\left(\frac{y}{h}-\frac{y^2}{2h^2}\right), \qquad (1)$$

where the velocity on the surface of a film of thickness h is computed by means of the formula

$$U=\frac{gh^2}{2\nu}. \qquad (2)$$

Formulas (1) and (2) are verified by experimental results [2-4] with a high degree of accuracy (to 1%) for a smooth laminar film.

A parabolic velocity profile in the form (1) is used in computing the wavy flow of a film in the majority of theoretical papers [5] using the method of integral relations, where h is the local film thickness and the velocity on the surface U is an unknown function of the time t and the longitudinal coordinate x. The case of a nonparabolic velocity profile is examined in [6, 7].

Data available in the literature [8-10] on the mean velocity profiles of a wavy film are distinguished by the significant spread, which does not permit making a deduction about the validity of (1) and (2) for a wavy film. Thus, it follows from the results of the most complete research [10] that the mean velocity profile of a laminar wavy fluid film is parabolic

$$u=Ay-By^2, \qquad (3)$$

but the form of the coefficients A and B, in contrast to (1) and (2), depends on the number Re and the fluid viscosity.

An analogous situation is observed in the literature on the results of measuring the surface velocity of a fluid film. As follows from [11], the measured values of the dimensionless surface velocity U_0/u_0 for a laminar wavy film fluctuate between 1.15 and 2.2, where $u_0 = Q/h_0$ is the mean mass flow rate; i.e., the question whether the values of U are greater or less for wavy flow as compared to a smooth film for which $U/u_0 = 1.5$ is not even clarified.

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