STABILITY OF FILM FLOW IN SHORT CHANNELS

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Data are shown on the breakaway of droplets from the film surface by an gas stream in straight and bent channels.

The loss of stability, when droplets are carried away from the film surface by an attendant stream of gas and vapor, has so far been analyzed primarily in developed flow modes in long channels. However, in many power aggregates such as separators, turbine stages with wet steam, etc., film flow occurs over short paths. The authors have tried to establish the range of stable film flow in relatively short channels.

The stability limit we determined experimentally for straight and for bent vertical channels with a compound descending flow under normal conditions, using a multichannel instrument for recording the local parameters in both the zone of droplet flow [1] and the zone of film flow [2] and supplementing these measurements with high-speed photography. The film, 90 mm wide, was generated by a discharge of liquid through an orifice at a zero exit angle onto one of the two wide channel walls. The rectangular channels were 450 mm long down to a tentative neutral section established by inserting into such a channel (58×136 mm^2) a confusor–diffusor segment with a small throat radius and with a bent wall. A series of methodic tests has revealed that in such a channel the breakaway will occur in the throat section or in its immediate vicinity.

Near the stability boundary, according to an analysis of photographs and oscillograms, the film surface is covered with irregular three-dimensional ripples of small wavelengths and amplitudes, but among them are larger ripples which move at higher velocities and induce the breakaway process. The occurrence of large ripples is statistical in nature: some confluence of ripples causes a local buildup of liquid which, upon rising above the film level, becomes exposed to a forceful gas stream and is set into an accelerated motion. As a result of this, more liquid builds up and the forms a wave with a steep front and a very irregular flat ramp. As the wave reaches a certain magnitude, there follows a random displacement of liquid forward along the ramp. At some instant of time the overloaded wave crest begins to oscillate and then breaks. Depending on the flow mode, several liquid spikes or jets emanate from here and break up to form a string of droplets along the wave crest. When part of the liquid is thus lost to the gas stream, the wave dimensions decrease sufficiently either for extinction or for repeating the cycle of liquid buildup and subsequent breakaway. At high gas velocities and low flow rates in the film, when the generation of large ripples is impeded, droplets break away already from ripples of small amplitudes.

A change in the film structure around a breakaway center is shown in Fig. 1. Curves I and II on the diagram divide the flow modes into three ranges: A) breakdown of the film; B) film flow without breakaway of droplets; and C) film flow with breakaway. At high flow rates and low gas velocities, droplets break away simultaneously from many ripples, inasmuch as a large mass of liquid is set into wave motion. Under such conditions, instability occurs before the wave amplitude has reached its maximum. As the flow rate in the film decreases, the stability boundary shifts toward the inflection range of the curve $\delta_c - \delta_d = f(V'')$, and at $q_f = 1$-2 cm^3/cm$\cdot$sec the maximum amplitude of wave motion corresponds to the beginning of breakaway. At low flow rates we note the effect of the solid channel wall. The wall tends to stabilize the development of the oscillatory process on the film surface and, therefore, a decrease in the film thickness causes the breakaway process to start at higher gas velocities, at which the amplitude of the wave motion is still far below maximum.

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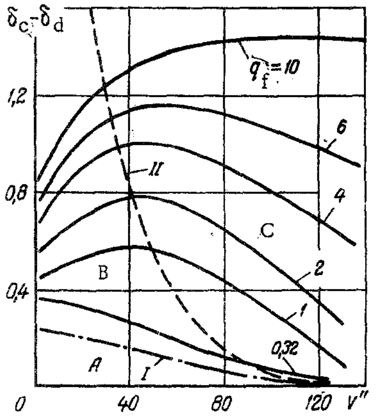

Fig. 1. Amplitude of the ripple structure during film flow in a straight channel 430 mm long and 58×136 mm^2 in cross section: $\delta_c - \delta_d$ mm; V", m/sec; q_f, cm^3/cm·sec.

It was also determined how the stability boundary is affected by the layout of the film feed into the channel. In the first case (Fig. 2, scheme A) the film formed directly within the region of a developed gas stream; in the second case (scheme B) the film formed within the region of low gas velocities so that toward the entrance to the test segment of the channel it acquired a developed undular structure. Breakaway was recorded at the exit from the channel. A comparison between the data 8) and 9) in Fig. 2 indicates that the initial film formation stage has almost no effect on the stability boundary in this version of the feed system.

We will now analyze the effect of the channel length on the flow stability. The data 1), 2), 3), 5), 10) in Fig. 2 indicate the stability boundary in channels of approximately the same cross section but different lengths. All tested flow modes fall tentatively into three ranges. Within the first range, at high gas velocities, the channel length has a very appreciable effect on the beginning of breakaway: the shorter the channel is, the more "stable" is the flow. The second range is characterized by a stronger dependence of the initial breakaway velocity on the flow rate in the film: the curves are steeper than within the first range; the effect of the channel length, although weaker, continues to be significant. Within the third range finally, at low gas velocities, the initial breakaway velocity depends on the flow rate in the film nearly as much as within the first range, while the effect of the channel length weakens and almost ceases already at $q_f \geq 2.0$ cm^3/cm·sec. The trend of the curves is analogous also for channels with other diameters.

The breakaway process is noted to occur within a definite flow time (or path length). At equal gas velocities, therefore, in a shorter channel it will occur with a thicker film, as has been confirmed in Fig. 3.

The fundamental difference between the mechanism of breakaway within the first range and the third range, respectively, can be interpreted as follows. Breakaway of droplets, according to an analysis of photographs and oscillograms, occurs when a sufficient amount of liquid accumulates on a wave crest; the wave crest becomes then yielding and begins to break. At low flow rates there forms also a very stable thin film. Some time elapses from the instant when a local concentration of liquid begins to build up, generating a wave, until the latter reaches a state of unstable deformation; the wave rolls on, gradually accumulating liquid from the film. Then the second stage of breakaway begins: the wave crest collapses. This stage also develops gradually, but it requires less time than does the buildup of an unstable wave. Thus, within the range of high gas velocities the breakaway proceeds in two stages: the first stage is slower. Within the range of low gas velocities, on the contrary, the first stage of breakaway is faster and, apparently, may be skipped altogether, inasmuch as an unstable wave is very easily generated in a thick film. On the other hand, waves which now travel much slower than at high gas velocities do not have sufficient time to move long distances before they collapse. Within the range of low gas velocities, therefore, the stability boundary is insensitive to the length of the film flow path. The range of medium gas velocities is intermediate and both stages of the breakaway process determine here the stability boundary.

No significant effect of the channel diameter on the flow stability has been detected in these tests, as is indicated by the data 5) and 9) in Fig. 2 pertaining to a ratio of equivalent diameters equal to 1.5.

Assuming that the channel diameter (when the diameter is sufficiently large) and the gas viscosity have no effect on the flow stability, one may express the stability boundary in terms of the parameter T:

$$\mathrm{K} = AT^{-0.29},$$

with parameter A depending on the channel length as follows:

$$T < 3\cdot 10^2;\ A = 180 - 175l;$$

$$3\cdot 10^2 < T < 6\cdot 10^2;\ A = (0.386l^{1.2} - 0.21)\,T + (243 - 175l - 116l^{1.2});$$

$$6\cdot 10^2 < T < 1.6\cdot 10^3;\ A = 75 + (48 - 65l^{0.6})(2.09 - T^{0.1})\,T^{-1}\cdot 3.08\cdot 10^3; \qquad 1.6\cdot 10^3 < T;\ A = 75$$

for $l > 0.6$, we take $l = 0.6$.

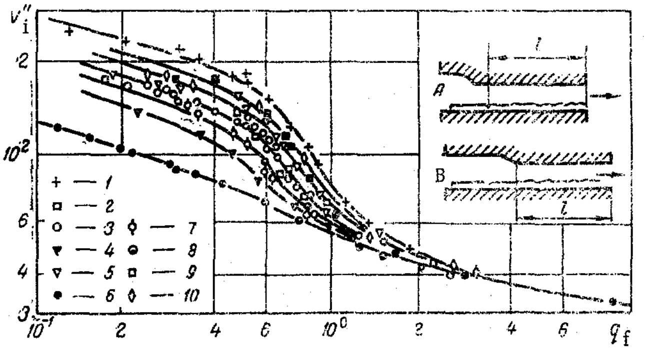

Fig. 2

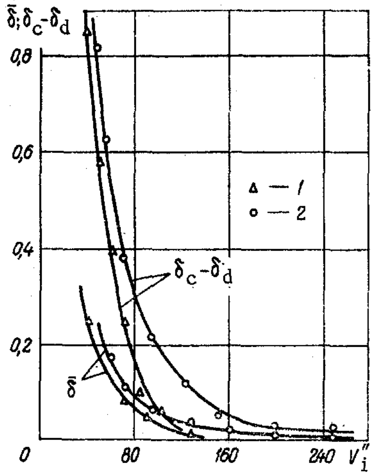

Fig. 3

Fig. 2. Initial velocity of breakaway droplets V_i'' (m/sec), as a function of the flow rate in the film q_f (cm^3/cm · sec): 1) 18 × 136 mm^2 with D_h = 31.9 mm and l = 0; 2) 18 × 136 mm^2 with 31.9 mm and 98 mm, respectively; 3) 18.5 × 136 mm^2 with 32.6 mm and 303 mm, respectively; 4) 43.5 × 136, 66.0 and 350; 5) 18.5 × 136, 32.6 and 200; 6) 58 × 136, 81.2 and 430; 7) 28.5 × 136, 47.1 and 375; 8) 28.5 × 136, 47.1 and 200; 9) 28.5 × 136, 47.1 and 200; 10) 18.5 × 136, 32.6 and 80.

Fig. 3. Structural parameters of the film (δ and $\delta_c - \delta_d$, mm) as a function of the initial breakaway velocity (V_i'', m/sec), for channels of various lengths: 1) 58 × 136 mm^2 and l = 430 mm; 2) 18 × 136 mm^2 and l = 0.

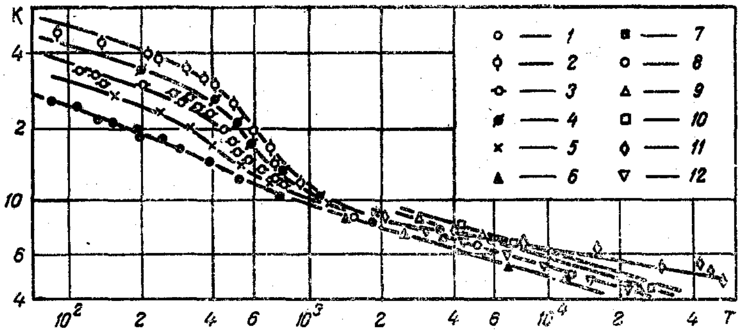

Fig. 4. Stability boundary of film flow in straight channels: 1) 58 × 136 mm^2, l = 430 mm; 2) 18 × 136, 0; 3) 18.5 × 136, 303; 4) 18 × 136, 98; 5) 43.5 × 360, 360; Mozharov [3] for vapor–water: 6) P = 4.5 kgf/cm^2; 7) 7.5; 8) 13.5; 9) 16.0; 10) 44.5; Sorokin et al. (TsKTI) for air–water: 11) 297 mm, l = 1800 mm; 12) Chen She-Foo and Ibele [5].

On this basis, then, the test data have been plotted in Fig. 4. The trend of the curves at low values of T indicates that the breakaway process is affected by the channel length up to 0.6-0.8 m. As the value of T increases, the effect of the channel length weakens and at T = (1.4-1.6) · 10^3 the breakaway process becomes independent of the channel length. The results obtained by Mozharov [3] with a vapor–water mixture indicate a systematic segregation of test values with respect to pressure: the largest spread of values with respect to parameter K is ±13%. This may be due to the difference in the methods of recording the breakaway.

The trend of the curves in Fig. 4 is characterized by a discontinuity on the left-hand side (film breakdown); our data approach this boundary closely. As to the flow modes with high values of T, there exists a limiting gas velocity below which no aerodynamic breakaway can occur. According to the data in [4], one may assume that this limit is within 5-8 m/sec under normal conditions. In very long channels droplets can break away from the film surface at already lower gas velocities, but such a loss of stability will then already be gravitational in nature.

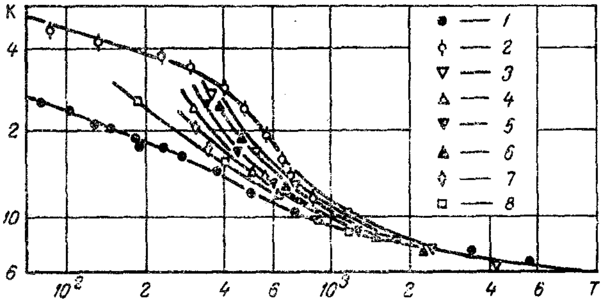

Fig. 5. Stability boundary of film flow in bent channels: 1) 58×136 mm^2, $l = 430$ mm straight; 2) 18×136, 0 straight; 3) 58×136, $\theta = 60°$ concave wall; 4) 58×136, 60° convex wall; 5) 58×136, 90° concave wall; 6) 58×136, 90° convex wall; 7) 58×136, 135° concave wall; 8) 58×136, 135° convex wall.

The bent channels had a cross section 58×136 mm^2 and a median length of 650 mm, with elbow angles of 30, 60, 90, and 135°. Each channel began and ended with a straight segment 180 and 100 mm long, respectively. Film flow was produced separately on the convex wide wall and on the concave wide wall, beginning at 20 mm ahead of the elbow.

The film flow in the 30° channel has shown that such a curvature has a negligible effect on the stability boundary. For this reason, we will consider the basic characteristics of the breakaway process only in channels with larger elbow angles.

Droplets break away from the convex wall of bent channels first along the initial segment of the arc, they form a narrow jet of droplets passing across the channel, and are reflected at the opposite wall. The breakaway process then continues, the breakaway zone spreads along the film all the way to the channel exit; the stream of carried away droplets fills now the entire channel cross section and generates a secondary film flow on the concave wall with its own attendant layer of droplets on top.

On the concave side the droplets break away almost simultaneously along the entire film path. The attendant layer of droplets builds up along the path, but its thickness does not exceed one third of the channel height even during the developed stages of breakaway.

In channels with a large elbow angle it is possible that the film or the droplets will separate as a result of unsatisfactory aerodynamic wetting. Such a pattern was noted on the convex wall along the exit zone in the 135° channel. Within this zone, according to measurements, the gas stream separates from the wall, which, when a film exists, results in the transformation of a steady liquid stream into a loop and a subsequent ejection of droplets into the gaseous mainstream. From the standpoint of flow stability at the convex wall, assuming that a breakaway of droplets occurs, such channel performs more reliably than a straight channel of equal length, inasmuch as the stability boundary is determined by the short entrance segment. With regard to the exit segment of such a channel, it is to be noted that flow without breakaway is hardly possible here at all. The existence of two separate breakaway zones is characteristic of channels with large elbow angles.

In order to compare the stability boundary in straight and in bent channels, we will represent our data in $K = f(T)$ coordinates. The results are shown in Fig. 5, with the stability boundary in the 135° channel considered to be within the entrance segment. On the same diagram, for comparison, are also shown data pertaining to the longest and the shortest straight channels tested here. Most of the breakaway modes in bent channels appear within a range not beyond the range for straight channels 0 to 0.4-0.6 m long. At low values of T the flow in bent channels is more stable than in straight channels. At high values of T the stability boundaries in both come closer and eventually coincide, i.e., the channel curvature ceases to affect the stability boundary within the range of this study.

NOTATION

$K = V_i'' \gamma'' / [g\sigma(\gamma' - \gamma'')]^{1/4}$	is the Kutateladze number;
$T = \mathrm{Fr}\, \mathrm{Ga}^{2/3}$;	
$\mathrm{Fr} = q_f(\gamma' - \gamma'')^{3/4} / (g^{1/2}\sigma^{3/4})]$	is the Froude number;
$\mathrm{Ga} = g\sigma^{3/2} / [\nu'^2(\gamma' - \gamma'')^{3/2}]$	is the Galileo number;
V''	is the velocity of the gas stream;
g	is the acceleration due to gravity;
γ''	is the specific weight of the gas;
γ'	is the specific weight of the liquid;
σ	is the surface tension;
ν'	is the kinematic viscosity;
q_f	is the specific flow rate in the film;
l	is the channel length;

P is the pressure;
δ_c is the film thickness at the wave crest;
δ_d is the film thickness at the wave dip;
$\bar{\delta}$ is the mean film thickness;
D_h is the hydraulic (equivalent) channel diameter;
θ is the elbow angle of a bent channel;
V_i'' is the gas velocity at the beginning of droplet breakaway.

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