THE UNIQUE FEATURES OF WAVE FLOW WITH A CHANGE IN THE LENGTH OF THE FILM PATH

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The maximum wave amplitudes are analyzed for a change in the spray density and in the length of the film path for a liquid flowing under the action of gravity on the outside surface of a vertical tube.

When a thin layer of a liquid flows by gravity along a vertically sprayed surface of a wall, even small Reynolds numbers (Re_{film} = 20-30) will produce waves on the outside surface of the film [1-4, 7, 8]. It is demonstrated in Kapitsa's paper [2] that the formation of waves is associated with the effect of the capillary forces which, even in the flow of thin liquid layers at low speeds and limited distortion of their external surface, become comparable in magnitude with the viscosity forces.

All other conditions being equal, the development of wave phenomena in the film is intensified as the spray density and the length of the film path are increased, and at the inlet segment it depends, moreover, on the design of the distribution mechanism [1]. It was noted in earlier theoretical and experimental papers [2-4, 7, 8] that the mean film thickness increases with the path length x_{path} and, consequently, the mean flow velocity for the film is reduced. At the moment there are no experimental studies dealing with the wave characteristics of film flow when the length of the film path changes. The need for such a study is obvious both for the determination of the hydrodynamic aspect of this phenomenon and to explain the processes of heat and mass transfer which frequently accompany that phenomenon.

The basis purpose of these experiments was to determine the unique features involved in the behavior of the mean film thickness $\bar{\delta}$ and the local film thicknesses at the highest wave crests (δ_{crest}) and in the troughs (δ_{att}) for various film-path lengths and spray densities. The tests were conducted with a tube 594 mm in length and an outside diameter of 27 mm; distilled water and aqueous solutions of sodium chloride were sprayed through the tube. The local characteristics of film wave flow – and where necessary, its local temperatures – were measured with five special sensors [5] uniformly positioned through the height and perimeter of the sprayed tube. The experimental installation and the measurement method were described earlier in [6].

The sensors of the instruments were mounted along the length of the film path at x_{path} = 45 and 200 (with two sensors along the perimeter), and at 355 and 545 mm. The first sensor (x_{path} = 45 mm) established the change in the thickness of the liquid layer at the inlet segment which was about 110 mm in length. Since the state of the flow of this segment is a function of the design of the distribution mechanism, the measurement results achieved with the first sensor are not characteristic for purposes of evaluating the overall development of wave formation and are thus not considered here.

The experimental results showing the relationship between the water-film thicknesses $\bar{\delta}$, δ_{crest}, and δ_{att} as a function of the Reynolds number Re_{film} for t_{film} = 20°C and various lengths of the film path are shown in Fig. 1. With an increase in the length of the film path the film thickness δ_{crest}, measured at the crests of the highest waves, also increases. Here we observe a change in the shape of the approximation curves for δ_{crest} as a function of the Reynolds number. Thus, for a film path length of x_{path} = 200 mm (curve 1) we find clearly delineated the following two regions:

a) $Re_{film} \leq 1530$, δ_{crest} is proportional to $Re_{film}^{0.41}$. In this region, with an increase in the spray density, the waves gradually increase in size. The resulting transverse waves are random in shape and are usually not closed along the perimeter.

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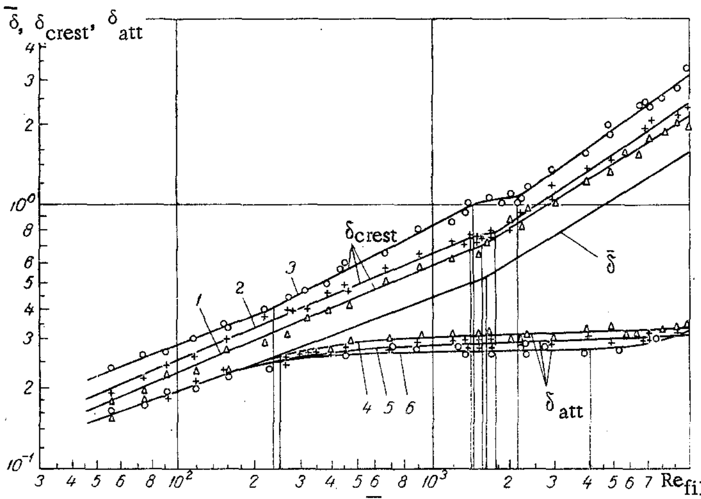

Fig. 1. Water-film thickness $\bar{\delta}$, δ_{crest}, and δ_{att} (in mm) as a function of the Reynolds number Re_{film} for t_{film} = 20°C and for various lengths of the film path x_{path}: 1, 4) δ_{crest} and δ_{att}, respectively, for the length of the path x_{film} = 200 mm; 2, 5) x_{path} = 355 mm; 3, 6) x_{path} = 545 mm.

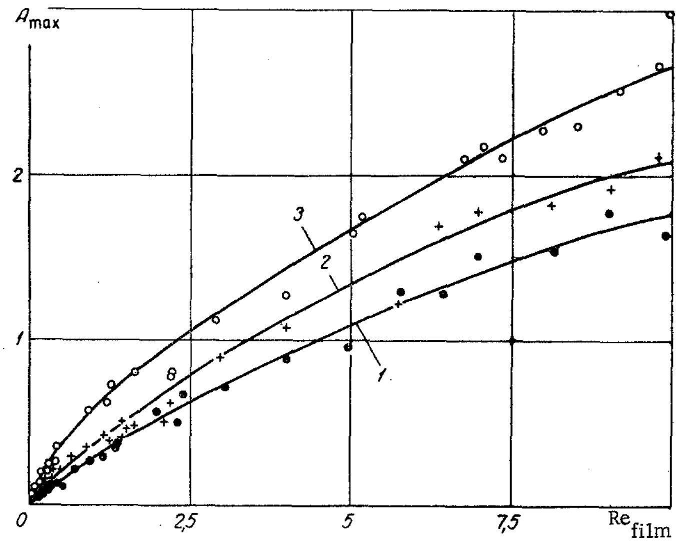

Fig. 2. Maximum wave amplitude A_{max} (in mm) as a function of the Reynolds number Re_{film} for a mean water-film temperature of t_{film} and various film path lengths: 1) x_{path} = 200 mm; 2) 355; 3) 545.

b) $Re_{film} \geq 1530$, δ_{crest} is proportional to $Re_{film}^{0.6}$. A characteristic feature of this region is the constancy of the ratio $\delta_{crest}/\bar{\delta} = 1.35$ and in this region we find the occurrence of large transverse ring-shaped waves which drop rapidly and whose amplitudes increase rapidly as the spray density is increased.

For a film path of x_{path} = 355 mm (curve 2) we find three regions clearly delineated, i.e., $\delta_{crest} = f(Re_{film})$: a) $Re_{film} \leq 1400$, δ_{crest} is proportional to $Re_{film}^{0.4}$; b) $1400 \leq Re_{film} \leq 1750$, δ_{crest} is proportional to $Re_{film}^{0.17}$ and; c) $Re_{film} \geq 1750$, δ_{crest} is proportional to $Re_{film}^{0.7}$.

Unlike $\delta_{crest} = f(Re_{film})$ when x_{path} = 200 mm for a path length of x_{path} = 355 mm in the region of Reynolds numbers $1400 \leq Re_{film} \leq 1750$ the film thickness δ_{crest} undergoes virtually no change with an increase in the spraying density. This phenomenon can be explained by the appearance of "oblique" waves (with their three-dimensionality in motion clearly visible).

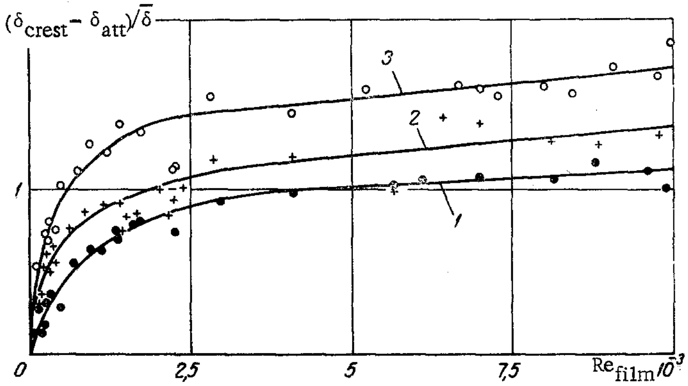

Fig. 3. Dimensionless maximum wave amplitude $(\delta_{crest} - \delta_{att})/\bar{\delta}$ as a function of the Reynolds number Re_{film} for a mean water-film temperature t_{film} = 20°C and of various film path lengths: 1) x_{path} = 200 mm; 2) 355; 3) 545.

Analyzing the curves $\delta_{crest} = f(Re_{film})$ for various film path lengths x_{path}, we can draw the following conclusions:

1. The film thickness δ_{crest} grows with an increase in the spray density and in the film path length.

2. For film path lengths of $x_{path} \geq 355$ mm in the region of Reynolds numbers including Re_{crit}, the film thickness δ_{crest} undergoes virtually no change with an increase in the spray density, which is explained by the appearance of "oblique" waves. With an increase in x_{path} this region of Reynolds numbers expands:

$$x_{path} = 355 \text{ mm} \quad - 1400 \leqslant Re_{film} \leqslant 1750,$$
$$x_{path} = 545 \text{ mm} \quad - 1440 \leqslant Re_{film} \leqslant 2170.$$

3. For small film path lengths $x_{path} < 355$ mm, the appearance of small "rough" waves above the main regular waves is not observed on the outside surface of the film.

The film thickness δ_{att} in the wave troughs differs from the value of the mean film thickness $\bar{\delta}$ for $Re_{film} \approx 120$-160:

$$x_{path} = 200 \text{ mm when } Re_{film} = 119,$$
$$x_{path} = 355 \text{ mm when } Re_{film} = 146,$$
$$x_{path} = 545 \text{ mm when } Re_{film} = 158.$$

With an increase in the spray density the values of δ_{att} for all film path lengths increase noticeably only up to $Re_{film} \approx 500$, subsequently remaining virtually constant, diminishing slightly only with an increase in x_{path}.

These data enable us to trace the nature of the change in the maximum wave amplitudes as a function of both the spray density and x_{path}. The relationship between the maximum wave amplitude $A_{max} = \delta_{crest} - \delta_{att}$ and the Reynolds number when t_{film} = 20°C and for various x_{path} is shown in Fig. 2. Tests have shown that A_{max} increases with an increase in x_{path} and this increase is all the greater, the greater the spray density.

There is some interest in an analysis of the development waves in the runoff film by means of a dimensionless representation of the maximum wave amplitude as a function of x_{path} and the spray density (Fig. 3). The dimensionless maximum wave amplitude $(\delta_{crest} - \delta_{att})/\bar{\delta}$ shows the magnitude of the maximum wave oscillation of the outside film surface for a specific path length x_{path} $(A_{max} = \delta_{crest} - \delta_{att})$ relative to the mean film thickness $\bar{\delta}$ with respect to the entire tube and it thus characterizes the intensity of wave development. We see from Fig. 3 that the greatest increase in wave dimensions, independent of x_{path}, is found in the region of Reynolds numbers $Re_{film} < 2500$, whereas when $Re_{film} > 2500$ the waves increase considerably more slowly as the spray density increases. Thus, while in the region $Re_{film} < 2500$

the dimensionless maximum wave amplitude increased with an increase in the spray density (from zero to 0.92 when x_{path} = 200 mm; to 1.08 when x_{path} = 355 mm, and to 1.45 when x_{path} = 545 mm), in the region of Reynolds numbers $2500 \leq Re_{film} \leq 10{,}000$ the dimensionless maximum wave amplitude varied, on the average, in the following respective range: 0.92-1.12, 1.08-1.38, and 1.45-1.72, i.e., with a Reynolds-number region greater by a factor of 3 the dimensionless maximum wave amplitude increased, on the average, by only 12%. This can be explained by the corresponding increase in the region of high spray densities, as recorded on the frequency oscillograms for large ring waves which appeared when Re_{film} = 1530-2170, which also serves to confirm the frequency analysis of regular waves, as performed earlier by Brauer [7].

With an increase in the spray density there is a relatively slower increase in the wave amplitude that is proportional to the increase in the film path length, and this can also be explained by the corresponding increase in the wave frequency.

NOTATION

t_{film}	is the mean temperature of the spray film, deg;
x_{path}	is the film path length, m (in mm);
$\underline{\Gamma}_V$	is the volume spray density, m^2/sec;
δ	is the mean thickness of the spray film, m (in mm);
δ_{crest}	is the film thickness at the highest wave crest, m (in mm);
δ_{att}	is the film thickness in the wave troughs, m (in mm);
ν	is the kinematic viscosity of the spray liquid, m^2/sec;
$Re_{film} = 4\Gamma_V/\nu$	is the Reynolds number for film flow of the liquid.

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