THE RETAINING POWER OF AN INCLINED CONDENSING TUBE

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A method is given for determining the undetached flow of condensate in the bottom layer of a tube inclined to the horizontal with allowance for the wave structure.

Tilted tube bundles in condensation systems have been used to intensify the heat transfer and have been extensively examined in recent years for use in large power units of output 800-1200 MW.

Nusselt [1] was the first to solve for the flow of condensate in an inclined tube. In subsequent papers such as [2-4], this solution was developed on the basis of the physical

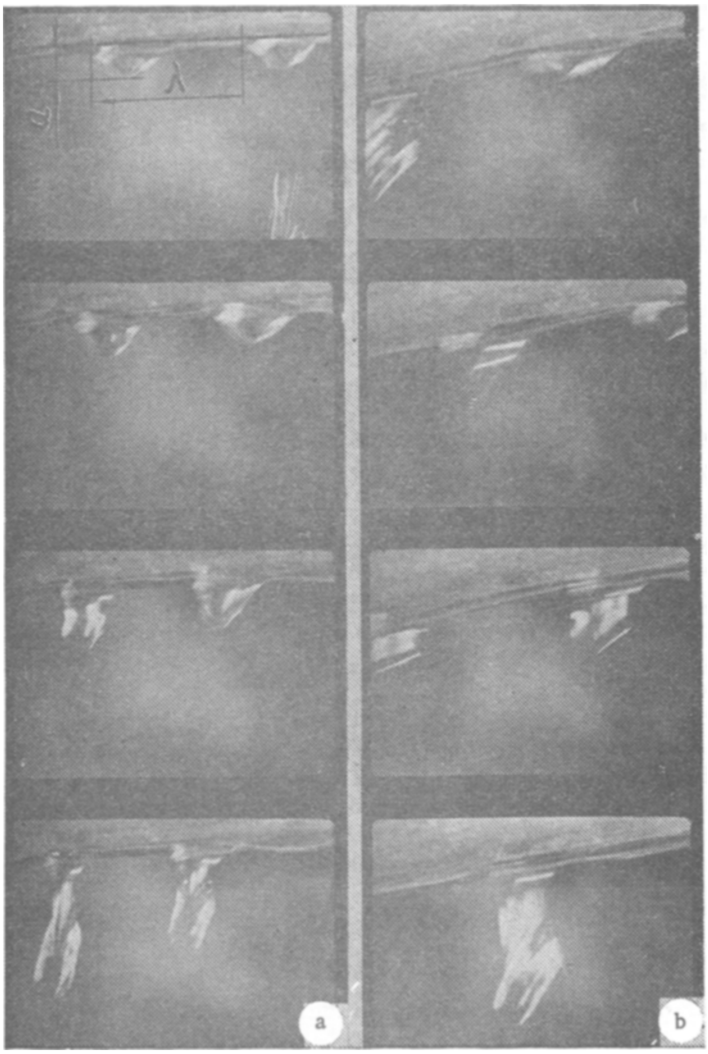

Fig. 1. Detachment developing in a bottom layer in an inclined tube, frame rate 22 frames a second: a) $\beta = 1°18'$; b) $8°50'$.

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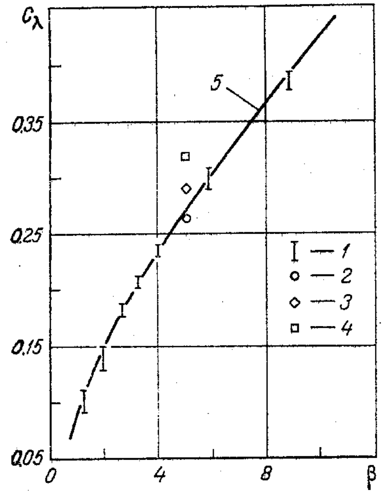

Fig. 2

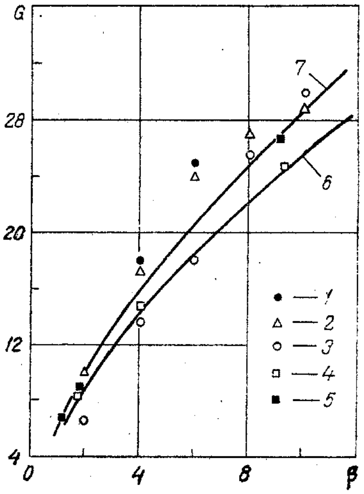

Fig. 3

Fig. 2. Speed of wave motion in predetachment region (C_λ in m/sec, β in deg): 1) water temperature 27°; 2) 22; 3) 40; 4) 62; 5) calculation from (2).

Fig. 3. Dependence of limiting detachment-free flow rate on tube tilt (G, kg/h): 1) from Aleksandrov's data; 2) after Linetskii and Yanchenko (1 and 2 cited from [4]); 3) Brodov [4]; our results: 4) water temperature 27°; 5) 62; 6) calculation from (1) for a temperature of 20°; 7) the same, for 60-85°.

properties of the liquid and the hydrodynamics of the bottom layer. In those studies, the structure of the bottom layer was represented as a film whose thickness and flow rate increase monotonically in the direction of motion. On the other hand, the wave transport mechanism is important in actual processes.

Here we determine the region of undetached flow of condensate with allowance for the wave structure. The experiments were performed with a cold model constituted by a single tube of diameter 28 × 1 mm made of MNZh-5-1 alloy with a surface having natural roughness and fitted with an irrigation system, a tilting mechanism, and a thermostatic system. The formation of the bottom layer was recorded with a Konvas-avtomat camera with illumination by a DRSh-1000 lamp.

The following physical picture was represented by the results. The flow in the bottom layer initially occurs as a film with a smooth surface, which acquires a wave character as liquid accumulates and in which the wave amplitude increases rapidly. When the mass force from the wave begins to exceed the retaining force from surface tension, the liquid begins to become detached from the tube. As an example, Fig. 1 shows two characteristic pictures of the detachment. The wave flow in the detachment region is represented by the motion of large droplets of extended form over a thin mobile film layer. The wave speed increases gradually from the point of generation to the point of detachment and is maximal at the moment where the wave loses integrity. The wave speed decreases at the time of detachment. Statistical processing of 17,000 frames showed that the following relationship applies between the limiting values of the velocity, length, and mass of the wave corresponding to the state preceding detachment and also the limiting nondetachment flow rate;

$$G = ql = \frac{c_\lambda m_\lambda}{\lambda}, \qquad (1)$$

which indicates that the wave mechanism predominates in the developed region. Figure 2 shows the experimental values of the phase (wave) velocity for water temperatures of 20-60°. The curve corresponds to

$$\mathrm{Re}_a = 0.51\,\mathrm{Ga}_a^{2/3}\sin^{2/3}\beta, \qquad (2)$$

where $\mathrm{Re}_a = c_\lambda a \nu^{-1}$ is the Reynolds number in terms of the phase velocity and wave amplitude, and $\mathrm{Ga}_a = g a^3 \nu^{-2}$ is the Galileo number.

We examined the layer dynamics with horizontal and inclined tubes of diameter 16, 28, and 70 mm and found that the tube diameter had virtually no effect on the velocity and strucural parameters, in the region of the developed layer, although the tilt and the physical properties of the liquid were decisive. According to these experiments, the wave amplitude corresponding to the maximum liquid thickness under the wave crest in the predetachment state is

$$a = 2{,}03\sigma^{1/2}(\rho g)^{-1/2}, \tag{3}$$

and the wavelength is

$$\mathrm{Ga}_\lambda = 31\mathrm{Fi}^{3/5}. \tag{4}$$

Here $\mathrm{Ga}_\lambda = g\lambda^3\nu^{-2}$ is the Galileo number in terms of the wavelength, and $\mathrm{Fi} = (\sigma/\rho)^3(g\nu^4)^{-1}$ is the film number.

The wave mass appearing in (1) can be found from the condition for equality of the mass force and the surface-tension one:

$$kmg = \sigma\lambda\cos\beta, \tag{5}$$

where k is the correction coefficient for the length of the detachment perimeter. According to our experiments, k = 0.042. On detachment, the wave loses up to 70-80% of its mass in accordance with the tilt and temperature.

The calculations on the retaining power were performed as follows. From (4) we calculated the wavelength, and then the wave mass from (5). Then from (3) we determined the amplitude of the wave motion, and then (2) gave the phase velocity. The nondetachment length in the layer was determined from (1) for the corresponding heat flux.

The phase velocity was zero for a horizontal tube and, according to (1), the retaining power of the bottom layer vanishes. Ordered motion of the liquid along the generator occurs when the tilt angle exceeds the flow-initiation angle, which is equal to about half the radius.

Figure 3 gives experimental values for the limiting detachment-free flow rate and curves given by our method. The spread in the experimental values was due to the methods used. The agreement between the calculated and experimental values we obtained, and also with data from experiments with a condensing tube of length 2 m [4], is quite satisfactory. When the water temperature varies from 20 to 60°, the limiting value for the nondetachment flow rate increases, because the increase in phase velocity predominates over the reduction in wave mass. An increase in temperature from 60 to 85° has practically no effect on the limiting detachment-free flow rate, since, in that range, the increase in phase velocity is compensated by the reduction in wave mass. This explains why the limiting detachment-free flow rate is independent of temperature in this range, as previously found by experiment [4].

The results in Fig. 3 indicate that this method of determining the retaining power can be used in engineering calculations on condensation systems for power units.

NOTATION

β, tube inclination angle; G, limiting nonseparated flow rate; c_λ, phase velocity; m_λ, wave mass; λ, wavelength; a, wave amplitude; q, flow rate per unit tube length; l, length of the nonseparated flow; ν, kinematic viscosity; g, acceleration due to gravity; σ, surface tension; ρ, density.

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