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PHENOMENA OF LIQUID TRANSFER IN TWO-PHASE DISPERSED ANNULAR FLOW

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Аннотация—Приводятся результаты эксперимента по определению количества жидкости, выпадающей на стенку прямоугольного канала из турбулентного воздушно-водяного дисперсно-кольцевого потока. Предлагается выражение для расчета расхода жидкости, текущей в пленке.

NOMENCLATURE

k, $= G_{dep}/c_0$, deposition factor;
G_{dep}, mean integral flow of depositing liquid;
c, mass liquid content in 1 kg gas in a flow core;
c_0, mass liquid content in 1 m^3 gas in a flow core;
w_g, mean gas velocity;
D, hydraulic channel diameter;
Re_g, $w_g D \rho_g / \mu_g$;
ρ_g, gas density;
ρ_l, liquid density;
σ, coefficient of surface liquid stress;
L, characteristic dimension;
μ_g, gas viscosity;
μ_l, liquid viscosity;
G_f, mass liquid flow in a film;
G_l, total mass liquid flow;
$\bar{\rho}$, $= \rho_g \left[1 + \dfrac{G_l(1 - G_f/G_l)}{F \rho_g w_g}\right]$;
F, cross-sectional channel area.

In reference [1] an experimental study was made of the separation of a liquid from a dispersed-annular flow, in a range of liquid concentration in a flow core of 0·02 to 0·12 kg per 1 kg of air.

The aim of the present work is to investigate the separation of a liquid for higher moisture contents. Except for the test section, the apparatus described earlier [1] has been employed. It consisted of a horizontal tube with the test section mounted at its end. Water was injected into the air stream by means of a set of centrifugal sprayers. The design and the basic dimensions of the test section are given in Fig. 1. A comb made of a number of safety razor blades packed together (40 to 50 blades in a set) was used as the absorbing surface. The pitch of the lattice formed by the edges of the blades was equal to 0·5–0·75 mm. The set was so formed that the channels for withdrawing the depositing water between the blade planes had a slope of 45° with respect to the flow axis. The film of liquid moving along the wall of the channel was completely sucked off into a slot in front of the absorbing surface. The separated liquid was withdrawn into a cavity directly under the set, and then into the settling tank to measure its volume. To protect the absorbing surface from any accidental penetration of the liquid from the film, the whole bottom section including the absorbing surface, downstream of the slot for suction of the film was raised by 0·5 mm. This caused a certain contraction of the channel. Together with the film some amount of air was sucked out from the stream so that the mean flow velocity should remain the same along the whole test section. Since suction was effected at a velocity close to the main flow velocity at the position of suction, if the contraction did not exist at all, and the construction of the section

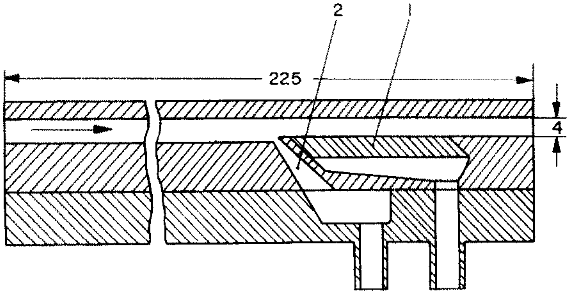

FIG. 1. Schematic diagram of test section for studying separation on channel wall.
1.—set of blades; 2.—slot for sampling film.

would ensure the removal at a sufficiently sharp angle to the direction of flow, then the disturbance caused by suction should not strongly influence the profiles of velocity and concentration. The absorbing surface was of a rectangular shape 38 mm wide (almost equal to the channel width) and its length depended on the number of blades in a set. Usually it was 40 mm. Liquid concentration in the flow core was measured at the end of the test section with the help of a special sampling probe [1]. Moisture content, c_0, in the flow core ranged from 0·1 kg/m^3 to 1·3 kg/m^3 and Re_g, from 3×10^4 to $8{\cdot}5 \times 10^4$.

In Fig. 2 the experimental results for liquid deposition are presented as a relation

$$\frac{G_{\text{dep}}}{c_0 w_g} Re_g^{0\cdot 25} = f(c). \tag{1}$$

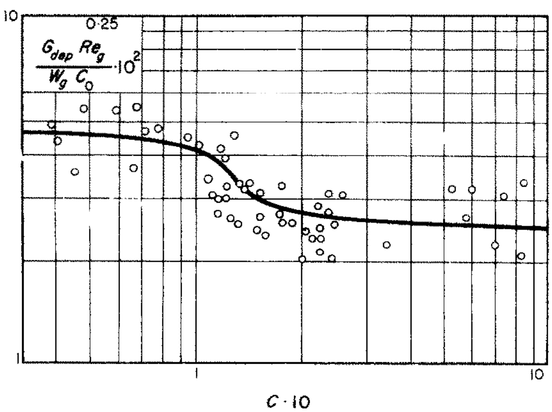

FIG. 2. Influence of liquid concentration in a flow core upon separation intensity.

G_{dep} is the relation of the total amount of the liquid to the absorbing-surface area, i.e. is the mean integral quantity. The curve has an almost horizontal section at small liquid concentrations where the relative velocity of separation k/w_g is a function of only Re_g. The quantity k/w_g in the region of great moisture contents at first decreases noticeably with a growth of liquid concentration in the flow core. However, in the remaining part of the investigated range this decrease is negligible and for the value of c from 0·2 kg per 1 kg air and above, the experimental data be approximated by the expression:

$$\frac{G_{\text{dep}}}{c_0 w_g} = \frac{0{\cdot}026}{Re_g^{0\cdot 25}} \tag{2}$$

Relations (1) and (2) each taken separately do not reflect the relationship of the separation factor to the liquid concentration in the flow core. However, from Fig. 2 it is seen that the moisture content effect takes place over the whole range of concentration. This is also obvious from physical considerations. Indeed, the change in moisture content in the flow core should influence the turbulence rate in a gaseous phase and, consequently, the rate of separation of the drops. The flow of the separating liquid G_{dep} will not therefore linearly depend on moisture concentration in a gaseous core as it follows from expressions (1) and (2). It appears to be more correct to use one relation for all the concentrations under consideration which would take into account this fact. The experimental data depicted in Fig. 2 well enough correspond to the expression:

$$G_{\text{dep}} = \frac{0{\cdot}022\, \rho_g}{Re_g^{0\cdot 25}} w_g\, c^{0\cdot 74} \tag{3}$$

The problem of stability of a liquid film moving under the action of a turbulent gas flow is of great interest for many branches of engineering. In references [2] and [3] it has been obtained experimentally that under certain conditions the stall of high waves occurs from a wavy liquid surface. The stall intensity increases with the gas velocity. The main aim of these works was to find out the moment of the stall rise and to obtain a general pattern of the liquid surface preceding its rise. No information was obtained of the process in question under the conditions of the developed liquid entrainment typical of the dispersed-annular flow.

The success of the analytical description mainly depends on the accumulation of the sufficient amount of experimental data on statistical properties of a liquid surface and, for example, of the mechanism of transfer of mechanical energy between a gas and a wall liquid.

Recently the experiments on the thickness of a liquid film or liquid flow rate in it under the conditions of the developed entrainment were carried out when in the flow core the moisture content reaches a considerable value. Despite the fact that a great number of the data[4–8] have been already accumulated under various experimental conditions so far there is no reliable generalization.

The steady liquid distribution over the cross-section results from the dynamic equilibrium between countercurrent flows of precipitated and entrained drops. Consequently, those quantities are important upon which both flows depend. In the study of interaction between a gas and a liquid during nozzle spraying the following groups,

$$\frac{\rho_g w_g^2 L}{\sigma}, \qquad \frac{\mu_l^2}{\rho_l \sigma L}, \tag{4}$$

are successfully used as the determining criteria. In the case of an infinite liquid thickness, it is necessary to exclude the characteristic length as being non-determining. This gives

$$\frac{\rho_g}{\rho_l}\left(\frac{\mu_l w_g}{\sigma}\right)^2. \tag{5}$$

For rather thick films also in our case, the liquid stall would be determined by this very group. Here, however, the liquid separation should be taken into account since, as already mentioned, the equilibrium conditions are achieved when the amounts of precipitated and entrained liquid become the same. Proceeding from this fact, it is possible to make as a first approximation an attempt to preserve the structure of the expression (5) replacing in it ρ_g/ρ_l by

$$\frac{\rho_g}{\rho_l}\left[1 + \frac{G_l(1 - G_f/G_l)}{F \rho_g w_g}\right].$$

By this means, the effect of the liquid content in the flow core and its separation are taken into consideration. The influence of the tube diameter and gas viscosity is determined by the dependence (2) of separation upon the gas Reynolds number, i.e. it appears not greater than power 0·25. Since the disturbed film surface is equivalent to a rough wall, this dependence may be much weaker or even absent. As a first approximation, the influence may be neglected, and finally we may look for an expression for a liquid distribution between a film and gaseous core in the following form:

$$\frac{G_f}{G_l} = f\left[\frac{\bar{\rho}}{\rho_l}\left(\frac{\mu_l w_g}{\sigma}\right)^2\right]. \tag{6}$$

A study was made of experimental data available in literature and obtained at the Thermal Physics Faculty of Leningrad Polytechnical Institute.* In Fig. 3 the results are given in logarithmic coordinates. In this figure the curve corresponds to the expression

$$\frac{G_f}{G_l} = 0{\cdot}985 - 0{\cdot}44 \log\left[\frac{\bar{\rho}}{\rho_l}\left(\frac{\mu_l w_g}{\sigma}\right)^2 \times 10^4\right] \tag{7}$$

In Fig. 3 the points are taken from the experimental curves of various authors [4–8] over certain intervals chosen to cover the whole range of the parameters considered in each work. As is seen from the figure, the scatter of the experimental data is sometimes rather

*The data used in this paper were obtained by K. P. Maluys-Malitsky and L. M. Dymant at Leningrad Polytechnical Institute.

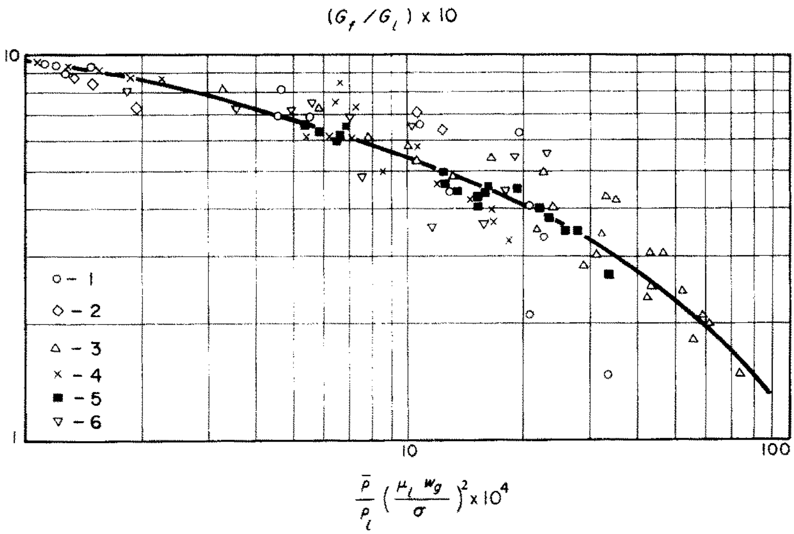

FIG. 3. Relation of G_f/G_l to $\bar{\rho}/\rho_l\,[(\mu_l\, w_g)/\sigma]^2$.
1.—reference [4]; 2.—reference [5]; 3.—reference [6]; 4.—Leningrad Polytechnical Institute, Ø 16 mm; 5.—Leningrad Polytechnical Institute, Ø 27·7 mm; 6.—reference [8].

large. It may be supposed that this comes mainly from the complexity of the experiments. Very often the data of various authors obtained apparently under the same conditions differ significantly. In addition, the results are used of the experiments both in horizontal and vertical tubes. The considerable non-uniformity of the liquid distribution over the cross-section is observed in the horizontal channels. Probably the wettability of the channel walls is of some importance. Regarding the effect of the shape of the cross-section it appears probable that it is negligible if the radius of curvature is sufficiently large over the whole perimeter, so that the film surface may be considered flat. In the presence of rather sharp angles the film thickness will be very non-uniform over the perimeter, and the effect of the cross-section shape of the channel may become considerable.

If entrainment of drops from a film surface depended upon the tube diameter, then the expression for G_f/G_l would have to include apart from expression (5) also of the groups (4), for example $\mu_l/(\rho_l\,\sigma\,D)$. However, the experiments with water air flows at the same temperatures did not reveal any clear dependence upon the diameter, and hence upon $\mu_l^2/(\rho_l\,\sigma\,D)$. The scatter of the experimental points is the same as in the cases of the same diameter and is obviously caused by the errors of the experiments.

Equation (7) is not valid in the limiting region where G_f/G_l is close to zero as the available data show that the liquid flow rate in a film tends to a constant value with an increase in the gas velocity. Equation (7) is easily solved by the trial-and-error method. Taking the value, for example, 0·5 of G_f/G_l it is possible as a rule to obtain a sufficient accuracy after 2 to 3 approximations.

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Abstract—The experimental results are presented of the quantities of separated liquid deposited on the wall of a rectangular channel from the turbulent air–water dispersed-annular flow are presented. The expression for the calculation of the liquid flow rate moving a film is proposed.

Résumé—On présente les résultats expérimentaux sur les quantités de liquide déposées sur la paroi d'un conduite rectangulaire avec un écoulement turbulent annulaire d'air et d'eau. On propose une expression pour calculer le débit de liquide dans le film.

Zusammenfassung—Versuchsergebnisse über die Flüssigkeitsmenge, die aus einem turbulenten ringförmigen Strom eines Luft-Wasser-Gemisches an der Wand eines Rechteckkanals abgelagert wird, sind angegeben. Eine Gleichung zur Berechnung der Geschwindigkeit des bewegten Flüssigkeitsfilms wird vorgeschalagen.