Calculations were also performed for liquids of identical density ($\rho_2/\rho_1 = 1$) with various relations between the viscosities ($\mu_2/\mu_1 = 1$, $\mu_2/\mu_1 = 2$, $\mu_2/\mu_1 = 4$), which showed that the degree of displacement even for Re = 1 is almost independent of the viscosity ratio.

NOTATION

x,y, Cartesian coordinates; t, time; u,v, velocity components; p, pressure; h, channel half-width; V_0, mean pumping rate; Re, Reynolds number; $\Delta x, \Delta y$, net steps; N_i, number of markers in a cell.

LITERATURE CITED

1. B. J. Daly, "Numerical study of two-fluid Rayleigh–Taylor instability," Phys. Fluids, 10, No. 2, 297-307 (1967).
2. B. J. Daly and W. E. Pracht, "Numerical study of density-current surges," Phys. Fluids, 11, No. 1, 15-30 (1968).
3. B. J. Daly, "Numerical study of the effect of surface tension on interface instability," Phys. Fluids, 12, No. 7, 1340-1354 (1969).
4. S. Uchida and M. Endo, "On some numerical solutions of the flow through a back-step channel," Mem. Fac. Eng., Nagoya Univ., 27, No. 1, 152-161 (1975).
5. S. I. Bakhtiyarov, "An experimental study of the dynamics of displacement of a liquid from a recess," in: Thermophysics and Physical Hydrodynamics [in Russian], Novosibirsk (1978), pp. 62-67.

STRUCTURE OF A TWO-PHASE EDGE WAKE

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Experimental results are presented on the structural and kinematic characteristics of the motion of a liquid in an edge wake.

The resistance law for a truncated sphere is used in calculating a two-phase edge wake, e.g., as in wet-steam turbine stages. Extensive evidence has been accumulated on the motion of individual droplets, and this allows one to incorporate the effects of various factors on the resistance coefficients, such as the nonstationary and turbulent nature of the carrying flow, the internal circulation of the droplets, the deformation, etc. At the same time, it remains unclear how far these results are applicable to the motion of droplets in an edge wake with high concentration and velocity gradients. As a consequence, it appears preferable to use the critical Weber numbers, which characterize the stability of droplets of maximum size, and the effects from droplet interaction on the structure of the edge wake.

There are serious difficulties in measuring the local structural and kinematic parameters of a high-speed droplet flow and determining whether one is justified in transferring the laws of motion of single drops to the conditions of an edge wake.

Here we examine some aspects of this problem. We have developed a statistical method of high-speed photography. The essence is a follows. We represent a droplet of diameter d moving with velocity c^{τ} in the median plane of the focal range of a camera (Fig. 1). The camera is fitted with a scan system, and the axis of rotation of the mirror is parallel to the direction of droplet motion. The image of the droplet in the appropriate scale is constructed by the input optical system 1 in the plane of the slot 2, which is conjugate to the axis of rotation of the mirror. Then part of the droplet image cut off by slot 2 is transferred by the lens 3 and the rotating mirror 4 to the film 5. During the exposure, the image of the drop at the film moves along the line AB, whose width along the slot is determined by the size of the droplet, while the angle α is determined by the ratio of the scan speed (line AC) and the speed of the droplet on the appropriate scale (line CB). If the slot width is sufficiently small and a collimated beam is employed, which lies at the optical axis of the camera, the error in imaging the droplet as a sphere is small and may be neglected. The optimum mutual disposition of the slot and the droplet image occurs when

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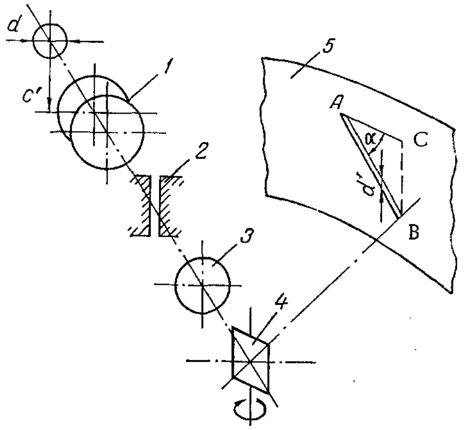

Fig. 1. Construction of the wake of a moving droplet by the statistical method of high-speed photoscan.

the slot divides the image into two equal parts. Then the slot width s will be determined by the acceptable (preset) error δ in measuring the droplet size d and by the magnification n of the input optical system via

$$s = 2n\left(\frac{d\delta}{2} - \frac{\delta^2}{4}\right)^{1/2}. \tag{1}$$

In the general case, the information provided by this method is statistical because of the randomness of the mutual disposition of the slot and the droplet image. If a flow consists of droplets of identical size and velocity, a frame will contain a series of parallel lines. The widths of the lines will be determined by the parts of the images dissected out by the slot, and therefore the determination of droplet diameter amounts to defining the lines of largest width.

In a polydisperse edge wake, this involves using the recording data to construct the functional relationship $d = f(c')$; here the first limiting condition is set by the maximum stable diameter of the droplets, while the second is set by the speed of the gas flow. The function $d = f(c')$ is statistical in character, since it is constructed from a large number of measurements as the envelope of the region containing the data from the scans. The use of a statistical curve instead of the individual diameters is also desirable because this form of processing eliminates the effects of random or noncharacteristic factors affecting individual droplets in such a flow.

Therefore, if we dispose of the statistical functions $d = f(c')$ for various distances from the edge along the axis of the wake together with the speed of the gas, we can readily determine the resistance coefficient for the droplets in the polydisperse flow.

It has been found by careful examination of the metrological features of this method that the resolution is usable up to 600 m/sec if one employs a standard SFR camera with a high-intensity discharge circuit and a film with a resolution of several hundred lines per millimeter, which applies for droplet flows differing substantially in structure. The error in measuring the droplet size is defined in general by (1), and it is only a few percent with optimum adjustment of the optical systems. If we assume that the measurements of the droplet sizes and velocities are equally accurate, it is desirable to use a sweep speed such that α is close to $\pi/4$. The necessary degree of localization of the parameters is determined by the depth of focus and is readily provided by using an input optical system with appropriate characteristics in conjunction with a suitable recording scale [1].

A difference from related methods such a multiple-pulse photography (holography) and high-speed motion-picture photography is that this method completely eliminates identification in the processing of the results.

The formation of an edge wake was examined under normal conditions in a vertical channel of section 140 × 60 mm, which contained a plate with a mechanism for producing a film flow over one or both surfaces. The thickness of the exit edge of the plate varied from 0.2 to

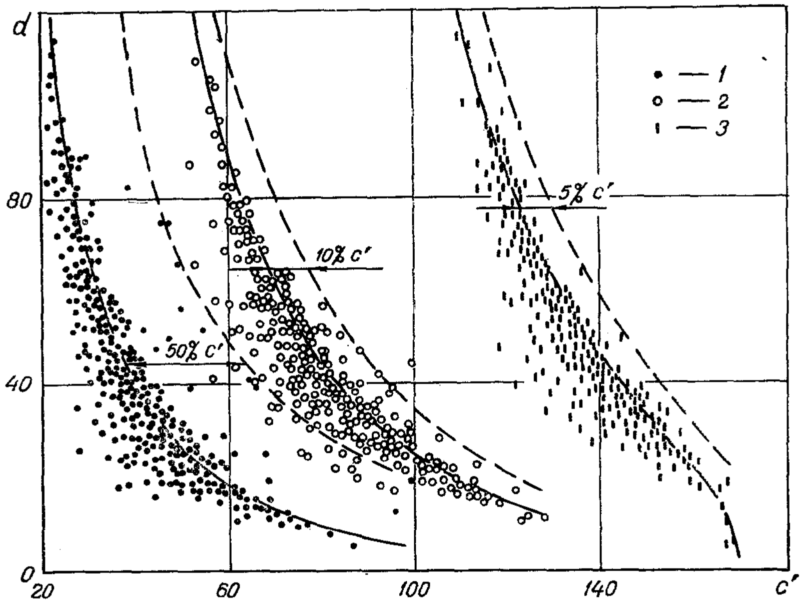

Fig. 2. Relationship of droplet speed to diameter at the axis of an edge wake; d in μm, c' in m/sec: 1) x = 13 mm; 2) 45; 3) 245.

6.0 mm, while the specific flow rates in the film ranged from 0.1 to 8.0 $cm^3/cm \cdot sec$, while the mean speed of the air ranged up to 185 m/sec. The structural and kinematic characteristics of the droplets in the wake in the steady state were measured by flash photography with an effective exposure of 10^{-6} sec as well as by the previous method, and the same was done for cases where droplets broke up once. In the region of incomplete break-up, and near the edge, we also used high-speed motion-picture photography (frame speed 6000 sec^{-1}). The parameters of the film flow at the exit edge of the plate were recorded by the methods of [2].

The following are some results. Figure 2 shows the experimental data and also calculations on the motion of the droplets at the axis as performed from the truncated-sphere law. The calculations were performed with an M-222 computer in accordance with the equations

$$m\frac{d^2x}{dt^2} = c_x\frac{\pi d^2}{4}\frac{\rho''}{2}(c''-c')^2 + mg, \tag{2}$$

$$c_x = \frac{21.12}{\mathrm{Re}} + \frac{6.3}{\mathrm{Re}^{1/2}} + 0.25. \tag{3}$$

The air speed and the initial droplet velocity were inserted into the calculations on the basis of our experiments.

Figure 2 shows that some of the droplets far from the edge have a speed higher than the calculated value, with some of them exceeding that value by 50%, which is due to the deviation of the fragmenting film from spherical in the range of Reynolds numbers where the resistance coefficient and cross section of a sphere are less than for bodies of other configurations. Fragments of irregular shape near the edge have speeds higher than droplets of the same mass. When the fragments broke up, droplets arose that naturally retain the initial elevated velocity.

Similarly, there appears to be a certain proportion of droplets deviating from the theoretical velocity (experimental values for the structural and kinematic characteristics of these droplets cannot be derived from the general body of information on account of the principle used in constructing the envelope of the curve via a statistical method).

Away from the edge, the deviations between the velocities decrease, and the maximum deviation, which relates only to a small fraction of the droplets, is 5% at x = 245 mm. This equalization of the velocities along the trace is readily explained from the physical viewpoint: droplets that initially have elevated velocities are subsequently accelerated less, since the aerodynamic forces acting on them are dependent more on the relative velocity than on the resistance coefficient.

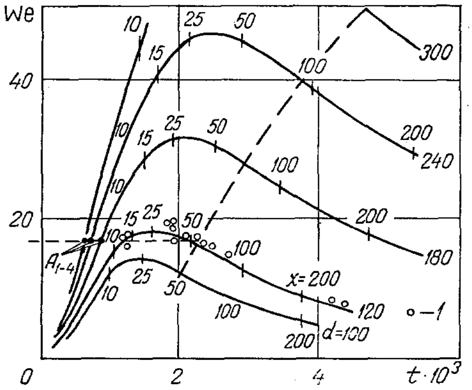

Fig. 3. Determination of the maximum droplet size in the wake from the critical Weber number: 1) observed values from the statistical method of high-speed photography.

Numerous experiments indicated that the speed of the main body of droplets in the steady-state part of the edge wake agrees satisfactorily with the calculations, which means that one can use the sphere resistance law to determine the speeds of droplets in a polydisperse edge wake.

A major question concerns the maximum stability of the droplet size. A basic condition, which determines the critical Weber number, is the character of the aerodynamic force on the droplets. If this is close to stationary, the critical value We_{cr} is given by the theoretical solution [3] as 17. In fact, experiment [4] for these conditions gave the range $We_{cr} = 15$-22 and the mean value corresponds to the theoretical value, while We_{cr} is independent of the Reynolds number in the range Re = 120-700.

The attainment of We_{cr} is necessary to breakup, but breakup occurs only if the aerodynamic load provides $We > We_{cr}$ for about three periods of free oscillations.

The nature of the load on the drops in the main part of the edge wake was established from the structural and kinematic parameters. Figure 3 shows the Weber number in relation to time of motion and path travelled along the axis for the conditions of the experiment. Points A_1-A_4 denote the onset of critical deformation, for which $We_{cr} = 17$. At the end of the breakup time, which is indicated by the broken line in Fig. 3, only droplets with $d \geq 120$ µm have $We > We_{cr}$, and therefore can break up. The experiments confirm these calculations, which shows that the loading on the droplets in the wake is stationary.

Experiment showed that droplets of maximum size, as determined by the aerodynamic load, are produced only when the initial diameter exceeds the maximum stable one. If this is not so, the droplet size is dependent on the structural parameters of the film flow at the edge. If we take the first stage of wake formation as breakup of jets detached from the film into droplets, with resonance between the natural oscillations of the jets and droplets, then at the minimum oscillation frequency we have

$$d = k\left(\frac{b\sigma}{2\rho'' c_{cr}''^2}\right)^{1/2}, \qquad (4)$$

where the coefficient k incorporates the deviation from the theoretical periods of longitudinal oscillation in a jet. It is recommended [5] that one should use k = 3.3 and $d_{max} = 2d$. In another approach [6], analysis of the physical picture of film breakup on the flow from a nozzle gave

$$d_{max} = b(67 + 3.44 \cdot 10^{-3} M_2) M_1^{-0,7}. \qquad (5)$$

Under otherwise equal conditions, (4) predicts a more marked influence from the air flow speed near the edge on the maximum size.

Experiment indicates that (5) can be used for an edge wake to a satisfactory approximation. The values of d_{max} given by (4) and (5) for the nominal states in the later stages of high-power steam turbines are in satisfactory agreement.

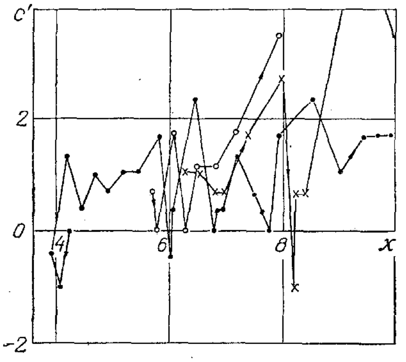

Fig. 4. Motion of fragments of a disintegrating film and droplets near an edge (c' m/sec; x, mm): $\Delta = 6$ mm, $c'' = 63$ m/sec, $q = 0.54$ cm^3/cm·sec.

In most studies on edge wakes [7, 8] it has been usual to assume a single-valued and constant relation between the mean and maximum droplet sizes for the spectrum, which has a single turning point. Usually, the ratio of the maximum to the mass-mean diameter has been taken as two. Our experiments showed that the spectra undergo continuous deformation in the wake, which means that the various parts each have their own curves. In particular, multiple-peak and open spectra are observed in the region where secondary breakup is occurring. However, even then there is a stable relationship between the maximum and mean diameters, although this is not constant over the width of the wake. We processed 263 spectra for various edge thicknesses, flowrates in the film, air speeds, and parts of the edge wake and found that $d_{max}/\bar{d} = 1.6$ to within 20% at the axis of the wake, while $d_{max}/\bar{d} = 1.4$ at the outer boundary, i.e., there is equalization of the mean size over the width of the wake, which is due to the motion of the liquid near the edge. The longitudinal and transverse pulsations in the liquid in this region go with the vortex motion of the droplets, and return of some of them to the edge, to set up conditions for mass equalization in the transverse direction. As an example, Fig. 4 shows the elements of the motion of parts of the film and of the droplets near the edge as recorded by high-speed motion-picture photography.

The departure of water from the edge is clearly pulsating. If the edge is thin ($\Delta = 0.2$-2.0 mm) and the liquid flow rate is low ($q = 1.0$-1.5 cm^3/(cm·sec)), the frequency of the pulsations in the droplet flow is close to that of the large waves in the film (80-160 Hz). At high flow rates, the frequency of the pulsations in the droplet flow is 2.0-2.5 times that of the waves.

A thick edge favors flow of the liquid to the rear part, and therefore the frequency of detachment from a thick edge is less than that for a thin one by a factor 1.5-2. If the flow rate in the film is low, the detachment frequency is less than the wave frequency by a factor 2-4, which shows that the edge has an accumulating action. When the flow rates are high, the frequency characteristics of the wake behind a thick edge are similar to those for a thin one.

In practical problems, there is the important aspect of the effects of edge thickness on the droplet size. Experiments on the region of the wake adjoining the edge [8, 9] have indicated a considerable effect from the thickness on the structure of the wake, while measurements in the stationary zone [10] have shown that the structural characteristics are independent of the thickness. A study of an extensive part of the wake in our experiments showed that the thickness of the edge does not influence the droplet size in the stationary region, but that the thickness displaces the boundary of secondary droplet fragmentation and increases the width of the liquid distribution in the wake. The thicker the edge, the later the completion of wake formation.

Flash photography shows that there are two types of droplet interaction in the wake. In the first, the sizes of the droplets are comparable and the speeds on encounter are low, so the result of collision may be a new droplet. If, on the other hand, the dimensions are larger than critical, there is immediately unstable deformation. In the second case, the sizes of the droplets differ considerably, and the collisional speed is considerable, in which case a small droplet passes through the large one and entrains a thin filament of liquid after it. This filament breaks up and forms one to three droplets.

These results supplement the physical picture of two-phase edge wake formation and enable one to refine the existing methods of calculation.

NOTATION

d, drop diameter; d_{max}, maximum drop diameter; m, drop mass; n, scale of photorecording; δ, error in d measurement; c' and c", local velocities of drop and flow, respectively; x, distance from the exit edge along the flow; c_x, resistance coefficient; q, specific flowrate in film; b, film thickness; c''_{cr}, flow velocity in the vicinity of the edge; c_{rel}, relative droplet velocity; ρ'', μ'', flow density and viscosity, respectively; σ, surface tension coefficient; Δ, exit edge thickness; g, acceleration due to gravity.

LITERATURE CITED

1. N. A. Ovsyannikov, Special Photography [in Russian], Nedra, Moscow (1966), p. 310.
2. R. M. Yablonik, O. T. Lebedev, V. A. Khaimov, and V. I. Belodedov, "Development of electronic instruments for measurement of local parameters of film flow," Tr. TsKTI, No. 99, 45-54 (1970).
3. N. Isshiki, "Theoretical and experimental study of atomization of liquid drops in a high-speed gas stream," Rept. Trans. Tech. Res. Just., No. 35, 107-117 (1959).
4. Yu. A. Korsunov and A. P. Tishin, "An experimental study of the breakup of liquid droplets at low values of Reynolds number," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 182-186 (1971).
5. R. G. Perel'man, "The stability of a liquid film in a gas flowing on one side and the size of the breakup droplets," Izv. Vyssh. Uchebn. Zaved., Aviatsion. Tekh., No. 1, 149-154 (1972).
6. B. V. Raushenbakh et al., Physical Principles of the Working Process in Combustion Chambers of Air-Breathing Jet Engines [in Russian], Mashinostroenie, Moscow (1964), p. 526.
7. I. P. Faddeev, Erosion in Wet-Steam Turbines [in Russian], Mashinostroenie, Leningrad (1974), p. 206.
8. R. Puzyrewski, "Theoretical and experimental studies of formation and growth of water drops in L. P. steam turbines," Prace Institutu Maszynprzepkywowych, No. 42-44, 289-304 (1969).
9. Yu. I. Abramov and A. V. Silin, "Formation of coarsely dispersed water at the exit edges of nozzles in wet-steam turbines," Teploenergetika, No. 2, 31-35 (1977).
10. V. N. Bykov and M. E. Lavrent'ev, "Destruction of the film of liquid flowing from the edge of a plate in a gas flow," Inzh.-Fiz. Zh., 31, No. 6, 1074-1079 (1977).