ELECTRICAL MEASUREMENT OF DROPLET SIZES IN FAST-FLOWING WET STEAM

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UDC 532.529.5

A new method has been developed for determining droplet sizes that extends the range of the Wicks–Dukler method. Experimental results are presented.

The Wicks–Dukler method is used in measuring the sizes of comparatively large water droplets (over $10\text{-}20 \cdot 10^{-6}$ m). The method becomes more reliable as the droplet size increases, and it is therefore convenient in determining droplet distributions in turbine systems handling wet steam. These dimensions are of interest in relation to the erosion hazard arising from detachment of films from blade surfaces.

Small-angle scattering and deposition are the usual techniques for measuring droplet sizes on such flows [5]; the optical method is complicated by the presence of films on the optical components, while the probe method perturbs the flow considerably because of the substantial size of the probe.

Deposition also perturbs the flow, since the probe has to be made large in order to obtain an adequate sample volume, as the size of the sample is governed by the dimensions of the trapping area.

These disadvantages are largely absent from the Wicks–Dukler method, but there are difficulties in applying this at speeds above 50 m/sec. The moving droplets become electrically charged by friction, and the charge may be proportional to the area of the drop and to the shear rate, with the latter itself increasing with the drop size, and the charge is then proportional to the cube of the drop size. The charged droplets passing the electrodes provide numerous spurious pulses.

The droplet-bearing flow in a wet-steam turbine is of low conductivity; the value is not more than $3 \cdot 10^{-3}$ $(\Omega \cdot m)^{-1}$, and values lower by two orders of magnitude have been quoted [4]. The pulse amplitude is then considerably affected by the conductivity. Parasitic capacitance is an additional reason for the reduced pulse height.

Measurements have been made on the wet-steam flows with the liquid of conductivity about $3 \cdot 10^{-3}$ $(\Omega \cdot m)^{-1}$; the usual circuit consists of series-connected dc source, resistor, and two electrodes, and this works satisfactorily at speeds below 40-50 m/sec. The parasitic capacitance is constituted by the connecting cables and mounting components; this converts the circuit to an integrator, which emphasizes the low-frequency interference arising from the charged droplets while suppressing the high-frequency signals from the droplet contacts.

We used the system shown in Fig. 1 to extend the range of the Wicks–Dukler method to higher speeds.

The dc potential from the stabilized source 1 passes to the input section (enclosed by the broken line). When the circuit between the electrodes 4 is closed by a moving drop, a current flows in the primary winding of the pulse transformer Tr1. The pulse from the secondary goes to the UIS-2 pulse amplifier 2, whose frequency response rises in the range from 0.1 to 20 MHz. The output pulses are of length 1.5 μsec. The secondary winding of the transformer works into the cable capacitance, and the frequency response was flat in the range from 0.1 to 30 MHz.

These circuit parameters provided efficient suppression of the interference from charged droplets passing near the electrodes, while the signals from droplets that close the gap pass to the counter after high-frequency correction. The latter is provided by the rising-frequency response and the fall in the response of the transformer at frequencies below 100 kHz. This also balances the fall in the pulse amplitude produced by small droplets.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 36, No. 5, pp. 841-846, May, 1979. Original article submitted May 3, 1978.

0022-0841/79/3605-0559$07.50

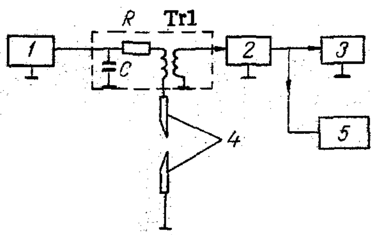

Fig. 1

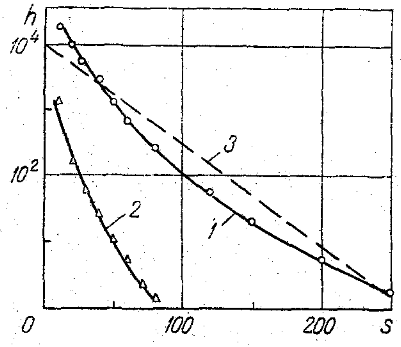

Fig. 2

Fig. 1. Circuit: 1) UIP-1 power supply; 2) UIS-2 pulse amplifier; 3) Ch3-12 frequency meter; 4) electrodes; 5) S7-5 strobe oscilloscope.

Fig. 2. Closure frequency as a function of distance between electrodes: 1) in the edge wake behind a plate, Re = 290; 2) after a nozzle, y_0 = 3%; 3) approximation from (2), with h in sec^{-1} and s in μm.

Our probe design was intended principally to measure droplet sizes in the edge wakes behind turbine blades. The design was simplified by grounding the mobile electrode. The electrodes were adjusted to be coaxial under the microscope, and the adjustment was monitored during the experiment by observation with a Töpler instrument. An intermediate lens was used to enlarge the image.

The circuit of Fig. 1 was used with needle electrodes to examine the effects of liquid flow in the films and of blade-edge thickness on droplet size in the edge wake produced by a plate of dimensions 0.006 × 0.06 × 0.18 m; a closed wet-steam tunnel was employed [7]. The working part was a gradient-free channel. The film was supplied by two symmetrically disposed slots on the plate. The flow of steam moved the film, which broke up into droplets in the wake. The limits to the utility of the method were examined at low electrical conductivities and also on wet steam emerging from a planar subsonic nozzle. The droplet speed was estimated by numerical solution of a system of differential equations [6] for the motion of the two-phase medium in the nozzle. Here we give some of the results that relate to the reliability of the method for high-speed wet-steam flows containing liquid of low electrical conductivity, in addition to details of the data-processing methods.

Figure 2 shows typical results for the closure frequency h as a function of the distance s between the electrodes. Curve 1 corresponds to flow in the film defined by Re = 290. The Mach number for the associated steam flow was deduced from the ratio of the static pressure to the dynamic pressure at the plate and was 0.6. The probe was set up at a distance of three times the thickness of the plate from the edge.

Curve 2 is the result for wet steam from a subsonic nozzle for an initial water content of 3% and a pressure drop across the nozzle of 0.850.

The size distribution is given by the following formula [4]:

$$f(D)=\frac{FD}{\pi}\int_{1}^{D_m/D}\sqrt{x^2-1}\left(\frac{d^4h}{dx^4}\right)dx, \tag{1}$$

where x = s/D is the variable of integration; F vanishes on normalization.

The following expression has been suggested [1] as a suitable approximation function:

$$h=A\exp(-\alpha s). \tag{2}$$

A better expression for our results is

$$h=A\exp(-\alpha\sqrt{s}). \tag{3}$$

Substitution of (3) into (1) gives

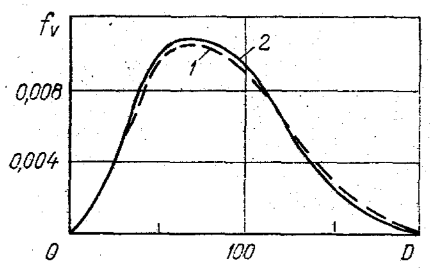

Fig. 3

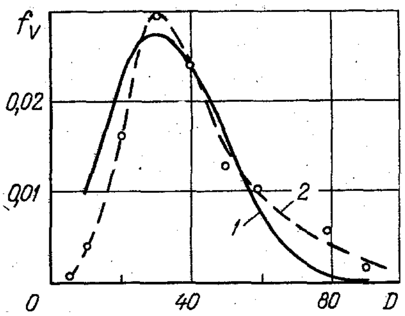

Fig. 4

Fig. 3. Droplet size distribution in an edge wake: 1) approximation from (2); 2) from (3), f_V in μm^{-1}, D in μm.

Fig. 4. Size distributions after a nozzle given by: 1) Wicks–Dukler method; 2) deposition method, f_V in μm^{-1} and D in μm.

$$f(D) = \frac{F\alpha A}{16\pi D}\int_1^{D_m/D}\frac{\sqrt{x^2-1}}{x^2}\left[15(Dx)^{-\frac{3}{2}} + 15\alpha(Dx)^{-1} + 6\alpha^2(Dx)^{-\frac{1}{2}} + \alpha^3\right]\exp(-\alpha\sqrt{Dx})dx. \quad (4)$$

The results were processed by numerical integration of (4) by Simpson's method followed by normalization.

It has been found [4] that the pulse frequency increases when the distance between the electrodes is small; it is considered [4] that this is due to breakdown in the space between the electrodes at the instant of closure if the voltage is too high. The following objections may be made to this view. In our experiments (at 100 V), (3) provides a close fit to the results for distances between the electrodes down to 400–500 · 10^{-6} m, at which breakdown is impossible at that voltage. Also, even if breakdown does occur, the output from the UIS-2 is only a single pulse, as the length of the output pulse is constant. If we take the upper limit to the closure time as the ratio of the diameter of a droplet to the velocity, we get the following results on the basis that the droplet diameters are 10, 20, 40, and 80 · 10^{-6} m, and the droplet speeds from calculations are 176, 148, 115, and 86 m/sec, correspondingly. For a maximum diameter of 80 · 10^{-6} m (curve 2 in Fig. 2), the closure time is less than the pulse length at the output of the UIS-2. Clearly, the breakdown probability increases with the water content and with the droplet size. If we take the view of [4], viz., that the rise at small s is due to electrical breakdown, then the slope of curve 2 (Fig. 2) should increase as s diminishes more slowly than that of curve 1. However, experiment does not confirm this, so we assume that the increase in the slope of the count-rate curve is a natural consequence of an increase in the number and speed of the small droplets, and that it is not due to breakdown.

It has been also stated [4] that the pulse frequency is dependent on the voltage on the electrodes, in that h(s) tends to vary on account of the increasing steepness of the count-rate curve at small s at the higher voltages. It is claimed [4] that breakdown occurs at various distances, and therefore low voltages were employed. However, it is readily shown that the count-rate data from a threshold device in principle should be dependent on the voltage, or, more precisely, on the ratio of the threshold level to the source voltage. The signal amplitude from a drop of a given size decreases as the electrodes are moved apart. If low voltages are used, this results in a lower frequency at large s, because the pulse amplitude may fall below the threshold. This is confirmed by experiment. Clearly, the frequency measurements are the more reliable the higher the voltage on the electrodes (in the absence of breakdown). In general, the choice of working voltage is governed by the conductivity of the liquid, the interference level, the droplet speed, the parasitic capacitance, and the frequency response of the circuit. The parasitic capacitance did not exceed 60 pF under our conditions, and the curves were equidistant at electrode voltages above 80 V. We therefore selected 100 V for the experiments.

Figure 3 shows the normalized distributions, where curves 1 and 2 correspond to curves 1 and 3 in Fig. 2; curve 1 in Fig. 3 is from (2), while curve 2 is from (3). The values for the maximum droplet diameters are the same. Clearly, fairly different h(s) correspond to virtually identical distributions. There is a more marked effect from the choice of maximum size. In all our experiments, the maximum diameter was taken as the value of s at which the number of pulses constituted 0.02% of the maximum.

The reliability of the data was examined by recording the distribution by deposition; the drops were trapped in a thin layer of silicone oil on a plate of dimensions $2 \times 3 \cdot 10^{-6}$ m, the total number of drops being 1240. Curve 1 in Fig. 4 is from the Wicks–Dukler method operating with the above circuit, while curve 2 is from the deposition method. The agreement is satisfactory, particularly in the region of the mode.

NOTATION

$Re = c\delta\rho/\mu$, Reynolds number; c, drop velocity; δ, film thickness; ρ, density of liquid; μ, dynamic viscosity coefficient of a liquid; f(D), size distribution; $f_V(D)$, volume distribution; F, cross-sectional area of flow; D, drop diameter; D_m, maximum drop diameter; s, distance between electrodes; h, pulse frequency; A, α, approximation coefficients.

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SOLID PARTICLE IMPURITY PROPAGATION IN A FLUID FLOW IN A PIPE

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UDC 533.73

A longitudinal diffusion model is proposed for planar flow in which the fluid particles and the impurities have different velocities.

The process of solid particle impurity propagation in an incompressible fluid flow in a flat pipe is investigated. The turbulent and convective diffusion processes as well as the settling of the particles under the effect of gravity result in the impurity concentration varying in both the stream depth and along it. Since the question of impurity propagation along the stream is of special interest for applications, a derivation is given in this paper for a one-dimensional diffusion mixing model to determine the mean particle concentration over the stream section. The turbulent and convective diffusion mechanisms, particularly the velocity distribution in the stream, are taken into account in such a model by an effective coefficient for which an expression is found in terms of the local velocity field characteristics. The proposed one-dimensional diffusion model refers to streams in which the fluid and impurity particles have different average velocities. The velocity of convective transport in this model does not equal the mean stream velocity, which distin-

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 36, No. 5, pp. 847-853, May, 1979. Original article submitted June 1, 1978.

 0022-0841/79/3605-0562$07.50