3. B. A. Kolovandin and J. A. Vatutin, Int. J. Heat Mass Transfer, 15, 2371-2383 (1972).
4. Z. Warhaft and J. L. Lumley, J. Fluid Mech., 88, 659-684 (1978).
5. G. R. Newman, B. E. Launder, and J. L. Lumley, J. Fluid Mech., 111, 217-232 (1981).
6. B. A. Kolovandin and N. N. Luchko, Dokl. Akad. Nauk BSSR, 25, No. 7, 601-604 (1981).
7. B. A. Kolovandin and N. N. Luchko, Lett. Heat Mass Transfer, 8, 321-328 (1981).
8. B. A. Sirivat and Z. Warhaft, J. Fluid Mech., 128, 323-346 (1983).
9. B. A. Kolovandin, Modeling the Dynamics of Turbulent Heat and Mass Transfer Processes Preprint No. 18, Inst. Heat Mass Transfer, Beloruss. Acad. Sci., Minsk (1986).
10. T.-H. Shih and J. L. Lumley, J. Fluid Mech., 162, 211-222 (1986).
11. S. E. Elgobashi and B. E. Launder, Phys. Fluids, 26, No. 9, 2415-2419 (1983).

VERTICAL DISPERSION OF INTENSIVE SHEAR FLOWS OF LOW-VISCOSITY FLUIDS

V. V. Gil', R. Dzhoshi,
V. L. Kolpashchikov, S. A. Kuleshov,
O. G. Martynenko, and A. I. Shnip

UDC 532.525.2

The method of high-speed visualization is used in conjuction with Doppler-laser anemometry to conduct an experimental study of the behavior of cylindrical jet of a low-viscosity fluid. A mechanism is proposed for the vertical dispersion of the fluid and is substantiated.

A jet travelling at moderate velocities decays under the influence of capillary forces. Rayleigh [1] examined a cylindrical jet the surface of which was subjected to as small a disturbance as desired. The source of the initial disturbance, meanwhile, can be either inside the channel (roughness, turbulence in the fluid, etc.) or outside (movement of the air surrounding the jet). The main characteristics of the jet decay process in this case are the length of its continuous part and the size of the drops which are formed. According to Rayleigh, the surface of the jet is unstable against disturbances with different wavelengths, but there is a wavelength at which pulsations in a jet with a free surface lead to its decay and disintegration into drops of a size on the same order of this wavelength $\lambda_{max} = 9.027$. Following Rayleigh, most investigators have maintained that, given sufficiently high discharge velocities, drops are formed due to instability of the jet surface against wavy disturbances as a result of an increase in the intensity of these perturbations. Here, we examine wave formation on the surface of a fluid with allowance for the dynamic effect of the gaseous medium on the surface of the jet. In well-known recent investigations ([2-4, etc.]), the transition from Rayleigh decay to atomization is described by means of laws governing the interaction of a gas with the surface of a free jet and the development of surface oscillations. These theories are based on the presence of a continuous jet section immediately adjacent to the nozzle orifice even at high discharge velocities. In our opinion, the kinetic energy of the gas transmitted to the liquid in the jet is also a source of dissipation and the formation of a new surface, i.e., the interaction of the external gaseous medium with the flow of liquid from the nozzle is the deciding factor in the decay process. Other investigators are not convinced that there is a continuous section even for moderate discharge velocities [5]. It is therefore of special interest to develop a method and conduct experiments which will make it possible to reliably determine the flow pattern at the nozzle outlet. The development of laser methods of diagnosis — in particular, Doppler-laser anemometry — and methods for high-speed visualization of two-phase flows makes it possible to conduct such studies. The diagnostic apparatus should have a high resolving power with respect to space and time and allow measurement of the velocity distribution in the cross section of the jet both at the orifice of the nozzle and in other characteristic sections. The equipment should also permit determination of the character of the drop-size distribution in these sections.

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 1, pp. 20-25, January, 1988. Original article submitted October 1, 1986.

0022-0841/88/5401-0013 $12.50

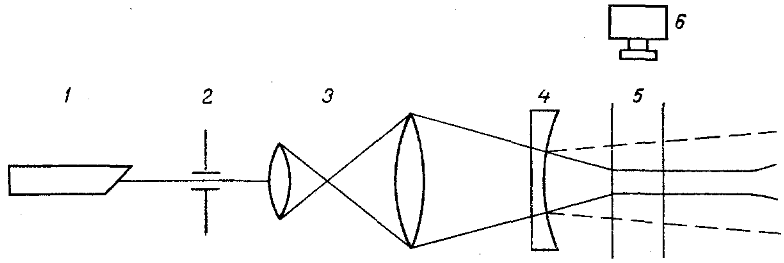

Fig. 1. Optical system of the unit used for high-speed visualization by the "light knife" method: 1) laser; 2) diaphragm; 3) telescopic system; 4) cylindrical lens; 5) test region; 6) camera.

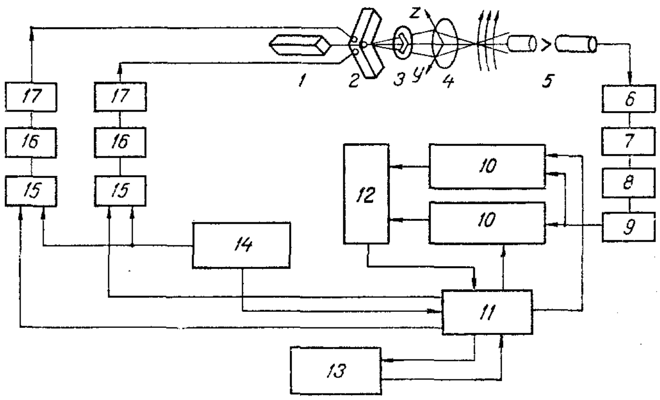

Fig. 2. Block diagram of the two-component Doppler-laser anemometer: 1) laser; 2) DUM; 3) diaphragm; 4) transmitting optics; 5) receiving optics; 6) photomultiplier; 7) filter; 8) selective amplifier; 9) clamping shaper; 10) recorders; 11) timer; 12) microcomputer; 13) store; 14) generator; 15) divider; 16) filters; 17) coincidence circuits.

We used the "light knife" method to study the structure of the flow of a drop-bearing liquid at the outlet of a nozzle and visualize the flow [6-7]. This method uses a light sensitive material to record the light scattered by the drops. In developing the experimental unit, we paid much attention to the spatial and temporal resolving power of the equipment in order to obtain a sharp image of the particles within the "light knife" region. With this in mind, as the light source we used a ruby laser with a modulated quality factor and a radiation energy of 25 J. With a pulse length of 40 nsec, we were able to reliably fix three-dimensional flows at velocities up to 100 m/sec, since the conditions for obtaining a sharp image of the drops are determined by the expression $\tau_p \ll r/v$, where r is the radius of the drop; v is its velocity; τ_p is the length of the pulse equal to the time of exposure. Figure 1 shows the optical system of the unit used for high-speed visualization.

We used a two-component Doppler-laser anemometer (DLA) which we developed to measure velocity. A dual ultrasonic modulator (DUM) with intersecting fields was used to divide the beams into two orthogonal systems and simultaneously shift the frequency. The study [8] demonstrated that such a modulator could be used in a DLA. Its operation is based on diffraction of a light wave on a three-dimensional lattice induced in the liquid by means of ultrasonic waves. We used first-order diffraction beams in the differential scheme of the DLA. A more detailed description of a DLA with a dual ultrasonic modulator was given in [6]. A block diagram of the unit is shown in Fig. 2.

The jets were formed with nozzles made of medical needles with an inside diameter of 0.3-1.75 mm and a channel length from 5 to 32 mm. The jets were discharged into a chamber, allowing us to record the ambient pressure in the range from 10^{-2} torr to 10 bar. The discharge velocity of the jet was regulated within the range 1-50 m/sec. We used water, acetone, and ethyl alcohol as the working fluids.

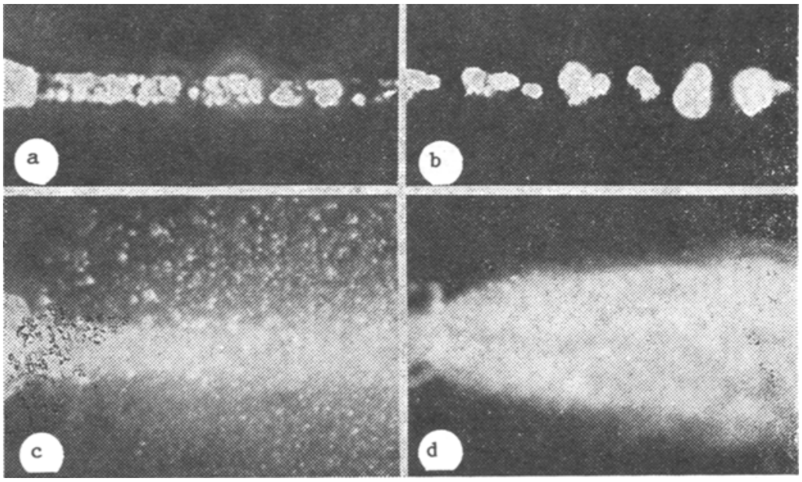

Fig. 3. Discharge of acetone from a cylindrical nozzle for different flow velocities: a) 35 m/sec; b) 40; c) 45; d) > 50.

The following was found to be true for all of the liquids. At discharge velocities below 8.5-14 m/sec (depending on the diameter of the nozzle and the physicochemical parameters of the liquid), the cylindrical jet has a continuous section. Waves with an increasing amplitude are visible on the surface of this section. These waves result is breakup of the jet into droplets corresponding to decay by the Rayleigh mechanism. This case of described fairly well by the Rayleigh theory. It should be noted that the high temporal resolution of the measurement system allowed us to establish that the continuous section of the jet is actually much shorter in this case (by a factor of 2-3) than reported in well-known experimental studies [3, 4].

Our tests showed that with an increase in discharge velocity to 15-35 m/sec (depending on the parameters of the channel and the physicochemical properties of the liquid), the jet disintegrates inside the nozzle. In this case, there is no continuous section, and the jet consists mainly of droplets equal in size to 1/2-1/3 the diameter of the nozzle (see Fig. 3a, and b). A further increase in discharge velocity leads to refinement of the liquid to drops with a size corresponding to 0.1-0.2 of the nozzle diameter and an increase in the spray-cone angle (Fig. 3c). The transition to higher velocities (more than 45 m/sec for acetone) leads to fine atomization, as shown in Fig 3d. Thus, the experimental studies we made of the mechanism of disintegration of a jet of low-viscosity fluid show that, even for moderate discharge velocities, there exist regimes in which the free jet does not contain a continuous section and disintegration begins inside the nozzle channel. Intrachennel disintegration of the liquid presumes the presence of a gas phase in the flow inside the channel. To obtain quantitative estimates of the gas phase, along with direct measurements of velocity at the nozzle edge by means of the DLA with DUM, we calculated this velocity from the volumetric expansion of the liquid. Thus, for acetone under a pressure of 8 bar, the measured velocity on the jet axis for a nozzle diameter of 0.75 mm with a length of 32 mm was v_m = 36.06 m/sec, while the mean velocity calculated from the volumetric expansion was v_a = 29 m/sec. Comparison of the measured and calculated velocities makes it possible to evaluate the volumetric concentration of the gas phase in the flow for the given case, which amounts to about 20%. This estimate is valid under the condition that the DLA measures velocity close to the mean velocity of the gas–liquid mixture formed in the channel. The flow outside the nozzle consists of individual droplets with a size about half the nozzle diameter, each droplet moving as a whole, while the diameter of the droplet chain is scarcely greater than the diameter of the nozzle (Fig. 3a). Thus, a velocity gradient can develop between the center of the jet and its periphery only as a result of droplet rotation. The magnitude of this gradient is limited by considerations of stability of the droplets against disruptive centrifugal forces and is estimated to be no greater than 1 m/sec, i.e., it can be assumed that the mean velocity of the decaying jet is sufficiently close to the velocity measured on the axis by means of the DLA.

The above estimates of the volumetric concentration of the gas phase in the flow agree satisfactorily with the results of visualization of a disperse flow in this regime and serve

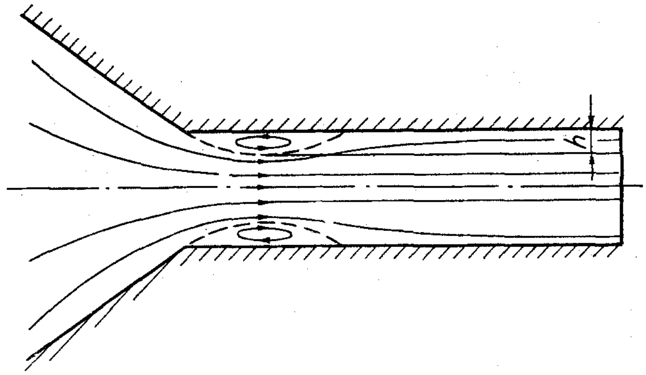

Fig. 4. Initiation of cavitation in the separation zone of a nozzle.

as additional confirmation of the existence of a disperse flow inside the channel. It should be noted that no significant deviations of the pressure gradient from the theoretical values are seen in this case. Approximate estimates of the pressure gradient for acceleration of the liquid and friction loss give

$$\Delta P = \frac{\rho v_m^2}{2} + \frac{f L v_m^2 \rho}{2d}, \quad (1)$$

where v_m is the maximum velocity in the nozzle; ρ is density; f is the drag coefficient; d and L are the diameter and length of the nozzle, respectively. The pressure gradient calculated from this formula is 7.6 bar. The deviation from the measured value (for the present case, ΔP_{exp} = 7 bar) is quite understandable if we consider the coarseness of the estimate due to the failure to allow for the fact that flow in the nozzle is unsteady (the Reynolds number in this case is $6.7 \cdot 10^4$).

The most likely mechanism of intrachannel decay of the flow is cavitation of the liquid in the separation zone at the channel inlet. In every experiment we conducted, the nozzle consisted of a cylinder joined to a conical inlet section with a generatrix having an angle of about 30°. The only exception was a glass nozzle with a main channel 0.75 mm in diameter and 32 mm long. Although this nozzle had a smoother transitional section, the minimum angle of convergence was less than 20°. It is known [9] that in flows in conical convergent nozzles with a convergence angle greater than 7°, flow separation and the formation of a stagnant vortical zone occur after the flow leaves the cone (Fig. 4). This leads to further constriction of the flow and a pressure drop in the flow. Let us evaluate this pressure drop in relation to the height of the stagnation zone h. Ignoring friction, for the axial streamline we write

$$P_m - P_0 = \frac{\rho v_f^2}{2} = \frac{\rho}{2}\left(\frac{v d^2}{(d-2h)^2}\right)^2, \quad (2)$$

where P_m is the pressure on the axis at the point of maximum constriction of the flow; v_f is the velocity at this point. For the flow regime examined above, $P_m - P_0 \sim 10$ bar, even for h = 0.1d. Since the pressure gradient created on the nozzle is 7 bar – which, with allowance for atmospheric pressure at the outlet, gives P_m = 8 bar – pressure on the nozzle axis is negative in the section corresponding to the center of the stagnation zone $P_0 = -2$ bar. Considering that the pressure at the center of the stagnation zone should be even lower, the absolute value of negative pressure in the zone will exceed 2 bar, i.e., in this section the liquid is unstable against the formation of a bubble filled with vapors of the substance – or even an empty bubble [10]. According to [11], the vortices which generate cavitation may be entrained by the flow so that gas cavities may appear a significant distance from the source of turbulence. This situation corresponds to the pattern seen in the experiment with a glass needle. The formation of a gas cavity in such a small volume leads to substantial restructuring of the flow, which is the reason for the appearance of new stagnant eddy regions and new sources of cavitation. Cavitation on uneven surfaces of the channel [11] may also play a significant role in the formation of gas bubbles. The catastrophic intensification of such processes leads to complete dispersion of the flow. This situation corresponds qualitatively to the increase in critical flow velocity (at which dispersion begins) seen in experimentally for the glass channels. These channels have a smoother transition from the conical part to the cylinder, a smaller convergence angle in the inlet section, and fewer irregularities on the inside surface of the channel. Thus, there is a reduction in the width of the stagnation zone and, in accordance with (2), a reduction in negative pressure.

LITERATURE CITED

1. D. Rayleigh, Theory of Sound [Russian translation], Vol. 2, Moscow (1944).
2. V. G. Levich, Physicochemical Hydrodynamics, Prentice-Hall (1962).
3. A. S. Lyshevskii, Fuel Atomization in Marine Engines [in Russian], Leningrad (1971).
4. Yu. F. Dityakin, L. A. Klyachko, et al., Atomization of Liquids [in Russian], Moscow (1977).
5. I. E. Ul'yanov, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 8, 23-28 (1954).
6. V. V. Gil', Optical Methods of Studying Combustion Processes [in Russian], Minsk (1984).
7. V. V. Gil', O. G. Martynenko, S. A. Kuleshov, and K. A. Lopes-Ruiz, Second All-Union Conference on the Physics of a Low-Temperature Plasma from a Laval Nozzle, Summary of Documents, Odessa (1985), pp. 48-49.
8. A. M. Kolychev, B. S. Rinkevichus, and V. L. Chudov, Radiotekh. Élektron., 20, No. 10, 2215-2219 (1975).
9. D. T. Harry and F. G. Ridron, Instability of Combustion in a Liquid-Fuel Rocket Engine [Russian translation], Moscow (1975).
10. Ya. B. Zel'dovich, Zh. Éksp. Teor. Fiz., 12, No. 11/12, 525-538 (1942).
11. K. K. Shal'nev, Zh. Tekh. Fiz., 21, No. 2, 206-220 (1951).

NUMERICAL MODELING OF THE UNSTEADY FLOW OF A VISCOUS FLUID IN ROTATING CHANNELS

V. E. Karyakin, Yu. E. Karyakin, and A. Ya. Nesterov

UDC 532.516

A finite-difference technique is proposed for calculating flows in plane channels with arbitrary curvilinear boundaries. The technique is used to study motion in a channel with a rotating section.

Curvilinear rotating channels are an important part of modern gasdynamic equipment. As the fluid moves on the curved section of such a channel, the centrifugal forces which develop create a transverse pressure gradient. This in turn results in significant restructuring of the flow, the appearance of secondary flows, and, in some cases, the appearance of a separation region. Detailed study of these features is possible only on the basis of the Navier–Stokes equations describing the dynamics of a viscous fluid.

The investigations [1-4] numerically modeled both laminar and turbulent flow in plane channels with an angle of flow rotation of 90°. Straight sections were located before and after the rotating part. Calculations were performed in a broad range of Reynolds number and channel curvature radii. It was found that two separation regions may form; on the external wall in the rotation section; on the internal wall after the rotation section.

Several methods are available for choosing the coordinate system when calculating flows in rotating channels. One approach employs a mixed system: cartesian coordinates for the straight sections and a polar system in the rotating part [2-4]. Here, certain difficulties are encountered in attempting to combine the solutions at the boundary between the straight and rotating sections. The best coordinate system [1, 5] is one in which the boundaries of the test channel coincide with the coordinate axes. This is the system we will use in the present study.

We will examine the unsteady laminar motion of a viscous incompressible fluid in a plane channel with arbitrary curvilinear boundaries. In the Cartesian coordinate system (y_1, y_2), the flow is described as follows in dimensionless form by the Navier–Stokes equations

I. I. Polzunov Central Boiler-Turbine Institute, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 1, pp. 25-32, January, 1988. Original article submitted August 26, 1986.