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ON THE MECHANISM OF ADHESION OF A JET TO THE WALL OF A JET AMPLIFIER–THE COANDA EFFECT

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The Coanda effect, consisting in the fact that a jet flowing into an expanding channel adheres to one of the walls, underlies the operation of one of the elements of fluidic technology ([1]). Many investigators have studied the nature of jet adhesion to a wall in connection with the formation of a pocket, i.e., a region of reduced pressure enclosed between the jet and the walls of the nozzle and diffuser ([2]).

Under the assumption that the pressure in the pocket is distributed uniformly and that the centerline of the jet is an arc of a circle, the formula ([3]) was derived

$$\frac{R}{a} = \frac{2}{C_p}, \tag{1}$$

where R is the radius of curvature of the jet centerline; a is the nozzle width; $C_p = (p_0 - p_b)/(p_\infty - p_0)$ is the wall pressure coefficient (p_b is the pressure in the pocket; p_∞ is the total pressure upstream of the nozzle; p_0 is the pressure in the diffuser chamber into which outflow through the nozzle takes place). Experimental verification of formula (1) was carried out in air at $\mathrm{Re} = 1650 \div 10500$, $\mathrm{Re} = va/\nu$, where v is the mean jet velocity at the nozzle exit, and ν is the kinematic viscosity. The model was asymmetric, with one adhesion wall, and the sudden expansion at the nozzle exit was $h/a = 5 \div 60$, where h is the height of the step of the nozzle wall.

The purpose of the present investigations was to verify dependence (1) for a symmetric model, with a splitter in the diffuser, with a small sudden expansion, and at higher values of the Reynolds number.

The investigations were carried out in the hydrodynamic flume of the Institute of Problems of Mechanics of the Academy of Sciences of the USSR, in water.

Fig. 1. Model of a jet amplifier

Figure 1: Fig. 1. Model of a jet amplifier

The model of the jet amplifier was located in a working chamber of cross section 12×25 mm^2. The model consisted of a nozzle 1 (Fig. 1) with exit cross section 3×12 mm^2, a diffuser 2 with expansion angle $2\alpha = 22^\circ$, and a splitter 3, located from the nozzle at distances $l = 4.7a$; $8.5a$; $12.4a$ and $l = \infty$, i.e., without a splitter. Grooves 4 and 5 behind the nozzle in the diffuser wall were intended for supplying a control flow in order to transfer the jet into one or the other channel of the diffuser, but in the present series of experiments they were used only for measuring pressure in the pockets. The flow velocity and pressure in the model were regulated independently of each other. The flow velocity at the nozzle exit was varied within the range $3.5 \div 25$ m sec^{-1}, the Reynolds numbers were $\mathrm{Re} = (1.0 \div 7.5) \cdot 10^4$, and the pressure above the free surface of the water in the hydrodynamic flume was within the range from zero to 2.5 atm. In this way, various cavitating and noncavitating flow regimes could be created in the model.

In these experiments, cavitation was used as a means of visualizing the flow in the model (^{4}). The places where bubbles arise may be taken as zones of minimum pressure, and in the initial stages of cavitation—as the location of pressure approximately equal to the pressure

water vapor. With sufficiently powerful illumination, the bubbles moving with the flow were photographed by a motion-picture camera at a filming rate of 4000 and 8000 frames/sec in transmitted (Fig. 2a, b) and reflected light (Fig. 2c).

To characterize the stages of cavitation, the cavitation number χ was calculated from the formula $\chi = (p_\infty - p_v)/q$, $q = \rho v^2/2$, where ρ is the density of water, p_v is the vapor pressure of water, and v is the mean velocity of the jet at the nozzle exit.

Visual observations showed that cavitation arises at $\chi = 1.5$ on the boundary of the concave surface of the jet and the fluid in the pocket. On the convex surface of the jet, cavitation arises at $\chi = 1.4$. At $\chi = 1.1$, cavitation of the splitter occurs. A considerable part of the flow is filled with bubbles. At $\chi = 1.0$, the separated stage of cavitation begins; the jet straightens and flows symmetrically around the splitter.

Fig. 1. Model of a jet amplifier

The motion-picture frames presented show the flow pattern at the nozzle exit (Fig. 2). It can be seen that the cavitation zones in the initial stages consist of periodically arising clusters of small bubbles moving in staggered order along the boundary of the jet. These clusters are nothing other than vortex regions filled with bubbles, since a vortex is a region of minimum pressure.

These photographs make it possible to measure the period of vortex formation

Figure 2

Figure 2: Figure 2

and to determine the Strouhal number for them. Calculations using the formula $Sh = a/\tau v$, where τ is the period of vortex formation and a is the characteristic dimension of the model—in this case the nozzle width—showed that on average $Sh = 0.1$.

Frame-by-frame viewing of the film leads to the conclusion that the moving vortices actively affect the jet. A vortex passing along the convex surface of the jet, on approaching the attachment wall, bends the jet toward this wall and thereby presses the pocket upward. After this vortex has left, the end of the jet straightens, and the pocket is drawn out in the direction of the flow. The next vortex again presses up the end of the jet, and the whole process is repeated. Oscillations of the end of the jet occur with the Strouhal frequency of vortex shedding; the amplitude of the oscillations in the direction of flow is equal to $(1 \div 1.5)a$. Such oscillatory motions of the end of the jet are apparently analogous to the action of a piston sucking liquid out of the pocket and thereby lowering the pressure in it.

Another effect of the presence of vortices on both boundary surfaces of the jet is that the jet, at a distance $(1 \div 1.5)a$ from the nozzle, undergoes contraction. Repeated measurements of the jet width a' on the motion-picture frames made it possible to determine the contraction coefficient $\varepsilon = a'/a$, which proved constant in the range $\mathrm{Re} = (3.0 \div 7.5) \cdot 10^4$ and equal to $\varepsilon = 0.85$.

The following explanation can be given for the active role of vortices in forming the jet and its attachment to the diffuser wall. There are known works ([4],[6]) that describe attempts to apply Zhukovsky' s theorem on lift force to a real vortex shed from the ends of the blades of a hydraulic turbine. This force can be determined by the formula $Y = \rho \Gamma v_s$, where $\Gamma = \pi d u$ is the circulation of velocity u at the periphery of the vortex, d is the diameter of the vortex, and v_s is the velocity on the surface of the jet. This force will be directed, for both systems of vortices moving along the convex and concave boundaries of the jet, inward into the jet. Since the velocities on the surfaces of the jet are different, a pressure difference is created which bends the jet.

The suction action of the end of the jet is a condition for the stability

Fig. 2. Enlarged photographic prints from motion-picture filming of the jet: **a** –motion of cavitation vortices along the concave surface of the jet, $\chi = 1.45$, $v = 10$ m/sec; **b** –motion of vortices along the convex surface of the jet, $\chi = 1.17$, $v = 25$ m/sec; **c** –jet, $v = 18$ m/sec, $\chi = 1.20$, and the centerline of the jet (dashed line), calculated by formula (4)

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bending and attachment of jets. In the separated stage of cavitation, when the jet is surrounded by water vapor and vortices are absent, the jet flows symmetrically.

As a result of the pressure measurement, the pressure coefficient C_p was determined in the range $\mathrm{Re} = (1 \div 7.5) \cdot 10^4$ and at different distances l of the splitter from the nozzle. The experimental data show (Fig. 3) that in the indicated range of Reynolds numbers the coefficient C_p depends only on l. In the absence of a splitter, $l = \infty$, $C_p = 0.16$. As the splitter approaches the nozzle, the coefficient C_p increases and the radius of curvature of the jet centerline decreases.

The contraction of the jet makes it necessary to introduce a correction into formula (1) (3). In determining the correction we shall also proceed from the fact that the jet axis is bent along a circle of radius R (5), and we shall neglect gravitational forces.

Selecting from the jet a certain segment of length Δ (Fig. 1) and assuming, in view of the smallness of the ratio a'/R, that $S_0 = S_b = S$ (S_0 and S_b are the surfaces of the selected volume on the side of action of the pressures p_0 and p_b, respectively), we may write

$$\frac{mv^2}{R} = (p_0 - p_b) \cdot S, \tag{2}$$

where m is the mass of the selected volume of liquid.

Suppose that the pressure on the concave surface of the jet is less than on the convex surface by some fraction of the velocity head, determined from the mean velocity of the jet. This fraction is equal to the pressure coefficient C_p. On the basis of what has been said, we may write

$$p_b = p_0 - C_p \frac{\rho v^2}{2}. \tag{3}$$

Solving equations (2, 3) and taking into account that $m = \rho S a$, we obtain

$$\frac{R}{a} = \frac{2}{C_p}\varepsilon. \tag{4}$$

It is evident that the radius of curvature of the centerline depends neither on the velocity of the jets nor on the density of the liquid.

Thus, the problem of investigating the jet trajectory, its dependence on hydromechanical and design parameters, reduces to the problem of determining the dependence of C_p on these parameters.

The relation between the geometry of the jet amplifier and the distance from the nozzle exit to the point where the jet centerline meets the attachment wall l_r can be derived using the scheme (Fig. 1) and formula (4):

$$\frac{l_r}{a} = \left(\frac{2\varepsilon}{C_p} - \frac{h}{a} - \frac{1}{2}\right)\sin\alpha + \sqrt{\left(\frac{2\varepsilon}{C_p}\right)^2 - \left(\frac{2\varepsilon}{C_p} - \frac{h}{a} - \frac{1}{2}\right)^2 \cos^2\alpha}.$$

Comparison of the jet centerline calculated by formula (4) with the experimental one shows sufficiently close agreement (Fig. 2).

Conclusions. 1. The phenomenon of attachment of a jet to a wall (the Coandă effect) is explained by the action of a periodic system of vortices shed from the nozzle edges.

Fig. 3. Above—values of C_p determined directly from pressures, and their mean values at different distances of the splitter from the nozzle l: 1—$l = 4.7a$, 2—$8.5a$, 3—$12.4a$, 4—$l = \infty$; below—the influence of the distance of the splitter from the nozzle on the magnitude of the coefficient C_p. $\mathrm{Re} = (1 \div 7.5) \cdot 10^4$

2. A formula is proposed for determining the position of the point of intersection of the jet centerline with the diffuser wall, taking into account the compression of the jet.

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