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Abstract

Full Text

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INVESTIGATION OF THE HYDRODYNAMICS AND MASS TRANSFER OF A "SHARP" GAS JET WITH A LIQUID

The greatest intensity of mass transfer between a gas jet and a liquid is observed when the gas jet is submerged in the liquid. We have called such a jet "sharp." The practical application of the method of feeding a sharp jet of oxidizing gas into a liquid has found use in metallurgy: in the oxygen-converter process of steel production and in the intensification of the operation of open-hearth and electric steel-melting furnaces by means of an oxygen jet. However, very few works are known that are devoted to the study of heat and mass transfer of such a gas jet with a liquid. This is explained both by the extraordinary complexity of the process and by its high intensity.

Fig. 1. Schematic of the interaction of a gas jet and a liquid and the variation of the depth of the cavity h, the diameter of the cavity D, the velocity of the return jet w_{obr}, and the Reynolds criterion for the return jet $\mathrm{Re}_{h\,\mathrm{obr}}$ with increasing nozzle exit velocity.

Theoretical studies of the flow of an ideal liquid show that the shape of the cavity formed in the liquid should be convex on the side of the flow (^{1}). From our investigations, with accuracy sufficient for practice, it follows that the cavity may be taken as a truncated cone joined to a spherical surface. On the basis of theoretical analysis and experimental observations on various liquids (^{2}), we can represent a two-jet scheme of interaction of a sharp gas jet with a liquid, as shown in Fig. 1. The direct jet dis—

extends from the orifice to the braking of the jet over two cavities; the reverse flow proceeds in an annular conical channel formed, on the inside, by the expanding direct jet, and, on the outside, by the surface of the liquid in the cavity. At the interface between the liquid and the reverse gas jet, owing to pulsations and curvature of the surface, a certain number of gas bubbles and droplets of liquid may be formed, preserving the direction and velocity of the reverse-jet flow; moreover, the number of gas bubbles and liquid droplets increases with increasing jet energy and, consequently, so does the contact surface of the reverse jet with the liquid. Some authors ($^{3-5}$) incorrectly represent the entire jet as a set of finely fragmented bubbles rising because of the difference in the densities of the gas and the liquid. This scheme is confirmed neither theoretically nor experimentally.

It should be noted that, under a steady blowing regime, pulsations of the depth and width of the cavity are observed, reaching ±50%, but amounting on average to ±5%.

There is no single view on calculating the depth of the cavity. Our studies on various liquids (water, glycerin, alcohol, acetic acid, and concentrated sulfuric acid) showed that, with an accuracy of ±25%, the experimental data are described by the equation of L. M. Efimov (^{6}), $h/d = \sqrt{\mathrm{Ar}}$, where $\mathrm{Ar} = w^2\rho_{\mathrm{g}}/gd\rho_{\ell}$ is the Archimedes criterion.

By measuring a large number of photographs of the cavity (at each blowing regime no fewer than 20 frames were taken), equations were obtained for determining the lower and upper diameters of the truncated cone:

$$D_1/d = 1 + 0.305(h/d)^{0.96}$$

and

$$D_2/d = 1 + 0.67(h/d)^{0.85}.$$

From these equations the angle of jet expansion was determined. For the direct jet this angle ranged from 18 to 14°, and for the reverse jet—from 20 to 5°, depending on the relative depth of the cavity. As is known, the angle of expansion of a free jet is from 18 to 26°.

The velocity of the reverse jet at unchanged gas flow rate in the cavity can be calculated, using the continuity equation for the mean cross section of the cavity, from the equation

$$w_{\mathrm{rev}} = w\,\frac{d^2}{D^2 - d^2},$$

Figure 2

Figure 2: Figure 2

where D is the diameter of the mean cross section of the cavity.

The experiments were carried out with cylindrical nozzles 2.2, 3.5, 6.2, and 10.3 mm in diameter.

Figure 1 presents the dependence of the depth of the resulting cavity, the diameter in the mean cross section, the velocity, and the Reynolds criterion for the reverse jet on the velocity of the gas jet at the outlet from a nozzle 2.2 mm in diameter. Because of the widening of the cavity as the velocity of the direct jet increases, the velocity of the reverse jet changes very little. It is interesting to note that in all cases it increases somewhat with an increase in the velocity of the direct jet up to the critical value, and, when the flow of the direct jet passes into the turbulent outflow regime, the velocity of the reverse jet begins to decrease. For the nozzle diameters studied, a laminar flow regime of the reverse jet is characteristic.

We have shown (^{2}) that, along the lower spherical surface of the cavity, mass transfer is negligibly small and occurs only through molecular diffusion of the practically braked gas jet into an almost immobile liquid, whereas on the lateral surface of the cavity turbulent transfer of large masses and intensive mixing occur in the liquid. Consequently, the cavity is a peculiar slit channel whose length varies depending on the blowing regime.

It is necessary to emphasize that, under the practical conditions of application of a sharp jet in metallurgy, the relative length of the channel is $h/d \leq 25$.

We have shown (^{7}) that, with accuracy sufficient for practice, under conditions of boundary-layer formation, flow around a plate and motion in a slit channel are hydrodynamically identical. Consequently, cal—

the mass-transfer case under consideration can be compared with the theoretically and experimentally well-developed heat exchange of a gas flow with a plate, or heat exchange in the initial section of a channel.

Fig. 2. Dependence of the diffusional Nusselt number on the Reynolds number, calculated from the velocity of gas outflow from the nozzle, for values of d:
a—2.2 mm; —3.5 mm; —4.8 mm; —6.2 mm; —7.7 mm; —9 mm; —10.3 mm; —1.1 mm

The authors carried out experimental studies of the mass-transfer process on a model with absorption of ammonia by water, when the principal resistance is the diffusion of gas in the boundary layer adjacent to the liquid. The gas flow rate in the cavity was varied only slightly; this was achieved by adding approximately 4 vol.% ammonia to the air being blown through. A weak acid solution or distilled water was used as the liquid. During blowing, samples of

Figure 3

Figure 3: Figure 3

Figure 4

Figure 4: Figure 4

gas and liquid were taken.

Fig. 3. Dependence of the diffusional Nusselt number on the Reynolds number for the reverse jet. The point designations are the same as in Fig. 2

Figure 2 presents the processing of the data obtained in the form of the dependence of the diffusional Nusselt number on the Reynolds number, in which the depth of the cavity was taken as the characteristic linear dimension, and the velocity of the gas leaving the nozzle as the characteristic velocity. It is evident from the figure that the points for different nozzle diameters fall on different curves, and the usual increase of Nu with increasing Re is not observed. The same result is obtained when the nozzle diameter is used as the characteristic dimension. These facts show the correctness of the process scheme proposed by the authors.

Figure 3 presents the same experimental data, but as a function of the Reynolds number for the reverse jet. These data are satisfactorily described by the equation $\mathrm{Nu}'_h = 4.81\,\mathrm{Re}_{h\,\mathrm{rev}}^{0.52}$, with a scatter of individual points not exceeding ±25%. The accuracy obtained should be considered satisfactory, since the scatter of the points can be explained by the strong influence on mass transfer of the geometrical dimensions of the cavity and of the accuracy with which they are determined. The exponent of the Reynolds number obtained in our equation confirms the laminar flow regime of the reverse jet; however, in comparison with the theoretical Pohlhausen equation for a plate, $\mathrm{Nu}_x = 0.664\,\mathrm{Re}_x^{0.5}$, an overestimated constant coeffi-

Fig. 4. Dependence of the transfer function, calculated from the velocity of gas outflow from the nozzle, on the Archimedes criterion. The designations of the points are the same as in Fig. 2.

coefficient. The difference in the coefficient obtained can be explained by the fact that the mass-transfer regime under consideration corresponds to the case of a hydrodynamically very destabilized flow on the wall of a curved channel. Allowance for all intensifying factors gives an increase in the constant coefficient in the Polhausen equation by a factor of 2–3. A substantial influence on the overestimation of the coefficient in the processing of the experimental data was, of course, exerted by the increase in the mass-transfer surface during pulsation of the cavity. Calculation shows that curvature of the cavity walls can increase the magnitude of the mass-transfer surface by approximately one and a half to two times. A known influence may also be exerted by small-scale pulsations and the formation of bubbles and droplets, which play the role of roughness on the cavity walls. Undoubtedly, mass transfer also takes place between the direct and reverse streams of gas.

For practical calculations it is more convenient to express the characteristic equation through the Archimedes criterion, on which the geometrical dimensions of the cavity depend. Fig. 4 presents a treatment of the experimental data in the form of the dependence of the transfer function φ on the Archimedes criterion. These data are satisfactorily described by the equation $\varphi = 0.15\,\mathrm{Ar}^{-0.71}$.

Determination of the Archimedes criterion and the transfer function is simpler in connection with the use in the calculations of directly measured parameters of the jet and the liquid.

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