NOTATION

S, pitch of screw swirler with 360° rotation; D, inside diameter of tube or outside diameter of swirler; $\bar{\alpha}$, mean heat transfer coefficient; F, area of heat-transfer surface; $\Delta\bar{t}_{\log}$, mean logarithmic temperature head; Q, heat flux; $\bar{t}_{wa}$, mean wall temperature; t_i, t_{i+1}, thermocouple readings; l_i, distance between thermocouples; K, number of thermocouples; $\overline{Nu}$, ξ, mean Nusselt number and fluid resistance coefficient of tube with swirler; $\overline{Nu}_0$, ξ_0, same, for smooth tube; Re, Reynolds number; Pr, Prandtl number; μ, effective viscosity of fluid; τ, shear stress; ρ, density of fluid; C_p, specific heat; λ, thermal conductivity of fluid.

LITERATURE CITED

1. V. K. Shchukin, Heat Transfer and Hydrodynamics of Internal Flows in Body Force Fields [in Russian], Mashinostroenie, Moscow (1970).
2. G. M. Kondrat'ev, Thermal Measurements [in Russian], Mashgiz, Moscow—Leningrad (1957).
3. Yu. G. Nazmeev and N. A. Nikolaev, "Evaluating the efficiency of flow swirlers intensifying the process of heat transfer," Inzh.-Fiz. Zh., 36, No. 4, 653-657 (1979).
4. É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Intensification of Heat Transfer in Channels [in Russian], Mashinostroenie, Moscow (1972).

NUMERICAL INVESTIGATION OF THE INTERACTION OF ISOTHERMAL, OPPOSITELY SWIRLING FLOWS IN AN ANNULAR CHANNEL

A. L. Dorfman and V. A. Maev

UDC 532.516

The influence of swirling of the flow in the recirculation zone behind the end surface separating oppositely swirling flows, in an annular channel in conditions of isothermal flow, is subjected to theoretical analysis.

A diagram of the investigated flow is shown in Fig. 1. At the inlet to an annular channel 1, formed by two coaxial cylinders 2, 3, swirling units 4, 5 are set up, separated by an annular divider 6, and creating swirling of the isothermal flow passing through them. The case where the swirling produced by the units 4 and 5 is oppositely directed is considered. The region investigated begins at cross section ad, and extends downstream a distance 4H (to cross section ef).

The system of equations of mean turbulent flow [1], considered in a cylindrical coordinated system under the assumption of axial symmetry, is closed by means of the introduction of the scalar turbulent viscosity, relating the components of the turbulent-stress tensor with the components of strain-rate tensor of the mean flow. To determine the turbulent viscosity, the mixing-path formula is used

$$\varepsilon = L^2 \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{v}{y}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + \left(y\frac{\partial}{\partial y}\left(\frac{w}{y}\right)\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2}.$$

The distribution of the mixing path is described, in turn, by the relations

$$L = 0.4(y - R) \text{ when } y \leqslant R + 0.0225x, \quad L = 0.4(R + H - y)$$
$$\text{when } y \geqslant R + H - 0.0225x,$$
$$L = 0.06\sqrt{x(y - R)} \quad \text{when } R + 0.0225x \leqslant y \leqslant H/2 + R,$$
$$L = 0.06\sqrt{x(R + H - y)} \quad \text{when } R + H/2 \leqslant R + H - 0.0225x.$$

These relations imply, in particular, the proportionality of the mixing path to the square root of the distance from the cross section bc to the axis of the wake, which is found

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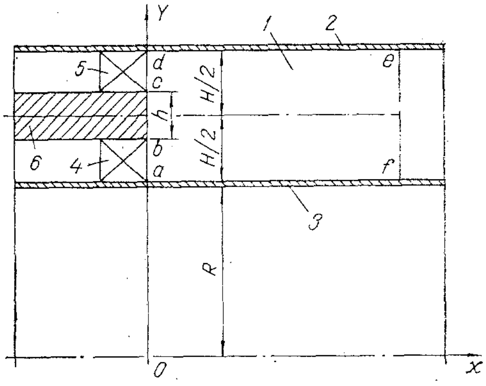

Fig. 1. Flow diagram.

in accordance with [1, 2]. In the boundary layers at the walls of the annular channel, the mixing path varies in proportion to the distance from the wall. The values of the numerical constants are determined from the condition of best matching of the calculated and experimental velocity distribution for the particular case of nonswirling flow (experimental observations were performed in the aerodynamics laboratory of the M. I. Kalinin Leningrad Polytechnic Institute under the guidance of O. N. Bushmarin on an experimental stand developed by the present authors).

The boundary conditions are formulated as follows: at the walls of the annular channel de and af, and also at the cross section bc, the conditions of adherence and nonpenetration are used; at the outlet from the swirling units, a uniform distribution of the axial and tangential velocities is specified, taking account of the boundary layers forming at the walls of the swirling units, which are assumed, on the basis of experimental data, to be of thickness 0.1 h. The velocity distribution in the boundary layers is assumed, for simplicity, to be linear. The following condition is assumed on ef

$$\frac{\partial^2 u}{\partial x^2}=\frac{\partial v}{\partial x}=\frac{\partial w}{\partial x}=0.$$

The system of equations and boundary conditions may be reduced to dimensionless form, selecting the annular-channel height H as the scale of length, the characteristic axial velocity at the outlet from the swirling unit U_0 as the scale of velocity, and the quantity ρU_0^2 as the pressure scale. The three dimensionless parameters of the problem are isolated here: the degree of initial swirling of the flow $\eta = W_0/U_0$ or the angle of initial swirling $\Omega = \tan^{-1}\eta$, where $W_0 \geqslant 0$ is the characteristic tangential velocity at the outlet from the swirling unit (note that, in the flow core at the outlet of swirling unit 4, $w = W_0$, while at the outlet from unit 5 $w = -W_0$); the degree of blocking of the channel $\Psi = h/H$; the characteristic radius of curvature of the annular channel $r = R/H$.

The solution of this problem is sought by the method of setting up using an explicit finite-difference scheme with physical separation [3, 4]. Taking the recommendations of [5] into account, a preliminary investigation of the effect of difference-scheme factors on the flow characteristics and, in particular, on the size of the recirculation zone was carried out. It was established that, when the steps of the finite-difference grid in the vicinity of the recirculation zone are less than h/20, the size of this zone no longer depends on the size of the steps. Outside the recirculation zone, the magnitude of the steps may be increased, except in the region of the boundary layers at the channel walls, where logarithmic compression of the finite-difference grid was used.

The numerical investigation was carried out in the following ranges of parameter values: $0° \leqslant \Omega \leqslant 75°$; $0.2 \leqslant \Psi \leqslant 0.5$; $1 \leqslant r \leqslant 10^3$. Curves of the axial and tangential velocity at four cross sections of the annular channel downstream from the cross section bc when $\Omega = 30°$, $\Psi = 0.37$, and $r = 1.85$ are shown in Fig. 2; the points correspond to experimental data. The agreement between the calculated and experimental velocity distributions may be regarded as satisfactory. Similar agreement is observed for most of the experimental data corresponding to other parameter ratios.

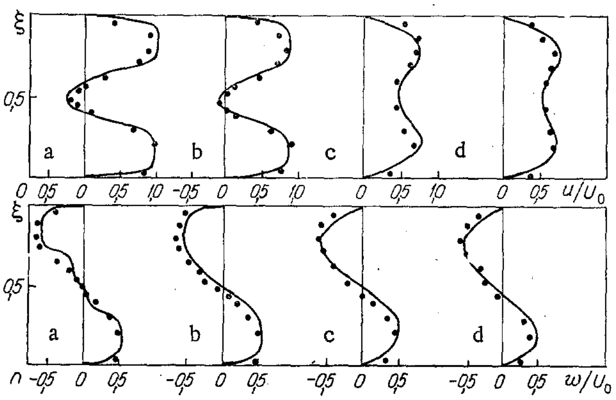

Fig. 2. Curves of the axial (upper) and tangential (lower) velocities in cross sections of the annular channel: a) x/H = 0.2; b) 0.5; c) 1.5; d) 2.0.

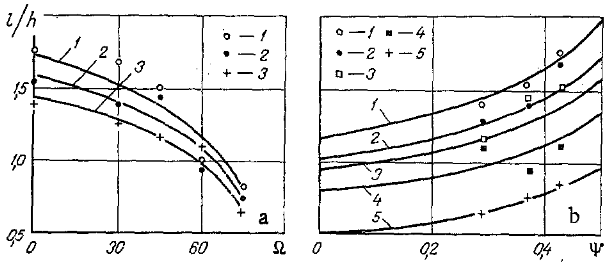

Fig. 3. The dependence of the relative recirculation-zone length on the angle of initial swirling (a) with Ψ = 0.427 (1), 0.37 (2), and 0.29 (3) and on the degree of blocking of the channel (b) with Ω = 0° (1), 30° (2), 45° (3), 60° (4), and 75° (5).

The dependence of the relative recirculation-zone length l/h on Ω, Ψ, and r is of the greatest interest. The results of calculations show that the degree (angle) of initial swirling of the flow has the greatest influence on the length of the recirculation zone. With increase in the degree of initial swirling, the length of the recirculation zone is found to monotonically decrease, which corresponds to the experimental observations. The main cause of this is evidently the increase in turbulent viscosity and, in consequence, the increase in intensity of mixing with increase in degree of initial swirling of the flow. The foregoing is illustrated in Fig. 3a, where the dependence of the relative recirculation-zone length on the angle of initial swirling is shown. Experimental data are shown for comparison.

With regard to the influence of the parameter Ψ, it may be remarked that increase in this parameter is associated with increase in the relative length of the recirculation zone, which is in agreement with experimental data (Fig. 3b).

As shown by the results of the calculations, variation of the characteristic radius of curvature r of the annular channel over the range from 1 to 10^3 has no pronounced effect on the length of the recirculation zone. The influence of r may be noted in the form of the axial-velocity profile at large differences from the inlet: at small r, the maximum on the axial-velocity profile shifts to the external wall of the annular channel, and at large r a completely symmetric velocity profile is observed.

Generalizing the results obtained, the total dependence

$$l/h = 1.19 \exp\left(0.51\,\frac{\Psi}{1-\Psi} - 0.224\eta\right)$$

may be obtained; this provides a good approximation to the calculated data, and is found to be in agreement with the experimental observations.

NOTATION

u, v, w, axial, radial, and tangential velocities; ε, scalar turbulent viscosity; L, mixing path; U_0, W_0, characteristic axial and tangential velocities at the outlet of the swirling units; η, Ω, degree and angle of initial swirling; Ψ, degree of blocking of channel; r, characteristic radius of curvature of annular channel; l, length of recirculation zone; $\xi = (y-R)/H$.

LITERATURE CITED

1. J. O. Hinze, Turbulence, McGraw-Hill, New York (1975).
2. G. N. Abramovich (ed.), Turbulent Jets of Air, Plasma, and Real Gas, Plenum Publ. (1969).
3. A. L. Dorfman, "Numerical solution of three-dimensional problem of the interaction of a system of jets in a carrier flow of viscous incompressible fluid," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 181-185 (1978).
4. A. L. Dorfman, "Explicit division scheme with application to the problem of three-dimensional interaction of jets of viscous incompressible fluid in a channel," in: Numerical Methods of Continuum Mechanics [in Russian], Vol. 9, VTs Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1978), No. 4, pp. 57-67.
5. A. G. Daikovskii and L. A. Chudov, "Effect of difference-scheme factors in calculating the wake behind a poorly streamlined body," in: Numerical Methods of Continuum Mechanics [in Russian], Vol. 6, VTs Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1975), No. 5, pp. 34-44.

MOTION AND MASS TRANSFER OF BUBBLES IN FLUIDIZED BED

V. A. Borodulya, Yu. A. Buevich, and V. I. Dikalenko

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Data on the rise velocity and mass-transfer coefficient of single gas bubbles in beds of particles of various dimensions in a state close to minimum fluidization are obtained and discussed.

Mixing processes in chemical reactors and other equipment with an inhomogeneous fluidized bed depend on the behavior of gas bubbles and their interaction with the dense phase of the bed, and to a considerable extent determine the efficiency of their operation.

Despite the considerable amount of factual material on the properties of bubbles and their effect on the distribution of the gas flows and particles obtained in recent years both in laboratories and in industrial conditions (see [1], for example), the complete picture of bubble behavior in the bed remains unclear in many important details. This is because many heterogeneous physical factors affect the behavior of the bubbles in a two-phase medium and because most experiments refer to a narrow range of variation of the determining parameters. Therefore, the present work is a systematic investigation of the dependence of the two most important bubble characteristics — the rise velocity and the mass-transfer coefficient with the dense phase of the bed — on only two parameters: the dimensions of the bubble itself and of the particles of which it is composed.

Experimental Method

The basic features of the apparatus used were described in [2]. Various fractions of quartz sand (see Table 1) were fluidized by air at the same temperature in a column of cross section 0.2 × 0.2 m; the height of the motionless filling in all experiments was 0.5 m. Tracing gas (CO_2) was introduced into a bed in a state close to minimum fluidization through a pipe of diameter 0.004 m running along the central axis of the column at a height of 0.04 m above the gas-distribution plane and through a system of reducers and an electromagnetic valve. The volume of the bubble forming was regulated by changing the duration of the voltage pulse supplied to the electromagnetic pulse from a monovibrator and the excess gas pres-

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Ural State University, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 41, No. 4, pp. 678-689, October, 1981. Original article submitted September 30, 1980.

0022-0841/81/4104-1123$07.50