# HEAT AND MASS TRANSFER IN SPIRAL GAS-LIQUID EDDIES

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An experimental study is made of heat and mass transfer in a spiral gas-liquid flow. The possibility of measuring the intensity of secondary flows by the electrocontact method is demonstrated.

Experimental studies of the structure of a gas-liquid flow and of heat transfer in the flow were conducted in a flow-through swirl element of the contact type with a central gas feed. A diagram of the contact stage is shown in Fig. 1a. The gas entered through a central tube 1, the lower end of which contained a tangentially-bladed swirler 2 immersed in the fluid. This type of swirler was chosen because of its high efficiency and the uniformity of the twisted flow compared to other swirlers [1]. The swirled gas-liquid flow formed in the interaction of the gas leaving the swirler slots and the liquid underwent a helical motion and reached the top edge of the gas-lift housing 3, where the phases were separated by centrifugal forces; the liquid flowed into the intertube space and then re-entered the reaction zone, while the gas was removed through an exhaust pipe.

When a fluid moves in a field of body forces, secondary flows may develop. The intensity of these flows is related to the velocity distribution in the original flow [2, 3]. The local velocity of the gas phase in the liquid, in the form of bubbles, was measured by a variant of the electrocontact method [4]. Here, we simultaneously measured local gas content, the surface of contact of the phases, and the size of the gas occlusions. In determining the velocity of the liquid, we considered the rate of rise of the bubbles in the centrifugal and gravitational force fields. An example of the distribution of the above-indicated parameters across the working zone is shown in Fig. 1b.

The regions in which the body forces were significant (the regions in which favorable conditions were created for the formation of secondary flows) were established by Rayleigh's approximate method [3]. The local condition of stability of the flow of a homogeneous liquid

$$\frac{d}{dr}\left[\rho\,(ur)^2\right] > 0 \tag{1}$$

takes the following form within the framework of a quasi-homogeneous approach for a gas-liquid flow

$$\frac{d}{dr}\left[(ur)^2(1-\varphi)\right] > 0, \tag{2}$$

where $\rho$ is the density of the medium at the test point. In deriving (2), we ignored the density of the gas phase and possible nonisothermality of the process.

Figure 2a shows the distribution of the gas phase in the flow obtained by the electrocontact method. The region of secondary flow, in the form of a gas-liquid eddy with the core coordinates ($r_0$, $z_0$), is readily distinguishable. Comparison with the radial distribution of the calculated complex $(ur)^2(1-\varphi)$ (Fig. 2b) shows that the boundaries of the secondary flow region coincide with the interval of its decay, which indicates that the condition of local stability of the gas-liquid flow (2) is adequate.

The effect of the secondary vortical flow on mass transfer was studied by the method of local contamination. An air-ammonia mixture was fed into the gas-liquid flow at different points by means of a miniature probe that could be translated in space. The concentration of ammonia in the gas phase at the exit of the stage was determined by the photocalorimetric method. Figure 2a shows the relative fraction of the substance removed by sections of the fluid layer at different heights along the unit. It can be seen from the distribution that

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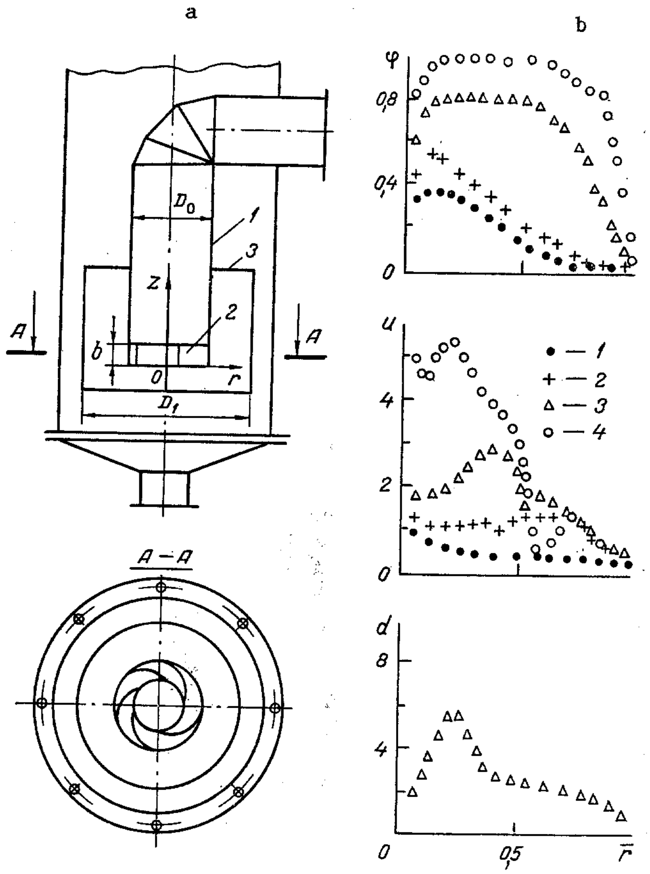


Fig. 1. Sketch of the contact stage and the structure of the gas-liquid flow: a) sketch of the contact stage ($D_0$ = 0.2 m, $D_1$ = 0.3 m, b = 40 mm, s = 0.42); b) distribution of gas content φ, across the reaction zone, tangential projection of flow velocity u, and size of bubbles d in the cross section z = 20 mm ($h_0$ = 0.065 m, 1) W = 2.8 m/sec; 2) 5.8; 3) 8.6; 4) 12.4 m/sec.

more than 50% of the entire mass of the absorbed substance is located in the secondary flow region.

The intensity of the secondary flow was measured by the electrocontact method. In accordance with the chosen flow scheme, we should expect redistribution to occur in velocity parallelograms at the boundaries of the spiral vortex. The relative intensity of the secondary flow i — defined as the ratio of circulation around the curvilinear axis of the spiral vortex to the circulation of the main flow around the vertical axis of the channel — can be expressed through the slope tangent of the velocity vector to the channel axis at the boundaries and in the core of the vortex: $i_A = (1 - k_A/k_0)/(1 + k_A/k_0)$, $i_B = (k_B - k_0)/(1 + k_0k_B)$, $i = (i_A + i_B)/2$, $i \equiv v_ir_i/ur_0$, $k \equiv u/v$, where v is the axial projection of flow velocity; $r_i$ is the radius of the vortex.

Figure 3b (points 1) shows the dependence of the intensity of the secondary flow on gas velocity. Also shown is the corresponding change in the coefficient expressing the efficiency of heat transfer $E = (I_1 - I_2)/(I_2 - I_{q.s.})$ measured by the psychrometric method in the evaporative cooling of water by air (points 2). Here, $I_1$ and $I_2$ are the initial and final enthalpies of the air; $I_{q.s.}$ is the enthalpy of the saturated air corresponding to the initial temperature of the water.

It can be concluded on the basis of the completed studies that it is possible to intensify heat and mass transfer in gas-liquid systems by realizing a regime in which spiral gas-liquid eddies are present in the flow. Equation (2) can be used as a criterion of the formation of macroscopic eddies in a gas-liquid flow when studies are conducted by the electrocontact method.

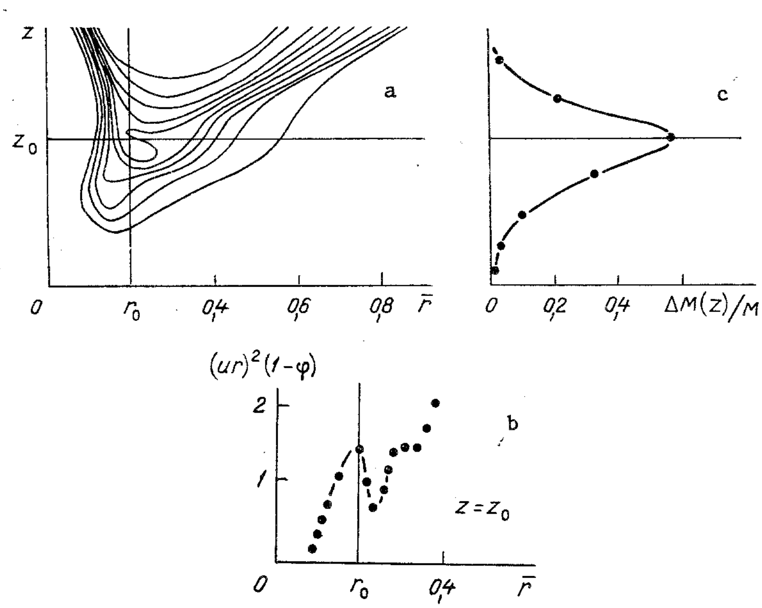


Fig. 2. Effect of secondary flow on the rate of mass transfer: a) radial section of the twisted gas-liquid flow in the reaction volume of the stage (lines of equal gas contents have been drawn); b) radial distribution of the complex $(ur)^2(1 - \varphi)$ over the height of the stage $z_0$; c) distribution of the relative efficiency of elements of the rotating gas-liquid flow located at different heights.

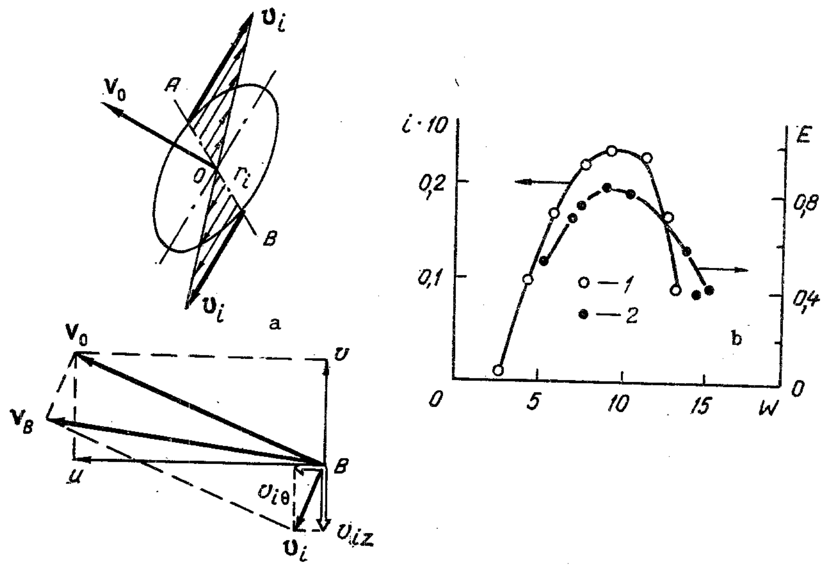


Fig. 3. Effect of the intensity of the secondary flow on the efficiency of heat transfer: a) diagram of motion of the gas-liquid mixture in the spiral vortex; b) dependence of the intensity of the secondary flow i and the heat-transfer efficiency E on the corrected velocity of the gas in the reaction zone.

## NOTATION

$D_0$, exit diameter of swirler, m; $D_1$, diameter of air-lift housing, m; b, height of swirler slots, m; s, free section of swirler, %; $\varphi$, local gas content; u, v, tangential and axial components of velocity, m/sec; d, diameter of bubbles, mm; $\Delta R = (D_1 - D_0)/2$, width of the annular reaction volume, m; M, mass of substance absorbed by the gas-liquid layer, kg;

$\Delta M(z)$, mass of substance absorbed on the section $z - z + \Delta z$ of the gas-liquid layer, kg; $k = u/v$, slope tangent of velocity vector to the vertical axis; $V_0$, velocity of flow on the axis of the secondary eddy, m/sec; $v_i$, tangential velocity on the boundary of the eddy, m/sec; W, corrected velocity of gas across the reaction zone, m/sec; $\bar{r} = (r - D_0/2)/\Delta R$, dimensionless coordinate reckoned from the wall of the gas-conducting tube.

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# THE HYDROMECHANICS OF SUSPENSIONS


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Thermodynamic forces are introduced into the momentum conservation equations for the phases of a monodisperse suspension of fine particles in order to permit effective description of the presence of diffusion processes in flows, thus circumventing the main difficulty encountered in the hydromechanics of suspensions.


The phases in flows of suspensions and other disperse systems undergo convective and diffusional redistribution, resulting in the formation of completely determined fields of concentration of the suspended particles. The concentration field, as the fields of mean pressure and mean velocity of the phases, is an unknown function. All of these unknowns should be determined simultaneously from the solution of the boundary-value problem corresponding to the given flow for the system of equations of the hydromechanics of disperse systems.

In actuality, in the overwhelming majority of specific situations the system of hydrodynamic equations traditionally used for suspensions does not have physically admissible solutions. Thus, the flows are approximately described at the cost of completely ignoring some of these equations and postulating certain a priori and usually poorly-substantiated assumptions regarding the character of the concentration distribution.

Below, we will limit ourselves to analyzing a finely-dispersed medium with identical particles. The medium is not necessarily uniform in the macroscopic sense. We write the system of conservation equations for its phases in the form [1]:

$$\begin{gathered}\varepsilon d_0 (\partial/\partial t + \mathbf{v}\nabla)\mathbf{v} = -\nabla p + \nabla(\mu\nabla\mathbf{v}) - \mathbf{f} - \varepsilon d_0 \nabla\Pi,\\ \rho d_1 (\partial/\partial t + \mathbf{w}\nabla)\mathbf{w} = \mathbf{f} - \rho d_1 \nabla\Pi,\\ \partial\varepsilon/\partial t + \nabla(\varepsilon\mathbf{v}) = 0,\ \partial\rho/\partial t + \nabla(\rho\mathbf{v}) = 0.\end{gathered} \tag{1}$$

Adding these equations in pairs, we can also obtain the momentum and mass conservation equations for the suspension as a whole.

The phase interaction force, calculated per unit volume, is usually represented in the following form for sufficiently small particles

$$\mathbf{f} = \mathbf{f}_A + \mathbf{f}_S + \mathbf{f}_B + \mathbf{f}_F + \mathbf{f}_I, \tag{2}$$

where the components in the right side describe the effective forces associated with buoyancy (Archimedes force), viscous interaction (Stokes force), the Basse force, the Faxon force, and the inertial force connected with acceleration of the apparent additional mass of the fluid


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