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Mass Transfer in Two-Phase Gas-Liquid Flow in a Tube and in Channels of Complex Configuration

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1. Introduction

Successive and versatile investigation of heat and mass transfer in two-phase flows is caused by their wide application in power engineering, cryogenics, chemical engineering, and aerospace industry, etc. Development of new technologies, upgrading of the methods for combined transport of oil and gas, and improvement of operation efficiency and reliability of conventional and new apparatuses for heat and electricity production require new quantitative information about the processes of heat and mass transfer in these systems. At the same time necessity for the theory or universal prediction methods for heat and mass transfer in the two-phase systems is obvious.

In some cases the methods based on analogy between heat and mass transfer and momentum transfer are used to describe the mechanism of heat and mass transfer. These studies were initiated by Kutateladze, Kruzhilin, Labuntsov, Styrikovich, Hewitt, Butterworth, Dukler, et al. However, there are no direct experimental evidences in literature that analogy between heat and mass transfer and momentum transfer in two-phase flows exists. The main problem in the development of this approach is the complexity of direct measurement of the wall shear stress for most flows in two-phase system. The success of the analogy for heat and momentum transfer was achieved in the prediction of heat transfer in annular gas-liquid flow, when the wall shear stress is close to the shear stress at the interface between gas core and liquid film.

Following investigation of possible application of analogy between heat and mass transfer and hydraulic resistance for calculations in two-phase flows is interesting from the points of science and practice.

The current study deals with experimental investigation of mass transfer and wall shear stress, and their interaction at the cocurrent gas-liquid flow in a vertical tube, in channel with flow turn, and in channel with abrupt expansion. Simultaneous measurements of mass transfer and friction factor on a wall of the channels under the same flow conditions allowed us to determine that connection between mass transfer and friction factor on a wall in the two-phase flow is similar to interconnection of these characteristics in a single-phase turbulent flow, and it can be expressed via the same correlations as for the single-phase flow. At that, to predict the mass transfer coefficients in the two-phase flow, it is necessary to know the real value of the wall shear stress.

2. Analogy for mass transfer and wall shear stress in two-phase flow

2.1 Introduction

The combined flow of gas and liquid intensifies significantly the heat and mass transfer processes on the walls of tubes and different channels and increases pressure drop in comparison with the separate flow of liquid and gas phases.

According to data presented in (Kutateladze, 1979; Hewitt & Hall-Taylor, 1970; Collier, 1972; Butterworth & Hewitt, 1977; et al), the methods based on semi-empirical turbulence models and Reynolds analogy are the most suitable for convective heat and mass transfer prediction in two-phase flows. Their application assumes interconnection between heat and mass transfer and hydraulic resistance in the two-phase flow.

Several publications deal with experimental check of analogy between heat and mass transfer and momentum in the two-phase flows. Mass transfer coefficients in the two-phase gas-liquid flow in a horizontal tube are compared in (Krokovny et al., 1973) with mass transfer of a single-phase turbulent flow for the same value of wall shear stress. The mass transfer coefficient in vertical two-component flow was measured by (Surgenour & Banerjee, 1980). Wall shear stress was determined by pressure drop measurements. The experimental study for Reynolds analogy and Karman hypothesis for stratified and annular wave film flows is presented in (Davis et al., 1975). Experimental studies mentioned above prove qualitatively and, sometimes, quantitatively the existence of analogy between heat and mass transfer and wall shear stress.

The main difficulties in investigation of analogy between heat and mass transfer and friction are caused by the measurement of wall shear stress. Determination of friction by measurements of total pressure drop in the two-phase flow can give significant errors at calculation of pressure gradients due to static head and acceleration. Therefore, friction measurements require methods of direct measurement, which allow simultaneous measurement of heat and mass transfer coefficients. Among these methods there is the electrodiffusion method of investigation of the local hydrodynamic characteristics of the single-phase and two-phase flows (Nakoryakov et al., 1973, 1986; Shaw & Hanratty, 1977).

The current study presents the results of simultaneous measurement of mass transfer coefficients and wall shear stress for the cocurrent gas-liquid flow in a vertical tube within a wide alteration range of operation parameters.

2.2 Experimental methods

The experimental setup for investigation of heat and mass transfer and hydrodynamics in the two-phase flows is a closed circulation circuit, Fig. 1. The main working liquid of the electrochemical method for mass transfer measurement is electrolyte solution $K_3Fe(CN)_6 + K_4Fe(CN)_6 + NaOH$; therefore, all setup elements are made of stainless steel and other corrosion-proof materials. Liquid is fed by a circulation pump through a heat exchanger into the mixing chamber, where it is mixed with the air flow. Then, two-phase mixture is fed into the test section. Experiments were carried out with single-phase liquid and with liquid-air mixture in a wide alteration range of liquid and air flow rates and pressure. The test section is a vertical tube with the total length of 1.5 m, inner diameter of 17 mm, and it consists of the stabilization section, the section for visual observation of the flow, and measurement sections. The measurement sections are changeable. They have different design and they are made for investigation of mass transfer and wall shear stress in a straight tube. There is also section for heat transfer study, and the sections for mass transfer measurement in channels of complex configuration.

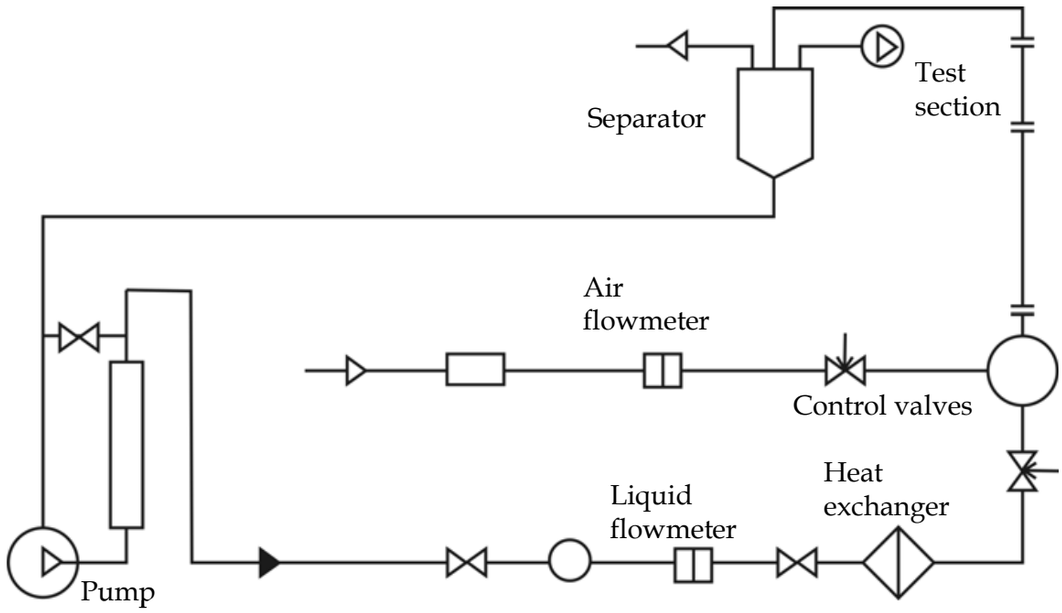


Fig. 1. Experimental setup

The method of electrodiffusion measurement of mass transfer coefficients is described in detail in (Nakoryakov et al., 1973, 1986). The advantage of this method is the fact that it can be used for the measurement of wall shear stress, mass transfer coefficient, and velocity of liquid phase only with the change in probe configuration. When this method is combined with the conduction method local void fraction in two phase flow can be measured. To determine the mass transfer coefficient is necessary to measure current in red-ox reaction $Fe(CN)_6^{3-} + e \Leftrightarrow Fe(CN)_6^{4-}$ on the surface of electrode installed on the wall, Fig. 2-1. The current in a measurement cell (cathode – solution – anode) is proportional to mass transfer coefficient (1)

$$I = kFSC_\infty \tag{1}$$

where k is mass transfer coefficient, S is area of probe surface; F is Faraday constant; and C_∞ is ion concentration of main flow.

Connection between wall shear stress and current is determined by following dependence

$$\tau = A \cdot I^3 \tag{2}$$

where τ is wall shear stress, Pa; I is probe current; A is calibration constant.

Probes for wall shear stress measurements were made of platinum wire with the diameter of 0.3 mm, welded into a glass capillary, Fig. 2-2. The working surface of the probe is the wire end, polished and inserted flash into the inner surface of the channel. The glass capillary is glued into a stainless steel tube, fixed by a spacing washer in the working section. Friction probes were calibrated on the single-phase liquid. The probe for velocity measurements, Fig. 2-3, is made of a platinum wire with the diameter of 0.1 mm, and its size together with glass insulation is 0.15 mm. The incident flow velocity is proportional to the square of probe current $v \sim I^2$.

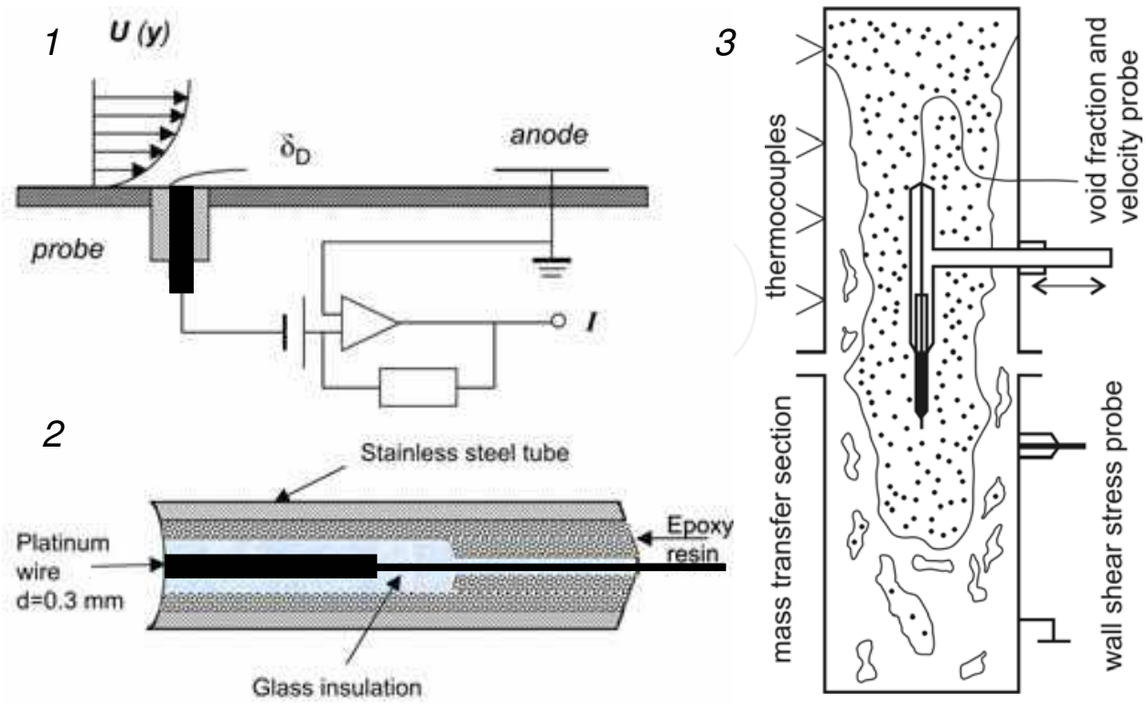


Fig. 2. The electrodiffusion method. *1* – electrochemical cell; *2* – probe for wall shear stress measurement; *3* – scheme of the test section for measurement of the mass transfer coefficient, wall shear stress and liquid velocity

To exclude the effect of entrance region and achieve the fully developed value of mass transfer coefficient, the probe for measurement mass transfer coefficient should be sufficiently long. Theoretical and experimental studies of (Shaw & Hanratty, 1977), carried out by the electrochemical method give the expression for dimensionless length of stabilization

$$L^+ \geq 1.9 \cdot 10^3 Sc^{1/4} \tag{3}$$

where $L^+ = L\upsilon_*/\nu$, $Sc = \nu/D$ is Schmidt number, and L is probe length. According to (3), the length of mass transfer probe should be not less than 70–100 mm.

2.3 Wall shear stress in two-phase flow in a vertical tube

Experiments on mass transfer and hydrodynamics of the two-phase flow were carried out in the following alteration ranges of operation parameters:

V_{L0}	Superficial liquid velocity	0.5–3 m/s
Re_L	Reynolds number of liquid	8500–54000
G_G	Mass flow rate of air	0.6–35 g/s
Re_G	Reynolds number of air	3000–140000
V_{G0}	Superficial gas velocity at p =0.1 MPa	2–100 m/s
p	Pressure	0.1–1 MPa

Table 1. Experimental conditions

Measurement error for the main parameters: for liquid flow rate it is 2%, for air flow rate it is 4%, for mass transfer coefficient it is 4%, and for wall shear stress with consideration of friction pulsations it is10%.

Experiments were carried out in the slug, annular and dispersed-annular flows. The main purpose of investigations on hydrodynamics of the two-phase flows was measurement of wall shear stress under the same flow conditions as for mass transfer investigations. Moreover, measurement of friction at the flow of gas-liquid mixtures is of a particular interest because there are no direct measurements of local friction in the range of high void fraction for the vertical channels and direct measurement of wall shear stress at high pressures. The friction probe was located at the distance of 60 calibers from the inlet of the test section. There is no effect of stabilization zone length at this distance. The currents of friction and velocity probes were registered simultaneously, Fig. 3. The velocity probe serves simultaneously for void fraction measurement. It is located in the same cross-section of the test section as the friction probe. When this probe is in liquid, its readings correspond to the value of liquid phase velocity. The moments, when the probe current drops to zero, correspond to the gas phase pass.

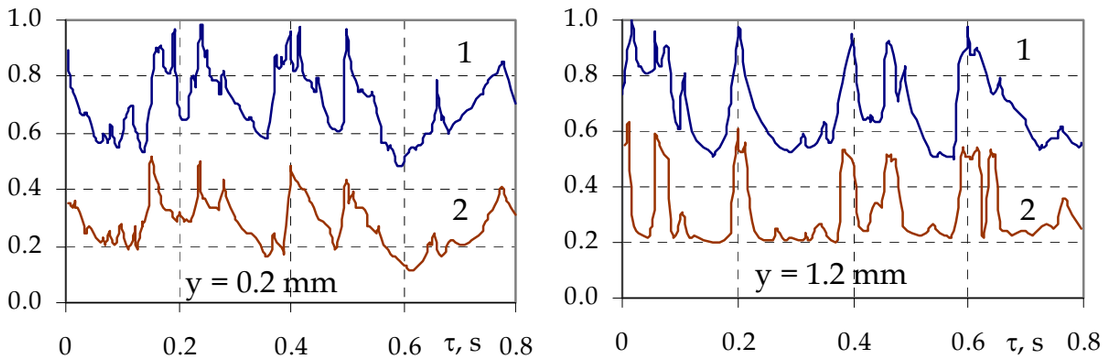


Fig. 3. Oscillograph tracings of wall shear stress (*1*) and liquid velocity in the film (*2*)

Oscillograms in Fig. 3 (left) correspond to distance from the wall y = 0.2 mm. In this position the velocity probe is in liquid during the whole measurement period; void fraction is zero. A synchronous change in the velocity of liquid in the film and wall shear stress is obvious. When the probe moves from the wall, void fraction in the flow core increases, and at the distance of 1–2 mm from the wall it becomes almost equal to one. Fig. 3 (right) corresponds to distance from the wall y = 1.2 mm. Here we can see rare moments, when the velocity probe is in liquid. These moments correspond to wave passing. At these particular moments, wall shear stress increases. Wave passing with simultaneous increase in wall shear stress causes an increase of velocity in a solid layer of the liquid film. Apparently, waves propagate over the film surface under the action of dynamic pressure of gas. The velocity of roll waves on the film surface will depend on wave amplitude and gas velocity. The motion of wave relative to the solid film layer will cause an increase in the velocity gradient in this layer. As a result, an additional shear stress appears on the wall, and it is observed in the form of friction pulsations. In the slug flow friction pulsations are caused by alternation of gas slugs and liquid plugs moving with the velocity of mixture. The level of wall shear stress pulsations depends on the flow conditions and void fraction, and it can reach the value of average friction for low flow rates of liquid. At maximal flow rates of liquid this value approaches the value typical for the single-phase turbulent flow.

Results on wall shear stress measurements under the atmospheric pressure are shown in Fig. 4. The effect of superficial velocities of liquid V_{L0} and gas V_{G0} is shown here. For constant superficial liquid velocities increase in the superficial gas velocity causes a nonlinear increase of wall shear stress, Fig. 4 (a). And for constant superficial gas velocities increase in the superficial liquid velocity results in increase of wall shear stress, Fig. 4 (b).

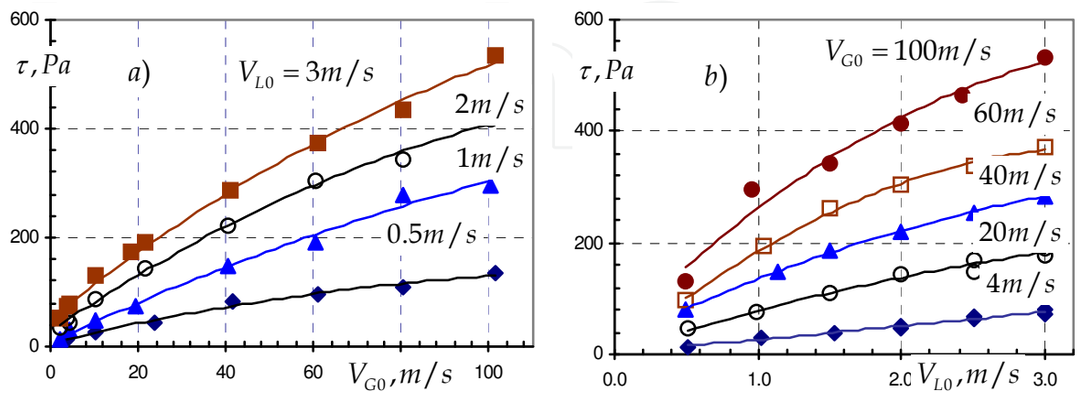


Fig. 4. The dependence of the wall shear stress on the gas superficial velocity (a), and on the liquid superficial velocity (b).

For all studied liquid flow rates at low superficial velocities of gas ($V_{G0} = 2-10$ m/s) wall shear stress depends weakly on pressure. At high velocities of air the effect of pressure on friction becomes significant. A change in pressure causes a change in following values: gas density ρ_G, mass flow rate $\rho_G V_{G0}$, and dynamic pressure $\rho_G V_{G0}^2$.

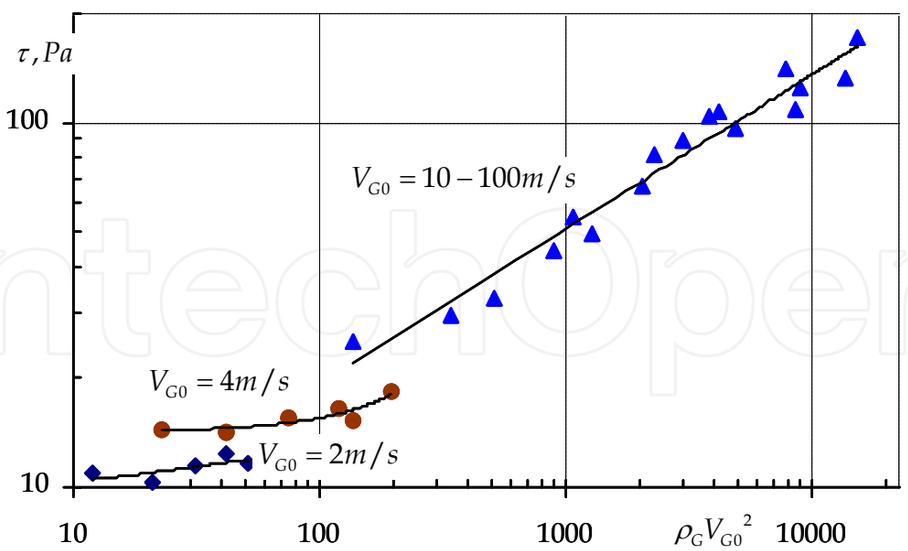


Fig. 5. The influence of the dynamic pressure on wall shear stress

According to analysis of data obtained, the effect of pressure on friction is weak in the bubble and slug flows, when liquid is continuous phase. Pressure effect is significant in the annular and dispersed-annular flows (high air velocities), when gas in flow core is

continuous phase. In the last case the liquid film is thin; therefore, wall shear stress is almost equal to friction at the film interface, determined by dynamic pressure of gas, Fig. 5.

The well-known homogeneous model is the simplest model for pressure drop prediction in the two-phase flows. According to this model, the two-phase flow is replaced by the single-phase flow with parameters $\rho_{TP}, \mu_{TP}, V_{TP}$ without slipping between the phases. To determine viscosity of the two-phase mixture there are several relationships; however, since there is some liquid on the tube wall at the two-phase flow without boiling, it is more reasonable to use the liquid phase viscosity instead of μ_{TP}. Experimental data on wall shear stress in the two-phase gas-liquid flow divided by τ_0 – wall shear stress for flow liquid with velocity V_{L0} are shown in Fig. 6 (a) depending on the ratio of superficial velocities of phases. Calculation of relative wall shear stress by the homogeneous model is also shown there. The satisfactory agreement with calculation by the homogeneous model is observed.

Correlations (Lockhart & Martinelli, 1949) are widely used for prediction of pressure drop in two-phase flows. Processing of experimental data in coordinates of Lockhart-Martinelli is shown in Fig. 6 (b) for all studied pressures and liquid and gas flow rates. There is satisfactory agreement of experimental results with Lockhart-Martinelli correlation.

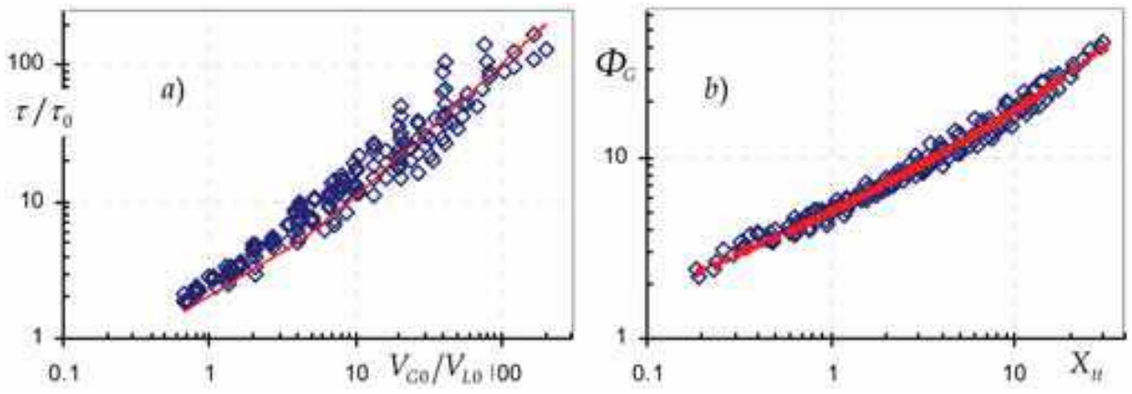


Fig. 6. Wall shear stress in gas-liquid flow: a) comparison with the homogeneous model; b) comparison with the model Lockhart – Martinelli. $X_{tt} = \sqrt{\tau_L/\tau_G}$, $\Phi_G = \sqrt{\tau/\tau_G}$.

The flow of two-phase mixture with high void fraction (the dispersed-annular flow) was experimentally studied in (Armand, 1946), and the following dependence was derived

$$\frac{\tau}{\tau_0} = \frac{1}{(1-\varphi)^n} \tag{4}$$

where τ_0 is friction in the single-phase flow; and φ is void fraction. Equation (4) was obtained with the assumption of the power law for the velocity distribution in the liquid phase. The friction factor in this case is determined by the Blasius equation with actual velocity of liquid phase. Results of our experiments show good agreement with this model.

However, there is a range of operation parameters at low velocities of liquid phase in the bubble flow regime, with an abnormal increase in friction on the tube wall, Fig. 8 (b). Wall shear stress in this area depends not only on the volumetric quality, but also on the distribution of gas bubbles in the cross section of the pipe. Mentioned above models do not predict wall shear stress in such regimes. Therefore, to check the analogy between heat and

mass transfer and wall shear stress, it is necessary to measure the coefficients of heat and mass transfer and wall shear stress under the same conditions of the two-phase flow.

2.4 Mass transfer in gas-liquid flow in a vertical tube

Mass transfer on the tube wall at forced two-phase flow was studied by the electrochemical method. In this case mass transfer is identified with ion transfer carried out by the gas-liquid flow between the test electrode (cathode) and reference electrodes (anode) in the electrochemical cell. In the diffusion limitation regime the diffusion current depends only on the rate of ion supply to the test electrode surface and therefore, it is the quantitative characteristic of mass transfer on a surface, Eq. (1). The diffusion coefficients of reacting ions in the chosen red-ox reaction correspond to Schmidt number $Sc \approx 1500$. Thickness of diffusion boundary layer δ_D, where the main change in concentration of reacting ions occurs, is significantly less than thickness of hydrodynamic boundary layer δ, i.e. $\delta_D / \delta \sim Sc^{-1/3}$. Application of the electrochemical method for mass transfer measurement has an advantage over other known methods (Kottke & Blenke, 1970) – it allows measurement of mass transfer and wall shear stress in one experiment. It is practically important for determination of interconnection between heat and mass transfer and hydrodynamics in the two-phase flows. Moreover, application of the electrochemical method for mass transfer measurement expands significantly the range of physical properties of the studied liquids towards the higher Prandtl numbers. Relatively thin near-wall liquid layer becomes the most important zone of the flow, and this allows us to study the role of the two-phase flow core in the process of heat and mass transfer.

The mass transfer coefficients in the two-phase flow were measured simultaneously with wall shear stress under the conditions shown in Table 1. The plate of the 5-mm width and 100-mm length was used as the probe. The probe length is sufficient for stabilization of the diffusion boundary layer (dimensionless length $L^+ > 4000$).

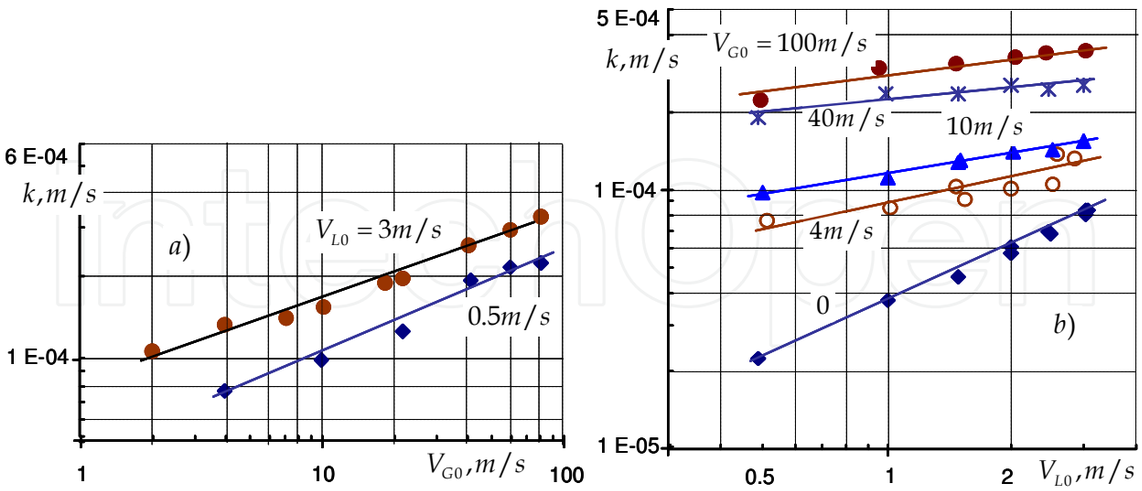


Fig. 7. The dependence of the mass transfer coefficient on the tube wall on superficial gas velocity (a), and superficial liquid velocity (b)

The effect of superficial gas velocity on mass transfer coefficient is shown in Fig. 7 (a). The mass transfer coefficient increases with a rise of superficial velocity of gas. The effect of

superficial gas velocity is almost the same for all studied liquid flow rates. The effect of superficial velocity of liquid V_{L0} on mass transfer coefficient k is shown in Fig. 7 (b). The lower line corresponds to the flow of liquid. With an addition of gas into the flow the effect of V_{L0} on k decreases in comparison with the single-phase flow. The effect of volumetric quality $\beta = V_{G0}/(V_{L0} + V_{G0})$ on the relative mass transfer coefficient for the straight tube is shown in Fig. 8 (a). It is obvious that for superficial velocities of liquid phase from 0.5 to 1 m/s the relative mass transfer coefficient depends not only on volumetric quality, but also on liquid flow rate. This ambiguous dependence of mass transfer intensity on the wall is connected with the character of void fraction distribution over the cross-section in the bubble flow. The similar effect of volumetric quality on the relative wall shear stress in the gas-liquid flows in tubes was observed in (Nakoryakov et al., 1973), Fig. 8 (b). It was explained by an increasing in bubble concentration near the wall at low superficial velocities of liquid and additional agitation of near-wall layer. Later it was shown on the basis of simultaneous measurements of wall shear stress and distribution of void fraction and velocity in an inclined flat channel (Kashinsky et al., 2003). At high velocities of liquid the level of these perturbations becomes insignificant on the background of high turbulence of the carrying flow. Under these conditions the relative mass transfer coefficients depend definitely on the value of void fraction and can be calculated by the known models. Figure 8 illustrates that it is impossible to use the known models, for instance, the homogeneous one for calculation of mass transfer coefficients and wall shear stress at low void fraction. Data on heat transfer in the two-phase bubbly flows illustrating an abnormal increase in heat transfer coefficients under similar conditions are also available (Bobkov et al., 1973).

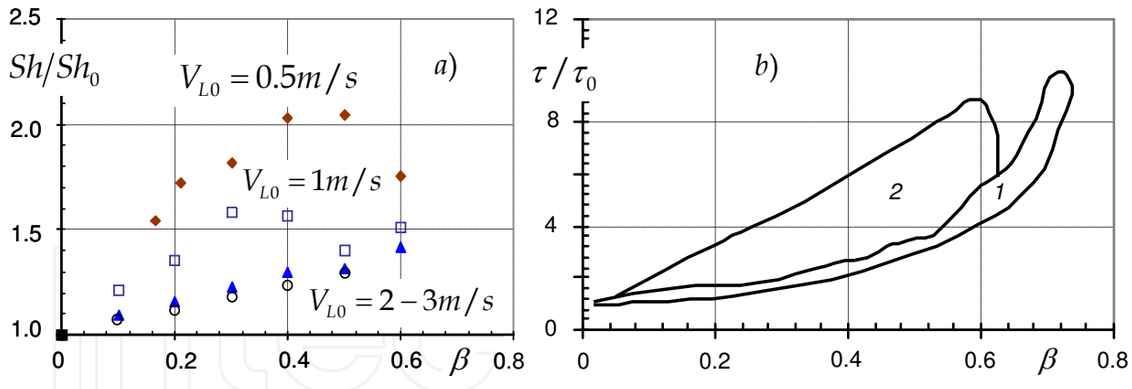


Fig. 8. Effect of volumetric quality on the relative mass transfer coefficient (a) and wall shear stress (b): *1* – homogeneous model; *2* – abnormal increasing of the wall shear stress

The relative mass transfer coefficient is shown in Fig. 9 depending on the ratio of superficial velocities of phases. It is obvious that relative wall shear stress and mass transfer coefficients depend similarly on relative velocity in the whole studied range of operation parameters. In these coordinates there are no deviations observed in the zone of low volumetric quality, Fig. 8. If we compare the relative friction and mass transfer coefficients under the same flow conditions, when inaccuracies of calculation dependences are excluded, we can see their qualitative and quantitative coincidence, Fig. 9.

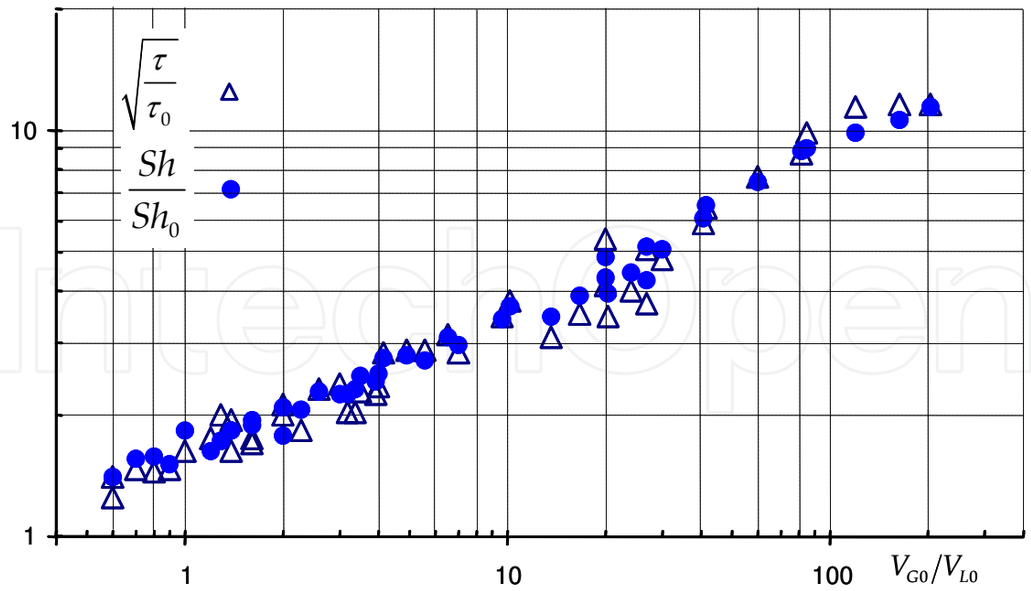


Fig. 9. Comparison of relative mass transfer coefficient and wall shear stress in two-phase flow.

It follows from data in Fig. 9 that

$$\frac{Sh}{Sh_0} = \sqrt{\frac{\tau}{\tau_0}} \tag{5}$$

i.e., connection between wall shear stress and mass transfer in the two-phase flow is the same as in the single-phase flow. Hence, the same dependences as for the single-phase flow can be applied for calculation of mass transfer in the two-phase flow. It is shown in (Chekhovich & Pecherkin, 1987) that relationship (5) is valid also for heat transfer in the two-phase gas-liquid flow.

For convective heat transfer at $\mathrm{Pr} \gg 1$ Kutateladze (1973) has obtained correlation

$$Nu = 0.115\sqrt{\zeta/8}\,\mathrm{Re}\,\mathrm{Pr}^{1/4} \tag{6}$$

Application of (6) for calculations in the two-phase flows is impossible because the specific velocity included into the Reynolds number and friction factor are not determined. However, their product $\sqrt{\zeta/8}\cdot u = v_*$ can be found experimentally from wall shear stress measurements, $v_* = \sqrt{\tau/\rho_L}$. Then $\sqrt{\zeta/8}\cdot \mathrm{Re} = v_* d/\nu' = \mathrm{Re}_*$ and correlation (6) can be applied for the two-phase flow. For mass transfer it can be written as

$$Sh = 0.115\,\mathrm{Re}_*\,Sc^{1/4} \tag{7}$$

where $Sh = \frac{kd}{D}$ is Sherwood number; $Sc = \frac{\nu}{D}$ is Schmidt number, D is diffusion coefficient, ν is kinematic viscosity of liquid phase. Experimental data on mass transfer in the gas-liquid flow at p = 0.1–1 MPa are shown in Fig. 10. The value of friction velocity is determined by

measurements of wall shear stress simultaneously with mass transfer coefficients. These data are compared with correlations on convective heat and mass transfer.

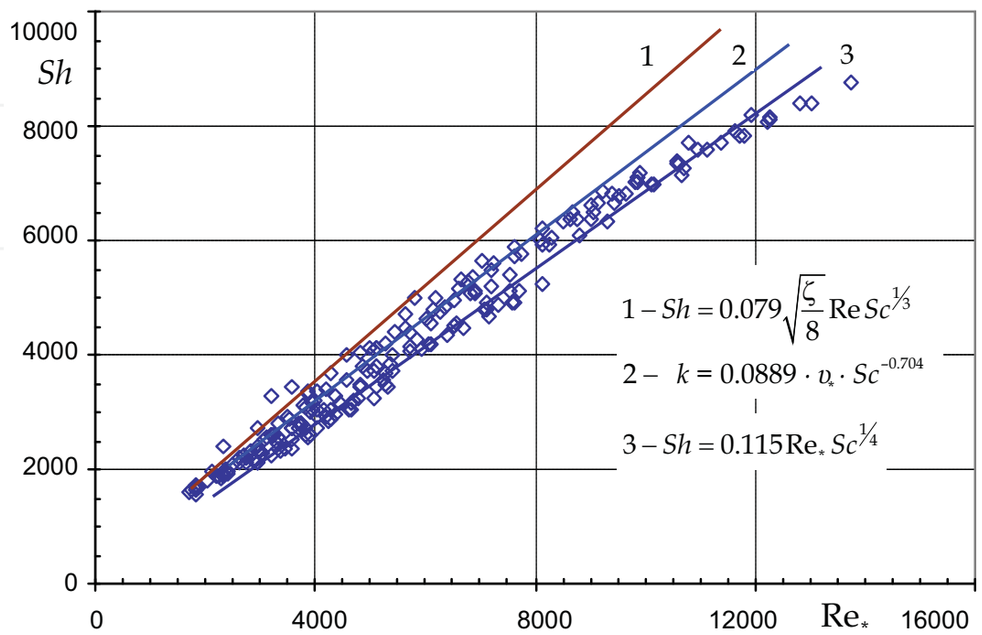


Fig. 10. Comparison of the mass transfer measurements in gas-liquid flow with calculation. 1 – Petukhov, (1967); 2 – Shaw & Hanratty, (1977); 3 –Kutateladze, (1973), Eq. (7).

In the whole range of studied parameters mass transfer coefficients in the two-phase flow coincide with calculation by correlations for the single-phase convective heat and mass transfer at $\mathrm{Pr} \gg 1$.

For liquid flows with $\mathrm{Pr} \gg 1$ heat and mass transfer occurs via turbulent pulsations penetrating into the viscous sublayer of boundary layer (Levich, 1959; Kutateladze, 1973). Thermal resistance of the turbulent flow core is insignificant. Apparently, the similar mechanism is kept in the two-phase flow. The measure of turbulent pulsations is friction velocity v_*. Since the turbulent core of the boundary layer does not resist to mass transfer, the flow character in the core is not important, either it is the two-phase or the single-phase flow with equivalent value v_*. Apparently, it is only important is that the liquid layer with thickness $\delta^+ > 5$ would be kept on the wall. The above correlations for calculation of mass transfer coefficients differ only by the exponent of Prandtl number, what is caused by the choice of a degree of turbulent pulsation attenuation in the viscous sublayer, (Kutateladze, 1973; Shaw & Hanratty, 1977). Scattering of experimental data on mass transfer in the two-phase flows is considerably higher than difference of calculations by available correlations; thus, we can not give preference to any of these correlations based on these data. It is shown in (Kutateladze, 1979) that the eddy diffusivity at $\mathrm{Pr} \gg 1$ changes proportionally to the fourth power of a distance from the wall in the viscous sublayer, therefore, dependence (6) should be considered more grounded.

According to analysis of results shown in Figs. 9–10, mass transfer mechanism in the two-phase flow with a liquid film on the tube wall is similar to mass transfer mechanism in the

single-phase flow and can be calculated by correlations for the single-phase convective mass transfer, if the wall shear stress is known.

3. Mass transfer in the channels with complex configuration

3.1 Introduction

Many components of the equipment in nuclear and heat power engineering, chemical industry are subject to erosion and corrosion wear of wetted surfaces. The channels of complex shape such as various junctions, valves, tubes with abrupt expansion or contraction, bends, coils, are affected most. The flow of liquids and gases in these channels is characterized by variations in pressure and velocity fields, by the appearance of zones of separation and attachment, where flow is non-stationary and is accompanied by generation of vortices. Analysis of the conditions in which there are certain items of equipment with two-phase flows, shows that the most typical and dangerous is the impact of drops, cavitation erosion, chemical and electrochemical corrosion (Sanchez–Caldera, 1988).

The process of corrosion wear in general consists of two stages: formation of corrosion products and their entrainment from the surface into the flow. The first stage is determined by the kinetics of the reaction or the degree of mechanical action of the flow on the surface. The supply of corrosion-active impurities to the surface and entrainment of corrosion products into the flow are determined by mass transfer process between the flow and the surface (Sydberger & Lotz, 1982). Due to significant non-uniformity in distribution of the local mass transfer coefficients the areas with increased deterioration appear on internal surfaces. Intensification of mass transfer processes caused by the above reasons can lead to a considerable corrosive wear of equipment parts. Changes in the temperature regimes due to heat transfer intensification result in the appearance of temperature stresses, which affect the reliability of equipment operation and the safety of power units (Poulson, 1991; Baughn et al., 1987). Therefore for safe operation of power plants it is very important to know the location of areas with maximal mass transfer coefficients in the channels with complex configuration and the mass transfer enhancement in comparison with the straight pipelines. The single-phase flow in the bend of various configurations with turn angles 90° and 180° was studied in (Baughn et al., 1987; Sparrow & Chrysler, 1986; Metzger & Larsen, 1986). For this purpose the authors used thin film coating with low melting temperature on internal surface of channels, temperature field measurements, Reynolds analogy for calculations of mass transfer coefficients based on heat transfer measurements, etc. In spite of the fact that two-phase coolants are widely used in cooling systems of various equipment, experimental studies on two-phase flow separation and flow attachment in channels are limited, (Poulson, 1991; Mironov et al., 1988; Lautenschlager & Mayinger, 1989). Intensity of these processes is determined by flow hydrodynamics within thin near-wall layers. Therefore the experimental study of these phenomena should be carried out using the methods which do not distort the flow pattern in the near-wall area in complex channels. The electrochemical method makes it possible to measure local values of wall shear stress and mass transfer rate for single-phase and two-phase flows in the channels with complex configuration.

In this section the results on experimental investigation on distribution of local mass transfer coefficients in single-phase and two-phase cocurrent gas-liquid flow in vertical channels with 90° turn and abrupt expansion are presented. The scheme of the experimental setup is shown on Fig. 1. The scheme of the test sections are presented in Fig. 11.

In a channel with turn flow the liquid or two-phase medium is fed from bottom and changes the flow direction at 90°. To provide fully developed flow straight tube of 20 mm diameter and 2 m long is installed before bend. The channel with the bend is made of two plexiglas sections, sealed with each other by rubber gaskets and pulled together by bolts, Fig. 11. The inner diameter of channel is 20 mm and the relative bending radius is $\tilde{R} = 5$. Fifteen electrochemical probes were installed on the test section: 5 – on inner generatrix, 5 – on middle generatrix, and 5 – on outer generatrix. The probes were installed in the cross-sections with turn angles $\varphi = 10, 28, 45, 63, 80^{\circ}$. One more probe was installed on a straight section of the tube in front of the inlet to the channel. This probe measures the local mass transfer coefficient in a straight tube. The electrochemical probes for measurements of local mass transfer coefficient were made of platinum wire of 0.3 mm in diameter welded into the glass capillary, Fig. 2-2. After probe mounting in test section their working surface was flushed to the internal surface of the channel. The assembled channel was fixed to the flanges of feed and lateral pipelines.

The channel with sudden expansion was made of plexiglass and enabled to visualize the flow, as well as to make photo – and video of the process.

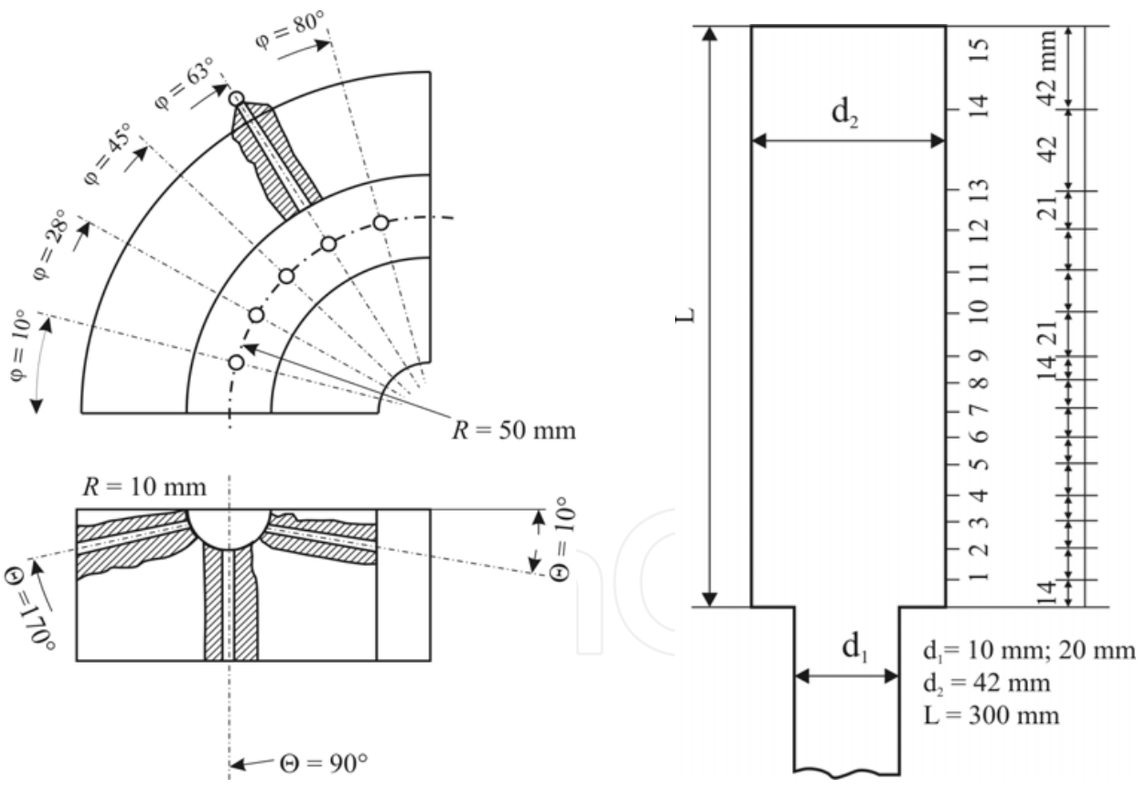


Fig. 11. Scheme of the test sections with turn angle 90° and with abrupt expansion

The inner diameter of the channel was $d_2 = 42$ mm, and the length was $L = 300$ mm. The channel was connected with the stabilization section in such a way that the assembly formed sudden expansion. The stabilization sections were made of two diameters: d_1 = 10 and 20 mm, correspondingly, and ratio $E = d_1/d_2$ was 1:2 and 1:4 (the exact values of E were equal to 0.476 and 0.238), and relative channel length was $L/d_2 = 7.1$.

3.2 Mass transfer in a channel with turn flow

In the experiments on measurements of local mass transfer coefficients on the wall of the channel with the turn flow the volumetric quality β was changed within the range from 0 to 0.6, and liquid superficial velocities from 0.5 to 2.6 m/s. At these parameters the main flow pattern of two-phase mixture is the bubble flow. In certain flow regimes at small liquid flow rates and maximal gas flow rates the slug fluctuating flow was observed. In order to mark out the effect of the flow turn angle the data obtained are presented in the form of ratio of the local mass transfer coefficients in the bend to the local mass transfer coefficient in the straight tube at the same values of the volumetric quality. Figure 12 shows variation of local mass transfer coefficient depending on the turn angle for two values of liquid superficial velocity: 0.5 m/s and 2.6 m/s (Pecherkin & Chekhovich, 2008). Data for the single-phase flow are shown in the same figure. In case of single-phase flow the first probe on inner generatrix ($\varphi = 10°$) indicates approximately the same value as in the straight tube independently of the flow rate. Further, as far as the turn angle increases the mass transfer coefficient diminishes and then slightly increases at the channel outlet. Probably, a significant decrease in mass transfer coefficients is associated with the flow separation in this area. The addition of gas into the liquid flow essentially changes distribution of the local mass transfer coefficient. In the first half of the channel at the turn angles from 10° to 45° the increase in mass transfer coefficients is observed as compared with that in straight tube. The increase in mass transfer coefficients comparing with the straight tube reaches up to 40% at low liquid flow rates, and approximately 20% at high flow rates. At the channel outlet at a horizontal part of the bend the mass transfer coefficients decrease comparing with the straight tube.

On the middle generating line, as a single-phase liquid flows, the intensification reaches 60% at the bend outlet. The mass transfer character in gas-liquid flow is the same as in the single-phase flow. As compared with the straight tube intensification makes up 10-20% at low liquid flow rates and 40-50% at high liquid flow rates depending on volumetric quality.

On the external generating line, for small velocities of single-phase liquid flows at the channel inlet, the mass transfer coefficient remains the same as in a straight tube. At the outlet of the bend mass transfer enhancement reaches 30%. An increase of volumetric quality causes rapid decrease in mass transfer coefficient at the inlet to the channel, and it reaches the minimal value at $\varphi = 10\text{-}30°$, and then smoothly increases downstream to the channel outlet. At high liquid superficial velocities maximal mass transfer coefficients are observed at the turn angles of 50-70° and increase with volumetric quality.

The highest mass transfer enhancement in the single-phase flow is observed at the channel outlet on the middle generatrix. The maximal mass transfer coefficient for these areas can be expressed by the following relation

$$Sh = 0.0287\,\mathrm{Re}^{7/8}\,Sc^{1/4} \tag{8}$$

Comparison of (8) with correlation for wall mass transfer coefficients in the coil (Abdel-Aziz et al., 2010) shows satisfactory agreement. Clearly expressed local maximum in a two-phase flow is situated on the inner generatrix within the zone of $\varphi = 10\text{–}45°$, and the absolute maximum is observed at the channel outlet on the middle and outer generatrices.

Figure 13 shows the effect of volumetric quality on distribution of local mass transfer coefficients in the bend. The data are presented in the form of ratio of mass transfer coefficients for gas-liquid flow to the mass transfer coefficients for single-phase flow at the same turn angles.

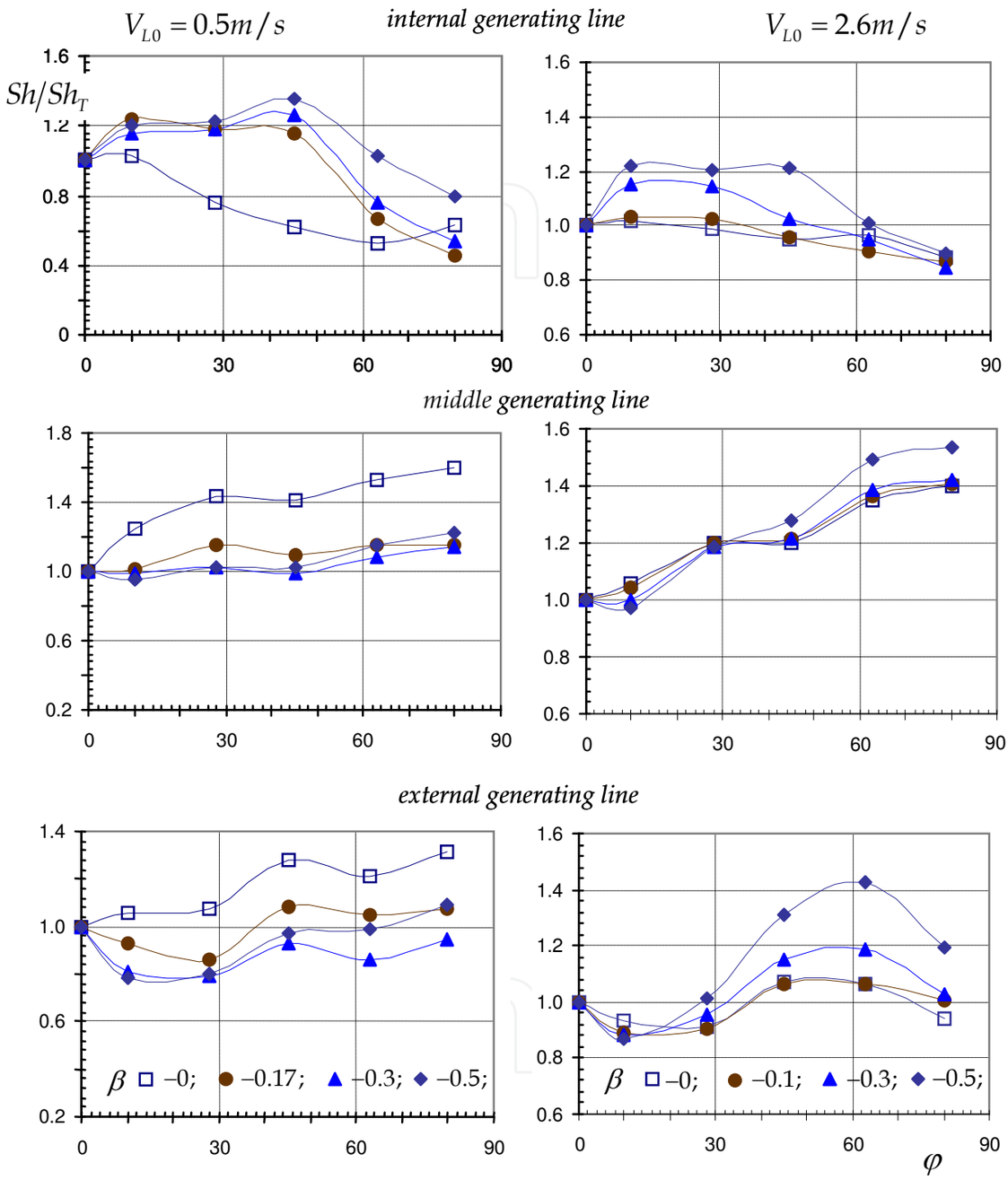


Fig. 12. The influence of the turning angle on the relative mass transfer coefficient in a bend.

At low liquid flow rate, $V_{L0} = 0.5$ m/s, on the inner generatrix at $\varphi = 45°$ mass transfer intensification is 5-fold higher as compared to that for the single-phase flow, Fig. 13 (a).
At higher liquid superficial velocity $V_{L0} = 2.6$ m/s, intensification reaches 60-80% at high volumetric quality, Fig. 13 (b).

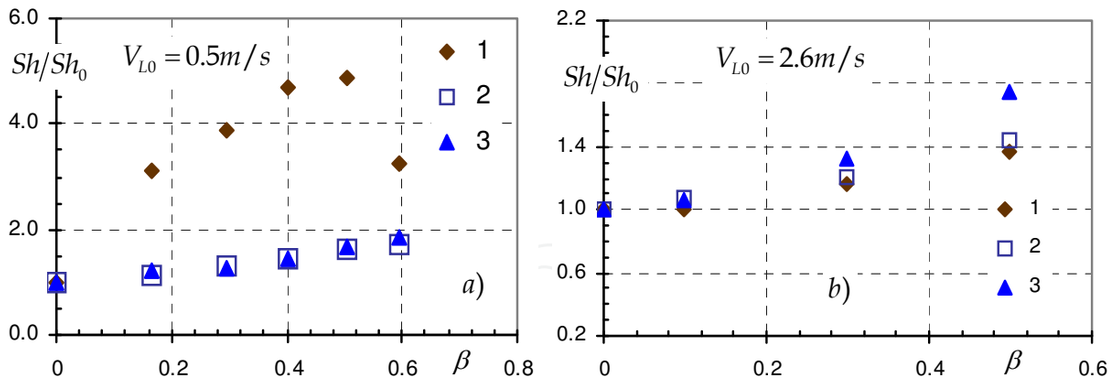


Fig. 13. The influence of the volumetric quality on the relative mass transfer coefficient in a bend. a – (1) Internal generating line, $\varphi = 45^{\circ}$; (2) middle generating line, $\varphi = 80^{\circ}$; (3) external generating line, $\varphi = 80^{\circ}$; b – (1) Internal generating line, $\varphi = 45^{\circ}$; (2) middle generating line, $\varphi = 63^{\circ}$; (3) external generating line, $\varphi = 63^{\circ}$.

The character of relationship between the local mass transfer coefficients and the volumetric quality is the same as in the straight tube, Fig. 8. Very likely, that due to the curvature effect and formation of vortex flow on inner generatrix of the tube surface, concentration of gas bubbles increases and their motion determines mass transfer intensity on the wall in this area. On the middle and outer generatrices the relative mass transfer coefficient depends only on the void fraction and it is practically irrespective of liquid flow rate and turn angle. On middle and outer generatrices the effect of void fraction consists mainly in increase of actual velocity of liquid near the wall due to flow swirl.

3.3 Mass transfer in a channel with abrupt expansion

3.3.1 Gas-liquid flows in a channel with abrupt expansion

The flow in the channel behind a backward facing step is characterized by the fact that at some distance from the step the heat and mass transfer coefficients may exceed by an order those in the straight smooth tube. The increase in heat or mass transfer coefficients is observed in the area of shear layer attachment to the tube wall. This area is usually situated at a distance of 5 to 15 step heights (Baughn et al., 1984; 1989). Then the heat and mass transfer coefficients gradually decrease and approach the value typical for fully developed flow in a tube. The qualitative behavior of the heat and mass transfer coefficients in single-phase and two-phase flows (Chouikhi et al. 1987) is similar. The measurements of local void fraction distribution and velocity components across the channel near the expansion cross-section have shown that there is a correlation between these values (Bel Fdhila et al., 1990).

In present work visual observations of the flow patterns were carried out as well as measurements of local mass transfer coefficients in channels with abrupt expansion. Volumetric quality β was varied within the range from 0 to 0.6, liquid superficial velocity V_{L2} was changed from 0.11 to 0.66 m/s. Figure 14 presents the photos of two-phase flow in a channel with abrupt expansion. The lower pictures show the flow near the outlet from the tube of the smaller diameter. Upper pictures show the flow in the upper part of the channel of the larger diameter. At low void fraction mainly bubble flow regime was observed, Fig. 14, left photo.

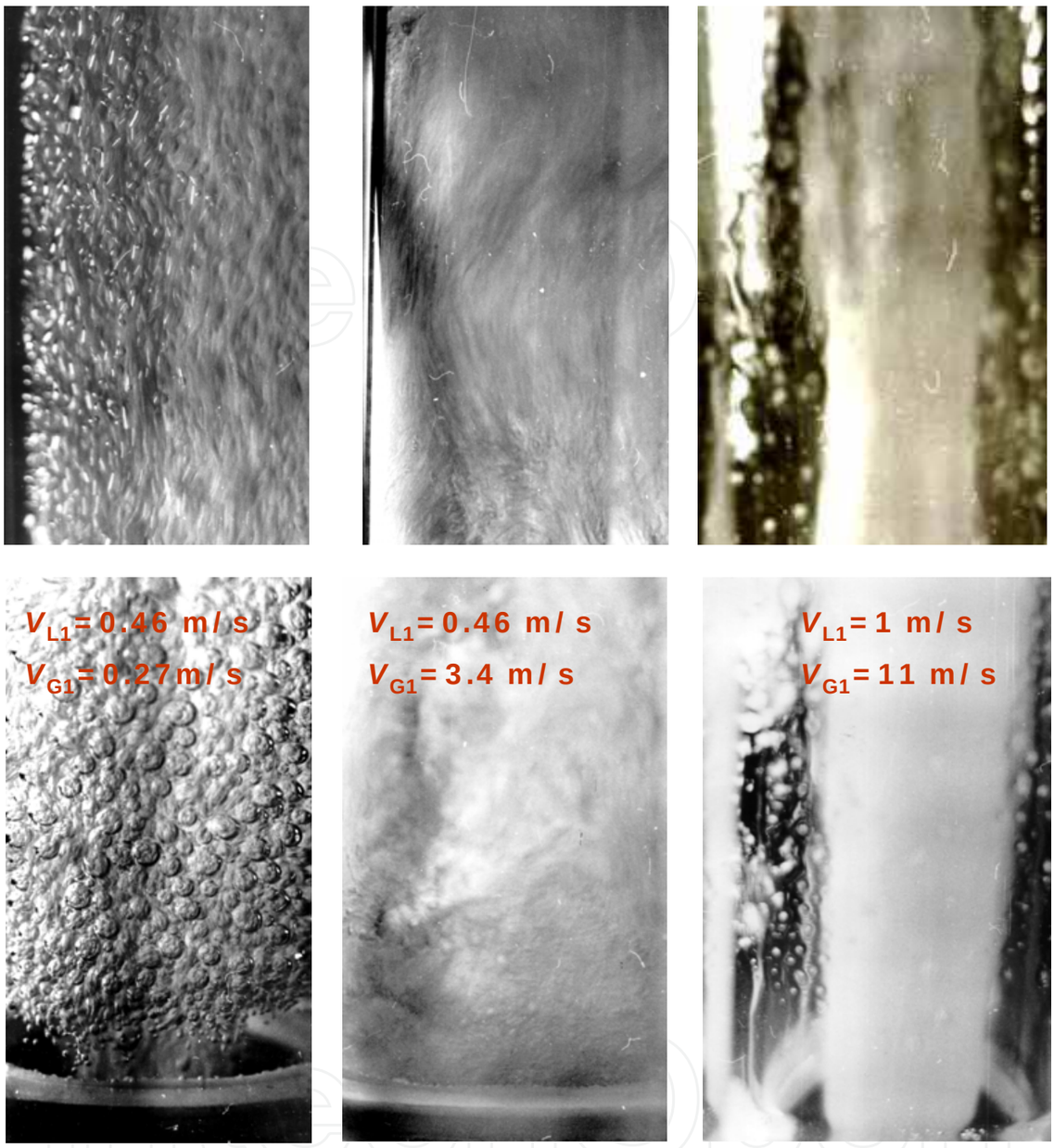


Fig. 14. View of two-phase gas-liquid flow in channel with abrupt expansion.

At an increase in expansion ratio ($E = 1:4$) the bubble flow exists at higher liquid velocities and lower gas flow rates. At an increase of void fraction we observed the churn flow, Fig. 14, in center. The flow pattern changes along the height of a channel. The zone near the expansion cross-section is free of gas bubbles, and this zone is significantly greater for expansion ratio $E = 1:4$. Here rotating flow of liquid is observed. Direction of rotation is changed periodically. In the zone of 1 to 3-4 tube diameters near the wall we observed the vortex flow and downflow, while stabilization of the upward flow takes place just at the channel outlet. The size of bubbles depends on expansion ratio. The smaller is the diameter of the tube where the outflow occurs, the smaller is the bubbles diameter. At an increase of

void fraction in the channel we observed the foamed flow with large-scale bubbles, while at very high outflow velocities the flow detaches from the channel walls, Fig. 14, right photo. After separation of the flow from the pipe wall the two-phase jet in the center of the channel was observed. Near the outlet from the test section the jet diameter increases, and the certain portion of liquid drops out to the channel walls and flows down as a film or rivulets. The location of flow attachment may move along the channel height depending on the velocity of jet. A decrease in flow rate of one of the components at constant flow rate of another component leads to step-like reverse transition: now the two-phase flow fills up the whole cross-section of the channel along its height.

Figure 15 (a) presents gas flow rates corresponding to transition to the jet flow depending on liquid mass flow rate. The less is liquid flow rate the larger gas flow rate is required to provide the transition to the jet flow. The kind of transition shows the change in the balance of inertial and mass forces in the flow.

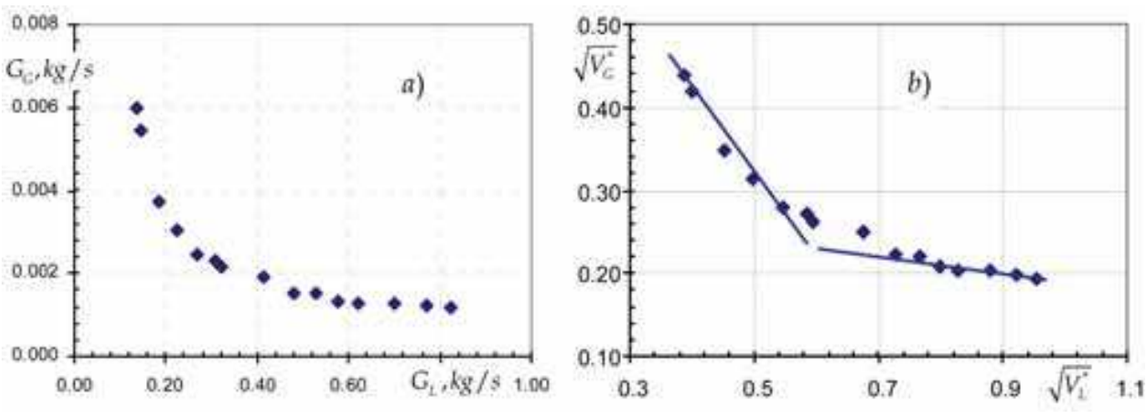


Fig. 15. The correlation between mass flow rate of liquid and gas phases at the boundary of the jet flow transition

The similar phenomenon is observed at counter-current two-phase flow in a vertical tube. Increasing gas flow rate over the critical value causes flooding. Though the flooding mechanisms and mechanisms of transition to jet pattern most likely are different, nevertheless the transition criteria in both cases may be the same. Froude numbers or their combinations may serve as dimensionless criteria to characterize interaction between the gravity forces and inertial forces. Wallis, (1969) proposed the empirical correlation for description of flooding process

$$V_G^{*1/2} + aV_L^{*1/2} = c \tag{9}$$

where $V_G^* = V_G\sqrt{\dfrac{\rho_G}{gD(\rho_L - \rho_G)}}$; $V_L^* = V_L\sqrt{\dfrac{\rho_L}{gD(\rho_L - \rho_G)}}$, V_L, V_G are superficial liquid and gas velocities; ρ_L, ρ_G are densities of liquid and gas. We obtained a = 1.02, c = 0.84 for $V_L^* < 0.4$ and a = 0.092, c = 0.29 for $V_L^* > 0.4$, Fig. 15 (b). More detailed investigations are needed to study the regime of two-phase jet flow in a channel with abrupt expansion.

3.3.2 Mass transfer on the wall of a channel with abrupt expansion

The results on measurements of mass transfer coefficients on the wall of channel with abrupt expansion in gas-liquid flow are presented in this section. Fifteen probes were installed to measure the local mass transfer coefficients at the internal surface. Along the initial section of the channel with expansion the probes were installed with the interval of 14 mm, and at the outlet of the channel, where the flow becomes stable, the interval was increased up to 42 mm, Fig. 11. The design and the size of electrochemical probes for measurements of the local mass transfer coefficients were similar to those used for measurements of wall shear stress, Fig. 2 - 2.

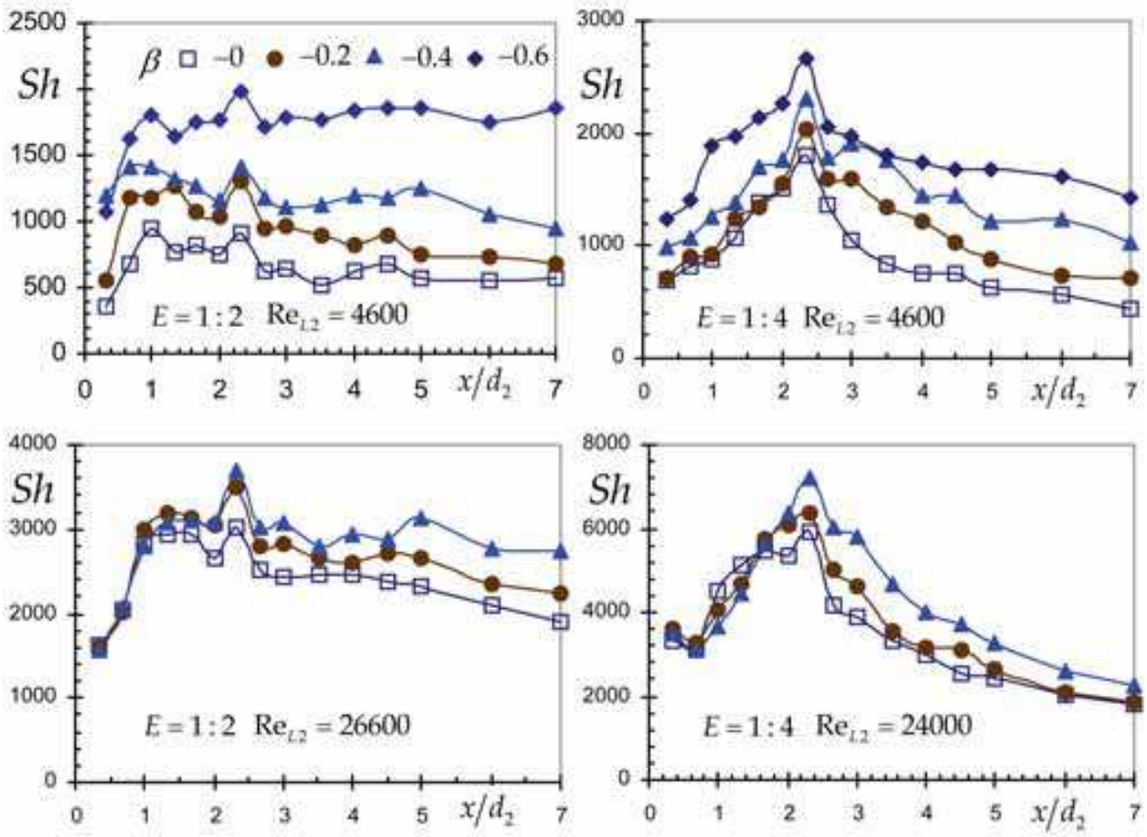


Fig. 16. Distribution of local mass transfer coefficient along the channel with abrupt expansion

Figure 16 represents the dimensionless mass transfer coefficient *Sh* depending on dimensionless length of the channel for various volumetric quality and diameter enlargement (Pecherkin et al., 1998). Distribution of the local mass transfer depends both on liquid velocity and volumetric quality β . Mass transfer coefficient depends on the length in a way similar to that for the single-phase flow, though there may appear local maximums in mass transfer depending on volumetric quality. The effect of volumetric quality becomes apparent in different ways for various liquid flow rates. At low liquid flow rates there are two local maximums at the distances of 1 and 2 channel diameters. In the second half of the channel the mass transfer coefficient practically does not change along the length at $E = 1:2$.

With the increase in liquid flow rate the local maximum is shifted to $x/d_2 = 2.3$. At a distance of up to $x/d_2 = 1$ the effect of volumetric quality diminishes and almost disappears at high liquid flow rates. The mass transfer coefficients at $\beta = 0.1 - 0.4$ practically do not differ from those for single phase flow. The visual observations show that under these conditions in the corners of the channel near the expansion cross-section there are almost no gas bubbles. At high liquid flow rates the local maximum appears at a distance $x/d_2 = 5$, probably due to generation of vortices of another scale. The visual observations show that the flow in this area is of the chaotic nature with no clear stream direction. For the channel with expansion ratio $E = 1:4$ distribution of mass-transfer coefficient has a clearly defined peak. Near the tube inlet the mass transfer coefficient does not differ practically from that for the single-phase flow, while at high liquid flow rates in this zone the local minimum appears as well. The mass transfer coefficient at the maximal point is significantly higher as compared with the channel $E = 1:2$. After reaching the maximum the mass transfer coefficients decrease abruptly, and at the channel outlet they approach the same values as for the channel with expansion ratio $E = 1:2$. Therefore within these distances the flow is almost fully developed and flow regime should depend only on void fraction. The effect of volumetric quality on a relative mass transfer coefficient is shown in Fig. 17.

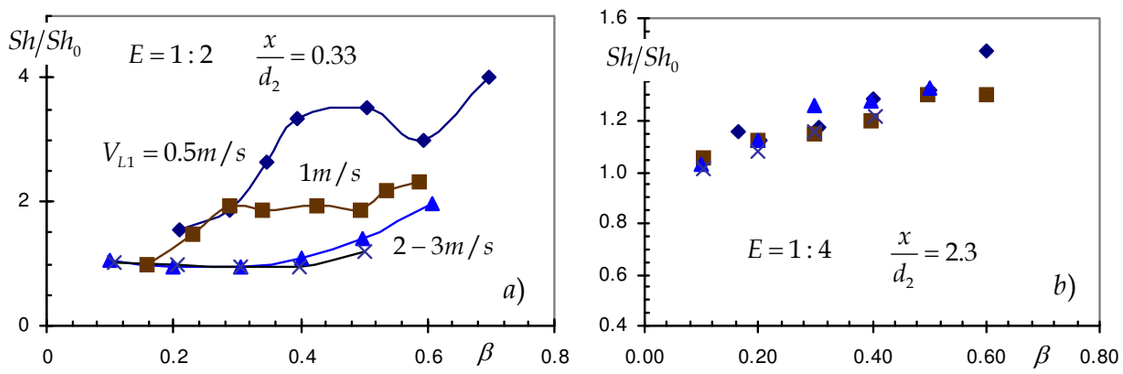


Fig. 17. Effect of volumetric quality on the relative mass transfer coefficient

At a distance of one diameter from the entrance for $E = 1:2$ and high flow rates of fluid there is no influence of volumetric quality. At low liquid flow rates the abnormal increase in mass transfer coefficients was observed. This was concerned with bubbles distribution over the cross-section and vortex flow near the channel inlet. In the vicinity of maximum mass transfer at $x/d_2 = 2.3$ the effect of liquid flow rate on relative mass transfer coefficient is lacking, here mass transfer increases in proportion to the two-phase mixture velocity like in the flow inside the tube.

Experimental results presented in Fig.13 and Fig.17 show, that the relative mass transfer coefficient is effected both by volumetric quality and, to a considerable degree, velocity of the liquid. Similarly to the gas-liquid mixture flow inside the tubes such dependence is explained exceptionally by distribution of void fraction over the tube cross-section. In case of the flow in the channel with abrupt expansion bubble distribution over the cross-section will be significantly effected by vortex zones. The size of these zones and flow intensity inside them depend on liquid velocity.

In the recirculation zone near the expansion cross-section at high liquid flow rates the effect of volumetric quality is not observed at all because this zone is almost free of bubbles. This zone is out of the interest in terms of mass transfer process enhancement. The most important in this respect is the zone between 2-4 calibers. In this area mass transfer maximum is observed within a sufficiently broad range of volumetric quality and flow patterns as well as for various expansion ratios. The maximum in heat and mass transfer in a single-phase flow almost coincides with the flow attachment location. Specific dimension in Nusselt and Reynolds numbers is the diameter of the outflow tube. The data on heat transfer in a single-phase flow in the expansion channels are generalized right in such a way (Zemanic & Dougall, 1970; Krall & Sparrow, 1966), as well as our data on mass transfer in a single-phase flow. In some publications the length of the recirculation zone is used as the reference dimension (Terekhov & Bogatko, 2008).

Processing of the data on maximal mass transfer coefficients in a two-phase gas-liquid flow in the channel with sudden expansion is carried out in (Chouikhi et al., 1987), and correlation has been proposed:

$$Sh_{\max} = A \cdot \mathrm{Re}_{L2}{}^{0.7} \cdot Sc^{1/3} \cdot \left(V_{G2}/V_{L2}\right)^{n} \tag{10}$$

where A, n are functions of the expansion ratio, n changes from 0.05 for $E = 1:2$ to 0.095 for $E = 1:6$, Re_{L2} is Reynolds number calculated by the liquid superficial velocity V_{L2} in a channel of larger diameter, V_{G2} is gas superficial velocity. Substitution of Reynolds number Re_{L2} by the Reynolds number for the tube of a smaller diameter, i.e. Re_{L1} similarly to a single-phase flow allowed us to summarize the data on the maximal mass transfer coefficient (Chouikhi et al., 1987) for all expansion ratios by the following relation within $\pm 15\%$:

$$Sh_{\max} = 0.23 \cdot \left(\mathrm{Re}_{L1}\right)^{0.7} \cdot Sc^{1/3} \cdot \left(V_{G1}/V_{L1}\right)^{0.07} \tag{11}$$

Processing of data on maximal heat and mass transfer coefficients in a single-phase flow has shown that the velocity of outflow from the tube of a smaller diameter identically determines intensity of heat and mass transfer in the area of flow attachment. Hence the attempt was made to process obtained data for the maximal mass transfer coefficient in two-phase flow based on actual velocity of liquid phase V'_{L1} in a channel, from where the two-phase medium outflows. The void fraction was calculated according to Armand (1946) correlation $\varphi = 0.83\beta$. The results obtained are shown in Fig. 18. This graph represents all data obtained for expansion ratios $E = 1:2$ and $E = 1:4$, as well as the data for single-phase flow. The effect of void fraction is identically taken into account by the actual velocity, and in contrast to correlation (10), does not require introduction of additional parameter, which is the ratio of the superficial velocities. The obtained data are satisfactorily generalized by the following correlation

$$Sh_{\max} = 0.252 \cdot \mathrm{Re}'_{L1}{}^{0.7} \cdot Sc^{1/4} \tag{12}$$

The visual observations of the flow and measured data show that flow stabilization after abrupt expansion takes place at the channel outlet. The effect of the expansion ratio on mass transfer coefficients both in the single-phase and two-phase flows disappears and specific

dimension is diameter d_2. Such processing by velocity of mixture $V_{TP2} = V_{L2} + V_{G2}$ in a channel with expansion is presented in Fig. 19.
The data on mass transfer coefficients in the single-phase flow and at high liquid flow rates in two-phase flow are satisfactorily generalized by correlation

$$Sh_2 = 0.135 \cdot \mathrm{Re}_{TP2}^{0.75} \cdot Sc^{1/4} \tag{13}$$

Deviations are observed in the area of abnormal effect of volumetric quality on mass transfer at low velocities of liquid phase.

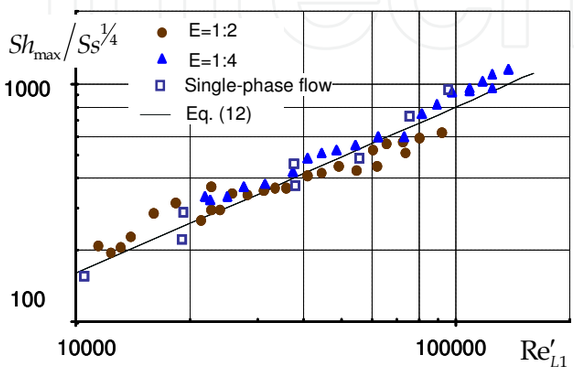


Fig. 18. The maximum coefficient of mass transfer in a channel with abrupt expansion

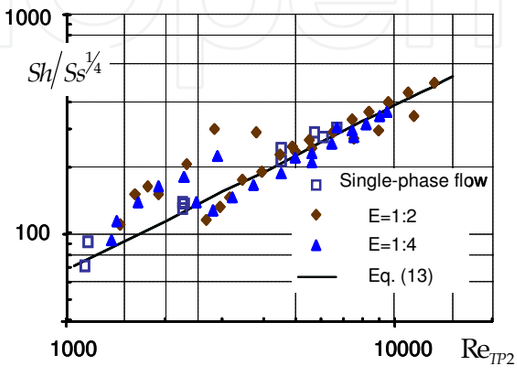


Fig. 19. The mass transfer coefficient in the zone of developed flow

For the studied flow patterns the maximal mass transfer coefficients in the channel with the flow turn of 90° are observed for intermediate and outer generatrices at the channel outlet. And only for lowest liquid flow rates the zone with maximal mass transfer coefficients is situated on the internal surface. The maximal effect of void fraction on the relative mass transfer coefficient is observed at the inner surface and most probably is explained by the higher concentration of gas bubbles. The increase in mass transfer at the outer generatrix of the bend may be related to the shift of velocity maximum towards this area, i.e. with redistribution of phases because of circulation flows.
Distribution of mass transfer coefficients in the channel with sudden expansion in the two-phase flow as a whole is of the same nature as for the single-phase flow. The maximal effect of void fraction is observed from the zone with mass transfer maximum up to the channel outlet. At distance $x/d_2 = 1 \div 1.5$ at high liquid flow rates the effect of void fraction is lacking, because gas practically does not flow into this area due to existence of circulation zones. The absolute values of mass transfer coefficients at the outlet of the channels with various expansion and the same values of volumetric quality are quite close to each other. This confirm the fact that for the given regime parameters the flow becomes almost developed.
The experimental data on the effect of volumetric quality on mass transfer intensity on a wall in the curvilinear channel and in the channel with abrupt expansion, obtained in the present work, may be used at modeling of the erosion- and corrosion wear process in channels of coolant circulation systems of the power and chemical equipment.

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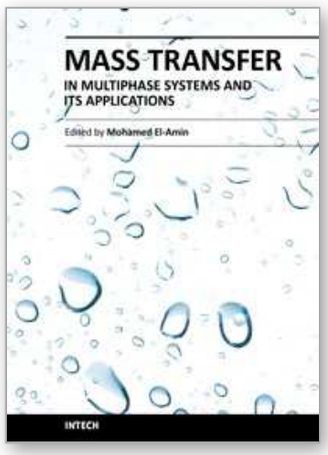
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