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# Hydrodynamics and heat transfer in an inclined bubbly flow

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ABSTRACT

Results of experimental and numerical investigations of heat transfer and wall shear stress, in upward bubble flow in a flat inclined channel, are presented. The hydrodynamic structure is measured using the electrochemical method with miniature friction sensors. Miniature platinum thermoresistors are employed to measure the wall temperature. The set of RANS equations is used to account for the feedback effect of bubbles on mean and fluctuating flow parameters. It is shown that we can observe a significant dependence of shear stress and heat transfer on angle of channel inclination, in the bubble gas-liquid flow. The largest values of wall shear stress and heat transfer correspond to channel inclination angles of 30–50°. Intensification of wall shear stress in inclined two-phase bubble flow leads to values of 30%, and up to 15% for heat transfer. For inclination angles close to horizontal, suppression of shear stress and heat transfer of 10% and 25% respectively, was registered. Bubble size distributions along the channel length were obtained for different regimes of two-phase flow.

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## 1. Introduction

Two-phase bubbly flows are common in chemical technologies, power engineering, and other technical applications. Typically, such flows are turbulent with a considerable interfacial interaction between the carrier liquid phase and the bubbles. They may be complicated by polydispersity of the gas phase, fragmentation, coalescence of bubbles, and interfacial heat transfer. Correct simulation of bubble distribution over a channel or pipe section is of great importance for safe operation, and for prediction of various scenarios such as emergency situations in the heat generators of energy equipment elements. The variety of flow regimes complicates significantly the theoretical prediction of hydrodynamics of a two-phase flow. It requires application of numerous hypotheses, assumptions, and approximations. Often the complexity of flow structure makes it impossible to describe theoretically its behavior, and so empirical data is applied instead. Therefore, experimental investigation of the gas-liquid flows has been limited to now. Most studies of bubble upward and downward flows, including heat transfer between phases, is concerned with vertical pipes and channels. In this case, gas phase distribution over the channel cross section is determined mainly by the Saffman force acting on floating bubbles, in the case of the velocity gradient [1]. Less attention has been paid to the bubbly gas-liquid flows in inclined channels, despite the fact that this particular channel orientation can be very important.

Refs. [2–4] concerned experimental studies of the isothermal bubble flows in inclined pipes and channels. It was shown that channel orientation significantly affects flow hydrodynamics. One of the first studies of the bubble flow structure in an inclined pipe was performed in [2]. It demonstrated that a small declination from horizontal has a strong influence on the flow structure. Measurements were performed at pipe inclination angles, $\Theta$, from 0–90° for pipes 25 and 51 mm in diameter. The authors of [3] carried out experimental research of mass transfer on the channel wall with gas bubbles in addition to liquid flow. Gas phase dispersion has a strong influence on mass transfer; mass transfer intensity grows with decreasing bubble size. At very small gas volumetric flow rate ratio, $\beta = W_b/(W_b + W) \le 5\%$, mass transfer increases. Afterwards, a monotonous mass transfer growth is observed with further void fraction increase. It was shown that the absolute mass transfer value increases slowly with liquid velocity growth. The extent of bubble influence on mass transfer increases with decreasing liquid velocity. Mass transfer reaches its maximum value for inclination angles of 30–50°.

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**Nomenclature**

*Latin*

| | |
|---|---|
| $C_D$ | drag coefficient of bubbles |
| $C_f$ | $C_f = 2\tau_W/(\rho U_{m1}^2)$ friction coefficient |
| $C_{Pf}$, $C_{Pb}$ | specific heat capacity of liquid phase (water) and air bubbles respectively (J kg$^{-1}$ K$^{-1}$) |
| $D$ | diffusion coefficient, (m$^2$ s$^{-1}$) |
| $d$ | bubble diameter, (m) |
| $Eo$ | $Eo = g(\rho - \rho_b)d^2/\sigma$ Eotvoes number |
| $Eo_b$ | $Eo_b = g(\rho - \rho_b)D_H^2/\sigma$ modified Eotvos number |
| $H$ | channel height, (m) |
| $h$ | convective heat transfer coefficient fluid flow and channel wall, (W K$^{-1}$ m$^{-2}$) |
| $h_c$ | convective heat transfer coefficient between liquid and bubble, (W K$^{-1}$ m$^{-2}$) |
| $J$, $J_b$ | superficial velocity of liquid (water) and bubbles respectively (m s$^{-1}$) |
| $k$ | $k = 0.5\langle u_i u_i\rangle$ turbulent kinetic energy, (m$^2$ s$^{-2}$) |
| $Nu$ | Nusselt number |
| $P$ | pressure, (Pa) |
| $Pr$ | $Pr = \mu C_P/\lambda$ Prandtl number |
| $\bar{R}_b$ | specific gas constant, (J kg$^{-1}$ K$^{-1}$) |
| $Re$ | $2HU_{m1}/\nu$ Reynolds number |
| $Re_b$ | $Re_b = \rho\lvert\boldsymbol{U}_R\rvert d/\mu$ Reynolds number of bubbles, based on the slip velocity |
| $r_1$ | function describing the break-up rate of the bubbles of the $k$-th fraction, (1/(m$^3$s)) |
| $r_2$ | function describing the coalescence rate of the bubbles of the $k$-th fraction, (m$^3$/s) |
| $T$ | temperature, (K) |
| $\lvert\boldsymbol{U}_R\rvert$ | $\boldsymbol{U}_R = \boldsymbol{U} - \boldsymbol{U}_{b,k}$ slip (interphase) velocity, (m s$^{-1}$) |
| $U_i$ | components of mean velocity, (m s$^{-1}$) |
| $U_{m1}$ | bulk mean velocity of the liquid flow at the pipe edge, (m s$^{-1}$) |
| $U^*$ | friction velocity, (m s$^{-1}$) |
| $\langle u\rangle$, $\langle v\rangle$ | intensity of velocity fluctuations in axial and radial directions respectively,(m s$^{-1}$) |
| $\langle u_j\theta\rangle$ | turbulent heat flux, (m K s$^{-1}$) |
| $\langle uv\rangle$ | turbulent Reynolds stress, (m$^2$ s$^{-2}$) |
| $\bar{v}$ | mean bubble volume, (m$^3$) |
| $W_b$, $W$ | volumetric gas and liquid flow rates respectively, (m$^3$s$^{-1}$) |
| $We$ | $We = \rho\lvert\boldsymbol{U}_R\rvert^2 d/\sigma$ Weber number |
| $x$ | longitudinal coordinate, (m) |
| $y$ | distance normal from the wall, (m) |

*Greek*

| | |
|---|---|
| $\alpha$ | void fraction of bubbles |
| $\beta$ | $\beta = W_b/(W_b + W)$ gas volumetric flow rate ratio |
| $\varepsilon$ | dissipation of the turbulent kinetic energy, (m$^2$s$^{-3}$) |
| $\Theta$ | inclination angle |
| $\lambda$ | heat conductivity, (W K$^{-1}$ m$^{-1}$) |
| $\mu$ | dynamic viscosity, (kg m$^{-1}$ s$^{-1}$) |
| $\nu$ | kinematic viscosity, (m$^2$ s$^{-1}$) |
| $\rho$ | density, (kg m$^{-3}$) |
| $\sigma$ | surface tension, (N m$^{-1}$) |
| $\tau$ | $\tau = 4\rho_b d^2/(3\mu Re_b C_D)$ dynamic relaxation time of bubbles, (s) |
| $\tau_W$ | wall shear stress, (Pa) |
| $\tau_\Theta$ | $\tau_\Theta = C_{Pb}\rho_b d^2/(6\lambda Nu_b)$ thermal relaxation time of bubbles, (s) |

*Subscripts*

| | |
|---|---|
| 0 | single-phase flow |
| 1 | parameter under initial conditions |
| $b$ | bubble |
| $f$ | fluid |
| $m$ | mean-mass parameter |
| $T$ | turbulent parameter |
| $W$ | parameter on the wall condition |

*Acronym*

| | |
|---|---|
| CV | control volume |
| RANS | Reynolds averaged Navier-Stokes equations |
| SMC | second moment closure |

Measured results for liquid velocity and local void fraction distributions, in developed upward bubble flow in rectangular channels, are presented in [4]. The channel inclination angle was from 0 to 30° to the vertical. It was shown that near upper channel wall liquid velocity distributions are distorted by the presence of bubbles. The authors concluded that a bubble layer near the upper wall may suppress mean shear stress on this wall. Gas liquid bubble flow in an inclined rectangular channel was studied in [5]. Measurements of mean longitudinal liquid velocity, local void fraction, and wall shear stress were obtained by the electro diffusional method [9,10].

In [6] an experimental study was performed of bubble flow in vertical and inclined pipes, 50 mm in diameter, using optical fiber probes. Local void fraction, bubble size and interfacial area concentration were measured for pipe inclination angles $\Theta$ = 5, 15, and 30° from vertical. It was shown that, at low superficial liquid velocity, the area of increased void fraction shifts from the central part of the pipe towards the upper part. This effect increases with increasing pipe inclination angle. The void fraction peak near the lower wall decreases until it disappears completely. The Sauter mean diameter gradually increases towards the upper pipe wall with rising inclination angle. Maximal wall shear stress and velocity distribution deformation are observed at $\Theta$ = 50°.

Ref. [7] describes measurements of liquid velocity and local void fraction distributions, in gas-liquid flow, in flat channels at inclination angles up to 30° from vertical. The authors also provided predictions of liquid velocity and void fraction using the Eulerian method, volume of fluid method, and a homogeneous model. Predictions agreed with the experiments rather well at small inclination angles. For angles $\Theta$ > 10° a deviation from measurements was observed.

Inclined bubbly flows without heat transfer [2–8] have been studied more extensively than those with heat transfer [11–16]. Gas liquid flows with heat transfer between the wall and two-phase flow are often used in practical applications. Heat transfer measurements in the bubble wake were performed in [11]. It was shown that as the bubble diameter grew, the value of the heat transfer coefficient decreased. In [12,13] results of an experimental study of heat transfer and wall shear stress, in upward bubble flow in an inclined flat channel, were presented. Measurements were carried out for liquid velocity in the range 0.3–1.1 m s$^{-1}$, and a gas flow rate ratio, $\beta$, of 0–10%. Bubbles were introduced into the flow at the upper channel wall. Hydrodynamic structure was measured using the electro diffusion method with miniature shear stress probes. Mean wall shear stress and heat transfer values were determined at different channel orientations. A dependence of

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