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Motion of a sphere in vicinity of the wall

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Abstract

The paper is focused on studies of particle's path deflection near the wall. Particle is modeled by a rigid sphere suspended on the thread. A specially designed rig has been constructed where systematic experiments were done to obtain sphere trajectories for its three different sizes. Mathematical analysis led to correlation describing the influence of wall on particle movement in function of initial distance of the sphere to the wall and its Reynolds number. The analysis was based on original model postulated by authors. Comparisons of experimental data against correlations available from literature shows a satisfactory agreement.

Keywords: Wall force; Force balance; Bubble flow

1 Introduction

From the point of view of thermodynamics and heat transfer two-phase flows introduce into the processes an important feature that they intensify heat transfer. The boiling process, particularly at a small content of vapour phase, enhances heat transfer in channels which is reflected in a significantly higher, compared to single phase flows, heat transfer coefficient. In the era of reduction of technical appliances sizes the idea of implementation of two-phase flows in systems of semiconductor laser cooling, or microprocessors in electronics seems inevitable. Hence investigations of boiling in small diameter channels or microchannels as well as extended microsurfaces are conducted in several research centers in the world [1, 2]. Similar investigations have also commenced at the Heat Technology Department at Gdańsk University of Technology [3]. Also two-phase flows

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without bubble generation, i.e. flows where bubbles coexists within liquid finds numerous practical applications. Here also mathematical modeling presents serious shortcomings.

Issues connected with the presence of a vertical wall and bubble movement around it are important in two-phase flows analysis [4]. There is no sufficient experimental data on the flow resistance of gas bubbles near vertical walls as well as mathematical description of that problem is incomplete. According to experimental data [5], characteristic feature of two-phase flow in the boundary layer is wall peaking and core peaking, which means bubbles grouping near the wall or core of the flow, respectively, depending upon the bubble size and flow conditions. Such phenomenon still strikes difficulties and there is no unanimous explanation to that fact. Mikielewicz [6], for example, postulated that some additional angular velocity causes that phenomenon. He devised a model, which allows to determine the two-phase flow in the boundary layer, where void fraction distribution is described by an original model. In order to improve the latter model he devised to study near wall behaviour of bubbles, as that is region where wall peaking occurs and the issues related to influence of the wall are still vaguely recognized. Availability of such data should greatly improve understanding of the flow in the wall vicinity and would enable to explain challenges in modeling of wall peaking and core peaking.

Hence the aim of present work is investigation focused on accurate experimental verification of forces acting on bubble flowing along the wall. The bubble is represented by a solid sphere suspended on a thin string. It is acknowledged that bubbles in motion near the wall exhibit some more specific patterns of motion, however, the authors are convinced that the presented model of a bubble motion captures at least a qualitative behaviour of a bubble in the flow and will compliment the transverse force balance acting on the bubble.

2 Presence of the wall in bubble flow

In general, the wall causes the bubbles to slow down, both in the parallel and the transverse direction with respect to wall alignment.

On the basis of potential flow theory Antal [7] presented the repelling force from the wall which yields:

$$-M_{cl}^{w} = M_{dv}^{w} = -\left[C_{w1} + C_{w2}\left(\frac{d_b}{y}\right)\right]\frac{\rho_l \alpha_b}{d_b}\left|u_R \cdot n_x\right|^2 n_y \tag{1}$$

where n_x, n_y are unit vectors, y – distance from the wall, u_R – buble relative velocity, α_b – void fraction and constants C_{w1} and C_{w2} are respectively: $C_{w1} = -0.1$, $C_{w2} = 0.12$. Some difficulty in using the Antal model is that it requires a distribution of local void fraction in order to take the advantage of correlation. In the present work a mean value was taken.

A number of relations describing near-wall particle motion are provided by Kabsch [8]. The presence of wall influencing the flow is accordingly taken into account by introducing a correction factor for the drag force computed for undisturbed motion. This is shown in the following equation:

$$F_W = \frac{F_0}{K} \tag{2}$$

where K is the correction factor and F_0 – the drag force determined for undisturbed flow.

For a spherical particle moving between parallel walls K is given by the Faxen formula:

$$K = 1 - 1.004\frac{d_b}{l} + 0.418\left(\frac{d_b}{l}\right)^3 + 0.21\left(\frac{d_b}{l}\right)^4 - 0.169\left(\frac{d_b}{l}\right)^5 \tag{3}$$

in which l is the distance between walls. Equation (3) is valid only for cases where $d_b/l < 1/20$, and the particle is located midway between the walls. Neglecting these conditions leads to substantial errors in estimation.

For a spherical particle in motion, located at the distance $l/2$ away from a planar wall of infinite breadth, the corrective factor may be obtained from:

$$K = 1 - \frac{9}{16}\frac{d_b}{l}. \tag{4}$$

For a spherical particle moving along the axis of a cylinder of diameter $l > 4d_b$ and of infinite length, the factor K is given by:

$$K = 1 - 2.104\frac{d_b}{l} + 2.09\left(\frac{d_b}{l}\right)^3 - 0.95\left(\frac{d_b}{l}\right)^5. \tag{5}$$

For smaller diameters of the cylinder ($d_b/l > 0.25$), the following is valid:

$$K = \left[1 + 2.25\frac{d_b}{l} + 5.06\left(\frac{d_b}{l}\right)^2\right]^{-1}. \tag{6}$$

No available source, however, provides equations for wall-particle interaction based on the fundamental conservation equations governing flow. The existing formulae are typically derived from empirical and numerical data, and consequently may be relied upon only under circumstances matching the original experiment. The indiscriminate use of such relations in various technical applications should be regarded as ill-advised. It seems obvious, in such circumstances, that further experimental investigations are indispensable. The present work is aimed at filling of that gap.

3 Experimental rig

In order to measure forces acting on the bubble an experimental rig, shown in Fig. 1, was designed and assembled at the Heat Technology Department of the Gdansk University of Technology. The rig consists of water vessel with vertical glass plate simulating the wall, sphere (the bubble model), suspended on the thread, aluminium wheel, velocity and acceleration measurement device, gravity-hydraulic constant velocity driver, positioning equipment of the glass plate, distance sphere-plate scale, sphere deflection sensor, data acquisition set, digital camera.

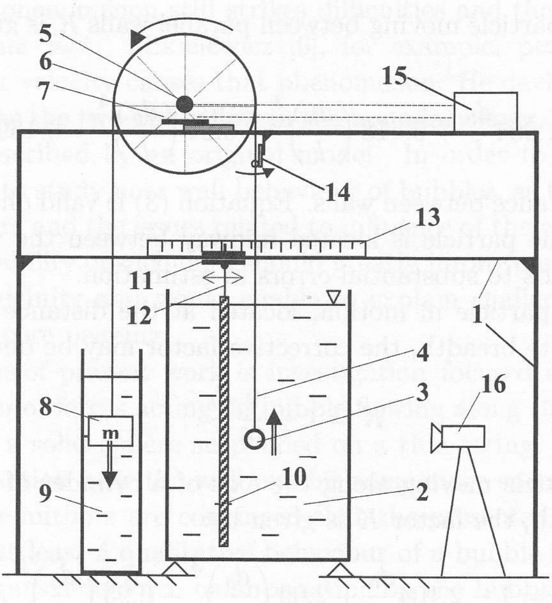

Figure 1. Experimental rig: 1 – frame; 2 – water vessel; 3 – sphere (the bubble model); 4 – steel string; 5 – velocity adaptor; 6 – wheel; 7 – tensometric beam; 8 – mass (hydraulic piston); 9 – cylinder filled oil; 10– vertical glass plate; 11– positioning equipment; 12– flexible suspension; 13– distance sphere-plate scale; 14– sphere deflection sensor; 15– data acquisition set; 16– digital camera.

Experimental rig is positioned in air-conditioned room with temperature 20 ±1°C . The vessel (0.5 × 0.5 × 1 m), containing distilled water, is made of 8 mm thick Plexiglass. It is assumed that water properties are: density $\rho = 998.2$ kg/m^3 [9], viscosity $\nu = 1.006 \cdot 10^{-6}$ m^2/s, surface tension $\sigma = 726.9 \cdot 10^{-4}$ N/m, i.e. they correspond to temperature 20°C.

The wheel with negligible mass was located on a stiff frame. The small mass of the wheel was obtained by selection of a special aluminium hoop with thin spokes and a light nave. The wheel is placed in two ball bearings with dimensions $\phi 6/10$ mm, which results in insignificant movement resistance. The aluminium wheel was cut with 130 000 notches in order to determine the acceleration of the wheel and its angular velocity. The sphere used in experiment is a physical model of gas bubble moving in vertical direction along the wall.

The positioning system has been fitted above the tank. A heavy glass slab is immersed in the tank, which simulates a solid wall during experiments. Its ideal vertical alignment results from gravitational force (very important here are elastic joints fastening the slab with positioning mechanism). The positioning mechanism itself is equipped with a millimeter vernier and enables for arbitrary precision adjustment of initial distance of the sphere with respect to the wall. The initial distance is an important parameter in investigations.

The movement of the wheel is forced by a gravitational fall of the suspended weight. Mass m falls freely in a cylinder filled with hydraulic oil, which constitutes natural source of a constant rotational velocity of the wheel and at the same time of a constant velocity of the sphere in vertical motion. The flow resistance of sphere is measured by means of tensometric transducers of force of SCAIME type by means of the measurements of force in a steel thread of diameter of 0.35 mm. Tensometric transducers are fitted at the location of wheel bearings support. In considerations there is assumed a lack of friction between a thread and liquid as the surrounding fluid is water having relatively small viscosity. Such effect would be more pronounced in the case of pulling the sphere in fluids with higher values of Prandtl number. Deflection of trajectory of dragged sphere, i.e. the effect of the influence of the presence of wall is recorded by means of a tensometric transducer of deflection (item 14 in the schematic in Fig. 1), specially manufactured and calibrated for the purpose of experiment. Recording of a sphere displacement in vertical direction is also a crucial measurement during experiments. Additionally, for visualization purposes the motion of a sphere is recorded by means of a digital camera with the frame speed of 25 frames per second. Such a shutter was regarded sufficient in present experiments bearing in mind experimental velocities.

Data acquisition was conducted by means of a PCL 1800 acquisition card by Advantech. Data processing was performed using a software developed based on a graphical environment DASYLab by DASYTEC. A basic measurement configuration enables recording of results with a time step of 0.01s and simultaneous visualization of experiments. Additionally developed has been application enabling conversion of data recorded in DASYLab format to the ASCII file, which permits their further utilization in a majority of available software.

Applied hydraulic piston (items $8 + 9$ in Fig. 1) enables investigations in the range of Reynolds number from 500 to 1700.

4 Model of wall forces acting on single bubble

Prior to performing experiments on the sphere gas bubble generator was submerged in water in vicinity of the wall and bubbles were introduced into the stagnant liquid. Example of the results has been presented in Fig. 2. A striking behaviour of bubbles has been observed. Namely in the range of parameters studied the bubble was "jumping" on the wall, i.e. performing a periodical wave motion on the wall. Observation from the transverse angle showed a rectilinear motion of a bubble.

Observation using two digital cameras in perpendicular position to each other shows that solid sphere (the bubble model) moves in a 2D fashion around the wall (Fig. 3). That finding encouraged further studies using the experimental rig presented above. Moreover experiments showed, that the sphere trajectory depends on the sphere initial position x_0, that is the distance in horizontal direction (Fig. 4). If the sphere, in the initial time, is located very close to the wall, then the trajectory encounters biggest deflection during the rising (Fig. 4) (innermost trajectory). It is a clear evidence of repelling force from the wall. This effect lessens with increasing initial distance between the sphere and the wall and finally disappears for initial position exceeding 1.5 sphere diameter. Observation using two digital cameras in perpendicular position to each other shows, that the sphere moves in a zigzag fashion, i.e. experiences deflection in XY plane, whereas in the other plane it shows linear motion. These observations were taken into consideration in development of a mathematical model describing the wall influence on single bubble motion.

The model is considering the force balance at the location of maximum deflection (Fig. 6). At that position the sphere "stops" in its motion along the X axis and the repelling force F_w is balanced by a horizontal component of the thread force N_x.
The sphere motion equation can be expressed in the form:

$$\begin{aligned} N\cos\alpha + W &= Q + F_0, \\ N\sin\alpha &= F_W \end{aligned} \tag{7}$$

where: N – string force, Q – gravity force, W – buoyancy, F_0 – drag force in vertical direction.

Mass of the sphere is determined with account of so called „added mass", i.e. total mass of a sphere and liquid taken by a sphere due to viscous action. Mass of accompanying water has been determined based on a force model due to Madejski [10], where it has been established as a half of the volume of sphere with density of liquid, namely $m_d = \delta_l \pi d_b^3/12$. However, that term is not present in the location of maximum deflection (distance h), as then the transverse velocity is equal zero.

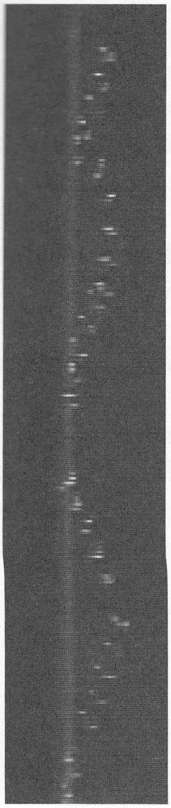

Figure 2. Photograph of the air bubble trajectory ($D \approx 3$ mm, $x_0 = 0$ mm).

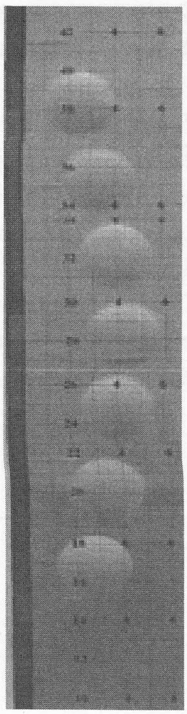

Figure 3. Photograph of the sphere trajectory ($D = 40$ mm, $x_0 = 8$ mm, $\mathrm{Re} = 970$).

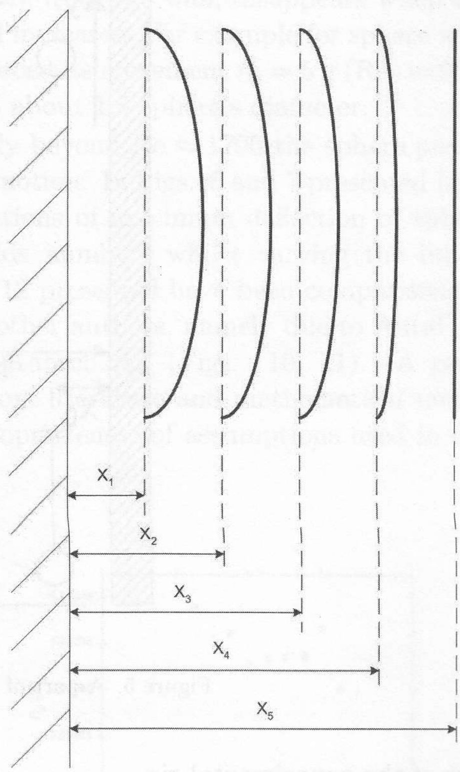

Figure 4. Sphere trajectory for different initial distance between sphere and wall.

Particular terms appearing in equation (7) will now be determined. The drag form can be expressed as:

$$F_0 = c_D \cdot \rho_l \cdot \frac{\vartheta_y^2}{2} \cdot A \tag{8}$$

where ϑ_y is the longitudinal velocity, ρ_l – liquid density, A – projection area of a sphere. Drag coefficient C_D depends on the Reynolds number and in the range $\mathrm{Re} \to 1000$ should be calculated from the Clift formula [11]:

$$c_D = \frac{24}{\mathrm{Re}}\left(1 + 0.15 \cdot \mathrm{Re}^{0.687}\right) + \frac{0.42}{1 + 4.25 \cdot 10^4 \cdot \mathrm{Re}^{-1.16}} \tag{9}$$

Ascending flow of a sphere is accompanied by a constant value of drag force F_0 due to a constant value of velocity ϑ_y, assured by the velocity stabilizer forming

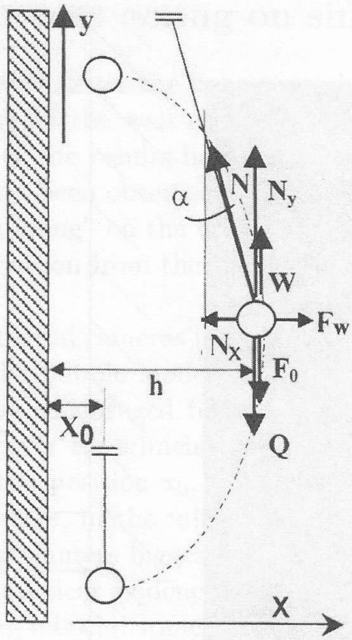

Figure 5. A part of the sphere trajectory.

part of the experimental rig.

Experimental rig enables for a more precise measurement of displacement in the direction perpendicular to the wall x, and at the same time deflection of sphere h, angle between a thread and vertical direction α, as well as longitudinal velocity ϑ_y. Also known is the mass of the sphere m. The only unknown is a force F_w connected with a maximum deflection of a sphere for a given initial location x_o with respect to a wall. That force is determined by solving the set of Eqs. (7):

$$F_W = (Q - W + F_0)\tan\alpha. \tag{10}$$

5 Experimental results

Experimental tests were carried out for sphere diameters $D = 30$, 40 and 50 mm. Data for Reynolds number ranging from 500 to 1700 were collected. The motion of the sphere has been forced by the gravity fall of mass m. Selected masses for forcing the motion were adjusted in such a way as to guarantee the plane motion of the sphere, i.e. the motion where only deflection in XY plane was present and not in the other planes. It must also be noted that the postulated model is valid only in that range of the flat motion. During the investigations it was found that that the force, which repels the sphere from the wall, disappears when the initial distance from the sphere to the wall increases. For example for sphere with diameter about 40 mm and mass, which forced its movement $m = 5$ g ($\mathrm{Re}_b \approx 950$) this effect disappears in distance equal to about 1.5 sphere's diameter.

As observed during investigations, only beyond $\mathrm{Re} \approx 1700$ the sphere passes from a 2D flat motion into the helical 3D motion. In Figs. 6 and 7 presented have been the results of authors own investigations of maximum deflection of sphere for given sphere dimensions and Reynolds numbers whilst varying the initial positioning of the sphere. In Figs. 9 and 12 presented have been comparisons of authors own results with correlations by other authors, namely due to Antal [7], (Figs. 8, 9), and correlations cited by Kabsch [8], (Figs. 10, 11). A good consistency between correlations taken from literature and mathematical model presented in the paper confirms the appropriateness of assumptions used in the study.

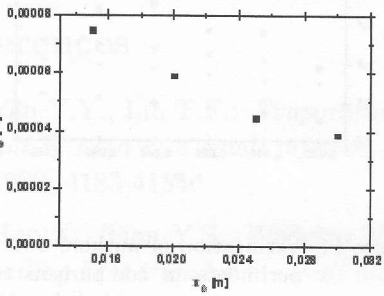

Figure 6. Influence of initial position x_0 on the influence of the wall; $D = 30$ mm, $\mathrm{Re} = 610$.

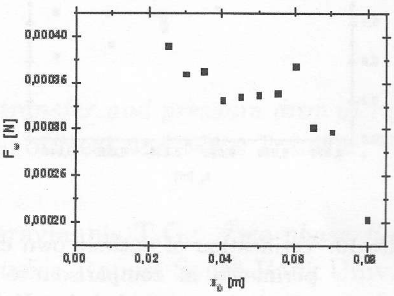

Figure 7. Influence of initial position x_0 on the influence of the wall; $D = 40$ mm, $\mathrm{Re} = 1200$.

Data collected in the course of experiments has been reduced to yield a general form of a correlation, which enables determination of the "wall effect":

$$\frac{F_w}{F_0} = 6.648 \cdot 10^{-7}\,\mathrm{Re}_b^{2.0}\left(\frac{x_0}{d}\right)^{-1.0} \tag{11}$$

Diagram shown in Fig. 12 shows the correlation between the "force effect" and initial position of the sphere x_0. It was assumed that the force effect can be described as a ratio of repulsive force to corresponding buoyancy force. Fig. 12 shows experimental data for different initial conditions x_0 and Reynolds number as well as different sphere diameters. Results are described using adjusted approximation, which reduces experimental data.

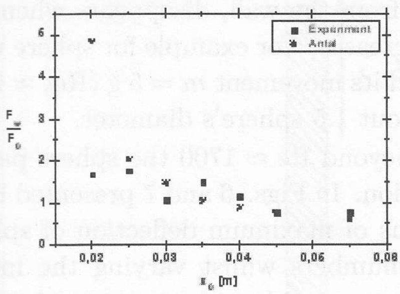

Figure 8. Verification of authors own experiments in comparison to a correlation provided by Antal [7], $D = 40$ mm, Re = 715.

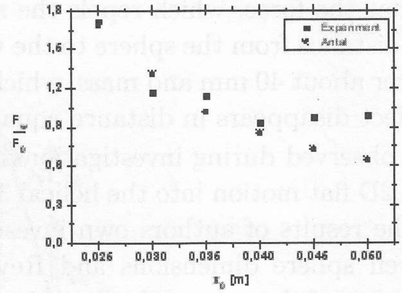

Figure 9. Verification of authors own experiments in comparison to a correlation provided by Antal [7], $D = 40$ mm, Re = 960.

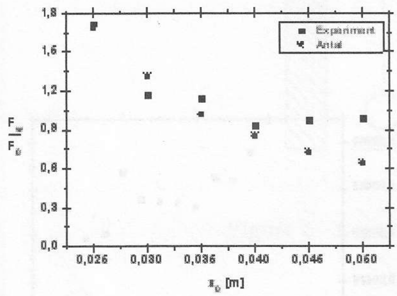

Figure 10. Verification of authors own experiments in comparison to a correlation provided by Kabsch [8] $D = 40$ mm, Re = 1200.

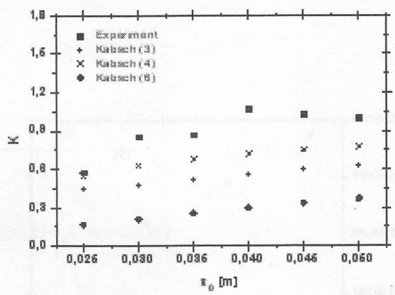

Figure 11. Verification of authors own experiments in comparison to a correlation provided by Kabsch [8] $D = 40$ mm, Re = 960.

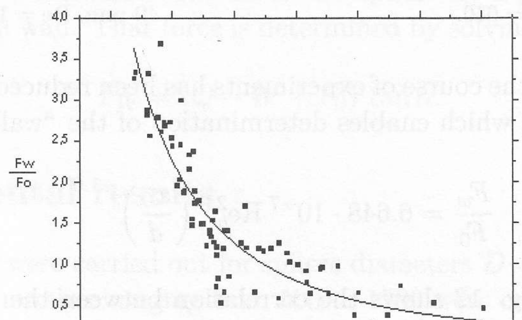

Figure 12. Correlation between the "force effect" and initial position of the sphere x_0.

6 Conclusions

Presented results of experimental research show periodic character of sphere movement (simplified bubble model) along vertical channel wall. Sphere trajectory visibly changes, what is caused by non-uniform fluid distribution of velocity field around the sphere related to non-uniform pressure field around it.

Mathematical model introduced by authors allows "to validate" wall presence in the flow by evaluation repulsive force on sphere. Proposed original model, valid for the flat motion, gives qualitatively good description of the sphere behaviour during experiment.

Mathematical correlation showed in Fig. 12, will be next used in the model developed by Mikielewicz [6] where flow of gas bubbles is considered in the boundary layer and phenomenon of wall peaking takes place.

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