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Velocity and gas-void fraction in two-phase liquid-gas flow in narrow mini-channels*)

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In the study, the values of velocity and gas void fraction in two-phase gas-liquid flow in narrow vertical mini-channels were experimentally determined. The influence of the physicochemical properties of liquid, the channel gap width and the superficial velocity of gas and liquid, on gas void fraction and gas bubble flow velocities in the flowing two-phase mixture in narrow, vertical mini-channels was investigated. The value of gas phase velocity was defined by means of a drift model, determining the values of distribution parameter C_0. The relation describing the value of gas void fraction depended on the Bankoff coefficient and gas input volume fraction.

Key words: mini-channel, gas void fraction, two-phase flow.

Notations

C_0 distribution parameter,
D diameter,
K_{B} Bankoff coefficient,
g gravitational acceleration,
u superficial velocity,
v velocity,
v_b drift velocity,
δ gap width,
ε void fraction,
ρ density,
η dynamic viscosity,
σ surface tension,
ξ input volume fraction.

Upper and lower indices
G gas,
L liquid,

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SG only gas flow,
SL only liquid flow,
TP two-phase,
W water,
z equivalent value.

1. Introduction

The problems connected with two-phase mixture flow in mini- and micro-channels have become the subject of intensive research recently [1–8]. The reason for such a keen interest in two-phase gas-liquid flow in the limited space is a possibility of intensification of the processes of heat and mass transfer as well as selectivity and miniaturization of the processes. Two-phase flows in mini- and micro-channels are applied to micro-heat exchangers, cosmic technique, cooling of micro-electronic elements and atomic reactors. They have found a wide application in the problems connected with bioengineering and biotechnology as well as environmental engineering. They are also used for describing the geophysical processes (geothermal waters or petroleum output).

In many experimental studies, a micro-channel was defined as a tube, the diameter of which – or in the case of the tubes other than circular ones – the equivalent diameter, is equal or smaller than 1 mm. It was the case in many research studies. Nevertheless, there are other criteria by means of which one may define a size limit of the equivalent diameter of a channel [4].

In micro- and mini-channels one may observe considerable differences in the hydrodynamics of two-phase flows and in the processes of heat exchange in comparison with the channels of greater size. One bears in mind flow structures, void fractions and flow resistances. Recently, many research studies have been published which are concerned the hydrodynamics of two-phase flows in micro- and mini-channels, e.g. [1–4, 7, 8]. In the literature concerning two-phase gas-liquid flows in micro- and mini-channels, the investigations in which water and liquids of similar physicochemical properties were used as the experimental media, are predominant [1, 7–16]. On the other hand, there are no studies in which liquids of higher viscosity are applied as a continuous phase.

To define velocity and void fraction in the flowing two-phase mixture in mini- and micro-channels, the drift model is most frequently applied [9–12]. Furthermore, there are publications in which the parameters of Lockhart–Martinelli model [13] are used to define the void fraction.

2. Experimental

Figure 1 shows a schematic diagram of the experimental set-up to measure hydrodynamics of two-phase flow in mini-channels. In the experiments, four vertical mini-channels of rectangular cross-section were used:

- Channel I – 15 mm wide with gap thickness $\delta = 2.31$ mm, of equivalent diameter $D_z = 4.01 \cdot 10^{-3}$ m,
- Channel II – 15 mm wide with gap thickness $\delta = 1.23$ mm, of equivalent diameter $D_z = 2.23 \cdot 10^{-3}$ m,
- Channel III – 15 mm wide with gap thickness $\delta = 0.65$ mm, of equivalent diameter $D_z = 1.25 \cdot 10^{-3}$ m,
- Channel IV – 7.5 mm wide with gap thickness $\delta = 0.73$ mm, of equivalent diameter $D_z = 1.13 \cdot 10^{-3}$ m.

The channel height was 400 mm in all cases.

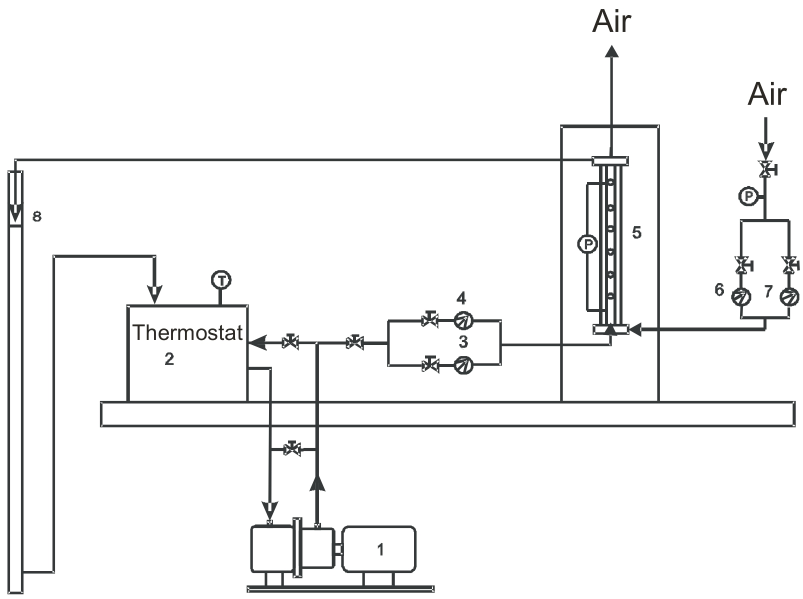

FIG. 1. Schematic of the experimental set-up; 1 – MONO pump, 2 – thermostat, 3, 4 – electromagnetic liquid flow-meters, 5 – mini-channel, 6, 7 – gas flow meters and control, 8 – de-aerating column, P and T – pressure and temperature measurement.

During the experiments the values of superficial velocities of liquid and gas flow were changed from 0.008 to 2.30 m/s and from 0.006 to 2.11 m/s, respectively. In the investigations, air was applied as a continuous phase. The liquid phase was water, glycol and water solutions of saccharose. The properties of liquids used in the investigations are given in Table 1.

With regard to the specifics of the investigated flow and channel size to be applied in measurements of velocity and gas void fraction, a method based on the digital image analysis was applied. This was enabled by the presence of a mini-channel made of polycarbonate. The image of the two-phase mixture

Table 1. Physicochemical properties of the media used in the experiments.

	Dynamic viscosity [Pa · s]	Density [kg/m^3]	Surface tension [N/m]
Water	$9.5{\cdot}10^{-4}$	0.998	0.072
Saccharose solution I	$4{\cdot}10^{-3}$	1160	0.0713
Saccharose solution II	$9.7{\cdot}10^{-3}$	1185	0.0708
Saccharose solution III	0.01	1204	0.0708
Saccharose solution IV	0.055	1274	0.0701
Glycol	0.035	1098	0.035

flowing in the channel was recorded using a high-speed MV-D752 160 camera (Photonfocus). The measuring system consisted of a CCD camera mounted in front of the column in which two-phase flow took place, a lightening system and a PC computer equipped with a card for image acquisition. Selected images from the CCD camera were directed to the computer via the image acquisition card. Due to a high speed of frame interception (about 300 frames/sec) and insufficient calculating power of the computer, the images were stored on the hard disc. The images were analysed using a computer program after the acquisition process in the off-line system had been completed.

To extract edges of the analyzed bubbles from the image, thresholding operation with an automatic threshold calculation with the use of bimodal histogram character is applied. Next, using the algorithm implemented in the LabView 7.1 environment and applying the Vision pack, the areas and flow velocities of gas bubbles were determined. On the basis of the determined values of the areas and flow velocities of gas bubbles and the independently determined value of the superficial gas flow velocity, the value of gas void fraction in the flowing two-phase mixture was determined. A detailed description of the applied experimental procedure was presented in [17].

3. The velocity of gas phase

In the literature there are many attempts to use the drift model in defining the flow in micro- and mini-channels [1, 8–11]. This model is as follows:

$$v_G = C_0 u_{TP} + v_{dr}. \tag{3.1}$$

Mishima and Hibiki [10] carried out the investigations for a two-phase water-air flow in mini-channels. For their research they used three narrow channels of gap thickness 1, 2.4 and 5 mm. The experiments which they carried out confirmed that distribution parameter C_0 in the drift model approached the value 1.2, in other words as in the case of ideal gas-liquid slug flow in bigger channels [4].

IDE and FUKANO [1] carried out the investigations of two-phase water-air flow in a channel of gap thickness 1.1 mm. To define the gas phase velocity they proposed also the drift model described by the following equations:

$$v_G = C_0 u_{TP} + 0.35\sqrt{gD_z} \tag{3.2}$$

or

$$v_G = C_0 u_{TP}, \tag{3.3}$$

where C_0 – the distribution parameter – equals 1.2.

Relation (3.3) is proposed for calculation of the gas phase velocity in two-phase flow in which the superficial velocity is greater than 0.3 m/s.

The experimentally determined gas phase velocities during two-phase flow in mini-channels with the liquid of various properties, including those being different from the properties of water, allowed us to check the dependences being earlier proposed in the literature. The drift model was applied to define the experimentally determined values of gas phase velocities.

Figure 2 shows a comparison of the values of gas velocity, being experimentally recorded and those calculated from Eqs. (3.2) and (3.3). It is worth noting that description of the experimental values of gas velocity by means of Eq. (3.3) is better than when Eq. (3.2) is used. Basing on the review of the subject in

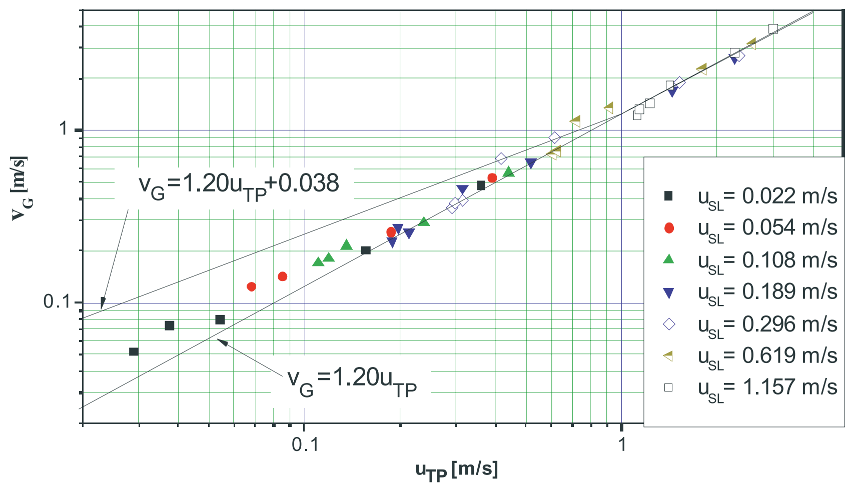

FIG. 2. The dependence of gas phase velocity on two-phase water-air mixture velocity in Channel III.

literature [1–16] as well as on our own experience with the investigations of flow in mini-channels, it can be concluded that the experimental determination of drift velocity is very difficult due to small values of gas bubble velocities, being comparable with the error of measurement. Furthermore, drift velocity is considerably dependent on the way in which gas is supplied to the flowing liquid. In literature there are many examples of different designs of gas distributors [9, 13–16]. Therefore, it is very difficult to obtain comparable results within the range of the smallest gas velocities.

In the case of two-phase flow with a liquid of viscosity higher than that of water, it was observed that the values of the distribution parameter C_0 determined on the basis of the experimental data exceed 1.2. Figure 3 shows the values of gas phase velocity determined during the two-phase flow of saccharose III – air mixture. It is worth stressing that in this case a considerably greater accuracy of the experimental data description was obtained with the application of Eq. (3.3).

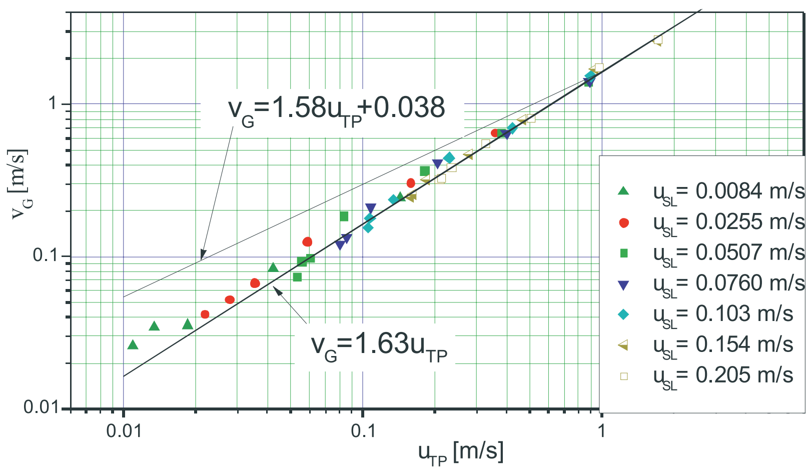

Fig. 3. The dependence of gas phase velocity on two-phase saccharose-air mixture velocity in Channel III.

In the remaining test series the results were similar. Table 2 gives all the determined values of the distribution parameter. On the basis of the analyses of images of two-phase mixture flows recorded during the investigation, it was confirmed that the higher was the liquid viscosity, the greater was the thickness of a liquid film separating gas bubbles from the channel wall. A greater thickness of the film contributed to a decrease of the effective cross-sectional area of two-phase flow, simultaneously increasing the value of gas phase velocity. On the other hand, a change in the value of surface tension caused a change in

Table 2. The values of distribution parameter C_0 and Bankoff coefficient K_B.

Liquid	Channel	C_0	K_B
Water	I	1.23	0.83
Saccharose solution I	I	1.45	0.69
Saccharose solution I	I	1.71	0.58
Glycol	I	1.72	0.58
Water	II	1.23	0.83
Saccharose solution II	II	1.6	0.63
Saccharose solution II	II	1.83	0.55
Water	III	1.27	0.83
Saccharose solution III	III	1.63	0.61
Saccharose solution IV	III	2.33	0.43
Glycol	III	1.79	0.56
Saccharose solution III	IV	1.77	0.56
Saccharose solution IV	IV	2.46	0.41

wettability of the channel wall by the liquid film. In the case when one kind of the channel wall material was used, it could be assumed that the liquid film thickness depended on the surface tension and liquid viscosity. On this basis the following relation is proposed:

$$v_G = C_0 \left(\frac{\sigma_L}{\sigma_w}\right)^a \left(\frac{\mu_L}{\mu_w}\right)^b u_{TP}. \tag{3.4}$$

Assuming the value of distribution parameter $C_0 = 1.2$ and correlating the experimentally determined values of gas phase velocity using Eq. (3.4), the values of exponents a and b were determined. Finally, the following equation was obtained:

$$v_G = 1.2 \left(\frac{\sigma_L}{\sigma_w}\right)^{0.32} \left(\frac{\mu_L}{\mu_w}\right)^{0.16} u_{TP}. \tag{3.5}$$

Figure 4 shows a comparison of the experimentally determined values of gas phase velocity with the values derived from Eq. (3.5). The accuracy of description of the experimental data was satisfactory. This constitutes the first attempt of a generalized description of the values of gas phase velocity for

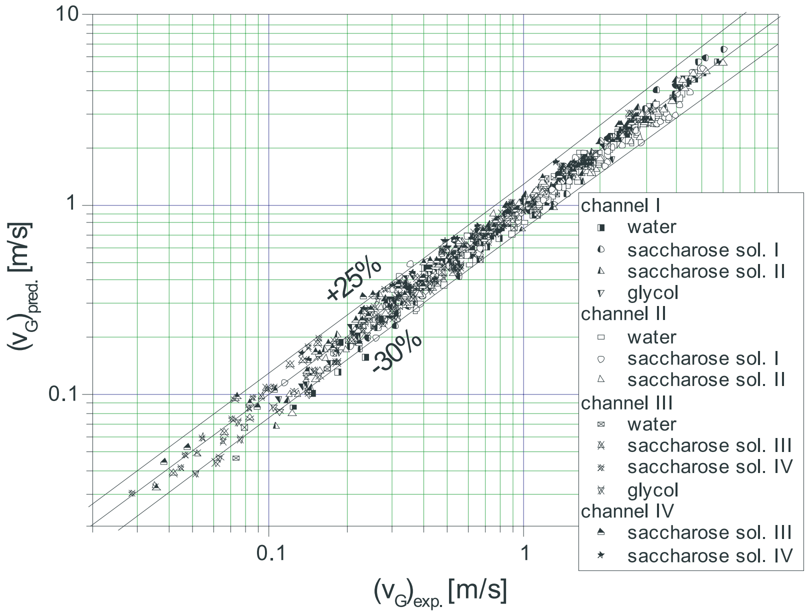

Fig. 4. The comparison of experimental values of superficial gas phase velocities with those calculated from Eq. (3.5).

a two-phase flow, with a liquid of properties different from those of water in the mini-channels. Equation (3.5) is valid for:

$$0.01 < u_{SG} < 2.11 \text{ m/s},$$
$$0.01 < u_{SL} < 2.3 \text{ m/s},$$
$$0.001 < \mu_L < 0.055 \text{ Pa} \cdot \text{s},$$
$$0.035 < \sigma_L < 0.072 \text{ N/m}.$$

4. Gas void fraction

The value of mean gas void fraction was derived from the relation:

$$\varepsilon_G = \frac{u_{SG}}{v_G}. \tag{4.1}$$

On the other hand, the value of gas input volume fraction was determined from the following equation:

$$\xi_G = \frac{u_{SG}}{u_{TP}}. \tag{4.2}$$

In majority of two-phase flows, the values of mean gas void fraction are smaller than the values of gas input volume fraction. Obviously, this phenomenon stems from the greater gas phase flow velocity than the liquid phase flow velocity. From the research carried out by ALI *et al.* [18] it may be concluded that, similarly, during two-phase flow in micro- and mini-channels gas input volume fraction ξ_G depends on mean gas void fraction ε_G in a mini-channel:

$$\varepsilon_G = K_{\mathrm{B}}\xi_G. \tag{4.3}$$

ALI *et al.* [18] also found that the value of the Bankoff coefficient K_{B} was equal to 0.8 during two-phase water-gas flow. In the study an attempt was made to determine the values of the Bankoff coefficient during the two-phase mixture flow in mini-channels. Figures 5 and 6 show a comparison of selected values of

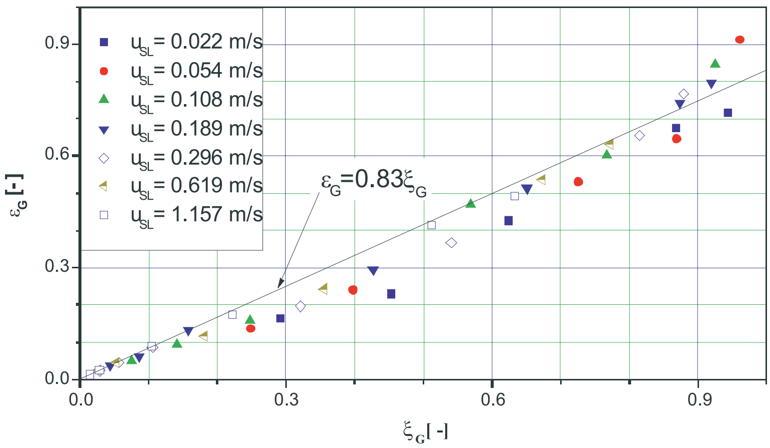

FIG. 5. The dependence of mean gas void fraction in the channel on the input gas volume fraction for two-phase flow of air-water mixture in Channel III.

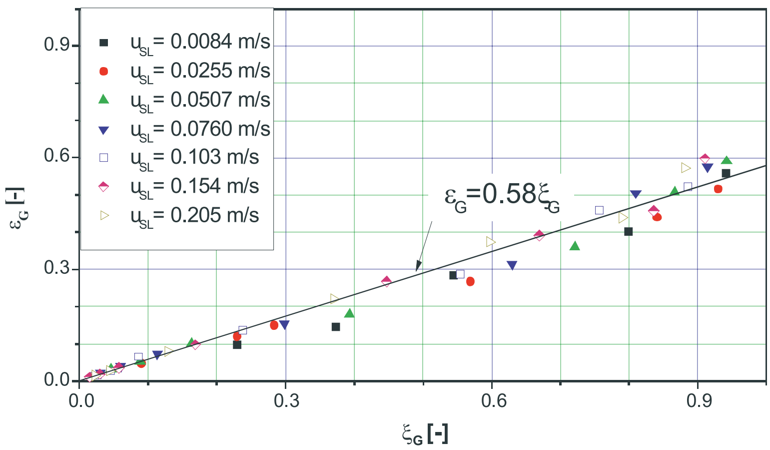

FIG. 6. The dependence of mean gas void fraction in the channel on the input gas volume fraction for two-phase flow of air-saccharose III mixture in Channel IV.

mean gas void fraction determined experimentally, with the values determined using Eq. (4.3). Table 2 gives all the determined values of the Bankoff coefficient. From the investigations one may infer that only for two-phase flow with water, agreement with Ali *at al.* results was obtained [18].

As it may be easily noticed, the higher is the liquid viscosity, the lower is the Bankoff coefficient. The increase in liquid viscosity causes an increase of the liquid film thickness separating gas bubbles from the channel wall, diminishing the effective cross-section area of two-phase flow. The smaller cross-section area contributes to the increase of gas phase velocity and slip between the phases. Similarly, an increase in liquid surface tension decreases the Bankoff coefficient. The study encompassed the bubble and slug structure but an annular structure was not observed. That is why one cannot be confident as to the dependence between the mean gas void fraction and input gas volume fraction at the inlet within the scope of the annular structure.

Basing on the determined relations of the drift model, a formula defining the Bankoff coefficient was suggested. Transforming Eq. (4.3), the Bankoff coefficient may be presented as the ratio of the mean gas void fraction to the gas input volume fraction:

$$K_{\mathrm{B}} = \frac{\varepsilon_G}{\xi_G}. \tag{4.4}$$

Using Eqs. (4.1) and (4.2) and relation (3.5) defining the gas phase velocity, the Bankoff coefficient may be demonstrated in the following way:

$$K_{\mathrm{B}} = \frac{\varepsilon_G}{\xi_G} = \frac{u_{SG}}{1.2\left(\dfrac{\sigma_L}{\sigma_w}\right)^{0.32}\left(\dfrac{\mu_L}{\mu_w}\right)^{0.16} u_{TP}} \frac{u_{TP}}{u_{SG}}. \tag{4.5}$$

Finally, the relation defining the Bankoff coefficient for two-phase gas-liquid flow in mini-channels has the form:

$$K_{\mathrm{B}} = 0.83\left(\frac{\sigma_L}{\sigma_w}\right)^{-0.32}\left(\frac{\mu_L}{\mu_w}\right)^{-0.16}. \tag{4.6}$$

Substituting Eq. (4.6) to Eq. (4.1) one obtains the relation which enables determination of the theoretical value of gas void fraction in a mini-channel:

$$\varepsilon_G = 0.83\left(\frac{\sigma_L}{\sigma_w}\right)^{-0.32}\left(\frac{\mu_L}{\mu_w}\right)^{-0.16}\xi_G. \tag{4.7}$$

Figure 7 shows a comparison of gas void fractions determined experimentally and derived from Eq. (4.7) for the whole measurements. Satisfying agreement was obtained between the experimentally determined value of gas void fraction during two-phase flow in mini-channels and that calculated from Eq. (4.7). Equation (4.7) is valid in the same range of variability of parameters as Eq. (3.5).

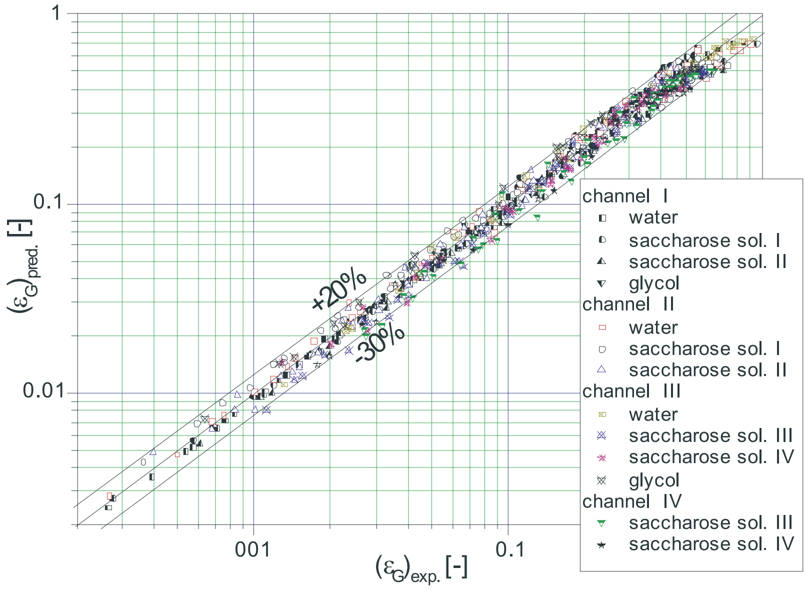

Fig. 7. The comparison of the experimentally determined value of mean gas void fraction during two-phase flow in mini-channels with the value calculated from Eq. (4.7).

5. Conclusions

The influence of selected process parameters and liquid properties on the velocity and gas void fraction during two-phase gas-liquid flow in narrow channels was established.

The drift model was applied to define the velocity and void fraction during two-phase gas-liquid flow in mini-channels. A relation was proposed to describe the distribution parameter for liquids of properties different than those of water.

A relation enabling determination of the values of mean gas void fraction in two-phase mixture flowing in a mini-channel was obtained. The value of mean gas void fraction was made dependent on the values of this fraction at the column inlet and on the liquid properties.

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