International Journal of Multiphase Flow 121 (2019) 103115

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Review

Void fraction predictive methods in two-phase flow across a small diameter channel

Marcin Pietrzak*, Małgorzata Płaczek

Opole University of Technology, Faculty of Mechanical Engineering, Department of Process Engineering, 45-271 Opole, Mikołajczyka 5, Poland

ARTICLE INFO

Article history:
Received 24 June 2019
Revised 18 September 2019
Accepted 23 September 2019
Available online 25 September 2019

Keywords:
Void fraction
Two-phase flow
Small diameter channel
Mini-channel

ABSTRACT

Predicting gas void fraction during two-phase flow in channels is a very important aspect of engineering calculations when designing process apparatus. There is a number of well known methods in the literature for calculating gas void fraction developed for two-phase flow in conventional channels. Unfortunately, there are still no of methods for calculating gas void fraction that would be applicable to two-phase flow in mini-channels. Due to the above, the paper attempts to evaluate methods for calculating gas void fraction for two-phase flow presented in literature: gas-liquid and vapour-liquid in channels of small diameter. To that end, calculation results were compared with 83 sets of experimental data for air-water flow and 171 sets for vapour-liquid flow (R717 and R744). The analysis which was carried out allowed us to select the most accurate calculation methods that can be successfully applied for calculations of gas void fraction in two-phase flow in small diameter channels.

1. Introduction

Two-phase flow studies are becoming more and more important in many engineering applications thanks to spreading of mini- and micro-devices such as compact heat exchangers that are used in power devices, supercomputers, lasers or nuclear reactors. Studies of flow at mini and micro-scale has been recently directed on devices used in biomedical and biochemical analyses.

Vapour/gas void fraction is an important parameter in determination of such values as pressure drop, heat transfer coefficient and flow patterns in many applications based on two-phase gas/vapour-liquid flow, including cooling and air conditioning systems, pipeline network systems, nuclear power systems or chemical process systems. Therefore, well-know methods for calculating gas void fraction in two-phase gas/vapour-liquid flow are of importance for designing such engineering systems.

The large, unparalleled on a macro scale, ratio of the wall surface area of mini-flow systems to the volume of fluid flowing through them can cause an increase in the impact of the walls and boundary layer on the flow pattern. In addition, relative wall roughness as well as surface tension of liquids plays an important role in mini-flow systems. A surface with a small roughness, which on a macro scale could be treated as smooth, after relating the size of the surface unevenness to the dimensions of the channel, gives a very large relative roughness, which can significantly modify the flow. The increased influence of the walls and their high relative roughness can also affect the value of the Reynolds number, at which the transition from laminar to turbulent movement occurs, and thus the working parameters determining the efficiency of mixing, heat and mass transfer change. Therefore, experimental research allows to learn about the nature of occurring phenomena, while providing material that can be used to verify the results of numerical simulation or theoretical predictions.

Up till now, studies aiming to predict gas void fraction in mini-channels were limited in comparison to studies for conventional channels. Furthermore, number of articles in this field has increased and engineering designers have trouble choosing calculation method appropriate for given flow conditions. This is mainly due to the fact that validity of published methods is often limited to specific liquids and measurement ranges, for which they have been developed.

Correlations from literature regarding calculation of gas void fraction in conventional channels can be divided into five categories, namely relations based on: homogeneous model, phase slip, $K\alpha_h$ model, drift-flux model, and individual correlations.

Correlations based on homogeneous model assume that liquid phase and gas phase flows as a homogeneous mixture with the same velocity u_{2P}. According to this model gas void fraction can be expressed with the following equation:

$$\alpha_h = \left[1 + \left(\frac{\rho_g}{\rho_c}\right)\left(\frac{1-x}{x}\right)\right]^{-1}. \tag{1}$$

* Corresponding author.
E-mail address: m.pietrzak@po.opole.pl (M. Pietrzak).

https://doi.org/10.1016/j.ijmultiphaseflow.2019.103115
0301-9322/

Nomenclature

d	hydraulic diameter of channel, m
g	gravitational acceleration, ms^{-2}
u	superficial velocity, ms^{-1}
Fr	Froude number,–
G	mass flux, $kgm^{-2}s^{-1}$
S	slip ratio,–
We	Weber number,–
x	mass fraction,–
α	void fraction,–
ρ	density, kgm^{-3}
η	dynamic viscosity, Pas
σ	surface tension, Nm^{-1}
Subscripts	
2P	two-phase mixture
g	gas
l	liquid
w	water
pred	calculated value
exp	measured value

Correlations based on the phase slip model assume that both phases flow separately with different velocities and gas void fraction is related to phase slip coefficient expressed as a ratio of gas phase velocity to liquid phase velocity, i.e. $S = u_g/u_l$:

$$\alpha = \left[1 + S\left(\frac{\rho_g}{\rho_l}\right)\left(\frac{1-x}{x}\right)\right]^{-1}. \tag{2}$$

For the homogeneous flow, gas velocity u_g and liquid velocity u_l are equal and slip coefficient $S = 1$. Moreover, correlations based on phase slip can be also expressed with Eq. (3) that involves liquid to gas mass fraction x, gas density ρ_g to liquid density ρ_l ratio, and liquid viscosity η_l to gas viscosity η_g ratio:

$$\alpha = \left[1 + A\left(\frac{\eta_l}{\eta_g}\right)^b\left(\frac{\rho_g}{\rho_l}\right)^c\left(\frac{1-x}{x}\right)^d\right]^{-1}, \tag{3}$$

where A, b, c and d are constants. This group of correlations includes among others methods developed by Lockhart-Martinelli (1949), Thom (1964), Smith (1969), Premoli et al. (1970), Chisholm (1973), Turner and Wallis (1965).

Correlations based on the correction K factor of the homogeneous model are described by the following equation:

$$\alpha = K\alpha_h. \tag{4}$$

This group of correlations includes correlations presented by Chisholm (1983) and Armand (1946).

In correlations based on drift-flux model, gas void fraction is determined by drift velocity u_{gm}, which represents difference between gas phase velocity u_g and two-phase mixture velocity u_m and so-called distribution parameter C_o. According to this model gas void fraction is calculated using the equation:

$$\alpha = \frac{u_g}{C_o u_m + u_{gm}}. \tag{5}$$

The correlations based on drift-flux model include methods developed among others by: Steiner (1993), Rouhani (1969), Nicklin et al. (1962) and Dix (1971).

2. Methods for calculating gas void fraction developed on the basis of two-phase flow in small diameter channels

Kanizawa and Ribatski (2015) have developed the Eq. (6) for calculating gas void fraction using 1877 measurement points for horizontal flow of the following types: air-water, air-Kerosene, R12, R22, R134a and R410A for channels with diameter d range from 0.5 to 13.8 mm, mass velocities range from 1.4 to 1620 $kgm^{-2}s^{-1}$ as well as saturated temperature range from 5 to 50 °C. The same authors have also developed the Eq. (7) for calculating gas void fraction for vertical upward air-water flow. This equation was developed for 1547 measurement points for channels with diameter d range from 6.0 to 89.0 mm, mass velocities range from 31 to 8477 $kgm^{-2}s^{-1}$ as well as saturated temperature range from 17 to 275 °C.

$$\alpha = \left[1 + 1.021 Fr_{2P}^{-0.092}\left(\frac{\eta_l}{\eta_g}\right)^{-0.368}\left(\frac{\rho_g}{\rho_l}\right)^{1/3}\left(\frac{1-x}{x}\right)^{2/3}\right]^{-1}, \tag{6}$$

$$\alpha = \left[1 + 14.549 We_{2P}^{-0.222}\left(\frac{\eta_l}{\eta_g}\right)^{-1.334}\left(\frac{\rho_g}{\rho_l}\right)^{1/3}\left(\frac{1-x}{x}\right)^{2/3}\right]^{-1}, \tag{7}$$

where

$$Fr_{2P} = \frac{G_{2P}^2}{(\rho_l - \rho_g)^2 g d}, \tag{8}$$

$$We_{2P} = \frac{G_{2P}^2 d}{(\rho_l - \rho_g)\sigma}. \tag{9}$$

Xu and Fang (2014) have developed a new correlation (10) for calculating gas void fraction based on the collected experimental data regarding horizontal and vertical flow of R11, R12, R22, R134a and R410A refrigerants, amounting to 1574 experimental points for channel diameter d range from 0.5 to 13.6 mm and mass fluxes ranging from 40 to 1000 $kgm^{-2}s^{-1}$.

$$\alpha = \left[1 + \left(1 + 2Fr_l^{-0.2}\alpha_h^{3.5}\right)\left(\frac{\rho_g}{\rho_l}\right)\left(\frac{1-x}{x}\right)\right]^{-1}, \tag{10}$$

where α_h is calculated using Eq. (1). The parameters in Eq. (10) cover the range of x = 0–1, Fr_l = 0.02–145 and $(\rho_g/\rho_l) = 0.004–0.153$.

Cioncolini and Thome (2012) developed a new Eq. (11) for determination of gas void fraction using 2673 measurement points for flows: steam-water, air-water, water-argon, water-nitrogen, air-alcohol, air-oil, R410A in the channel diameter d range from 1.05 to 45.5 mm, mass flux density range from 22 to 3420 $kgm^{-2}s^{-1}$, pressure range from 0.11 to 7.0 MPa, mass fraction range from 0.01 to 0.98 and inlet void fraction range from 0.7 to 0.99.

$$\alpha = \frac{hx^n}{1 + (h-1)x^n}, \tag{11}$$

where:

$$h = -2.129 + 3.129\left(\frac{\rho_g}{\rho_l}\right)^{-0.2186}, \tag{12}$$

$$n = 0.3487 + 0.6513\left(\frac{\rho_g}{\rho_l}\right)^{0.5150}. \tag{13}$$

Winkler et al. (2012a) studied flow of R134a refrigerant in mini-channels of hydraulic pipe diameters from 2.00 to 4.91 mm and mass flux density range from 150 to 750 $kgm^{-2}s^{-1}$. On the basis of 140 measurement points, they have developed a new method for determination of void fraction in mini-channels based on drift-flux model:

$$\alpha = \frac{\alpha_h}{1.131 - \frac{5.361 \cdot 10^{-3}}{u_{2P}}}, \tag{14}$$

where α_h can be calculated from Eq. (1) and u_{2P} is a velocity of two-phase mixture.

Sowiński et al. (2009) investigated two-phase flow of air-water, water-glycol and air-sucrose solution systems in mini-channels with hydraulic diameter from 1.13 to 4.01 mm, and with liquid and gas superficial velocities u_{lo} = 0.008–2.30 m/s and u_{go} = 0.006–2.11 m/s, respectively. Based on drift-flux model and the model $K\alpha_h$, the authors have developed an equation to determine gas void fraction in the form:

$$\alpha = 0.83\left(\frac{\sigma_l}{\sigma_w}\right)^{-0.32}\left(\frac{\eta_l}{\eta_w}\right)^{-0.16}\alpha_h, \tag{15}$$

where the liquid surface tension σ_l and the liquid viscosity η_l refers to the water surface tension σ_w and water viscosity η_w, respectively.

Nino (2002) in his experiments for two-phase flow of the following types: air-water, R134a, R410A in channels with hydraulic diameters of d = 1.54 and 1.02 mm, as well as mass fluxes from 50 to 300 kgm^{-2}s^{-1}, proposed to use the following equation for determination of gas void fraction:

$$\alpha = \left[1+\left(X_{tt}+\frac{1}{We_g^{1/3}}\left(\frac{\rho_l}{\rho_g}\right)^{0.9}\right)\right]^{-0.06}, \tag{16}$$

where Lockhart-Martinelli parameter X_{tt} and Weber number We_g are calculated as follows:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\eta_l}{\eta_g}\right)^{0.1}, \tag{17}$$

$$We_g = \frac{G_{2P}^2 d}{\rho_g \sigma}. \tag{18}$$

Yashar et al. (2001) in their studies on flow of R134a and R410A refrigerants in pipes with diameters of d = 7.3 and 8.9 mm, proposed an equation for gas void fraction in form (18) applicable for mass flux density of 75–700 kgm^{-2}s^{-1}, inlet qualities of 0.10–0.80 and temperature of 5 °C:

$$\alpha = \left[1+\frac{1}{Ft}+X_{tt}\right]^{-0.321}, \tag{19}$$

where the X_{tt} parameter can be calculated from Eq. (17), while Ft from the following relation:

$$Ft = \left[\frac{G_{2P}^2 x^3}{(1-x)\rho_g^2 g d}\right]. \tag{20}$$

Kopke et al. (1998), based on the experiments calculated for flow of R134a and R410A refrigerants in pipes with diameter of d = 7.04 mm and 6.04 mm, developed a equation for calculating gas void fraction, which was distinguished depending on the value of Ft parameter calculated from the Eq. (19). The test section inlet temperature was always set to 35 °C. The four mass fluxes which are tested are 75, 150, 300 and 450 kgm^{-2}s^{-1}. For the range $0.044 \le Ft \le 454$, the gas void fraction shall be calculated using the equation:

$$\alpha = 1.045 - \exp\left[-1 - 0.342\ln(Ft) - 0.0268(\ln(Ft))^2 + 0.00597(\ln(Ft))^3\right]. \tag{21}$$

For $Ft < 0.44$, gas void fraction shall be calculated from the homogeneous model (1).

Graham et al. (1997) in their studies on two-phase flow of R134a and R410A in pipe with diameter of d = 7.04 mm developed the following correlation for calculating gas void fraction by use Eq. (22). Tests that encompass a range of mass fluxes from 75–450 kgm^{-2}s^{-1} and inlet qualities of 0.13–0.9 were performed at a temperature of 35 °C.

$$\alpha = 1 - \exp\left[-1 - 0.3\ln(Ft) - 0.0328(\ln(Ft))^2\right], \tag{22}$$

where Ft can be calculated from Eq. (20).

Kawahara (2005) in own studies for adiabatic water-nitrogen two-phase flow and ethanol-water-nitrogen, tested effect of channel diameter and liquid properties on gas void fraction in horizontal micro-channels with diameters of d = 50, 75, 100 and 251 µm. The conducted analysis provoked authors to propose a new transition boundary between micro- and mini-channels in a range of channel diameters 100 and 251 µm. Measurements of gas void fraction were performed using image analysis technique. The conducted studies allow them to developed a correlation for calculating gas void fraction based on the $K\alpha_h$ model:

$$\alpha = \frac{C_1\alpha_h^{0.5}}{1-C_2\alpha_h^{0.5}} \tag{23}$$

where constants C_1 and C_2 are dependent on the channel diameter. For d = 50 µm – 0.02, 0.98, as well as for: d = 100 µm – 0.03, 0.97. Value α_h in Eq. (22) can be calculated using Eq. (1). For channels of diameter d > 251 µm, the authors recommended to use Armand method (1946) for calculations of gas void fraction.

3. Other studies on measurement of gas void fraction in small diameter channels

Barreto et al. (2015) measured of void fraction for air-water flow in the pipe with hydraulic diameter of d = 1.2 mm. The range of water and air superficial velocities were u_{wo} = 0.1–3.5 m/s and u_{go} = 0.1–34.8 m/s, respectively. Void fraction was measured by means of resistance measurement method.

De Kerpel et al. (2013) studied gas void fraction for R134a and R410A refrigerants in the pipe with diameter of d = 8 mm for variations of mass flux density from 200 to 500 kgm^{-2}s^{-1} and gas mass fraction from 0.025 to 0.975. As a result of conducted calculations and analyses, they proposed to determine the gas void fraction using Steiner (1993) method based on Rouhani-Axellson (1970) method derived from drift-flux method.

Portillo et al. (2008) studied gas void fraction for flow of refrigerants R410A in the channel with diameter of d = 3 mm for variations of mass flux density from 200 to 400 kgm^{-2}s^{-1}, at temperatures 30 and 50 °C.

Jassim and Newell (2006) developed a new model for determination of gas void fraction based on probabilistic flow regime for R134a and R410A refrigerants as well as air-water in 6-port mini-channels. Similarly, Jassim et al. (2008) developed a new model for single pipes, as well as fitted homogeneous model and other models to 427 measurement points of R11, R12, R134a, R22 and R410A refrigerants flow with mass flux density range from 70 to 900 kgm^{-2}s^{-1} and pipes diameter from 4.26 to 9.58 mm. It was found that methods by Yashar et al. (2001), Premoli et al. (1971), Steiner (1993) and Smith (1969) show the best accuracy of calculations.

Adams et al. (2006) studied gas void fraction for adiabatic flow of carbon dioxide and ammonia using 6- and 14-port mini-channels with diameter of d = 1.54 mm and 1.02 mm. Mass flux density of gas in this experiment was varied from 50 to 300 kgm^{-2}s^{-1} while gas mass fraction varied between 0 and 1. The result show that gas void fraction depends on the channel hydraulic diameter, mass flux and two-phase flow patterns.

Wojtan et al. (2005) compared the homogeneous model and other calculation models with experimental data for flow of R22 and R410A refrigerants with pipes diameter of d = 13.6 and 8 mm. It was found that Steiner method (1993) is the most accurate with calculations of gas void fraction.

Koyama et al. (2004) studied gas void fraction for adiabatic flow of R134a refrigerant in a smooth pipe with internal diameter of d = 7.52 mm. Mass flux density in this experiment from 125 to 250 kgm^{-2}s^{-1} whereas gas mass fraction varied from 0.01 to

Table 1
Characteristics of experimental data.

Authors	Type of flow	Hydraulic diameter, *d* [mm]	Mass flux density, G_{2P} [$kgm^{-2}s^{-1}$]	Temperature, *t* [°C]	Number of experimental points
Wongwises and Pipathattakul (2006)	Air-water	8	69–4600	20	41
Triplett et al. (1999)	Air-water	1.097–1.49	60-6000	25	42
The total number of experimental points for air-water flow					83
Adams et al. (2006)	R744	1.02	50–300	15	71
Adams et al. (2006)	R717	1.02–1.54	100–300	35	100
Σ					**251**

Table 2
Comparison of measured and calculated gas void fraction.

Authors	Air-water $d = 8$ mm		Air-water $d = 1.097–1.49$ mm		R744 $d = 1.02$ mm		R717 $d = 1.02–1.54$ mm	
	MAE %	*MRE %*	*MAE %*	*MRE %*	*MAE %*	*MRE %*	*MAE %*	*MRE %*
Correlations for flow in small diameter channels								
Kanizawa and Ribatski (2015)	11.8	−6.9	22.8	0.6	6.9	−3.1	12.8	12.6
Xu and Fang (2014)	13.8	5.0	20.4	11.8	14.3	−12.5	17.1	17.1
Cioncolini and Thome (2012)	19.1	15.2	25.5	19.8	8.3	0.1	14.2	14.1
Winkler et al. (2012)	13.2	1.4	16.2	7.5	12.7	−1.3	8.1	1.8
Sowiński et al. (2009)	17.8	−12.1	17.3	−7.5	–	–	–	–
Nino (2002)	41.4	24.9	15.1	11.0	26.2	26.2	10.5	−7.7
Yashar et al. (2001)	15.5	−4.9	26.3	5.1	7.0	4.6	14.2	14.1
Kopke et al. (1998)	18.8	6.1	37.2	26.2	8.7	4.3	20.5	1.0
Graham et al. (1997)	23.1	13.5	36.6	19.3	8.6	−1.3	16.6	16.6
Correlations for flow in conventional channels								
Lockhart-Martinelli (1949)	20.2	−18.2	25.2	−14.1	10.3	9.7	14.5	14.4
Baroczy (1966)	25.5	−22.6	31.3	−18.8	15.3	−12.9	16.1	9.8
Smith (1969)	11.9	−5.1	17.2	0.2	12.8	−7.7	15.7	15.7
Premoli et. al. (1970)	44.8	−44.5	50.7	−50.7	33.3	33.2	69.9	−69.9
Steiner (1993)	12.5	−6.4	21.6	−4.4	16.6	−13.2	10.3	9.8
Homogeneous model	19.7	11.4	22.4	17.1	11.1	0.3	17.1	17.1

0.96. They compared the homogeneous model and other calculation models with experimental data and concluded that the best calculation methods are the ones proposed by Smith (1969) and Baroczy (1966).

Triplett et al. (1999) measured gas void fraction and pressure drop in transparent mini-channels for two-phase flow of air-water type. The studies involved use of channel with circular and triangular cross-section for range of channels hydraulic diameter from 1.09 to 1.49 mm. The authors compared experimental data with existing calculation methods developed for conventional channels. It was found that homogeneous model gives the best fit to experimental results for calculations of gas void fraction.

Bao et al. (1994) investigated the gas void fraction in smooth vertical and horizontal circular pipes with diameter from 0.74 to 3.07 mm. The systems such as air and liquids including water, water with glycerine and kerosene have been tested. The experiments were conducted in range of Reynolds number for liquid phase $Re_l = 0.05$-4000 and for gas phase $Re_g = 15$-12,000. It was stated that both methods propose by Lockhart-Martinelli (1949) and Premoli et al. (1971) allow to calculate of gas void fraction with satisfactory accuracy.

4. Results

Table 1 presents characteristic of the analysed experimental data set for air-water flow and for environmentally-friendly R744 and R717 refrigerants. The experimental data derived from was used to evaluate the accuracy of above-presented methods for calculating gas void fraction.

Statistical analysis includes determination of mean absolute error *MAE* and mean relative error *MRE*:

$$MAE = \frac{1}{N}\sum_{k=1}^{N}\left|\frac{\alpha_{i,pred} - \alpha_{i,\exp}}{\alpha_{i,\exp}}\right|100\%, \tag{24}$$

$$MRE = \frac{1}{N}\sum_{k=1}^{N}\frac{\alpha_{i,pred} - \alpha_{i,\exp}}{\alpha_{i,\exp}}100\%. \tag{25}$$

Table 2 presents results of statistical analysis for discussed methods for calculations of gas void fraction separately for air-water flow in a channel with diameter of 8 mm and 1.097–1.49 mm and for flow of R744 and R717 refrigerants in channels with diameters of 1.02 and 1.54 mm. Additionally, statistical analysis was done separately for methods developed for the channels of small diameters and for methods developed for conventional channels that are recommended in the literature for calculating gas void fraction in mini-channel for flow of refrigerants, mainly R134a and R410A.

As shown by the statistical analysis presented in Table 2, the best results of calculating gas void fraction in conventional channels of small pipe diameter ($d = 8$ mm) can be obtained using methods proposed by Kanizawa and Ribatski (2015), Xu and Fang (2014), Winkler et al. (2012b) that were developed for small diameter of channels, and methods by Smith (1969), Steiner (1993) and Lockhart-Martinelli (1949) recommended for conventional channels.

In case of air-water flow in channels with diameter range from 1.097 to 1.49 mm, the best accuracy was found for methods proposed by Winkler et al. (2012a), Xu and Fang (2014) and Kanizawa and Ribatski (2015) based on mini-channels, and

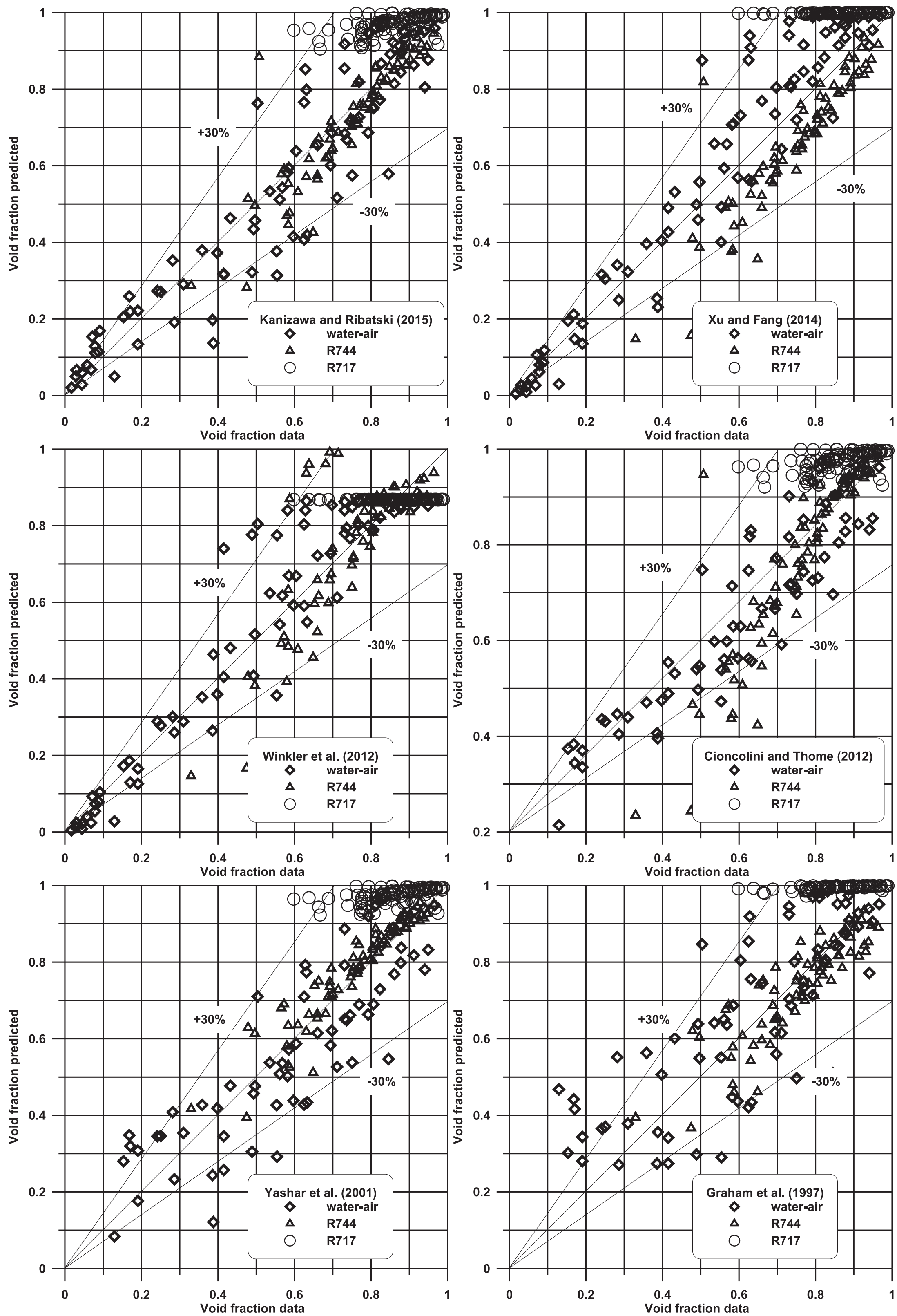

Fig. 1. Comparison of measured and calculated gas void fraction using methods developed for small diameter channels.

methods by Smith (1969), Steinera (1993) and Lockhart-Martinelli (1949) based on the conventional channels. For calculating gas void fraction in flow of R744 and R717 refrigerants all the presented calculation methods proved to be successful, while the best calculation methods of gas void fraction for R717 refrigerant proved to be: Kanizawa and Ribatski (2015), Cioncolini and Thome (2012), Yashara et al. (2001), Graham et al. (1997), Kopke et al. (1998), Winkler et al. (2012b), Xu and Fang (2014), Lockhart-Martinelli (1949), and Smith (1969). In order to calculate the gas void fraction in flow of R717 refrigerant, it is

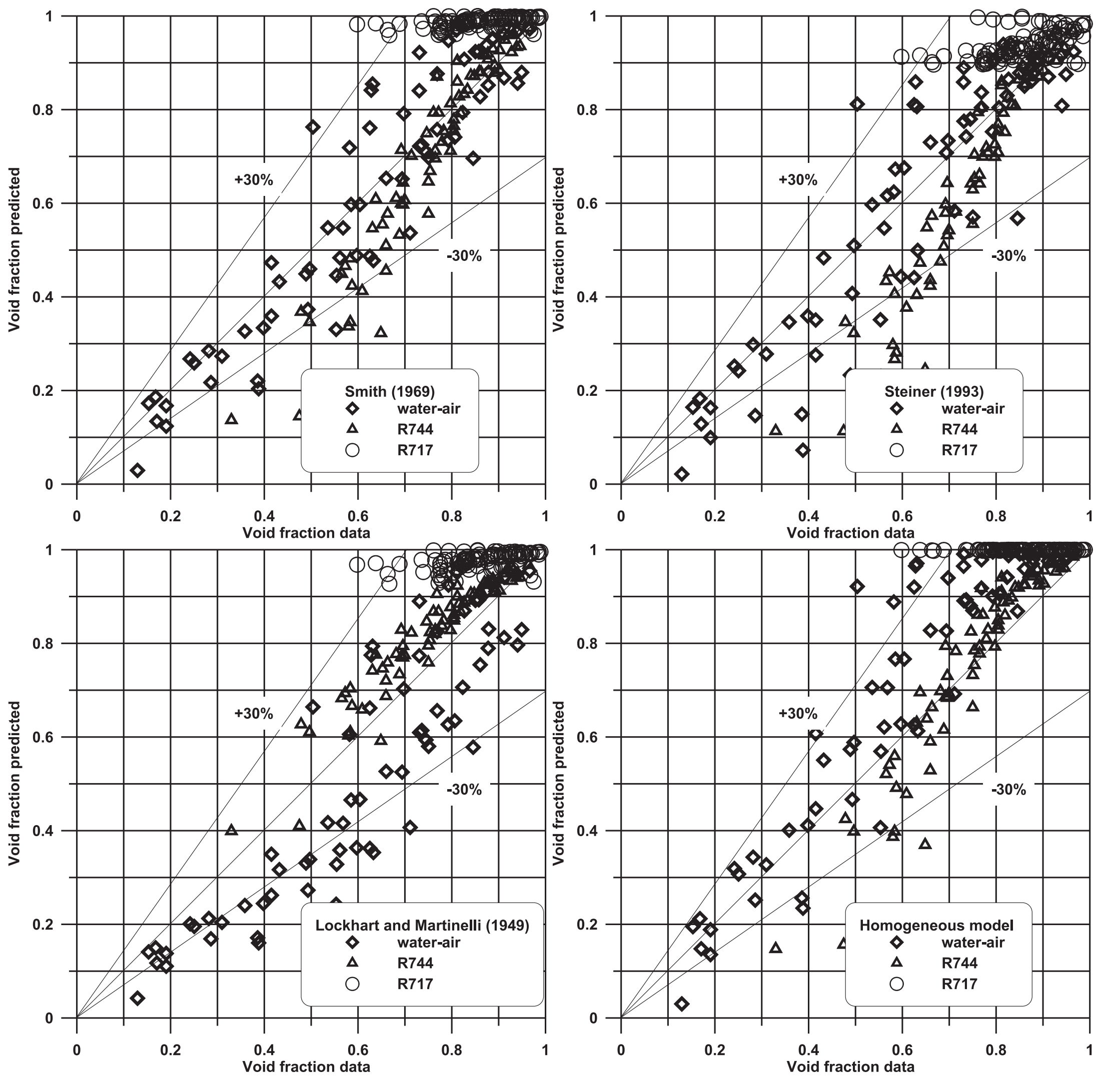

Fig. 2. Comparison of measured and calculated gas void fraction using methods developed for conventional channels and homogeneous model.

convenient to use methods developed by Winkler et al. (2012a), Cioncolini and Thome (2012), Xu and Fang (2014), Kanizawa and Ribatski (2015) Steiner (1993), and Lockhart-Martinelli (1949). It should be noted that the homogeneous model also shows a good fit of calculations to measurement results for analysed flow conditions.

Figs. 1 and 2 present a comparison of measured and calculated gas void fraction using selected calculation methods developed for mini-channels and conventional channels. The analysis of data (Figs. 1 and 2) shows that average scatter of measurement points is in range of ±30% of MAE, which according to many papers in that field, is treated as satisfactory.

5. Summary and conclusions

The paper presents the comparison of methods for calculating gas void fraction using the collected experimental data, both gas-liquid and vapour-liquid two-phase flow in mini- and macrochannels. The results indicate that methods developed based on the flow in mini-channels, such as ones proposed by Kanizawa and Ribatski (2015) as well as Xu and Fang (2012) provide good predictability for three types of flow analysed in this paper, i.e. air-water, R744 and R717. When using calculation methods developed for flow in conventional channel, the following methods are convenient to use for calculation of gas void fraction: Smith's (1969) and Steiner's (1993).

Discussed paper issues should be continued, both in terms of research and analysis, in order to develop a "universal" method for calculations of real gas void fraction during two-phase flow in small hydraulic diameter channels that would be applicable to a wide range of two-phase flow parameters.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijmultiphaseflow.2019.103115.

References

Adams, D.C., Burr, J., Hrnjak, P., Newell, T., 2006. Void Fraction of CO2 and ammonia in multiport aluminum micro-channel tubes. International Refrigeration and Air Conditioning Conference, Paper 741. Purdue University, United States.

Armand, A.A., 1946. The resistance during the movement of a two-phase system in horizontal pipes. IzvVseTepl Inst. 1, 16–23.

Bao, Z.Y., Bosnick, M.G., Haynes, B.S., 1994. Estimation of void fraction and pressure drop for two-phase flow in finepassages,Trans. Inst. Chem. Eng. 72, 625–632.

Baroczy, C.J., 1966. A systemic correlation for two phase pressure drop. Chem. Eng. Progr. Symp. Ser. 62, 232–249.

Barreto, E.X., Oliveira, J.L.G., Passos, J.C., 2015. Frictional pressure drop and void fraction analysis in air–water two-phase flow in a micro-channel. Int. J. Multiphase Flow 72, 1–10.
Chisholm, D.A., 1973. Pressure gradients due to friction during the flow of evaporating two-phase mixture in smooth tubes and channels. Int. J. Heat Mass Transf. 16 (2), 347–358.
Chisholm, D.A., 1983. Two Phase Flow in Pipelines and Heat Exchangers. George Godwin in association with The Institution of Chemical Engineers, London.
Cioncolini, A., Thome, J.R., 2012. Void fraction prediction in annular two-phase flow. Int. J. Multiphase Flow 43, 72–84.
De Kerpel, K., Ameel, B., T'Joen, C., Caniere, H., De Paepe, M., 2013. Flow regime based calibration of a capacitive void fraction sensor for small diameter tubes. Int. J. Refrig. 36 (2), 390–401.
Dix, G.E., 1971. Vapor Void Fractions for Forced Convection with Subcooled Boiling at Low Flow Rates. University of California, Berkeley, USA.
Graham, D.M., Newell, T.A., Chato, J.C., 1997. Experimental Investigation of Void Fraction During Refrigerant Condensation, ACRC TR-135. University of Illinois at Urbana-Champaign, USA.
Jassim, E.W., Newell, T.A., 2006. Prediction of two-phase pressure drop and void fraction in micro-channels using probabilistic flow regime mapping. Int. J. Heat Mass Transf. 49 (15-16), 2446–2457.
Jassim, E.W., Newell, T.A., Chato, J.C., 2008. Prediction of refrigerant void fraction in horizontal tubes using probabilistic flow regime maps. Exp. Therm. Fluid Sci. 32 (5), 1141–1155.
Kanizawa, F.T., Ribatski, G., 2015. Void fraction predictive method based on the minimum kinetic energy. J. Braz. Soc. Mech. Sci. Eng. 38 (1), 209–225.
Kawahara, A., Sadatomi, M., Okayama, K., Kawaji, M., Chung, P.M.-Y., 2005. Effects of channel diameter and liquid properties on void fraction in adiabatic two phase flow through micro-channels. Heat Transf. Eng. 26 (3), 13–19.
Kopke, H.R., Newell, T.A., Chato, J.C., 1998. Experimental Investigation of Void Fraction During Refrigerant Condensation in Horizontal tubes, ACRC TR-142. University of Illinois at Urbana-Champaign, USA.
Koyama, S., Lee, J., Yonemoto, R., 2004. An investigation on void fraction of vapor-liquid two-phase flow for smooth and microfin tubes with R134a at adiabatic condition. Int. J. Multiphase Flow 30 (3), 291–310.
Lockhart, R.W., Martinelli, R.C., 1949. Proposed correlation of data for isothermal two-phase, two component flow in pipes. Chem. Eng. Prog. 39–48.
Nicklin, D.J., Wilkes, J.O., Davidson, J.F., 1962. Two-phase flow in vertical tubes. Trans. Inst. Chem. Eng. 40, 61–68.
Nino, V.G., 2002. Characterization of Two-Phase Flow in Micro-Channels. University of Illinois at Urbana-Champaign, USA.
Portillo, G., Shedd, T.A., Lehrer, K.H., 2008. Void Fraction measurement in mini-channels with in-situ calibration. International Refrigeration and Air Conditioning Conference Paper 887.
Premoli, A., Francesco, D., Prima, A., 1970. An Empirical Correlation For Evaluating Two-Phase Mixture Density Under Adiabatic Conditions. European Two-Phase Flow Group Meeting, Milan, Italy.
Rouhani, S.Z., Axelsson, E., 1970. Calculation of void volume fraction in the sub cooled and quality boiling regions. Int. J. Heat Mass Transf. 13 (2), 383–393.
Rouhani, Z., 1969. Modified Correlations For Void and Two-Phase Pressure Drop (No. AE-RTV-8841). Aktiebolaget Atomenergi.
Smith, S.L., 1969. Void fractions in two-phase flow: a correlation based upon an equal velocity head model. Proc. Inst. Mech. Eng., Lond. 184 (1), 647–657 Part I.
Steiner, D., 1993. Heat Transfer to Boiling Saturated Liquids. VDI-Gessellschaft Verfahrenstechnikund Chemiein genieurwesen (GCV), Düsseldorf VDI-Wärmeatlas (VDIHeat Atlas), Verein Deutscher Ingenieure.
Sowiński, J., Dziubiński, M., Fidos, H., 2009. Velocity and gas-void fraction in two-phase liquid-gas flow in narrow mini-channels. Arch. Mech. 61 (1), 29–40.
Thom, J.R.S., 1964. Prediction of pressure drop during forced circulation boiling of water. Int. J. Heat Mass Transf. 7 (7), 709–724.
Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khalik, S.I., LeMouel, A., McCord, B.N., 1999. Gas- liquid two-phase flow in micro-channels: part II: void fraction and pressure drop. Int. J. Multiphase Flow 25, 395–410.
Turner, J.M., Wallis, G.B., 1965. The Separate-Cylinders Model of Two-Phase Flow. Thayer's School Eng., Dartmouth College, Hanover, NH, USA Paper No. NYO-3114-6.
Winkler, J., Killion, J., Garimella, S., 2012a. Void fraction for condensing refrigerant flow in small channels. Part II: void fraction measurement and modeling. Int. J. Refrig. 35 (2), 246–262.
Winkler, J., Killion, J., Garimella, S., Fronk, B.M., 2012b. Void fraction for condensing refrigerant flow in small channels: part I literature review. Int. J. Refrig. 35 (2), 219–245.
Wojtan, L., Ursenbacher, T., Thome, J.R., 2005. Measurement of dynamic void fractions in stratified types of flow. Exp. Therm. Fluid Sci. 29 (3), 383–392.
Wongwises, S., Pipathattakul, M., 2006. Flow pattern, pressure drop and void fraction of two-phase gas–liquid flow in an inclined narrow annular channel. Exp. Therm. Fluid Sci. 30 (4), 345–354.
Xu, F., Fang, X., 2014. Correlations of void fraction for two-phase refrigerant flow in pipes. App. Therm. Eng. 64, 242–251.
Yashar, D.A., Graham, D.M., Wilson, M.J., Chato, J.C., Kopke, H.R., Newell, T.A., 2001. Investigation of refrigerant void fraction in horizontal microfin tubes. HVAC&R Res. 7, 67–82.