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Experimental investigation of void fraction in horizontal air-water flow through FeCrAlY foam

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Abstract

The paper presents the experimental results relevant to gas void fractions under conditions of the two-phase air-water flow through a horizontal pipe which was packed with open cell steel foam. The experimental data were used to evaluate whether the models were valid which had been suggested for prediction of volumetric phase void fractions in two-phase gas-liquid mixtures flowing in channels with porous packing materials. The verified mathematical models in most cases turned out incapable of predicting the volumetric phase void fractions with the acceptable accuracy. Among the analysed methods, the best agreement of experimental and calculated gas void fraction values was obtained for the model by Ford [17].

Keywords: Steel foam; horizontal gas-liquid flow; gas hold-up, co-current flow

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1. Introduction

The cellular materials with open structures, the so-called solid open cell foams, may be produced of various materials like polymers, mineral materials and/or metals [1,2].

Nomenclature

A	pipe cross-section area, m^2
G	gas phase mass flow rate, kg/s
K	permeability, m^2
L	liquid mass flow rate, kg/s
Q	volume flow rate, m^3/s
V	volume, m^3
d_p	pore diameter, m
n	number of experimental points
u_{sg}	superficial gas velocity, m/s
u_{sl}	superficial liquid velocity, m/s
Greeks	
χ	Lockhart-Martinelli parameter
δ	porosity
ε_g	gas void fraction
ε_l	liquid void fraction
ξ_g	inlet gas void fraction
ξ_l	inlet liquid void fraction
μ	viscosity, Pa·s
ρ	density, kg/m^3
Re	Reynolds number
Subscripts/Superscripts	
calc	calculated
exp	experimental
f	fluid
g	gas phase
g(l)	alternatively gas or liquid

l	liquid phase
p	pore
s	solid, superficial

The metal foam manufacturing processes make it possible to expand various metal alloys, hence they are capable of producing foams with a wide variability of such physical properties like thermal conductivity, thermal and chemical resistance, density (relative), rigidity, etc. The production methods and properties of metal foams were presented extensively by Banhart [3].

Because of their high voidages (up to 97%) and high specific surface area values, the metal foams are applicable in the construction of heat exchange and/or mass transfer flow equipment. By way of example, one may specify compact high-efficiency heat exchangers, heat regenerators and accumulators, catalytic reactors and packed columns. Numerous examples can be found in reports for the advantages resulting from the use of porous materials with high thermal conductivity and large surface area values, e.g. heat sinks which improve heat transfer considerably and thus are widely employed in various industrial outlets [4,5]. Super light-weight items which incorporate porous materials are commonly used as parts of aircraft equipment, or they make elements of compact heat exchangers which dissipate heat from electronic systems [6-8]. The experimental results obtained by Kim et al. [5] show that the use of aluminium foam heat sinks improves the heat transfer conditions by more than 30% in relation to high-efficiency plate fin heat exchangers. Zhao et al. [9] demonstrated that the heat exchange rate for the boiling fluid flowing along horizontal tubes which were packed with copper foam was three times higher than in plain tubes. The benefits which result from the use of metal foams in liquid boiling processes were also highlighted by the authors of [10] and [11].

Reduced pressure drop, more advantageous hydrodynamic conditions (higher turbulence of the liquid phase) and wider area of stable operating conditions for a piece of equipment considered make some of principal advantages of foamed metal structural packing as referred to other classical packing systems. Also, a relatively highly extended surface allows for the use of higher feed loads to catalysts in chemical reactors. That provides a better phase contact in multi-phase systems which yields directly improved mass transfer conditions [12]. According to Stemmet [2], flooding under counter-current flow conditions makes one of some few factors which impose restraints in the use of that type of packing in actual industrial processes. Continual efforts to reduce costs, to optimise and to intensify chemical processes (hydrodynamics of flow, heat exchange and mass transfer) drive the research programmes in which those packing types are tested and compared with more conventional packing types or with spherical particles used as packing [2,12-15].

The literature data show that the experiments within metal foams are directed on the one hand at developing new materials with improved performance parameters which satisfy pre-defined hydraulic and thermal requirements, and on the other hand at operational optimisation of the equipment in which such materials are to be installed. Few research studies were carried out to define the optimum properties and to model the fluid transfer in metal foams, and additionally those studies were restricted to the single-phase flow only.

The research projects within chemical engineering cover first of all multi-phase flows in packed columns and in catalytic reactors. In both those cases, such design parameters as friction factor, pressure drop, bubble size, phase void fraction, heat and mass transfer coefficients, need to be known for reliable engineering. Hence, the process design and/or equipment design procedures must involve the formulas to predict the values of those parameters with good accuracy. The thermal and hydrodynamic processes which appear under single-phase flow conditions through cellular materials may be declared to be pretty

well known and understood. Our knowledge is much poorer on multi-phase flows. A few literature reports are available only on the gas-liquid flow through foamed metal structures installed in column-type (vertical) equipment [2]. Which is especially painful is the lack of research reports on multi-phase flows through process equipment and pipes with horizontal orientation.

This study attempts to describe the volumetric void fraction ε for the gas-liquid flow along the horizontal pipe which has been packed with the type FEC steel foam prepared from the FeCrAlY alloy. The void fraction is the key physical value for determining numerous other important parameters such as two-phase density and viscosity for obtaining the relative average velocity of the two phases, and it is of fundamental importance in models which predict the flow pattern transition, heat transfer and pressure drop values. The volumetric void fraction, called just void fraction, for the two-phase gas-liquid flow is defined as [16]:

$$\varepsilon_{g(l)} = V_{g(l)} / (V_g + V_l) \quad (1)$$

In practice, the formula (1) does not make it possible to calculate the volumetric void fractions since the actual volumes (V_f) taken up by individual phases inside a channels are not known. That is the case for the definite majority of the flowing multi-phase systems [16]. In the absence of mathematical models to calculate the volumetric void fractions for a two-phase flow in the pipes packed with a FEC foam, the authors conducted their independent research tests. The findings from those tests were referred to the mathematical relations as published in literature for the prediction of the void fraction values in two-phase gas-phase mixtures which are passed through pipes or columns which had been packed with porous materials.

The models were verified which had been developed by Ford [17], Larkins and White [18], Weber [19],Turpin and Huntington [20], Saada [21,22]. Most of those correlation were derived for the air-water system and at moderate up to large liquid- and gas-phase Reynolds numbers. The correlations were based on superficial velocities, Reynolds numbers or mass fluxes, and they differ distinctly in the way they correlate the void fractions as functions of flow conditions. However, all those studies involve the liquid flows through the bulk material bed sand they give no consideration to the case which was analysed within the authors' research.

2. Experimental equipment and procedure

2.1. Experimental set-up

The two-phase gas-liquid flow tests, for the water-air system, were conducted at the test stand as presented in Fig. 1. The principal component of the stand is a horizontal test pipe (TP) with the internal diameter of 21.7 mm and the total length of 2.84 m. The test pipe is make up of three parts: leader part with the length of 0.98 m, measuring section with the length of 1.38 m, and discharge part (0.48 m long) made of plexiglass. That section allowed the researchers to observe the flow patterns which were formed under given flow conditions.

The leader part of the test pipe was utilised to stabilise the flow parameters and a specific flow pattern could be formed there which resulted from the ratio of the feed streams and from the properties of the phases which were charged to the pipe. The measuring length was packed with foamed high-alloy steel FeCrAlY (FEC) with the pore packing density of 40 PPI, produced by Porvair. The average cell diameter in that metal foam amounted to 1.6 mm, and its porosity was 91.4%. Fig. 2 presents a picture of the FEC foam. Air was fed to the stand directly from the compressed air system, while water was taken from the

water tank (TW) and it was supplied by the impeller pump (PW). The water flow rate was measured with the use of the electronic turbine flowmeters from Kobold (FW) with the measuring accuracy of 1.5%, while the air flow rate was measured at the accuracy of 0.3%, with a mass flowmeter.

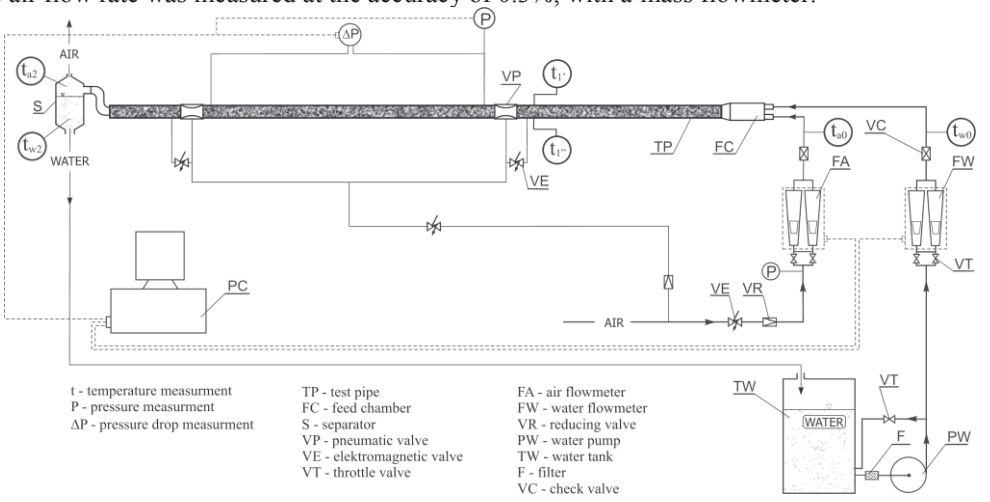


Fig. 1. Diagram of test stand

a) b)

Fig. 2. View of tested FEC foam: a) channel packing; b) pore structure

The temperature values of both test media (T) were established with Ni-Cr-Ni thermocouples. The output signals from measuring instruments were recorded by the computerised data registration system (PC).

2.2. Experimental procedure

The experiments involved the measurements of pressure drop and phase void fraction values. The flow patterns were also observed visually. The test conditions were provided in Table 1.

Table 1. Specification of test conditions

Fluid	$\mathbf{u_{sf}}$, m/s	$\mathbf{Re_f}$, -	ξ_f, -
Air	0.063 ÷ 1.074	0.5 ÷ 9.57	0.295 ÷ 0.988
Water	0.013 ÷ 0.116	2.33 ÷ 15.7	0.12 0.705

The values specified in Table 1 can be calculated from the equations as presented below:

- superficial gas velocity

$$u_{sg} = (Q_g/A) \tag{2}$$

- superficial liquid velocity

$$u_{sl} = (Q_l/A) \tag{3}$$

The Reynolds number values are calculated as:

$$Re_f = (u_{sf} K^{0.5} \rho)/\mu \tag{4}$$

where: K stands for permeability [m^2].
The inlet void fraction for gas or liquid phase is defined as

$$\xi_{g(l)} = Q_{g(l)} / (Q_g + Q_l) = [u_{s,g(l)}/(u_{sg+} u_{sl})] \tag{5}$$

The sum of gas and liquid void fractions for the two-phase flow is equal to 1.

Before every series of two-phase tests, water was fed to the test pipe and the flow of that single-phase system was stabilised. Then, a series of measurements was taken: the flow rate of liquid was fixed and the flow rate of gas was increasing. The flow was stabilised for a measuring point and the following measurements were taken (and recorded) at the same time: flow rates of individual media, temperatures of those streams, and pressure drop. The flow patterns were also observed visually which were formed in the test pipe. A set of thermocouples was employed to measure temperatures of both components of the two-phase mixture, at the inlet to and at the outlet from the test pipe. Changes in temperatures of individual components were each time taken into consideration when calculating the properties of those media; the average value was taken of the inlet and outlet temperatures.

The volumetric method which is generally referred to as a trap method was used to measure the volume fraction of water in the flowing air-water mixture. The measurement of actual volume fractions in that method came down to closing quickly and simultaneously the inlet to and outlet from the measuring section of the test pipe with the use of two pneumatically controlled membrane valves (VP). When closed at the same time, the valves trapped a volume of the test mixture in the measuring section with the phase composition which was specific for given flow conditions. The trapped liquid was then displaced with compressed air to a graduated cylinder to learn its volume. Once the volume of water was known, and the

fixed volume of the measuring section was known, too, the actual void fractions could easily be obtained for both phases involved in tests.

At least three measurements were taken for each measuring point. The arithmetic mean of those measurements was accepted as the value of the measured actual void fraction. The measurements were taken for six constant superficial velocities of water which were changed within 0.013÷0.116 m/s (Table 1) and for more than ten air velocity values; 72 averaged measuring points were obtained in that way.

Since the Lockhart-Martinelli method was utilised in the comparative calculations, for which unit pressure drop values should be available, the study involved also evaluation of the pressure drop (Fig. 1). The pressure drop (ΔP) was measured over the length of 1.1 m with the use of the electronic differential pressure sensors.

3. Experimental results

Within the experimental programme, applicability was verified for the models which were presented in the papers to calculate the void fraction for the gas flowing through channels with various spatial orientations and packed with porous materials. The evaluated calculation models were specified in Table 2. The table also provides the information on the test conditions for which individual calculation models were developed.

Different forms of correlation equations which are used to describe gas (or liquid) void fractions (Table 2) result mainly from different research procedures assumed by individual researchers, from the use of different porous packing beds, from different geometry of test systems, from different scopes assumed for changes in gas/liquid flow parameters, and/or from different correlation methods applied to experimental data.

The results of authors' tests within evaluation of gas void fraction in the flow through the FEC foam were presented in Figs 3-6.

Fig. 3 shows the changes in gas void fraction values (for the analysed FEC foam) as a function of gas and liquid superficial velocities, for each method of analysis. The profiles in the plots demonstrate that the gas void fraction increases for the increasing superficial gas velocity. Fig 4 indicates that for most experimental data at the same superficial gas velocity increasing in liquid velocity provided decreases of gas void fraction. Change in this trend was connected with flow patterns transition from stratified to plug flow.

The selected calculation methods yield much divergent results when applied to the authors' experimental findings (Fig. 3). The methods developed by Larkins and White [18], by Saada [21], and by Weber [19] give the calculation results which are over rated or much under rated. That can be accounted for by the fact that most of those methods pertain to the flow through loosely "poured" systems, e.g. packed columns, mineral sand, Raschig rings. The best approximation was obtained for the methods by Ford [17] and Turpin et Huntington [20]. The calculated results were similar to experimental ones in both cases, they differed by about 25% (*in* +), which should be found satisfactory as compared to the results of other methods.

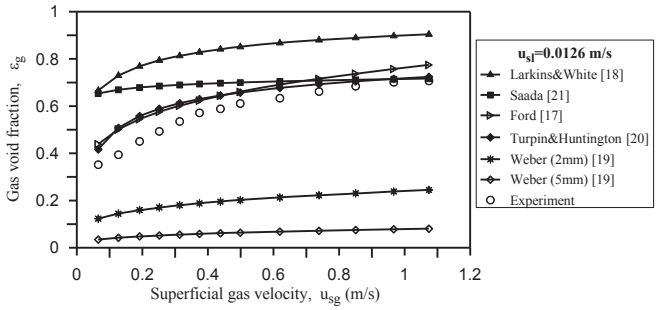
The detailed comparison for the measured and calculated values of the phase void fractions, for 4 selected methods, is provided in Fig. 6. Additionally, Table 3 presents the statistical analysis of the calculation results. Table 3 gives Root Mean Square (RMS) deviations and the relative error (δ(ε)) of the experimental data with the correlations reported in Table 2. The RMS deviation is estimated from the following equation:

$$RMS = \left[\frac{1}{n} \left(\sum_{n=1}^{n} \left(\frac{x_{exp} - x_{calc}}{x_{exp}} \right)^2 \right) \right]^{0.5} \quad (6)$$

Table 2. Correlation for prediction of gas and liquid void fraction

Author(s)	System	Type and packing size/system geometry (m)	Correlation	Range of application
Ford [17]	air-water	Spheres: 1×10^{-3} Column diameter : 4.52×10^{-2}	$\varepsilon_g = 0.212(Re_g/Re_l)^{0.2}(\mu_l/\mu_g + 0.182(L/G)^{0.24}$	Turbulent flow, single and two-phase pore flow
Larkins and White [18]	vertical downward flow: air-water air-water (methyl-cellulose) air-water (0.033% soap) air-ethylene glycol natural gas-kerosene natural gas-lube oil CO_2-lube oil,	Raschig rings: 9.52×10^{-3} 3.17×10^{-3} Cylinders: 3.17×10^{-3} Glass beads: 3×10^{-3} Column diameter: 0.508×10^{-2} $101{,}6 \times 10^{-2}$	$\log_{10}\varepsilon_l = -0.774 + 0.525(\log_{10}\chi) - 0.109(\log_{10}\chi)^2$ where: $\chi = [(\Delta P_l/L)/\Delta P_g/L)]^{0.5}$	$5 \leq \delta \leq 0.52$ $0.05 < \chi < 30$ Homogenous and heterogeneous flow regime
Weber [19]	air-water	Spheres: 2×10^{-3} 5×10^{-3} Cylinders: $a \times b = (4 \times 10) \times 10^{-3}$ Raschig rings 6.2×10^{-3}	$\varepsilon_g = 0.079\ u_{sg}^{0.3}$ $\varepsilon_g = 0.078\ u_{sg}^{0.24}$	For d_s=5 mm and cylinders For d_s=2 mm
Turpin and Huntington [20]	air-water	Tubular alumina particles: 7.62×10^{-3} 8.23×10^{-3} Column diameter: 5×10^{-2} 10×10^{-2} 15×10^{-2}	$\varepsilon_l = -0.035 + 0.182(L/G)^{0.24}$	$1 \leq (L/G)^{0.24} \leq 6$ Bubble flow, pulse, spray flow
Saada [21,22]	air-water	Spheres: 5.14×10^{-4} 9.73×10^{-4} 20.64×10^{-4} Column diameter: 4.52×10^{-2}	$\varepsilon_l = K(Re/Re_g)^a$ Transition point exist for: $Re_g^* = 0.44 Re_l^2 (d_s/d_c)^{0.38}$ below transition point: $K = 0.48$ and $a = 1.25$ above transition point: $K = 0.32$ and $a = 0.07$	Bubbly and churn turbulent flow regimes

a)



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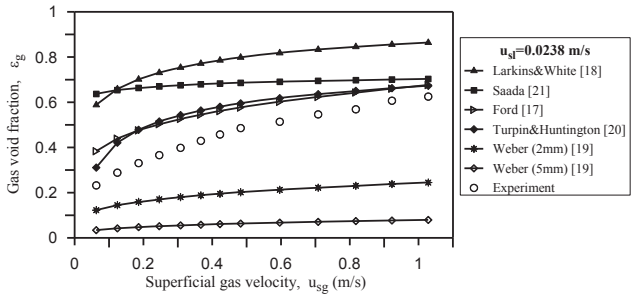

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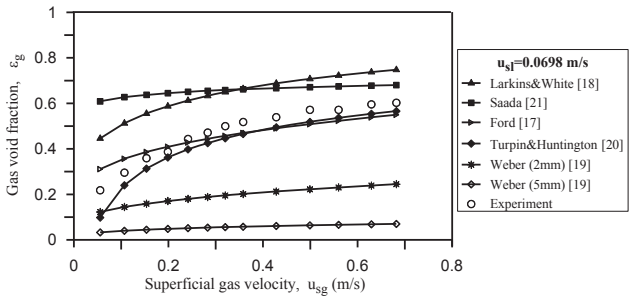

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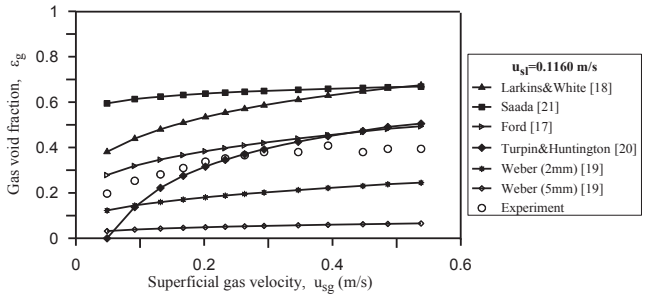

Fig. 3. Gas void fraction according to analysed methods, versus superficial gas velocity, at constant superficial liquid velocity values: a) u_{sl}=0.0126 m/s, b) u_{sl} = 0.0238 m/s, c) u_{sl} = 0.0698 m/s, d) u_{sl} = 0.116 m/s

It is essential to compare the void fraction value at the measuring section inlet with the bulk mean value as measure in the section. Those values were related against each other as $\varepsilon_i=f(\xi_i)$ in Fig. 5. The test results suggest that the actual gas void fraction in a two-phase mixture (ε_g) is much less than one could expect from the inlet gas void fraction (ξ_i). This phenomenon is particularly evident in the case of stratified flow, when the gas phase flows in the upper part of the measuring channel with a much higher velocity than the liquid phase. This phenomenon is called interfacial slip.

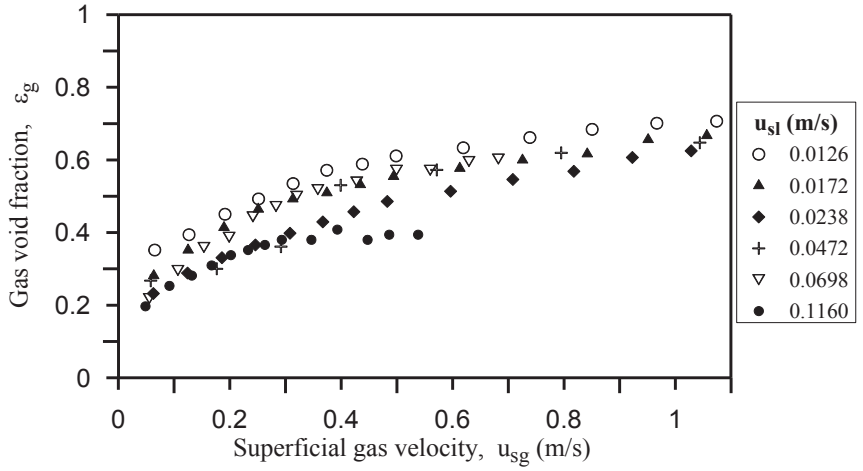

Fig.4. Experimental gas void fraction as a function of superficial gas velocity

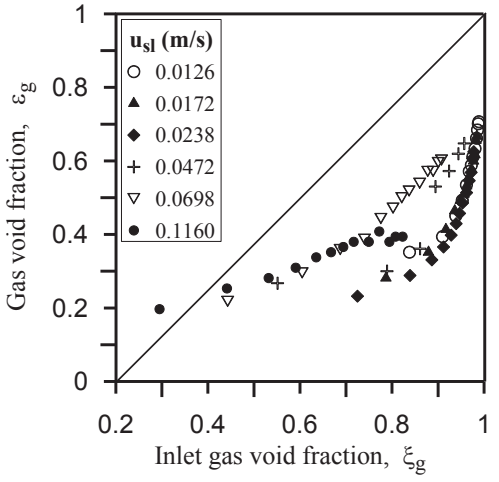

Fig. 5. Comparison of measured and inlet gas void fraction

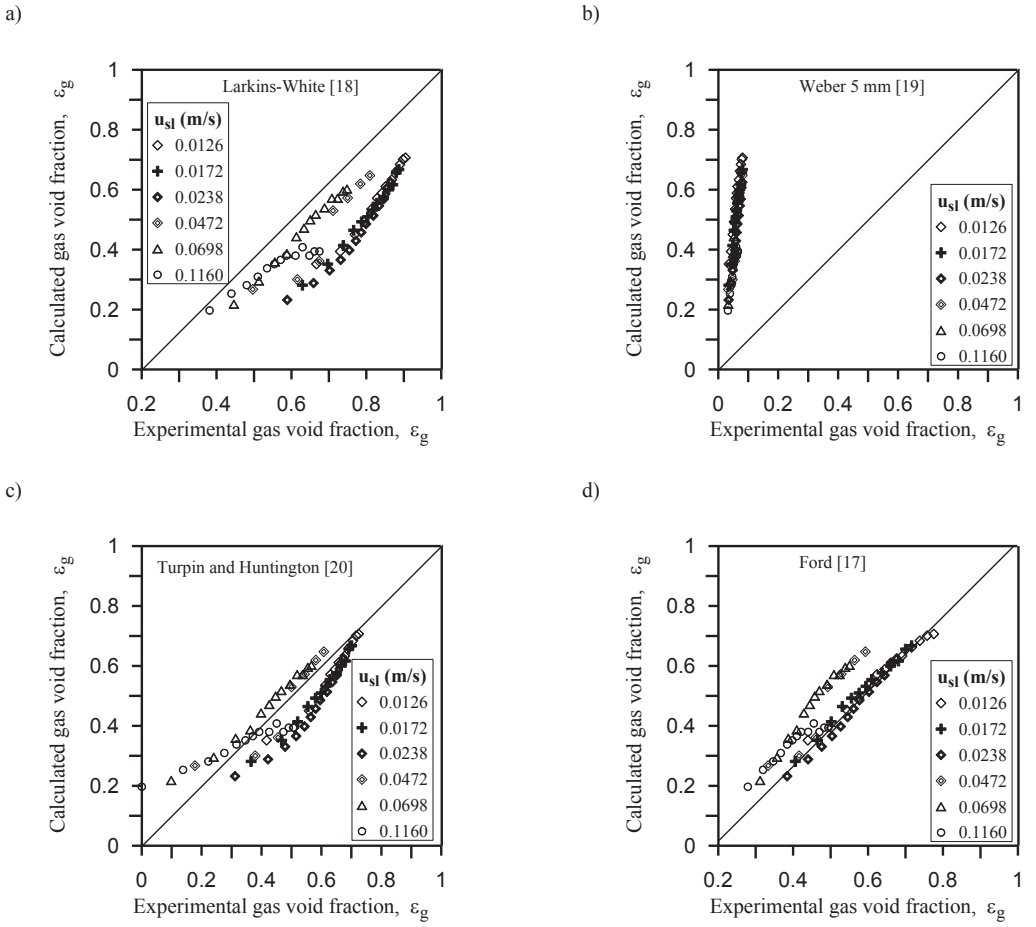

Fig. 6. Comparison of the measured gas void fraction with those calculated according to model a) Larkins-White [18], b) Weber 5 mm [19], c) Turpin-Huntington [20], d) Ford [17]

Table 3. RMS deviations for the gas void fraction

Data	Correlation	RMS	δ(ε)
Ford [17]	$\varepsilon_g = 0.212(Re_g/Re_l)^{0.2}(\mu_l/\mu_g + 0.182(L/G)^{0.24}$	0.25	0.06
Larkins & White [18]	$\log_{10}\varepsilon_l = -0.774 + 0.525(\log_{10}\chi) - 0.109(\log_{10}\chi)^2$	0.72	0.52
Weber (5 mm) [19]	$\varepsilon_g = 0.079\ u_{sg}^{0.3}$	0.95	0.90
Weber (2mm) [19]	$\varepsilon_g = 0.078\ u_{sg}^{0.24}$	0.63	0.39
Turpin & Huntington [20]	$\varepsilon_l = -0.035 + 0.182(L/G)^{0.24}$	0.27	0.07
Saada [21,22]	$\varepsilon_l = K(Re/Re_g)^a$	0.70	0.49

4. Conclusions

For the most of evaluated methods for predicting gas void fraction there is not good agreement between predicted and experimental data. The best approximation was obtained for the methods by Ford [17] and Turpin et Huntington [20] with accuracy about 25% and relative error adequately 6 and 7%. The experimental observation of horizontal air-water flow through FEC foam indicates the dependency of gas void fractions on bubble size and fluid velocities. The gas void fraction increases for the increasing superficial gas velocity and decrease when liquid superficial velocity increase. Deviation from this trend is connected with flow patterns transition. The interfacial slip provided the significant difference between the value of actual gas void fraction in a two-phase mixture flow and inlet void fraction.

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