VERIFICATION OF METHODS FOR CALCULATING THE GAS VOLUME FRACTION IN THE VERTICAL DESCENDING FLOW OF TWO-PHASE GAS-LIQUID MIXTURES

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Abstract: The paper presents the results of research on the vertical falling flow and their analysis. Methods for calculating the gas volume fraction, which are characterized by high accuracy, and are often proposed in the literature. Their accuracy was presented, as well as the methods with the highest computational usefulness when designing devices in which two-phase gas - liquid flow is used.

Keywords: two phase flow gas-liquid, volume share of gas, hydrodynamic flow

1. INTRODUCTION

Two-phase flow occurs in many branches of industry. It is also used in many technological processes such as sedimentation, fluidization, filtration, etc. For this reason, two-phase flows are the goal of many tests and analyzes. In the two-phase flow there is simultaneous flow of the continuous phase, which is a gas or liquid and a dispersed phase, where it is a solid, liquid or gas.

A characteristic feature of two-phase flow is the phase separation boundary, which forms and changes during movement. The individual phases of the two-phase mixture should be able to be separated mechanically by, e.g. centrifugation, filtration or percolation.

The basic parameters that characterize two-phase flow are:
- two-phase flow resistance,
- two-phase flow structure,
- volume fraction of one of the phases.

Determining the volume fraction of the gas is very complicated due to the density of the flowing mixture, which is related to the value of the gas volume fraction R_G or the value of the volume fraction of the liquid $1-R_G$. The value of the volume fraction is influenced by, inter alia, occurrence of phase slip phenomenon, which should be taken into mind that both phases flow at different velocity.

If no phase slip is taken into account, the volume fraction takes the form (1):

$$R_g = \frac{1}{1+\frac{1-x}{x}\frac{\rho_g}{\rho_c}}.$$ (1)

However, the volume share, taking into account the phase slip, generally takes the form (2):

$$R_g = \frac{1}{1+\frac{1-x}{x}\frac{\rho_g}{\rho_c}\frac{w_g}{w_c}},$$ (2)

where:
ρ_g – gas density, kg/m³,
ρ_c – liquid density, kg/m³,
w_g – gas velocity, m/s,
w_c – liquid velocity, m/s.

In the literature various calculation models are presented: non-slip models, where value $w_g/w_c = 1$ and slip models, in which $w_g/w_c > 1$. The calculation models of the average value of gas volume fraction presented by the authors often differ not only in the form itself, but also in the ranges of use as well as the types of two-phase mixtures.

Tab. 1. General characteristics of grinding conditions

Method	Characteristics of the method
Armand	$R_g = 1 - \dfrac{4 + \frac{4}{7}m}{5 + m\left(\frac{\varepsilon}{1-\varepsilon} + \frac{8}{7}\right)}$ $m = 4Re_{c,0}^{\frac{1}{8}}\left(\dfrac{\rho_g}{\rho_c}\right)^{0,5}$ $\left[0,69 + (1-\varepsilon)\left(4 + 21,9\sqrt{Fr_{c,0}}\right)\right]$
Bankoff	$R_g = \varepsilon\left(0,71 + 2,35\dfrac{\rho_c}{\rho_g}\right)$
Baroczy	$R_g = \dfrac{1}{1 + \left(\frac{1-x}{x}\right)^{0,74}\left(\frac{\rho_g}{\rho_c}\right)^{0,65}\left(\frac{\eta_c}{\eta_g}\right)^{0,13}}$
Chen	$R_g = \dfrac{1}{1 + 0,18\left(\frac{1-x}{x}\right)^{0,6}\left(\frac{\rho_g}{\rho_c}\right)^{0,33}\left(\frac{\eta_c}{\eta_g}\right)^{0,07}}$
Harrison	$R_g = \dfrac{1}{1 + \left(\frac{1-x}{x}\right)^{0,8}\left(\frac{\rho_g}{\rho_c}\right)^{0,515}}$
Locharta-Martinelli	$R_g = \dfrac{1}{1 + 0,28\left(\frac{1-x}{x}\right)^{0,64}\left(\frac{\rho_g}{\rho_c}\right)^{0,36}\left(\frac{\eta_c}{\eta_g}\right)^{0,07}}$
Spedding, Chen	$R_g = \dfrac{1}{1 + \left(\frac{1-x}{x}\right)^{0,65}\left(\frac{\rho_g}{\rho_c}\right)^{0,65}}$
Stomm	$R_g = 1 - \dfrac{\varepsilon_g^2 - x^2}{2\left[\ln\left(\frac{1-x}{1-\varepsilon_g}\right) - (\varepsilon_g - x)\right]}$ $x = \dfrac{w_g\rho_g}{w_g\rho_g + w_c\rho_c}; \quad \varepsilon_g == \dfrac{w_g}{w_g + w_c}$
Thom	$R_g = \dfrac{\gamma x}{1 + x(\gamma - 1)};$ $\gamma = W^{1,6};$ $W = \left(\dfrac{\rho_c}{\rho_g}\right)^{0,555}\left(\dfrac{\eta_g}{\eta_c}\right)^{0,111}$
Turner and Wallis	$R_g = \dfrac{1}{1 + \left(\frac{1-x}{x}\right)^{0,72}\left(\frac{\rho_g}{\rho_c}\right)^{0,40}\left(\frac{\eta_c}{\eta_g}\right)^{0,08}}$
Zivi	$R_g = \dfrac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_c}\right)^{0,67}}$
Zuber-Findlay	$R_g = \dfrac{x}{\rho_g}\left[C_0\left(\dfrac{x}{\rho_g} + \dfrac{1-x}{\rho_c}\right) + \dfrac{V_0}{g_{2F}}\right]^{-1}$ $V_0 = V^*\left[\dfrac{\breve{g}\sigma(\rho_c - \rho_g)}{\rho_c^2}\right]^2$ $C_0 = 1,2 \; ; \; V^* = 1,14$

2. RESULTS AND DISCUSSION

Based on the literature review [1-16, 18-28], regarding the methods for determining the volume fraction of gas in two-phase flows, it was noticed that many methods have particular ranges of their use and various forms of equations that do not allow for a direct comparison of individual calculation methods. An attempt was made to assess the applicability of selected calculation methods for typical two-phase systems:
– water-air,
– ethanol-air,
– glycerin-air.

The experimental data used for the analysis of calculation methods was taken from the dataset of Department Process Engineering of University of Technology in Opole [17]. The tests were carried out in vertical cannels with a diameter of 20, 24, 25, 32, 44 and 50 mm, with co-current descending two-phase gas and liquid flow. The range of apparent gas velocities (w_g) was 0.01-75 m/s and the liquid (w_c) 0.01-2 m/s. The preliminary assessment allowed for the selection of 12 calculation methods (Tab. 1), determining the gas volume fraction characterizing the interfacial slip (e.g. the Lockhart-Martinnelli model) and the different validity of using only in narrow ranges or for selected two-phase mixtures, e.g. the Zuber-Findlay method.

The assessment of the accuracy of individual methods and their usefulness in determining the gas volume participation consisted in determining the characteristic statistical parameters including the determination of the mean value of the relative error δR_g as well as the mean value of the absolute error $\left|\delta R_g\right|$ (Tab. 2).

Tab. 2. Statistical evaluation of gas volume participation

Data	Method	Value of statistical values	
		δR_g %	$\left\|\delta R_g\right\|$ %
Dawydow ethanol-air	Armand	28.92	28.92
	Bankoff	42.65	42.65
	Baroczy	59.68	59.68
	Chen	19.36	23.43
	Harrison	79.41	79.41
	Lockhart-Martinelli	45.92	45.92
	Spedding, Chen	44.14	44.14
	Stomm	44.81	44.81
	Thom	74.20	74.20
	Turner, Wallis	87.14	87.14
	Zivi	86.02	86.02
	Zuber-Findlay	36.66	36.66

Tab. 2. Statistical evaluation of gas volume participation
– *contiuned*

Data	Method	Value of statistical values	
		δR_g %	$\left| \delta R_g \right|$ %
Dawydow glycerin- air	Armand	23.68	29.28
	Bankoff	42.58	42.58
	Baroczy	82.11	82.11
	Chen	41.96	42.24
	Harrison	81.50	81.50
	Lockhart-Martinelli	64.44	64.44
	Spedding, Chen	37.61	38.05
	Stomm	39.95	39.95
	Thom	92.85	92.85
	Turner, Wallis	93.26	93.26
	Zivi	88.67	88.67
	Zuber-Findlay	37.45	37.45
Dawydow water-air	Armand	30.06	30.28
	Bankoff	44.36	44.36
	Baroczy	60.23	60.23
	Chen	20.82	28.37
	Harrison	81.06	81.06
	Lockhart-Martinelli	47.89	47.89
	Spedding, Chen	44.22	44.30
	Stomm	45.26	45.26
	Thom	75.24	75.24
	Turne, Wallis	88.03	88.03
	Zivi	87.55	87.55
	Zuber-Findlay	39.30	39.30
Oshinowo water-air	Armand	-12.78	19.09
	Bankoff	2.95	27.68
	Baroczy	0.42	12.48
	Chen	-18.77	20.83
	Harrison	19.24	21.70
	Lockhart-Martinelli	-3.15	15.10
	Spedding, Chen	-6.61	14.74
	Stomm	59.59	79.15
	Thom	1.78	13.13
	Turner, Wallis	37.24	37.24
	Zivi	18.01	19.75
	Zuber-Findlay	-3.79	20.69
Oshinowo glycerin- air	Armand	16.16	16.40
	Bankoff	22.46	22.46
	Baroczy	14.09	15.06
	Chen	7.09	8.46
	Harrison	24.29	24.29
	Lockhart-Martinelli	14.34	14.69
	Spedding, Chen	10.19	11.18
	Stomm	80.37	80.37
	Thom	8.77	13.32
	Turner, Wallis	44.46	44.46
	Zivi	18.89	20.73
	Zuber-Findlay	14.29	14.32
Lorenzi water-air	Armand	-12.47	28.46
	Bankoff	42.67	42.67
	Baroczy	47.19	47.19
	Chen	-48.45	53.28
	Harrison	78.84	78.84
	Lockhart-Martinelli	15.15	30.71
	Spedding, Chen	9.72	29.31
	Stomm	27.02	27.47
	Thom	79.87	79.87
	Turner, Wallis	84.96	84.96
	Zivi	90.41	90.41
	Zuber-Findlay	43.06	43.06
Andreussi water-air	Armand	1.66	2.03
	Bankoff	24.22	24.22
	Baroczy	0.21	1.07
	Chen	-0.28	0.93
	Harrison	4.26	4.31
	Lockhart-Martinelli	1.97	2.01
	Spedding, Chen	0.88	1.13
	Stomm	89.35	89.35
	Thom	-3.74	3.74
	Turner, Wallis	16.50	16.50
	Zivi	-0.43	2.07
	Zuber-Findlay	12.11	12.11

Tab. 2. Statistical evaluation of gas volume participation – *contiuned*

Data	Method	Value of statistical values	
		δR_g %	$\left\|\delta R_g\right\|$ %
Tisyn water-air	Armand	23.41	23.53
	Bankoff	43.42	43.42
	Baroczy	54.57	54.57
	Chen	-3.04	26.30
	Harrison	80.82	80.82
	Lockhart-Martinelli	36.48	36.48
	Spedding, Chen	32.71	33.49
	Stomm	36.38	36.38
	Thom	76.58	76.58
	Turner, Wallis	87.03	87.03
	Zivi	89.17	89.17
	Zuber-Findlay	39.03	39.03
Tisyn glycerin- air	Armand	21.84	22.86
	Bankoff	43.40	43.40
	Baroczy	61.93	61.93
	Chen	4.83	27.03
	Harrison	81.45	81.45
	Lockhart-Martinelli	42.39	42.39
	Spedding, Chen	31.14	32.33
	Stomm	34.78	34.78
	Thom	82.47	82.47
	Turner, Wallis	88.81	88.81
	Zivi	89.89	89.89
	Zuber-Findlay	38.79	38.79
Tisyn ethanol-air	Armand	21.77	22.43
	Bankoff	42.12	42.12
	Baroczy	54.57	54.57
	Chen	-10.40	28.64
	Harrison	79.35	79.35
	Lockhart-Martinelli	31.85	33.53
	Spedding, Chen	30.00	31.94
	Stomm	78.05	78.05
	Thom	77.85	77.85
	Turner, Wallis	86.37	86.37
	Zivi	88.71	88.71
	Zuber-Findlay	33.46	33.46
Jasek glycerin- air	Armand	22.66	22.83
	Bankoff	10.00	11.58
	Baroczy	27.52	29.44
	Chen	6.23	14.11
	Harrison	33.03	34.77
	Lockhart-Martinelli	20.24	22.27
	Spedding, Chen	5.91	15.68
	Stomm	66.21	66.21
	Thom	27.14	32.89
	Turner, Wallis	62.64	62.64
	Zivi	29.56	34.93
	Zuber-Findlay	8.61	13.89

Figure 1 shows a graphic interpretation of comparisons of computational methods that were characterized by high accuracy of calculations. The best accuracy with experimental data is characterized by the Armand and Chen method (Figs. 2-3) for which approximately 70% of the points are within ± 30% of the absolute error. Both methods are characterized by high accuracy, because they are based on a slip model that best reflects the effect of viscosity changes and liquid density on the value of gas volume fraction. In addition, the Armand and Chen methods include interfacial slip, which contains the ratio of the actual velocities of the individual phases.
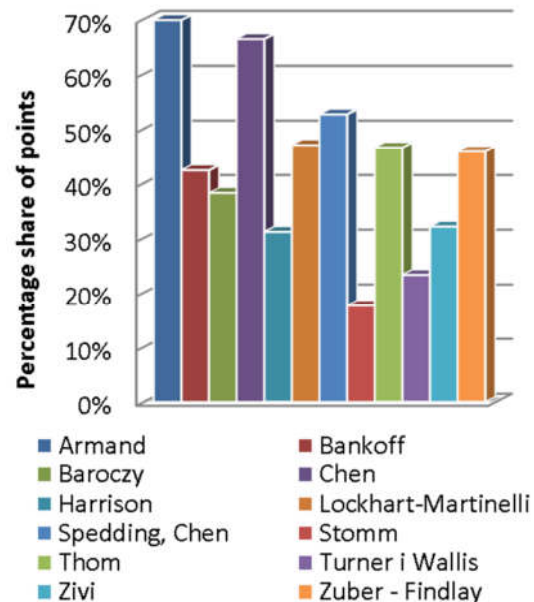

Fig. 1. Comparison of the accuracy of calculation methods for the volume fraction of gas in the falling flow of a two-phase mixture

The impact of selected parameters on the calculation results (distribution of points) in the $R_{g,obl.}$-$R_{g,zm}$ system was evaluated. Graphical interpretations of selected calculation methods for gas volume fraction for various mixtures are shown in the Figures 2-13.
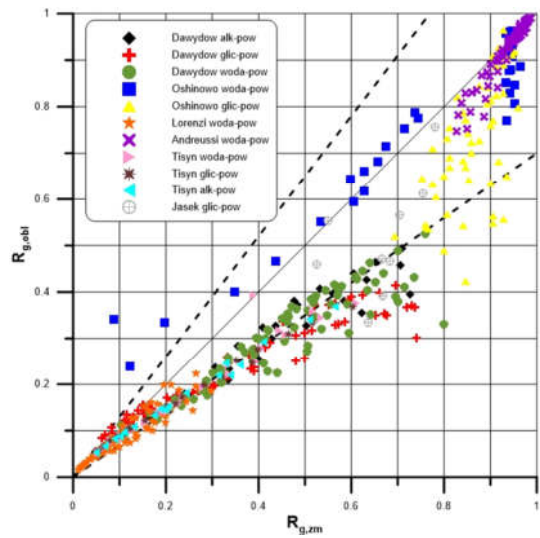

Fig. 2. Comparison of measured and calculated values of the gas volume fraction using the Armand method
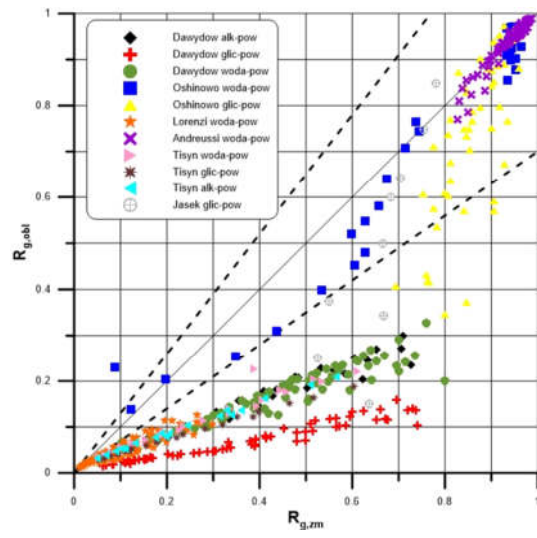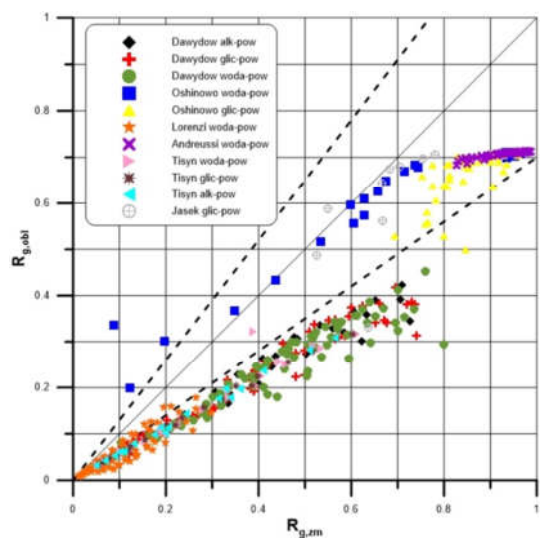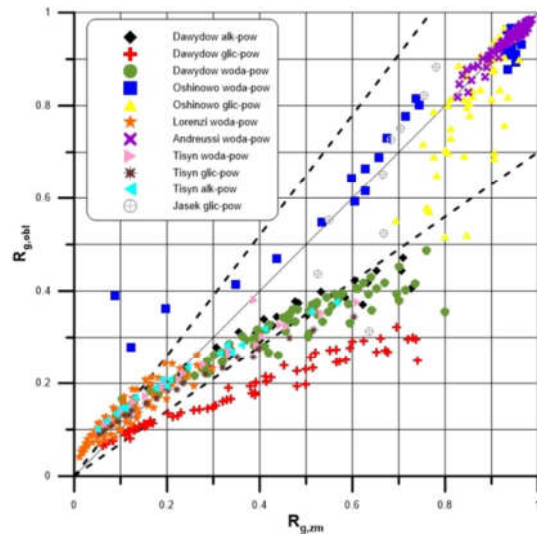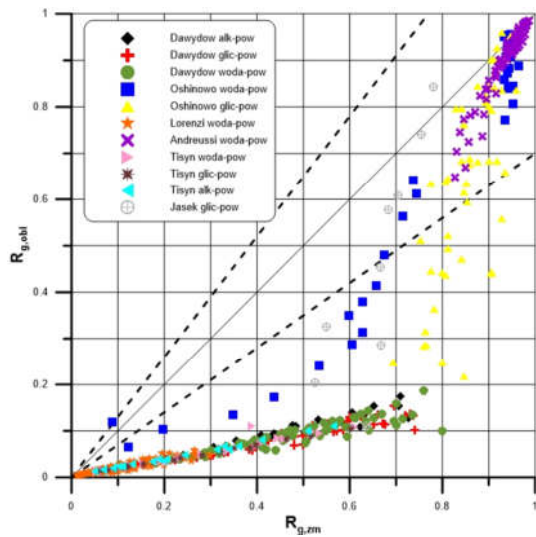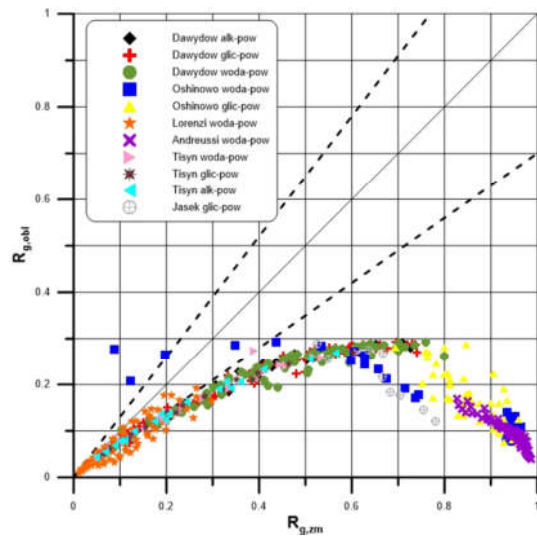

Fig. 4. Comparison of measured and calculated values of the gas volume fraction using the Baroczy method

Fig. 3. Comparison of measured and calculated values of the gas volume fraction using the Bankoff method

Fig. 5. Comparison of measured and calculated values of the gas volume fraction using the Chen method

Fig. 6. Comparison of measured and calculated values of the gas volume fraction using the Harrison method

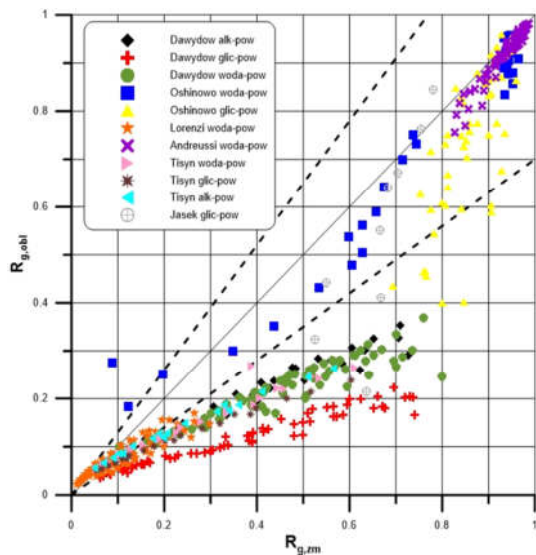Fig. 8. Comparison of measured and calculated values of the gas volume fraction using the Stomm method

Fig. 7. Comparison of measured and calculated values of the gas volume fraction using the Lockhart-Martinelli method
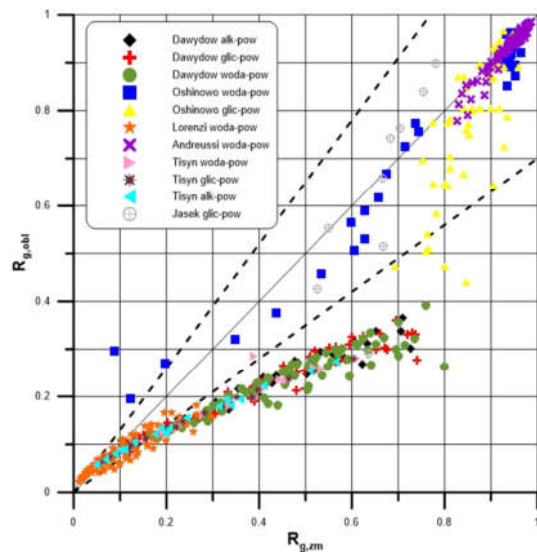

Fig. 9. Comparison of measured and calculated values of the gas volume fraction using the Spedding, Chen method

3. CONCLUSIONS

Determining the volume fraction of gas in two-phase flow as one of the three most important parameters is immensely important, so can be found so many calculation methods that have been proposed by different researchers. The authors of individual methods make their accuracy dependent on hydrodynamic parameters and ranges of applicability. Determining the volume fraction of gas is necessary to determine other parameters, including densities of a two-phase mixture that guarantee the correct design of equipment and apparatus, where two-phase flows are used.

After analyzing the results of the volume fraction of gas using the methods proposed by the authors, it should be noted that in different ranges the volume fraction of gas does not coincide with the obtained experimental results. In a wide range of changes in flow parameters as well as physicochemical properties of two-phase mixture components, the highest accuracy of results is obtained using the methods of Armand and Chen, and therefore they can be recommended to calculate the gas volume fraction.
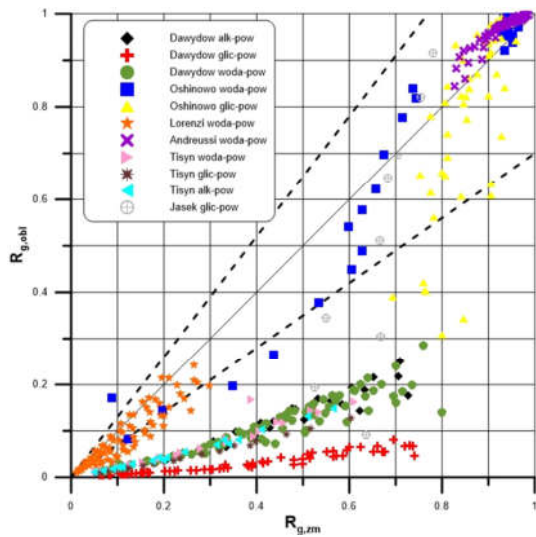
Fig. 10. Comparison of measured and calculated values of the gas volume fraction using the Thom method
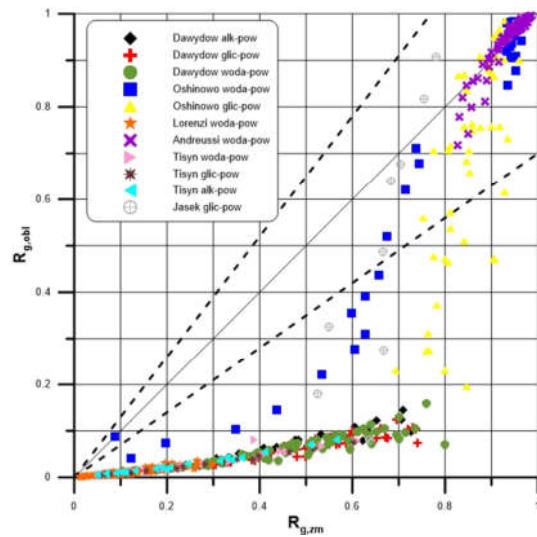

Fig. 12. Comparison of measured and calculated values of the gas volume fraction using the Zivi method
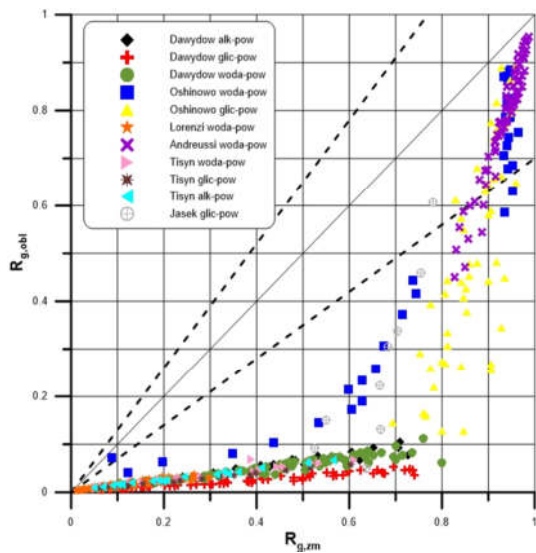

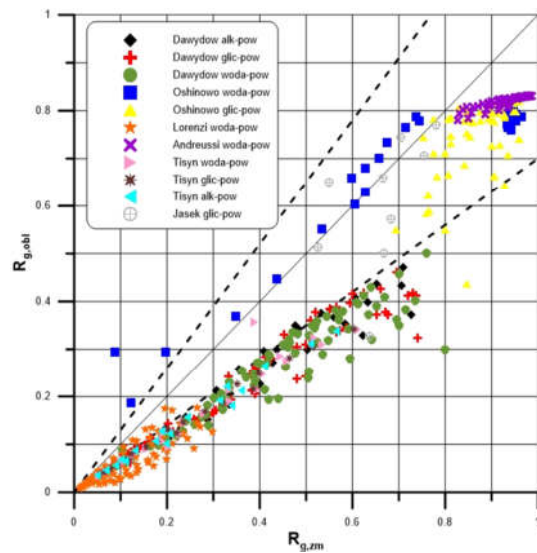Fig. 11. Comparison of measured and calculated values of the gas volume fraction using the Turner an Wallis method

Fig. 13. Comparison of measured and calculated values of the gas volume fraction using the Zuber-Findlay method

References

1. Bankoff S.G. (1960). A variable density single-fluid model for two-phase flow with particular reference to steam-water. *Transactions ASME, Serie C,* Vol. 82, No. 4, pp. 265-271.

2. Baroczy C.J. (1966). A systemic correlation for two phase pressure drop. *Chemical Engineering Progress Symposium,* Vol. 62, No. 64, pp.232-249.

3. Chen J.J. (1986). A further examination of void-fraction in annular two-phase flow. *International Journal of Heat and Mass Transfer,* Vol. 29, No. 11, pp.1760-1763.

4. Chen J.J.J., Spedding P.L. (1983). The analysis of holdup in horizontal two-phase gas-liquid flow. *International Journal of Multiphase Flow*, Vol. 9, No. 2, pp.147-159.

5. Czernek K. (2013). *Hydrodynamiczne aspekty projektowania aparatów cienkowarstewkowych dla cieczy bardzo lepkich.* Opole University of Technology, Opole, Poland.

6. Czernek K. (2003). The method of gas volume fraction calculation for two-phase gas-high viscosity liquid flow. *Mechanika*, Vol. 77, pp.15-23.

7. Czernek K., Filipczak G., Witczak S. (2006). Gas volume fraction in two-phase gas-liquid flow for very viscous liquid. *Chemical Engineering and Equipment*, Vol. 6s, pp. 46-47.

8. Czernek K., Filipczak G., Witczak S. (2008). Dynamics of annular two-phase flow of gas and a highly viscous liquid. *Przemysł chemiczny*, Vol. 87, No. 2, pp. 105-110.

9. Czernek K., Palińska K., Witczak S. (2006). *Analysis of the calculation methods of gas volume fraction at two-phase flow very viscous liquid on the base of experimental data*

[in] VI Workshop "Modeling of multiphase flows in thermo-chemical systems. Numerical methods", Stawiska, Poland.

10. Czernek K., Witczak S. (2013). Non-invasive evaluation of wavy liquid film. *Chemical and Process Engineering*, Vol. 34, No. 2, pp. 241-252.

11. Dalkilic A.S., Laohalertdecha S., Wongwises S. (2008). Effect of void fraction models on the two-phase friction factor of R134a during condensation in vertical downward flow in a smooth tube. *International Communications in Heat and Mass Transfer*, Vol. 35, No. 8, pp. 921-927.

12. Dalkilic A.S., Wongwises S. (2010). Validation of void fraction models and correlations using a flow pattern transition mechanism model in relation to the identification of annular vertical down flow in-tube condensation of R134a. *International Communications in Heat and Mass Transfer*, Vol. 37, No. 7, pp. 827-834.

13. Delhaye J.M. (1984). Les divers modeles d'ecoulements diphasiques azliquide. *Houille Blanche*, Vol. 3-4, p.179-192.

14. Dziubiński M., Fidos H. (2003). Uogólnienie korelacji Lockharta-Martinellego dla określania udziału faz w prze-pływającej mieszaninie ciecz nienewtonowska-gaz, *Chemical Engineering and Equipment*, Vol. 5, p. 51.

15. Dziubiński M. (2005). *Hydrodynamika przepływu mie-szanin dwufazowych ciecz-gaz.* Łódz University of Technology, Łódź, Poland.

16. Harrison R.F. (1975). *Methods for the analysis geothermal two-phase flow.* ME thesis, University of Auckland, Auckland, New Zealand.

17. Katedra Inżynierii Procesowej (2004). *Przepływy dwu-fazowe gaz-ciecz.* Bank danych doświadczalnych. Poli-technika Opolska, Opole.

18. Lockhart R.W., Martinelli R.C. (1949). Proposed correlation of data for isothermal two-phase two-component flow in pipes. *Chemical Engineering Progress*, Vol. 45, No. 1, pp. 38-48.

19. Palińska K. (2006). *Udział objętościowy w przepływie dwufazowym gaz-ciecz bardzo lepka.* ME thesis, Opole University of Technology, Opole, Poland.

20. Spedding P.L., Chen J.J.J. (1984). Holdup in two phase flow. *International Journal of Multiphase Flow*, Vol. 10, No. 3, pp. 307-339.

21. Stomma Z. (1979). *Two-phase flows-void fraction values determination.* IBJ, Raport No. INR/1818/IX/R/A, Świerk, Poland.

22. Thom J.R.S. (1964). Prediction of pressure drop during forced circulation boiling of water. *International Journal of Heat and Mass Transfer*, Vol. 7, No. 7, pp. 709-724.

23. 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.

24. Ulbrich R. (1989). Identyfikacja przepływu dwufazowego gaz-ciecz. *Zeszyty Naukowe WSI w Opolu, Mechanika*, No. 32.

25. Troniewski L., Ulbrich R., Łukaszewicz S. (1982). Metody obliczania udziału objętościowego gazu przy przepływie dwufazowym. *Zeszyty Naukowe WSI w Opolu, Mechanika*, No. 16, p. 57.

26. Troniewski L., Witczak S., Czernek K. (2006). Hydro-dynamics and heat transfer during two-phase gas-high viscous liquid flow in film reactor. *Chemical and Process Engineering*, Vol. 27, No. 4, pp. 1341-1359.

27. Witczak S., Czernek K. (2004). Hydrodynamics of high viscosity liquid and gas downflow in vertical pipes. *Chemical Engineering and Equipment*, Vol. 3s, pp. 176-177.

28. Woldesemayat M.A., Ghajar A.J. (2007). Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes. *International Journal of Multiphase Flow*, Vol. 33, No. 4, pp. 347-370.

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