Scientific paper

Effect of Highly Viscous Non-Newtonian Liquids on Gas Holdup in a Concurrent Upflow Bubble Column

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Dedicated to the memory of professor Vojko Ozim

Abstract

In a bubble column the effect of gas velocity and consequently the effective viscosity of the selected non-Newtonian liquids on gas holdup as the most important hydrodynamic parameter was studied.

Experiments were carried out in a bubble column of 0.14 I. D. and 2.4 m of total height. A perforated plate served as the gas distributor. The column operated in a two-phase concurrent upflow mode and also as the liquid-batch. Different concentrations of aqueous solutions of carboxyl methyl cellulose and xanthan took the role of non-Newtonian liquids, and air was used as the gas phase. Due to the experimental conditions most of these experiments were taken in the heterogeneous hydrodynamic regime. The superficial gas velocity affected the gas hold-up most, for both polymer solutions, while the impact of the effective viscosity was much more pronounced in the case of xanthan solutions. The liquid flow rate showed a minor effect on the measured parameter.

Finally, empirical correlations for the gas holdup prediction as a function of gas velocity and effective viscosity of the liquid were developed for CMC solutions. The xanthan solutions exhibit a more complex dependence on the prevailing effective liquid viscosity, which still needs to be studied.

Keywords: Bubble column, non-Newtonian liquids, gas holdup, cocurrent upflow

1. Introduction

Bubble columns are very popular as absorber/reactor devices in chemical processes. Though simple in construction, the presence of two phases (gas-liquid system) is responsible for a very complex fluid dynamic behaviour, even when the liquid properties are close to those of the Newtonian ones. In biochemical processes highly viscous liquids take part, which in most cases exhibit a far more complex rheological structure, and the hydrodynamic conditions in a bubble column change drastically. In laboratory experimental studies the aqueous solutions of carboxyl methyl cellulose (CMC) are usually used to simulate non-Newtonian liquids. The viscosity of these pseudoplastic liquids also depends on the shear action, not only on temperature and pressure. Nishikawa et al.[1] proposed a simple correlation for evaluating the effective shear rate prevailing in a bubble column, based on superficial gas velocity

$$\dot{\gamma} = 50\, u_G \qquad (1)$$

where u_G is in cm.s^{-1}. Accordingly the shear rates in bubble columns are between 10 s^{-1} to 1200 s^{-1} in most experimental studies. For this range of shear rates a simple power-law relation between the so-called effective viscosity of the liquid in the column and the shear rate holds:

$$\eta_{eff} = K\dot{\gamma}^{(n-1)} \qquad (2)$$

Gas holdup is the basic hydrodynamic parameter of the two-phase dispersion system in a bubble column. It represents an integral value of all bubble volumes throughout the column. The gas holdup depends on the geometry of the column and design of the gas distributor, physical properties of the phases, and mainly on the gas superficial velocity. It is a measure for an efficient interphase contact in the column and also provides information about the residence time of the phases. Numerous experimental studies are available in the open literature, either dedicated to the gas holdup prediction in the case of both Newtonian or non-Newtonian liquids. Mandal and coworkers[2] did the latest literature survey. Some of the most important publications are listed in Table1.

Table 1. Experimental studies on bubble column hydrodynamics

Authors	Type of operation	D (m)	Liquid phase	u_L (m.s^{-1})	u_G (m.s^{-1})	ε_G (/)
Zahradnik et al.[3]	upflow	0.29	water	0.008–0.029	0.004–0.076	0.05–0.24
Bando et al.[4]	downflow	0.07	water	0.10–0.20	0.01–0.10	0.01–0.32
Yamagiwa et al.[5]	downflow	0.034–0.07	water	0.4–0.912	0.1–0.50	0.15–0.40
Ohkawa et al.[6]	downflow	0.02–0.026	water	0.05–0.20	0.05–0.20	0.01–0.4
Mandal et al.[2]	downflow	0.0516	water	0.08–0.144	0.004–0.058	0.38–0.50
Schumpe and Deckwer[7]	upflow	0.10–0.14	$CMC_{up\ to\ 1,8\ \%}$		0.003–0.025	0.03–0.20
Das et al.[8]	horizontal	0.019	$CMC_{0.5–1.0kg/m^3}$	0.141–1.00	0.067–1.55	0.10–0.40
Das et al.[8]	upflow	0.019	$CMC_{0.5–1.0kg/m^3}$	0.296–1.00	0.17–1.60	0.12–0.45
Mandal et al.[2]	downflow	0.0516	$CMC_{1.0–2.5kg/m^3}$	0.05–0.117	0.004–0.058	0.45–0.61
Godbole et al.[9]	liquid–batch	0.10	CMC		0.05–0.3	0.1–0.28

The role of highly viscous non-Newtonian liquids on the bubble column performance is still not fully understood. In this study the effect of gas velocity and consequently of the effective viscosity of the selected non-Newtonian liquids on the quality of gas-liquid structure was examined in a concurrent upflow mode, which is rather rare in the experimental studies to-date. Two different polymers (carboxyl methyl cellulose and xanthan) were used in the preparation of solutions. As the key experimental parameter, the gas holdup was measured and the values were compared to those evaluated from the most cited correlations.

1. 1. Gas Holdup Correlations

For the concurrent flow or liquid-batch operation, the gas holdup in a bubble column is correlated mainly as the function of the gas superficial velocity or the gas superficial velocity and geometry of the column together. Some of the correlations involve the effective viscosity of the liquid, besides the gas superficial velocity.

In the homogeneous flow regime Schumpe and Deckwer[7] proposed the following correlation based on gas superficial velocity

$$\varepsilon_G = 0.0908\, u_G^{0.85} \tag{3}$$

They used a sintered plate as the gas distributor. In the case of a perforated plate the authors recommended the following expression

$$\varepsilon_G = 0.0258\, u_G^{0.876} \tag{4}$$

In slug flow the following correlation should be used for both types of distributor[7]

$$\varepsilon_G = 0.0322\, u_G^{0.674} \tag{5}$$

The gas superficial velocity is in cm.s^{-1} in all three equations above. The authors collected the data at the liquid velocity u_L = 0.6 cm.s^{-1}.

For highly viscous aqueous solutions of CMC (up to 230 mPas and more) and liquid batch operation, the experimental results of Godbole et al.[9] lead to a correlation valid in the heterogeneous regime

$$\varepsilon_G = 0.225\, u_G^{0.532}\, \eta_{eff}^{-0.146} \tag{6}$$

where the gas superficial velocity is in m.s^{-1}. Their experimental data were in close agreement with those of Franz´s research group.[10] In the slug flow conditions the authors represented the effect of column diameter on gas holdup with the following expression

$$\varepsilon_G = 0.239\, u_G^{0.634}\, D^{-0.50} \tag{7}$$

The correlation should be valid for η_{eff} in the range of 18 mPas to 280 mPas.

For large diameter columns Godbole et al.[11] recommended the following correlation

$$\varepsilon_G = 0.2075\, u_G^{0.6} \eta_{eff}^{-0.19} \tag{8}$$

They experimented at the approximate up-flow liquid velocity of 0.6 cm.s^{-1}.

More complex correlation for gas holdup prediction in slug flow in a vertical pipe is the one of Das et al.[8], which is based on several dimensionless groups

$$\varepsilon_G = 1\text{-}exp[\text{-}4.25*10^{-3} Re_G^{0.86}\, Re_L^{-0.6} N_{PL}^{-0.8}], \tag{9}$$

valid for two-phase flow in a vertical pipe. Extremely high flow rates of both phases were used in their experimental study.

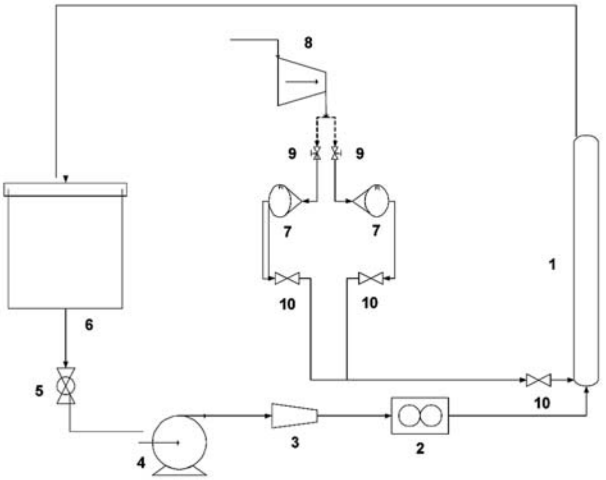
For a highly viscous Newtonian liquid in the heterogeneous regime (the viscosity in the range of 4.23 mPas to 246 mPas) Godbole et al.[9] proposed the following correlation

$$\varepsilon_G = 0.319\, u_G^{0.476} \eta_L^{-0.058} \tag{10}$$

developed from the data from liquid-batch mode of operation.

2. Experimental

The experimental system used in the present work is shown in Figure 1. The Plexiglas column consisted of six equivalent cylindrical segments of 0.14 m ID and 2.62 m of total height. The column operated in a concurrent upflow mode. At the bottom, a perforated plate with 43 holes of 1.2 mm ID was placed to serve as the gas distributor (Figure 2). The effective height of the column was lowered to 236.8 cm. The top section of the column was connected with the gas-liquid separator. A blower supplied the air into the column. The gas flow rates were measured on the rota meters. The liquid phase kept in a 300 l storage tank was pumped into the column through the grooves of the gas distributor and was circulated. The liquid flowrates were detected with the electromagnetic flow measuring device. The valves made it possible to stop the flow of both phases immediately. Different concentrations of aqueous carboxyl methylcellulose and xanthan took the role of the non-Newtonian liquids. Both types of operations, that are the liquid batch and the two-phase flow, were performed on each liquid. For comparison the same experiments were recorded for tap water as a Newtonian liquid. The gas superficial velocity was in the range of 1.8 cm.s^{-1} to 25.2 cm.s^{-1}, and the liquid superficial velocity was varied from 0 to a maximum value of 24.8 cm.s^{-1}.



1 – column
2 – liquid flow meter
3 – reducing element
4 – centrifugal pump
5 – ball valve
6 – storage tank
7 – gas rota meter
8 – blower
9 – regulating valve
10 – valve

Figure 1. Schematic diagram of experimental set-up.

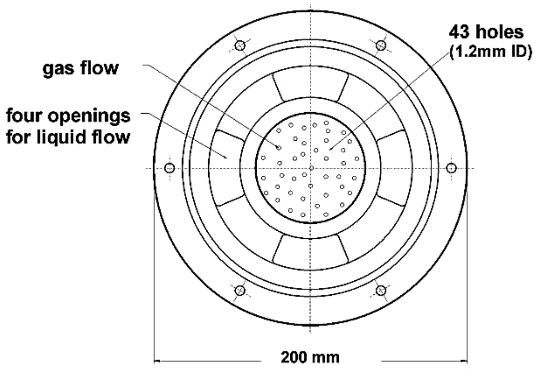


Figure 2. Outline of the gas distributor.

The pseudoplastic flow behaviour of the polymer solutions was examined with the RV 100 viscosimeter (Table 2). The MVI system covered the shear rates between 100 s^{-1} and 1000 s^{-1}. The Nishikawa et al.[1] correlation provides approximately the same range of shear rates as are found in the column at the stated operating conditions.

The structure of the gas-liquid dispersion was observed visually and documented by photos.

The gas holdups were measured by recording the levels of an aerated (h_{LG}) gas-liquid mixture during the steady state operation and non-aerated (h_L) liquid in the column after the flow of the phases were simultaneously stopped, thus

$$\varepsilon_G = (h_{LG} - h_L) / h_{LG} \qquad (11)$$

When a few experiments were repeated randomly, the values of gas holdups were found within 2%.

3. Results and Discussion

The rheological properties of polymer solutions were tested before and after a set of experiments. The CMC solutions were stable for a few days and were not affected

Table 2. Rheological properties of non-Newtonian liquids studied

Solutions	n	K	Solutions	n	K
0.2 wt% CMC	0.725	0.073	0.1 wt% xanthane	0.505	0.168
0.25 wt% CMC	0.81	0.056	0.2 wt% xanthane	0.414	0.445
0.4 wt% CMC	0.64	0.27	0.3 wt% xanthane	0.32	1.056
0.5 wt% CMC	0.60	0.49	0.4 wt% xanthane	0.30	1.50
0.85 wt% CMC	0.48	2.8			

by constant circulation through the system at all. On the other hand the aqueous solutions of xanthan were extremely sensitive to the contamination from the surrounding and had to be prepared freshly before experimentation. The effective viscosities of the liquids were in the range of 270 mPas – 10 mPas for the CMC solutions and 64 mPas – 5 mPas for the xanthan solutions.

Since the perforated plate was used the majority of experiments ran in the heterogeneous flow regime. At the lowest gas velocity ($u_G = 1.8$ cm.s^{-1}) for water, 0.1% xanthan, and 0.2% CMC solution, the column operated in transition between the homogeneous and heterogeneous regimes. In the case of 0.85% CMC solution the slug flow developed already at $u_G = 1.8$ cm.s^{-1}. Small amounts of CMC or xanthan in the water highly affected the gas holdup structure in the column. The bubbles which formed in the water were nearly of the same size (about 10 mm) and evenly distributed. In low concentrated polymer solutions at low gas velocities the bubbles were of different sizes, from 1 mm to 15 mm, found in small regions throughout the column. Even relatively large bubbles retained the spherical shape. At higher concentrations the coalescence became very intensive – large prolonged bubbles were formed just above the gas distributor and travelled violently upward the column. Regions of smaller bubbles with low velocities were observed at the wall; they became nearly stationary in the case of xanthan solutions.

3. 1. Impact of System Variables on Gas Holdup Data

Quite a few variables affected the gas holdup were tested in this experimental study. First the role of liquid velocity on the measured values of ε_G was clarified. The effect of liquid flow on the gas holdup is shown in Figure 3. For all liquids the highest values of the gas holdup were obtained in the liquid-batch operation ($u_L = 0$). A faint decrease in the gas holdups was observed for water and CMC solutions when the operation was switched from the liquid batch to the two-phase flow operation. For xanthan solutions the drop in ε_G was more pronounced and with increasing liquid velocity the values of the gas holdup settled down approximately at half after the liquid velocity passed 5 cm.s^{-1}. Even though bubble columns usually operate at low velocities of the liquid ($u_L < 1$ cm.s^{-1}) higher liquid velocities are found in a modified bubble column reactors (airlift reactor with internal or external loop). For an air-water system Hills[12] found that the gas holdup decreases with the liquid velocity at high liquid throughputs ($u_L > 30$ cm.s^{-1}).

Aqueous solutions of xanthan and CMC were prepared from the same packages, therefore it was possible to check the impact of the polymer concentration on the measured gas holdups. In Fig. 4 the gas holdup values at the constant gas velocity $u_G = 5.4$ cm.s^{-1} are shown. In all solutions used the liquid batch operation gave higher gas holdups than the two-phase flow operation, and in both mode of operation the values decreased with increasing polymer concentration in the water. Taking into account all the data this decrease in the gas holdup values was less pronounced in case of liquid batch operation. With 0.5% CMC solution the holdups were very close to those with 0.85% CMC solution, which already promoted the slug flow regime. The comparison with the literature data is possible only through the effective viscosity of the liquids.

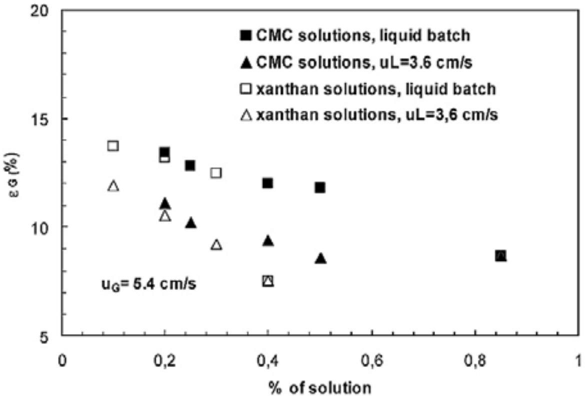


Figure 4. Gas holdup as a function of polymer concentration in the liquid.

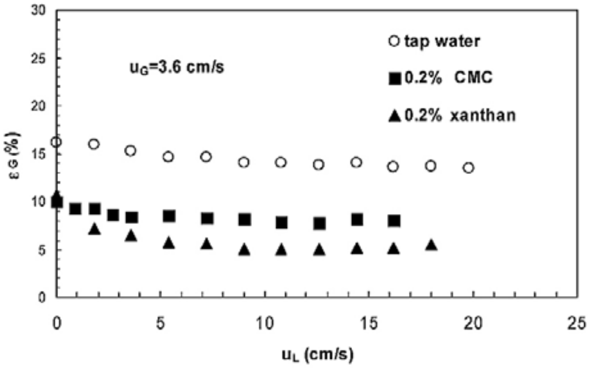


Figure 3. Gas holdup as a function of liquid superficial velocity.

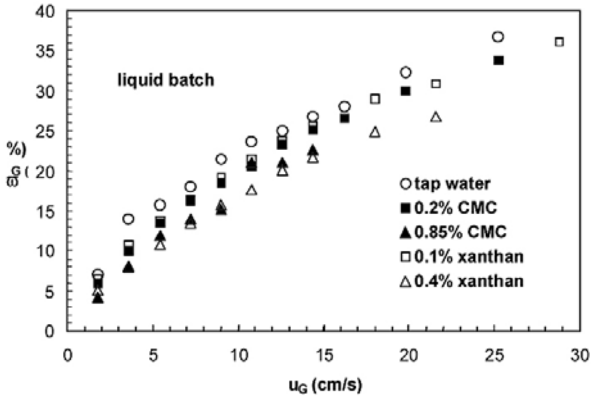


Figure 5. Gas holdup as a function of gas superficial velocities.

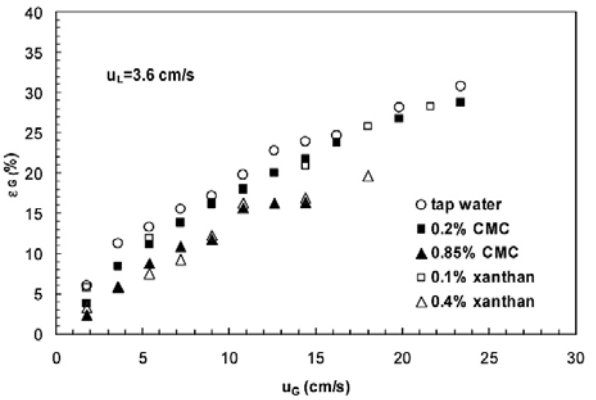


Figure 6. Gas holdup as a function of gas superficial velocity.

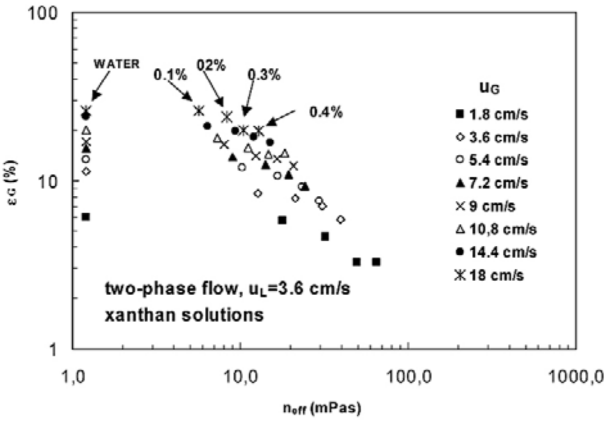


Figure 8. Gas holdup as a function of liquid effective viscosity for xanthan solutions.

As expected, the gas superficial velocity affected the gas holdups at the most. In Fig. 5 the liquid batch operation is presented and the experimental values of ε_G shown in Fig. 6 were obtained at $u_L = 3.6$ cm.s^{-1}. For clarity reason only the data for the lowest and the highest concentrated solutions for each polymer are presented.

In order to figure out the influence of the effective viscosity of the liquid on the gas holdup, experimental data were plotted as a function of η_{eff} with the gas superficial velocity as a parameter (Fig. 7 and Fig. 8). Both figures refer to the two-phase flow operation. For the CMC solutions at fixed values of u_G a slight systematic negative trend in the gas holdups was observed over the entire range of viscosities (Figure 7). Godbole et al.[9] reported a maximum in ε_G at the effective viscosity of about 3 mPa.s, which is beyond the operating conditions in this study (10.2 mPa.s < η_{eff} < 280 mPa.s). As one can see, in log-log diagram (Fig. 7) the straight lines resulted with u_G as a parameter.

For the xanthan solutions the effect of η_{eff} on gas holdups (Fig. 8) proved to be more complex. Although these solutions exhibited much lower effective viscosities of the liquid (5 mPa.s < η_{eff} < 65 mPa.s), the values of the gas holdups are within those for the CMC solutions. A decrease in ε_G with effective viscosity is higher than in the case of CMC solutions and could not be described in the same way, because the plot does not yield straight lines as in case of CMC solutions. More experimental data is needed to elaborate the effect of effective viscosity on gas holdups for the xanthan solutions.

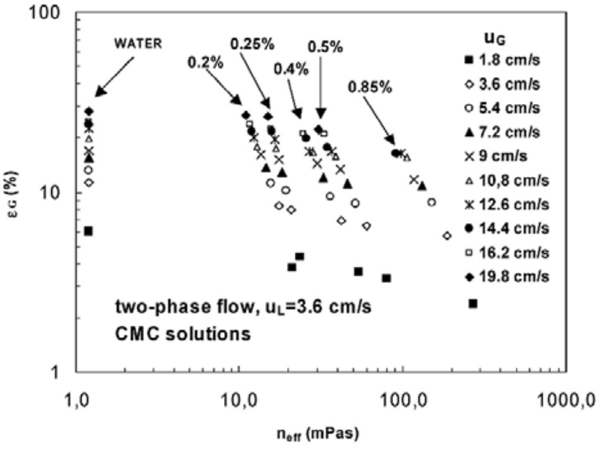


Figure 7. Gas holdup as a function of liquid effective viscosity for CMC solutions.

3. 2. Analysis of Gas Holdup Data

The gas holdup data measured under two-phase flow conditions were first analysed with the models, which were developed for better understanding of two-phase flow in pipes. In 1963 Behringer[13] first introduced the so called *slip velocity model*. The slip velocity of bubbles relative to the surrounding liquid is defined as

$$u_S = +\left[\frac{u_G}{\varepsilon_G} - \frac{u_L}{1-\varepsilon_G}\right], \tag{12}$$

the + sign indicates a cocurrent upflow operation. The holdup is thus a function of gas and liquid superficial velocity. The computed values of the slip velocities were

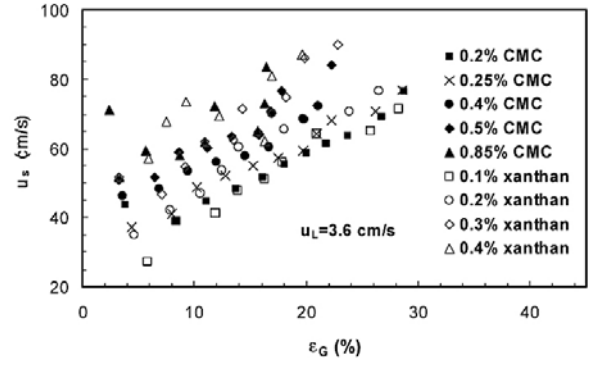


Figure 9. Slip velocity as a function of gas holdup.

plotted against the corresponding gas holdups as shown in Fig. 9. The liquid velocity was kept constant (u_L = 3.6 cm.s^{-1}) and the gas holdup was increased with the gas velocity according to the data sets such as shown in Fig. 6.

For each solution the data fall around a straight line, which are best represented with the following equation

$$u_s = u_b + C_1\varepsilon_G \qquad (13)$$

In the equation above u_b is the velocity of a single bubble in an infinite medium at no gas hold up ($\varepsilon_G = 0$). Once u_b and C_1 are known for a given liquid, the gas holdup can be predicted from Eq. (12) and Eq. (13). Both coefficients, which provide the best fit, are listed in Table 3.

The same gas holdup data sets were also analysed with the well known *drift flux model* of Zuber and Findley[14]. The model is based on the existence of local slip in the column. The following equation represents the model

$$\frac{u_G}{\varepsilon_G} = C_0 u_m + u_d \qquad (14)$$

The constant C_0 is known as a distribution parameter and accounts for the interaction of velocity and gas holdup distribution. The drift velocity term u_d is a measure of a local slip between the phases and for the heterogeneous flow regime is equated to the bubble rise velocity in an infinite medium, i.e. to u_b. Figure 10 shows the result of applying the drif flux model onto the experimental data.

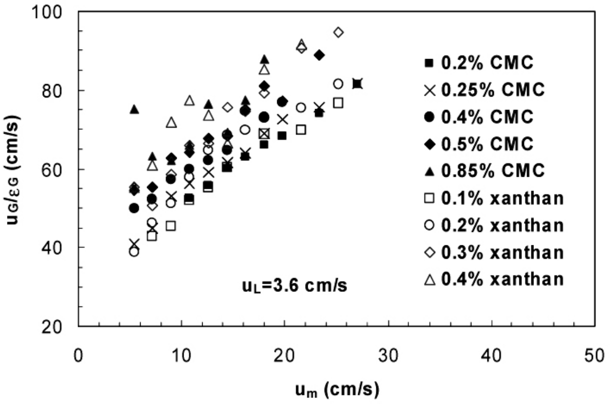


Figure 10. Actual gas velocity as a function of liquid mixture velocity.

As in the previous model, the coefficients of the straight lines resulting for each solution were computed and are given in Table 3.

Clark and Flemmer[15] found u_b to be equal to 25 cm.s^{-1} for an upflow air-water system. Mandal and his coworkers[2] in analysing the downflow experiments in a bubble column found quite similar values with a negative sign indicating the downflow operation. They used two different CMC solutions. In the present work the sole values of u_b might be questionable – insufficient number of data was used in the regression analysis of each straight line.

Nevertheless an increase in a single bubble velocity at zero voidige by increasing the concentration of either polymer in the water can be observed, up to the value of 50 cm.s^{-1} in case of 0.4% xanthan solution (Table 3). Das et al.[8] measured the gas holdups in CMC solutions (CMC concentration in the range of 0.05% to 0.1%) under the slug flow conditions. They observed an average drift velocity u_d to increase with concentration from 53 cm.s^{-1} to 0.62 cm.s^{-1}.

The computed values of C_1 and C_0 do scatter and the conclusion wheather these two factors depend on the polymer concentration is very uncertain. The C_1 values seem to increase with the concentration, and are found to be a little higher in case of xanthan solutions. The distribution factor C_0 might be independent on the solution, and the values are much higher than that for an air-water system, for which Clark and Flemmer[15] found the value of C_0 to be 1.07 for upflow and 1.17 for downflow operation. Das et al.[8] operated in an upflow mode and reported the values of 1.4 to 1.67, what is about 20% lower compared to those in Table 3.

Quite complex correlations may be found in the open literature for the evaluation of these parameters – one can find a list of available correlations in the work of Majumder et al.[16] They operated in a downflow cocurrent mode and found the slip velocity model parameters to depend on the column and nozzle diameter, besides the liquid viscosity and liquid surface tension. Both coeffi-

Table 3. Computed coefficients of *Slip velocity model* and *Drift flux model*

	Slip velocity model			**Drift flux model**		
	C_1	**ub (cm.s^{-1})**	**R^2**	**C_0**	**ud (cm.s^{-1})**	**R^2**
0.2% CMC	1.43	30.6	0.92	1.74	34.3	0.99
0.25% CMC	1.59	30.3	0.98	1.84	34.4	0.97
0.4% CMC	1.50	38.6	0.91	1.92	39.2	0.96
0.5% CMC	1.63	43.0	0.90	1.87	43.9	0.96
0.8% CMC	1.68	47.5	0.58	2.13	44.8	0.80
0.1% xanthan	1.85	20.7	0.96	1.89	30.7	0.96
0.2% xanthan	1.89	29.3	0.94	2.09	33.3	0.92
0.3% xanthan	2.23	36.7	0.90	2.25	39.6	0.96
0.4% xanthan	1.60	50.4	0.63	1.95	48.6	0.79

cients in the drift flux model were also affected by the liquid velocity.

Even though both models fit the present data well the dependence of model parameters defined with Eq. (13) and Eq. (14) on the solution properties represents a severe drawback for using these models for design purposes in case of non-Newtonian liquids.

3. 3. Comparison With Literature Correlations for Gas Holdup Prediction

Some of the frequently cited correlations valid for non-Newtonian liquids were tested on the measured gas holdup data. Godbole et al.[9] worked with highly viscous Newtonian and non-Newtonian liquids in a liquid batch bubble column. A smaller dependency on the gas velocity and viscosity of the liquid was found in the case of glycerin solutions (Eq. 10) as Newtonian comparing to CMC solutions (Eq. 6) as non-Newtonian liquids. At higher gas velocities (see Fig. 6) both correlations yield considerably lower values to those measured in this study and are quite in consistence at the lower gas velocities (Figure 11).

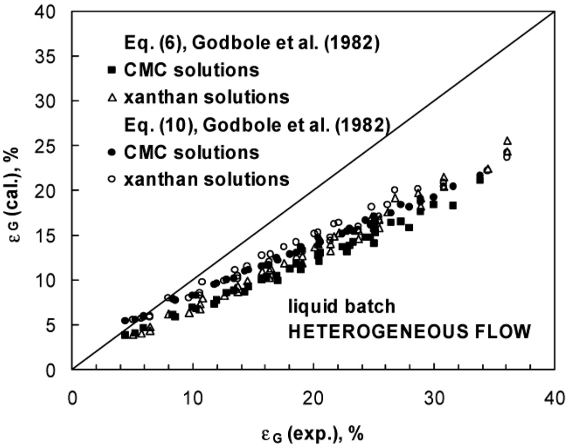


Figure 11. Comparison of experimental gas holdup data with those predicted from the available literature correlations.

Both correlations fit the data in xanthan solutions better than in CMC solutions (Table 4). Later Godbole et al.[11] studied the mass transfer coefficients in CMC solutions under two-phase flow conditions. The published correlation (Eq. 8) also underestimates the gas holdups in CMC solutions for about 26% in average but seemed to be quite acceptable in case of xanthan solutions (e_y = 17.24%). Schumpe and Deckwer[7] correlation (Eq. 4) gives the nearest values of the gas holdups to the experimental ones in CMC solutions, though slightly overestimated at high gas velocities. Tested on xanthan solutions the e_y was about 27%, what is higher than in case of CMC solutions (e_y = 17%). The authors neglected the influence of the liquid effective viscosity on the gas holdups (Figure 12). This agreement of the experimental holdups with those from Eq. (4) is not surprising, since the authors used column of the same diameter as in this study. Godbole et al.[11] experiments were produced in a column which was two-times wider (D = 30 cm). To predict the gas holdup in slug flow Godbole et al.[9] also took into account the column geometry. Their correlation (Eq. 7) fits the experimental data in 0.85% CMC solution under liquid batch conditions extremely well (Fig. 13). For the two-phase flow Schumpe and Deckwer[7] correlation (Eq. 5) in the slug flow regime shows a slightly higher disagreement to the measured values than the previous one. For the same set of experiments Das et al.[8] correlation gives much higher values of ε_G. Their experiments were performed in a vertical pipe of 1.9 cm in diameter at extremely high liquid velocities, up to 1m.s^{-1}.

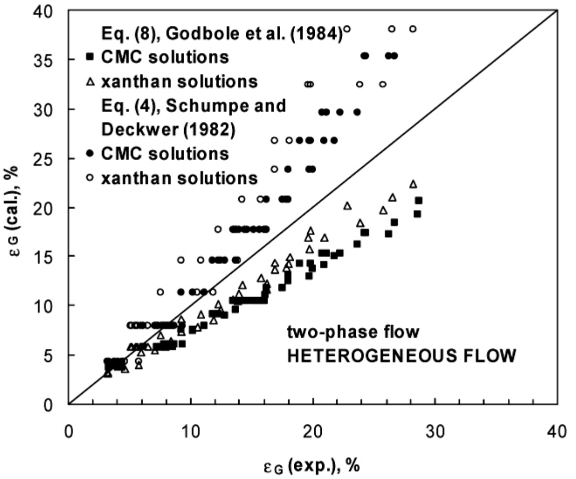


Figure 12. Comparison of experimental gas holdup data with those predicted from the available literature correlations.

For each correlation tested on the experimental data base the mean relative deviation e_y and the standard deviation σ were computed. According to the behaviour, which exhibit the polymer solutions under the operating condi-

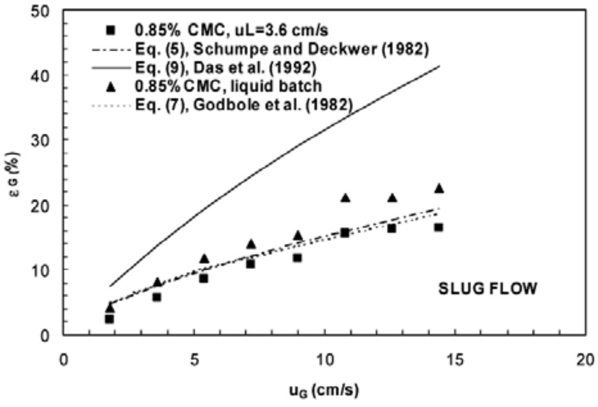


Figure 13. Gas holdup as a function of liquid superficial velocity.

Table 4. Performance of literature correlations for gas holdup prediction

			CMC solutions			xanthan solutions		
		Authors	**N**	**e_y (%)**	**σ (%)**	**N**	**ey (%)**	**σ (%)**
LIQUID BATCH	hetero-geneous flow	**Eq. (6),** Godbole et al.[9]	42	26.52	10.25	43	24.9	16.93
		Eq. (10), Godbole et al.[9]		36.45	8.38		32.42	16.93
	slug flow	**Eq. (7),** Godbole et al.[9]	8	15.52	/	no slug flow		
TWO- PHASE FLOW	hetero-geneous flow	**Eq. (4),** Schumpe and Deckwer[7]	112	19.80	13.60	47	33.6	18.02
		Eq. (8), Godbole et al.[11]		26.9	6.40		17.24	11.1
	slug flow	**Eq. (5),** Schumpe and Deckwer[7]	16	23.3	22.46	no slug flow		
		Eq. (9), Das et al.8		136.2	35.2			

tions (Fig. 7 and Fig. 8), CMC and xanthan solutions were treated separately. The results are given in Table 4.

3. 4. Correlation of Experimental Data

In columns operating with non-Newtonian liquids bubble separation and coalescence are taking place throughout the column incessantly. Also the behaviour of the gas-liquid dispersion is very unstable with time. In such a complicated system theoretical approach for the gas holdup prediction is extremely difficult. In this work effort was made to develop an empirical correlation for the gas holdup prediction valid for non-Newtonian liquids.

Only the gas holdups measured in CMC solutions were taken into the consideration. As already mentioned in the previous sections, the data gathered in xanthan solutions were extracted from those in CMC solutions with a reason. The mode of operation is also important in bubble column performance (Figure 3) so the correlations for the liquid batch system and two-phase flow should differ. Three types of the model equations were tested, a simple power law dependency of the gas holdup on the gas velocity (Eq. 15 and Eq. 18), power law dependency on the gas velocity and the effective liquid viscosity in addition (Eq. 16 and Eq. 19), and an exponential type of equation (Eq. 17 and Eq. 20). The results of the numerical analysis are shown in Table 5.

In all three types of equations the gas velocity and the liquid effective viscosity affect the gas holdup less in the liquid batch system than in the two-phase flow. The differences in the equations proposed are very small. Yet in both modes of operation the equation based on a single operating parameter u_G disagrees a little bit more with the data. The other two models are very close in the statistic parameters. However the following equations are proposed for the gas holdup prediction in CMC solutions

$$\varepsilon_G = 0.0524\, u_G^{0.623}\, \eta_{eff}^{-0.0531} \tag{16}$$

for liquid batch systems, and

$$\varepsilon_G = 0.0485\, u_G^{0.666}\, \eta_{eff}^{-0.1181} \tag{19}$$

for the two-phase flow operation. In the two equations above the liquid superficial velocity is in cm.s^{-1} and the effective liquid viscosity in mPa.s.

Table 5. Best- fit coefficients and statistics of the proposed correlations for gas holdup prediction in CMC solutions

	Type of equation		**N**	**A (/)**	**b (/)**	**c (/)**	**e_y (%)**	**σ (%)**
LIQUID BATCH	$\varepsilon_G = Au_G^b$,	**Eq. (15)**	50	0.0409	0.653	/	5.26	6.40
	$\varepsilon_G = Au_G^b\eta_{eff}^c$,	**Eq. (16)**		0.0524	–0.0531	0.623	4.32	5.28
	$\varepsilon_G = 1 - Exp(Au_G^b\eta_{eff}^c)$,	**Eq. (17)**		–0.505	0.698	–0.0611	4.25	5.76
TWO- PHASE FLOW	$\varepsilon_G = Au_G^b$,	**Eq. (18)**	128	0.0272	0.746	/	8.96	8.75
	$\varepsilon_G = Au_G^b\eta_{eff}^c$,	**Eq. (19)**		0.0485	0.666	–0.118	6.97	7.15
	$\varepsilon_G = 1 - Exp(Au_G^b\eta_{eff}^c)$,	**Eq. (20)**		–0.0479	0.730	–0.132	6.28	7.06

Table 6. Performance of the proposed correlations for gas holdup prediction in xanthan solutions

		N	e_y (%)	σ (%)
LIQUID BATCH	**(Eq. 13)**	43	6.67	5.17
TWO-PHASE FLOW	**(Eq. 16)**	47	17.5	10.02

The proposed correlations were tested on the data measured in xanthan solutions. The results are shown in Table 6.

Obviously the effective liquid viscosity is of minor importance when the column is operating as liquid batch and the proposed correlation (Eq. 16) fits the data in xanthan solutions quite well (Figure 14). It seems that in two-phase flow runs the effective liquid viscosity has an important role in the gas holdup values. The proposed correlation for the holdup prediction developed from the data of highly viscous CMC solution (Eq. 16) overestimates the gas holdup in xanthan solutions substantially. The comparison of the predicted and the measured gas holdups in both polymer solutions are shown in Figure 15.

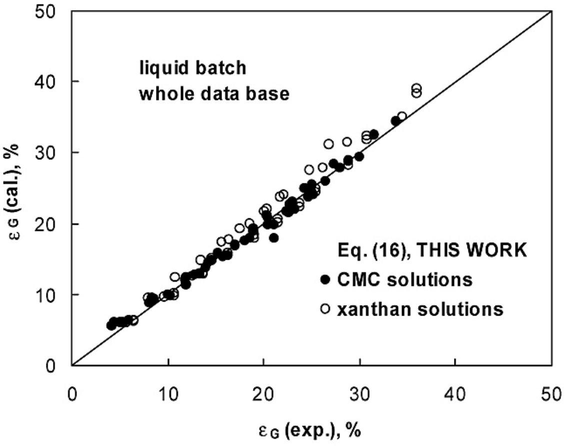


Figure 14. Comparison of experimental gas holdup data with those predicted from the proposed correlation.

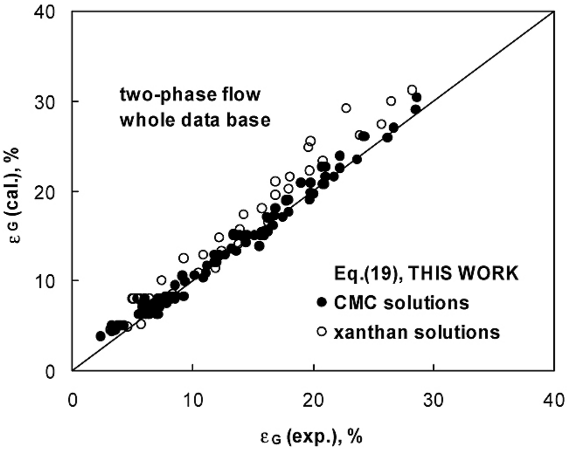


Figure 15. Comparison of experimental gas holdup data with those predicted from the proposed correlation.

4. Conclusions

The aqueous solutions of CMC and xanthan were employed as non-Newtonian liquids. The measured gas holdup was always found higher in the liquid batch runs than in the two-phase flow system and was increased with increasing gas superficial velocity and decreased with effective liquid viscosity. Both effects were less pronounced in the liquid batch runs. In CMC solutions the gas holdup obeyed power-law dependency on the effective liquid viscosity, which yield simple correlations for the prediction of gas holdup for both mode of operations. Both correlations overpredict the gas holdup in xanthan solutions, though moderately in the liquid batch. It seems that xanthan solutions behave quite differently. Though both types of solutions are viscoelastic and pseudoplastic in their nature, xanthan exhibit weak jell behaviour, while the CMC solutions shows polymer solution behaviour. The liquid velocity showed minor effect on the gas holdup but not negligible in the case of xanthan solutions.

The measured data were also analysed with the *slip velocity model* and the *drift flux model*. The coefficients of the models seem to depend on the polymer and its concentration in the liquid.

5. Acknowledgments

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6. Notation

C_0	distribution parameter, defined by Eq. (14)	/
C_1	constant, defined by Eq. (13)	
D	column diameter	m
g	acceleration due to gravity	$m.s^{-2}$
h	height	m
h_L	liquid height	m
h_{LG}	gas-liquid suspension height	m
K	consistency index in the power-law model	$Pa.s^n$
e_y	mean relative deviation, $\left(=\frac{100}{N}\sum_{i=1}^{N}\left\vert\frac{y_{MES}(i)-y_{PRED}(i)}{y_{MES}(i)}\right\vert\right)$	[%]
N	number of experiments	
N_{PL}	characteristic liquid number, $g\eta_{ef}^4/\rho_L\sigma_L^3$	/
n	flow behaviour index in the power-law model	/
Re	Reynolds number, $\frac{uD\rho}{\eta}$	/
u	superficial velocity	$m.s^{-1}$

u_b	bubble velocity rise, defined by Eq.(13)	$m.s^{-1}$
u_d	drif velocity, defined by Eq. (14)	$m.s^{-1}$
u_m	mixture superficial velocity, $u_G + u_L$	$m.s^{-1}$
u_s	slip velocity,	$m.s^{-1}$
	Greek letters	
τ	shear stress	Pa
η_{eff}	effective viscosity of the liquid	Pa.s
η	viscosity	Pa.s
ε_G	gas holdup	%
ρ	density	$kg.m^3$
σ	surface tension	$N.m^{-1}$
σ	standard deviation, $\left(=100\cdot\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left[\left\|\frac{y_{PRED}(i)-y_{MES}(i)}{y_{MES}(i)}\right\|-e_y\right]^2}\right)$	%
$\dot{\gamma}$	shear rate	s^{-1}
	Subscripts	
G	gas phase	
L	liquid phase	

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Povzetek

Kolona z mehurčki je zelo preprost reaktor, ki brez uporabe mešal zagotovi znatno medfazno površino, kar je še posebej pomembno v procesih, kjer celotno produktivnost določa hitrost medfaznega snovnega prenosa plin/tekočina. Čeprav je pri večini procesov v koloni tekočina nenewtonskega tipa (odpadno blato, mikrobiološke kulture, polimerne raztopine), v literaturi primanjkuje zaokroženih eksperimentalnih študij na tem področju.
Zato je bil namen pričujočega dela osvetliti problem vloge nenewtonske tekočine na celotno hidrodinamsko sliko dogajanja v koloni, predvsem na kvaliteto plinske disperzije in delež plina v odvisnosti od linearnih hitrosti obeh mobilnih faz. Vodne raztopine karboksi–metil-celuloze in ksantana so predstavljale tekočino z upadajočo viskoznostjo, zrak je služil kot plinska faza. Kolona s premerom 0,14 m in obatovalne višine 2,4 m je delovala polšaržno in z sotokom obeh faz navzgor. Distributor je predstavljala perforirana plošča. Obratovanje kolone je bilo v področju heterogenega tokovnega režima, delno tudi v homogenem, in v režimu čepastega toka plina. V odvisnosti od obratovalnih parametrov je bila ovrednotena kvaliteta plinske disperzije in merjen delež plina. Primerjalno so bili eksperimenti posneti še z vodo kot newtonskim medijem.
Rezultati so pokazali razliko v obnašanju vodnih raztopin karboksi metil celuloze in vodnih raztopin ksantana, predvsem v pogojih dvofaznega toka. Raztopine CMC so pokazale potenčno odvisnost deleža plina od efektivne viskoznosti tekočine, kar je omogočilo razvoj korelacije za napoved deleža plina v odvisnosti od obratovalnih pogojev. Raztopine ksantana izkazujejo lastnosti šibkih gelov, tako da je vpliv efektivne viskoznosti tekočine na performanco kolone kompleksnejši, kar stimulira nadaljne raziskave na tem področju.