Closure relations for CFD simulation of bubble columns

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Abstract

This paper describes the modelling of bubbly flow in a bubble column considering non-drag forces, polydispersity and bubble induced turbulence using the Eulerian two-fluid approach. The set of used closure models describing the momentum exchange between the phases was chosen on basis of broad experiences in modelling bubbly flows at the Helmholtz-Zentrum Dresden-Rossendorf. Polydispersity is modeled using the inhomogeneous multiple size group (iMUSIG) model, which was developed by ANSYS/CFX and Helmholtz-Zentrum Dresden-Rossendorf. Through the importance of a comprehensive turbulence modeling for coalescence and break-up models, bubble induced turbulence models are investigated. A baseline has been used which was chosen on the basis of our previous work without any adjustments. Several variants taken from the literature are shown for comparison. Transient CFD simulations are compared with the experimental measurements and Large Eddy Simulations of Akbar et al. (2012).

Introduction

Bubble columns are widely used in industrial applications since they enable an effective mass transfer between the gaseous and liquid phase, e.g. for heterogeneous chemical reactions. The performance of a bubble column strongly depends on the characteristics of the flow. Basically two regimes with different characteristics exists, a more or less homogenous flow pattern with a relative narrow bubble size distribution and a uniform distribution of the gas content over the cross section. The other flow regime is characterized by an inhomogeneous flow pattern with a broader bubble size distribution and uneven distributed gas content over the cross section. The inhomogeneous flow pattern is characterized by emerging coalescence and break-up effects (Mudde et al. 2009). The modeling of these effects depends on a good prediction of the void-fraction profile, the liquid velocity profile and the turbulent characteristics as described e.g. by Liao et al. (2011) or by Liao & Lucas (2010).

At Helmholtz-Zentrum Dresden-Rossendorf comprehensive experience exists on the modeling of mono-dispersed and poly-dispersed bubbly flows in pipes based on the two- and multi-fluid approach. The importance of the consideration of bubble induced turbulence was investigated as well as different models for bubble forces and bubble coalescence and breakup. An outcome of recent work is a validation of closure models, which describe multiphase flows in a broad range as can be found e.g. in the publications (Lucas & Krepper 2007), (Krepper et al. 2008), (Krepper et al. 2009), (Krepper et al. 2011), (Lucas & Tomiyama 2011), (Rzehak et al. 2012). Krepper et al. (2007) have demonstrated the possible importance of the consideration of the lateral forces including lift and wall force also for bubble columns by experimental and numerical investigations on a rectangular bubble column. They found a need for consideration a complete set of forces. Also the stability of homogeneous bubbly flow respective the transition between the homogeneous and the heterogeneous regime may be influenced by this forces (Lucas et al. 2006). The applicability of bubble induced turbulence models using a source term for the kinetic energy and the turbulent dissipation has been shown in the last years, e.g. by Morel (1997).

In the present paper it is shown by validating against the recently published results of Akbar et al. (2012) that the consideration of the non-drag forces and using the bubble induced turbulence model by Rzehak & Krepper (2012) is suitable for this application. The used closure models are chosen on the bases of the present work at the Helmholtz-Zentrum Dresden-Rossendorf. A focus of the present work is on the validation of bubble induced turbulence models. In particular the two concepts of modeling bubble induced turbulence through a zero equation model as e.g. described by Sato (Sato et al. 1981) and the modeling through source terms for the turbulent kinetic energy and turbulent dissipation rate as described by many authors, e.g. by Rzehak & Krepper (2012) are considered.

Nomenclature

C	constant
C_D	drag force coefficient
C_W	wall force coefficient
d	diameter (m)
Eo	Eötvös number
F	force (N)
g	gravitational constant (ms^{-2})
k	turbulent kinetic energy ($m^2\ s^{-2}$)
Re	Reynolds number
S	source

u	velocity (m s^{-1})
V_T	terminal velocity
w	velocity in z direction (m s^{-1})
x	horizontal-coordinate (mm)
$\hat{y}$	normal wall distance
Z	vertical-coordinate (mm)

Greek letters

α	void fraction (-)
ϵ	turbulent dissipation (m^2 s^{-3})
μ	viscosity (Pas)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
τ	turbulent time scale

Super-/Sub-scripts

B	bubble
G	gas
k	turbulent kinetic energy
ϵ	turbulent dissipation
ω	Specific turbulent dissipation
L	liquid
R	rise
turb	turbulent
$\perp$	maximum horizontal dimension

Experimental Facility

As experimental reference the recently published results of Akbar et al. (2012) have been used. The experiments were executed in a rectangular water/air bubble column at ambient conditions. The inlet is realized through needles at the bottom. A sketch of the test facility is shown in figure 1.
Measurements using a laser Doppler velocimetry system, an electrical conductivity probe and a high speed camera were taken for 3 mm/s and 13 mm/s superficial gas velocity. The measurement plane was 500 mm above the inlet. The results are presented for one half of the column, the results can be found in figure 3. The measured bubble sizes are shown in figure 2. The bubble sizes were measured near the Inlet and 500 mm above the inlet.
Detailed information about the used measurement techniques can be found in the original paper (Akbar et al. 2012).
As can be seen in figure 2, the Experiments of Akbar et al. (2012) cover a broad range of void fraction between 1 and 8 percentages which is interesting for an investigation of possible swarm-effects. Also the liquid velocity gradient near the wall varies in a wide range, which is important for lateral force e.g. the lift force. Through relative easy optical accessibility of the domain, turbulence data in form of liquid velocity fluctuations are measured. With the liquid velocity fluctuations the turbulent kinetic energy can be direct calculated. Also the bubble size distributions vary in an interesting range, especially concerning the modeling of polydispersed bubbly flow with more than one velocity field for the gas phase. All in all the experiments covers a broad range of effects and are suitable for validation.

Physically modeling

In the present paper the conservation equations of the Euler-Euler two-fluid model are used. The two fluid

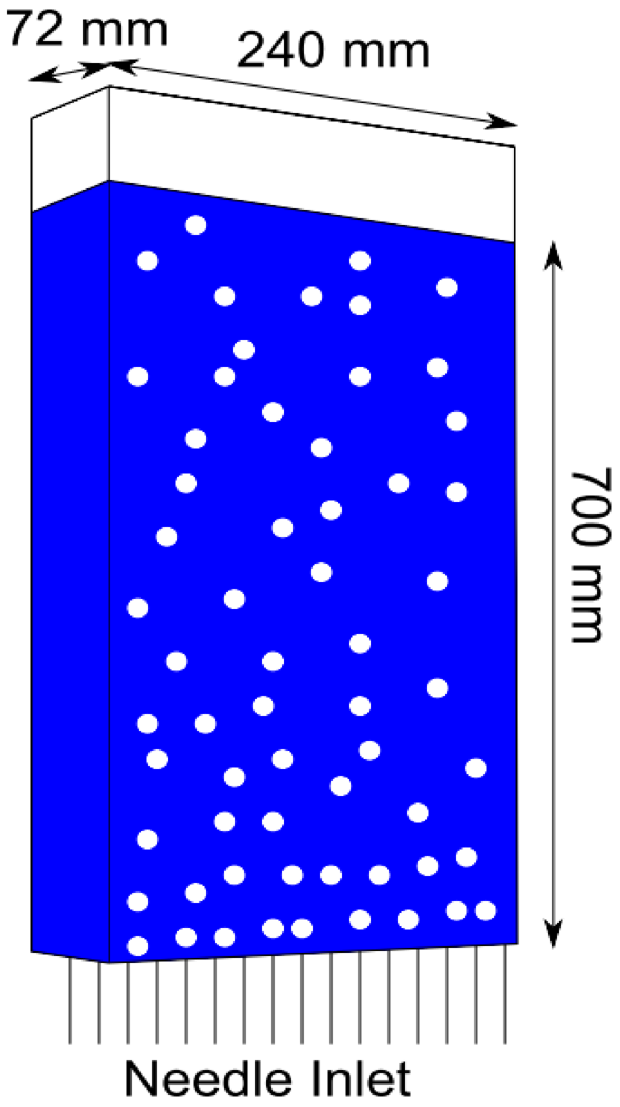

Figure 1 Experimental setup of the experiment of Akbar et al. (2012)

approach has been extended discussed and a number of books, e.g. the book of Yeoh et al. (2010) exists. Also the reliability of this approach has been discussed in the last years and can be found in many reviews, e.g. the review of Joshi (2001) or of Jakobsen et al. (2005). As a result of the averaged description, closure models which describe the interaction between the gas phase and the liquid phase are needed. In general there are forces, acting on the liquid and gas phase and induced turbulence in the liquid as a result of the motion of the gas phase. The acting forces in a bubble column depend on the bubble size. To describe the bubble diameter there are also models needed to describe the polydispersity and the coalescence and break-up of bubbles.
As can be seen in figure 2 the distribution of the bubble sizes for the used bubble column is near the sparger and 500 mm above the sparger near the same. Therefore coalescence and break-up will be neglected.
For a general modeling of multiphase flows all necessary forces acting on a bubble have to be considered. Therefore a complete set of forces would include the so called “non-drag forces”, namely the lift-force, the turbulent dispersion force and the wall force. The influence of these forces has been described in many works in the past, e.g. by Tabib et al. (2008), Ekambara & Dhotre (2010) or Zhang et al. (2006).

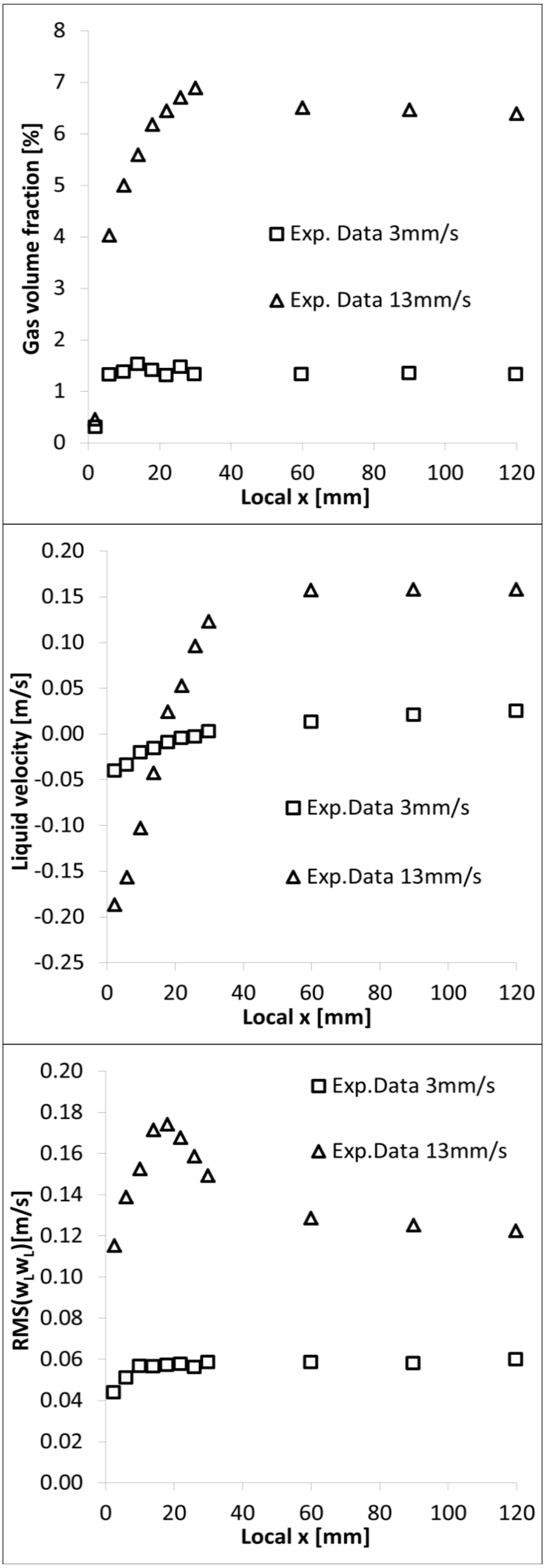

Figure 2 Experimental results of Akbar et al. (2012)

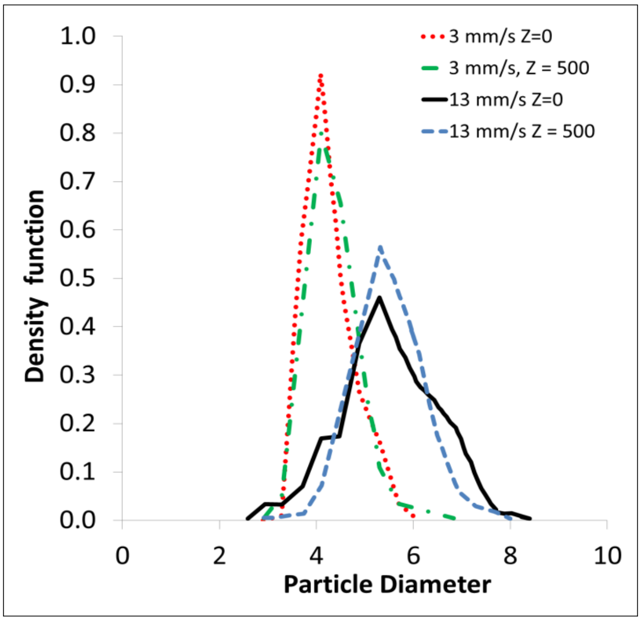

Figure 3 Measured bubble size distribution of Akbar et al. (2012)

To describe the turbulence in a bubble column two equation turbulence models, like the turbulence shear stress model according to Menter (1994), are applicable, as investigated e.g. by Sokolichin & Eigenberger (1999), by Sokolichin (2004) or by Borchers et al. (1999). The turbulence induced through bubbles is still not well understood. The most common used approach is the modeling of Sato et al. (1981). The model of Sato has the characteristic of a zero-equation model by calculating direct an additional term for the turbulent viscosity from the flow variables and the bubble diameter. Anticipating the modeling of problems with coalescence and break-up, a more detailed description of the turbulence is needed, in particular for turbulent kinetic energy and dissipation. Therefore many two-equation based bubble induced turbulence models exist, e.g. Rzehak & Krepper (2012), Politano et al. (2003), Troshko & Hassan (2001) or Morel (1997).

Modeling of the Momentum Transfer

Drag Force

The drag force describes a momentum exchange as a result of a slip velocity between gas and liquid phase. The corresponding gas phase momentum sink is defined as

$$F_{drag} = -\frac{3}{4d_B} C_D \rho_L \alpha_G |\boldsymbol{u}_G - \boldsymbol{u}_L| (\boldsymbol{u}_G - \boldsymbol{u}_L) \qquad (1)$$

The drag coefficient C_D for the here investigated bubble regime mainly depends on the Reynolds number and the Eötvös number. A correlation distinguishing different shape regimes has been suggested by Ishii & Zuber (1979), namely

$$C_D = \max\left(C_{D,Sphere}, C_{D,ellipse}\right) \qquad (2)$$

Where

$$C_{D,Sphere} = \frac{24}{Re}(1 + 0.1Re^{0.75}) \tag{3}$$

$$C_{D,ellipse} = \frac{2}{3}Eo^{0.5} \tag{4}$$

Tomiyama et al. (1998) validated this correlation and found good agreement except at high values for the Eötvös number. Swarm effects regard in general only the effect on the drag force coefficient. The dependency is mostly given by a function concerning the ratio between C_D and a $C_{D,Swarm}$ in a swarm, as can be found e.g. by the formulation of Garnier et al. (2002) or Simonnet et al. (2007). The influence of considering the swarm effect is investigated below.

Lift Force

In a shear flow a bubble experiences a force lateral to the direction of flow. This effect is in general referred to the lift force and described by the definition of Zun (1980):

$$F_{Lift} = -C_L \rho_L \alpha_G (\boldsymbol{u}_G - \boldsymbol{u}_L) \times rot(\boldsymbol{u}_L) \tag{5}$$

For a spherical bubble the shear lift coefficient C_L is positive so that the lift force acts in the direction of decreasing liquid velocity, i.e. in case of co-current pipe flow in the direction towards the pipe wall. Experimental (Tomiyama et al. 2002) and numerical (Schmidtke 2008) investigations showed that the direction of the lift force changes its sign if a substantial deformation of the bubble occurs. From the observation of the trajectories of single air bubbles rising in simple shear flow of a glycerol water solution the following correlation for the lift coefficient were derived:

$$C_L = \begin{cases} \min[0.288\tanh(0.121Re, f(Eo_\perp)] \\ f(Eo_\perp) \\ -0.27 \end{cases} \tag{6}$$

with

$$f(Eo_\perp) = 0.00105Eo_\perp^3 - 0.0159Eo_\perp^2 - 0.0204Eo_\perp + 0.474 \tag{7}$$

This coefficient depends on the modified Eötvös number given by:

$$Eo_\perp = \frac{g(\rho_L - \rho_G)d_\perp^2}{\sigma} \tag{8}$$

where $d_\perp$ is the maximum horizontal dimension of the bubble. It is calculated using an empirical correlation for the aspect ratio by Wellek et al. (1966) with the following equation:

$$d_\perp = d_B\sqrt[3]{1 + 0.163Eo^{0.757}} \tag{9}$$

Where Eo is the usual Eötvös number.
The experimental conditions on which Eq. (6) is based, were limited to the range $-5.5 \le \log10\ Mo \le -2.8$, $1.39 \le Eo \le 5.74$ and values of the Reynolds number based on bubble diameter and shear rate $0 \le Re \le 10$. The water-air system at normal conditions has a Morton number Mo = 2.63e-11 which is quite different, but good results have nevertheless been reported for this case as shown by Lucas & Tomiyama (2011). As can be seen at Eq. (6) and Eq. (7) the value of bubble size where the lift force changes its direction is at 5.8mm in this case.

Turbulent dispersion Force

The turbulent dispersion force describes the effect of the turbulent fluctuations of liquid velocity on the bubbles. Burns et al. (2004) derived an explicit expression by Favre averaging the drag force as:

$$F_{Disp} = -\frac{3}{4}C_D\frac{\alpha_G}{d_B}\,|\boldsymbol{u}_G - \boldsymbol{u}_L|\frac{\mu_L^{turb}}{\sigma_{TD}}\left(\frac{1}{\alpha_L} + \frac{1}{\alpha_G}\right)\nabla(\alpha_G) \tag{10}$$

In analogy to molecular diffusion σ_{TD} is referred to as a Schmidt number. In principle it should be possible to obtain its value from single bubble experiments also for this force by evaluating the statistics of bubble trajectories in well characterized turbulent flows but to our knowledge this has not been done yet. A value of $\sigma_{TD} = 0.9$ is typically used.
In the same work the expression for the so-called Favre averaged drag (FAD) model has also been compared with other suggestions and it was shown that all agree at least in the limit of low void fraction.

Wall Force

A bubble translating next to a wall in an otherwise quiescent liquid also experiences a lift force. This wall lift force, often simply referred to as wall force, has the general form:

$$F_{wall} = \frac{2}{d_B}C_W\rho_L\alpha|u_G - u_L|^2\hat{y} \tag{11}$$

where $\hat{y}$ is the unit normal perpendicular to the wall pointing into the fluid. The dimensionless wall force coefficient C_W depends on the distance to the wall y and is expected to be positive so the bubble is driven away from the wall.
Based on the observation of single bubble trajectories in simple shear flow of glycerol water solutions Tomiyama et al (1995) and later Hosokawa et al. (2002) concluded the functional dependence:

$$C_W(y) = f(Eo)\left(\frac{d_B}{2y}\right)^2 \tag{12}$$

Where in the limit of small Morton number (Hosokawa et al. 2002).

$$f(Eo) = 0.0217Eo \tag{13}$$

The experimental conditions on which Eq. (13) is based are $2.2 \le Eo \le 22$ and log10 Mo = -2.5 … -6.0 which is still different from the water-air system with Mo = 2.63e-11 but a recent comparison of this other distance-dependences that have been proposed in the literature (Rzehak et al. 2012) has nonetheless shown that good predictions could be obtained for a set of data on vertical upward pipe flow of air bubbles in water.

Two-phase Turbulence

Concerning turbulence in bubbly flows it suffices to consider the continuous liquid phase based on the small density and small spacial scales of the dispersed gas. We adopt a two equation turbulence model with additional source terms describing bubble induced turbulence. The formulation given is equally applicable to either k-ε, k-ω or SST model, but the latter will be used in the calculations. Model parameters take their usual single phase values.

Concerning the source term describing bubble effects in the k-equation there is large agreement in the literature. A plausible approximation is provided by the assumption that all energy lost by the bubble due to drag is converted to turbulent kinetic energy in the wake of the bubble. Hence, the k-source becomes

$$S_L^k = F_L^{drag} |u_G - u_L| \quad (14)$$

For the ε-source a similar heuristic is used as for the single phase model, namely the k-source is divided by some time scale τ so that

$$S_L^{\epsilon} = C_{\epsilon B} \frac{S_L^k}{\tau} \quad (15)$$

For use with the SST model, the ε-source is transformed to an equivalent ω-source which gives

$$S_L^{\omega} = \frac{1}{C_{\mu} k_L} S_L^{\epsilon} - \frac{\omega_L}{k_L} S_L^k \quad (16)$$

This ω-source is used independently of the blending function in the SST model since it should be effective throughout the fluid domain.

Modeling of the time scale τ proceeds largely based on dimensional analysis. Obviously there are two length and two velocity scales in the problem, where one of each is related to the bubble and the other to the turbulent eddies, so that four plausible time scales can be formed. A comparison of all of these four possibilities for vertical upward two phase flow in a pipe (Rzehak & Krepper 2012) showed that the best predictions were obtained for the choice

$$\tau = \frac{d_B}{\sqrt{k_L}} \quad (17)$$

This variant will be used also here. The coefficient $C_{\varepsilon B}$ is set to unity.

The used two equation bubble induced turbulence models are summarized in table 1.

Since bubble-induced effects are included in k and ε / ω due to the respective source terms, the turbulent viscosity is evaluated from the standard formula

$$\mu^{turb} = C_{\mu} \rho \frac{k^2}{\epsilon} \quad (18)$$

Author	$1/\tau$	$C_{\epsilon B}$
Morel (1997)	$\left(\frac{\epsilon}{d_b^2}\right)^{1/3}$	1
Troshko (2001)	$\frac{\|u_G - u_L\|}{d_b}$	0.45
Politano (2003)	$\frac{\epsilon}{k}$	1.93
Rzehak (2012)	$\frac{\sqrt{k_L}}{d_B}$	1

Table 1 Used BIT models

Polydispersity/iMUSIG

The inhomogeneous multiple size group (iMUSIG) model as introduced by Krepper et al. (2008) assign the bubble classes used in the MUSIG model in different velocity groups. Each velocity group has therefore his own velocity field. This is important to describe effects like the bubble size depended movement of the gas phase caused by the lift force. In the present case the coalescence is neglected, therefore the bubble classes and the velocity groups are the same. The bubble classes are chosen in a way that the bubble size distributions, as figured in figure 2, are split up at the diameter where the lift force changes its sign. The resulting bubble classes for 13 mm/s superficial velocity can be found in table 2. The case of 3 mm/s superficial velocity is treated as monodisperse, because almost all bubbles are smaller so that there is no need for considering different velocity groups.

	d_B	α	$Eo_{\perp}$	C_L
Bubble Class 1	5.3 mm	0.63 %	3	0.288
Bubble Class 2	6.3 mm	0.37 %	7.3	-0.116

Table 2 Used Bubble classes

Baseline

The presented closure models including the bubble induced turbulence model of Rzehak et al. (2012) are from now on summarized by the concept of a baseline model. The closure models summarized in the baseline model are chosen based on the comprehensive experience at the Helmholtz-Zentrum Dresden-Rossendorf. Several variants are used to access the relative performance.

Solution Method

The rectangular bubble column was discretized in structured hexahedral Volumes. The calculation domain is resolved by 60x18x175 (W x D x H) cells, which are around 200 T Cells and 4 mm cell size. The independence of the solution regarding the grid size has been tested. The spatial discretization used a second order scheme. The equations

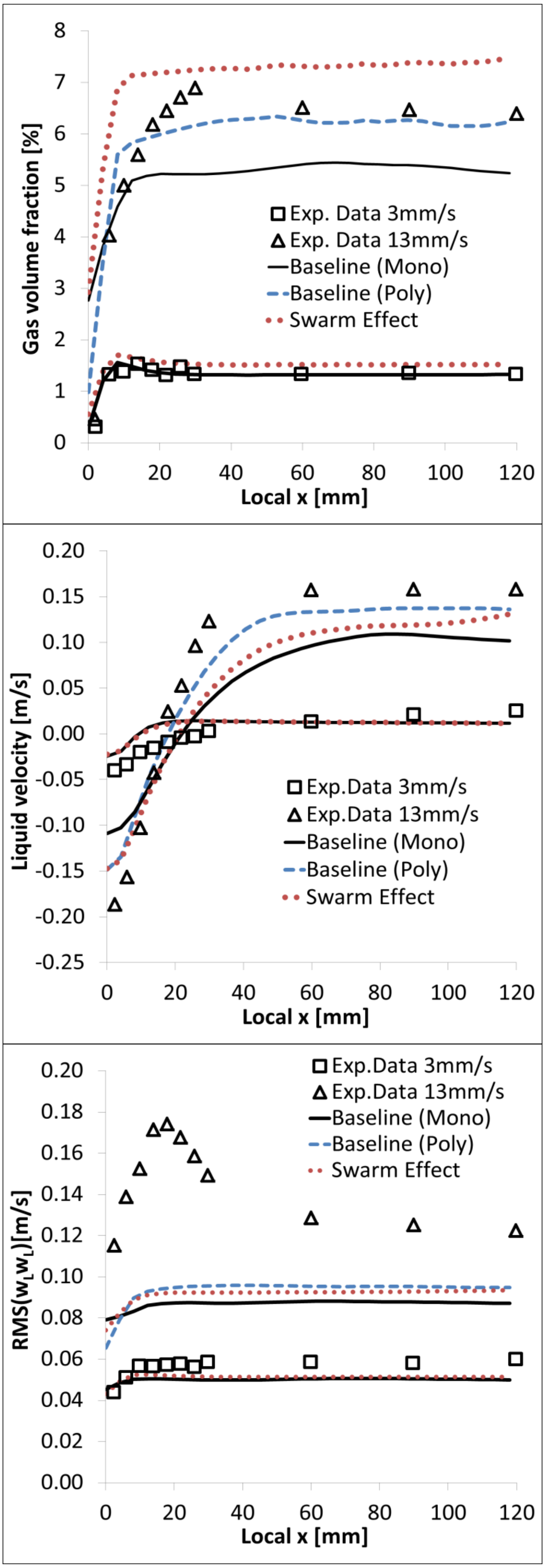

Figure 4 Study regarding the swarm effect and the treatment of polydispersity for different values, experimental data from (Akbar et al. 2012).

were solved transient with a second order backward Euler scheme. A CFL-number between 1 and 2 showed sufficient convergence in time. The results are presented averaged over a minimum of 240 s simulation time. All calculations are performed with a customized version of ANSYS-CFX 13.

Results and Discussion

Influence of polydispersity and swarm effects

To study the treatment of the polydispersity, the baseline model set is tested with and without the iMUSIG approach using two bubble classes as described above. The variation is only performed for a superficial gas velocity of 13 mm/s, because of the neglect able effect at 3 mm/s caused by the smaller bubbles within a narrow bubble size distribution. The results are shown in figure 4.
As can be seen, the baseline model with monodisperse treatment for a superficial velocity of 3 mm/s fits the experimental data very well. The hinted trend of a peak in the gas fraction profile near the wall can be reproduced.
This trend is also described by Krepper et al. (2007), who used a similar experimental facility. The liquid velocity near the wall is a little bit over predicted and fits the experimental data in the core region very well. The RMS of the upward velocity is a little bit underpredicted, but still well reproduced.
The difference between the monodisperse treatment and the polydispersed treatment for 13 mm/s using the measured bubble size distribution, shown in figure 2, is significant. The polydispersed treatment reproduces the gas volume fraction and the liquid velocity very well. The monodisperse treatment is in general too low for these values and the gradient of the gas volume fraction near the wall is much better reproduced by the polydispersed treatment compared to the monodisperse treatment. The RMS of the upward velocity is for both setups too low regarding the experimental data. The polydispersed setup gives slightly higher values than the monodisperse setup. Not reproduced is the peak in the RMS of the upward velocity for 13 mm/s. This peak is located at the change of sign of the liquid velocity.
To study the swarm effect, the correlation of Riboux et al. (2010), Eq. (19), as also submitted by Akbar et al. (2012) is used.

$$w_R = V_T(1 - \alpha^{0.49}) \qquad (19)$$

Estimated for a void fraction of six percentages, the ratio between the terminal velocity of a single bubble V_T and the rise velocity in the swarm w_R would be 0.75. Which is relative high considering other studies, e.g. by Roghair et al. (2011), Simonnet et al. (2007) or Ishii & Zuber (1979). The swarm effect is implemented by multiplying the correlation of Riboux et al. (2010) with the drag coefficient described in Eq. (2). For 13 mm/s the polydispersed treatment is used, for 3 mm/s the monodisperse treatment is used. The results are shown in figure 4.
For 3 mm/s superficial gas velocity the effect of the swarm is neglect able. The experimental data for the gas velocity are between the Baseline model set with swarm effect and without considering the swarm effect. The gradient near the wall is better reproduced without the swarm effect.

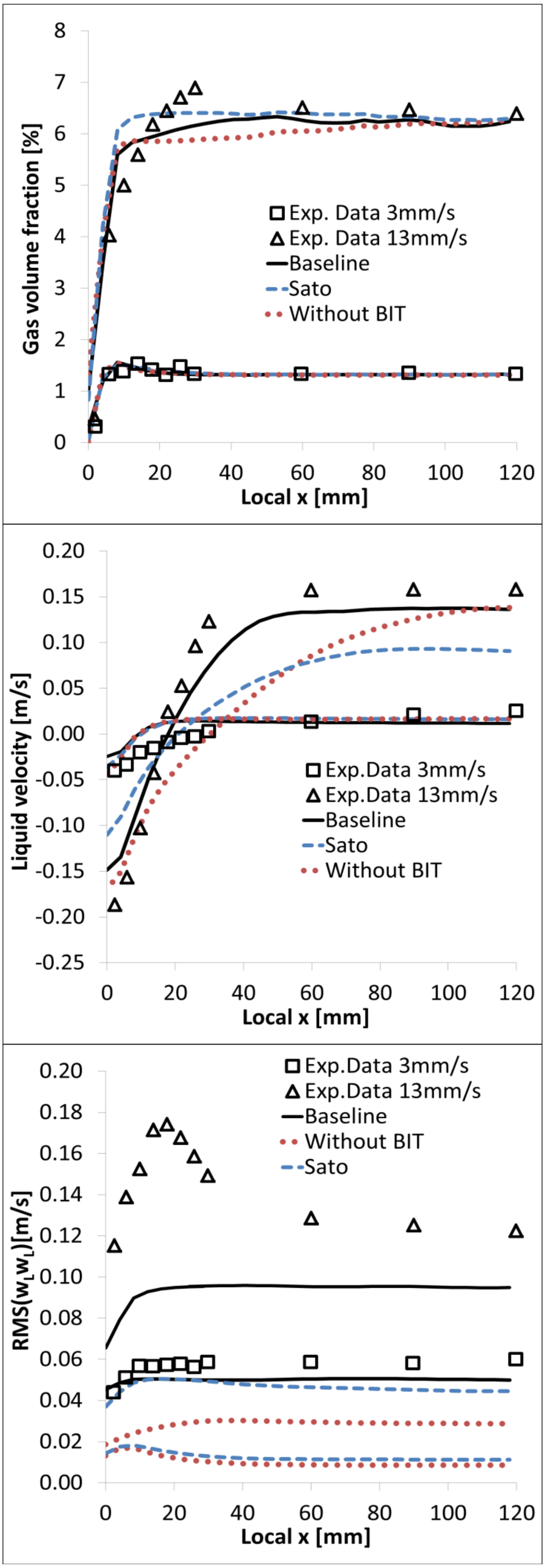

Figure 5 Results using the Sato model and using no bubble induced turbulence model for different superficial velocities, experimental data from (Akbar et al. 2012).

The resulted liquid velocity with the swarm effect is situated below the setup without considering the swarm effect and is therefore in general too low. An important result is that the swarm effect on the drag force has less influence on the RMS of the upward velocity. Regarding the presented results, in further investigations the baseline model set is used without considering the swarm effect on the drag coefficient and the case of 13 mm/s superficial gas velocity is treated as polydispersed.

Sensitivity of bubble induced turbulence

Next the general influence of the bubble induced turbulence (BIT) is studied. Therefore the baseline model set is compared with the Sato model (Sato et al. 1981) and a model using no bubble induced turbulence. The study is performed for both superficial gas velocities of 3 mm/s and 13 mm/s and is compared with the experimental data. The results are shown in figure 5.
For a superficial gas velocity of 3 mm/s the gas volume fraction and the liquid velocity profile is not influenced by the effect of the bubble induced turbulence. The RMS of the upward velocity is influenced by the bubble induced turbulence. As would be expected the Sato model and the treatment without using a BIT model yield nearly the same results. This is because the Sato model is a zero equation model which only models an additional term for the turbulent viscosity. The Sato model is described by the following equations:

$$\mu^{\text{turb}} = \mu^{\text{turb,Single Phase}} + \mu^{\text{turb,BIT}} \qquad (20)$$

$$\mu^{\text{turb,BIT}} = 0.6\rho_l \alpha d_B |u_G - u_L| \qquad (21)$$

The Sato model under predicts the RMS of the upward velocity.
For a superficial velocity of 13 mm/s the gas volume fraction profile is less influenced. In contrast the liquid velocity profile is very strong influenced. The Sato model results in a very low and a very smooth liquid velocity profile. This is because of the higher turbulent viscosity predicted by the Sato model and therefore also a higher turbulent dispersion force as can be seen at Eq. (10). Using no BIT model the liquid velocity has a smaller gradient next to the wall. Without a BIT model the RMS of the upward velocity is highly underpredicted. With the Sato model the RMS of the upward velocity is also underpredicted and is situated in the region of the prediction of the Baseline model for 3 mm/s. The Sato model predicts the RMS of the upward velocity higher than using no BIT model. The single phase source for the kinetic energy is proportional to the turbulent viscosity:

$$S_L^{\epsilon} = \mu_T S^2 \qquad (22)$$

Therefore the Sato model has an indirect influence on the turbulence parameters appearance in two equation models.
The results show that for a correct prediction of the turbulent kinetic energy and consequently a correct prediction of coalescence and break-up mechanism a BIT model is necessary and that the frequently used Sato model is not sufficient.

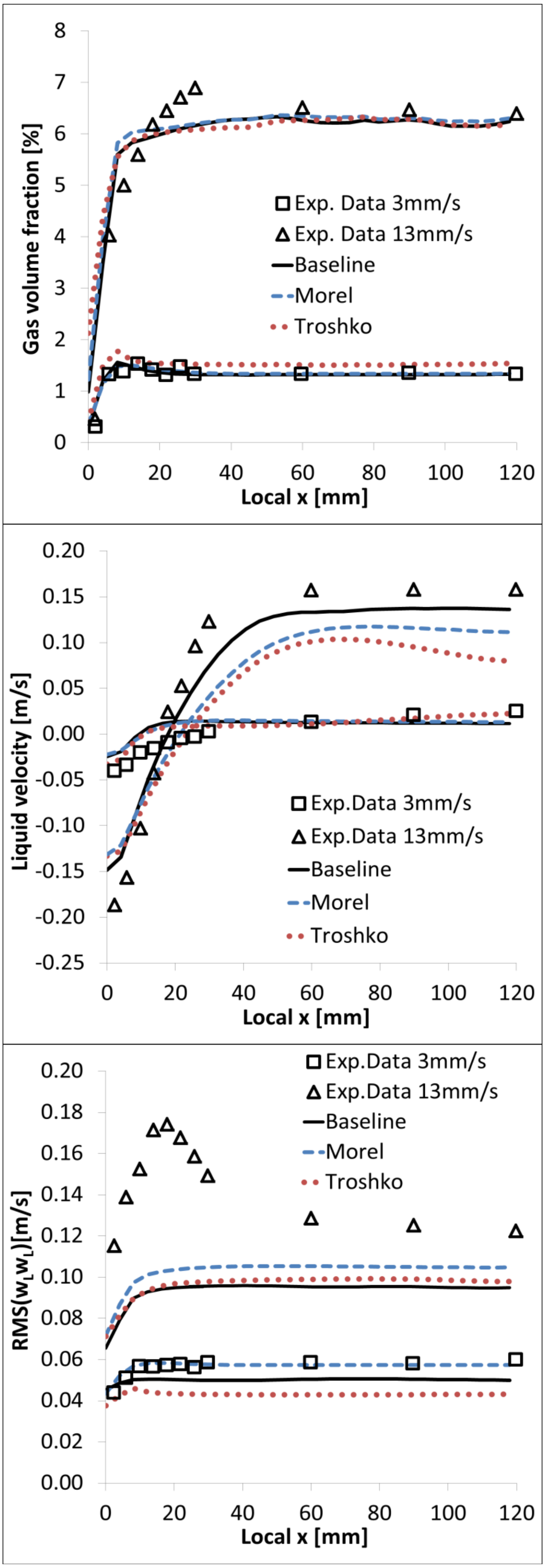

Figure 6 Results using the BIT models of Morel (1997) and Troshko & Hassan (2001) for different superficial velocities, experimental data from (Akbar et al. 2012).

Comparison with other BIT models

In the next section four different bubble induced turbulence models for the k-ϵ/ω turbulence model are investigated. The used models are summarized in table 1. The main different between these bubble induced turbulence models is the definition of the turbulence time scale τ. Through dimensional analysis four options for defining the time scale can be found. These four options are represented by the four used models, as described by Rzehak & Krepper (2012). The study is performed for 3 mm/s and 13 mm/s superficial velocity. The results are shown in figure 6 and figure 7. For 3 mm/s superficial velocity the differences between the four BIT models are marginal. Just for the gas volume fraction profile using the model of Troshko & Hassan (2001) differences could be observed. Differences occur for the RMS of the upward velocity. The results using the model of Rzehak & Krepper (2012) (Baseline) are situated between the results using the model of Morel (1997) and of Troshko & Hassan (2001). The model of Troshko & Hassan (2001) underpredicted the RMS of the upward velocity, the model of Morel (1997) hits the measured profile of the RMS of the upward velocity. Using the model of Politano et al. (2003) the RMS of the upward velocity profile is strongly underpredicted.

Higher differences occur for the 13 mm/s superficial velocity setup. For 13 mm/s the model constants of the Politano et al. (2003) model is adjusted to the measured turbulence intensity. This is reached by halving the sources given in table 1. The gas fraction profile is well reproduced by all BIT models. The varied Politano et al. (2003) model predicts the gas fraction profile also good. The liquid velocity profile is well reproduced by the Rzehak & Krepper (2012) model (Baseline) and the model by Morel (1997). Using the model by Troshko & Hassan (2001) and Politano et al. (2003) the characteristic flat profile in the column center is not reproduced. The variation of the Politano et al. (2003) model gives a strong underpredicted liquid velocity profile. This is due a very high turbulent viscosity caused through the variation. The predicted RMS of the upward velocity is for the Politano et al. (2003), Troshko & Hassan (2001) and the Rzehak & Krepper (2012) model nearly the same but the predicted profiles are still lower than the experimental profiles. The model of Morel (1997) gives a slightly higher profile as the Rzehak & Krepper (2012) model. The varied Politano et al. (2003) model reproduces the RMS of the upward velocity best, but over predicted in return the turbulent viscosity very strong as can be seen at the lower liquid velocity profile.

Summarizing the baseline model reproduces the experimental data best. Using the model of Morel (1997) the RMS of the upward velocity is better reproduced, but the resulting liquid velocity profile is underpredicted. The fitting of the Politano et al. (2003) model to the RMS of the upward velocity does not show good results.

Baseline variation and comparison with LES results

Basing on the previous results the baseline model shows the best agreement with the experimental data. Therefore the baseline model is compared to the LES made by Akbar et al. (2012). Akbar et al. (2012) used a Lagrangian modeling to

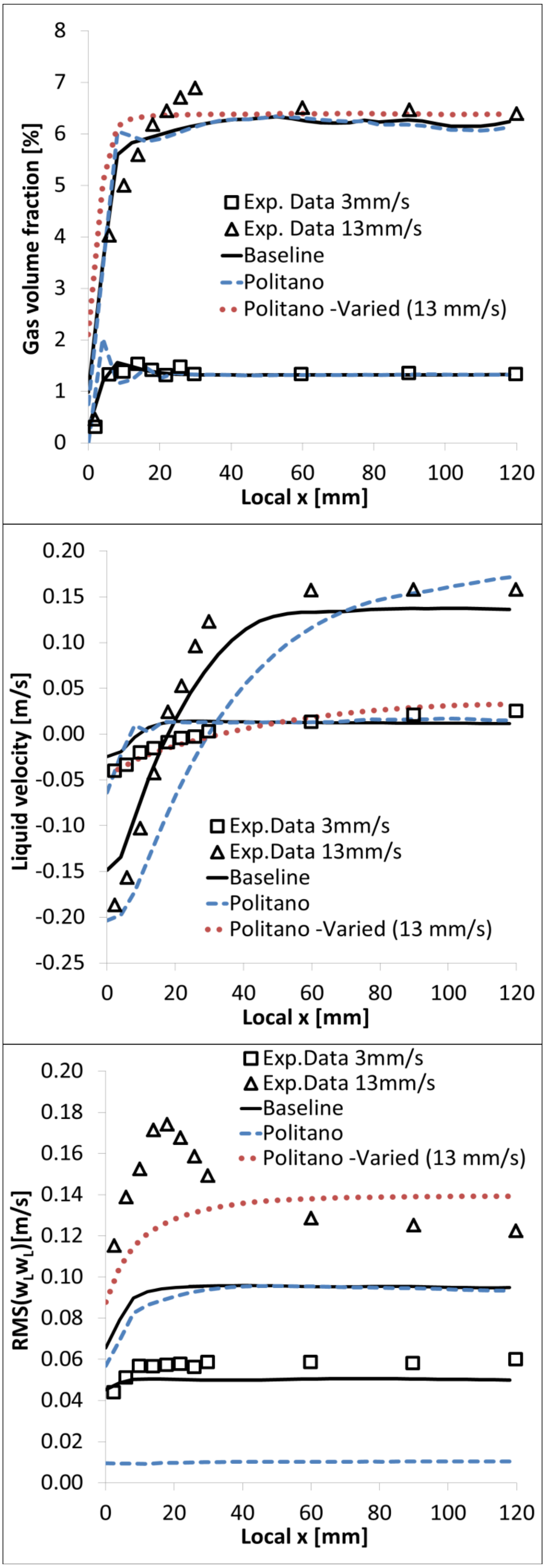

Figure 7 Results using the BIT model of Politano et al. (2003) for different superficial velocities and a variation of it for 13 mm/s, experimental data from (Akbar et al. 2012).

describe the bubbles.

The used momentum closure models are comparable to the here defined baseline model, a slightly different drag model by Tomiyama et al. (1998) is used and the coefficient for the wall force C_w is set constant to 0.05 according to Tomiyama et al. (1995). Also the virtual mass is taken into account. Bubble interactions are represented through a collision model by Sommerfeld et al. (2003), the simulation was performed using two way coupling.

The bubble induced turbulence model of Rzehak & Krepper (2012) in the baseline model set is varied by changing the model constant $C_{\epsilon B}$. By halving the model constant to $C_{\epsilon B} = 0.5$ it is intended to reproduce the measured RMS of the upward velocity profile better.

In figure 8 the results of the baseline model, of the LES of Akbar et al. (2012) and the variation of the baseline model is shown.

The results of the LES are very similar to the results obtained using the baseline model set. The gas fraction and the liquid velocity profile are in good agreement. Differences occur for the profile of the RMS of the upward velocity. Using the LES method described above the turbulent intensity is scaled for different superficial velocities in another way than the BIT model of Rzehak & Krepper (2012). For 3 mm/s superficial velocity the LES method under predicts the experimental data and the calculated profile using the Rzehak & Krepper (2012) model. For 13 mm/s the LES method gives in average similar results compared to the calculated profile using the Rzehak & Krepper (2012) model, but under predicts the experimental data as well. Also the peak of the experimental data is not reproduced by the LES method.

With the variation of the BIT model the gas volume fraction is well reproduced. The liquid velocity profile is underpredicted. This trend is consistent to the results obtained through the variation of the Politano et al. (2003) model. The RMS of the upward velocity profile is better reproduced. Compared to the previous results the variation of the Rzehak & Krepper (2012) model gives for the gas fraction profile and the liquid velocity profile nearly the same results as using the Sato model. Also the turbulent viscosity which is not shown here is nearly the same as obtained using the Sato model.

The results show that using the Eulerian approach similar results can be obtained compared to the LES. Adjusting the model parameter of the BIT model of Rzehak & Krepper (2012) the RMS of the upward velocity is better predicted, but the liquid velocity profile is underpredicted. Parameter adjustments improves some aspects but worsens other, in general it is not recommended.

Conclusions

In the present paper it is shown that through a conscientious model selection very good results for the investigated bubble column can be obtained without fitting the model constants. The used model set includes comprehensive modelling of non-drag forces, polydispersity and bubble induced turbulence. Considering the lift force, the turbulent dispersion force, the wall force, polydispersity with the inhomogeneous multiple size group model (iMUSIG) by Krepper et al. (2008) and modeling turbulence with two equation models reproduce the experimental data for two

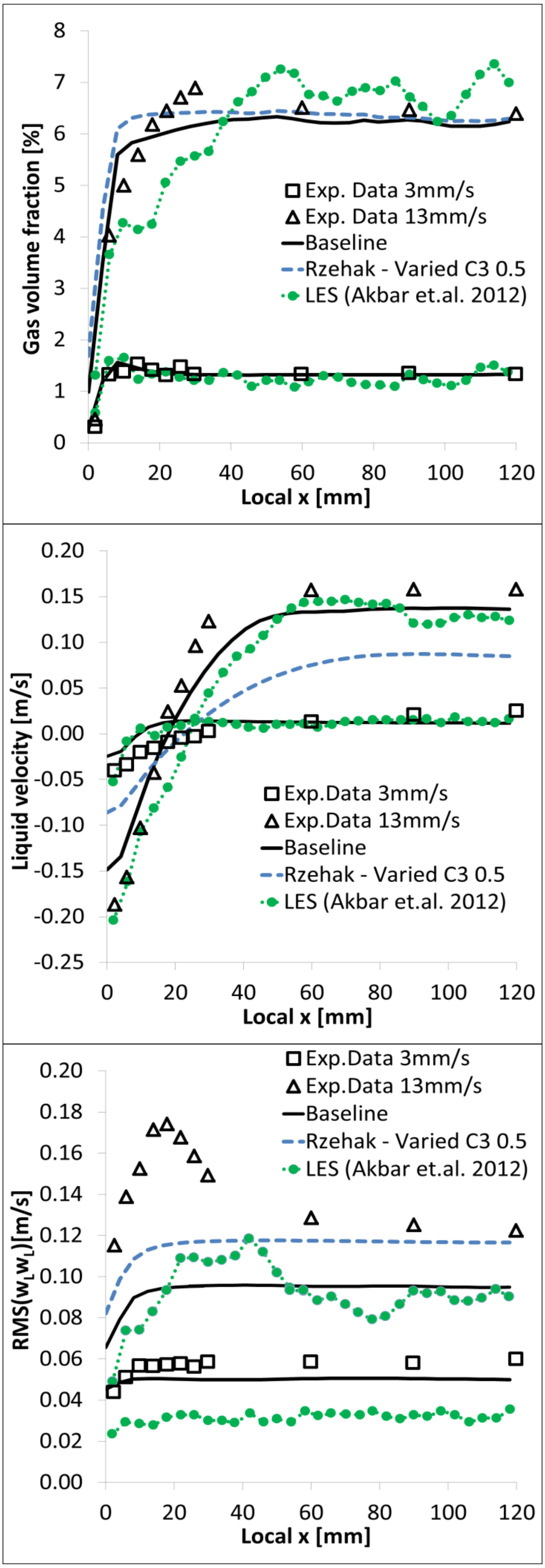

Figure 8 Comparison of the defined baseline mode with LES data and a variation of the baseline mode, LES and experimental data from (Akbar et al. 2012).

superficial velocities very good. The validation of bubble induced turbulence (BIT) models is still not in an advanced stage and new models are postulated, e.g. the model of Rzehak & Krepper (2012). Therefor five representative BIT-models are validated and the model of Rzehak & Krepper (2012) shows the best results. Zero equation models like the model of Sato et al. (1981) cannot reproduce the turbulence values, which are very important for modelling coalescence and break-up effects.

The closure models concerning lift, turbulent dispersion and wall force are chosen based on the experiences at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and are summarized with the iMUSIG model and the bubble induced turbulence model of Rzehak & Krepper (2012) to a baseline model set. The results obtained with this model set are compared with experimental data and Lagrangian Large Eddy Simulations, very good accordance is reached.

All turbulence models and the LES under predict the turbulence intensity in general for a higher superficial velocity. Moreover a peak in the turbulence intensity could not be reproduced, weather using two-equation turbulence models or using LES. Concerning this a broader study has to be done, clarifying the effect causing this peak.

All in all through the very good results obtained with the defined model set, the fact that no model fitting was necessary and that the used models are intensively validated for pipe flows at the HZDR, the endeavor of formulating a general closure model set for a broad range of bubbly flow problems is confirmed.

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