Ninth International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
10-12 December 2012

ON THE EFFECT OF LIFT FORCES IN BUBBLE PLUMES

Jan Erik OLSEN* and Mihaela POPESCU

SINTEF Materials & Chemistry, 7465 Trondheim, NORWAY

*Corresponding author, E-mail address: Jan.E.Olsen@sintef.no

ABSTRACT

A preceding study concluded that the lift force in dense bubble plumes in mixing vessels had no influence on the flow. Since the lift force is generally assumed to be of importance, a new study has been conducted in order to shed more light on the issue. It is found that the lift force is of little importance in turbulent plumes with little influence of walls.

NOMENCLATURE

C_D drag coefficient
C_L lift coefficient
d bubble diameter
e specific energy rate
Eo Eotvos Number
F force / mass
g gravitational constant
H ladle height
k turbulent kinetic energy
M ladle mass
p pressure
Q volumetric gas rate at STP conditions
Re Reynolds number
T temperature
u velocity
V volume

α volume fraction
ε turbulent energy dissipation
μ viscosity
ρ density
σ surface tension

Subindexes

0 ambient conditions
b bubbles
eq equilibrium
g gas
l liquid
t turbulence

INTRODUCTION

Bubble plumes are driven by the buoyancy of bubbles and they are significantly affected by drag forces on bubbles. It is also assumed that lift forces are important. Lift is the perpendicular component of the hydrodynamic force relative to the flow direction. The lift coefficient is well known for a single bubble, but for bubbles in a turbulent plume uncertainty remains. Some authors set the coefficient to zero and some use it as a tuning parameter. Whether the lift force is significant or not is still open for debate. The effect of lift is therefore considered in the following study.

When assessing the lift force and its influence in a turbulent flow, it is important to also properly account for turbulent dispersion. If this is neglected, the entire plume spreading force might be falsely attributed to the lift force. This was properly handled by Lucas *et.al.* (2004) who studied the effect of lift forces on the stability of a bubble column, while e.g. Díaz *et.al.* (2009) neglects turbulent dispersion and thus the findings on the lift force is onlyt valid for modelling concepts were these are smeared into an overall spreading force.

Bubbles in plumes are affected by the lift force. Lucas & Tomiyama (2011) recently showed that the lift force plays an important role in pipe configurations. Olsen & Cloete (2009) concluded that the lift force was insignificant in their studies on a bubble plume in a more open vessel. This was due to the bubble size which tended towards the size where the lift coefficient is very small. The difference between these two studies is mainly the geometry and the gas rates. Olsen & Cloete (2009) studied less confined plumes at higher void fractions. The bubble size in their work was completely dominated by turbulence breakup. This study focuses on bubble plumes where turbulence is sufficiently high to govern the bubble size and on vessels in which walls are not strongly confining the plume.

MODEL DESCRIPTION

In order to study the effect of lift forces on bubbles in bubble plumes, a modelling concept capable of capturing the physics of a bubble plume is applied. The lift force is included in the force description on the bubbles. The plumes have been studied by an Eulerian-Lagrangian modelling concept based on a coupling of DPM and VOF models.

Lift force

The lift force on the bubbles is included as

$$\mathbf{F}_L = C_L \rho_l V_b \left(\mathbf{u}_l - \mathbf{u}_g\right) \times \left(\nabla \times \mathbf{u}_l\right) \qquad (1)$$

where C_L is the lift coefficient. For a single spherical particle, the coefficient is 0.5. For dilute bubble plumes and single bubbles, the lift coefficient is known to vary with bubble size and shape. Small bubbles tend to move towards the edge of a plume and larger bubbles tend to move towards the centre of a plume.. Tomiyama (2002) published an expression for the lift coefficient which captures this. The lift coefficient of Tomiyama C_{LT}

$$C_{LT} = \begin{cases} \min\left[0.288\tanh\left(0.121\,\mathrm{Re}\right),\ f(\mathrm{Eo})\right] & \text{for } \mathrm{Eo} < 4 \\ f(\mathrm{Eo}) & \phantom{\text{for }} 4 < \mathrm{Eo} < 10.7 \end{cases} \qquad (2)$$

$$f(\mathrm{Eo}) = 0.474 - 0.0204\mathrm{Eo} - 0.0159\mathrm{Eo}^2 + 0.00105\mathrm{Eo}^3$$

is a function of the Eotvos number which accounts for particle size and shape. The coefficient is positive for small bubbles and negative for large bubbles. The transition is roughly between 5 and 6 mm for air bubbles in water. The lift coefficient of Tomiyama is valid for single bubbles or dilute plumes. For dense bubble plumes with high void fractions, little is known about the lift coefficient. To accurately model dense plumes, a lift coefficient accounting for higher void fractions might be necessary. Behzadi *et.al.* (2004) published a model for the lift coefficient which accounts for higher void fractions. Unfortunately this model does not account for bubble size and shape. The expression is based on very few data points, and varies as a function of void fractions according to

$$C_{LB} = 6.51 \times 10^{-4} \alpha^{-1.2} \qquad (3)$$

The value is limited to a maximum value of 0.5 at low void fractions.

Modelling concept

The coupled Volume of Fluid (VOF) and Discrete Phase Model (DPM) applies the VOF model to describe the fluid behaviour of the liquid in a vessel, the continuous gas phase above the liquid and the interface between them. Since the VOF model can not resolve the bubbles with an affordable grid resolution, a Lagrangian method, DPM, is used to track the bubbles. The Lagrangian bubbles are connected to the Eulerian phases with a two-way coupling through interchange terms such as the drag force in the respective momentum equations.

The bubbles are modelled as discrete particles without particle-particle interaction. This is carried out with a *Discrete Particle Model* (DPM) which tracks the bubbles with a Lagrangian momentum equation:

$$\frac{d\mathbf{u}_b}{dt} = \frac{\mathbf{g}\left(\rho_b - \rho\right)}{\rho_b} + \mathbf{F}_D\left(u - u_b\right) + \mathbf{F}_{VM} + \mathbf{F}_L \qquad (4)$$

Five forces are accounted for: buoyancy, drag, lift, virtual mass and turbulent dispersion. These are the four first terms on the right hand side of equation 4. The fifth force is turbulent dispersion. Turbulent dispersion is an additional drag force due to the velocity fluctuations in a turbulent flow. Unless turbulence is resolved in the modelling concept, the standard drag force only accounts for drag due to the average velocity field. Turbulent dispersion creates a random addition to the liquid velocity of the drag force in Eq.(2). The random velocity is accounted for by a *random walk model* (Cloete *et.al.*, 2009a). It results in a wider plume. Further details on the modelling concept is described in Cloete et.al. (2009a) and Cloete et.al. (2009b).

In order to validate the model, modeling results have been compared to experimental results (Engebretsen *et.al.*, 1997). A series of experiments were conducted in a rectangular basin with a depth of 6.9 m and a surface area of 6 x 9 m. The basin was filled with water and air was released at the bottom at gas rates of 83, 170 and 750 Nl/s (equivalent to 50, 100 and 450 l/s referred to the state at the inlet). Comparison without a lift force gave good agreement with experiments regarding velocity profiles, rise times and fountain height (Cloete *et.al*, 2009b). Velocity profiles based on modelling and experiments are compared in Figure 1 for a chosen gas rate.

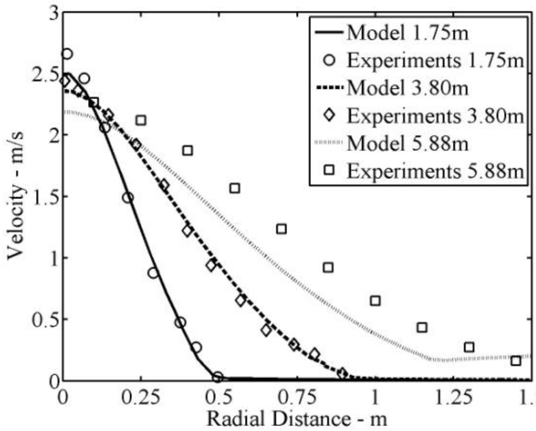

Figure 1: Modelling results of velocity profiles of the liquid phase at different heights above gas release point compared with experiments at a gas rate of 170 Nl/s.

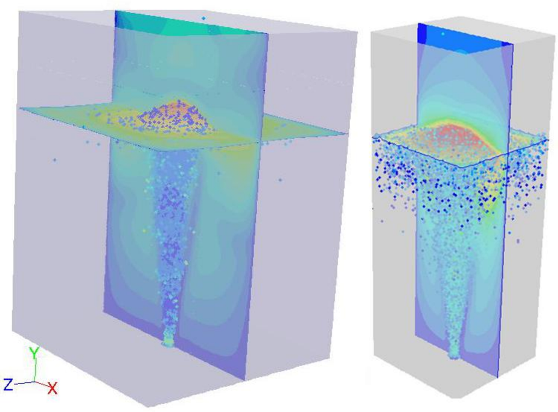

Figure 2: Wide and narrow vessels used for assessment of lift force.

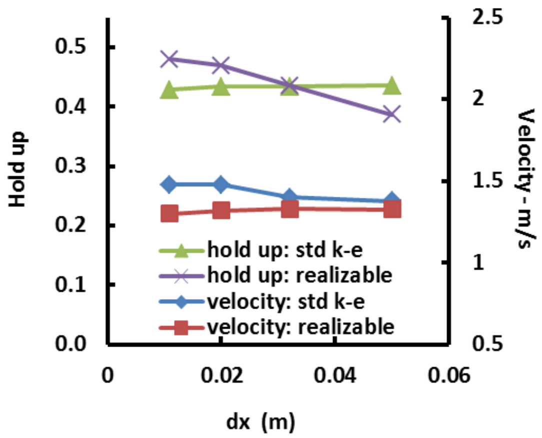

Figure 3: Grid dependence and effect of turbulence model

RESULTS

An assessment of the lift force in vessels with bottom injected gas was performed with the modelling concept described above. Two vessel geometries were studied, both with a liquid height of 1 meter. The vessel that we will refer to as the wide vessel has a base geometry of 1.0x1.0 m (liquid volume = 1.0 m^3), and the vessel that we will refer to as the narrow vessel has a base dimensions of 0.5x0.5 m (liquid volume = 0.25 m^3). The vessel geometries are illustrated in Figure 2.

Initially a grid dependence study was performed. The grid is constructed from a chosen base resolution (x-axis on Figure 3) with 2 levels of refinement in the regions with gas bubbles and closeness to walls. The effect on gas holdup and liquid velocity is seen in Figure 3. Grid independence is not perfect, but acceptable. The study was chosen to be performed with a base resolution of 0.02 m. The curves also show some variation with respect to choice of turbulence models. Since results with the standard k-ε model compared well against experimental results (Cloete *et.al*, 2009b), we have used this in the current study.

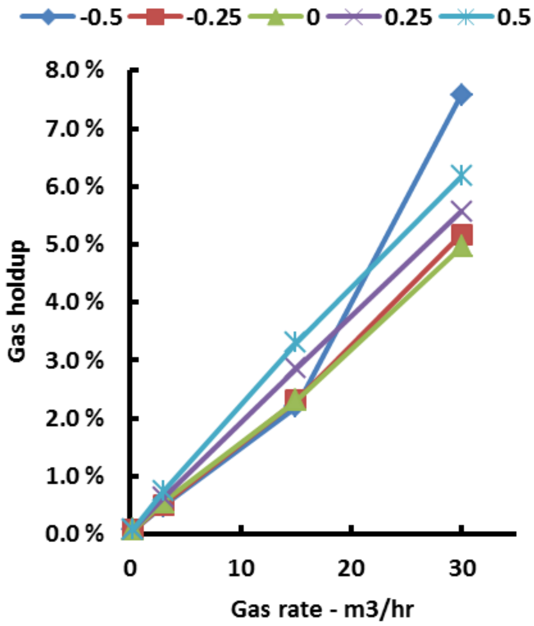

Figure 4: Gas holdup for different lift coefficients as function of gas rate for the narrow vessel.

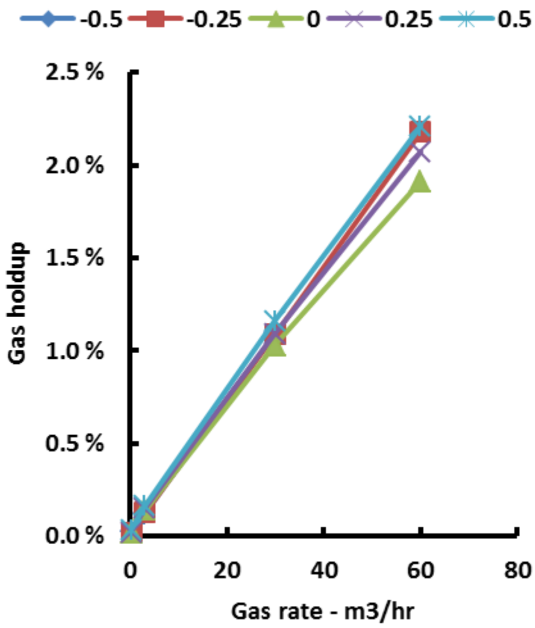

Figure 5: Gas holdup for different lift coefficients as function of gas rate for the wide vessel.

Simulations were performed with air bubbles in water under ambient conditions. First we studied the effect of various lift coefficients on vessel velocities and gas holdup. Gas holdup is the percentage total volume of gas in the liquid compared to the total liquid volume in the vessel. Figure 4 and 5 show the gas holdup for different lift coefficients. The curves show that the lift force influences the holdup. It increases with the lift force for both positive and negative values of the lift coefficients. It can also be noted that the narrow vessel has a higher holdup than the wide vessel.

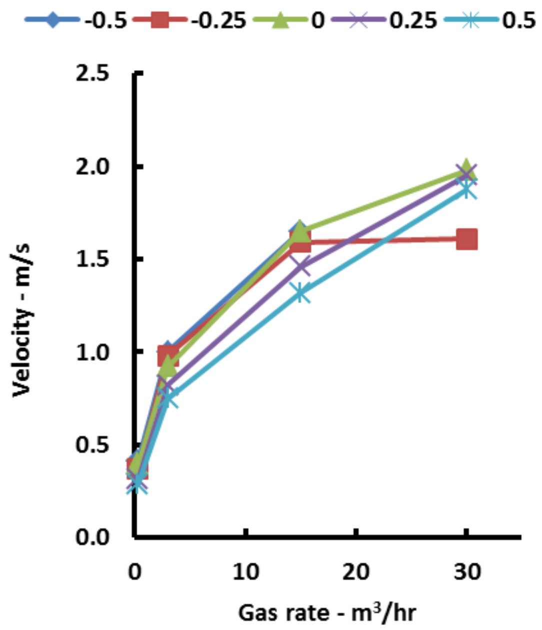

Figure 6: Centre velocity for different lift coefficients as function of gas rate for the narrow vessel.

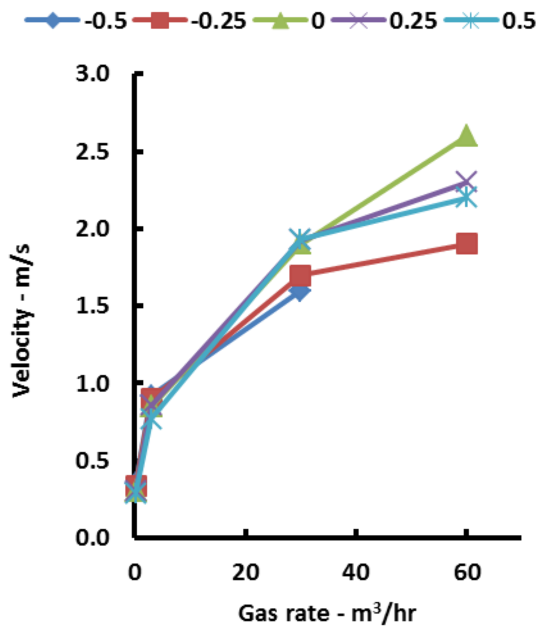

Figure 7: Centre velocity for different lift coefficients as function of gas rate for the narrow vessel.

The same type of plots is seen in Figures 6 and 7 for the velocity magnitude in the centre of the vessel (0.5 meter above release point). The velocity is highest for no lift and decreases for both positive and negative lift coefficients. The effect of the lift force is significant. This study was performed with an assumed bubble size of 5mm. In reality the bubble size is function of flow parameters and the lift coefficient is a function of the bubble size. With this in mind, simulations were performed with a bubble size model (Cloete *et.al*.,2009b) and the lift formulas mentioned above (Eqs.(2) & (3)).

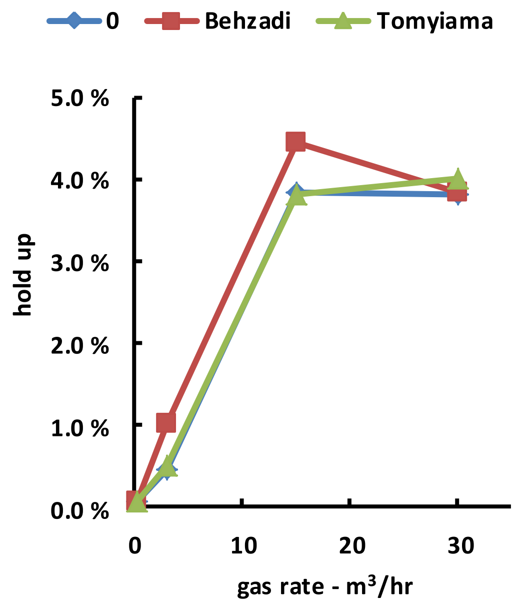

Figure 8: Gas hold up in narrow vessel for different lift expressions as function of gas rate.

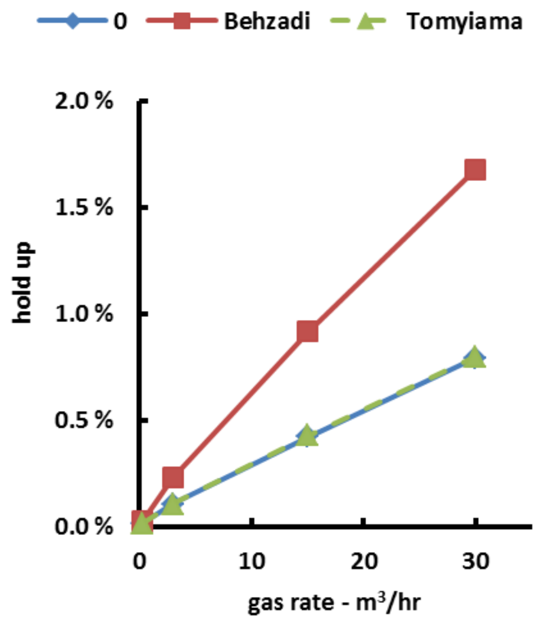

Figure 9: Gas hold up in wide vessel for different lift expressions as function of gas rate.

With varying bubble size and lift coefficients the gas holdup varies according to Figures 8 & 9 for the narrow and wide vessels respectively. We see that the lift expression of Tomiyama, Eq.(2), gives no effect on the gas holdup compared to no lift forces, while the expression of Behzadi causes an increased holdup. The centre velocity plotted in Figures 10 & 11 show little influence on lift coefficient. Thus one might say that for the cases studied the Tomiyama lift formulation has no influence on the vessel hydrodynamics, while the Behzadi formulation affects the gas holdup. The reason for this is found in the bubble size distribution resulting from the gas rates, the

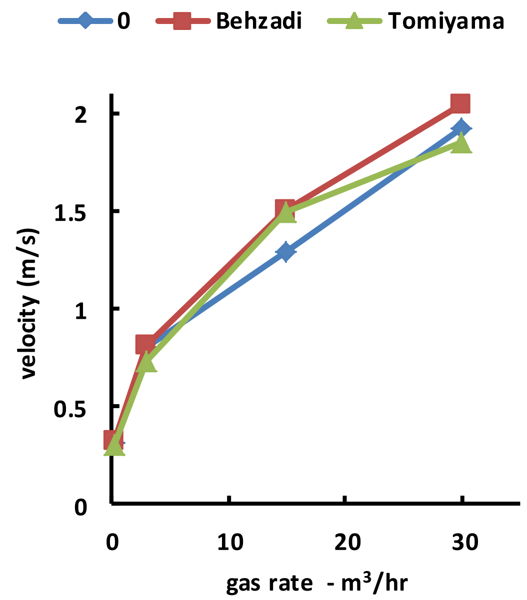

Figure 10: Centre velocity in narrow vessel for different lift expressions as function of gas rate.

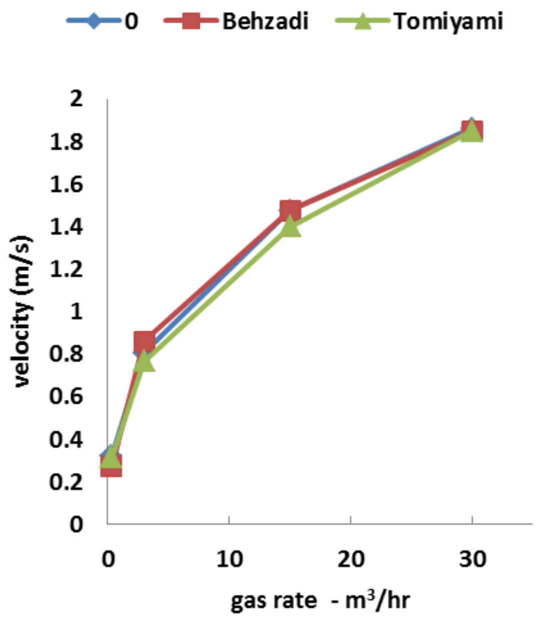

Figure 11: Centre velocity in wide vessel for different lift expressions as function of gas rate.

vessel geometries and the fluid properties (air-water). The average bubble size as a function of gas rates is seen in Figures 11 & 12. The Behzadi expression is here also the one which makes a difference. Typically the bubble size stays between 4 and 6 mm which is the range where the lift coefficient of Tomiyama is quite small. This explains why there is little effect of lift when using the expression of Tomiyama. This bubble size is typical for intense bubble plumes where turbulent breakup is the dominating factor for bubble size. For the lift coefficient of Behzadi we have a clear effect of the lift force. This is due to high values of the lift coefficient at the outskirts of the bubble plumes where the gas fraction is low. This should cause more spreading and higher gas holdup as observed in Figures 7 & 8.

From the correlations found between expressions for lift coefficients and the liquid velocity and gas holdup, we can conclude that the expression of Tomiyama gives an insignificant contribution to the vessel hydrodynamics while the expression of Behzadi significantly affects the flow. The expression of Behzadi is the only known expressions which try to acknowledge that the lift coefficient is altered at higher void fractions. It is however based on a very limited set of data. Also it does not account for bubble size which we know is important at lower void fractions. The previous study on lift coefficients in a vessel (Olsen & Cloete, 2009) used a combined Behzadi and Tomiyama expression where the Tomiyama expression governed the lift coefficient at void fraction below 0.05. This study concluded that lift was insignificant, since the lift coefficient was very small throughout the domain. The Tomiyama expression is established as the state of the art expression, but it does not account for higher void fractions. Thus there is a certain uncertainty in the expressions used for lift coefficients in dense bubble plumes.

CONCLUSION

The effect of lift forces on turbulent bubble plumes in vessels has been studied by a modelling concept. It is shown by varying the lift coefficients, that the lift force can influence the hydrodynamics of the vessel. In reality the lift coefficient is a function of bubble size and void fraction. When applying such expressions (Tomiyama, 2002) it is found that the effect of lift is quite small. This is mainly due to turbulence breakup which produces a bubble size in the range associated with very small lift coefficients. The so-called Behzadi expression, which accounts for high void fraction, shows a certain effect of the lift coefficient, but this is produced by the bubbles in the dilute regions which are actually not well described by the Behzadi expressions.

Based on this, it is difficult to draw a solid conclusion. It seems like the lift force has very little effect on the hydrodynamics of a vessel stirred by a dense bubble plume since the bubble size and void fractions promote very small lift coefficients. However, there is still an uncertainty related to the expression for lift coefficients and more work needs to be carried out before making a clear statement. Note that the study has been carried out for an air-water system at ambient conditions. For other systems and conditions the bubble size will not necessarily match the bubble size associated with small lift coefficients.

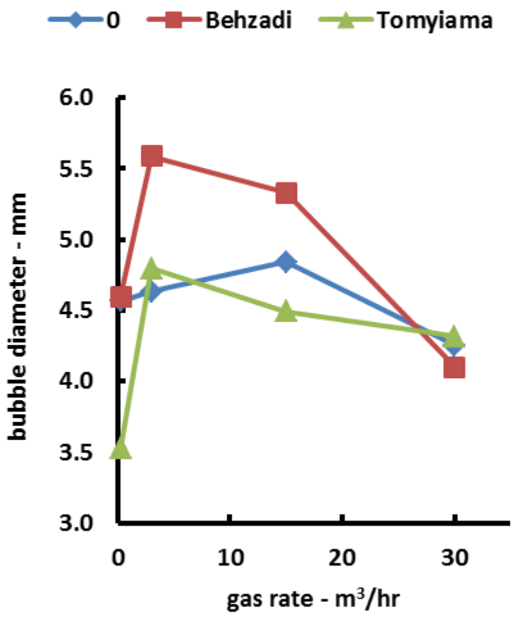

Figure 12: Bubble diameter in narrow vessel for different lift expressions as function of gas rate.

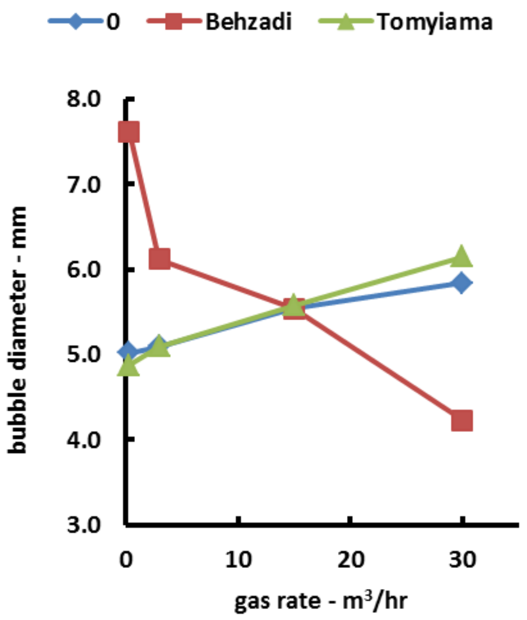

Figure 13: Bubble diameter in wide vessel for different lift expressions as function of gas rate.

REFERENCES

BEHZADI, A., IZZA, R.I. and RUSCHE. H, (2004), "Modelling of dispersed bubble and droplet flow at high phase fractions", *Chemical Engineering Science*, **59**: 759-770.

CLOETE, S., EKSTEEN, J.J. and BRADSHAW, S.M., (2009a) "A mathematical modelling study of fluid flow and mixing in full scale gas stirred ladles", *Progress in Computational Fluid Dynamics*, **9**(No.6/7):345-356.

CLOETE, S., OLSEN, J.E. and SKJETNE, P. (2009b), "CFD modelling of plume and free surface behaviour resulting from sub-sea gas release.", Accepted for publication in *Applied Ocean Research*.

DÍAZ, M.E., MONTES, F.J., GALÁN, M.A. (2009), "Influence of the lift force closure on the numerical simulation of bubble plumes in a rectangular bubble column", *Chemical Engineering Science*, **64**: 930-944.

ENGEBRETSEN, T., NORTHUG, T., SJØEN, K., and FANNELØP, T.K. (1997), "Surface flow and gas dispersion from a subsea release of natural gas.", *Seventh Int. Offshore and Polar Engineering Conference*, Honolulu, USA.

LUCAS, D., PRASSER, H.-M & MANERA, A. (2004), "Influence of the lift force on the stability of a bubble column", *Chemical Engineering Science*, **60**: 3609-3619.

LUCAS, D., TOMIYAMA, A.(2011), "On the role of the lateral lift force in poly-dispersed bubbly flows", *International Journal of Multiphase Flow*, doi: 10.1016/j.ijmultiphaseflow.2011.05.009

OLSEN, J.E. & CLOETE, S., (2009) "Coupled DPM and VOF model for analyses of gas stirred ladles at higher gas rates", *Proceedings of the 7th International Conference on CFD in the Process Industries*, Melbourne.

TOMIYAMA, A. TAMAI, H., ZUN, I., HOSOKAWA, S., (2002). "Transverse migration of single bubbles in simple shear flows", *Chem. Eng. Sci.* **57**, 1849 - 1858