B. VISCOUS SLUG FLOW MODEL

At large liquid viscosities it is possible for large diameter bubble columns to operate in the slug pattern. In fact aqueous CMC solutions of 2 wt% cause the slug flow pattern to occur in the six inch diameter column.

To model this effect for viscous non Newtonian flows, material balances and empirical equations have been combined. The empirical equations for the most part have been determined from our experimental data. The shear rate has also been derived and is used in the solution algorithm.

The material balance equations are given below. For a material balance on gas flow around the slug unit, the equation is

$$USG = \beta \alpha TB\ UGTB + (1-\beta)\alpha LSUGLS \tag{1}$$

or $$\alpha TB = [USG-(1-\beta)\alpha LSUGLS]/\beta\ UGTB$$

For a material balance on liquid flow around the slug unit, the equation is

$$USL = (1-\beta)(1-\alpha LS)(ULLS- \beta\ (1-\alpha TB)ULTB \tag{2}$$

or $$\beta = [(1-\alpha LS)ULLS-USL]/[(1-\alpha LS)ULLS+(1-\alpha TB)ULTB]$$

Average void fraction over a slug unit is obtained from the total gas volume and is given by the equation

$$\alpha SU = \beta \alpha TB + (1-\beta)\alpha LS \tag{3}$$

Liquid flow relative to the nose of the Taylor bubble obtained from Continuity relationship is given by the equation

$$ULLS = UN - [(UN+ULTB)(1-\alpha TB)]/[1-\alpha LS] \quad (4)$$

Gas flow relative to the nose of the Taylor bubble obtained from the Continuity relationship is given by the equation

$$UGLS = UN-(UN-UGTB) \quad (5)$$

The rise velocity of small bubbles in the liquid slug is given by the equation

$$UGLS = ULLS + 0.25 \;\; V^{1/6} \; (1-\alpha LS)^{0.5} \quad (6)$$

The rise velocity of a Taylor bubble given by our empirical correlation as

$$UN = 0.417 + 2.32\ USG \quad (7)$$

Area average velocity of liquid in film around the Taylor bubble is given by the equation

$$ULTB = \frac{n}{2n+1} r_o \; (\rho g/K)^{1/n} \; \frac{(r_o - r_f)^{2n+1/n}}{(r_o^2 - r_f^2)} \quad (8)$$

Length of the Taylor bubble given by our empirical correlation as

$$LTB = 0.439 + 22.1\ USG \quad (9)$$

Length of liquid slug obtained from the material balance is given by the equation

$$LLS = LTB/\beta \;\; - LTB \quad (10)$$

The model can also calculate the average shear rate of the liquid phase in the column from

$$\dot{\gamma} = \frac{2LTB\ (\rho g/K)^{1/n} \left(\frac{r_0 - r_f}{1/n + 2}\right)^{1/n+2} + r_f(r_0 - r_f)^{1/n+1} + 1.15(LLS)(ULLS)(r_0)}{LTB\ (r_o^2 - r_f^2) + r_o^2\ LLS\ (1 - \alpha_{LS})}$$

This can be derived from the volume average of the shear rate and the velocity gradient in a falling film.

$$u = \frac{n}{n+1}\left(\frac{\rho g}{K}\right)^{1/n}\left[(r_0 - r_f)^{n+1/n} - (r - r_f)^{n+1/n}\right]$$

The set of equations used for the solution of this model are given in Table 3.

Table 3

Material balance on gas flow

$$USG = \beta\alpha TB\ UGTB + (1-\beta)\alpha LSUGLS \qquad (1)$$

Material balance on liquid flow

$$USL = (1-\beta)(1-\alpha LS)\ ULLS - \beta(1-\alpha TB)ULTB \qquad (2)$$

Average void fraction over a slug unit

$$\alpha SU = \beta\alpha TB + (1-\beta)\alpha LS \qquad (3)$$

Liquid flow relative to the nose of the Taylor bubble

$$ULLS = UN - [(UN+ULTB)(1-\alpha TB)]/[1-\alpha LS] \qquad (4)$$

Gas flow relative to the nose of the Taylor bubble

$$UGLS = UN-(UN-UGTB) \qquad (5)$$

Rise velocity of small bubbles in the liquid slug

$$UGLS = ULLS + 0.25\ V^{1/6}\ (1-\alpha LS)^{0.5} \qquad (6)$$

Rise velocity of a Taylor bubble

$$UN = 0.417 + 2.32\ USG \qquad (7)$$

Area average velocity of liquid in film around the Taylor bubble

$$ULTB = \frac{n}{2n+1} r_o\ (\rho g/K)^{1/n}\ \frac{(r_o - r_f)^{2n+1/n}}{(r_o^2 - r_f^2)} \qquad (8)$$

Length of a Taylor bubble

$$LTB = 0.439 + 22.1\ USG \tag{9}$$

Length of liquid slug

$$LLS = LTB/\beta - LTB \tag{10}$$

Notation

A	Cross sectional area of the pipe
A	Coefficient for average liquid velocity profile expression (46)
A_{GLB}	Effective cross-sectional area of large bubble at its maximum diameter
A_{GLS}	Effective cross-sectional area occupied by the gas of the small bubbles in the liquid slug region
A_{GSB}	Effective cross-sectional area occupied by the gas of the small bubbles in the large bubble region
A_{GTB}	Effective cross-sectional area of the cylindrical portion of the Taylor Bubble
B'	Coefficient for average liquid velocity profile expression
C	Coefficient for gas holdup as function of gas rate correlation
C'	Coefficient for average liquid velocity profile expression
d_b	Mean bubble diameter
D'	Coefficient for average liquid velocity profile expression
K	Exponent for bubble swarm term
ℓ_{BSU}	Length of the Bubble-Slug Unit
ℓ_{LB}	Length of the large bubble region
ℓ_{LS}	Length of the liquid slug region
ℓ_{SU}	Length of the Slug Unit
ℓ_{TB}	Length of the Taylor Bubble
N	System parameter to account for the shape of the gas void radial profile
Q_G	Volumetric gas flow rate entering the tube or column
Q_L	Volumetric liquid flow rate entering the tube or column
r	Radial position from tube or column center line
$\underline{r}$	Dimensionless radial position (= r/R)

r_b Radius of large bubble

R Radius of tube or column

Δt_{BSU} Time interval for bubble-slug unit to pass reference plane

Δt_{LB} Time interval for large bubble portion to pass reference plane

Δt_{LS} Time interval for liquid slug portion to pass reference plane

Δt_{SB} Time interval for small bubbles in large bubble region to pass reference plane

$\underline{U}$ Dimensionless velocity ratio (= U/Umax)

$U_{b\infty}$ Rise velocity of bubble due to buoyancy in a stagnant liquid

U_{BSU} Approximated average translational velocity of bubble-slug unit

U_{GLB} Area average insitu velocity of the gas in the large bubble

U_{GLS} Area average insitu velocity of the gas of the small bubbles in the liquid slug region

U_{GSB} Area average insitu velocity of the gas of the small bubbles in the large bubble region

U_{GTB} Area average insitu velocity of the gas in the Taylor bubble

U_L Average insitu velocity of the liquid phase

$\underline{U_L}$ Integrated area average velocity of the liquid phase.

U_{LB} Experimental large bubble rise velocity from data of Beinhauer

U_{LLB} Area average insitu velocity of the liquid in the large bubble region.

U_{LLS} Area average insitu velocity of the liquid in the liquid slug region

U_{LTB} Area average insitu velocity of the liquid in the film around the Taylor bubble

U_m Mixed phase average superficial velocity

U_{max} Maximum or center line liquid velocity

U_N Average translational velocity of Taylor bubble/slug unit

U_S Average slip velocity between the gas and liquid phases

U_S Approximated average slip velocity between the gas bubbles and the liquid phase

U_{SB} Experimental small bubble rise velocity from data of Beinhauer

U_{SG} Superficial velocity of the gas based on the input volumetric-quantity and total tube or column cross-sectional area

U_{SL} Superficial velocity of the liquid based on the input volumetric quantity and total tube or column cross-sectional area

V_{BSU} Volume of the bubble-slug unit (=-BSU A)

V_G Total volume of gas present in the bubble-slug unit

V_{GLB} Volume of gas in the large bubble

V_{GLB} Volume of gas in the small bubbles of the liquid slug region

V_{GSB} Volume of gas in the small bubbles of the large bubble region

V_L Total volume of liquid present in the bubble-slug unit

V_{LLB} Volume of liquid in the large bubble region

V_{LLS} Volume of liquid in the liquid slug region

<u>Greek Letters</u>

α_{BSU} Volume average void fraction of Bubble-Slug Unit

α'_{BSU} Approximation to average void fraction of bubble-Slug Unit

α_{EXP} Experimental data value for total average gas holdup

α_G Local fractional gas void

$\bar{\alpha}_G$ Total average void fraction occupied by the gas

α_H Local gas void fraction in wake behind Taylor Bubble

α_{LB} Area average void fraction of the large bubble

α_{LS} Area average void fraction of the small bubbles in the liquid slug region

α_{SB} Area average void fraction of the small bubbles in the large bubble region

α_{SU} Volume average void fraction of Slug Unit

α_{TB} Area average void fraction in the cylindrical portion of the Taylor bubble

β Fractional length of Taylor/large bubble to the length of Slug/Bubble-Slug Unit

γ Liquid rheology characterizing term

Δ Error between experimental and bubble-slug model predicted values

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

CONCLUSIONS

Hydrodynamic experiments have been performed to assist in understanding the design and operation of bubble column reactors useful in direct coal liquefaction.

These have included measurements of gas holdup and bubble sizes and their distribution. Flow patterns and their boundaries were also studied in these experiments. Calculations included interfacial area as a function of holdup and shear rate in the liquid. Modelling involved the bubble-slug pattern and the slug pattern.

Based on the results of this study a number of conclusions may be drawn about the effect of Newtonian and non-Newtonian liquids on two phase flow parameters:

1. There is an entrance region of about 1 meter.
2. There is no column diameter effect on gas holdup between 6 and 13 in.
3. A flow pattern called bubble-slug has to be introduced to account for the difficulty in forming a Taylor bubble in large diameter columns.
4. There is an axial variation of gas holdup in tall columns in the bubble pattern.
5. Use of porous plate gas distributors significantly increases gas holdup in the bubble pattern over sieve plate distributors.
6. A maximum in gas holdup exists when using porous plates.
7. Rheological properties can effect gas holdup in bubble columns.
8. Gas holdup decreases as apparent viscosity is increased.
9. The bubble to bubble-slug transition is dependent on apparent viscosity. The transition gas velocity decreases with increasing liquid viscosity. There is no effect on liquid velocity on this transition in the range studied.

10. The bubble slug - slug transition is dependent on apparent viscosity.
11. The effect of alcohol on two-phase flow parameters was extreme. Holdup in the bubble flow pattern was very high, often greater than 0.5 at peaks. The bubble to bubble-slug transition occurred at higher gas velocities than in aqueous CMC solutions. There also appeared to be competing effects between alcohol and CMC concentrations.

Bubble diameter measurements and observations indicate:

12. a unimodal distribution in the bubble pattern.
13. a bimodal distribution in the bubble-slug pattern.

Interfacial area was observed.

14. to reach a maximum when porous plate gas distributors are used.
15. to be predicted correctly in the bubble-slug pattern when a two term equation is used.
16. to decrease as apparent viscosity is increased.
17. Average shear rate in the liquid in the slug pattern (high viscosity) is dependent on superficial gas velocity and apparent viscosity.

RECOMMENDATIONS

Further experimentation is suggested to verify the flow map's dependency on surface tension of fluids. It would also be helpful to determine the usefulness of the flow map for non-Newtonian fluids in three phase systems encountered in coal liquefaction studies.

Shear rates need to be determined in the bubble flow pattern to help understand the effect of apparent viscosity on gas holdup. Shear rates are only known for heterogeneous flow at gas velocities above 0.04m/s.

Further work is recommended using other types of gas distributors to assist in optimizing the design of the reactor. Experimental determination of the effect of pore size, thickness, and porous plate material, on the hydrodynamic parameters is recommended.

Further work is needed in modelling two phase and three phase flow especially in the bubble-slug flow pattern. Specific recommendations in complex three phase flows should include:

1. proper characterization of three phase flow patterns in the regions of interest that coal liquefaction reactors will be operated..
2. characterization of flow pattern boundaries dependence on viscous liquids, Newtonian and non-Newtonian, in three phase systems. The characterization should include empirical modelling.
3. determination of the effect of solids on bubble size, holdup, and interfacial area.

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