# Application of New Inflection Point Method for Hydrodynamics Study in Slurry Bubble Column Reactors

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**ABSTRACT:** Bubble column reactors are used in a wide variety of applications such as multiphase bioreactors, catalytic slurry reactors, and absorption processes. The superficial gas velocity-gas holdup relationship and transition point are two important parameters for characterizing the hydrodynamics of a bubble column reactor. In this study, systematic investigation of a nitrogen - water - glass beads bubble column was conducted using the Taguchi experimental design method. The  $L_{16}$  (45) orthogonal array was selected for experiments design. Results showed that the order of importance of parameters is as follows: bed porosity, the ratio of height to diameter, and superficial gas velocity. A novel mathematical model was developed using the experimental data and based on 4th order polynomial. This model was successfully used to obtain the transition point with a high accuracy. The results of the mathematical method were in close agreement with those of the drift flux method. For liquid level of H=12D and slurry content of 13 vol%, transition velocity of 2,98 cm/s was calculated using the presented method, while a velocity of 3.14 cm/s was obtained from the drift flux method.

**KEY WORDS:** Bubble column, Slurries, Mathematical modeling, Hydrodynamics, Inflection point, Taguchi method.

## **INTRODUCTION**

Proper design and scale-up of Slurry Bubble Column Reactors (SBCRs) depend largely on the accurate prediction of the gas holdup and flow regime transition point. For example, mass and heat transfer coefficients depend strongly on the local fluid dynamics and are mostly calculated using correlations in which gas holdup plays an important role. Many correlations have been proposed to determine the transition point and the relation between gas holdup and superficial gas velocity. However, these methods are not accurate for certain liquids and are not applicable for both homogeneous and heterogeneous flow regimes. The main purpose of this work is

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to introduce a novel mathematical model to determine transition point independent of the liquid type and properties.

# **Conventional correlations**

Gas holdup in slurry bubble columns depends mainly on gas velocity. There are many correlations in literature to quantify this relation [1-3]. Some of these correlations contain a transitional gas holdup at a corresponding transitional superficial gas velocity to describe the dependence of gas holdup to superficial gas velocity.

Various empirical methods have been used to determine the flow regime transition. Dynamic Gas Disengagement (DGD) method and change in the liquid height due to induced gas bubbles are used to determine flow regimes [4]. In both methods, the plotted gas holdup against the superficial gas velocity graph exhibits either an extremum or a significant break-up which is considered as the transition point. These two methods do not clearly show the transition.

The drift-flux model is a widely accepted method for analyzing gas holdup in bubble columns. It was first proposed by *Richardson & Zaki* (1954) by plotting  $u_{b} \cdot \varepsilon_{g} (1 - \varepsilon_{g})^{2.39}$  against  $\varepsilon_{g}$  [5]. A change in the flow pattern was designated by a change of slope in the curve. *Zuber & Findlay* (1965) modified the classic drift flux theory for the heterogeneous regimes by plotting  $U_{g}/\varepsilon_{g}$  against  $(U_{g} + U_{l})$  [6]. Flow patterns can be correctly identified in water but in some liquids such as water/butanol borders between regimes are less clear [7]. Drift-flux analysis of *Wallis* (1969) consists of plotting  $U_{g} (1 - \varepsilon_{g})$  against  $\varepsilon_{g}$ for the homogeneous regime [8]. Generally, these methods suffer from a lack of accuracy because the differences between slopes are very small when the transition occurs.

Dependence of the gas holdup on the superficial gas velocity can be expressed by the following power-law expression [8]:

$$\varepsilon_{\rm g} = a U_{\rm g}^{\rm n}$$
 (1)

Initially, the gas holdup seems to increase sharply and almost linearly with the superficial gas velocity in the homogeneous flow regime where the exponent n in Eq. (1) is generally reported to be in the range of 0.7-1.2 [3,9,10]. The gas holdup then reaches a maximum where the transition from homogeneous to heterogeneous flow regime occurs, and consequently a non-linear increase

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with the superficial gas velocity beyond that point is observed. The exponent n in the heterogeneous flow regime is reported to be in the range of 0.4-0.7 [9, 10]. The range of the exponent n in Eq. (1) suggests that the effect of superficial gas velocity on gas holdup in both homogeneous and heterogeneous flow regimes depends strongly on the operation variables, physical properties of the system, as well as the design characteristics of the column.

*Moshtari et al.* (2009) found that Eq. (1) for a system of water and air is as follows [11]:

 $\varepsilon_g = 0.45 U_g^{0.954}$  Homogeneous flow regime (2)

$$\varepsilon_{g} = 1.335 U_{g}^{0.449}$$
 Heterogeneous flow regime (3)

*Ivan et al.* (2009) introduced a simple correlation to predict the gas holdup, liquid circulation time, down comer liquid velocity and volumetric mass transfer coefficient in dilute alcohol solutions (CN wt %) in bubble columns and draft tube airlift reactors with a single orifice sparger as[12]:

$$Y = P_{1}U_{g}^{P_{2}} (1 + C_{N})^{P_{3}}$$
(4)

Where, Y represents the gas holdup and  $P_1$ =1.58,  $P_2$ =0.86 and  $P_3$ =0.18

# Taguchi method

Taguchi method is a powerful tool for determining the optimum test criteria. It assumes that engineering optimization contains three phases: system design, parameter design and parameters variation design. The method uses orthogonal arrays to obtain acceptable results with a smaller number of experiments. One of the important advantages of Taguchi method is analysis of qualitative and discrete factors. The most important step in Taguchi design method is to choose control parameters. Appropriate orthogonal array would then be selected based on the selected factors and their levels, and the experiments would be performed according to the proposed array [13-15]. The next step is the analysis of variance (ANOVA) on the experimental data. This method helps to determine the influence of different parameters and their contributions on the experimental results. Moreover, this method presents the optimum experimental conditions and predicts the results based on the desired criteria [16].

## **EXPERIMENTAL SECTION**

The bubble column was composed of three Pyrex® cylindrical sections (D=15cm, H= 80 cm) that were joined by aluminum flanges. Gas holdup was calculated using manometer pressure drop data. Fig. 1 represents schematic of measurement set up.

According to Fig. 1, pressure is equal in two arms of manometer. Then we have the following equations.

$$Patm + \rho_D g \hat{z}_1 + \rho_L g \left( h_1 - \hat{z}_1 \right) =$$
(5)

 $Patm + \rho_{L}g\hat{z}_{2} + \rho_{L}g(h_{2} - \hat{z}_{2}) + \rho_{m}g(h_{1} - h_{2})$ 

$$\rho_{\rm D}\hat{z}_1 + \rho_{\rm L}h_1 - \rho_{\rm L}\hat{z}_1 = \tag{6}$$

$$\rho_{\rm D} \hat{z}_2 + \rho_{\rm L} h_2 - \rho_{\rm L} \hat{z}_2 + \rho_{\rm m} \left( h_1 - h_2 \right)$$

$$\left(\rho_{\rm D} - \rho_{\rm L}\right)\hat{z}_{\rm I} = \tag{7}$$

$$(\rho_{\rm D} - \rho_{\rm L}) z_2 + \rho_{\rm L} (n_2 - n_1) + \rho_{\rm m} (n_2 - n_1)$$

$$(\rho_{\rm D} - \rho_{\rm L})(\hat{z}_1 - \hat{z}_2) =$$
(8)
$$\rho_{\rm L} (h_2 - h_1) - \rho_{\rm L} (h_2 - h_1)$$

$$(\rho_{\rm L} - \rho_{\rm D})d\hat{z} = -(\rho_{\rm L} - \rho_{\rm m})dh_{\rm m}$$
<sup>(9)</sup>

$$dh = 0_{r} - 0_{r}$$

$$\frac{\mathrm{dn}_{\mathrm{m}}}{\mathrm{d}\hat{z}} = \frac{\rho_{\mathrm{L}} - \rho_{\mathrm{D}}}{\rho_{\mathrm{m}} - \rho_{\mathrm{L}}} \tag{10}$$

For the term  $\rho_D$  we have the Eq. (11).

$$\rho_{\rm D} = \rho_{\rm L} \left( 1 - \varepsilon \right) + \rho_{\rm G} \varepsilon \tag{11}$$

Form Eqs. (10) and (11) we have the Eqs. (12) and (13).

$$\frac{dh_m}{d\hat{z}} = \frac{\rho_L - \rho_G}{\rho_m - \rho_L}$$
(12)

$$\varepsilon = \frac{\rho_{\rm m} - \rho_{\rm L}}{\rho_{\rm L} - \rho_{\rm G}} \frac{\mathrm{d}h_{\rm m}}{\mathrm{d}\hat{z}} \tag{13}$$

According to Eq. (13), it's the accuracy of measuring  $dh_m$  that determines the accuracy of Eq. (13). In this method, the error is calculated from the resolution of the manometer ruler (1mm). Then the error of measuring gas holdup would be 0.1%.

Manometer connections were provided at four different heights along the column. The bottom segment was attached to a chamber that contained gas inlet and drain valve (Fig. 2).



Fig. 1: Schematic of U- shaped manometer.

A sintered glass gas sparger was used in this chamber. According to the Fig. 2 nitrogen gas after passing the inlet valve enters the hopper shaped space under the sintered glass plate and after passing this plate enters the bubble column in the bubble form. The column was loaded with small glass beads as the solid phase. Table 1 shows size distribution of the glass beads. All experiments were carried out with distilled water and nitrogen gas at the ambient pressure and temperature (1 bar, 295 K). The gas was delivered through a regulator and two calibrated rotameters for low and high ranges of the gas flow rate. The error of measuring Ug with the typical values of up to 5cm/s is 2.8%. Pressure differences were taken at different liquid heights.

Three main factors namely solid content, superficial gas velocity and column height to diameter ratio were studied in order to investigate the gas holdup and the regime transition point.

## **RESULTS AND DISCUSSION**

Experiments were conducted in two stages. In the first stage, Taguchi's method of experimental design was employed to obtain importance of the parameters, as well as their optimum values. Next, a new mathematical model was used to obtain the transition gas holdup, transition superficial gas velocity, and their analyzing.

## Design of experiments

Experiment design for the first section

Three main factors were considered, as mentioned before. These factors and their levels are presented in Table 2.

Table 1: Glass Beads Size Distribution.					
Particle Size(µm)	Weight Percent				
75 < dp<150	82.1				
63 < dp<75	12.8				
45 < dp<63	5.1				

Table 2: Parameters &	Levels- 1st Design
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Parameter	L	$L_2$	$L_3$	L <sub>4</sub>
ε <sub>s</sub>	0	0.13	-	-
H/D	8	10	12	-
Ug (cm/s)	0.853	1.792	2.73	3.14



Fig.2. Schematic of experimental set up.

A L16 (45) orthogonal array was selected by applying the Taguchi method. Upgrading and downgrading methods were used to make the array appropriate for the case study of this work. The final orthogonal array with the desired levels is presented in Table 3. The experiments were performed according to the rows in Table 3 and the results are presented in the last column of this table. The main effects were obtained and presented in Table 4. It can be concluded from Table 4 that the solid content is the most effective factor and that the superficial gas velocity and H/D are the next important parameters respectively. From the analysis of variance (Table 5),

contribution of each factor was determined separately. The experimental error was about 6%, which is in the acceptable range of less than 15% [16].

# Experimental design for second section

For the second section, the factors and their levels were the same as the previous design, but the superficial gas velocity was studied at eight levels. The new configuration of factors and their levels are presented in Table 6.

Like the previous design a  $L_{16}$  (45) orthogonal array was selected and the method of upgrading and

L <sub>16</sub>	1	2	3	4	5	Result
1	1	1	1	0	0	0.0313
2	1	2	2	0	0	0.087
3	1	3	3	0	0	0.114
4	1	1	4	0	0	0.204
5	2	1	3	0	0	0.066
6	2	2	4	0	0	0.101
7	2	3	1	0	0	0
8	2	1	2	0	0	0.0139
9	1	1	3	0	0	0.148
10	1	2	4	0	0	0.219
11	1	3	1	0	0	0.043
12	1	1	2	0	0	0.0941
13	2	1	4	0	0	0.115
14	2	2	3	0	0	0.073
15	2	3	2	0	0	0.01
16	2	1	1	0	0	0

Table 3: L<sub>16</sub> (45) Orthogonal array- 1st design.

 Table 4: Main effects - 1st design.

	L <sub>1</sub>	$L_2$	L <sub>3</sub>	$L_4$	ΔL
ε <sub>s</sub>	0.11755	0.047363			0.070188
H/D	0.084038	0.12	0.04175		0.07825
Ug	0.018575	0.05125	0.10025	0.15975	0.141175

Table	5:	Analysis	of	variance	-	1st	design.
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Parameter	$\mathbf{f}_{i}$	SSi	Vi	SS'i	P (%)
ε <sub>s</sub>	1	0.106777	0.106777	0.106777	36.57995
H/D	2	0.103866	0.051933	0.103866	35.58273
Ug	3	0.099149	0.03305	0.099149	33.9668
error	9	-	-	-	6.12948

L <sub>16</sub>	1	2	3	4	5	Result
1	1	1	1	0	0	0.0313
2	1	2	1	0	0	0.052
3	1	3	2	0	0	0.0623
4	1	1	2	0	0	0.0607
5	2	1	3	0	0	0.014
6	2	2	3	0	0	0.006
7	2	3	4	0	0	0.0384
8	2	1	4	0	0	0.0439
9	1	1	5	0	0	0.111
10	1	2	5	0	0	0.173
11	1	3	6	0	0	0.114
12	1	1	6	0	0	0.148
13	2	1	7	0	0	0.09
14	2	2	7	0	0	0.087
15	2	3	8	0	0	0.0996
16	2	1	8	0	0	0.115

Table 6: L16 (45) Orthogonal array- 2nd design.

downgrading was used to change the number of levels in the columns. The final orthogonal array is presented in Table 7. The experiments were carried out according to the orthogonal array and the results are listed in the last column of Table 7. The analysis of variance showed that the order of importance of factors was as follows (Table 8): the solid content, the ratio of height to diameter in reactor, and the superficial gas velocity. Experimental error of about 13% was achieved which is in the acceptable range.

# New 4th order polynomial correlation

Experimental values for the gas holdup were correlated by a fourth order polynomial (Eq.(14)). The results were then compared with those from the drift flux method.

$$\varepsilon_{g} = a U_{g}^{4} + b U_{g}^{3} + c U_{g}^{2} + d U_{g} + e$$
 (14)

In this equation, Ug is the superficial gas velocity

in the homogeneous or the transient region below the second transition point. The inflection point of the polynomial (Eq.(14)) is used as the transition velocity between homogeneous and transient flow regimes. The inflection point of the Eq. (14) was calculated as follows:

$$\frac{\partial^2 \varepsilon_g}{\partial U_g^2} \Big|_{Ug=Ug,t} = 0 \qquad \left(b^2 \ge \frac{8}{3}ac\right) \tag{15}$$

According to Eq. (15), the inflection point method is applicable when there is an inflection point in the

homogeneous or the transient region  $\left(b^2 \ge \frac{8}{3}ac\right)$ .

Fig. 3 is an example of the drift flux velocity vs. gas holdup. This figure was obtained for a water column with a height of H=8D and a slurry content of 13 vol%. As it can be found from the drift flux plot, the gas holdup corresponding to the transition occurs at a gas velocity of 2.734 cm/s.

Fig. 4 is an example of gas holdup against superficial gas velocity for the liquid level of H=12D and slurry

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Parameter	L	L <sub>2</sub>	L <sub>3</sub>	L <sub>4</sub>	L <sub>5</sub>	L <sub>6</sub>	L <sub>7</sub>	L <sub>8</sub>
ε <sub>s</sub>	0	0.13	-	-	-	-	-	-
H/D	8	10	12	-	-	-	-	-
U <sub>g</sub> (cm/s)	0.853	1.322	1.792	2.265	2.497	2.73	2.919	3.14

Table 7: Parameters and levels- 2nd design.

Parameter	$\mathbf{f}_{i}$	SSi	Vi	SS'i	P (%)
ε <sub>s</sub>	1	0.095482	0.095482	0.095482	32.71037
H/D	2	0.093204	0.046602	0.093204	31.93003
Ug	7	0.065073	0.009296	0.065073	22.2929
error	5	-	-	-	13.0667







Fig. 3: The drift flux velocity against gas holdup for a standing water column height of H=8 D and particles content of 13 vol%.

content of 13 vol%. This figure also shows a fourth order curve describing the fitted data. The corresponding equation for this graph is as follows:

$$\varepsilon_{g} = -0.0190 U_{g}^{4} + 0.1942 U_{g}^{3} -$$
(16)  
0.7233 U\_{g}^{2} + 1.2273 U\_{g} - 0.7877

As Eq. (16) shows, higher order terms of the polynomial have smaller coefficients. Consequently, at low superficial gas velocities, only the lower order terms of the expression are significant. This is in agreement with the Eq. (1) in which the power of the superficial gas velocity is around one. As the superficial gas velocity

Fig. 4: Gas holdup against gas velocity for H=12 D,  $\varepsilon s = 0.13$  and related fourth order fitted plot.

increases, the higher order terms will become more important.

From this method for a liquid level of H=12D and a slurry content of 13 vol%, a transition velocity of 2.98 cm/s was calculated while a value of 3.14 cm/s was obtained from drift flux method. Application of this mathematical method does not depend on visual observation of the slope change used in the drift flux method.

# Gas holdup

In SBCRs, the volumetric solid concentration greatly affects the hydrodynamics. The solid particles in the bubble column reactors are typically in the micron size



Fig. 5: Gas holdup against gas velocity for H=12 D and zero particles content.

range and are suspended in the liquid phase to form a slurry. Consequently, their concentration in the liquid phase changes the physical properties of the slurry, namely the density and viscosity. Several investigators have reported that an increase in the solid content decreases the total gas holdup [17-20]. The decrease of gas holdup with the solid concentration was attributed to the increase of pseudo-viscosity of the slurry phase, which enhances formation of large gas bubbles [21-23].

Fig. 5 is a representative example of the gas holdup against the gas velocity for H=12D and zero slurry content. The data points in the low ranges of velocity and holdup belong to homogenous flow regime. The data points in the high ranges of gas velocity and holdup belong to the churn-turbulent regime. The intermediate data points show the approximate range of the velocity transition.

The homogeneous flow regime generally occurs at low to moderate superficial gas velocities. It is characterized by uniformly sized small bubbles traveling vertically with minor axial oscillations. There is practically no coalescence and break-up. With increasing the superficial gas velocity, Due to coalescence all the bubbles will be large. The large bubbles have higher rise velocity than small bubbles, therefore residence time of large bubbles decreases and causes decreasing the rate of increasing gas hold up.

Influence of glass particle content up to 17 vol % was studied on the regime transition and the gas holdup. The slurry content  $\varepsilon$ s is expressed as the volume fraction of solids in the gas-free slurry. Fig. 6 shows the relation between the gas holdup and the gas velocity when



Fig. 6: The influence of glass particles content on gas holdup for the liquid level of H=12 D.

the slurry bubble column reactor contains glass particles. It can be observed from this figure that for a liquid level of H=12D the maximum gas holdup near the first transition point decreases at high slurry content. At lower slurry content, you can see a change between uniform bubbles size distribution in homogenous regime to a wide size distribution of bubble sizes in the heterogeneous regime and resulting sharp decrease in gas holdup.

Note the sharp maximum in the total gas holdup near the regime transition point for slurry content smaller than 13 vol%. The behavior of the slurry bubble column is close to that of a solid free bubble column. At higher slurry content, the influence of solids concentrations is dominant.

In the homogeneous regime, therefore, the gas holdup decreases with increasing slurry content due to increasing bubble diameters of the small-bubble population. This phenomenon also manifests itself in the heterogeneous flow regime and there is not any sharp change in gas holdup.

Some investigators reported no obvious change in the gas holdup when H/D ratios were above 5 - 6 [24,25]. Figs. 7a and 7b show dependence of gas holdup on gas velocity in the slurry bubble column reactor with the particle contents of 0 vol% and 13 vol% at different column heights. The liquid level has a very small influence on the gas holdup at lower superficial gas velocities. The maximum gas holdup values clearly decrease with increase in the liquid level. The same trend has also been reported earlier [26].

According to the gas-liquid theories [27], the gas hold-up increases linearly with the gas velocity while in the bubbly regime with a velocity of 0 cm/s producing

	<i>y y</i> 0	1	8 9 1	5	
	Drift Flux Method		Inflection Point Method		
Solid Content (vol %)	Ug_t	εg_t	Ug_t	ɛg_t	
0	1.792	0.0941	1.86	0.0989	
8	2.734	0.0788	2.608	0.0771	
13	2.734	0.0662	2.48	0.0541	
17	2.734	0.0188	2.845	0.026907	

Table 9: The influence of glass particles content on regime transition for liquid level of H = 8 D.

Drift Flux Method			Inflection Point Method	
	$U_{g_t}$	€ <sub>g_t</sub>	$U_{g_t}$	$\epsilon_{g_t}$
Vandu C.O.et al.,2004[27]:air, porous catalyst, paraffin oil(ɛ <sub>s</sub> =0.05)	0.0206(m/s)	0.064	0.024(m/s)	0.0804
Letzel H.M. et al., 1997[28]:air, water system	0.106(m/s)	0.0733	0.132(m/s)	0.150
U. Parasu Veera and Joshi J.B., 2000 [29]: air butanol system	0.0573(m/s)	0.170	0.0458(m/s)	0.138



Fig. 7: The influence of liquid level on gas holdup, Particles content:  $\epsilon s = 0$  (a);  $\epsilon s = 0.13$  (b).

no holdup [28]. This is observed in the zero particle content case. For the case of 13 vol% particles content, a gas velocity of around 1.8 cm/s is required to fluidize the particles accumulated at the bottom of the column. Below this gas velocity, there is no bubble inside the column and the gas holdup is assumed to be zero.

# **Regime transition**

The stability of the homogeneous regime was expressed by the values of the gas flow rate and the holdup at the first transition point  $[U_{g_t}, \varepsilon_{g_t}]$ . The transition points were determined using the inflection point and drift- flux method. The effect of the solid

particle content was especially visible on the transition point. The transition points for the glass particle contents up to 17 vol% and a liquid level of H=8D are shown in Table 9. The results obtained from both the drift flux and the inflection point methods are shown in this table. According to Table 9, the results of these two methods are in a good agreement. Table 10 shows the transition points obtained from the results presented by some investigators [29-31]. The results are in an agreement too. For air, butanol system the transition velocity obtained from drift flux method is not so clear but can be exactly clear from inflection point method.



Fig. 8: The effect of particles content on the transition superficial gas velocity (a) and Transition gas holdup (b).



Fig. 9: The effect of column height on the transition superficial gas velocity (a) and the transition gas holdup (b).

Figs. 8a and 8b show the relationship between the transition point and the particle content at different column heights. According to Fig. 8, at low solid loadings, the transition superficial velocity initially raises with increase in the particle content and for the higher solid loadings, a small reduction in the transition superficial velocity is observed with the increase in particle content.

The regime transition point shifts to a lower gas holdup with increasing the solid loading. These results suggest that particle content can play a dual role in the homogeneous regime stability: low particle contents up to 8vol% stabilize the homogenous regime, while high particle contents over 8vol% destabilize.

This is in agreement with the experimental observations of *Mena et al.* (2005) for air-alginate beadsdistilled water slurry systems [32] that they showed a same behavior for their system for the particle content up to 3vol% and over.

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Figs. 9a and 9b show the influence of liquid level on the transition superficial gas velocity and the transition gas holdup. According to Fig. 8, there is no significant change in the transition superficial gas velocity and the transition gas holdup by increasing liquid level. This is in agreement with results obtained by *Ruzicka et al.* (2001) for the H/D ratios above 5 - 6[26].

#### CONCLUSIONS

Effects of the liquid level, the gas flow rate and the particle content on the gas holdup and regime transition point were studied for nitrogen-water-glass particles with particles contents of up to 17 vol% using inflection point and drift flux methods. Taguchi method was used for experimental design using two configuration of a L16 (45) orthogonal array. The following conclusions can be made from this work:

1- Experimental results for gas holdup against superficial gas velocity are expressed satisfactorily with a fourth order polynomial correlation. Inflection point of the fourth order polynomial correlation is considered as the transition point and the results obtained from this method and the drift flux method agree fairly well.

2- Maximum gas holdup values after transition decrease by increasing the liquid level. The liquid level has a very small effect on the gas holdup at lower superficial gas velocities.

3- The glass particle content has a stabilizing effect at lower contents, while high contents tend to destabilize the reactor flow regime.

4- With H/D ratios above 5 used in this study, there is no significant change in the transition point by increasing the liquid level.

5- In gas holdup measurements, the solid content is proved to be the most important parameter followed by H/D and the superficial gas velocities at the next importance levels.

# Nomencluture

j	Drift fulx velocity,cm/s
Ug	Superficial gas velocity, cm/s
$U_l$	Liquid velocity, cm/s
$U_{g\_t}$	Superficial gas velocity at regime transition, cm/s
u <sub>b</sub>	Single bubble velocity in an infinite medium
$V_{g}$	Gas volume
$V_1$	Liquid volume
dp	Solids particle diameter, µm
fi	Degree of freedom
SSi	Sum of squares
SS'i	Pure sum of squares
Vi	Variance
Р	Factor contribution

# **Greek Letters**

 $\begin{array}{ll} \epsilon_g & Gas \ holdup \\ \epsilon_s & Weight \ fraction \ of \ glass \ particles \ in \ the \ slurry \ phase \\ \epsilon_{g_t} & Gas \ holdup \ at \ regime \ transition, \ dimensionless \end{array}$ 

# Subscripts

G	Rreferring to gas phase
1	Referring to liquid phase
m	Referring to manometer liquid
S	Referring to solids

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