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Hydrodynamic Investigation And Modeling Of A New Type Air-Lift Tube Reactor

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Abstract

The hydrodynamic behavior of air-lift type tube reactor (ALT reactor) was investigated in laboratory and pilot scale, established theoretical models were developed for the description of superficial liquid velocity in the recycle tube and of pressure losses in the reaction tube.

Using different tube sizes for recycle and reaction tubes, the next parameters were measured under various operation conditions: superficial liquid velocity in recycle tube, pressure drop, real liquid and gas velocity, minimum and maximum gas velocity in reaction tube.

The new theoretical models were proved on the base of measured data with a maximum deviation of 10% .

الخلاصة

الاختبار الهيدروديناميكي للمفاعل الانبوبي اجري على المستوى المختبري والريادي، حيث تم استنتاج موديلات نظرية للتعبير عن سرعة السائل السطحية في انبوب الرجوع والفقدان في الضغط في انبوب التفاعل. باستخدام حجوم مختلفة من أنابيب الرجوع و أنابيب التفاعل وتحت ظروف عمل مختلفة تم قياس العوامل التالية: سرعة السائل السطحية في أنبوب الرجوع, الهبوط بالضغط, السرعة الحقيقية للسائل والغاز, السرعة الدنيا والقصوى للغاز في أنبوب التفاعل.

الموديلات النظرية الجديدة تم برهنتها باستخدام قاعدة البيانات التي تم الحصول عليها اثناء عملية الاختبارالهيدروديناميكي للمفاعل الانبوبي وكان أقصى انحراف لا يتجاوز عن 10%.

Nomenclature

(Remark: In the text, figures and tables some of the variables are expressed in commonly used dimensions)

A	cross-sectional area of one reaction tube or of all reaction tubes (m^2)
A_G	cross-sectional area of the gas phase in one reaction tube (m^2)
A_L	cross-sectional area of the liquid phase in one reaction tube (m^2)
A_{rec}	cross-sectional area one recycle tube or of all of recycle tubes (m^2)
A_{rec}/A	area ratio of recycle to reaction tubes
d	inside diameter of reaction tube (m)
d_{rec}	inside diameter of recycle tube (m)
g	acceleration due to gravity (m/s^2)
G	inlet gas load (m^3/s)
h	liquid height (m)
$h\rho_L g$	hydrostatic pressure of clear liquid ($kg/m\,s^2$)
h_0	minimum liquid height (m)
h_L	fountain height as shown in Figure 1. (m)
l	length of reaction tube (m)
l_L	length of recycle tube (m)
L	inlet liquid load (m^3/s)
L_{rec}	recycle liquid rate (m^3/s)
n	number of reaction tubes
n_{rec}	number of recycle tubes
p	pressure (Pa)
p.w.	present work
Δp	pressure drop in reaction tube (Pa)
Δp_h	hydrostatic pressure drop for gas-liquid mixture (Pa)
Δp_{hL}	hydrostatic pressure of liquid, expressed by lifting work (Pa)
Δp_{hG}	hydrostatic pressure of gas, expressed by lifting work (Pa)
Δp_{irr}	Irreversible losses, friction and entrance losses and losses caused by vortexes around the dispersed phase (Pa)
Δp_{kL}	dynamic pressure of liquid calculated with the v_L^* real liquid velocity in reaction tube (Pa)
Δp_{kG}	dynamic pressure of gas calculated with the v_G^* real gas velocity ($v_G^* > v_L^*$), (Pa)
Δp_{rec}	pressure drop in recycle tube (Pa)

$Re_G = \dfrac{d\, v_G\, \rho_G}{\mu_G}$	Reynolds number of gas
$Re_L = \dfrac{d\, v_L\, \rho_L}{\mu_L}$	Reynolds number of liquid
S	surface area of all reaction tubes (m^2)
T	temperature (°C)
v	fluid velocity in the tube (m/s)
$v_L^2\, \rho_L/2$	dynamic pressure or kinetic outflow loss for liquid phase (Pa)
v_G	superficial gas velocity in reaction tube (m/s)
v_G^*	real gas velocity in reaction tube (m/s)
v_L	superficial recycle liquid velocity in recycle tube (m/s)
v_L^*	real liquid velocity in reaction tube (m/s)
V	total liquid holdup in the reactor (m^3)
W_G	gas flow rate in one reaction tube (m^3/s)
W_L	liquid flow rate in one reaction tube (m^3/s), which is equal to the sum of recycling liquid rate (L_{rec}) and the inlet liquid load (L), $W_L = L + L_{rec}$ While $L \ll L_{rec}$, therefore L could be neglected

Greek symbols

$\varepsilon_L = \dfrac{W_L}{W_L + W_G}$	liquid holdup in the reaction tube
$\varepsilon_G = \dfrac{W_G}{W_L + W_G}$	gas holdup in the reaction tube
ρ	density of the fluid (kg/m^3)
ρ_G	density of gas (kg/m^3)
ρ_L	density of liquid (kg/m^3)
ρ_{GL}	density of gas-liquid mixture (kg/m^3)
μ_G	viscosity of air (kg/m s)
μ_L	viscosity of liquid (kg/m s)
λ	friction loss factor
$\lambda \dfrac{l_{rec}}{d_{rec}} \dfrac{v_L^2 \rho_L}{2}$	friction loss
ζ_{BC}	Borda-Carnot loss factor
$\zeta_{BC} \dfrac{v_L^2}{2}$	Borda-Carnot loss

Subscripts

1	position one at Figure 1.
2	position two at Figure 1.
3	position three at Figure 1.
4	position four at Figure 1.
BC	Borda-Carnot
h	hydrostatic
hG	hydrostatic of gas phase
hL	hydrostatic of liquid phase
irr	irreversible
G	gas
GL	gas-liquid mixture
k	kinetic energy
kG	kinetic energy of gas phase
kL	kinetic energy of liquid phase
L	liquid
max	maximum
min	minimum
rec	rec

1. Introduction

Air-lift reactors are special class of pneumatic devices for gas purification, fermentation and water treatment on account of their simple construction, ease of operation and low energy consumption together with high mass and heat transfer rate compared to conventional stirred tank type reactors and bubble columns. Beyond the improved mixing the air-lift reactors have no moving elements and the power required comes only from the air supply [1-3]. Different air-lift tube reactors were investigated by several investigators. To predict the superficial recycle liquid velocity in the recycle tube of a partly perforated tube system, Szczuka *et al* [4] developed an expression, which gives a good approximation for our reactor as well. Vodnar *et al* [5] developed pressure drop correlation for laboratory scale air-lift tube reactor with bend-ended tube. The expression can be applied as a good approach for our straight tube system as well.

Laurent *et al* [6] collected bubble column models for calculation of liquid velocity in the recycle tube and pressure drop in the reaction tube, while Gharat *et al* [7] developed model for two-phase pressure drop in bubble column. The models of Laurent and Gharat and other bubble column models are not valid for present work reactor, because they are based on low liquid and gas velocities. Kawahara *et al* [8] investigated the two phase gas-liquid flow pattern, void fraction, slip velocity, and pressure drop in micro channel. Govier *et al* [9] published measured pressure drop data of air/water mixture in an infinite length of vertical tube using a wide range of velocities. Verba [10] reviews the calculation method of Lockhart and Martinelli for two phase gas-liquid flow in tube and gives examples for the calculation, while Dario *et al* [11] provided an empirical correlation to estimate the two phase gas-liquid flow pressure drop in trickle-bed reactor based on the Lockhart-Martinelli parameters as well.

2. Theoretical Model

In order to obtain mathematical relations to design the new type of air-lift tube reactor (ALT reactor), labor-scale models and pilot reactor were installed. The basic idea of the operation of the ALT reactor is shown in Figure (l). The gas and liquid inlet is at the lower part of the reactor, where the liquid level is constant. The gas enters the reaction tube carrying with some liquid. The gas-liquid interaction takes place mostly in the reaction tube, where foam or a liquid film appears depending on gas velocity. The gas flows out through the upper part of the apparatus, while the liquid falls back into the upper liquid surface.

One part of the liquid returns to the lower part of the apparatus through the recycle tube, while the other part flows out as overflow through the overflow line, which keeps liquid level constant. This process is true for the steady-state, steady-flow (SSSF) throughout the test section. The recycling liquid flow rate (L_{rec}) is influenced by the height of the liquid layer (h) and the pressure difference between the upper and lower parts of the reactor. The hydrodynamic behaviour of the liquid in the recycle tube and the liquid-gas mixture in the reaction tube can be followed theoretically by the energy equation [9].

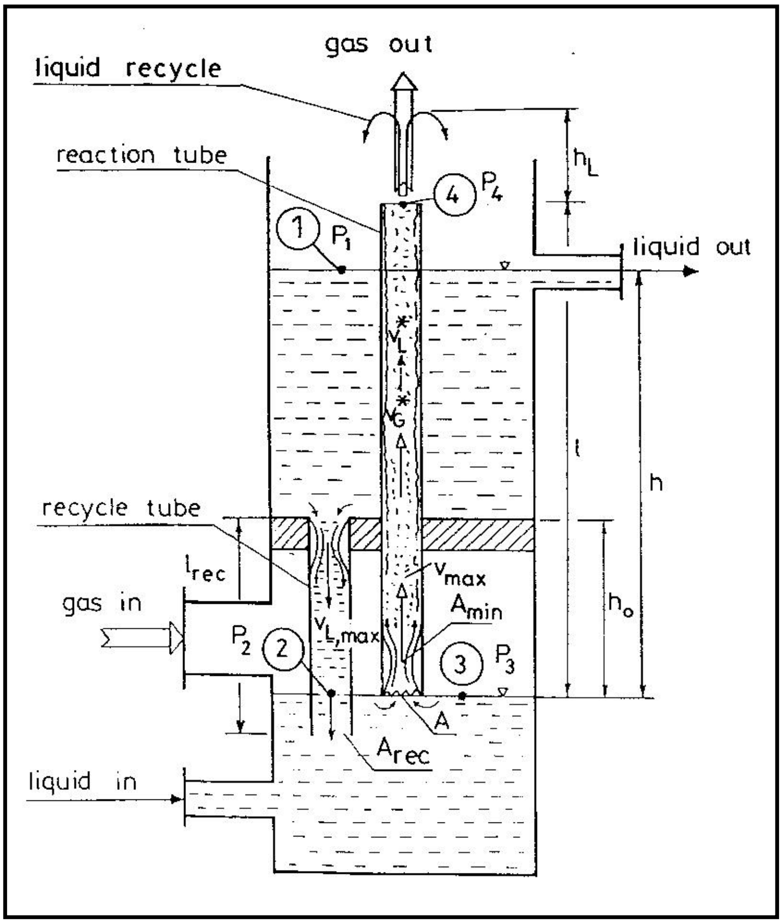

Figure (1) Sketch of air-lift tube reactor

2.1 Energy Equation for Recycle Tube of ALT Reactor

According to Figure (l).

At point 1: $p_1 = p_0 =$ atmospheric pressure, $v_L \cong 0$

At point 2: $p_2 > p_0$, $h = 0$, $v = v_L$

The hydrostatic energy of liquid covers the pressure work of gas, the kinetic energy and losses of flowing out liquid [9]:

$$h \rho_L g W_L = (p_2 - p_0) W_L + \frac{v_L^2 \rho_L}{2} W_L + \text{irreversible losses} \ldots\ldots(1)$$

After dividing both sides of equation (1) by W_L and rearranging it the result is as follows:

$$p_2 - p_0 = h \rho_L g - \frac{v_L^2 \rho_L}{2} - \lambda \frac{l_{rec}}{d_{rec}} \frac{v_L^2 \rho_L}{2} \quad \zeta_{BC} \frac{v_L^2 \rho_L}{2} \ldots\ldots(2)$$

Where $\lambda \frac{l_{rec}}{d_{rec}} \frac{v_L^2 \rho_L}{2}$ is the friction loss:

This loss depends on the roughness of the tube surface, the length and diameter of the tube as well as on Reynolds number [11] and is expressed by loss factor and kinetic energy term. $\zeta_{BC}\frac{v_L^2\rho_L}{2}$ is the Borda-Carnot loss: For sharp edge inlet of tube Figure (1), the streamlines change their direction and give rise the velocity to reach a maximum value (v_{max}) in the minimum cross-sectional area of the stream (A_{min}). This loss occurs in the region, when v_{max} decreases to reach uniform fluid velocity (v). The deviation of Borda-Carnot loss (Δp_{BC}) for sharp edge tube is as follows [12]:

$A_{min}/A = 0.6$, and $v_{L,max}/v_L = 1/0.6$

$$\Delta p_{BC} = (v_{L,max} - v_L)^2\frac{\rho_L}{2} = \zeta_{BC}\frac{v_L^2\rho_L}{2} \quad \text{.......(3)}$$

$$\zeta_{BC} = \left[\frac{1}{0.6} - 1\right]^2 \cong 0.44$$

Therefore, the theoretical value of the Borda-Carnot factor for sharp edge $\zeta_{BC} \cong 0.44$ [12]. The pressure difference p_2-p_0 is equal to the pressure difference at the ends of the reaction tube:

$$p_2 - p_0 = p_3 - p_0 = \Delta p \quad \text{.......(4)}$$

With that equation (3) can be written as follows:

$$\Delta p = p_2 - p_0 = h\rho_L g - \frac{v_L^2\rho_L}{2}\left[1 + \lambda\frac{l_{rec}}{d_{rec}} + \zeta_{BC}\right] \quad \text{.......(5)}$$

Let $f_L = 1 + \lambda\frac{l_{rec}}{d_{rec}} + \zeta_{BC}$ ....(6)

The final form of equation (5) is:

$$\Delta p = h\rho_L g - f_L\frac{v_L^2\rho_L}{2} \quad \text{.......(7)}$$

The recycling of the liquid is caused by the recycle pressure drop (Δp_{rec}), which is the difference of the hydrostatic pressure of liquid and pressure difference of gas above the surfaces. The hydrostatic pressure promotes, the pressure, the pressure difference hinders the flow down of liquid. From equation (7):

$$\Delta p_{rec} = h\rho_L g - \Delta p = f_L\frac{v_L^2\rho_L}{2} \quad \text{.......(8)}$$

The recycle liquid velocity (v_L) is:

$$v_L = \sqrt{\frac{2(h\rho_L g - \Delta p)}{f_L \rho_L}} = \frac{1}{\sqrt{f_L}} \sqrt{\frac{2\Delta p_{rec}}{\rho_L}} \quad \text{.........(9)}$$

For open system Figure (2) the pressure at both ends of the reaction tube is equal, therefore equation (9) in this system is:

$$v_L = \frac{1}{\sqrt{f_L}} \sqrt{2gh} \quad \text{.........(10)}$$

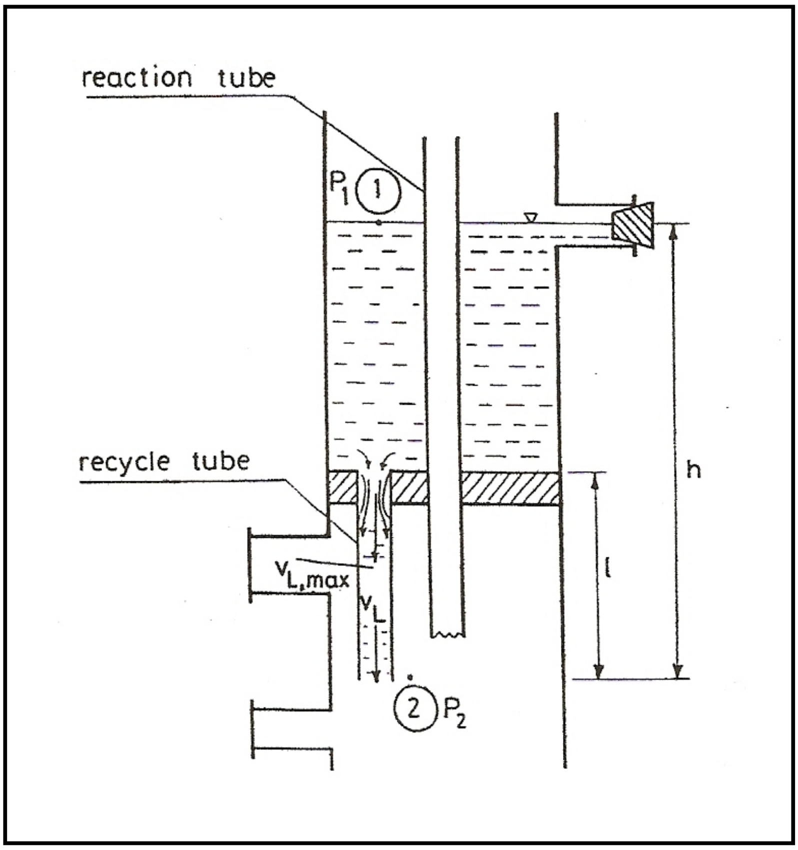

Figure (2) Opened system to measure recycle liquid velocity in recycle tube (v_L)

2.2 Energy Equation for Reaction Tube of ALT Reactor

According to Figure (1).

At point 3: $p_3 > p_0$, $v_L \approx 0, h = 0$

At point 4: $p_4 = p_0$, $v_L^* \neq v_G^*, h = 1$

Energy balance for the two phase flow at points 3 and 4 is as follows:

The pressure work is the sum of hydrostatic energy, kinetic energy and irreversible losses of the two phases, taking account that $v_G^* > v_L^*$ [9]:

$$(p_3 - p_0)(W_L + W_G) = (1\rho_L g W_L + 1\rho_G g W_G) + (\frac{v_L^{*2}\rho_L}{2} W_L + \frac{v_G^{*2}\rho_G}{2} W_G) = \text{irreversible losses} \ldots \qquad \ldots\ldots\ldots\ldots(11)$$

$$\Delta p = p_3 - p_0 = 1g\frac{\rho_L W_L}{W_L + W_G} + 1g\frac{\rho_G W_G}{W_L + W_G} + \frac{v_L^{*2}\rho_L}{2}\frac{W_L}{W_L + W_G} + \frac{v_G^{*2}\rho_G}{2}\frac{W_G}{W_L + W_G} + \Delta p_{rec} \ldots \qquad \ldots\ldots\ldots\ldots(12)$$

The pressure drop in the reaction tube for two phase flow (gas-liquid) was expressed separately for liquid and gas because, $v_G^{*2} \neq v_L^{*2}$, so in equation (12) appears the sum of hydrostatic pressure of liquid and gas the kinetic energy of liquid and gas. After introducing the volumetric ratios:

$$\Delta p = \varepsilon_L 1 \rho_L g + \varepsilon_G 1 \rho_G g + \varepsilon_L \frac{v_L^{*2}\rho_L}{2} + \varepsilon_G \frac{v_G^{*2}\rho_G}{2} + \Delta p_{irr} \ldots\ldots\ldots\ldots(13)$$

Simple form of equation (13) could be written as follows:

$$\Delta p = \Delta p_{hL} + \Delta p_{hG} + \Delta p_{kL} + \Delta p_{kG} + \Delta p_{irr} \ldots\ldots\ldots\ldots(14)$$

The kinetic terms are evaluated separately for liquid phase due to the difference in v_L^* and v_G^*. The kinetic energy of liquid is:

$$\Delta p_{kL} = \varepsilon_L \frac{v_L^{*2}\rho_L}{2} \ldots\ldots\ldots\ldots(15)$$

v_L^* is the real liquid velocity which is equivalent to the velocity of falling down liquid drops after reaching maximum liquid fountain height (h_L) and could be defined as:

$$v_G^* = \sqrt{2gh_L} \ldots\ldots\ldots\ldots(16)$$

The kinetic energy of gas is:

$$\Delta p_{kG} = \varepsilon_G \frac{v_G^{*2}\rho_G}{2} \ldots\ldots\ldots\ldots(17)$$

Where

$$v_G^* = \frac{W_G}{A_G}, \; A_G = A - A_L \text{ and } = \frac{W_L}{v_L^*}$$

Total irreversible losses of two phase flow is:

The irreversible losses in the reaction tube (Δp_{irr}) using equation (13, 15, and 17 has the following definition:

$$\Delta p_{irr} = \Delta p - lg\ (\varepsilon_L \rho_L + \varepsilon_G\ \rho_G) - \varepsilon_L \frac{v_L^{*2} \rho_L}{2} - \varepsilon_G \frac{v_G^{*2} \rho_G}{2} \quad \text{...(18)}$$

The final simple form of equation (18) is as follows:

$$\Delta p_{irr} = \Delta p - \Delta p_h - \Delta p_{kL} - \Delta p_{kG} \quad \text{..(19)}$$

Where Δp pressure drop in the reaction tube, which can be calculated from $\Delta p / \Delta p_W$ correlation[13] , while the hydrostatic term (Δp_h) and the kinetic terms (Δp_{kL} and Δp_{kG}) can be calculated from the theoretical expressions.

3. Experimental Work

3.1 Laboratory Scale Reactors

3.1.1 Laboratory scale reactor with one reaction tube and one recycle tube

Details of the equipment are shown in Figure (3). The main parts of the tube reactor (1) are made of glass and consists of two cylindrical parts, the upper part of 80 mm inside diameter and 265 mm height, the lower part of 80 mm inside diameter and 135 mm height with water jacket.

The main complementary equipment are as follows: peristaltic pump (9), water tank (11), thermostat (12), thermometer (13) water manometer (15) and air rotameter (17). Air/water system was used in this study. The water temperature was kept constant (25 ± 1) by circulated water from thermostat (12).

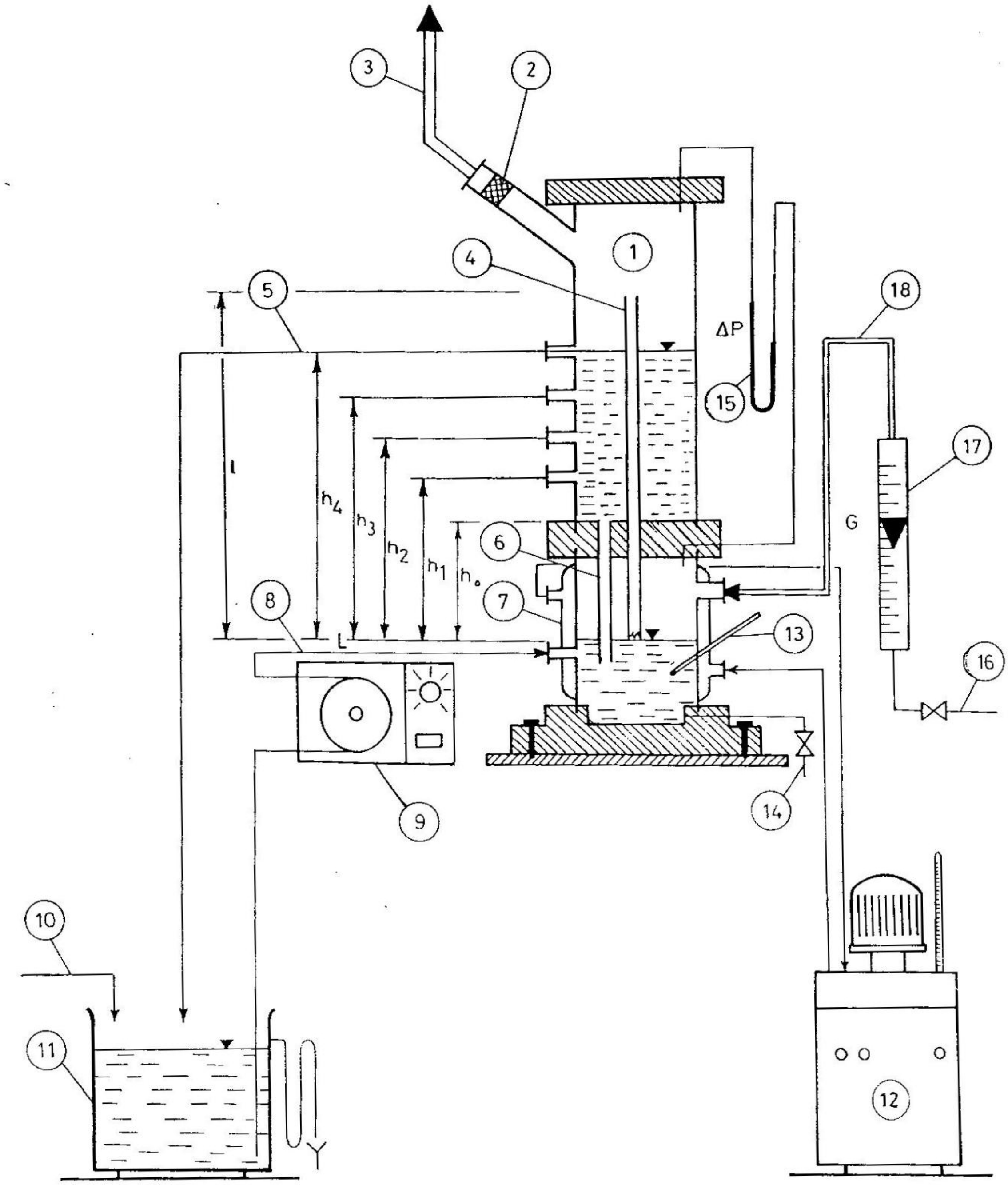

Figure (3) Schematic diagram of experimental apparatus for laboratory ALT reactor: 1. tube reactor, 2. mist eliminator, 3. exhaust air line, 4. reaction tube, 5. overflow line, 6. recycle tube, 7. water jacket, 8. water inlet line, 9. peristaltic pump, 10. water, 11. water tank, 12. thermostat, 13. thermometer, 14. discharge point, 15. water manometer, 16. compressed air, 17. rotameter, 18. air feeding line.

The geometrical data of the reactor are shown in Table (1), while the experimental conditions are summarized in Table (2), the arrangement of tubes is shown in Figure (4).

Table (1) Tube geometry in ALT reactor

No	Type of reactor	Tubes specifications				Cross section area of tubes		Area ratio
		reaction		recycle		Reaction A (m^2x10^{-5})	Recycle A_{rec} (m^2x10^{-5})	A/A_{rec}
		Diameter, d (mm)	length, l (mm)	diameter, d_{rec} (mm)	length, l_{rec} (mm)			
	Laboratory scale	1 tube		1 tube		1 tube	1 tube	
1		7	270	7	120	3.848	3.848	1.00
2		7	270	5	120	3.848	1.963	0.51
3		8	270	3	120	5.026	0.706	0.14
4		8	270	5	120	5.026	1.963	0.39
5		10	270	5	120	7.854	1.963	0.25
6		10	570	5	120	7.854	1.963	0.25
7		10	270	10	120	7.854	7.854	1.00
8		10	1000	5	120	7.854	1.963	0.25
9		20	270	10	120	31.415	7.854	0.25
10		20	570	10	120	31.415	7.854m	0.25
11		20	1000	10	120	31.415	7.854	0.25
12	Pilot scale	28	270	14	135	61.575	15.394	0.25
13		28	570	14	135	61.575	15.394	0.25
14		28	750	14	135	61.575	15.394	0.25
15		28	1000	14	135	61.575	15.394	0.25
	Laboratory	4 tubes		1 tube		4 tubes	1 tube	
16		10	270	7	120	31.415	3.848	0.1225
17		10	270	10	120	31.415	7.854	0.2500
18		10	270	14	120	31.415	15.393	0.4900
19		10	270	20	120	31.415	31.415	1.0000
	Pilot scale	48 tubes		12 tubes		48 tubes	12 tubes	
20		28	570	28	135	2955.61	738.90	0.2500
21		28	1000	28	135	2955.61	738.90	0.2500
22	Laboratory scale reactor sizes: Ø 80x500 mm							
23	Pilot scale reactor sizes: Ø 400x1600 mm							

Table (2) Experimental conditions for laboratory and pilot scale reactor

Type of reactor	Gas velocity (v_G)	Inlet gas load (G)	Inlet liquid load (L)	Liquid height (h)	Liquid temperature (T)
	m/s	m^3/s	m^3/s	m	°C
* Laboratory scale ALT reactor	0.22-22	(0.018-1.73) x10^{-3}	(0-0.003) x10^{-3}	0.126-0.246	25 ± 1
** Laboratory scale ALT reactor	0.38-7.07	(0.03-2.22) x10^{-3}	(0-0.003) x10^{-3}	0.136-0.237	25 ± 1
Pilot scale ALT reactor	4.83-13.45	(142.78-5148) x10^{-3}	(0-0.03) x10^{-3}	0.20-0.47	16-17
* reactor with one reaction tube and one recycle tube ** reactor with four reaction tubes and one recycle tube					

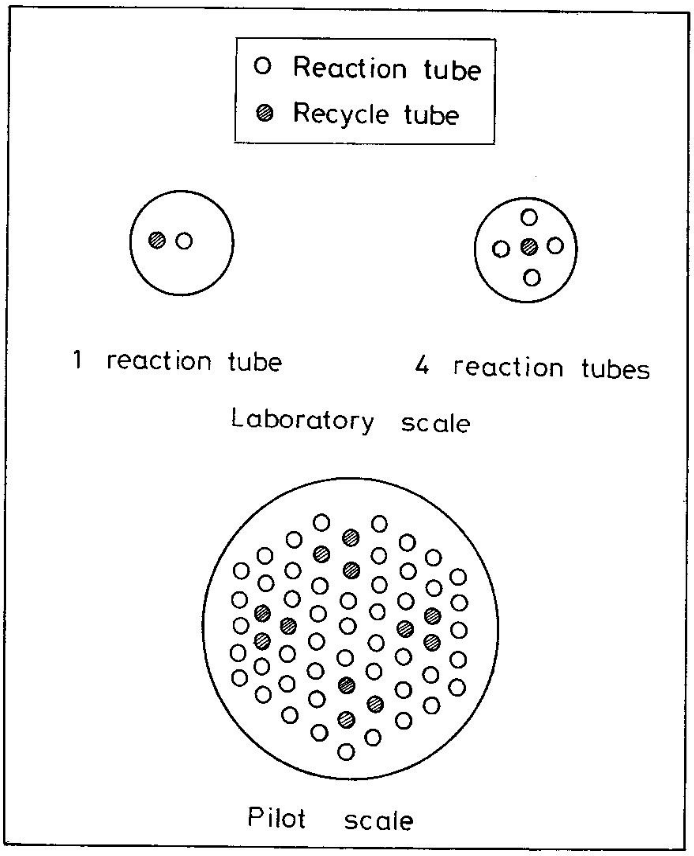

Figure (4) Tubes arrangement in ALT reactors

The next parameters were measured:

a. The recycle liquid velocity (v_L) was measured in opened system Figure (2) by varying the liquid heights in the range of h = 5-250 mm. The liquid was fed to the upper part of the reactor, the liquid was flowing down through the recycle tube. When the liquid reached constant height (h), the liquid flowing down was measured by graduated cylinder at certain time and it was equivalent to the measured inlet liquid load.

b. The pressure drop in the reaction tube (Δp) was measured by using water manometer (15).

c. The real liquid velocity in the reaction tube (v_L^*) was determined from equation (16) by measuring the liquid fountain height (h_L) (see Figure 1) for different area ratios (A_{rec}/A = 0.25-1) at constant liquid height (h = 245 mm) by varying gas velocity in the reaction tube in the range of $v_G = 3.54\text{-}14.16$ m/s.

d. The real gas velocity in reaction tube (v_G^*) was determined from the equation: $v_G^* = \dfrac{W_G}{A_G}$ as described before.

3.1.2 Laboratory scale reactor with four reaction tubes and one recycle tube

To increase the gas-liquid interfacial area, the experimental apparatus of Figure (3) was modified as: 4 reaction tubes were built in. The geometrical data are summarized in Table (1), experimental conditions in Table (2), the arrangement of tubes is shown in Figure (4).

The parameters were measured by the above mentioned methods.

3.2 Pilot Scale Reactor

The pilot scale reactor contained bigger size of tubes (Ø 28 mm) and column diameter (Ø 400 mm) and the inlet gas load was 4248 times higher than that of laboratory scale reactor. The geometrical data are summarized in Table (1), experimental conditions in Table (2), the arrangement of tubs is shown in Figure (4).

4. Experimental Results and Discussion

The results of hydrodynamic measurements are shown in the following figures: Figure (5) represents the recycle liquid velocity in the recycle tube (v_L) as a function of pressure drop of recycle tube (Δp_{rec}) for laboratory and pilot scale reactors at different diameter of recycle tubes (d_{rec}).The v_L increases with the increase of Δp_{rec} and d_{rec}. The edges of recycle tubes for pilot scale reactor were non sharp for that reason the v_L of pilot scale reactor is higher than that of laboratory scale reactor as well. The shape of the curves is parabolic form as expected.

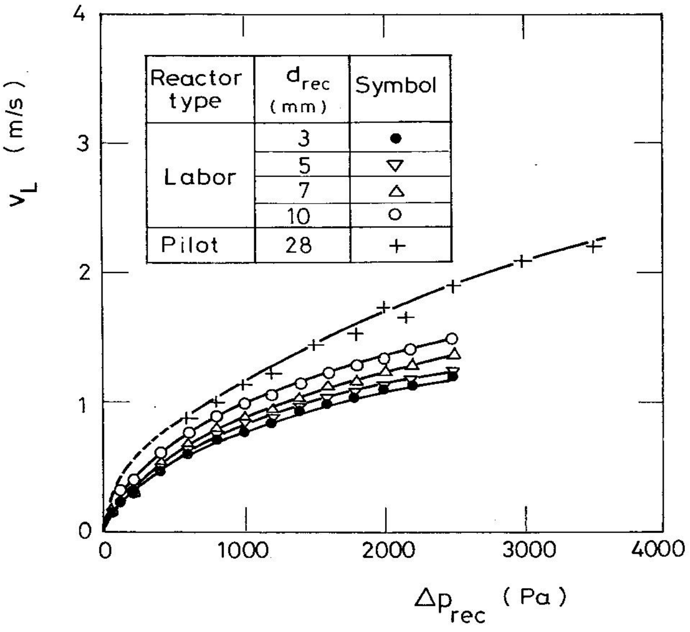

Figure (5) Influence of recycle pressure drop (Δp_{rec}) on recycle liquid velocity (v_L) in laboratory and pilot scale reactors

Figure (6) represents measured pressure drop in reaction tube (Δp) for laboratory scale reactor of four reaction tubes and one recycle tube as function of superficial gas velocity in reaction tube (v_G), at constant area ratio ($A_{rec}/A = 0.25$), constant inlet liquid load (L = 0 1/h) and different liquid heights in the range of h = 136-237 mm . The pressure drop increases with the increase of v_G and h, but the influence v_G is small in the range of v_G = 0.38-7.07 m/s.

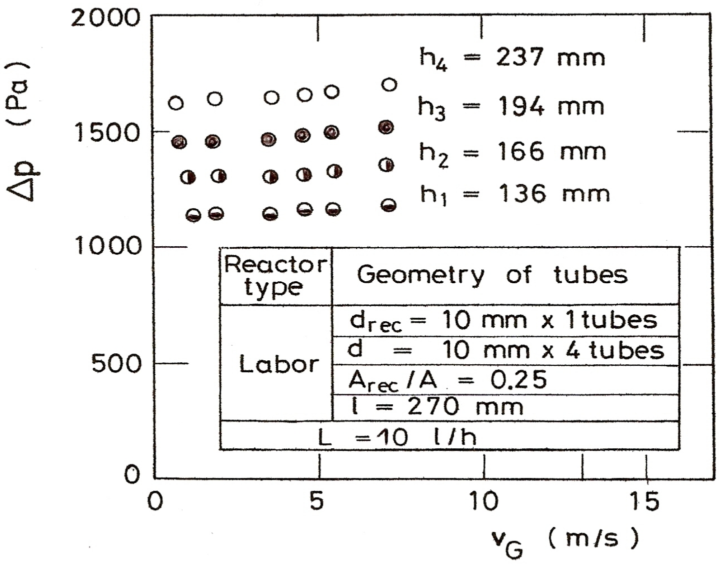

Figure (6) Influence of superficial gas velocity (v_G) on pressure drop (Δp) in laboratory scale ALT reactor

Figure (7) represents the pressure drop in (Δp) for pilot scale reactor as a function of gas velocity (v_G), for area ratio ($A_{rec}/A = 0.25$), at different liquid heights in the range of (h = 200-470 mm) and inlet liquid load was (L = 0 1/h). The pressure drop increases with the increase of liquid height, but the influence of gas velocity on the pressure drop is small in the range of v_G = 4.83-13.45 m/s.

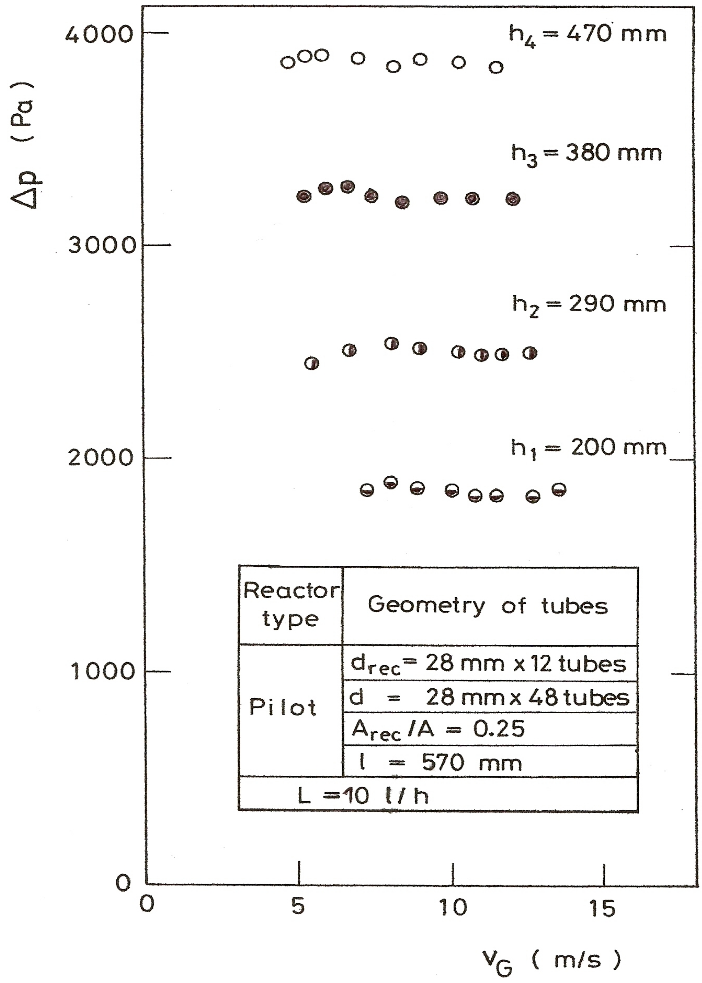

Figure (7) Influence of superficial gas velocity (v_G) on pressure drop (Δp) in pilot scale ALT reactor

5. Verification of the Theory

5.1 Verification of the Mathematical Model of v_L with Measured Data

The model of superficial recycle liquid velocity in recycle tube (v_L), Equation (9) was verified with our measured data for laboratory and pilot scale reactors. Theoretical and measured values are compared at Figure (8). The theoretical v_L values are similar to the measured ones with maximum deviation of about 9 % as shown in Figure (9).

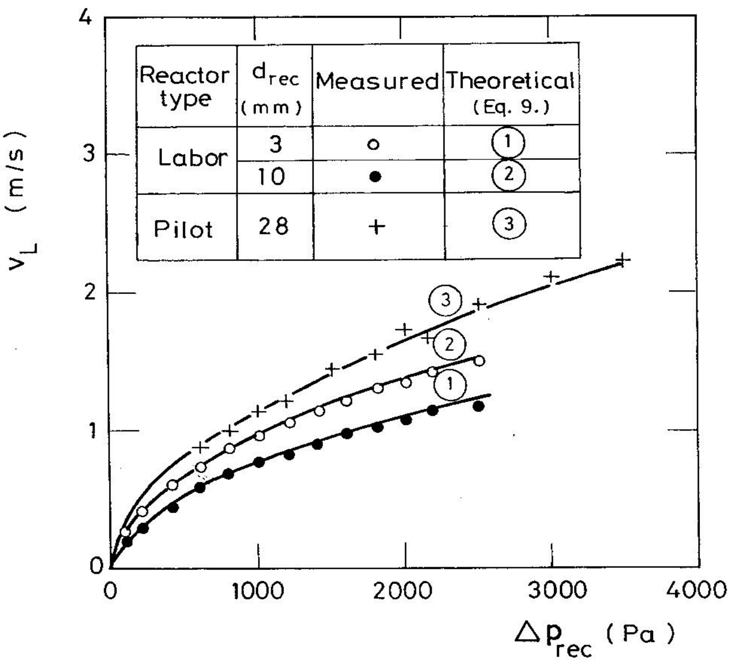

Figure (8) Verification of model of recycle liquid velocity (v_L), Eq. (9) with present work measured data in laboratory and pilot scale reactors

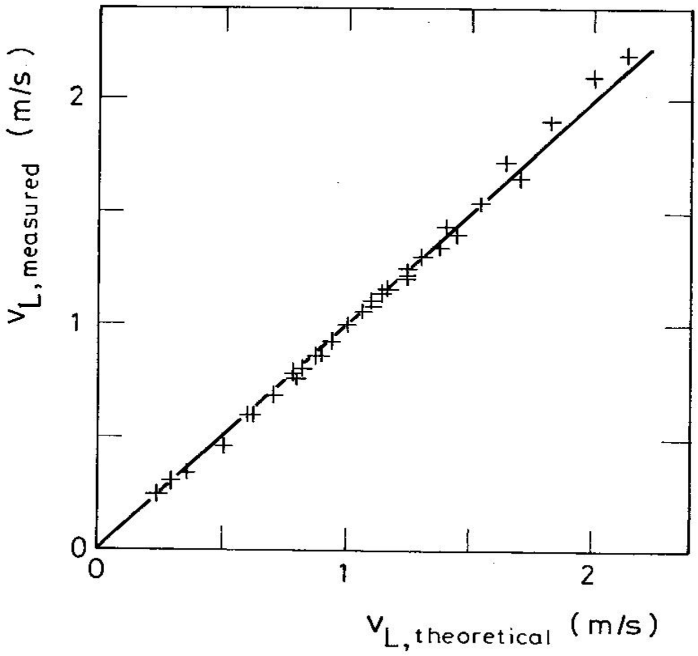

Figure (9) Accuracy of the model of recycle liquid velocity (v_L) in laboratory and pilot scale ALT reactors

5.2 Comparison of the Model of Δp_{irr} with Measured Data of Govier *et al* [9]

The model of irreversible pressure drop in the reaction tube (Δp_{irr}), Equation (18) was verified with present measured data and the data of Govier *et al* [9]. Govier measured the total and the irreversible pressure drop in a vertical tube using air/water system. The pressure drops were measured between two points of an infinite tube, so the kinetic term of liquid and gas are subtracted, the irreversible losses contains only the friction and vortex losses.

Figure (10) shows irreversible losses calculated from present work model Equation (18) in case of laboratory and pilot reactors and measured irreversible losses of Govier. It can be established, that in the infinite length of tube the losses are lower, because they do not contain entrance and kinetic losses of liquid and gas.

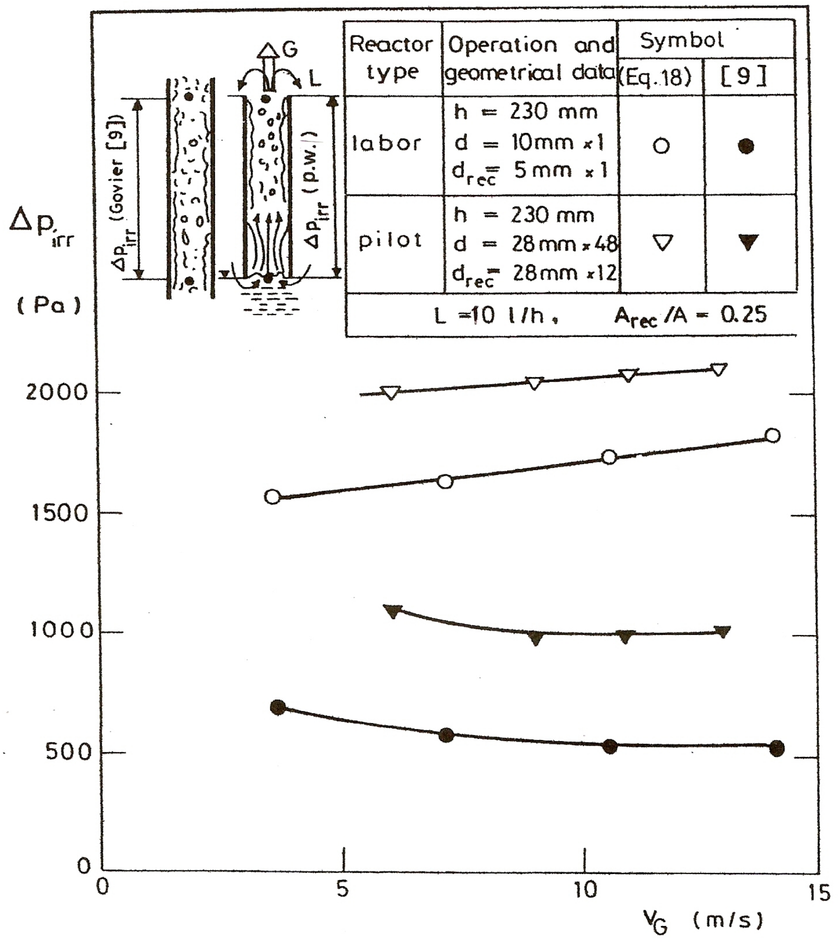

Figure (10) Comparison of present work model of Δp_{irr} with the measured data of Govier el al [9]

The measured total pressure drop data of Govier *et al* [9] and the pressure drop calculate on the base of Verba [10] were compared with the measured total pressure drop data in laboratory and pilot scale reactors Figure (11). The present work data showed higher total pressure drop, because of the entrance losses as it was shown in Figure (10).

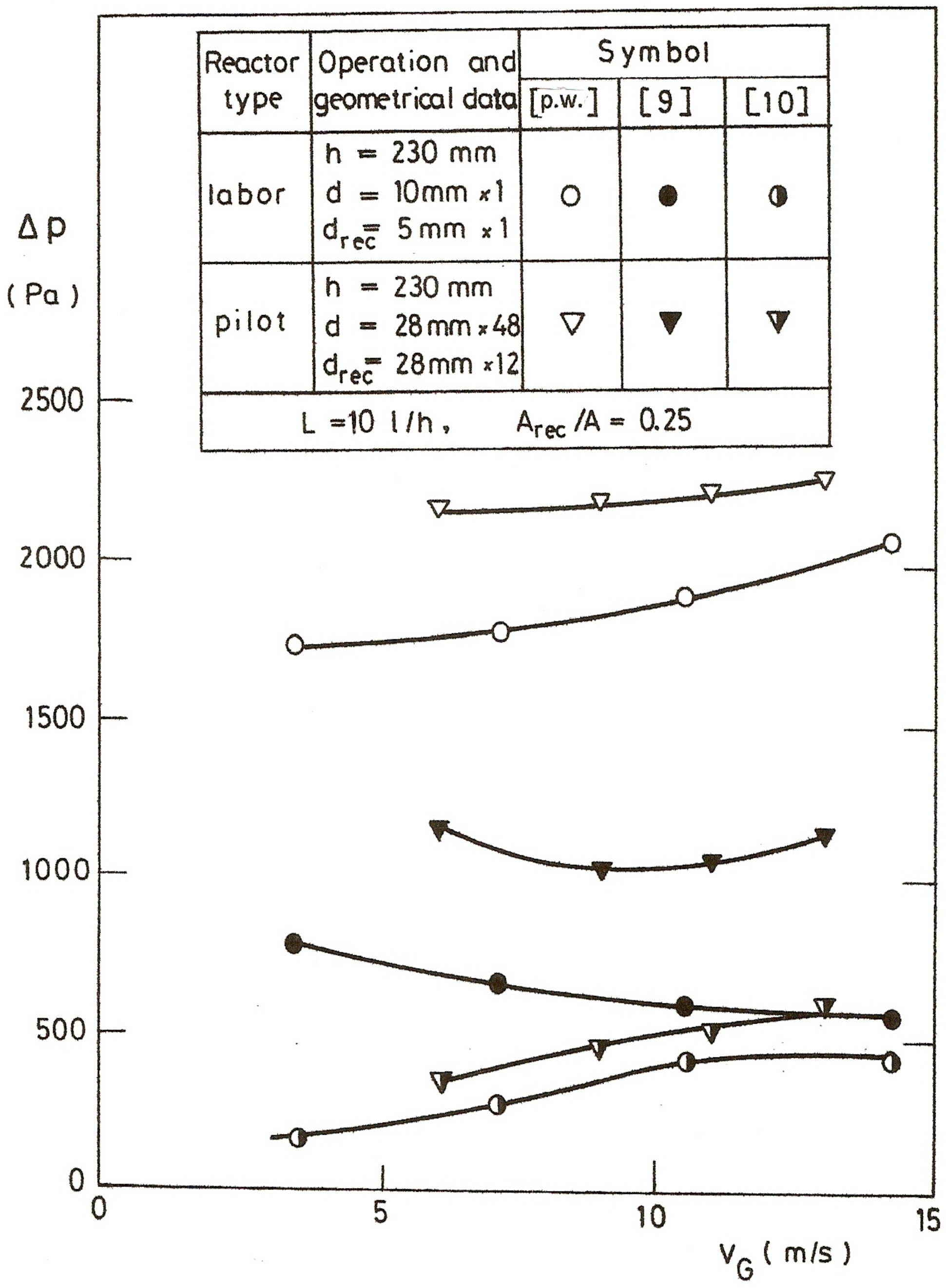

Figure (11) Comparison of the present work measured data of Δp with the measured data of Δp of Govier et al [9] and the calculated Δp based on Verba [10]

6. Main Result and Conclusions

1. Theoretical model for liquid velocity in recycle tube (v_L) , Equation (9) was derived from energy equation and was verified with present work measured data obtained in laboratory and pilot scale reactors. The maximum deviation was about 9 %. Comparison of our measured data with literature correlations has been calculated. The model of Szczuka [4] showed a good approximation for the present work tube system, while the models for v_L of bubble column collected by Laurent [7] could not be used for the present work tube system, because they are valid for low v_L velocities.

2. Theoretical model for irreversible pressure drop in reaction tube (Δp_{irr}) Equation (18) was developed based on the energy balance taking account the difference between the real gas velocity (v_G^*) and the real liquid velocity (v_L^*) in the tube (v_G^* is always higher than v_L^*). The calculated values of irreversible pressure losses from the model for ALT reactor were compared with measured data of Govier *et al* [9]. The measured Δpirr data by Govier is lower than the calculated irreversible losses of ALT reactors, because the losses of Govier do not contain entrance and kinetic losses of liquid and gas (see Figure 10).

3. Two correlations are widely used [15] to estimate the two phase pressure drop in pipe, the Lockhart-Martinelli correlation and homogenous model of Dukler and others, the estimated pressure drop can be ± 40%. Dukler's correlation will be used slightly better for most applications. Both correlations are expected to give better accuracy for horizontal flow than vertical flow. Only when the two phase pressure drop is high, the estimate will be relatively independent of orientation.

7. References

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