CHAPTER 4

Results and Discussion

4.1 Performances of Gas-Liquid Contactors

The hydrodynamic performance of the airlift contactor with perforated plate (ALC-P) is compared with those of the bubble column (BC) and the conventional concentric tube airlift contactor (ALC) as depicted in Figures 4.1.1 to 4.1.5. General observation from experimental data leads to the following conclusions:

- Overall gas holdup are more or less the same in all types of contactor.
- Riser gas holdup in the ALC-P is much higher than that in the ALC.
- Downcomer gas holdup (ε_d) in the ALC-P is much lower than that in the ALC. (In most cases, ε_d in the ALC-P was found to be very close to zero.)
- Liquid velocities, both riser and downcomer of the ALC-P are lower than those in the ALC. (Note that the average liquid velocity in the BC is zero.)

Figure 4.1.1 illustrates the comparison between overall gas holdup in all types of contactors. The result clearly shows that overall gas holdups vary proportionally with superficial gas velocity. This finding is similar to those of Chakravarty *et al.*, 1973; Chisti and Moo-Young, 1988; and Gavrilescu *et al.*, 1998. Gas holdup in the BC is found to be slightly higher than that in the ALC, which also agrees well with the reported experimental data (Koide *et al.*,1983; Jones, 1985; Siegal *et al.*, 1986). The same observation is also found with the riser gas holdups in the ALC and ALC-P where gas holdups vary with superficial gas velocity as shown in Figure 4.1.2. It is interesting to note that in most cases, the gas holdup increases with the gas flow rate at low range of superficial gas velocity (U_{sg}), after which it tends to level off (at $U_{sg} \approx$ 4 cm/s). However these gas holdups start to vary proportionally with U_{sg} again at higher range of gas flowrate. This phenomenon is still not well-understood with the present set of experimental data.

Turning now to the effect of perforated plate on liquid velocity in the system. It is found that, in the conventional ALC, the liquid velocity is much higher than that in the BC. This high liquid motion promotes the upward movement of gas bubbles resulting in a shorter gas residence time, and hence, gas holdup in the conventional ALC is usually found to be less than that in the bubble column. However, inserting the perforated plate into the ALC decreases free area for the liquid flow, or in other words, increases the flow resistance or pressure drop of the fluid along the length of the column. Gas bubbles are also being retarded by the perforated plate, as it can be observed from the same figure that gas holdup in the riser of ALC-P is much higher than that in the ALC.

It is noted that the increase in the riser gas holdup in the ALC-P is compensated by the reduction in the downcomer gas holdup. This is why we did not see the effect of perforated plate on the overall gas holdup. In fact, the downcomer gas holdup in the ALC-P is not detected at all (Figure 4.1.3). This is because the liquid velocity in the ALC-P is too low, not capable of bringing gas bubbles down in the downcomer.

Liquid velocities in the ALC-P are found to be much lower than that in the ALC due to the high flow resistance created by the perforated plate, as mentioned above (Figures 4.1.4 and 4.1.5). The trajectory of the liquid velocity as a function of superficial gas velocity is rather confusing but interesting. It is observed that liquid velocity increases with the superficial gas velocity during the low range of superficial gas velocity (U_{sg} from 1-4 cm/s) after that it tends to level off or in some circumstances lower down slightly. These two flow regimes are demonstrated by the sketch in Figure 4.1.6 where Region I represents the range that the liquid velocity still increases with the gas flowrate, and the liquid velocity starts to be independent of the gas velocity in Region II. However, liquid velocity starts to increase with gas velocity again at high range of superficial gas velocity. This part is illustrated as Region III in Figure 4.1.6. Note that this up-and-down trajectory of the velocity profile is similar to that of gas holdup. In Regions I and III, liquid velocity is directly driven through the plate by the pressure induced by the bubbles behind the perforated plate. On the other hand, it is anticipated that, in Rigion II, when gas bubbles collide with the perforated plate, a high level of back pressure is generated, and this back pressure forces the liquid to move backwards, reducing the liquid velocity. In actual practice, the ALC when operated at this range of gas throughput was trembling due to this back pressure. However, it is still not understood why this back pressure does not affect the liquid velocity at high range of U_{sg}.

4.2 Effects of Number of Holes in The Perforated Plate on Hydrodynamics in ALCs

4.2.1 Gas holdup

The influences of number of holes in the perforated plate on overall and riser gas holdups are illustrated in Figures 4.2.1 and 4.2.2 respectively. Both overall and riser gas holdups increase when the perforated plate is inserted into the draft tube. As explained in Section 4.1, the increases in gas holdups occur because the perforated plate blocks the pathway of bubbles, reducing the free area that bubbles can go through which results in a longer gas bubble residence time. To investigate the influence of the number of holes in the perforated plate, the experiment was carried out in the ALC-P with various numbers of holes (free area) in the plate. The plate with more holes provides more free area for the fluid flow. It is found that when the plates with less free area are used, gas holdups (riser and overall) tend to increase. There are two possibilities that explain this phenomenon. Firstly, less free area exerts more resistance to liquid movement, which leads to the reduction in liquid velocity. This effectively increases bubble residence time in the system and results in an increase in gas holdups. Secondly, a small number of holes inevitably result in a sparse population of holes in the perforated plate. Observation indicated that bubbles from this kind of perforated plate tend not to coalesce too rapidly once they pass through the plate. These small size bubbles have lower terminal velocity and leave the contactor more slowly than larger ones. Hence, gas holdup in this case is higher than that obtained when the perforated plate with larger number of holes is employed.

4.2.2 Liquid velocity

The effect of number of holes in the perforated plate on riser liquid velocity is illustrated in Figure 4.2.3 which clearly shows that riser liquid velocity increases with increasing superficial gas velocity for all types of perforated plate. Liquid velocities in the ALC-P with 37-hole perforated plate are higher than those with 21 holes; and 13 holes configuration gives the lowest liquid velocity. As the plate free area corresponds to the number of holes, it can also be said that liquid velocity decreases with decreasing free area in the perforated plate. In other words, a smaller free area plate has a greater flow resistance and pressure drop for fluid flow.

Figure 4.2.4 reveals the effect of plate voidage on downcomer liquid velocity. The results illustrate that liquid velocity in downcomer increases with superficial gas velocity until it reaches its maximum value before starts to decrease. It is noticed (by tracer injection) that the decrease in downcomer liquid velocity is a result of back pressure produced when the fluid collides with the plate. In other words, when the liquid flows against the perforated plate, there exists a reaction force acting on the liquid in the opposite direction to the fluid flow or what is called "back pressure". This results in an interval of "no liquid movement" in the column. The observation shows that this back pressure increases with superficial gas velocity and also is higher in ALC-P with less number of holes on the plate, i.e. Figure 4.2.4 shows that liquid velocity in the ALC-P with a 13 hole perforated plate inversely varies with U_{sg}.

To investigate the relationship between the gas holdup and liquid velocity in the ALC-P, it is considered appropriate here to consult additional information from literature. It was usually found that the gas holdup and the liquid velocity in the ALC are dependent quantities and the correlations between these two parameters are often in the form of:

$$\varepsilon \propto U_{sg}^{\alpha} \tag{4.1}$$

where

ε = gas holdup [-]

U_{sg} = superficial gas velocity [cm/s]

α = constant [-]

The constant in Equation 4.1, α, was found to vary in a range from 0.2-1.26 depending on the configurations of the ALC (Chakravarty *et al.*, 1973, Chisti *et al.*, 1988 and Tung *et al.*, 1997). In the experimental setup of this work, this constant is found to be approximately 0.347 for conventional ALC and 0.401, 0.552, 0.466, and 0.536 for the ALC-P with one 13, 21, 37, and 45-hole perforated plate, respectively. It is found that the percentage increase in riser gas holdup obtained from the ALC-P is about 3% to 12% more than that from the ALC during the selected operating range (gas velocity from 1.89 to 8.45 cm/s).

One important notice from these experimental results is that when the number of holes in the perforated plate decreases, the liquid velocity decreases greatly (over a hundred percent), whilst the gas holdup increases only by a small margin. Figure 4.2.5 provides a schematic picture of a potential answer to this. Figure 4.2.5 is the sketch according to the visual observation and the digital record of bubble coalescence in the ALC-P with different number of holes. From the experiment, it can be noticed that there exists a high-pressure zone under the perforated plate. This zone occurs as a consequence of the low free area for the flow path of gas and liquid where gas bubbles are allowed to accumulate at the nonporous region. The high-pressure region produces high gas bubble velocity as the gas passes through the plate. Decreasing number of holes on the perforated plate is observed to increase this pressure zone as more bubbles are allowed to remain under this plate due to lower free area for the bubble movement. This is beneficial for the gas bubble velocity through the plate and it is expected that the plate with smaller number of holes does not reduce the gas bubble velocity as much as the plate with higher number of hole does. This negatively influences the gas holdup because if bubbles pass the plate at high velocity, they will spend less time in the ALC. As a result, unlike the effect on the liquid velocity, we do not see a significant enhancement of the gas holdup in the ALC-P.

4.3 Effects of Hole Diameter in The Perforated Plate on Hydrodynamics in ALCs

4.3.1 Gas holdup

Figures 4.3.1 and 4.3.2 illustrate overall gas holdup and riser gas holdup obtained from the ALC-Ps where the perforated plates consist of various hole sizes (the number of hole in this case is fixed at 21). The increase in gas holdups is observed when the plate hole diameter decreases. This experimental result well agrees with that obtained by Miyahara *et al.* (1999) who reported that gas holdups decreased as hole diameter increased in the ALC with the perforated plate install in the riser. It is observed that small hole-size perforated plate does not allow both gas and liquid to pass through as easily as the larger hole plate does. This reduces the collision frequency of bubbles that pass through the plate. Hence, smaller gas bubbles are formed which enhances the bubble residence time and consequently overall and riser gas holdups.

4.3.2 Liquid velocity

Figures 4.3.3 and 4.3.4 show the effect of hole diameter on riser and downcomer liquid velocities respectively. Riser liquid velocity decreases proportionally with the decreasing hole diameter. This is because there is a small free area for the passage of liquid in the small hole perforated plate, which simply means more flow resistance.

The effect of hole diameter on downcomer liquid velocity is plotted in Figure 4.3.4, the results seem to follow the same trend as the results obtained from the experiment with various number of holes. That is to say that downcomer liquid velocity increases as superficial gas velocity increases. At superficial gas velocity greater than 4 cm/s, the back pressure begins to influence the downcomer liquid velocity in the same fashion with that explained in the last part of Section 4.2.2.

Again, the results in Figures 4.3.2 and 4.3.3 show a controversial conclusion over the relationship between the reduction in liquid velocity and the increase in gas holdup in the ALC. It is common to expect an increase in gas holdup as the liquid velocity decreases because when the liquid velocity is low, gas bubbles tend to stay longer in the system and that enhances the gas holdup. The results in Figure 4.3.3 reveal that the liquid velocity in the ALC-P is significantly slower when the perforated plate with a smaller hole size is employed. However, the information on the gas holdup in Figure 4.3.2 indicates that there is not a significant increase in the gas holdup when a smaller hole perforated plate is used. This may be explained by considering Figure 4.3.5 which is the schematic diagram for the formation of gas bubbles in the ALC-P with various sizes of hole in the inserted perforated plate. In all cases when the perforated plate is inserted into the column, there exists a high pressure zone underneath the plate. This high pressure zone leads to a high gas bubble velocity through the plate which negatively influences the gas holdup in the system. It is observed from the experiment that this high pressure zone increases in its intensity when the perforated plate with a smaller hole size is used. Hence, although inserting the perforated plate will help enhance the gas holdup due to lower liquid velocity, a too small hole perforated plate will not be beneficial for this purpose as a small hole size will tend to increase bubble velocity through the plate. It is found from this experiment that reducing the hole size from 5 to 3 mm. can only improve the gas holdup from 0.17 to 0.18 which is equivalent to about 6% enhancement (at the same time, the liquid velocity decreases from 34 to 22 cm/s or about 32% reduction).

4.4 Effects of Number of Perforated Plates on Hydrodynamics in ALC

4.4.1 Gas holdup

Figures 4.4.1 and 4.4.2 reveal the effect of number of perforated plate on overall and riser gas holdups respectively. The results show that increasing number of perforated plates in the column results in a higher gas holdup in the system. Previous sections have shown that the perforated plate helps break bubbles into smaller size.

However, bubbles tend to coalesce rapidly after they leave the perforated plate. Inserting more perforated plates into the column will help break bubbles again. Since smaller bubbles stay longer in the column, ALC-P with more perforated plates will therefore have a greater gas holdup.

4.4.2 Liquid velocity

Figures 4.4.3 and 4.4.4 show the effect of number of plates on riser and downcomer liquid velocities respectively. The results show that increasing the number of baffle plates reduces liquid velocities both in riser and downcomer. It is noticed (by tracer injection) that there exists a wavy flow of liquid along the column when the perforated plate is inserted and also that the intensity of this wavy motion increases when increasing the number of plates. As illustrated in Figure 4.4.4, the downcomer liquid velocity begins to decrease when superficial gas velocity, U_{sg}, increases up to the level about 4 cm/s. This decrease is expected to be the result from the back pressure in the system with perforated plate.

As observed from Figures 4.4.2 and 4.4.3 that the reduction in liquid velocity induces just a little increasing in gas holdup, e.g. at $U_{sg} \approx 7.5$ cm/s, about 20% reduction in liquid velocity can only give 5% rise in riser gas holdup. As explained in earlier sections, the main cause of this cannot be drawn directly from the experimental data, but it is expected that the high pressure zone underneath the perforated plate is the key factor. Inserting a perforated plate results in the formation of a high pressure zone which tends to increase the bubble velocity in the system, and inserting more than one perforated plate, in effect, means a higher number of this high pressure zone. This essentially lower the ability of the system to retain the gas bubbles. It is therefore not a straight-forward means to increase the gas holdup simply just by increasing the number of perforated plate.

4.5 Effects of Perforated Plates on Gas-Liquid Mass Transfer in ALCs

4.5.1 Comparison of performances of gas-liquid mass transfer on different designs of gas-liquid contactors

The effect of perforated plates on overall volumetric mass transfer coefficient (k_La) is shown in Figure 4.5.1. The k_La in the ALC-P is found to be higher than that in the BC, whilst the lowest is found in the conventional ALC. From visual observation (and digital-camera recorded evidence), the perforated plate plays a significant part in breaking up the gas bubbles to smaller size, and also in increasing the turbulence in the column. These phenomena are beneficial for the rate of gas-liquid mass transfer as the smaller bubble size increases the interfacial mass transfer area (a) between gas bubbles and liquid. As overall gas holdups in ALC, ALC-P and BC are not significantly different from each other (Figure 4.1.3), whilst the riser gas holdup in the ALC-P is markedly higher than the holdup in the ALC or in the BC, it may be reasonable to conclude that the rate of mass transfer is principally affected by the riser gas holdup.

Figure 4.5.2 is sketched to describe the bubble forming phenomenon in the ALC-P with one perforated plate inserted at the middle of the riser. Compressed air is sparged through a porous sparger at the center of the base of the reactor where gas bubbles with diameter d_1 are formed and flow along Region 1 (height H_1) with a uniform diameter. Region 1^* (height H_1^*) is the intermediate region where small bubbles from the sparger still coalesce to form "d_1 diameter" bubbles. This means that gas bubbles leave the sparger with diameter d_1^* and then rapidly coalesce into a larger size with diameter of d_1 (*Otake et al.*, 1977). However, this intermediate region is found (visual observation) to be insignificant as $H_1^* << H_1$. When bubbles with d_1 diameter pass through the perforated plate, located midway through the riser, they are broken into smaller size with diameter d_2 and flow along the column during Region 2 (height H_2), after which these bubbles tend to coalesce to form larger bubbles with diameter d_3. In Region 3, located above region 2 with the height of H_3, bubbles diameter is observed to be approximately the same as in H_1 ($d_3 = d_1$ from digitally recorded evidence). Hence, it can be concluded that bubble characteristics during Region 3 is the same as that found in Region 1. To calculate the percentage increase in the specific interfacial mass transfer area, the following calculation is carried out:

$$A_B = a_T V_T = a_1 V_1 + a_2 V_2 + a_3 V_3 \qquad (4.2)$$

where

A_B = total gas-liquid interfacial area [cm^2]

a_T = overall/average specific gas-liquid interfacial area in the ALC-P [cm^{-1}]

a_i = specific gas-liquid interfacial area in Section i [cm^{-1}]

V_i = fluid volume in Section i [cm^3]

The fluid volume in each section can be calculated from the product between cross sectional area (A) and fluid height (H_i):

$$V_i = AH_i \qquad (4.3)$$

therefore

$$A_B = a_T AH_T = a_1 AH_1 + a_2 AH_2 + a_3 AH_3 \qquad (4.4)$$

Divide Equation (4.4) by $a_1 A$ gives:

$$\frac{a_T}{a_1} H_T = H_1 + \frac{a_2}{a_1} H2 + \frac{a_3}{a_1} H_3 \qquad (4.5)$$

for gas-liquid contacting devices:

$$a = \frac{6\varepsilon}{d_B} \qquad (4.6)$$

where

ε = gas holdup [-]

d_B = bubble diameter [cm]

Gas bubble diameters are measured from the photos taken by the digital camera as demonstrated in Figure 4.5.3. The sizes of each bubble are measured for the calculation of Sauter mean diameter as derived in Equation 3.24. The number of samples used in this experiment was approximately ten.

It is assumed that gas holdup (ε) is constant for each section:

$$\frac{a_2}{a_1} = \frac{d_{B1}}{d_{B2}} \tag{4.7}$$

and since

$$a_3 = a_1 \tag{4.8}$$

Substitute Equations (4.7) and (4.8) into Equation (4.4) gives:

$$\frac{a_T}{a_1} H_T = H_1 + \frac{d_{B1}}{d_{B2}} H_2 + H_3 \tag{4.9}$$

or,

$$a_T = \frac{\left(H_1 + \frac{d_{B1}}{d_{B2}} H_2 + H_3 \right) \times a_1}{H_T} \tag{4.10}$$

The difference in specific interfacial area between the ALC and ALC-P can then be calculated from

$$\% \, a_{diff} = \left(\frac{a_T - a_c}{a_c} \right) \times 100 \tag{4.11}$$

where

a_c = specific interfacial area in concentric ALC [cm^{-1}]

Provided that the ratio of overall volumetric mass transfer coefficients $(k_L a)$ between ALC-P and ALC can be calculated from experimental data, the difference between the overall volumetric mass transfer coefficients (k_L) in the ALC and ALC-P can subsequently be calculated from:

$$\%k_{Ldiff} = \left(\left(\frac{k_L a_T}{k_L a_c} \times \frac{a_c}{a_T} \right) - 1 \right) x\ 100 \qquad (4.12)$$

where

k_La_c = overall volumetric mass transfer coefficient in conventional concentric ALC [s^{-1}]

k_La_T = overall volumetric mass transfer coefficient in ALC-P [s^{-1}]

With the above derivation it is possible to investigate the effect of perforated plate on both specific interfacial area (a), and the rate of gas-liquid mass transfer (k_L). Table 4.1 shows the effect of perforated plate on gas-liquid mass transfer in the ALC-P with various numbers of holes and plates. It is found that the interfacial mass transfer area is highly promoted by the perforated plate, but not the mass transfer coefficient (k_L). For instance, in the case of the ALC-P with one perforated plate (13 holes with diameter of 4 mm.) at U_{sg} of 1.889 cm/s, the overall mass transfer coefficient (k_La) is found to be 82.848% more than that in the conventional ALC. However, most of this increase is derived from the increase in the specific interfacial mass transfer area (a) which is calculated to be about 72%, while the rate of mass transfer (k_L) only accounts for as small as 5.9% increase (over the conventional ALC). Interestingly, Table 4.1 reveals that in almost all cases, the rate of mass transfer (k_L) in the ALC-P is found to be less than that in the ALC. This means that most of the increase in the overall mass transfer rate is responsible by the increase in the interfacial mass transfer area (a).

4.5.2 Effects of number of holes in the perforated plate on gas-liquid mass transfer in ALC-P

The number of holes in the perforated plate corresponds to the free area for the passage of liquid and gas bubbles. i.e. the plate with higher number of holes gives more free area than the plate with less number. Figure 4.5.4 illustrates the effect of this free area on the rate of gas liquid mass transfer in the ALC-P, and it shows that the overall volumetric mass transfer coefficient (k_La) in the ALC-P with the 37-hole-plate inserted in the column is often found to be less than those obtained from the 21 hole. Table 4.1 shows that decreasing the number of holes in the perforated plate results in a great enhancement in the specific interfacial area between gas bubble and liquid (a). For instance, at U_{sg} = 5.64 cm/s, hole diameter of 3 mm, and with 2 perforated plates, decreasing the number of holes from 37 to 21 causes '*%a difference*' to increase from 49.34 to 82.28% (*%a difference* is the percentage ratio between 'a' in the ALC-P and 'a' in the conventional concentric ALC). Note that there are large fluctuations in the calculation shown in Table 4.1, and sometimes the results disagree with each others, i.e. there are few instances where 'a' in the 37 hole perforated plate is higher than 'a' in the 21 hole plate. However, these circumstances are few and most of the resulting calculation proves the aforementioned conclusion.

In the view point of the rate of mass transfer, k_L, it is found from the same table that the k_L varies directly with the amount of free area in the perforated plate. This is to say that if there is a large free area on the plate, the percentage increase in the k_L in the ALC-P with respect to k_L in the ALC is large (and positive). This is obvious with the results for the ALC-P with one perforated plate in Table 4.1, where the plate consists of 37 holes, each hole has a diameter of 4 or 5 mm. In other cases where the free area is small, the percentage increase in k_L is found to be negative which means that decreasing the free area inversely influences the rate of mass transfer. Hence, it can be concluded here that the observed increase in the overall mass transfer rate (k_La) when decreasing the number of holes in the perforated plate is primarily caused by the increase in the interfacial mass transfer area (a) between gas and liquid, and not the k_L.

However, a further decrease in the free area (from 21 to 13 holes) in the perforated plate does not seem to give an appreciation improvement in the value of overall mass transfer coefficient in the ALC-P. In fact, the overall mass transfer rate in the ALC-P with 13 holes seems to be a little less than that in the ALC-P with 21 holes. Table 4.1 is again consulted to investigate this finding. It is found that decreasing the number of holes in this case results in a similar effect on the specific interfacial area (a) as '*%a difference*' in the ALC-P with 13 holes is higher than that in the ALC-P with 21 holes. On the other hand, in most cases, the '*%*k_L *difference*' in the ALC-P with 13 holes is found to be much lower, and this causes the resulting overall mass transfer coefficient to be relatively low.

In summary, it was found from this experiment that the optimal rate of mass transfer between gas and liquid was obtained from the operation on the ALC-P with 21 holes on the perforated plate.

4.5.3 Effects of hole diameter in the perforated plate on gas-liquid mass transfer in ALC-P

Figure 4.5.5 illustrates the effect of hole diameter on the rate of gas-liquid mass transfer. It is found that k_La at a low range of superficial gas velocity from all cases is approximately in the same level. At a high range of superficial gas velocity ($U_{sg} > 5$ cm/s), k_La obtained from the perforated plate with 4 mm. diameter hole size becomes significantly greater than the other cases (the 3 mm. diameter hole size perforated plate seems to provide the worst case scenario in terms of the rate of mass transfer). Table 4.1 explains this finding as follows.

Table 4.1 shows that the '*%a difference*' in the ALC-P with 3 mm. hole diameter in the perforated plate is usually not as great as those found with the systems with higher hole diameter perforated plates. In addition, the '*%k_L difference*' obtained from this 3 mm. hole diameter plate is often the lowest among the three cases. This results in the system with the poorest gas-liquid mass transfer rate. The performances of the ALC-Ps with 4 mm. and 5 mm. hole plates are not significantly different from each other in terms of '*%a difference*' and '*%k_L difference*', both of these parameters are found to be a little higher for the case of 4 mm. hole perforated plate.

4.5.4 Effects of number of perforated plates on gas-liquid mass transfer in ALC-P

Figure 4.5.6 illustrates the effect of number of perforated plate(s) on gas-liquid mass transfer in the ALC-P. The result shows that the mass transfer performance is enhanced with increasing the number of perforated plates. The important role of these plates is to break large bubbles into smaller ones which increases the number of gas bubbles and also the interfacial area between gas and liquid as described in previous sections. Hence, when more perforated plates are inserted into the column, even more gas bubbles are retained in the system, and an even higher gas-liquid interfacial area is obtained, and so the k_La value is found to increase. Table 4.1 clearly illustrates the effect of the number of plates on both 'a' and 'k_L'. In all cases, the three perforated plate ALC-P is found to give the highest value of '*%a difference*' where the one perforated plate ALC-P gives the lowest. The '*%k_L difference*' in the ALC-Ps with 13 and 21 hole perforated plates are also found to be highest when three perforated plates are inserted into the system. However, the result is opposite when the number of holes becomes 37. The reason for this is still unclear.

It is interesting to note that the rate of increase in k_La is not directly proportional to the increase in the number of plates, especially at low superficial gas velocity. For instance, as demonstrated in Figure 4.5.6, at gas velocity about 4.7 cm/s, changing from 1 plate to 2 plates increases k_La from 0.0529/s to 0.0651/s, which corresponds to 23.06% increase in k_La. A further increase in the number of plates (2 to 3) results in a further enhancement of k_La from 0.0651 to 0.0706 (8.45%). However, increasing number of plates simply means the addition of pressure drop into the ALC. This affects the hydrodynamic behavior of the liquid in the ALC significantly. As obvious from the experiment, the liquid velocity drops from 15.36 to 12.95 m/s when increasing the number of plates from 1 to 2, and from 12.95 to 8.33 cm/s when the third plate is inserted (at the same U_{sg}). This might not be attractive particularly in the application when liquid circulation is a significant feature, e.g. in the industries of mixing and liquid aeration.

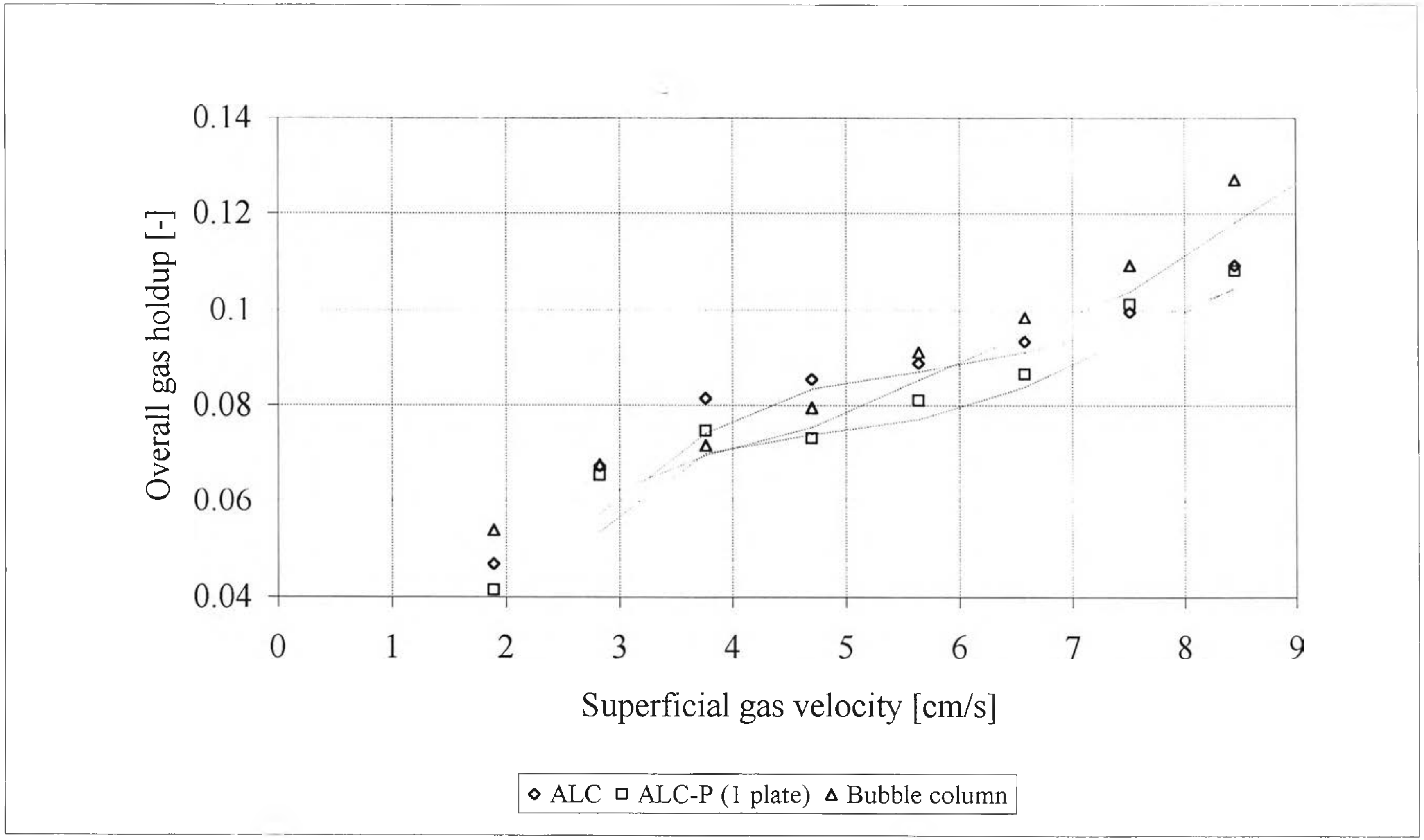

Figure 4.1.1. The comparison between overall gas holdup in conventional ALC, ALC-P and bubble column

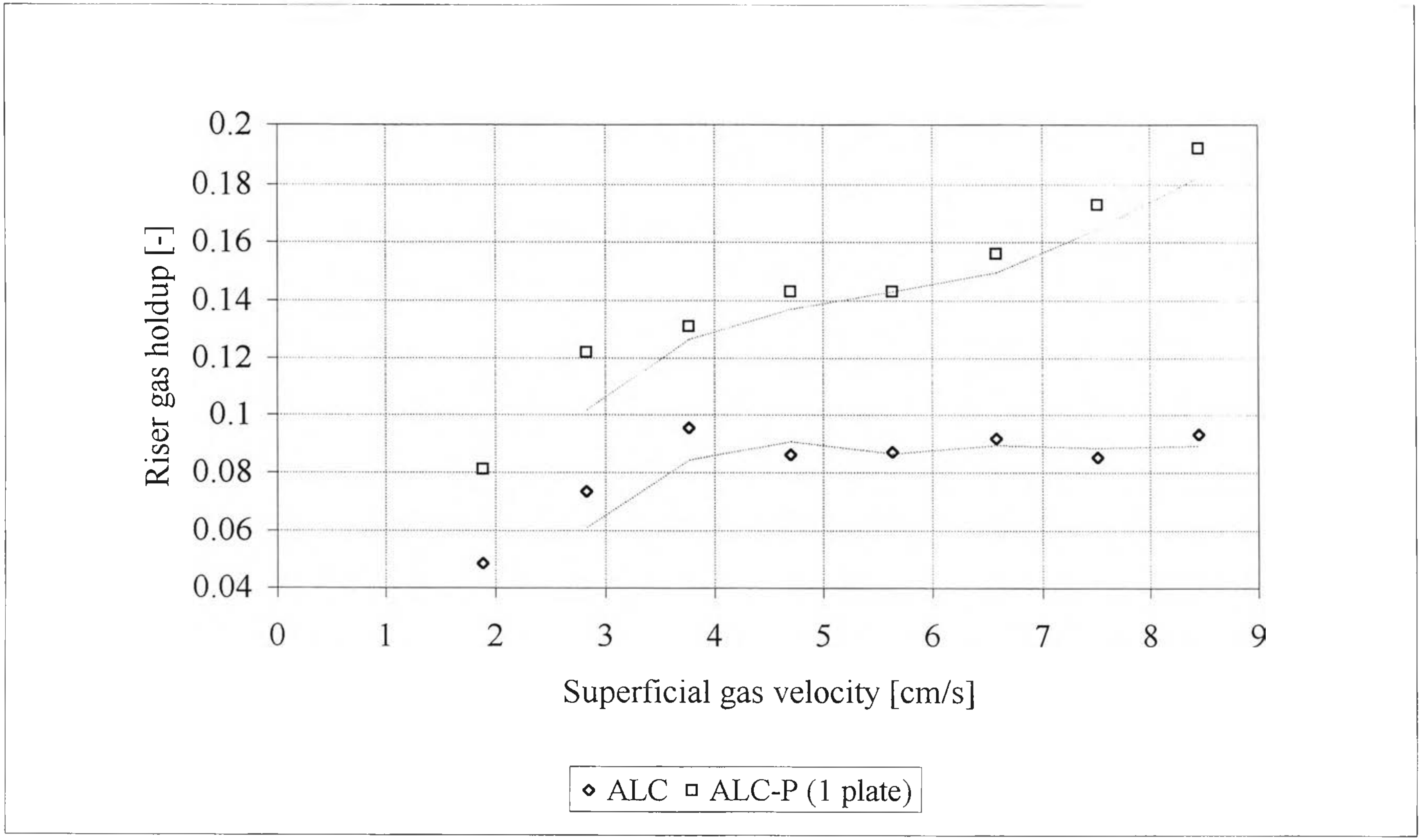

Figure 4.1.2. The comparison between riser gas holdup in conventional ALC and ALC-P

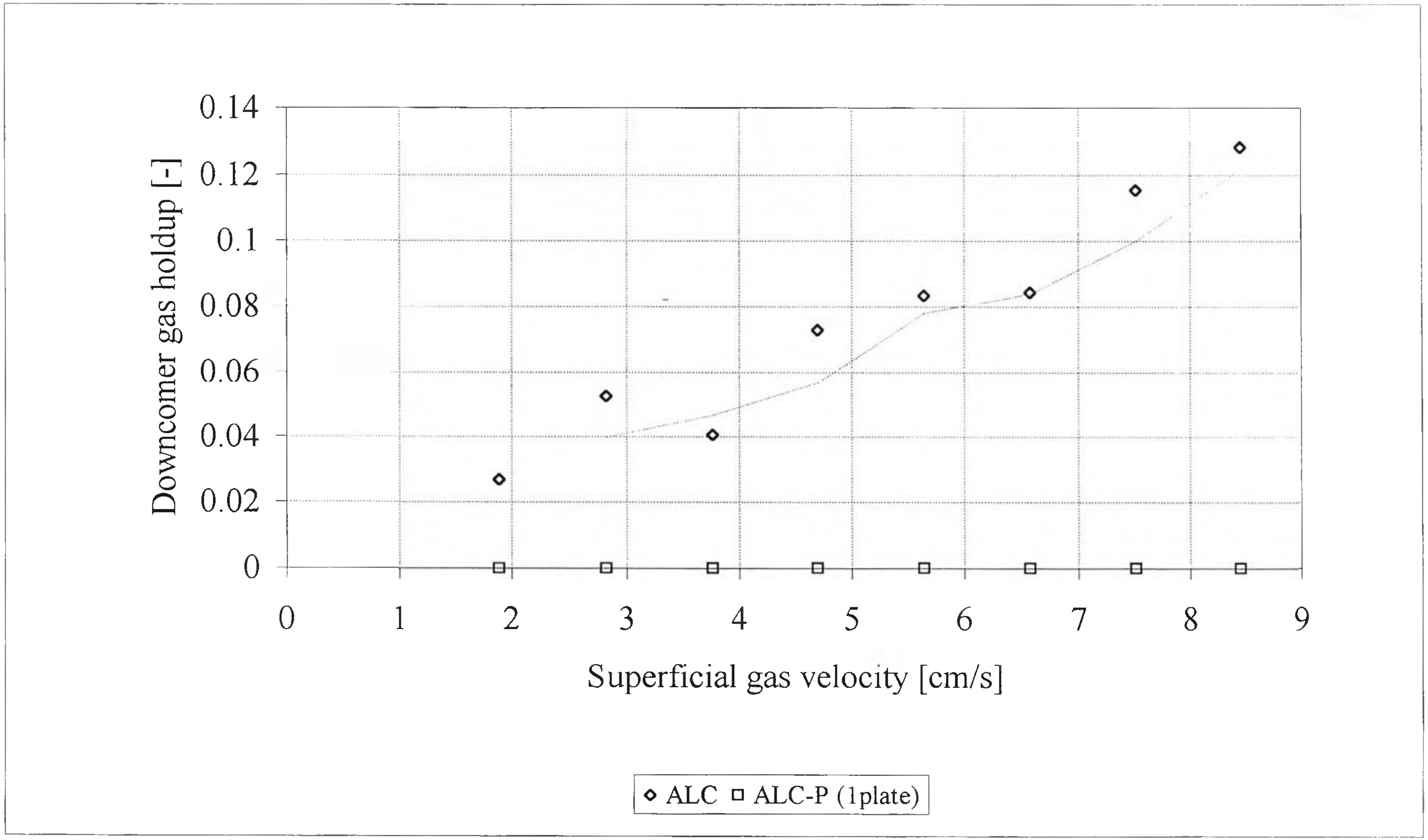

Figure 4.1.3. The comparison between downcomer gas holdup in conventional ALC and ALC-P

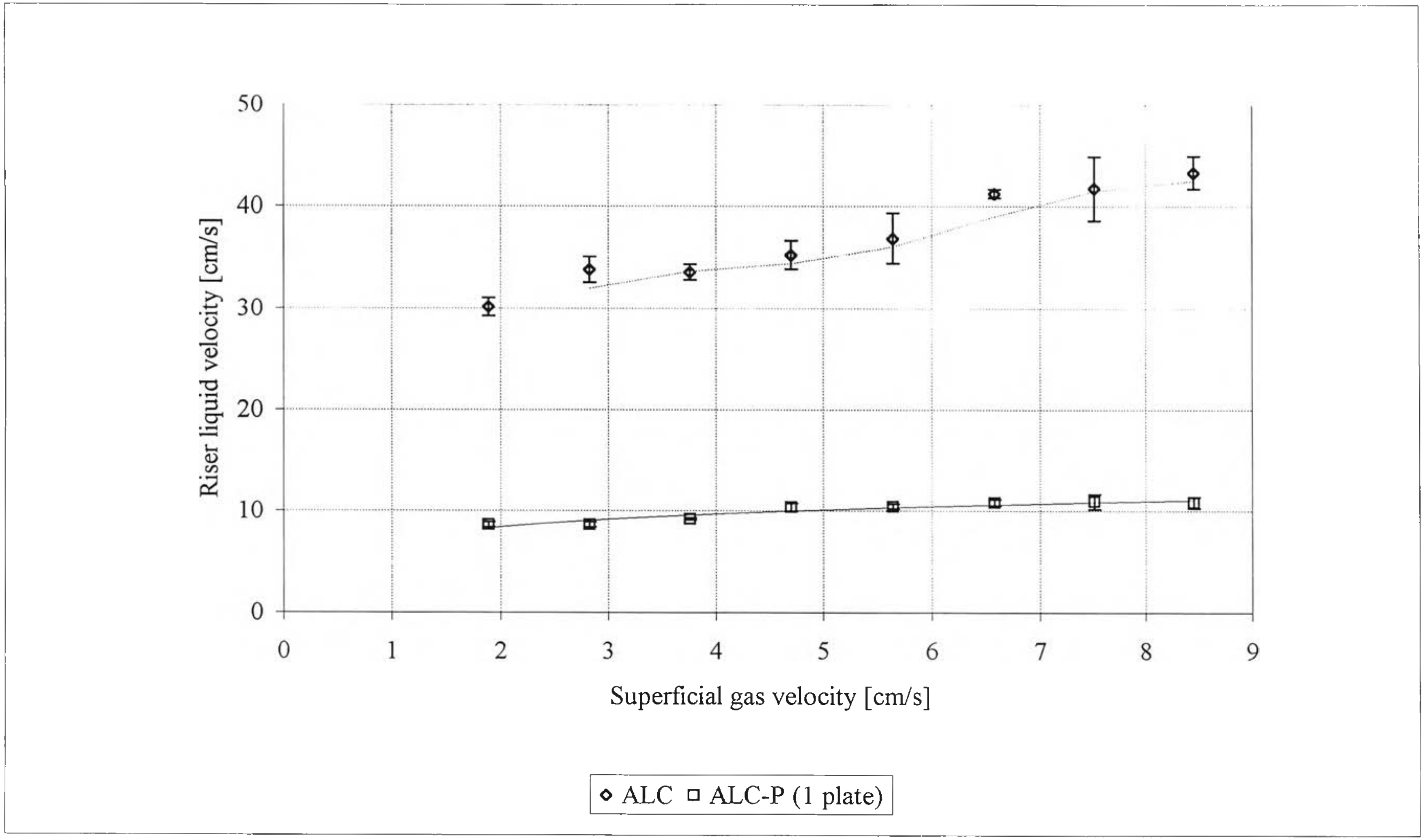

Figure 4.1.4. The comparison between riser liquid velocity in conventional ALC and ALC-P

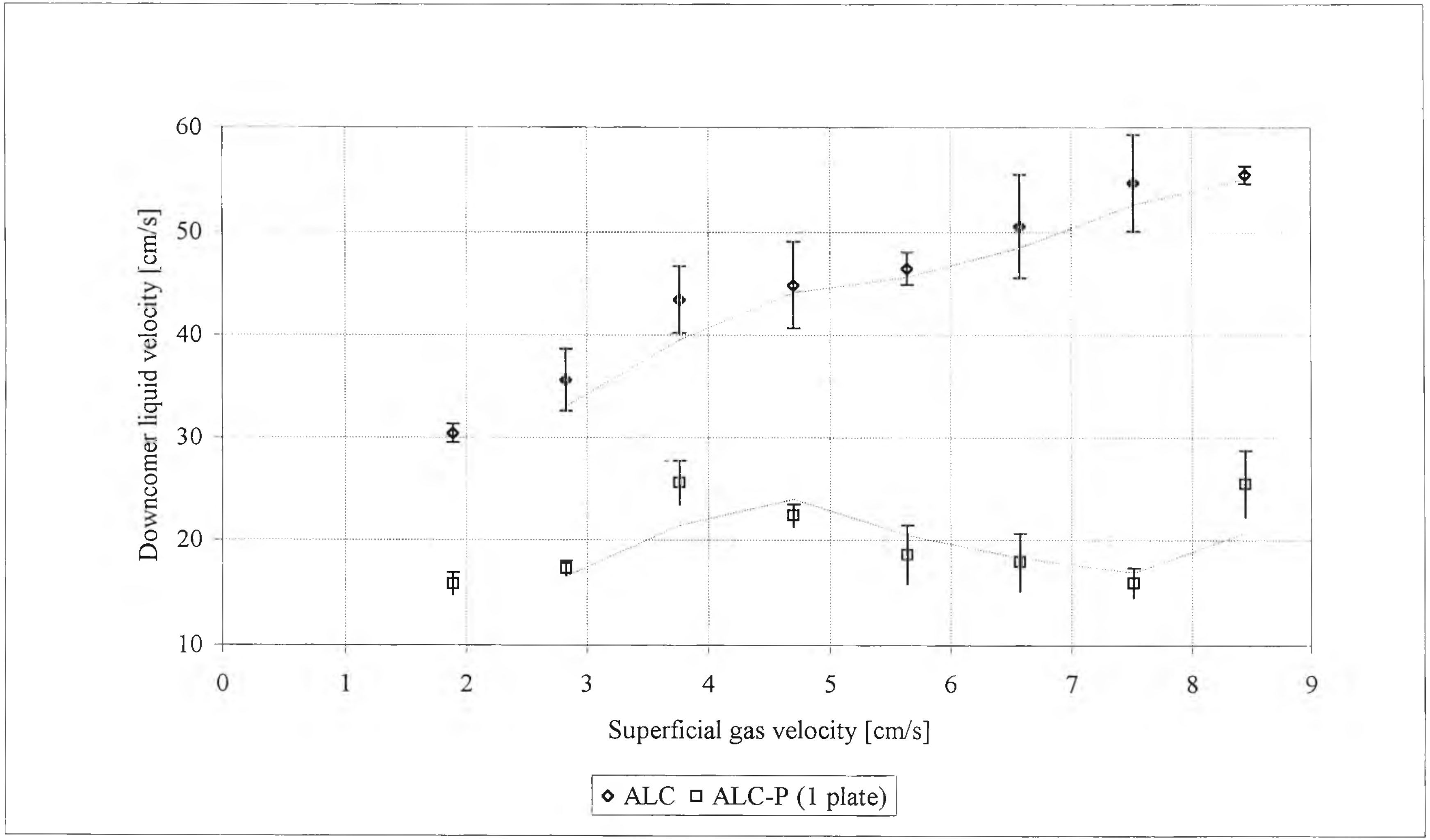

Figure 4.1.5. The comparison between downcomer liquid velocity in conventional ALC and ALC-P

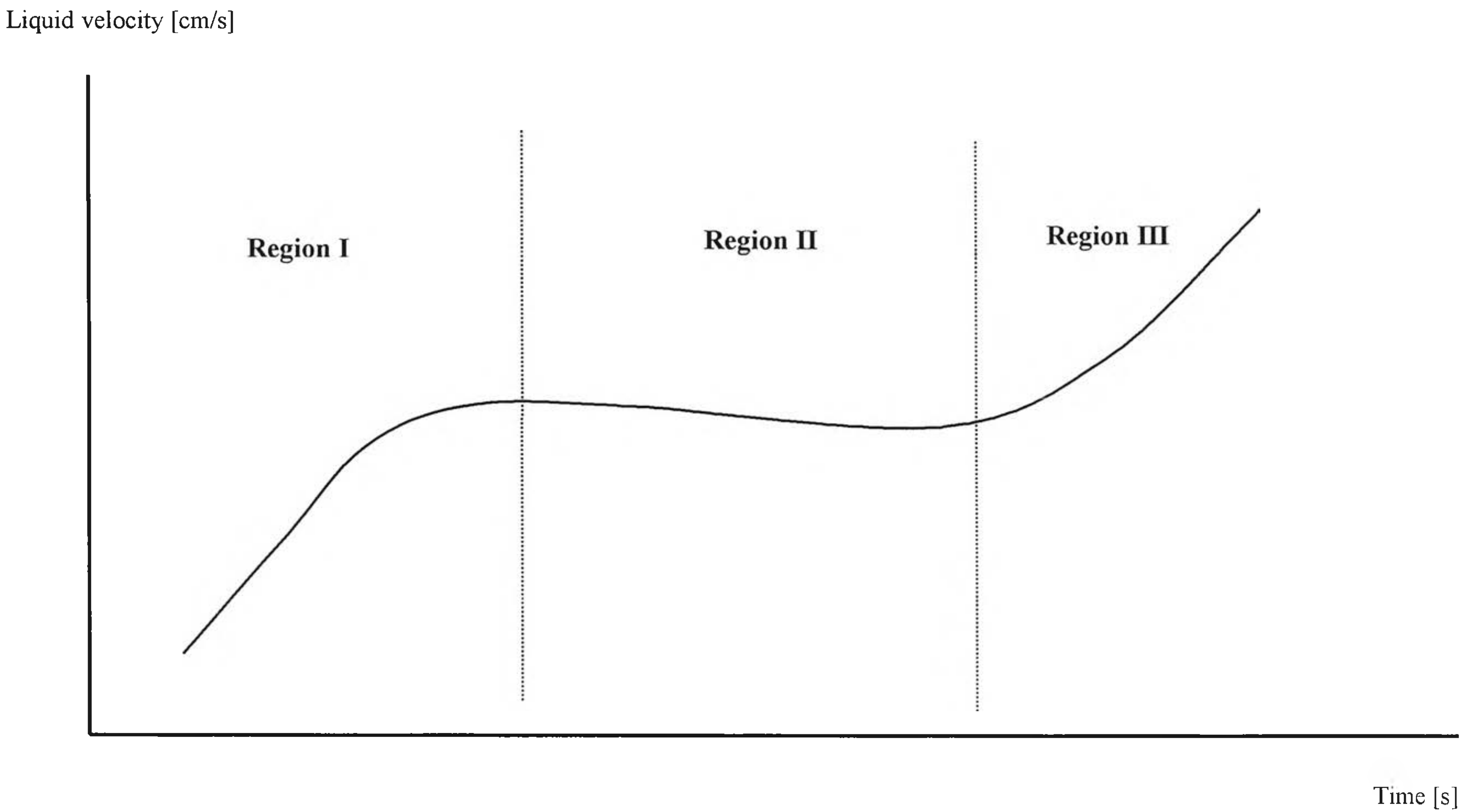

Figure 4.1.6. Liquid velocity trajectory in the ALC-P

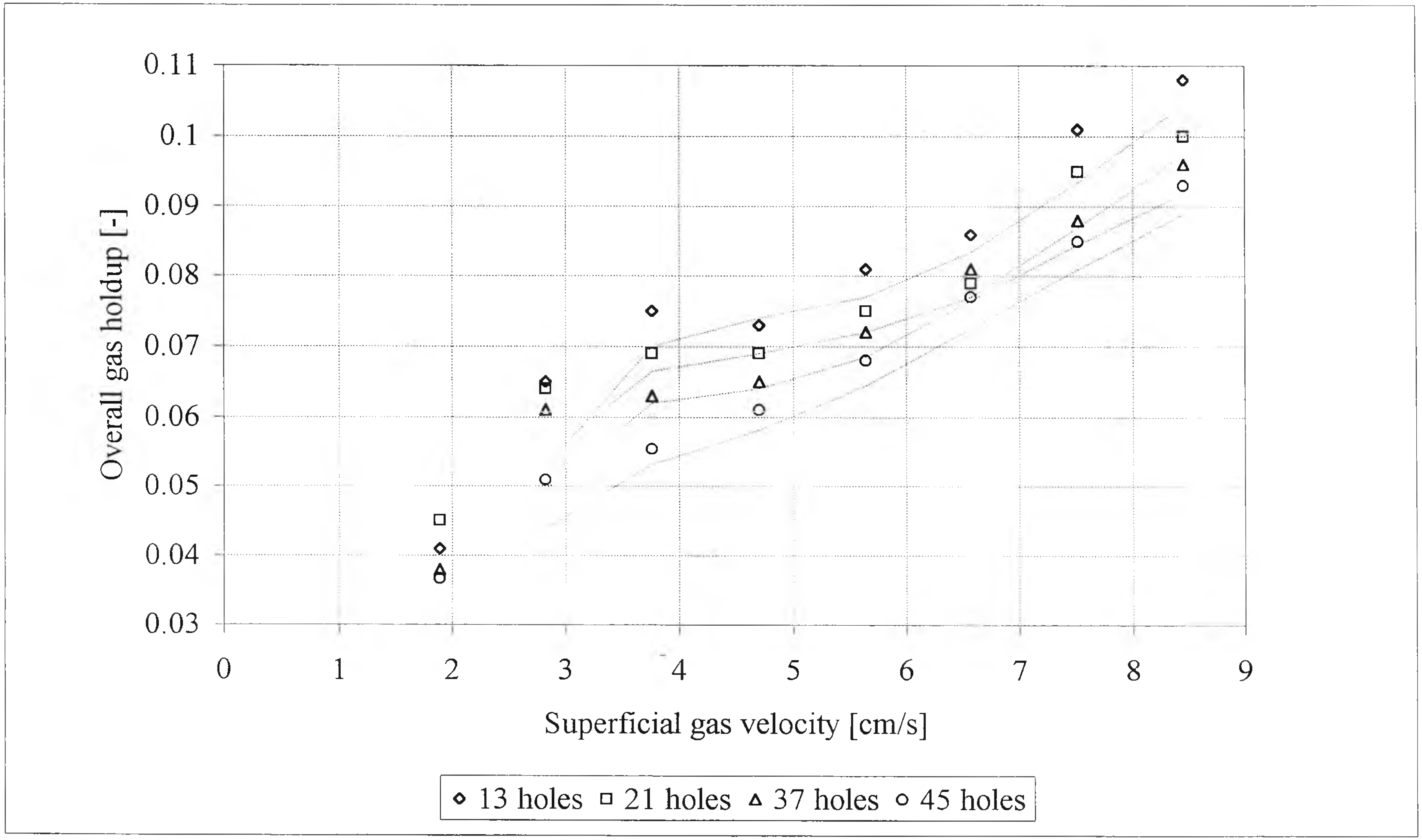

Figure 4.2.1. Effect of number of holes in the perforated plate on overall gas holdup in the ALC-P

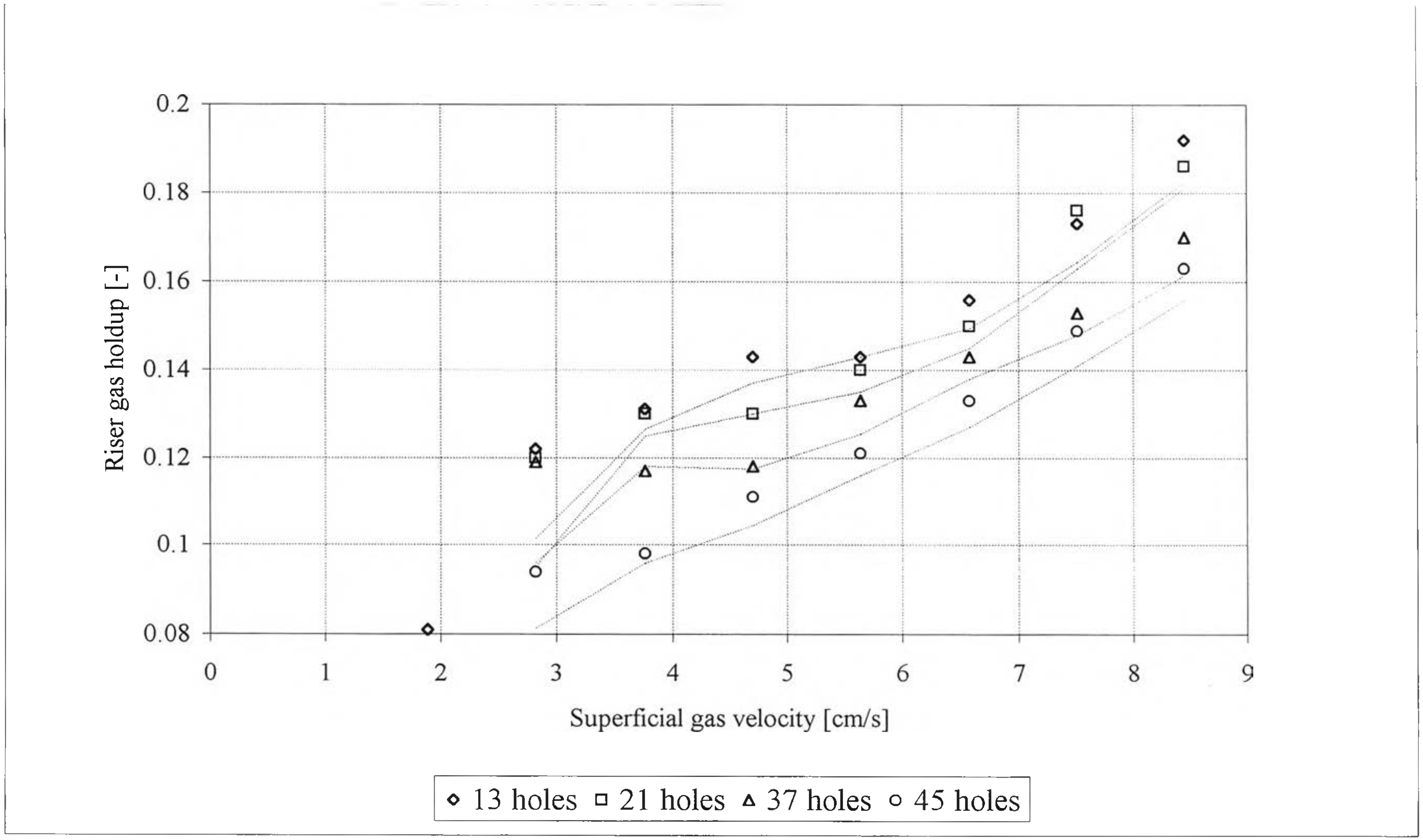

Figure 4.2.2. Effect of number of holes in the perforated plate on riser gas holdup in the ALC-P

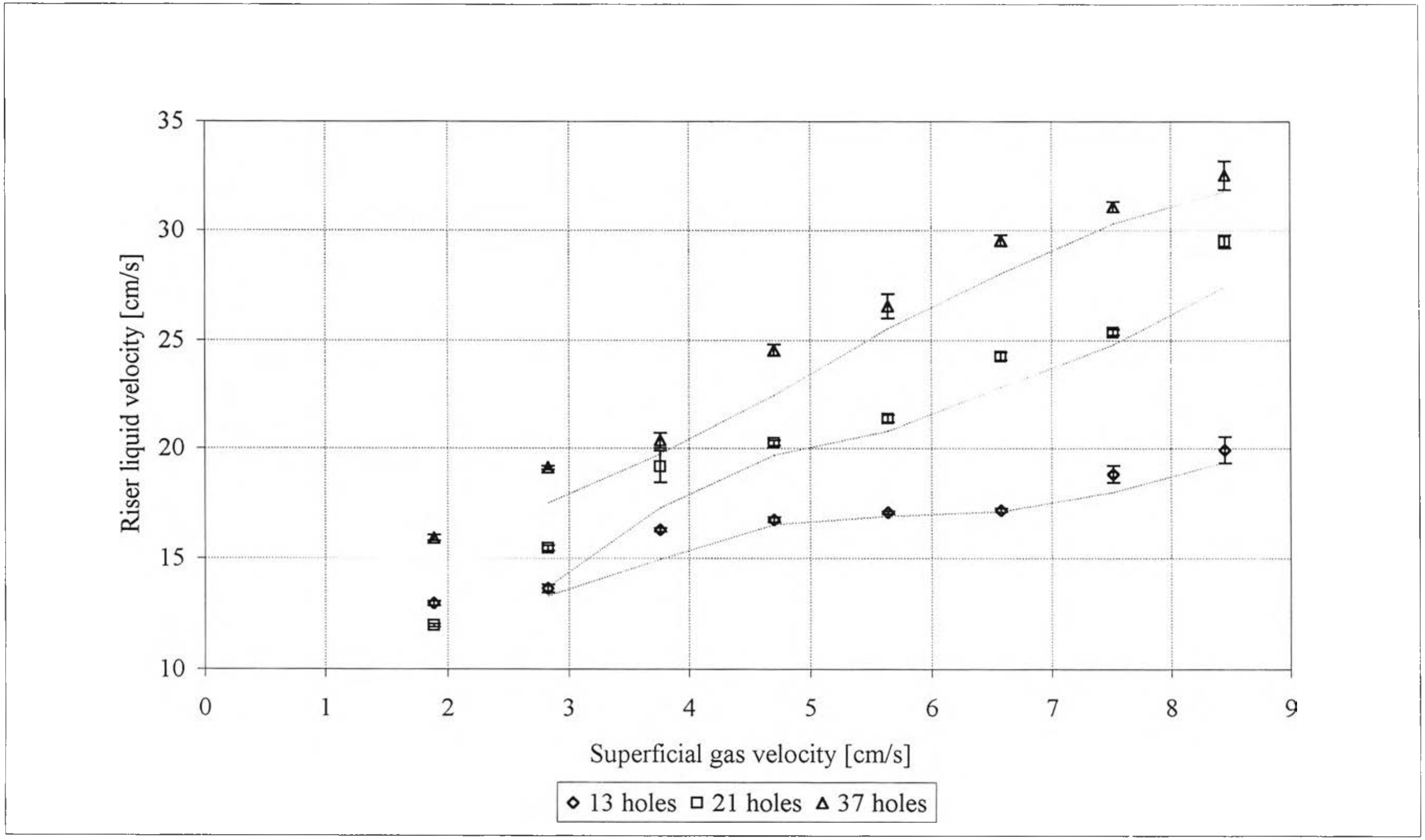

Figure 4.2.3. Effect of number of holes in the perforated plate on riser liquid velocity in the ALC-P

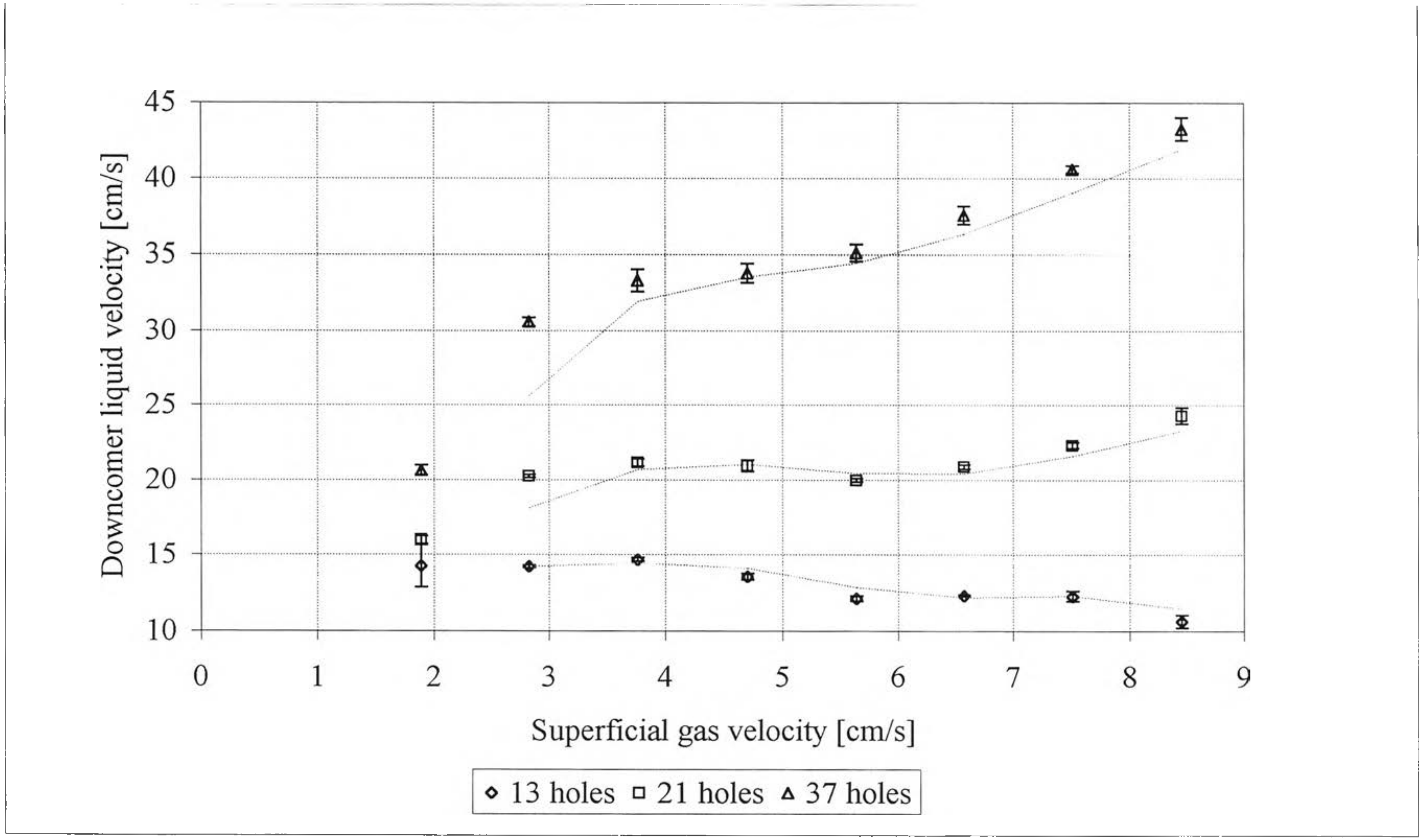

Figure 4.2.4. Effect of number of holes in the perforated plate on downcomer liquid velocity in the ALC-P

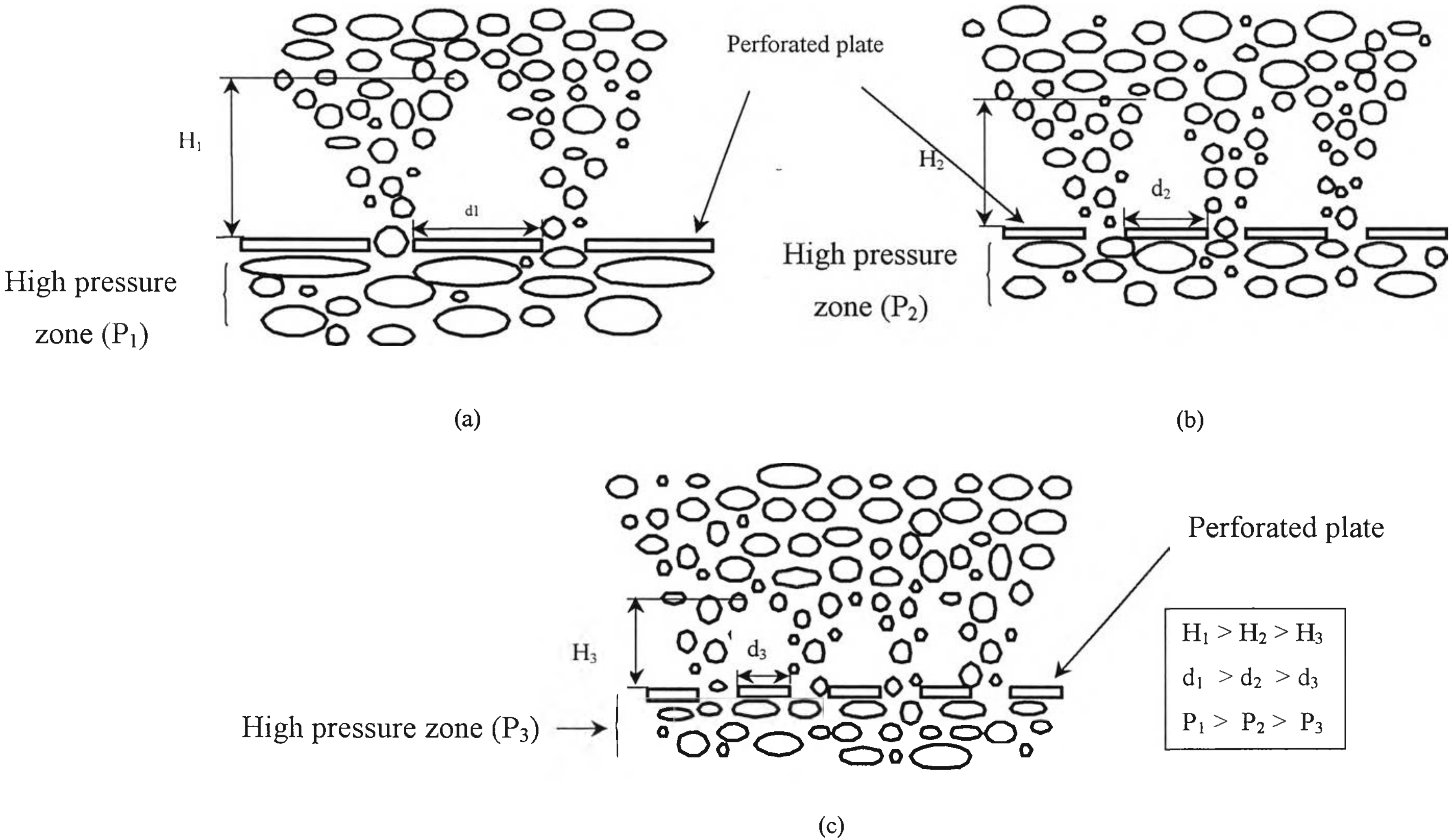

Figure 4.2.5. Effect of number of holes in the perforated plate for the gas bubbles formation in the ALC-P

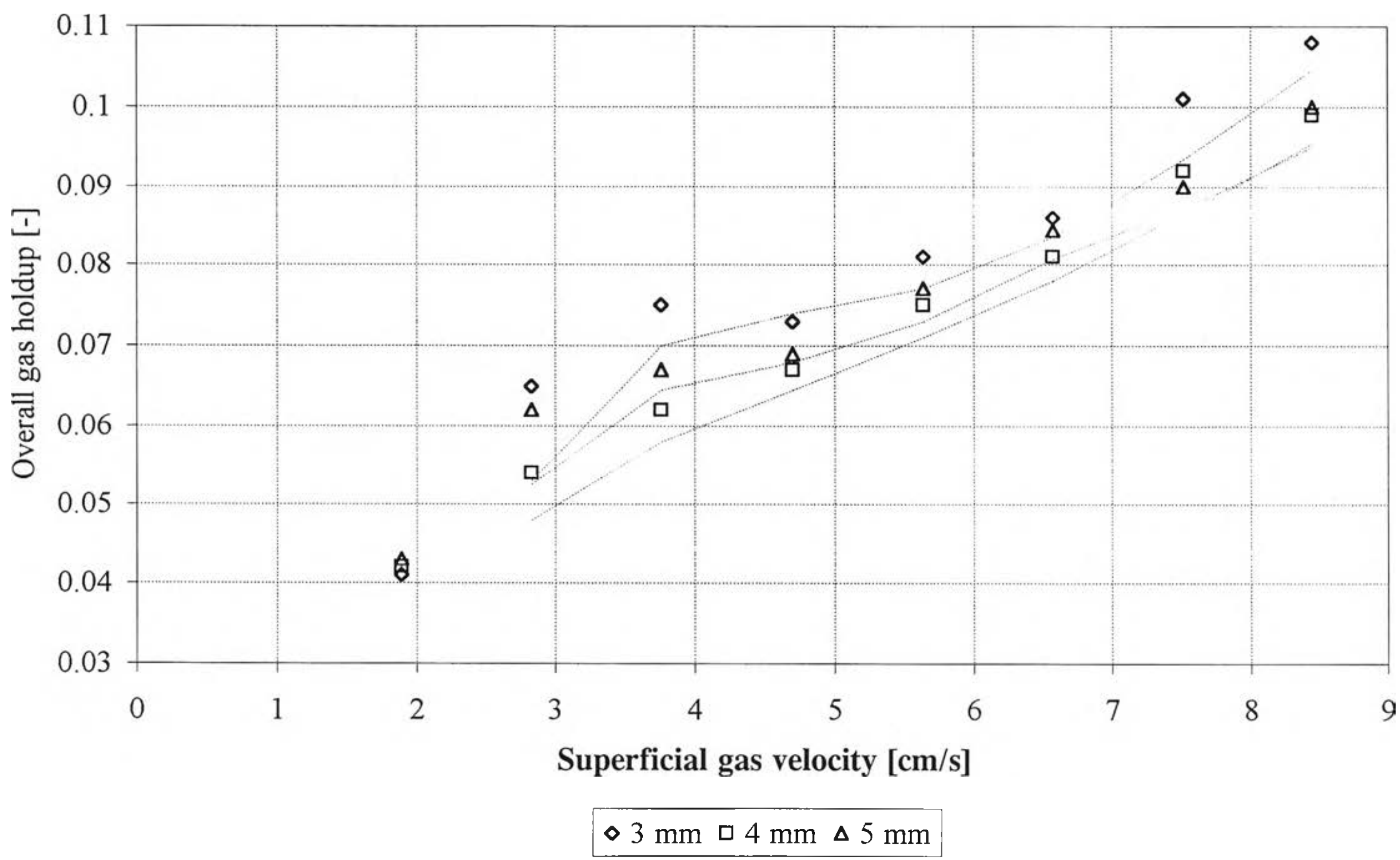

Figure 4.3.1. Effect of hole diameter on overall gas holdup in the ALC-P

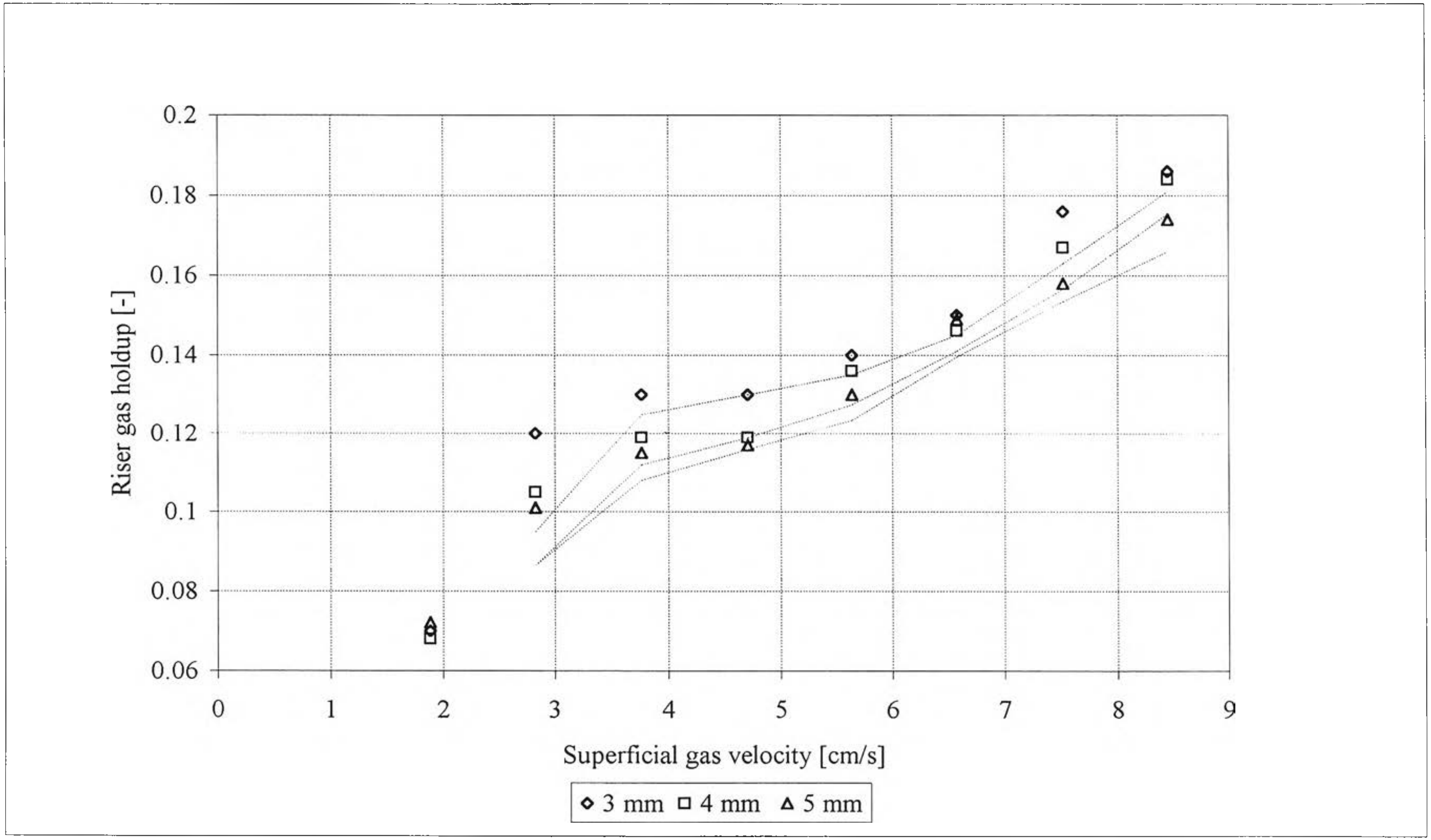

Figure 4.3.2. Effect of hole diameter on riser gas holdup in the ALC-P

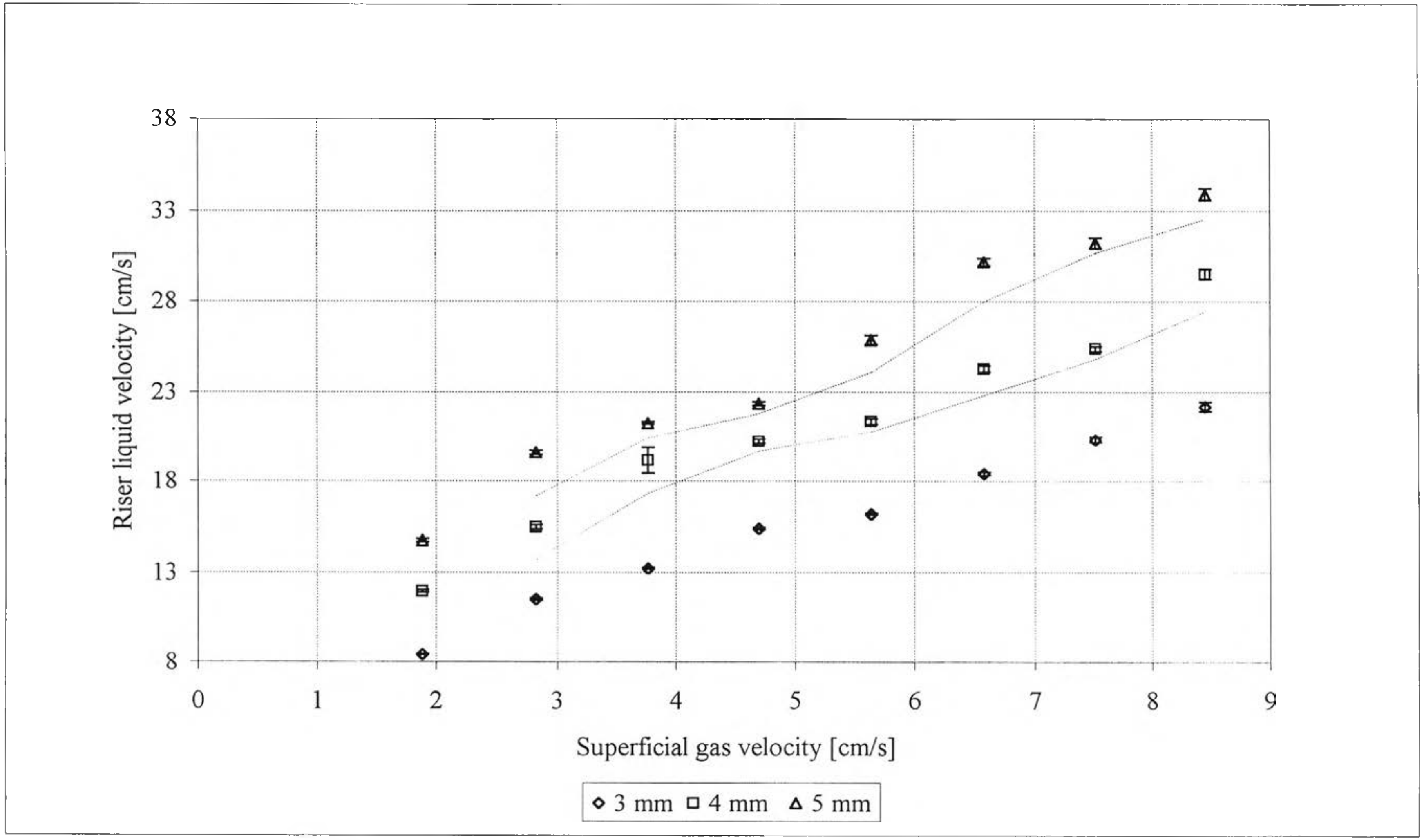

Figure 4.3.3. Effect of hole diameter on riser liquid velocity in the ALC-P

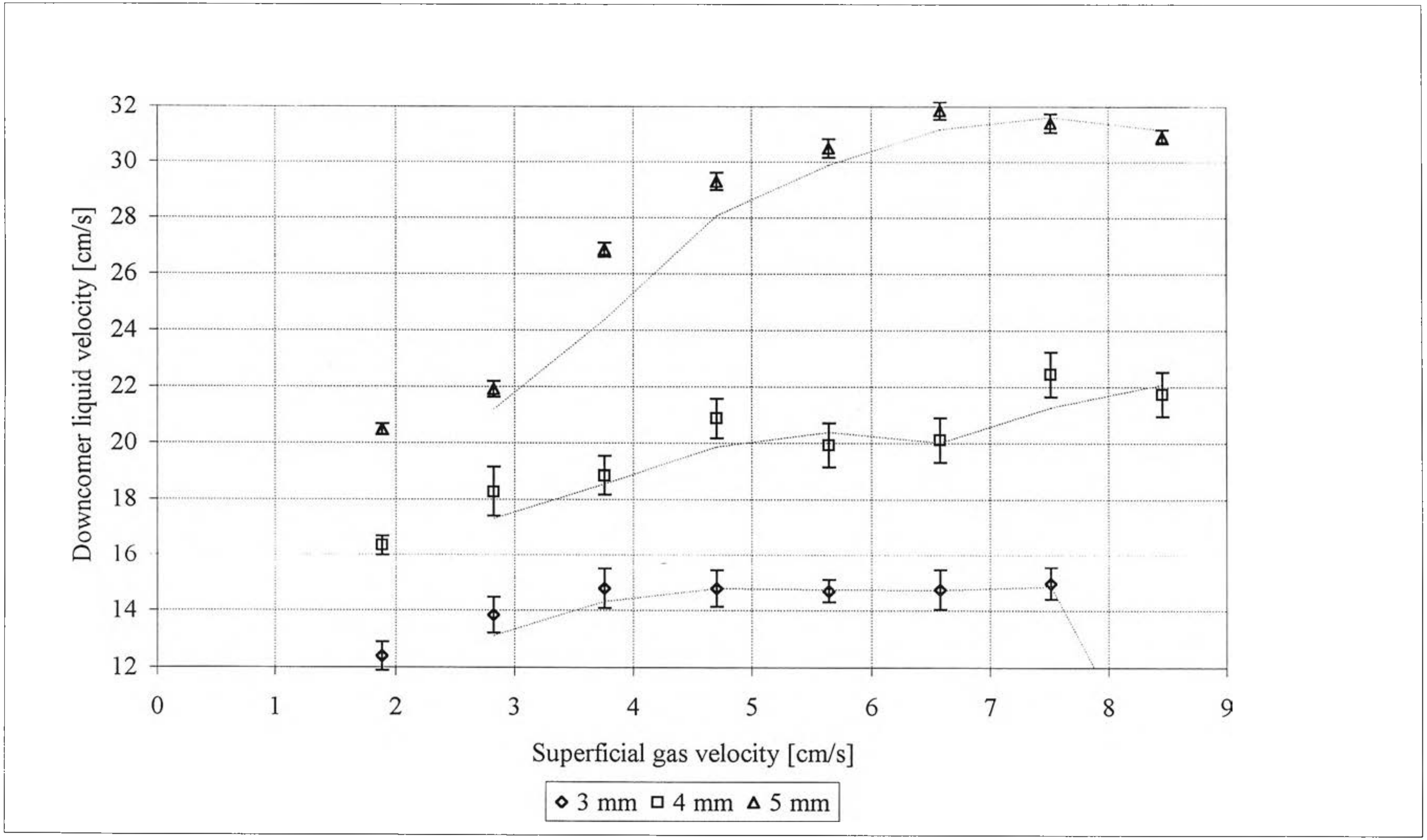

Figure 4.3.4. Effect of hole diameter on downcomer liquid velocity in the ALC-P

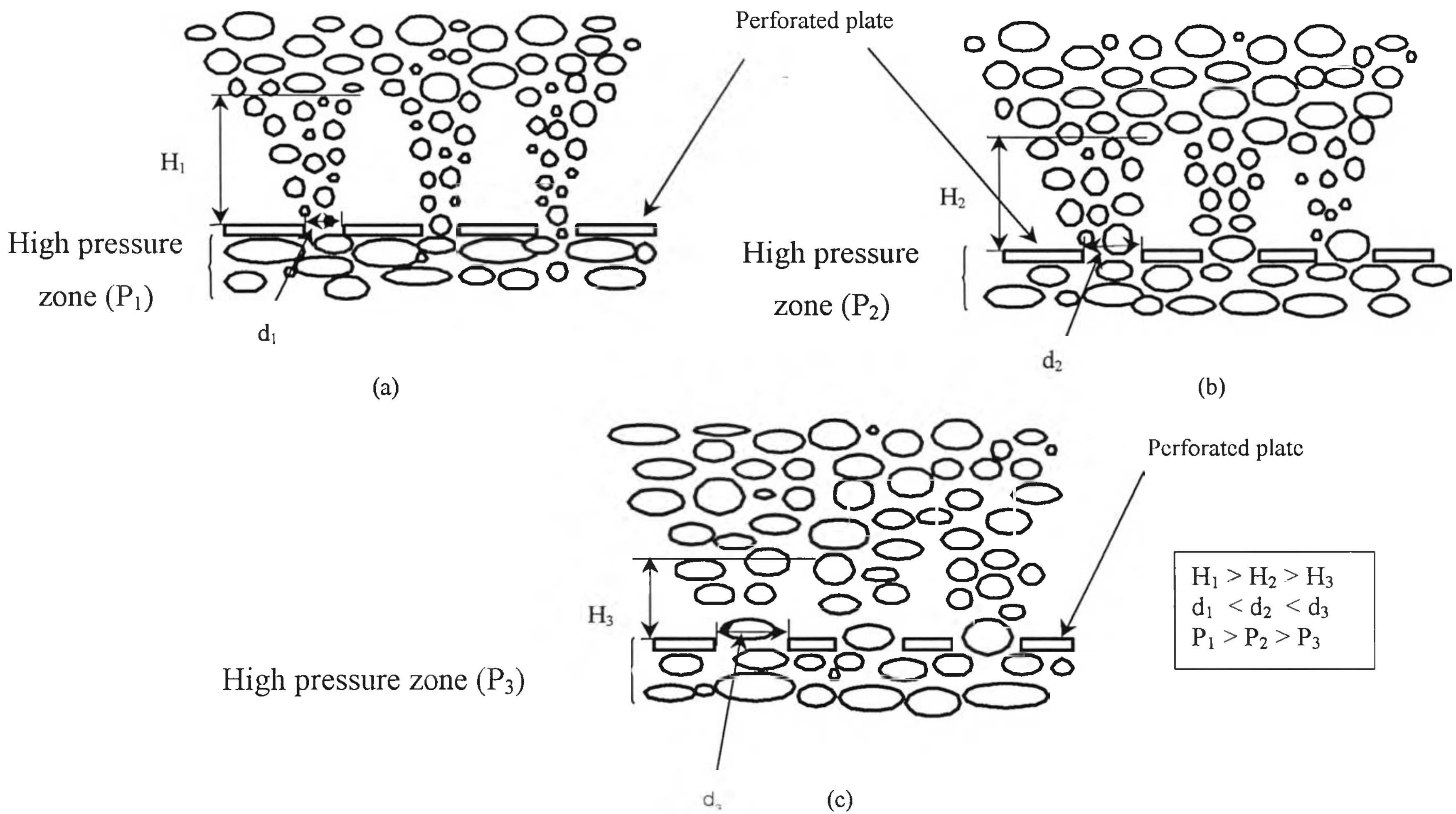

Figure 4.3.5. Effect of holes diameter on the perforated plate for gas bubbles formation in the ALC-P

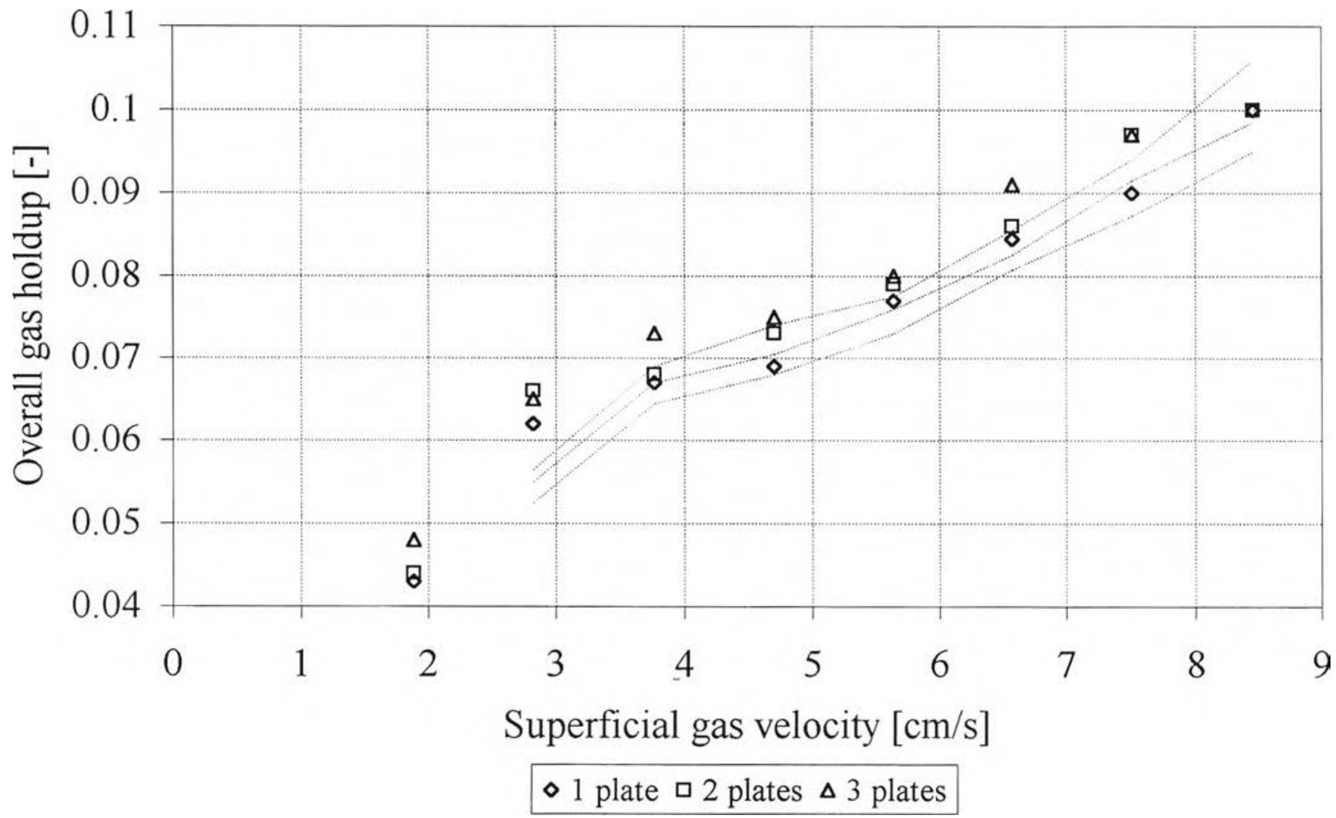

Figure 4.4.1. Effect of number of perforated plates on overall gas holdup in the ALC-P

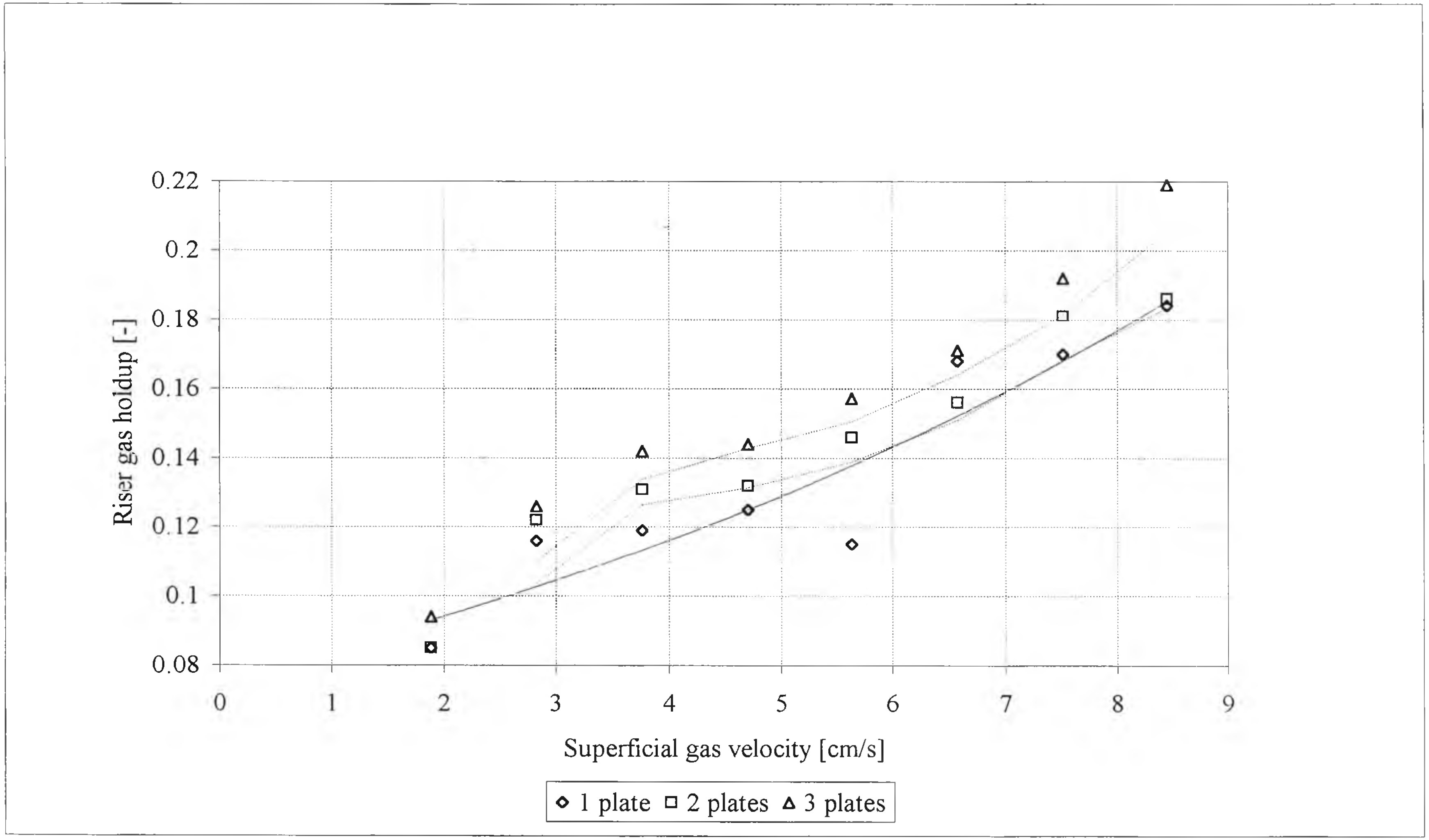

Figure 4.4.2. Effect of number of perforated plates on riser gas holdup in the ALC-P

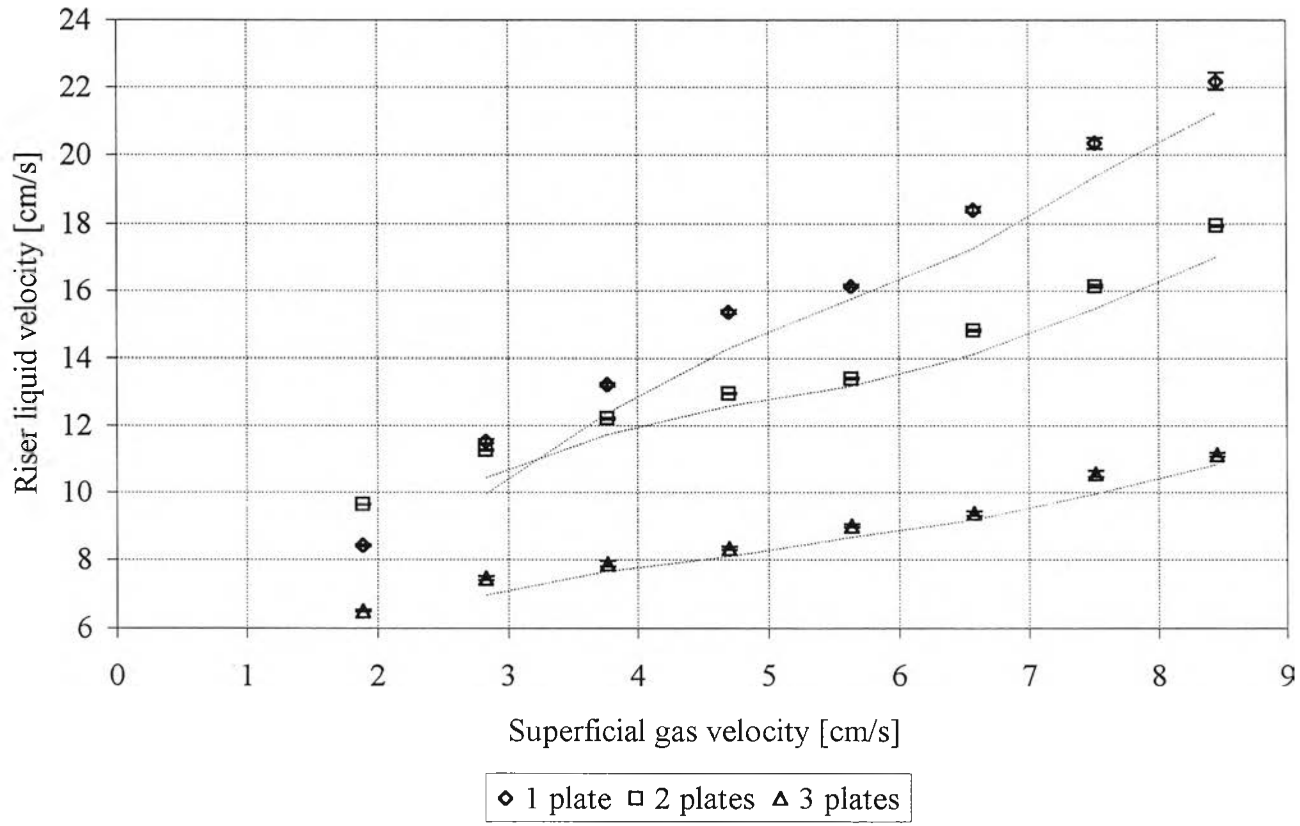

Figure 4.4.3. Effect of number of perforated plates on riser liquid velocity in the ALC-P

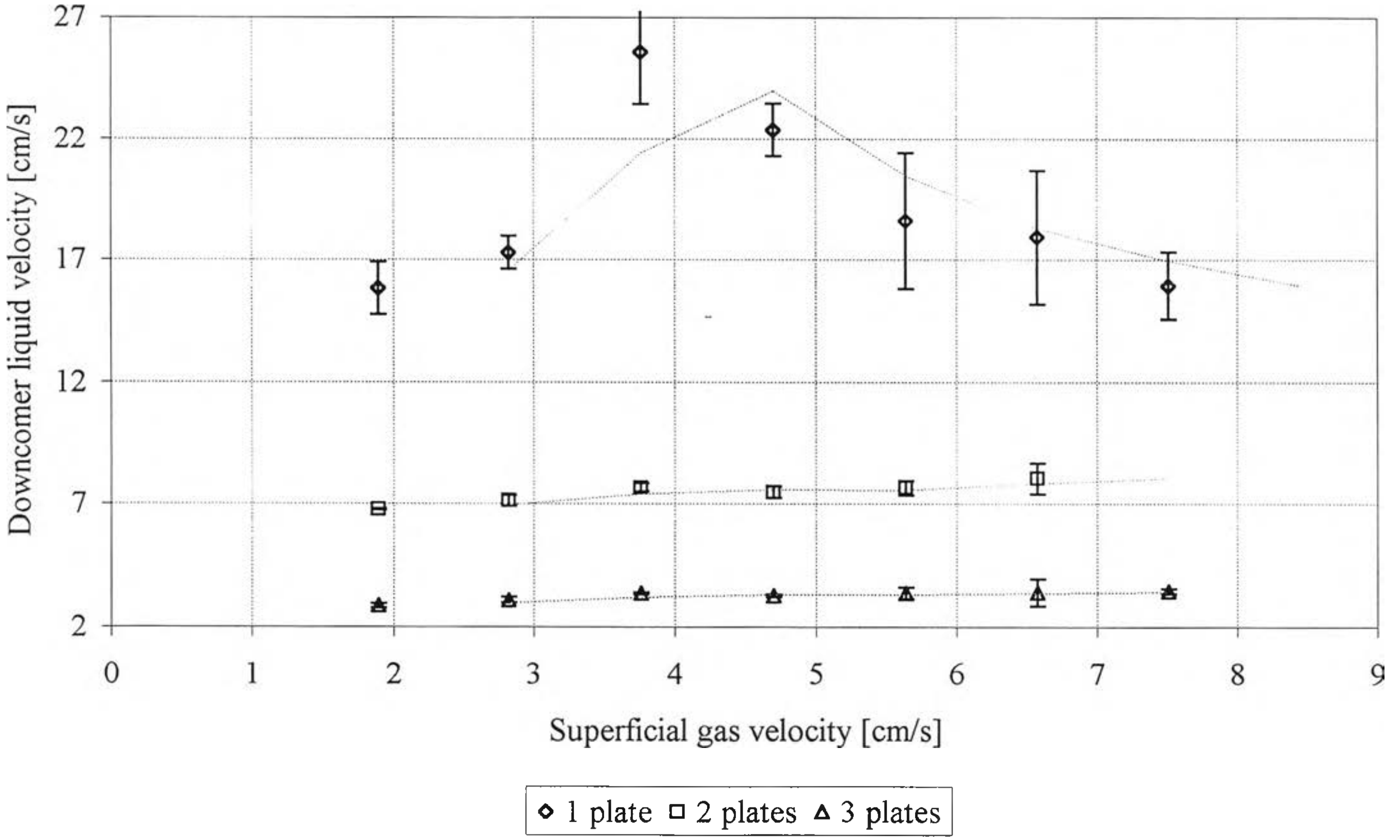

Figure 4.4.4. Effect of number of perforated plates on downcomer liquid velocity in the ALC-P

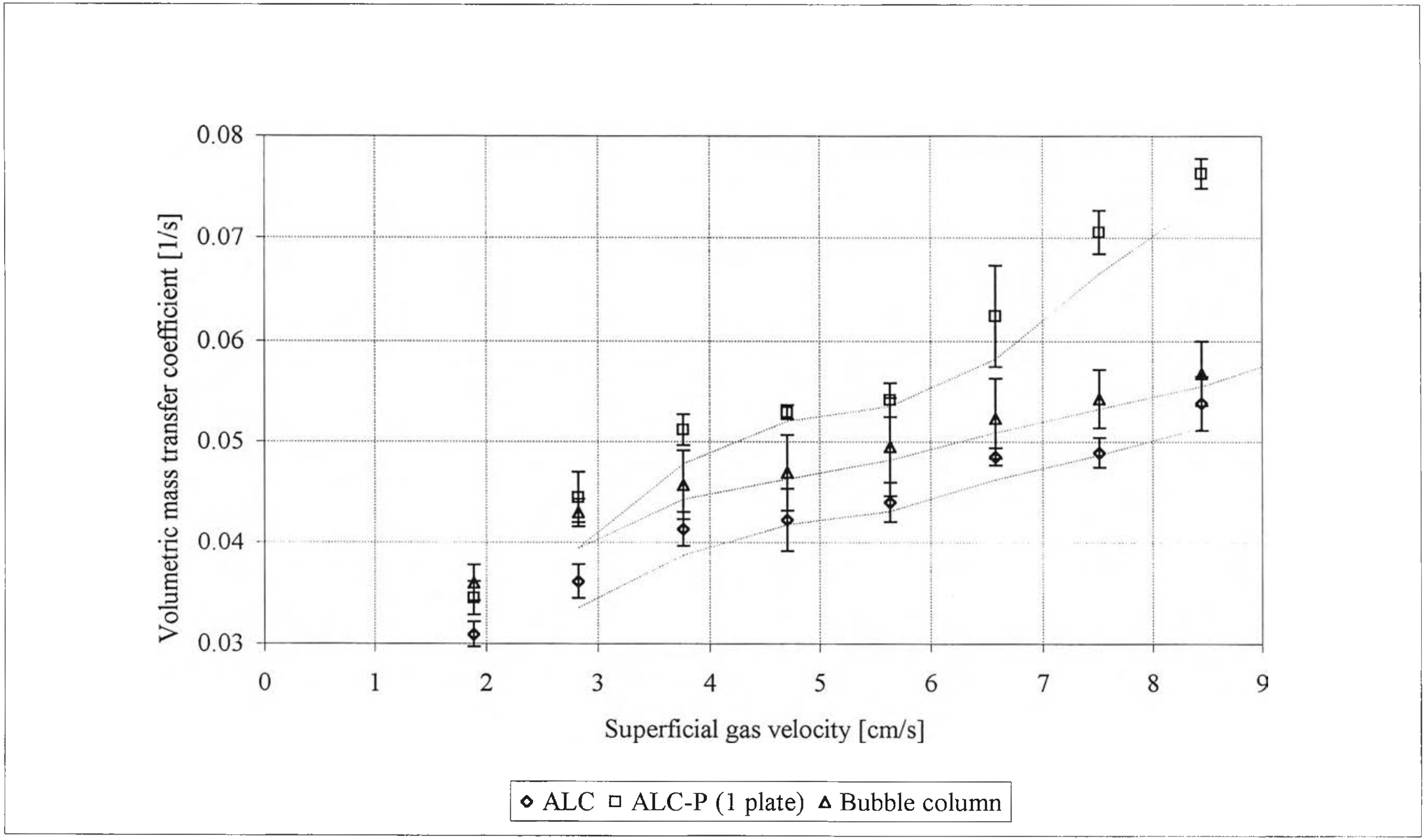

Figure 4.5.1. The comparison between mass transfer coefficient in conventional ALC, ALC-P and bubble column

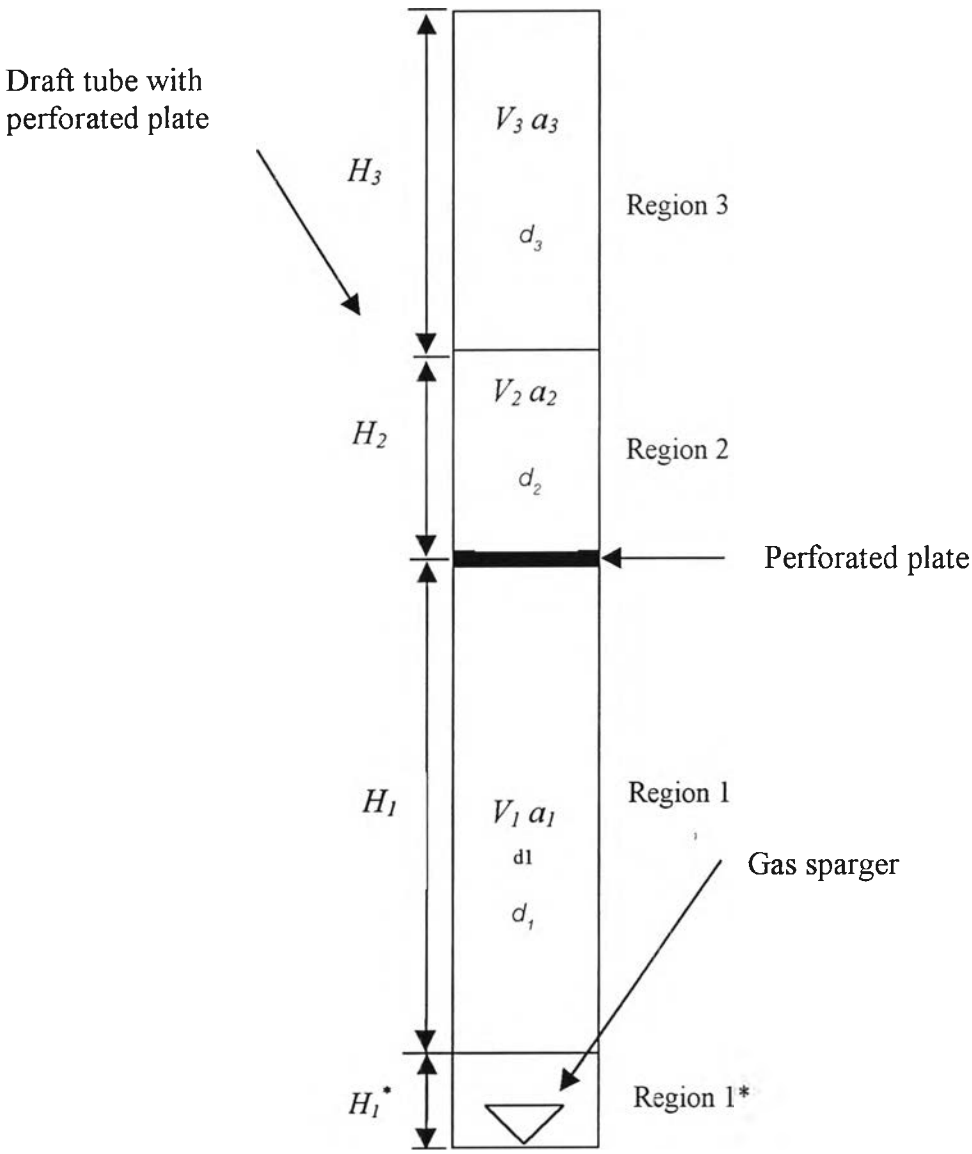

Figure 4.5.2. Bubbles flow phenomenon in riser of ALC-P

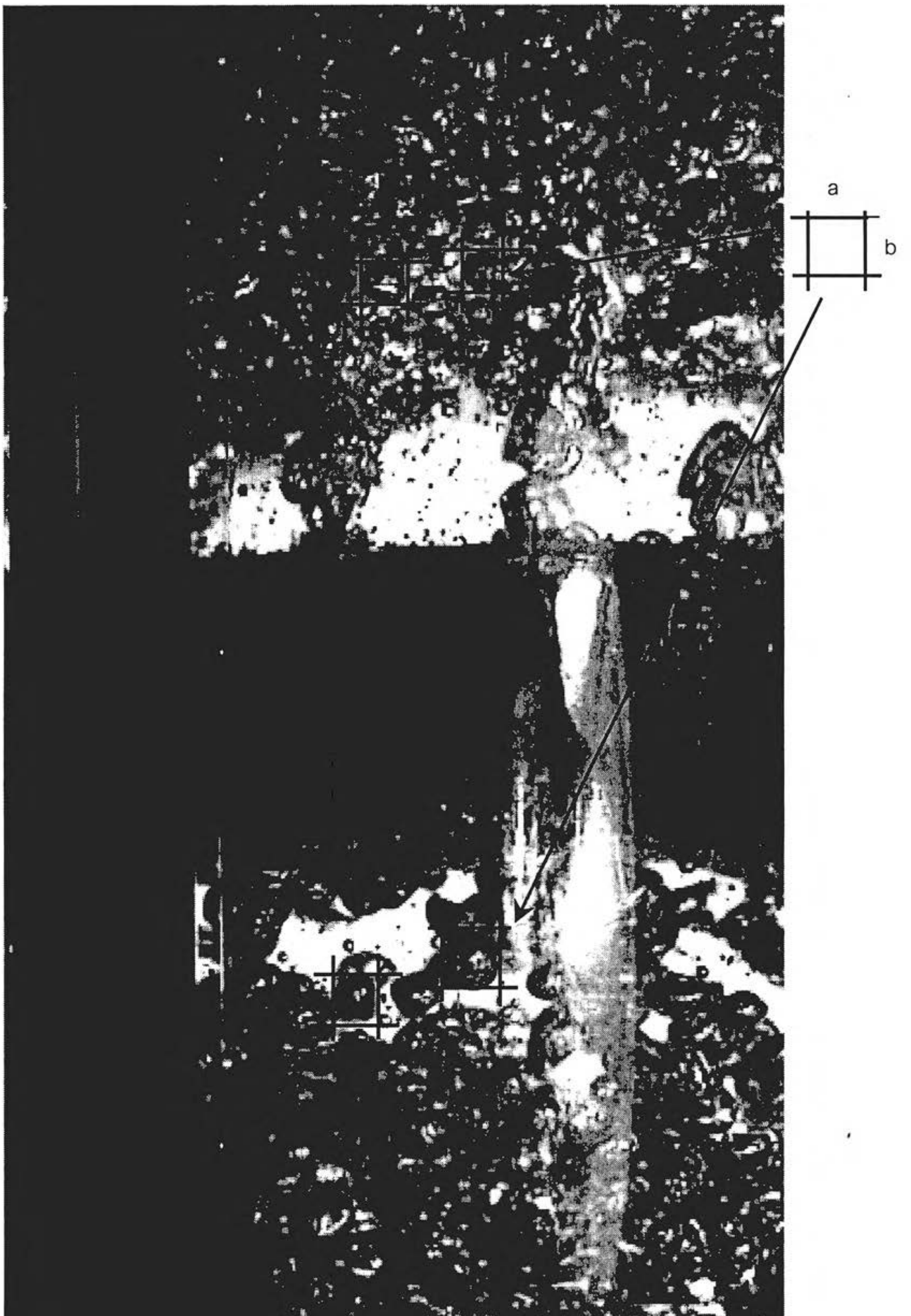

Figure 4.5.3 Bubbles formation in the ALC-P

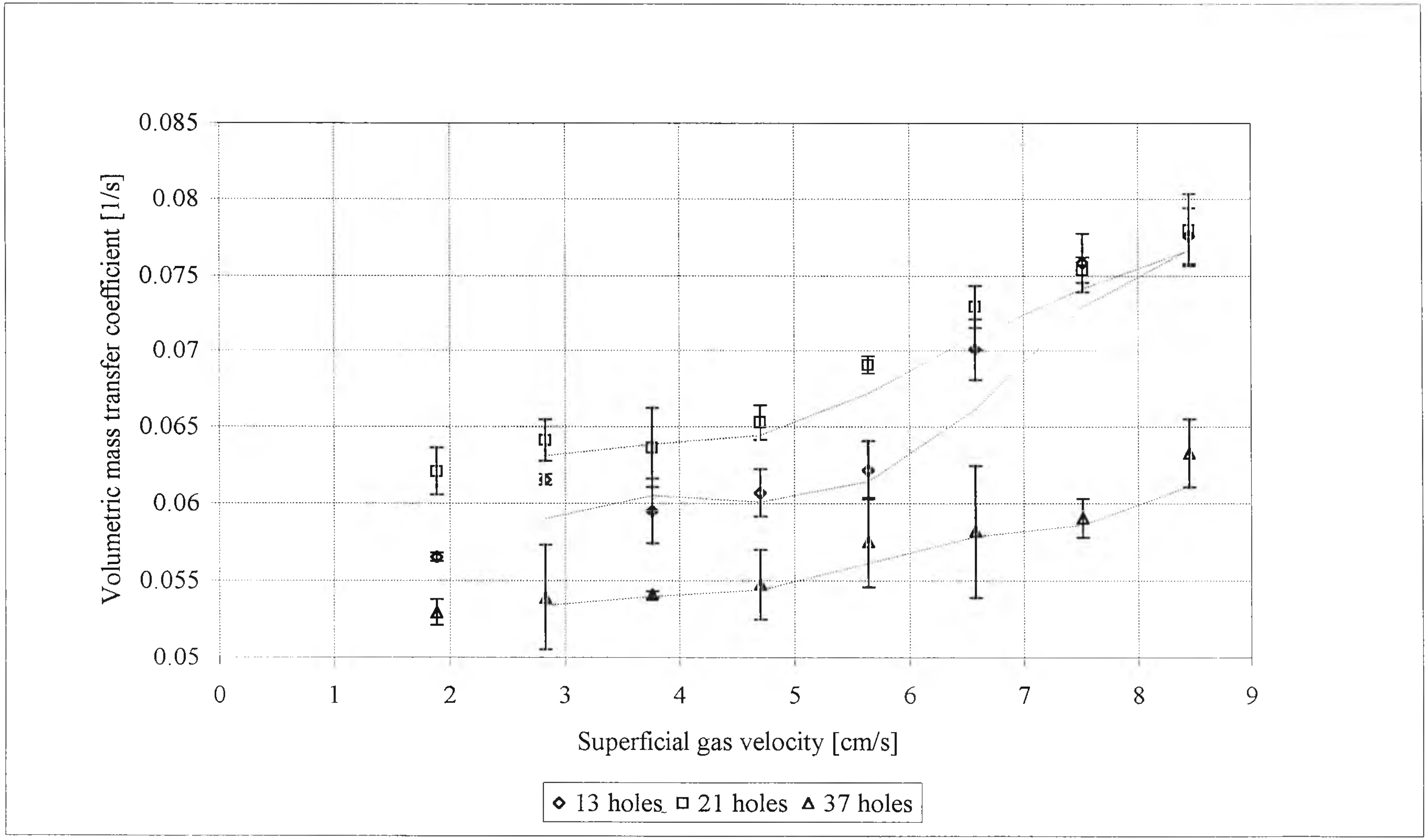

Figure 4.5.4. Effect of number of holes (4 mm. in hole diameter) in the perforated plate on mass transfer coefficient in the ALC-P (1 perforated plate)

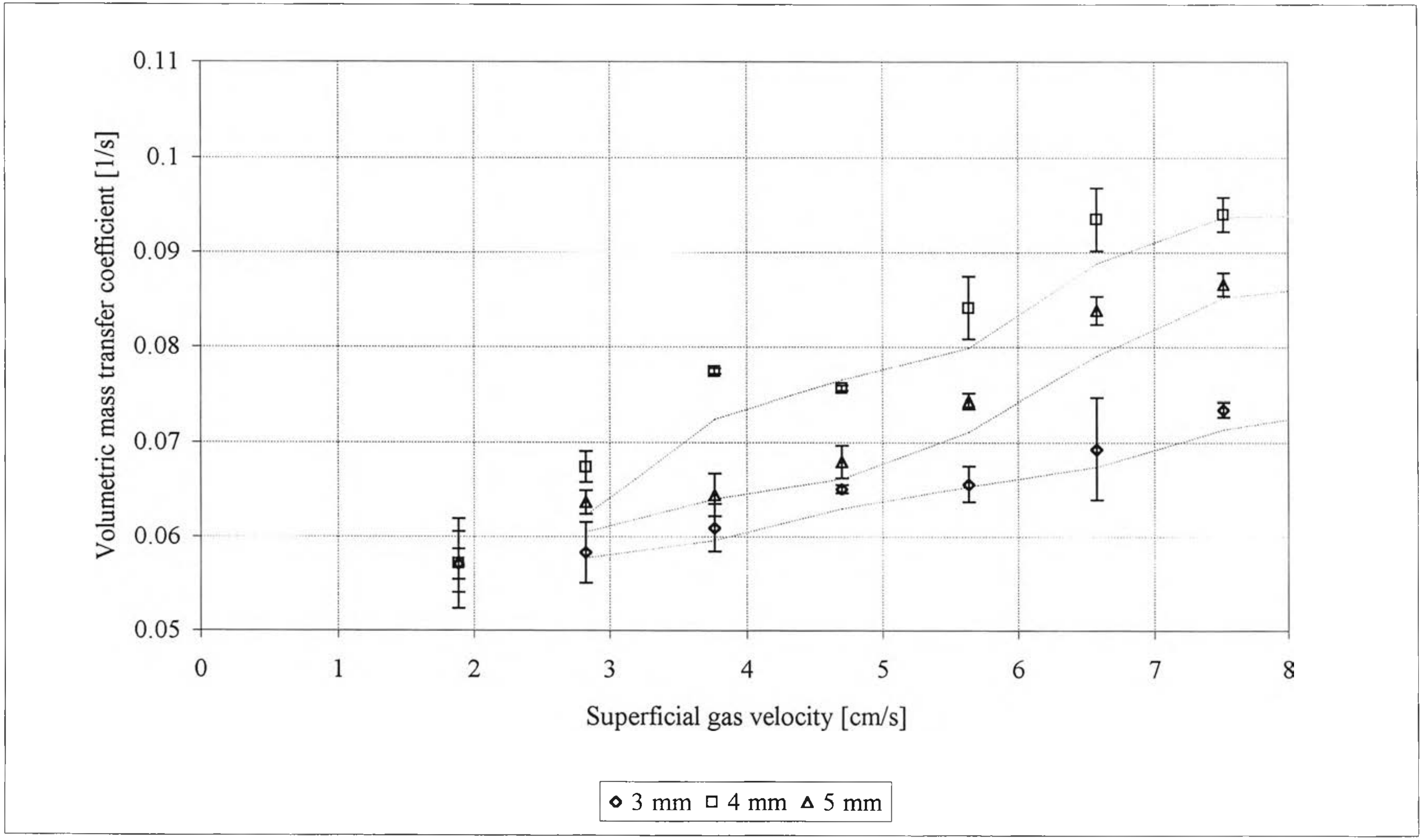

Figure 4.5.5. Effect of holes diameter on mass transfer coefficient in the ALC-P with two-13-hole perforated plate

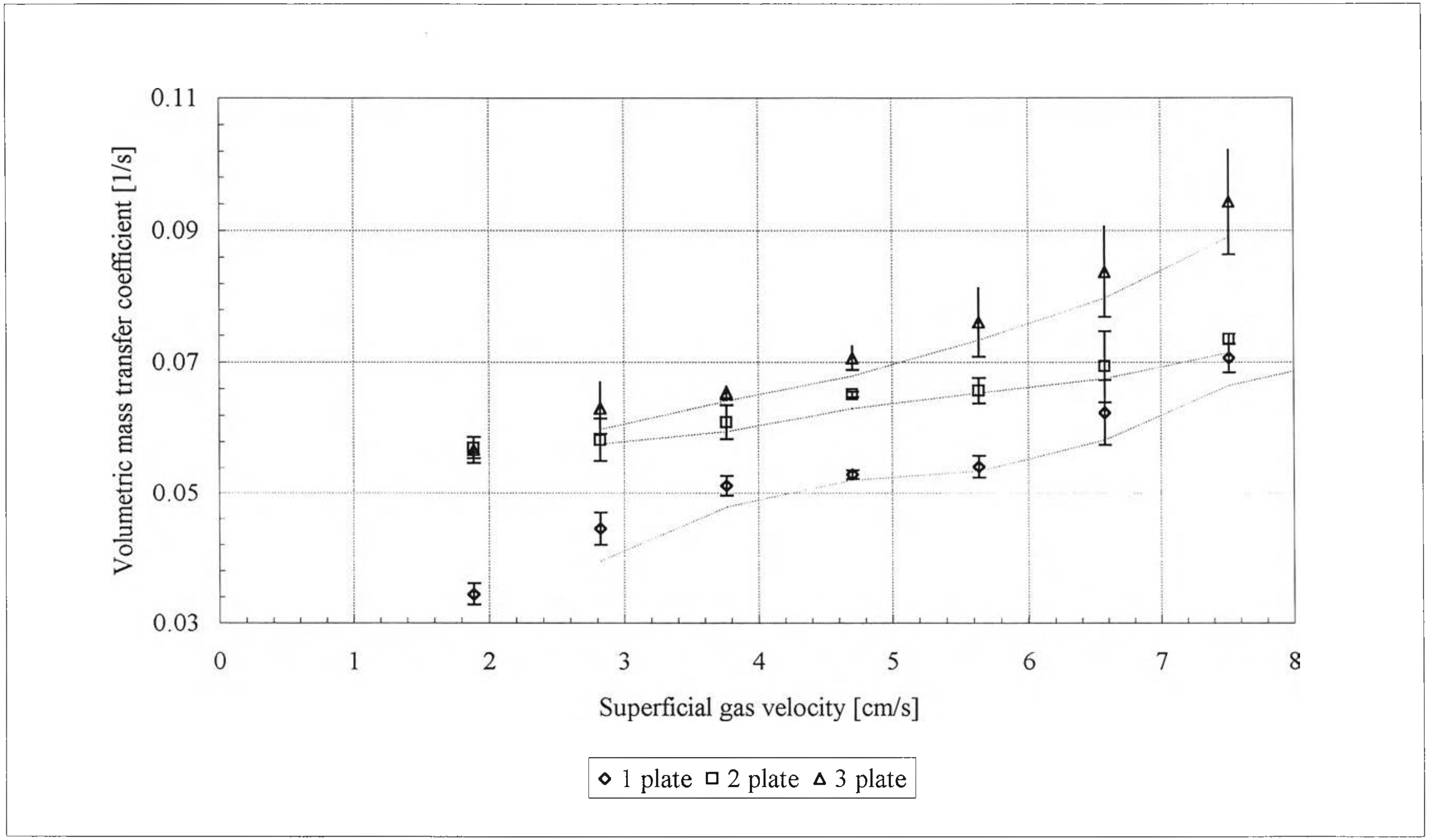

Figure 4.5.6. Effect of number of perforated plates on mass transfer coefficient in the ALC-P (13 holes with 3 mm holes diameter)

Table 4.1 The comparison of mass transfer coefficient between the ALC and ALC-P.

Comparison between mass transfer parameters from conventional ALC and ALC-P with 13-hole perforated plate(s) ALC-P (hole diameter 3 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.034	11.392	74.746	-36.255	0.057	84.628	107.625	-11.077	0.057	83.495	89.575	-3.207
2.826	0.036	0.045	23.269	70.631	-27.757	0.058	61.404	89.312	-14.742	0.063	74.654	62.266	7.634
3.764	0.041	0.051	23.851	78.359	-30.561	0.061	47.396	82.843	-19.387	0.065	57.958	79.946	-12.219
4.702	0.042	0.053	25.296	72.064	-27.181	0.065	54.046	67.924	-8.264	0.071	66.943	69.389	-1.444
5.640	0.044	0.054	23.069	70.057	-27.631	0.066	49.099	73.475	-14.052	0.076	72.725	82.863	-5.544
6.577	0.049	0.062	28.607	75.413	-26.684	0.069	42.828	81.832	-21.451	0.084	72.575	94.713	-11.369
7.515	0.049	0.071	44.207	110.478	-31.486	0.073	50.082	108.315	-27.954	0.094	92.685	123.827	-13.913

Comparison between mass transfer parameters from conventional ALC and ALC-P with 13-hole perforated plate(s) ALC-P (hole diameter 4 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.057	82.848	72.583	5.948	0.057	84.898	132.695	-20.541	0.059	92.233	103.624	-5.594
2.826	0.036	0.062	70.499	46.889	16.073	0.067	86.842	95.155	-4.260	0.068	89.104	83.386	3.118
3.764	0.041	0.060	43.928	52.532	-5.640	0.077	87.308	91.437	-2.156	0.075	81.362	87.389	-3.217
4.702	0.042	0.061	43.635	45.613	-1.359	0.076	78.971	76.796	1.230	0.084	97.823	70.748	15.857
5.640	0.044	0.062	41.224	59.376	-11.390	0.084	91.125	87.268	2.060	0.089	102.578	87.989	7.761
6.577	0.049	0.070	44.477	67.562	-13.777	0.094	92.704	93.599	-0.462	0.095	95.280	100.753	-2.726
7.515	0.049	0.076	54.986	102.004	-23.276	0.094	92.072	132.558	-17.409	0.102	107.874	139.521	-13.213
8.453	0.054	0.078	44.077	109.059	-31.083	0.109	101.820	134.668	-13.998	0.105	95.414	146.257	-20.646

Comparison between mass transfer parameters from conventional ALC and ALC-P with 13-hole perforated plate(s) ALC-P (hole diameter 5 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.055	77.265	83.370	-3.329	0.057	85.356	94.059	-4.485	0.063	104.693	119.932	-6.929
2.826	0.036	0.058	59.488	62.251	-1.703	0.064	76.362	80.430	-2.254	0.075	108.310	90.958	9.087
3.764	0.041	0.059	42.114	62.049	-12.302	0.064	55.902	88.611	-17.342	0.077	85.131	109.398	-11.589
4.702	0.042	0.061	43.457	50.538	-4.704	0.068	60.850	67.912	-4.206	0.081	92.381	87.631	2.531
5.640	0.044	0.065	46.751	59.366	-7.916	0.074	68.730	83.523	-8.060	0.093	112.328	102.127	5.047
6.577	0.049	0.069	42.003	88.915	-24.832	0.084	72.815	85.360	-6.767	0.095	96.362	107.987	-5.589
7.515	0.049	0.080	64.385	106.878	-20.540	0.087	77.002	132.625	-23.911	0.106	116.728	152.634	-14.213
8.453	0.054	0.086	59.580	104.604	-22.005	0.089	64.501	118.439	-24.693	0.112	107.947	162.995	-20.931

% kLa difference = the percentage difference of kLa in the ALC-P with any number of plate(s) comparing to the kLa obtained from the conventional ALC.

% kL difference = the percent difference of kL in the ALC-P with any number of plate(s) comparing to the kL obtained from the conventional ALC.

% a difference = the percentage difference of interfacial area (a) in the ALC-P with any number of plate(s) comparing to the interfacial (a) area obtained from the conventional ALC.

Table 4.1 Continued

Comparison between mass transfer parameters from conventional ALC and ALC-P with 21-hole perforated plate(s) ALC-P (hole diameter 3 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.054	76.052	51.002	16.589	0.056	82.632	82.630	0.001	0.064	106.472	103.653	1.385
2.826	0.036	0.050	39.058	67.836	-17.147	0.059	63.435	83.401	-10.886	0.070	92.521	72.829	11.394
3.764	0.041	0.054	29.576	77.019	-26.801	0.067	61.345	97.249	-18.202	0.077	86.563	82.969	1.964
4.702	0.042	0.055	29.752	56.434	-17.056	0.077	81.732	76.796	2.792	0.079	86.110	70.759	8.990
5.640	0.044	0.058	31.607	66.511	-20.962	0.087	97.289	82.278	8.235	0.086	96.047	91.877	2.173
6.577	0.049	0.060	22.699	68.691	-27.264	0.095	96.551	103.137	-3.242	0.087	80.080	95.923	-8.086
7.515	0.049	0.071	45.552	114.157	-32.035	0.097	98.270	144.203	-18.809	0.103	110.564	144.816	-13.991
8.453	0.054	0.074	37.393	106.828	-33.571	0.108	101.216	135.973	-14.729	0.104	93.390	134.294	-17.458

Comparison between mass transfer parameters from conventional ALC and ALC-P with 21-hole perforated plate(s) ALC-P (hole diameter 4 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.062	100.906	46.706	36.945	0.058	86.812	66.687	12.074	0.054	74.563	101.291	-13.278
2.826	0.036	0.064	77.562	46.879	20.890	0.064	77.285	64.181	7.982	0.057	57.687	74.369	-9.567
3.764	0.041	0.064	53.907	62.055	-5.028	0.066	60.256	88.571	-15.015	0.076	84.486	88.878	-2.325
4.702	0.042	0.065	54.401	43.211	7.814	0.067	59.548	69.173	-5.689	0.078	84.256	73.355	6.288
5.640	0.044	0.069	56.823	61.760	-3.053	0.075	69.809	75.961	-3.496	0.086	95.650	95.671	-0.011
6.577	0.049	0.073	50.350	64.186	-8.427	0.074	51.948	90.078	-20.060	0.103	112.541	97.128	7.819
7.515	0.049	0.075	54.015	103.229	-24.216	0.083	70.515	106.907	-17.588	0.111	126.536	146.055	-7.933
8.453	0.054	0.078	44.820	104.604	-29.220	0.088	64.036	71.429	-4.313	0.127	135.611	133.128	1.065

Comparison between mass transfer parameters from conventional ALC and ALC-P with 21-hole perforated plate(s) ALC-P (hole diameter 5 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.054	75.000	55.324	12.668	0.059	90.615	96.313	-2.903	0.060	94.175	80.295	7.698
2.826	0.036	0.061	68.075	41.290	18.957	0.066	83.380	55.369	18.028	0.064	76.039	75.838	0.114
3.764	0.041	0.063	53.362	56.615	-2.077	0.067	62.494	59.891	1.628	0.066	58.986	87.346	-15.138
4.702	0.042	0.063	50.181	40.808	6.657	0.066	55.387	47.646	5.243	0.073	73.687	69.422	2.517
5.640	0.044	0.066	50.310	54.619	-2.786	0.068	54.362	63.498	-5.588	0.086	95.593	80.264	8.504
6.577	0.049	0.070	44.064	67.532	-14.008	0.073	50.660	72.360	-12.590	0.091	86.727	89.839	-1.639
7.515	0.049	0.076	55.156	92.267	-19.302	0.082	67.075	112.170	-21.254	0.093	89.926	135.617	-19.392
8.453	0.054	0.085	58.234	93.505	-18.227	0.087	61.777	99.662	-18.974	0.092	71.494	124.785	-23.708

% kLa difference = the percentage difference of kLa in the ALC-P with any number of plate(s) comparing to the kLa obtained from the conventional ALC.
% kL difference = the percent difference of kL in the ALC-P with any number of plate(s) comparing to the kL obtained from the conventional ALC.
% a difference = the percentage difference of interfacial area (a) in the ALC-P with any number of plate(s) comparing to the interfacial (a) area obtained from the conventional ALC.

Table 4.1 Continued

Comparison between mass transfer parameters from conventional ALC and ALC-P with 37-hole perforated plate(s) ALC-P (hole diameter 3 mm.)														
		1 plate				2 plates				3 plates				
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.035	13.657	57.497	-27.836	0.040	29.126	50.771	-14.356	0.037	20.442	110.479	-42.777
2.826	0.036	0.040	10.360	66.451	-33.698	0.042	17.636	18.483	-0.715	0.046	26.537	77.312	-28.636
3.764	0.041	0.040	-2.177	59.338	-38.607	0.045	7.966	29.722	-16.771	0.047	14.457	94.632	-41.193
4.702	0.042	0.041	-2.130	42.008	-31.081	0.048	13.642	33.693	-14.998	0.049	15.570	77.149	-34.761
5.640	0.044	0.044	1.045	58.194	-36.126	0.054	22.974	45.935	-15.733	0.053	21.195	92.991	-37.202
6.577	0.049	0.046	-5.565	60.812	-41.276	0.056	14.489	59.355	-28.155	0.054	11.861	95.756	-42.857
7.515	0.049	0.048	-1.962	86.198	-47.347	0.061	23.825	91.657	-35.392	0.056	15.243	132.683	-50.472
8.453	0.054	0.050	-6.907	89.057	-50.759	0.061	13.009	90.393	-40.644	0.059	10.100	129.384	-52.002

Comparison between mass transfer parameters from conventional ALC and ALC-P with 37-hole perforated plate(s) ALC-P (hole diameter 4 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.053	71.305	16.516	47.023	0.062	100.647	30.208	54.097	0.052	67.098	84.894	-9.625
2.826	0.036	0.054	49.307	-11.882	69.440	0.072	98.338	56.834	26.464	0.063	73.269	62.195	6.827
3.764	0.041	0.054	30.866	-7.395	41.316	0.068	63.845	69.921	-3.576	0.070	70.416	75.510	-2.902
4.702	0.042	0.055	29.516	-8.538	41.606	0.071	67.475	60.348	4.445	0.071	67.830	70.692	-1.677
5.640	0.044	0.058	30.622	17.741	10.941	0.072	64.414	68.446	-2.394	0.071	61.427	81.545	-11.082
6.577	0.049	0.058	19.882	22.569	-2.192	0.077	58.217	75.854	-10.030	0.076	57.007	95.861	-19.837
7.515	0.049	0.059	20.624	44.823	-16.710	0.084	71.843	123.678	-23.174	0.078	60.033	130.258	-30.499
8.453	0.054	0.063	17.465	40.128	-16.173	0.085	58.698	114.869	-26.142	0.085	58.234	131.884	-31.761

Comparison between mass transfer parameters from conventional ALC and ALC-P with 37-hole perforated plate(s) ALC-P (hole diameter 5 mm.)													
		1 plate				2 plates				3 plates			
Usg[cm/s]	kLc	kLa1	%kLa difference	%a difference	% kL difference	kLa2	%kLa difference	%a difference	% kL difference	kLa3	%kLa difference	%a difference	% kL difference
1.889	0.031	0.048	54.693	-18.011	88.676	0.056	79.935	30.166	38.235	0.044	42.638	56.858	-9.066
2.826	0.036	0.051	40.720	-16.083	67.689	0.058	60.803	49.443	7.602	0.058	59.903	27.447	25.466
3.764	0.041	0.055	32.317	14.360	15.703	0.064	53.604	26.644	21.288	0.065	57.172	31.251	19.750
4.702	0.042	0.056	32.395	2.263	29.464	0.065	53.159	10.646	38.422	0.065	54.815	34.156	15.400
5.640	0.044	0.065	47.206	-10.812	65.052	0.071	60.609	39.464	15.161	0.069	57.504	40.258	12.296
6.577	0.049	0.065	34.378	3.445	29.902	0.076	56.018	36.609	14.208	0.073	49.835	37.394	9.055
7.515	0.049	0.071	44.360	47.213	-1.938	0.080	63.568	90.217	-14.010	0.076	55.241	89.429	-18.048
8.453	0.054	0.075	38.322	25.628	10.104	0.092	70.674	103.075	-15.955	0.078	44.356	91.977	-24.806

% kLa difference = the percentage difference of kLa in the ALC-P with any number of plate(s) comparing to the kLa obtained from the conventional ALC.
% kL difference = the percent difference of kL in the ALC-P with any number of plate(s) comparing to the kL obtained from the conventional ALC.
% a difference = the percentage difference of interfacial area (a) in the ALC-P with any number of plate(s) comparing to the interfacial (a) area obtained from the conventional ALC.