พฤติกรรมทางด้านอุทกพลศาสตร์และการถ่ายเทมวลสารภายในถังสัมผัสแบบอากาศยกขนาดใหญ่ที่มีท่อภายในหลายท่อ

นางสาวลินี ตัณฑิกุล

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HYDRODYNAMICS AND MASS TRANSFER BEHAVIOR IN LARGE SCALE MULTIPLE DRAFT TUBE AIRLIFT CONTACTORS

Miss Nalinee Tanthikul

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By	Miss Nalinee Tanthikul
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Thesis Advisor	Associate Professor Prasert Pavasant, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

……………………………………Dean of the Faculty of Engineering
(Professor Direk Lavansiri, Ph.D.)

THESIS COMMITTEE

……………………………………….. Chairman
(Assistant Professor Seeroong Prichanont, Ph.D.)

……………………………….……. Thesis Advisor
(Associate Professor Prasert Pavasant, Ph.D.)

……………………………………….. Member
(Associate Professor Chirakarn Muangnapoh, Dr.Ing.)

……………………………………….. Member
(Joongjai Panpranot, Ph.D.)

นลินี ตัณฑิกุล : พฤติกรรมทางด้านอุทกพลศาสตร์และการถ่ายเทมวลสารภายในถังสัมผัสแบบอากาศยกขนาดใหญ่ที่มีท่อภายในหลายท่อ. (HYDRODYNAMICS AND MASS TRANSFER BEHAVIOR IN LARGE SCALE MULTIPLE DRAFT TUBE AIRLIFT CONTACTORS) อ. ที่ปรึกษา : รศ. ดร. ประเสริฐ ภวสันต์, 72 หน้า. ISBN 974-53-1113-8.

งานวิจัยนี้มีจุดมุ่งหมายเพื่อพัฒนาความรู้พื้นฐานเกี่ยวกับพฤติกรรมของถังสัมผัสอากาศยกขนาดใหญ่แบบที่มีท่อภายในหลายท่อโดยเฉพาะแบบที่มีพื้นที่หน้าตัดกว้างมากเพื่อเป็นประโยชน์ในการออกแบบใช้งานในระดับอุตสาหกรรมต่อไป โดยในการศึกษานี้แบ่งออกเป็น 3 ส่วนหลัก คือ (ก) การศึกษาถึงผลของจำนวนท่อภายในที่ใช้ในระบบถังสัมผัสฯ (ข) การศึกษาถึงอิทธิพลของค่าสัดส่วนระหว่างพื้นที่หน้าตัดของส่วนที่ไหลลงกับส่วนที่ไหลขึ้นภายในถังสัมผัสฯ แบบที่มีท่อภายในหลายท่อ และ (ค) ศึกษาถึงผลของความเค็มของของเหลวในระบบต่อพฤติกรรมพื้นฐานต่างๆในถังสัมผัสฯ แบบที่มีท่อภายในหลายท่อ

การศึกษาพบว่าจำนวนท่อภายในที่ใช้ในถังสัมผัสฯส่งผลสำคัญต่อประสิทธิภาพของระบบ การประยุกต์ใช้ท่อภายในหลายท่อในระบบถังสัมผัสฯที่มีพื้นที่หน้าตัดกว้างพบว่าทำให้การถ่ายเทมวลระหว่างก๊าซกับของเหลวมีค่าสูงขึ้นเมื่อเปรียบเทียบกับระบบที่ใช้ท่อภายในเพียงท่อเดียว ระบบถังสัมผัสฯที่มีจำนวนท่อมากกว่าจะส่งผลให้มีปริมาณฟองก๊าซถูกเหนี่ยวนำลงไปในส่วนที่ไหลลงมากขึ้นและทำให้มีค่าสัดส่วนของก๊าซในส่วนที่ไหลลงและปริมาณก๊าซรวมในระบบมากขึ้น นอกจากนี้ความเร็วของของเหลวในระบบที่มีท่อภายในหลายท่อยังมีค่าสูงกว่าระบบที่มีท่อภายในเพียงท่อเดียว ทั้งนี้เนื่องจากระบบที่มีท่อขนาดใหญ่เพียงท่อเดียวเกิดการไหลวนภายในเกิดขึ้น

ค่าสัดส่วนระหว่างพื้นที่หน้าตัดของส่วนที่ไหลลงกับส่วนที่ไหลขึ้นเป็นตัวแปรสำคัญที่ส่งผลต่อประสิทธิภาพของระบบถังสัมผัสฯเช่นกัน ค่าสัดส่วนดังกล่าวที่มากจะทำให้ระบบมีพื้นที่ของส่วนที่ไหลลงมากซึ่งทำให้ความเร็วของของเหลวในส่วนที่ไหลลงมีค่าต่ำ ส่งผลให้ก๊าซจำนวนมากลอยหลุดออกจากระบบขณะที่ก๊าซจำนวนน้อยถูกเหนี่ยวนำลงไปในส่วนที่ไหลลง ดังนั้นจากการทดลองจึงพบว่าสัดส่วนของก๊าซทั้งระบบ, สัดส่วนของก๊าซในส่วนที่ไหลขึ้น, และสัดส่วนของก๊าซในส่วนที่ไหลลงจะมีค่าลดลงเมื่อค่าสัดส่วนระหว่างพื้นที่หน้าตัดของส่วนที่ไหลลงกับส่วนที่ไหลขึ้นมีค่าเพิ่มมากขึ้น นอกจากนี้การสูญเสียก๊าซจำนวนมากออกจากระบบที่ค่าสัดส่วนนี้สูงๆ ส่งผลให้ระบบโดยรวมมีพื้นที่ผิวสัมผัสระหว่างฟองก๊าซกับของเหลวลดลง จึงทำให้ค่าการถ่ายเทมวลสารของระบบลดลงด้วย

การศึกษาครั้งนี้ยังรวมถึงการศึกษาถึงอิทธิพลของความเค็มต่อพฤติกรรมภายในถังสัมผัสฯ ซึ่งพบว่า ความเค็มส่งผลทำให้แรงตึงผิวของของเหลวมีค่าเพิ่มขึ้นซึ่งทำให้ฟองก๊าซที่เกิดขึ้นมีขนาดเล็กลง ฟองก๊าซขนาดเล็กนี้จะถูกเหนี่ยวนำลงมาในส่วนที่ไหลลงได้ง่ายขึ้น ทำให้ระบบที่ยิ่งมีความเค็มสูงจะมีค่าสัดส่วนของก๊าซรวมภายในระบบสูงซึ่งช่วยเพิ่มพื้นที่ผิวของการถ่ายเทมวลและทำให้ค่าอัตราการถ่ายเทมวลระหว่างเฟสเพิ่มมากขึ้น

ภาควิชา.....วิศวกรรมเคมี.....ลายมือชื่อนิสิต..........
สาขาวิชา.....วิศวกรรมเคมี.....ลายมือชื่ออาจารย์ที่ปรึกษา..........
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KEY WORD: AIRLIFT CONTACTOR / HYDRODYNAMICS / MASS TRANSFER / SEA WATER / MULTIPLE DRAFT TUBES

NALINEE TANTHIKUL: HYDRODYNAMICS AND MASS TRANSFER BEHAVIOR IN LARGE SCALE MULTIPLE DRAFT TUBE AIRLIFT CONTACTORS. THESIS ADVISOR : ASSOC.PROF. PRASERT PAVASANT, Ph.D., 72 pp. ISBN 974-53-1113-8

This work aimed at the development of the basic knowledge regarding the behavior of the large scale multiple draft tube airlift contactor especially in the case of a large cross sectional area. Three main aspects were investigated including: (i) the influence of airlift configuration; (ii) the influence of the downcomer to riser cross sectional area ratio (A_d/A_r); and (iii) the effect of salinity of liquid phase on the airlift performance.

The configuration of draft tube was found to significantly affect the performance of the airlift contactor. The multiple draft tube configuration demonstrated a better gas-liquid mass transfer performance when compared with the conventional one draft tube system. The airlift with a larger number of draft tubes allowed a higher level of bubble entrainment which rendered a high gas holdup in downcomer. This resulted in a higher overall gas holdup in the contactor. Liquid velocity was also higher in the system with a larger number of draft tubes. This was believed to be due to the effect of internal liquid circulation which could take place more significantly in the airlift contactor with one large draft tube than in the system with multiple draft tubes.

The ratio between downcomer and riser cross sectional areas, A_d/A_r, was also shown to have great effects on the system performance. The larger A_d/A_r exhibited the larger downcomer area which caused the lower downcomer liquid velocity and less quantity of gas bubbles being dragged into the downcomer. Therefore the overall, riser and downcomer gas holdups decreased with an increase in A_d/A_r. As a large fraction of gas bubbles left the system with large A_d/A_r, the interfacial area for mass transfer also decreased which led to a reduction in the overall volumetric mass transfer coefficient.

This work also examined the influence of salinity on the airlift performance. Salinity raised the liquid phase surface tension which resulted in smaller bubble formation. This greatly enhanced the gas entrainment within in the system. This enhanced both the gas holdup and the gas-liquid interfacial area which resulted in a higher rate of gas-liquid mass transfer.

Department ……Chemical Engineering……Student's signature...................................

Field of study……Chemical Engineering……..Advisor's signature...................................

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NOMENCLATURE

<u>Notations</u>

a	specific gas-liquid interfacial area of bubble per volume of reactor [$m^2\ m^{-3}$]
A	cross-sectional area [m^2]
A_d	downcomer cross-sectional area [m^2]
A_r	riser cross-sectional area [m^2]
C_L	dissolved oxygen concentration in liquid phase [*% air saturation*]
C_L^*	saturation dissolved oxygen concentration in liquid phase [*% air saturation*]
C_0	initial oxygen concentration in liquid phase [*% air saturation*]
g	gravitational acceleration [$m\ s^{-2}$]
h_D	dispersed liquid height [m]
h_L	liquid height [m]
k_La	overall volumetric mass transfer coefficient [s^{-1}]
Q_L	volumetric liquid flow rate [$m^3\ s^{-1}$]
t	time [s]
t_c	circulation time [s]
u_L	superficial liquid velocity [$m\ s^{-1}$]
$\bar{u}_{Lc}$	liquid circulation velocity [$m\ s^{-1}$]
u_{sg}	superficial gas velocity [$cm\ s^{-1}$]
v_L	linear liquid velocity [$m\ s^{-1}$]
V_D	dispersion volume [m^3]
V_G	gas volume [m^3]
V_L	liquid volume [m^3]
x_c	circulation length [m]

Greek letter

ΔH	distance between pressure measurement point [m]
ΔP	hydrostatic pressure difference between two measuring points [Pa]
ΔZ	distance of liquid height in manometer [m]
ε_G	gas holdup [-]
ε_d	downcomer gas holdup [-]
ε_r	riser gas holdup [-]
ε_O	overall gas holdup [-]
ρ	density [$kg\ m^{-3}$]

Subscript

d	downcomer
g	gas
l	liquid
o	overall
r	riser
T	total

CHAPTER I

INTRODUCTION

1.1 Motivations

Conventional bubble columns in which gas is sparged through a pool of liquid are now increasingly applied in chemical industry; examples include units such as neutralization of wastewater and fermentation processes. Significant developments in biotechnology in recent years have led to several modifications of the bubble column concept. Airlift contactor is an important class of modified bubble columns. This type of contactor has several advantages, e.g. simple design, low power requirement, absence of moving parts, low shear stress, high mass and heat transfer, high fluid circulation rate, short mixing time, etc. In comparison with bubble columns the minimum gas velocity needed for complete suspension is less. In comparison with mechanically stirred systems shear rates and power consumption are less (Chisti, 1989; Heijnen *et al.*, 1997).

Airlift contactor can be operated as two phase (liquid and gas), as well as three phase (liquid, gas and solid particles) systems, and can be operated both in batch and flow-through modes. The design of an airlift contactor necessitates accurate estimate of several parameters. In general, the three most important parameters that describe the performance of airlift systems are gas hold-up, liquid circulation velocity and mass transfer coefficient. These parameters are sensitive to operational variations such as gas flow rate and physical properties of the system, and also are subject to geometrical modifications, particularly downcomer to riser cross-sectional area ratio (A_d/A_r).

Most research focused mainly on laboratory scale airlift systems whose behavior was much different from an actual larger scale system. Understanding the performance of large-scale airlifts is necessary for industrial purpose. Conventional configuration (one draft tube internal loop airlift type) in large scale airlift systems, especially in the case of a very large cross-sectional area, usually encounters design problems, e.g. aeration, which led to a poor distribution of gas bubbles and mixing. A multiple draft tube airlift system is a potential configuration that might facilitate the design and operation of such large scale reactor. In multiple draft tube airlift, each draft tube is connected with individual gas sparger that helps distribute gas within the contactor, and hence, the gas-liquid mass transfer may be improved.

In this work, three configurations of internal loop airlifts (170L), i.e. single (conventional type), triple, and four draft tubes are compared in terms of hydrodynamics and mass transfer properties. Three ratios between downcomer and riser cross sectional areas, i.e. 1.27, 2.03 and 2.82, are examined with the superficial gas velocity varied in the range from 0.4 to 2.0 cm/s. Four salinity levels (0, 15, 30 and 45 ppt) are also investigated to determine its effect on the system performance.

1.2 Objectives

1. To investigate the influence of the configuration (single, triple and four draft tubes) on hydrodynamics and gas-liquid mass transfer properties in large-scale airlift contactors.
2. To investigate the influence of the downcomer to riser cross-sectional area ratio (A_d/A_r) on hydrodynamics and gas-liquid mass transfer properties in large-scale multiple draft tube airlift contactors.
3. To investigate the influence of salinity on hydrodynamics and gas-liquid mass transfer properties in large-scale multiple draft tube airlift contactors.

1.3 Scopes of this work

1. Internal-loop airlift contactors employed in this work and all draft tubes have dimensions and sizes as specified in Figure 3.2 and Figure 3.3.
2. The range of superficial gas velocity employed in this work is between 0.4-2.0 cm/s.
3. Water with 0, 15, 30 and 45 ppt salinity levels is used as liquid phase and ambient air as gas phase
4. All experiments were performed at ambient temperature.

CHAPTER II

LITERATURE REVIEWS

2.1 Airlift contactors

Airlift is one form of gas-liquid contactor. The configuration of airlift is similar to bubble column in that there are no mechanical devices within the column. However, airlift contactors consist of an additional non-aeration partition, which is interconnected with the aerated partition. The part in which the sparger is located is called riser, and the other one, downcomer. Compressed air can be sparged into either the draft tube or the annular compartment in the internal loop airlift column type with draft tube installed as an inner column at the center of the outer column. Circulation in airlift is induced by (i) the energy transfer from the aeration, and (ii) the net density difference between the riser and downcomer resulting form injecting air.

2.1.1 Type of airlift contactors

There are two types of airlift contactors, i.e. internal-loop and external-loop. Each type is different in configuration, which results in their application diversity.

2.1.1.1 Internal-loop airlift contactors

In internal-loop types, the division section is achieved either by installation of draft tube in the cylindrical column as illustrates in Figure 2.1(a) or by a tightly fitting vertical baffle to give a split-cylinder geometry as illustrated in Figure 2.1(b). Some of these types are also mounted with enlarged gas-liquid separator at the top in order to avoid gas flow into the downcomer section as Figure 2.1(c).

2.1.1.2 External-loop airlift contactors

External loop airlift contactors consist of two columns of liquid connected together at the top and the bottom, in which little or no gas recirculates into the downcomer. As the downcomer is, in this case, physically separated from the riser, one might assign the riser and downcomer to very different applications. For instance, riser might be used as a nitrification section (aerobic) whereas downcomer can be employed as anaerobic denitrification (Silapakul, 2002). Figure 2.2 shows the schematic for the external-loop airlift contactor.

2.1.2 Advantages of airlift contactors

Airlift contactors have several advantages over another kind of reactors (bubble columns and stirred tanks), some are listed below (Chisti, 1989; Chisti and Moo-Young, 1987):

- Simple design
- Absence of moving parts, stirrer shaft, seals and bearings
- Ease of maintenance
- Eliminating the danger of contamination through seals
- Low power consumption
- Low capital cost
- Low shear stress
- Better defined flow pattern
- Controllable liquid circulation rate
- High mass and heat transfer
- Short mixing time
- Mild and uniform mixing
- Minimum gas velocity needed for complete suspension
- Ease of suspending solid particles (in three phases)
- Intimate contact between gas, liquid and solid phases

Despite these several advantages, mass transfer efficiencies in airlift are inferior to that obtained in stirred tanks. However shear stress in stirred tanks is often very large, which renders this type of reactor not suitable for several types of cell cultures.

Bubble columns are also appropriate for cell culture but they lack liquid circulation which results in poor mixing and circulation particularly for the systems with high cell density, where cells tend to sediment to the bottom of the system.

Because of several advantages as mentioned above, airlift contactors are finding increasing applications in various processes such as and wastewater treatment and cultivate cells such as algae (Loataweesup, 2002; Silapakul, 2002; Rasrikrangkrai, 2003).

2.2 Hydrodynamics in airlift contactors

Generally, gas hold-up, liquid circulation velocity, and mass transfer coefficient are the most important parameters used to describe performance of airlift contactors. The hydrodynamics behavior (gas hold-up and liquid circulation velocity) in airlift contactors is discussed in this section whereas the mass transfer in the next section.

2.2.1 Gas holdup

The volume fraction of gas or gas holdup is an essential parameter for the design of airlift contactors. Due to the configuration of airlift contactors that allow aeration in the riser, gas holdup in riser is usually higher than the downcomer. This difference in gas holdups is the main cause of pressure difference, which creates liquid circulation pattern.

Gas holdup, ε, is the ratio between volume of gas phase and the total volume of reactor (volume gas phase plus volume of liquid phase) or can be expressed as:

$$\varepsilon = \frac{V_G}{V_G + V_L} \tag{2.1}$$

where V_G is gas volume and V_L liquid volume in reactor.

Many aspects of airlift contactors depend not only on the overall gas holdup but also on the distribution of holdups between the riser and the downcomer. The volumetric flow rate of liquid in airlift can be expressed as the product between the superficial liquid velocity and the empty column cross-sectional area:

$$Q_{Lr} = u_{Lr} A_r \tag{2.2}$$

$$Q_{Ld} = u_{Ld} A_d \tag{2.3}$$

where Q_L is the liquid flow rate, u_L superficial liquid velocity, and A cross-sectional area. Subscript r denotes riser section and d as downcomer section. Because all of the liquid in the downcomer must circulate back to the riser:

$$u_{Lr} A_r = u_{Ld} A_d \tag{2.4}$$

Equation (2.4) can be written in terms of the linear liquid velocities (true velocities that include the effect of bubble holdup) or

$$v_{Lr} A_r \left(1 - \varepsilon_r\right) = v_{Ld} A_d \left(1 - \varepsilon_d\right) \tag{2.5}$$

where v_L is the linear liquid velocities and ε is the gas hold-up. Rearrangement of Equation (2.5) leads to

$$\varepsilon_d = \frac{v_{Lr} A_r}{v_{Ld} A_d} \varepsilon_r - \left(\frac{v_{Lr} A_r}{v_{Ld} A_d} - 1 \right) \tag{2.6}$$

Equation (2.6) is a rather common expression for the relationship between riser and downcoemr gas holdups which could often be found in literature. A general form of Equation (2.6) is:

$$\varepsilon_d = \alpha \varepsilon_r - \beta \tag{2.7}$$

where

$$\alpha = \frac{v_{Lr} A_r}{v_{Ld} A_d} \tag{2.8}$$

and

$$\beta = \alpha - 1 \tag{2.9}$$

Literatures revealed that increasing superficial gas velocity (u_{sg}) increased the gas holdup (Al-Masry, 1999; Gavrilescu and Tudose, 1997; Reinhold *et al*, 1996). On the other hand, the gas holdup was found to decrease with an increase in the downcomer to riser cross-sectional area ratio (A_d/A_r) (Al-Masry and Abasaeed, 1998). Because increasing A_d/A_r enhances the liquid circulation velocity and shortens the time that the bubbles spend in riser, gas holdup in riser decreases. For more detailed information on the correlations for the calculation of gas holdups in airlift system, a review provided in Wongsuchoto (2002) is recommended.

2.2.2 Liquid velocity

As stated earlier, the difference in gas hold-up is the main cause that induces the liquid circulation in airlift contactors. Liquid flows upward in riser and downward in downcomer where circulation velocity ($\bar{u}_{Lc}$) is

$$\bar{u}_{Lc} = \frac{x_c}{t_c} \tag{2.10}$$

when x_c is circulation length and t_c an average time for one complete recirculation.

To find the relationship between the riser and downcomer liquid velocities, the continuity equation is formulated:

$$u_{Lr} A_r = u_{Ld} A_d \tag{2.11}$$

The superficial liquid velocity is different from the true linear velocity because of the existence of bubbles in liquid phase. The linear liquid velocity v_L and the superficial liquid velocity are related as follows:

$$v_{Lr} = \frac{u_{Lr}}{1-\varepsilon_r} \tag{2.12}$$

and

$$v_{Ld} = \frac{u_{Ld}}{1-\varepsilon_d} \tag{2.13}$$

A large number of literatures could be found on the experimental determination of liquid velocity in airlift contactors, and most concluded that increasing the superficial gas velocity (u_{sg}) increased the liquid circulation velocity (v_L) (Al-Masry, 1999; Gavrilescu and Tudose, 1997; Reinhold *et al*, 1996). The liquid circulation velocity was found to increase with an increase in the downcomer to riser cross-sectional area ratio (A_d/A_r) (Al-Masry and Abasaeed, 1998). Generally, a decrease in A_r rendered the liquid in riser to move faster and led to an increase in liquid circulation. The correlations for the estimation of circulation velocity can also be found in the review by Wongsuchoto (2002).

2.3 Mass transfer in airlift contactors

One of the most important factors for the operation of bioreactor is the gas-liquid mass transfer. As general criteria in most aerobic cultures, cells need oxygen to stay alive and active. However, the level of dissolved oxygen in the culture is always limited by thermodynamics where solubility of oxygen in water is only around 7 ppm at ambient condition. The rate at which oxygen is dissolved into the water is therefore an important key step in accelerating cell growth, and for this, we need to know the behavior of the system in transferring gas between the two phases.

The overall volumetric mass transfer coefficient (or k_La) is a combination of two variables, i.e. k_L and a. k_L is mass transfer coefficient and a is surface area of transferring. The determination of each of these parameters requires a tedious experimental work on the measurement of bubble size distribution and this is often not practical in large scale systems. A more conventional method of determining the rate of gas-liquid mass transfer is to find the product of the two quantities, k_La.

To determine this parameter, the method based on a dynamic approach of oxygen is employed. Oxygen balance performed across an aerated bioreactor in which a living culture is actively growing is formulated:

$$\frac{dC_L}{dt} = k_L a(C_L^* - C_L) - r_{o_2} \qquad (2.14)$$

where C_L is the dissolved oxygen concentration, C_L^* the dissolved oxygen concentration in equilibrium with partial pressure of oxygen in the air, k_La the volumetric oxygen transfer coefficient, and r_{O_2} the rate of oxygen used per unit mass of organisms. For systems without reaction, r_{O_2} disappears and Equation (2.14) becomes

$$\frac{dC_L}{dt} = k_L a(C_L^* - C_L) \qquad (2.15)$$

From literatures, it is clear that increasing the superficial gas velocity (u_{sg}) increases the mass transfer coefficient (k_La). In contrast, when A_d/A_r ratio increases, mass transfer was found to decrease (Al-Masry and Abasaeed, 1998). When A_r

decreases bubbles can move faster because of large velocity of liquid, hence transferring time is poor. The correlations for calculate mass transfer coefficient was reported in Wongsuchoto (2002).

2.4 Large scale airlift contactors

Gas holdup, liquid circulation velocity and mass transfer coefficient are among the most important parameters essential for understanding the behavior of airlift reactors. These parameters are often employed for designing airlift systems. At the present time, most research usually focused these parameters only on laboratory-scale airlift whose behavior was much different than actual larger scale systems. As a result, problems in designing large-scale airlift contactors are often encountered due to the lack of information on system performance. Hence, it is necessary to investigate the performance of large-scale airlift systems.

Al-Masry and Abasaeed (1998) studied the scale-up of external loop airlift contactors. Hydrodynamics and mass transfer data were investigated in three external loop airlifts with the volumes of 60, 350 and 700 liters, respectively. They found that, at constant gas throughputs, a system with larger volume provided higher liquid circulation velocity and lower gas hold-up and mass transfer coefficient (results shown in Figures 2.3 and 2.5). However, in their experiment, the ratio of the cross-sectional areas between downcomer and riser (A_d/A_r) varied with the contactor size, i.e. A_d/A_r=0.25, 0.44 and 1.0 for the systems with the size of 60, 350, 700L, respectively. Therefore the configuration of the three scales of airlift was not similar (different A_d/A_r), and the performance of large-scale airlift could still not be generalized.

Lindert *et al.* (1992) studied the scale-up of airlift–loop bioreactors to examine the applicability of several oxygen mass transfer models. They compared the results from external loop airlift systems with the volumes of 2, 80 and 800 liters, respectively, along with the internal loop airlift with the volume of 70 liters. Several model methods in estimating oxygen mass transfer were examined and the conclusion revealed that the CSTR dynamic model could be well applied to interpret mass transfer data for all systems investigated. They concluded that the most important factor for mass transfer was the reactor height, which dominated the mean pressure, and thus influenced the saturation concentration and the mass transfer driving force. However, they could not summarize the effect of other design parameters as the geometry of their airlifts was not well controlled and different ratios between A_d/A_r were applied to different airlift systems. This non-similarity also created doubts on the applicability of results of contactor height.

Heijnen *et al.* (1997) proposed the hydrodynamic model to predict the liquid circulation velocity in two- and three-phase internal loop airlift reactors. In their work, the experimental apparatus included three different scales, i.e. laboratory-scale with the volume of 19L, pilot-scale with the volume of 400L, and a large scale with 284,000L, all with approximately the same ratio of A_d/A_r (see results in Figure 2.6). The results demonstrated that higher liquid velocity was obtained in the larger scale airlift operated within the same gas flow rate. This was because the wall friction generated in the large-scale airlift contactors was usually lesser than the smaller scale systems. However, no results on gas hold-up and mass transfer coefficient were presented.

Recently, a clearer evidence of the performance of the large-scale airlifts were proposed by Blazej *et al.* (2004) who studied the effect of reactor scale on the hydrodynamics of an internal loop airlift. Three different reactor sizes of similar geometry (the same A_d/A_r and *H/D* ratio) were selected with the working volumes of 10.5, 32 and 200 liters where temperature was controlled within 18–21^{o}C under atmospheric pressure, and with air-water as gas-liquid media. The circulation velocity was investigated in two regimes based on the generation of bubbles and on the entrainment of gas bubbles as detailed hereafter.

Flow regimes based on the generation of bubbles:

1. Homogeneous bubble flow: This regime occurred at low superficial gas velocity (less than 0.015 m/s). Bubbles in this region had narrow size distribution and liquid flowed at low intensity of turbulence.

2. Heterogeneous bubble flow or Churn turbulent flow: This regime occurred at high superficial gas velocity. The intensity of turbulence in the liquid phase was much higher when compared to the homogeneous flow regimes. This increased the bubble coalescence and led to a wider range of bubble sizes.

Flow regimes based on the entrainment of gas bubbles:

1. <u>No gas entrainment (Regime I)</u>: This regime occurred at low gas velocity (u_{sg} <0.0005 m/s), no air bubbles were entrained into the downcomer as the liquid velocity in the downcomer was lower than the average slip velocity of the air bubbles in the liquid.

2. <u>Gas entrainment but no gas recirculation (Regime II)</u>: In this regime (u_{sg}= 0.0005-0.015 m/s), the liquid velocity in the downcomer became equal to the slip velocity of the air bubbles, which resulted in air bubbles being maintained at stationary in the downcomer. Bubbles were entrained into the downcomer but no bubbles were recirculated back into the riser.

3. <u>Complete gas recirculation (Regime III)</u>: This regime occurred when the liquid velocity in the downcomer became higher than the slip velocity of the air bubbles (u_{sg} >0.015 m/s) . The air bubbles recirculated with the liquid form the downcomer into the riser again. Figure 2.9 shows the three flow regimes of internal loop airlift.

From their investigation in all regimes above, Blazej *et al.* concluded that the average liquid circulation velocity increased with increasing reactor scale for the same superficial gas velocity as illustrated in Figure 2.6. This tendency was found to be the same for all regimes. There was an exception in the change of liquid velocity in Regime II where no change in liquid velocity was observed with superficial gas velocity. This was believed to be due to the presence of bubbles in downcomer which reduced the difference between gas holdups in riser and downcomer.

The gas holdup driving force (ε_r-ε_d) was found to be important only for lower values of the gas flow rate. In the range of higher values of the gas input, the circulation velocity seemed to be governed only by friction in the reactor wall.

From the results of Blazej *et al.*, it can be generally assumed that reactor scale can significantly influence airlift behavior. To provide higher circulation velocities (short mixing time) and better distribution of the gas phase (higher gas hold-up), it is suitable to use larger reactor volumes to avoid unfavorable influences of the gas hold-up reduction due to wall effects.

2.5 Multiple draft tube airlift contactors

To date, there were no investigations on the configuration of large scale airlift systems. Our experience showed that, in the systems with large riser, it was difficult to obtain good distribution of bubbles. Tung *et al.* (1998) studied the bubble characteristics and mass transfer in an airlift with multiple net draft tubes. They employed an internal loop airlift with 29 cm in diameter and 300 cm height with four modules of net draft tubes. Their primary concern was on the distribution of gas through the surface of the four net draft tubes which was not involved with the comparative investigation on hydrodynamic and gas transfer performance along with conventional single draft tube configuration. Tung *et al.*'s work was summarized in Figures 2.4 and 2.8.

(Note that: Experimental details for Figures 2.3 - 2.8 are shown in Table 2.1)

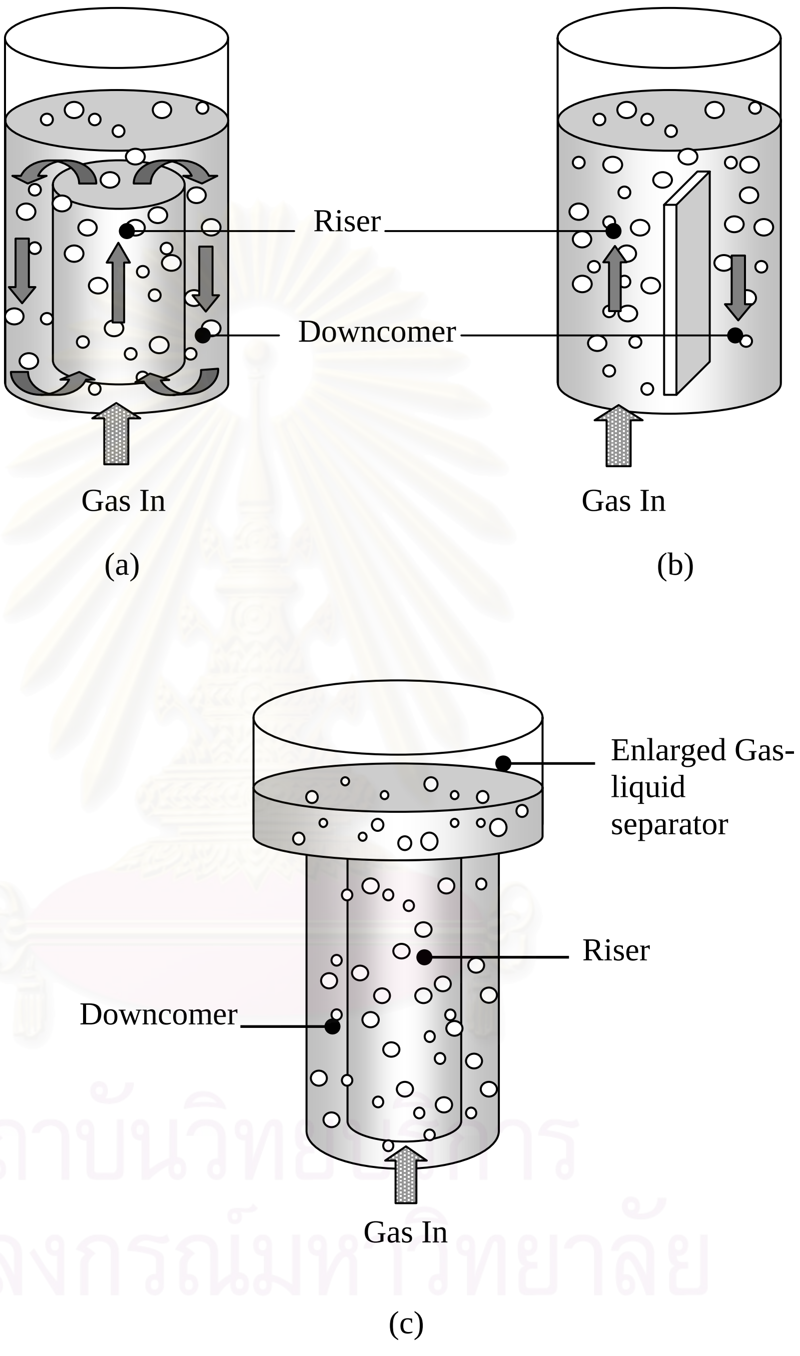


Figure 2.1 Internal-loop airlift contactors (a) draft tube in the cylindrical column which air is sparged in draft tube section (b) vertical baffle in cylinder (c) draft tube in cylinder with gas-liquid separator on the top.

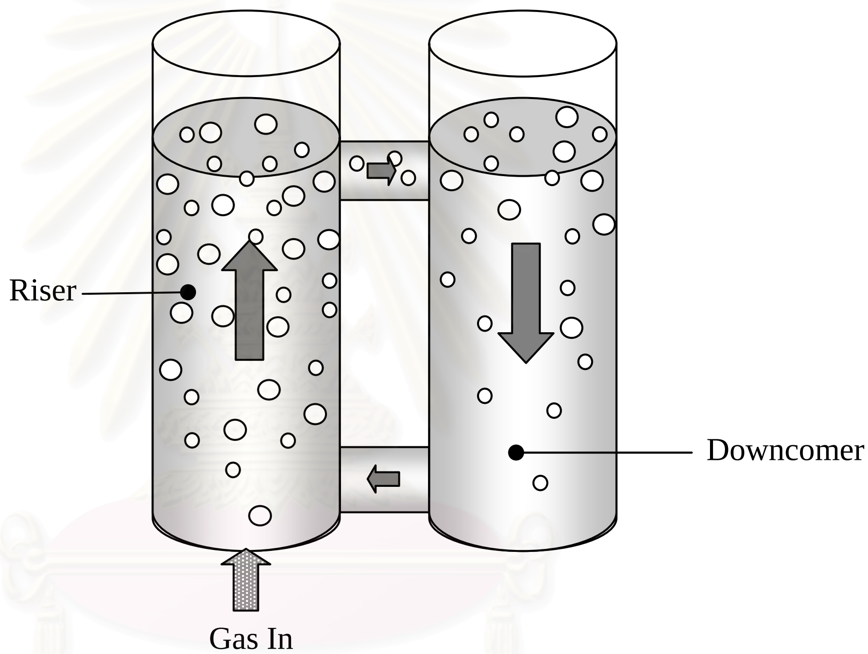


Figure 2.2   External-loop airlift contactors

Table 2.1 Experimental details for Figures 2.3 - 2.8

Author (year)	**Details**	**System**	**Sparger**
Al-Masry et al. (1998)	External loop airlift A_d/A_r = 0.25 (60L) External loop airlift A_d/A_r = 0.44 (350L) External loop airlift A_d/A_r = 1.00 (700L)	air-water	plate sparger with 1 mm diameter
Baten et al. (2002)	Internal loop airlift A_d/A_r = 1.25 (35L) Internal loop airlift A_d/A_r = 2.03 (48L) Internal loop airlift A_d/A_r = 1.25 (882L)	air-water	perforated plate with 625 holes of 0.5 mm diameter
Blazej et al. (2004)	Internal loop airlift A_d/A_r = 1.23 (10.5L) Internal loop airlift A_d/A_r = 0.95 (32L) Internal loop airlift A_d/A_r = 1.01 (20)	air-water	plate sparger (teflon) with 25 holes of 0.5 mm diameter plate sparger (teflon) with 25 holes of 0.5 mm diameter plate sparger (stainless steel) with 90 holes of 1.0 mm diameter
Choi et al. (1996)	Internal loop rectangular airlift A_d/A_r = 1 (114L)	air-water	perforated plate with 30 holes of 0.002 m diameter
Heijnen et al. (1997)	Internal loop airlift A_d/A_r = 1.04 (19L) Internal loop airlift A_d/A_r = 1.47 (400L) Internal loop airlift A_d/A_r = 1.04 (284,000L)	air-water	

Table 2.1 (cont.)

Author (year)	**Details**	**System**	**Sparger**
Lindert et al. (1992)	Internal loop airlift A_d/A_r = 0.11 (800L)	air-water	
Tung et al. (1998)	Internal loop airlift (4 net draft tubes) 132L	air-water	perforated ring sparger
Wang et al. (2003)	External loop airlift A_d/A_r = 0.36 (20 ml)	air-gluconate buffer	glass plate with pore size of 40-100micron
Wongsuchoto et al. (2002)	Internal loop airlift A_d/A_r = 0.067 (15L) Internal loop airlift A_d/A_r = 0.43 (15L) Internal loop airlift A_d/A_r = 1.0 (15L)	air-water	perforated ring sparger with 14 holes of 1 mm diameter

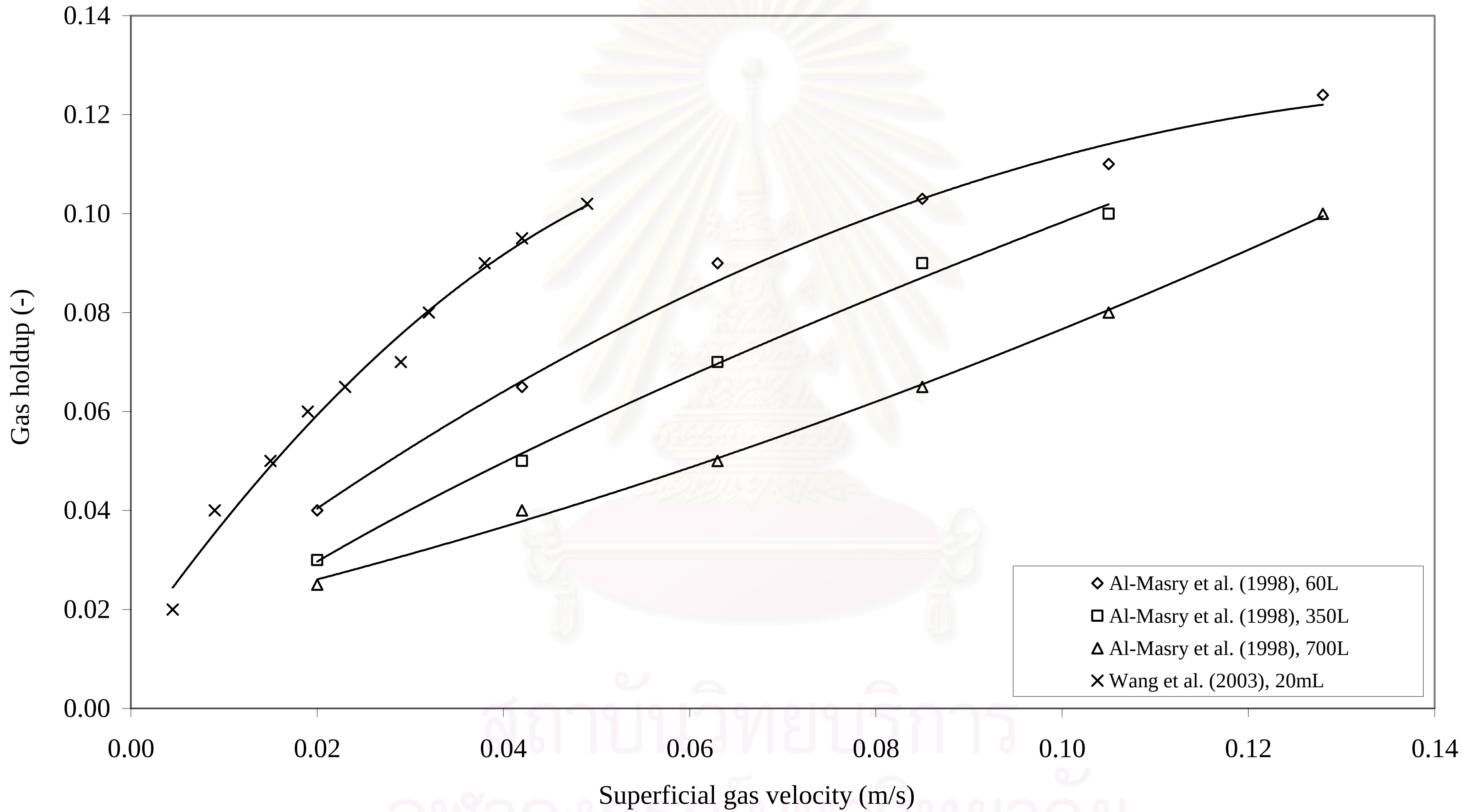


Figure 2.3 Relationship between gas holdup and superficial gas velocity of external loop airlift

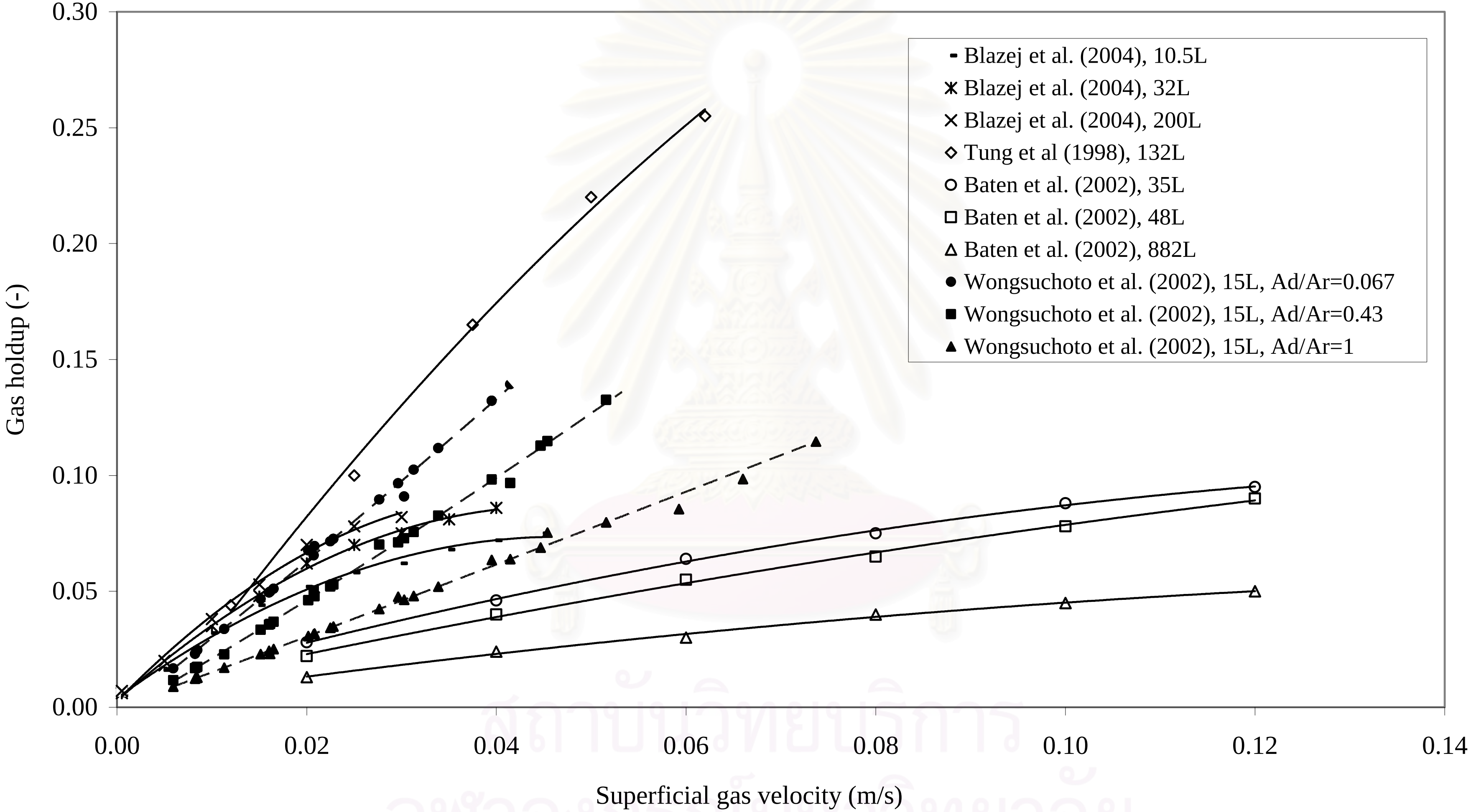


Figure 2.4 Relationship between gas holdup and superficial gas velocity of internal loop airlift

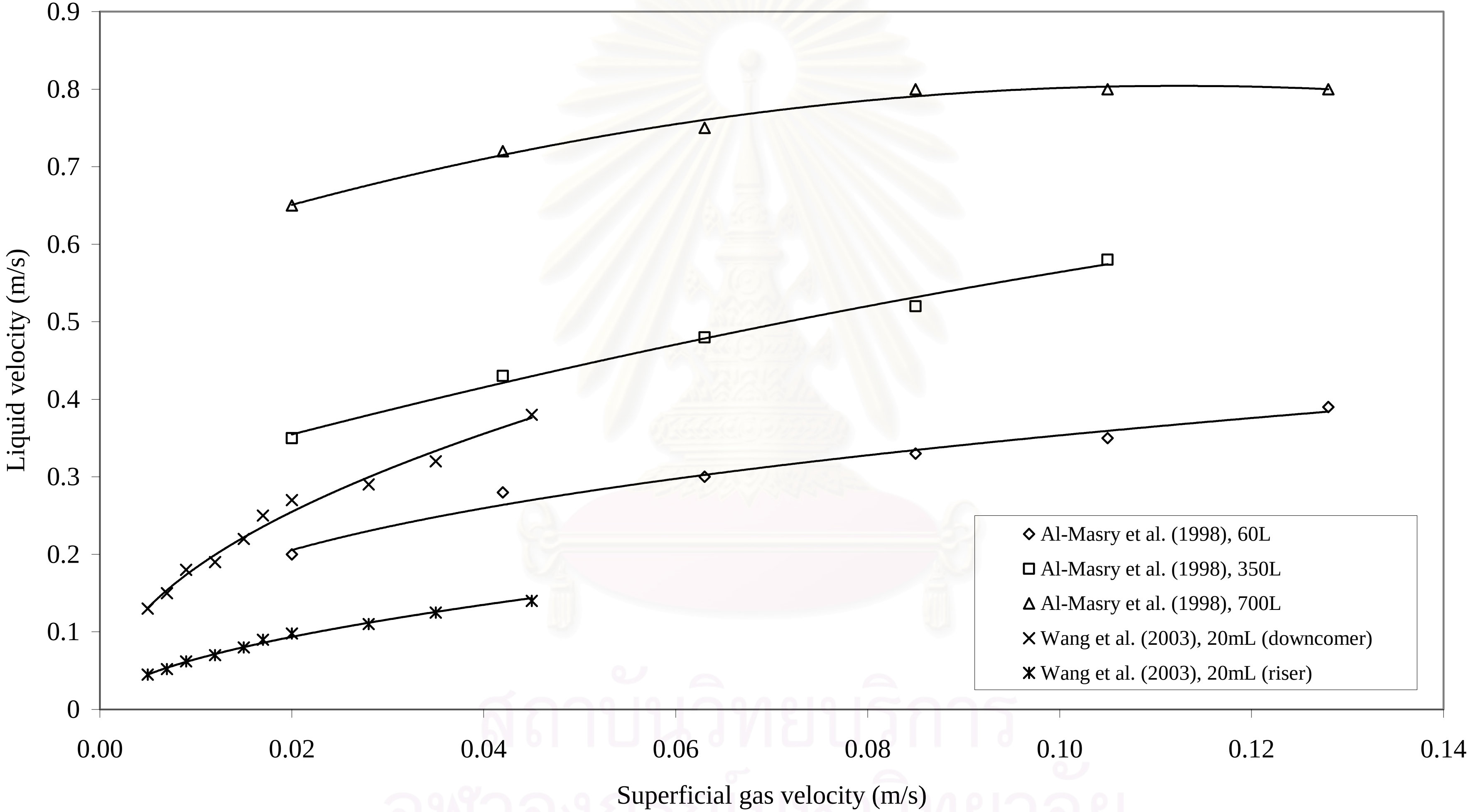


Figure 2.5 Relationship between liquid velocity and superficial gas velocity of external loop airlift

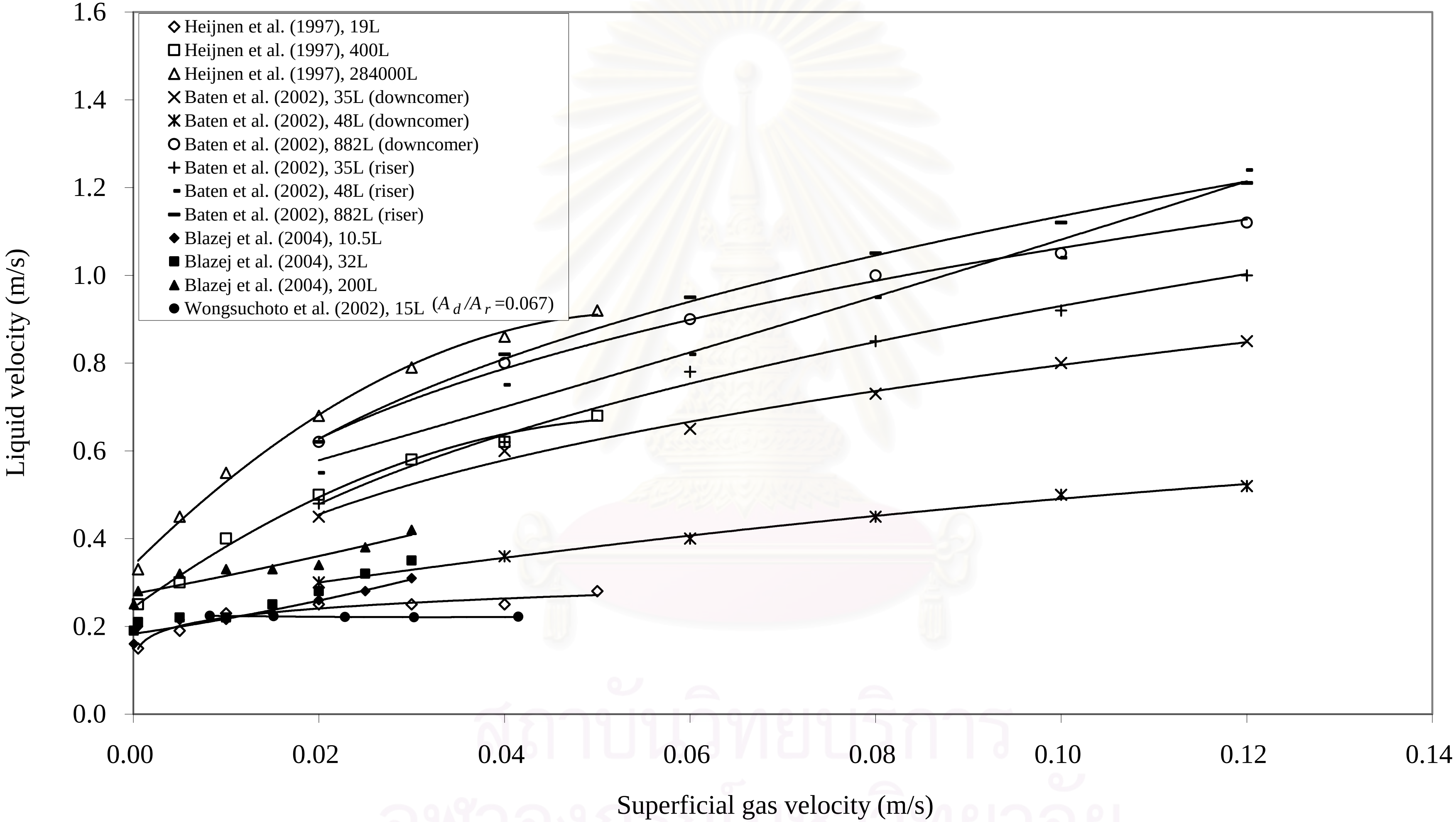


Figure 2.6 Relationship between liquid velocity and superficial gas velocity of internal loop airlift

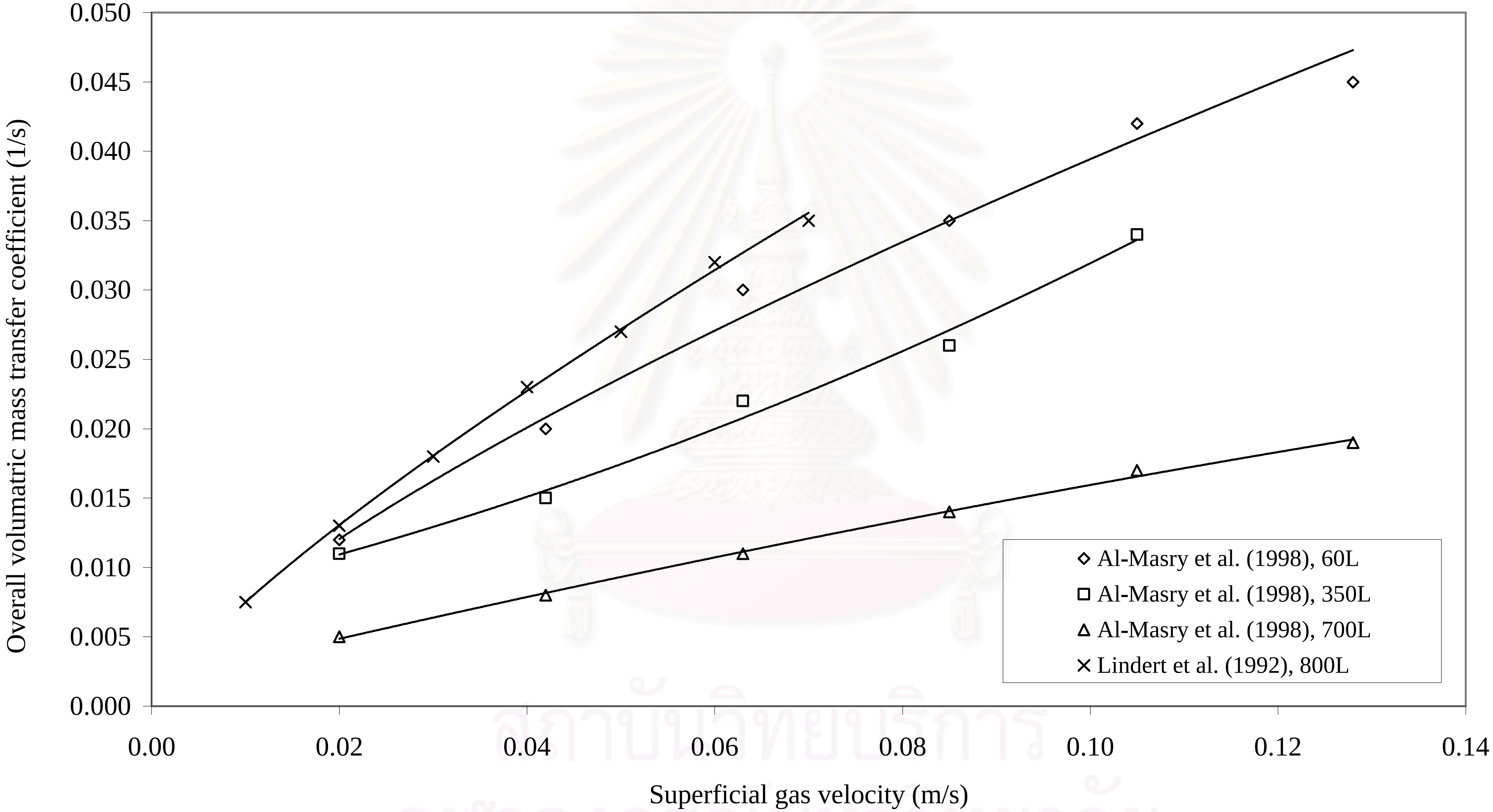


Figure 2.7 Relationship between mass transfer coefficient and superficial gas velocity in external loop airlift

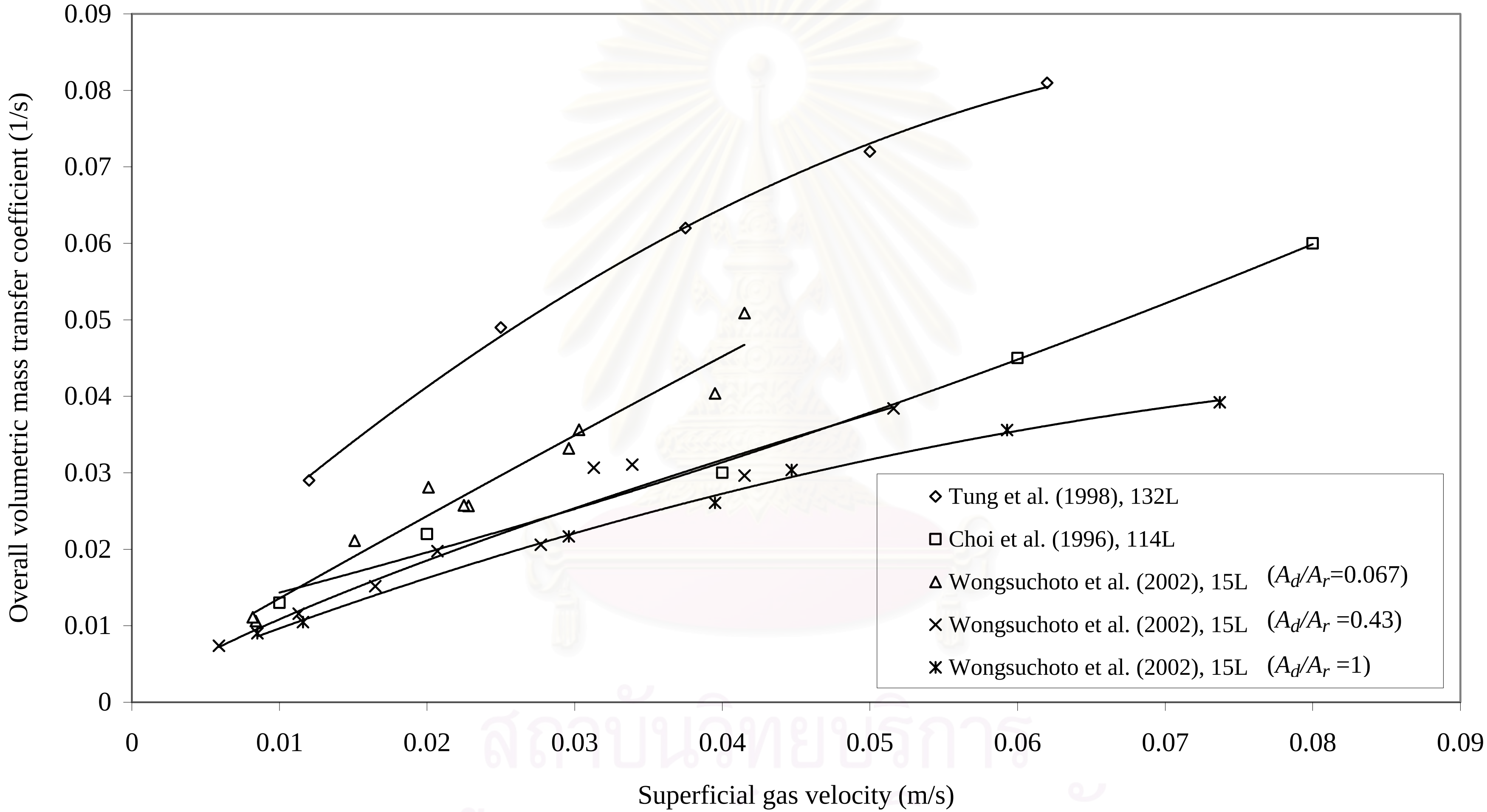


Figure 2.8 Relationship between mass transfer coefficient and superficial gas velocity in internal loop airlift

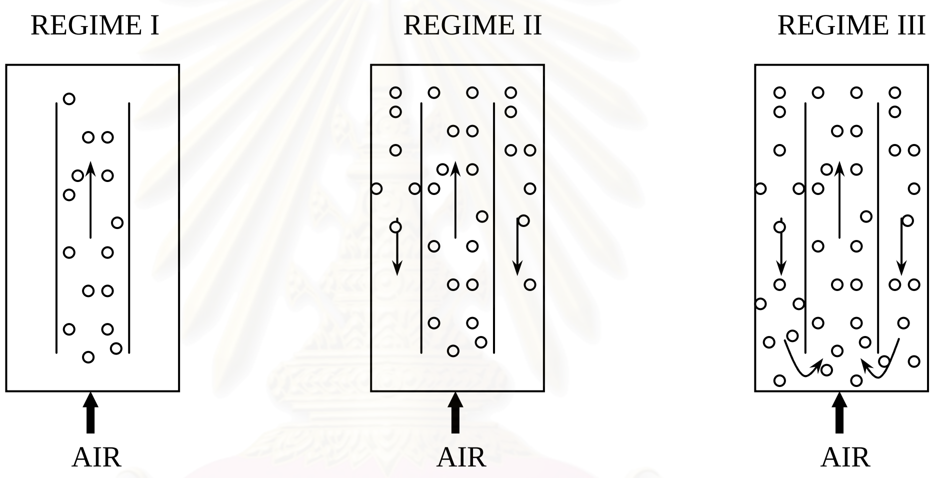


Figure 2.9 Flow regimes in internal-loop airlift contactor (base on the entrainment of gas bubbles).

CHAPTER III

MATERIALS AND METHODS

3.1 Experimental setup

The airlift system in this work was only operated with liquid and gas phases, where the liquid phase was either tab water or seawater and the gas phase was air. The operation was semi-batch where the liquid was filled in the column and the gas was continuously supplied by air pump. The installation of the systems was shown in Figure 3.1. In this study, we focused on the large scale internal-loop type airlift with the working volume of about 170L. The airlift column (or tank) and the draft tubes were made of transparent acrylic in order to facilitate the observation. The main column was cylindrical with a diameter of 69 cm. and height of 56.5 cm. For all experiments, air was dispersed by 28 porous spargers installed in the middle of each draft tube and gas flow rate was regulated by calibrated rotameters in the range of 0.4 – 2.0 cm/s. Liquid phase was filled up to the level of 7 cm. above the draft tubes before dispersing compressed air into the column.

The experimental setup can be divided into 3 parts according to the objectives of this work as follows:

3.1.1 Airlift with various designs of draft tubes

The first purpose of this work was to investigate the influence of the airlift configuration. The conventional one draft tube and the multiple draft tube (more than one draft tubes) were examined. AC1 was referred to airlift configuration#1which represented the conventional type with only one large draft tube. Configuration#2 (AC2) and Configuration#3 (AC3) were the airlifts with multiple draft tube with 3 and 4 internal draft tubes in the contactor, respectively. The schematic diagram of the airlift systems with various designs of draft tubes is shown in Figure 3.2 with the details as displayed in Table 3.1. In order to examine the effect of these airlift configurations, all configurations were set to perform with the same A_d/A_r ratio (2.03) and seawater concentration (30 ppt). The three basic parameters of concerns in airlift:

gas holdup, liquid velocity, and overall volumetric mass transfer coefficient were determined. The measurements of such parameters were described in Section 3.2.

3.1.2 Airlift systems with variation in downcomer to riser cross sectional area ratio (A_d/A_r)

The next objective was to investigate the effect of geometrical structure such as the ratio of downcomer to riser cross sectional area (A_d/A_r) on the performance of airlift with multiple draft tubes. Three ratios of A_d/A_r, i.e. 1.27, 2.03, and 2.82, were operated by fixing the salinity level at 30 ppt and using airlift with 4 draft tubes. The schematic diagram of A_d/A_r setup performed in this section was illustrated in Figure 3.3 with the details in Table 3.2. Similar to the previous section, the gas holdup, liquid velocity and overall volumetric mass transfer coefficient were also evaluated.

3.1.3 Salinity experiment

The influence of salinity of liquid phase was considered in this section. The variation of seawater (15, 30 and 45 ppt) was compared with tap water (or 0 ppt). The experimental setup in this section was controlled with the same airlift configuration (4 draft tube) and A_d/A_r (2.03). Table 3.3 demonstrates the experimental details in this section. The hydrodynamics and mass transfer behavior were also examined.

3.2 Experiments

3.2.1 Gas holdup measurement

The U-tube manometer was used to measure the pressure difference between the two defined levels, which enabled the determination of gas holdup. The experimental steps follow:

1. Set equipment as display in Figure 3.1
2. Measure the liquid level before and after disperse gas in to airlift to calculate overall gas holdup (see Equation 3.5)
3. Measure pressure difference in airlift with an attached manometer
4. Calculate downcomer gas holdup (Equation 3.10) and riser as holdup (Equation 3.16)

5. Repeat steps 2 and 3 by varying gas superficial velocity from 0.4 to 2.0 cm/s

3.2.2 Liquid velocity measurement

The measurement of liquid velocity in the airlift system was achieved by employing the tracer injection method as described below:

1. Set equipment as displayed in Figure 3.1
2. Define two vertical distances for the dye tracer to travel
3. Turn on the air at a defined flow rate and then inject the color tracer at the fixed point (in the bottom of riser zone)
4. Measure the time required for the tracer to travel between the two defined points
5. Calculate riser liquid velocity (Equation 3.17) and downcomer liquid velocity (Equation 3.20)
6. Repeat steps 2 to 5 by varying gas superficial velocity from 0.4 to 2.0 cm/s

3.2.3 Mass transfer coefficient measurement

Mass transfer coefficient can be estimated from the tracking of the dissolved oxygen concentration in the system with the dissolved oxygen (DO) meter. The steps are:

1. Set equipment as illustrated in Figure 3.1
2. Remove dissolved oxygen by purging nitrogen into column until DO reaches zero % air saturation
3. Turn off nitrogen valve and turn on air valve at pre-defined flow rate
4. Collect data on % saturation of DO until it reaches 100% saturation
5. Calculate k_La (Equation 3.22)
6. Repeat steps 2 to 5 by varying gas flow rate from 0.4 to 2.0 cm/s

3.3 Calculations of data

3.3.1 Calculation of gas holdup

The gas holdup is a volumetric gas fraction in each section. The overall gas holdup was determined by using a volume expansion technique, and was measured from the difference between the ungassed and gassed liquid level. The definition of gas holdup is

$$\varepsilon = \frac{V_G}{V_G + V_L} \tag{3.1}$$

Because the volume of gas cannot be measured directly, we defined V_D (dispersed volume) as the total volume of gas phase plus volume of liquid phase. Then

$$\varepsilon_o = \frac{V_D - V_L}{V_D} \tag{3.2}$$

$$\varepsilon_o = 1 - \frac{V_L}{V_D} \tag{3.3}$$

$$\varepsilon_o = 1 - \frac{h_L A}{h_D A} \tag{3.4}$$

finally,

$$\varepsilon_o = 1 - \frac{h_L}{h_D} \tag{3.5}$$

where ε_o : overall gas holdup

h_D : dispersed liquid height (*cm*)

h_L : liquid height (*cm*)

The downcomer gas holdup was estimated by measuring the pressure difference between the two measuring ports of the column where

$$\Delta P = \Delta Z_{manometer} \tag{3.6}$$

$$(\rho_L \varepsilon_L + \rho_G \varepsilon_G) g \Delta H = \rho_L g \Delta Z \tag{3.7}$$

Neglecting the wall friction loss and based on the fact that $\rho_L >> \rho_G$, Equation 3.7 can be deduced to

$$\varepsilon_L = \frac{\rho_L g\Delta Z}{\rho_L g\Delta H} \tag{3.8}$$

$$1-\varepsilon_G = \frac{\rho_L g\Delta Z}{\rho_L g\Delta H} \tag{3.9}$$

$$\varepsilon_G = 1-\frac{\Delta Z_{manometer}}{\Delta H} \tag{3.10}$$

where ρ_G : density of gas

ρ_L : density of liquid

ΔP : pressure difference of defined liquid level

ΔZ : distance of liquid level in manometer

ΔH : distance of liquid level

The riser gas holdup was calculated from following equation:

Firstly,

$$\varepsilon_r = \frac{V_{Gr}}{V_{Gr}+V_{Lr}} \tag{3.11}$$

$$\varepsilon_r = \frac{V_{GT}-V_{Gd}}{V_{GT}-V_{Gd}+V_{LT}-V_{Ld}} \tag{3.12}$$

$$\varepsilon_r = \frac{\varepsilon_o V_T - \varepsilon_d V_d}{V_T - V_d} \tag{3.13}$$

$$\varepsilon_r = \frac{\varepsilon_o - \varepsilon_d (V_d / V_T)}{1-(V_d / V_T)} \tag{3.14}$$

$$\varepsilon_r = \frac{\varepsilon_o - \varepsilon_d [A_d h/(A_d + A_r)h]}{1-[A_d h/(A_d + A_r)h]} \tag{3.15}$$

Finally,

$$\varepsilon_r = \varepsilon_o + (A_d / A_r)(\varepsilon_o - \varepsilon_d) \tag{3.16}$$

where ε_o : overall gas hold up

ε_r : riser gas holdup

ε_o : downcomer gas holdup

$A_d \,/\, A_r$: the ratio between cross sectional area of downcomer to riser

3.3.2 Calculation of liquid circulation velocity

The tracer injection method was used to measure the liquid velocity in riser. We can determined the time that tracer traveled between two fixed positions and calculate liquid velocity in riser from:

$$v_{Lr} = \frac{x}{t} \tag{3.17}$$

wher v_{Lr} : riser liquid velocity (*cm/s*)

x : distance of tracer travel (*cm*)

t : tracer travel time (*s*)

Downcomer liquid velocities were calculated from the continuity equation. The relationship between liquid velocity in riser and downcomer was

$$u_{Lr} A_r = u_{Ld} A_d \tag{3.18}$$

$$v_{Lr} A_r (1-\varepsilon_r) = v_{Ld} A_d (1-\varepsilon_d) \tag{3.19}$$

Then

$$v_{Ld} = \frac{v_{Lr} A_r (1-\varepsilon_r)}{A_d (1-\varepsilon_d)} \tag{3.20}$$

where u_{Lr} : superficail liquid velocity in riser (*cm/s*)

u_{Ld} : superficail liquid velocity in downcomer (*cm/s*)

v_{Ld} : liquid velocity in downcomer (*cm/s*)

3.3.3 Calculation of mass transfer coefficient

The volumetric mass transfer coefficient was determined by the dynamic method. The oxygen balance in bioreactor gave:

$$\frac{dC_L}{dt} = k_L a (C_L^* - C_L) \tag{3.21}$$

Integrating both sides of Equation 3.21 from $C_L = 0$ to $C_L = C_L$ led to

$$\ln\frac{(C_L^* - C_o)}{(C_L^* - C_L)} = k_L at \qquad (3.22)$$

where C_L^* : saturation dissolved oxygen concentration. (*%air saturation*)

C_o : initial oxygen concentration in liquid phase (*%air saturation*)

C_L : dissolved oxygen concentration in liquid phases (*%air saturation*)

k_La : overall volumetric mass transfer coefficient (s^{-1})

t : time (s)

In this experiment, liquid was deoxygenated by stripping with nitrogen, and after that nitrogen feed was replaced by air stream. The time profile of dissolved oxygen (DO) concentration in the solution was measured until equilibrium concentration was reached, where k_La was calculated from the slope of DO time profile or, equivalently, from Equation 3.22.

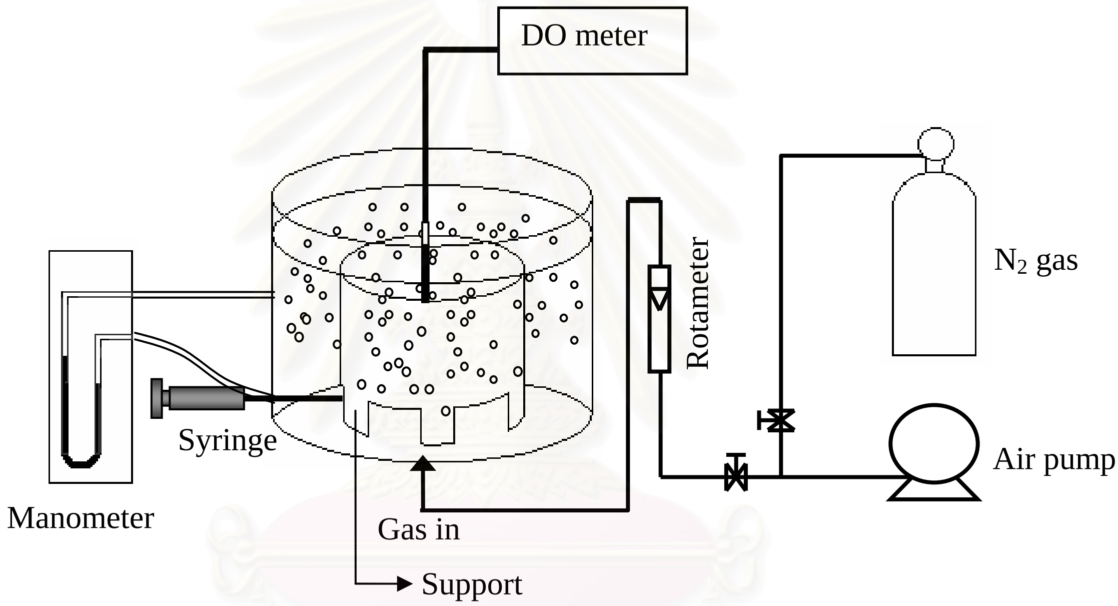


Figure 3.1 Experimental system

Table 3.1 Experimental details for three airlift configurations

Key	Airlift configuration no.	No. of draft tubes used	Draft tube diameter [cm^2]	A_d/A_r	Salinity [ppt]
AC1	1	1	39.5	2.03	30
AC2	2	3	23	2.03	30
AC3	3	4	20	2.03	30

Table 3.2 Experimental details for airlift systems with three downcomer to riser cross sectional area ratios (A_d/A_r)

A_d/A_r	No. of draft tubes used	Draft tubes diameter [cm^2]	Downcomer area [cm^2]	Riser area [cm^2]	Salinity [ppt]
1.27	4	23	1997.34	1576.96	30
2.03	4	20	2402.76	1182.85	30
2.82	4	18	2652.90	940.63	30

Table 3.3 Details for experiments with four salinity levels

Key	Salinity [ppt]	No. of draft tubes used	Draft tube diameter [cm^2]	A_d/A_r
Tap water	0	4	20	2.03
SW15	15	4	20	2.03
SW30	30	4	20	2.03
SW45	45	4	20	2.03

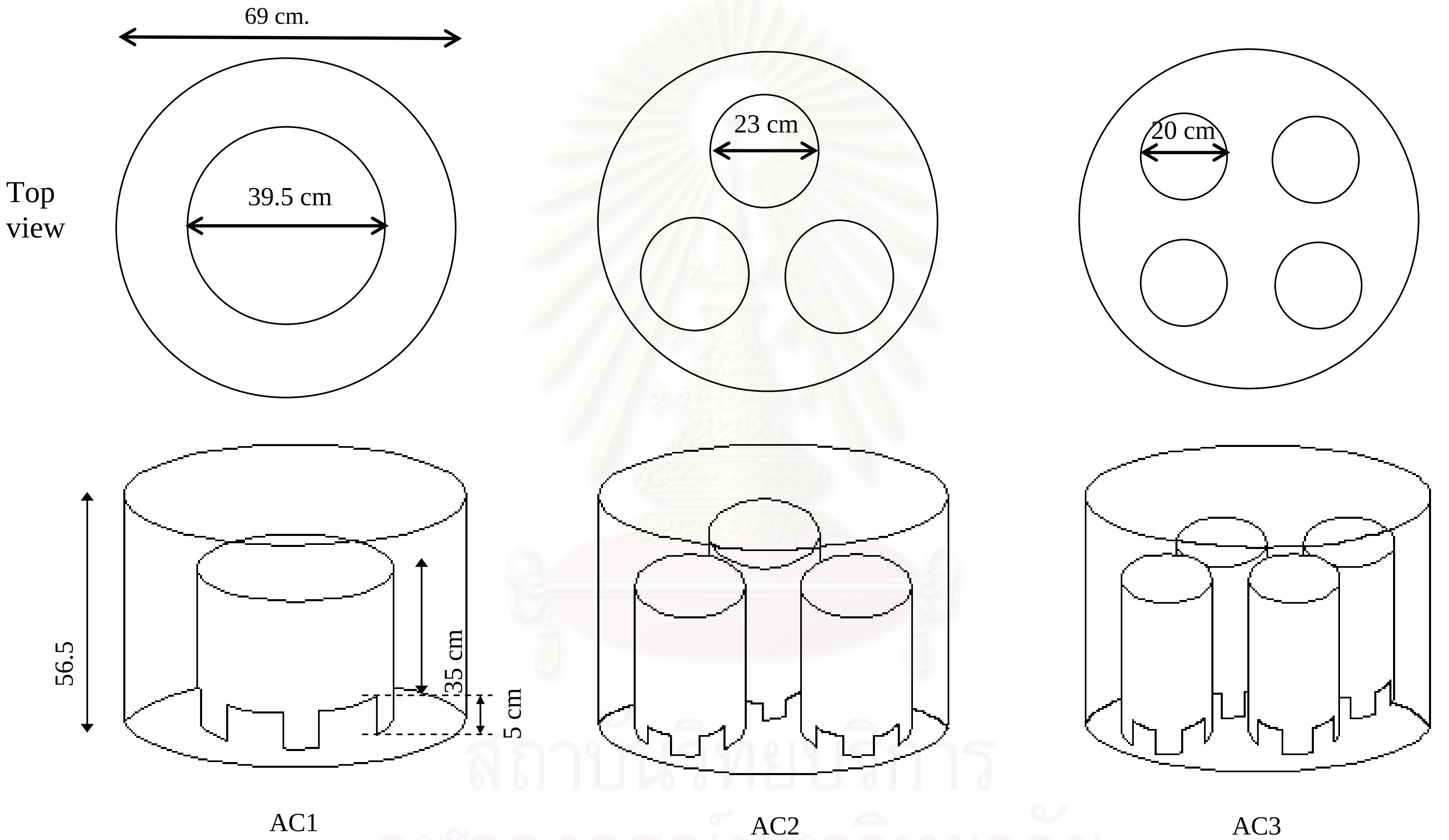


Figure 3.2 Schematic diagram of three airlift configurations

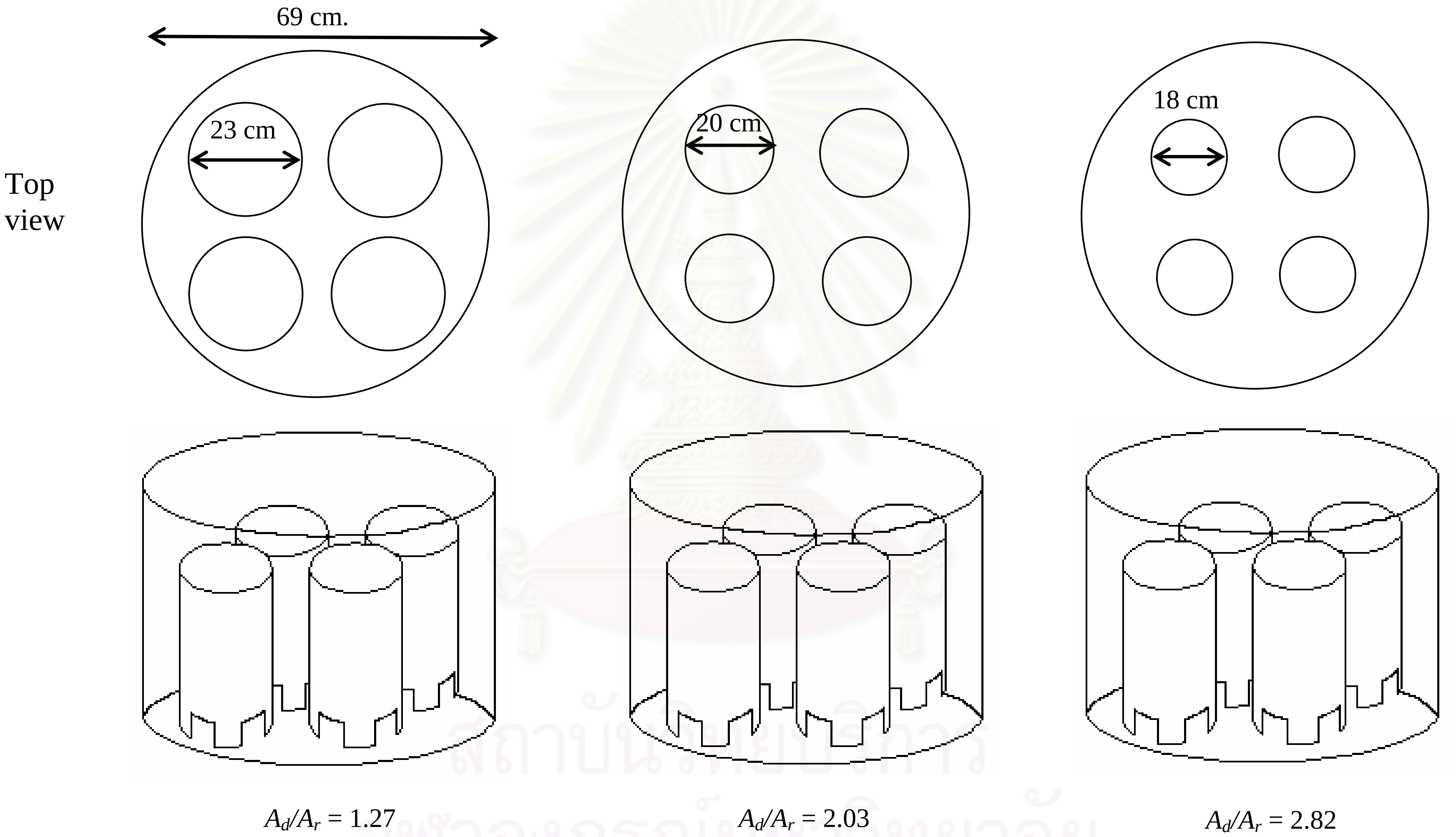


Figure 3.3 Schematic diagram of airlift systems with three A_d/A_r ratios

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Influence of configuration on airlift contactor performance

A large number of research works on the performance of airlift systems have been reported, but few have investigated the influence of configuration of airlift. In the case of airlift contactors with large cross sectional area, the configuration of draft tube could be adjusted to ease the design and operation of the system. This work investigated the potential of applying the multiple draft tube configurations (more than one draft tube) in the airlift system with large cross sectional area with the hypothesis of improving the system performance in terms of gas-liquid mass transfer rate when compared with the conventional, one draft tube, configuration.

Three configurations of airlift contactors were proposed: Configuration#1 (1 draft tube), Configuration#2 (3 draft tubes), and Configuration#3 (4 draft tubes). Note that it was difficult to have the two draft tube configuration as the resulting downcomer area would be highly uneven. The following experimental results were discussed in terms of hydrodynamics and overall volumetric mass transfer coefficient. All configurations in this section were carried out using the downcomer to riser cross sectional area ratio (A_d/A_r) of 2.03 and salinity concentration of 30 ppt. In the following, the notations AC1, AC2 and AC3 are used to refer to airlift Configuration#1, Configuration#2 and Configuration#3, respectively, and the details are shown in Table 3.1 in previous chapter.

4.1.1 Effect of airlift configuration on gas holdups

Gas holdup is the parameter that quantified the fraction of gas in the system. The sectioning in airlift system rendered an uneven distribution of gas bubbles in the system, i.e. gas holdups in riser, in downcomer and overall gas holdups which are the amount of gas in riser and downcomer sections and the overall quantity of gas in the system, respectively. These parameters are affected by the design parameters and the airlift configurations.

From the experimental results, AC1 contained the lowest overall gas holdup (Figure 4.1(a)). The overall gas holdup became larger as the number of draft tubes increased (AC2 and AC3). Similar findings were found for the downcomer and riser gas holdups as displayed in Figures 4.1(b) and 4.1(c), respectively. This phenomenon could be explained as follows:

Visual observation suggested that bubble size was slightly larger in AC1 than those in AC2 and AC3, respectively. This was illustrated by photographs in Figure 4.2 which was the photos of the bubbles inside the riser. However, it was difficult to obtain high precision in photographs of the bubbles in this section due to the focal obstruction of the bubbles in the downcomer which were in between the camera and the riser. These slightly large bubbles might be the result of the bubble coalescence due to the self-contact between individual bubbles. Wongsuchoto and Pavasant (2004) showed that in the system with large riser, the local internal liquid circulation (within riser itself) would play a significant role in controlling the hydrodynamics in the reactor. This local internal circulation might promote the bubble coalescence leading to large bubbles. These bubbles could escape from the system more easily than the small ones and therefore a less number of bubbles were found in the downcomer.

In AC3, the four draft tube configuration provided more area for the recirculation of the bubbles and therefore a much larger fraction of small bubbles were entrained into the downcomer than that in AC2 and AC1 (see Figure 4.3 for the actual photos of the system and Figure 4.4 for the schematic diagram of the recirculation of bubbles). To clarify this point, the following calculation was introduced for the calculation of the ratio between the circumference of the draft tube and the riser cross sectional area, ϕ:

$$\phi = 2\pi R / \pi R^2 \tag{4.1}$$

ϕ AC1 = 0.1013

ϕ AC2 = 0.1739

ϕ AC3 = 0.2000

where R = radius of the draft tube

ϕ represented the opportunity for the small bubbles to be dragged down into the downcomer by the liquid flow. In AC1, ϕ was small which meant that there was only a small space for the bubbles to move down in the downcomer and therefore a large fraction of small bubble left the system at the liquid surface instead. In AC3, ϕ was the largest and, hence, provided more chance of small bubbles to be dragged into the downcomer and caused a higher level of downcomer gas holdup.

In addition, it is generally known that gas bubbles can be entrained into the downcomer when liquid velocity in downcomer is greater than bubble rise velocity. In this case, it was found that, for the same level of superficial gas velocity, the liquid velocity in AC3 was the greatest (see Figure 4.5), followed by that in AC2 and AC1, respectively. This supported the finding that the downcomer gas holdup in AC1 was the lowest among the three, where the greatest value of downcomer gas holdup was obtained in AC3.

In this work, the riser gas holdup was calculated once the overall and downcomer gas holdups were measured using the following equation:

$$\varepsilon_r = \varepsilon_o + (A_d / A_r)(\varepsilon_o - \varepsilon_d) \qquad (4.2)$$

As the overall and downcomer gas holdups exhibited similar characteristics, the product riser gas holdup also presented similar trend. Note that the riser gas holdup in AC2 and AC3 would slightly be affected by the recirculation of bubbles from the downcomer which should marginally increase the level of riser gas holdup. This occurrence should not be found in AC1 where the recirculation of bubbles was not observed at this superficial gas velocity.

4.1.2 Effect of airlift configuration on liquid velocity

Liquid velocity is the main characteristics that differentiate bubble columns from airlift contactor and is one of the key parameters in design and scale-up. Liquid velocity in airlift reactors affects the mixing characteristics of fluids, volumetric mass transfer coefficient, which determines the performance of the contactor.

Although the larger bubbles that generated in AC1 tended to move faster, the one large cross sectional riser area caused the crucial internal recirculation inside itself. This behavior, which was similar to that of the bubble column, led to the lowest value of riser liquid velocity (Figure 4.5).

On the other hand, the highest riser liquid velocity can be achieved from AC3, which had the smallest draft tube diameter. Although AC3 had equal A_d/A_r ratio to other configurations, it had 4 draft tubes. Each draft tube then had only one-forth cross sectional area when compared with AC1. The smallest riser diameter led to the large liquid movement between the riser and the downcomer zones. Liquid and gas moved straightly upward in riser and downward in downcomer (smaller internal recirculation).

The downcomer liquid velocity was determined from the mass conservation equation including the effect of both riser and downcomer gas holdups. This parameter showed the same trend as of the riser liquid velocity. The highest downcomer liquid velocity was also found in AC3 (Figure 4.5). All configurations demonstrated the less values of downcomer liquid velocity than riser liquid velocity. It was because, in this experiment, the cross sectional of the downcomer area was 2.03 times larger than that of the riser. Hence, all downcomer liquid velocities were lower than riser liquid velocities based on the continuity equation.

4.1.3 Effect of airlift configuration on overall volumetric mass transfer coefficient

Overall volumetric mass transfer coefficient (k_La) is one of the major parameters for the design of bioreactors. k_La usually depends on several design parameters such as A_d/A_r, types of sparger, liquid phase properties, and more importantly as the result would reveal, the configuration of the draft tube in the system.

Figure 4.6 illustrates that the configuration or the number of draft tubes in the airlift system (with constant A_d/A_r) significantly influenced the level of k_La. The airlift with one draft tube (AC1) was clearly shown to have inferior level of k_La than the other two configurations whereas the airlift with four draft tube (AC3) was proven to exhibit the highest level. Generally, it was possible to evaluate k_La value in terms of k_L and a separately where "k_L" is the overall mass transfer coefficient and "a" is the specific interfacial area for gas-liquid mass transfer. The reasons for low k_La in AC1 can be detailed as follows:

Firstly, it was previously shown that AC1 was operated with the smallest quantity of air and also with the lowest liquid velocity (Sections 4.1.1 and 4.1.2). The low liquid velocity suggested that there was a rather low level of gas bubbles in the downcomer. In addition, a large, single draft tube did not provide adequate space for the return of the gas bubbles as some of the gas bubbles, if they were in the middle of the draft tube, would not be dragged down to the downcomer but would leave the system at the liquid surface. In fact, the gas-liquid mass transfer should depend more significantly on the riser gas fraction as it was still fresh with high level of oxygen which enhanced the driving force for the transfer between gas and liquid. However, since the system employed in this work was rather short with the height of only 47 cm, gas bubbles in the downcomer were therefore still enriched in oxygen and could play a significant role in interfacial mass transfer. Hence, the loss of gas bubbles indicated the loss of total amount of gas required for mass transfer in the system, and therefore a lower k_La could be well observed.

Next, it seemed that bubble size in AC1 was found to be larger than those in other configurations. This might be due to a greater coalescence of bubbles. The surface area of large bubble is evidently lesser when compared with small bubble size.

The two reasons above led to the reduction of mass transfer area (a) in the system and, hence, the decrease of k_La values. Finally, it can be concluded that, in case of multiple draft tube configuration (AC2 and AC3), the more number of draft tube presented the more perimeter of draft tube which contributed to enhance the contacting surface between riser and downcomer. Thus, large quantity of gas was dragged within the system. This was exposed to improve the interfacial area of gas for mass transfer in the system. Therefore AC3 which possessed the largest perimeter obtained the greatest value of k_La.

4.2 Influence of downcomer to riser cross-sectional area ratio on airlift contactor performance

The information about the influence of airlift reactor geometry such as the downcomer to riser cross sectional area ratio (A_d/A_r) was always used in the consideration during scale-up and design purposes. Most of the literature demonstrated that higher A_d/A_r provided lower gas holdups and lower overall volumetric mass transfer coefficient but higher riser liquid velocity. However, only few works had focused on large-scale airlift systems, and often they only considered the configuration with one-draft tube in the system. In this section, the effect of A_d/A_r in the airlift system with multiple draft tubes was the main focus. Only the system with four draft tubes was selected as a modeled study as they were demonstrated to have the best performance with respect to the gas-liquid mass transfer. The superficial gas velocity supplied to the contactor was set at 2 cm s^{-1} and the salinity was at 30 ppt. The details for the various configurations (with three A_d/A_r) of the airlift contactor employed in this section were illustrated in Table 3.2 (Chapter3)

4.2.1 Effect of A_d/A_r on gas holdups

Figure 4.7 demonstrates the influence of A_d/A_r on the gas holdups in the airlift system at the superficial gas velocity of 2.0 cm/s. It was found that the operation at the largest downcomer (highest A_d/A_r of 2.82) provided the lowest gas holdups in all regions of the airlift. As A_d/A_r became smaller than this level, the gas holdups increased. To explain this result, it is recommended that the riser liquid velocity be examined, and this is shown in Figure 4.11. At the same gas input, the liquid in riser moved faster in the airlift with the larger A_d/A_r. This was because the larger A_d/A_r system had a smaller riser cross sectional area (A_r) where bubbles seemed to be stream-lined and moved at a faster speed to the top and therefore most bubbles tended to leave the system instead of moved down into the downcomer. In addition, it was also noted that high A_d/A_r was referred to the system with a large downcomer area (A_d). This simply meant that, according to the continuity equation, the liquid velocity in the downcomer was rather low when compared with the system with smaller A_d/A_r (See details of liquid velocity in Section 4.2.2). Since the bubble size did not vary significantly with A_d/A_r (see the variation in bubble sizes in the systems with different levels of A_d/A_r as shown in Figure 4.8), the bubble rise velocity did not change with a change in A_d/A_r. In this case, the downcomer liquid velocity was not high enough to drag the bubbles down to the downcomer. Figure 4.9 illustrates the magnitude of bubble entrainment in the downcomer which shows that the system with the largest A_d/A_r had the lowest quantity of bubble entrained. This is schematically described again in Figure 4.10 (c). As a result, a large fraction of gas bubbles were separated from the system at the top part. Hence, low level of gas holdups both overall and in the downcomer became obvious at A_d/A_r = 2.82.

On the other hand, in the system with A_d/A_r of 1.27, or the smallest A_d/A_r employed in this study, a faster liquid movement in downcomer became apparent. This was because smaller A_d enhanced the entrainment of gas bubbles to the downcomer part (Figures 4.9 and 4.10 (a)). Therefore, a higher level of downcomer and overall gas holdups was noticed.

It was observed that A_d/A_r significantly affected the riser gas holdup where a higher riser gas holdup was observed in the airlift with smaller A_d/A_r as illustrated in Figure 4.7. Although the bubbles size did not notably change with A_d/A_r (as stated earlier), a higher level of riser liquid velocity in the airlift with larger A_d/A_r led to a decrease in the time bubbles spent in the riser and, hence, the reduction of the gas fraction in the riser could be seen. This occurrence was also consistent with those of previous reports regarding the conventional one draft tube configuration.

4.2.2 Effect of A_d/A_r on liquid velocity

As described in the previous section, the system with a larger draft tube area, which appeared in the airlift with smaller A_d/A_r, had a lower riser liquid velocity than the system with higher A_d/A_r. In reality, the hydrodynamic behavior of the airlift with a large fraction of riser approached to that in a bubble column. Hence, most liquid and gas bubbles recirculated within the draft tube itself (large internal recirculation). Therefore Figure 4.11 evidently demonstrates the lowest riser liquid velocity in the airlift with A_d/A_r 1.27. In fact, it was expected that the internal liquid circulation would take place more significantly in the airlift with large riser as it was difficult to obtain a well distributed bubble density in the riser (see Wongsuchoto and Pavasant, 2004). The poor distribution of gas around the contactor also caused the inferior contacting of gas bubbles and liquid phase which exerted negative effects for gas-liquid mass transfer. Figure 4.12 schematically describes the internal liquid circulation in the airlift system with large A_d/A_r.

According to the continuity equation, the downcomer liquid velocities were found to be lower than riser liquid velocities for all A_d/A_r. Although the riser liquid velocity increased with an enlarged A_d/A_r, the downcomer liquid velocities exhibited a reverse trend. The greatest value of downcomer liquid velocity was observed in the system with the smallest A_d/A_r (1.27) (Figure 4.11). This was not surprising as a small downcomer has lower area for the liquid movement, and therefore, to keep the flow balanced between riser and downcomer, the small downcomer area needs to let the fluid flowed through at higher velocity.

4.2.3 Effect of A_d/A_r on overall volumetric mass transfer coefficient

The overall volumetric gas-liquid mass transfer coefficient, k_La, is strongly influenced by many factors as described above. The geometrical structure, A_d/A_r, is also the one, which represented the basic parameter that most of research focused on. However, the effect of A_d/A_r on multiple draft tube airlift configuration was not available. Figure 4.13 shows the effects of A_d/A_r on k_La for this proposed configuration. It was found that k_La increased with decreasing A_d/A_r.

As mentioned earlier, the condition of low downcomer liquid velocity, found in the airlift with a large A_d/A_r, led to a significant loss of gas bubbles at the liquid surface which then resulted in small downcomer and overall gas holdups. These incidents caused a decrease of mass transfer interfacial area. As a result, the poorest k_La was observed in A_d/A_r of 2.82. In other words, A_d/A_r of 1.27, the smallest downcomer area employed in this work, caused the highest entrainment of gas bubbles and, hence, the highest surface area for gas-liquid transfer.

Moreover, although an airlift with a lower A_d/A_r tended to have a greater k_La than the system with a large A_d/A_r, the behavior of such system would approach that of the bubble column. In this case, a very low liquid velocity and the crucially large internal recirculation inside the draft tube took place. This, although does not show notable impact on the transfer between gas and liquid, will not be attractive in the system with solid suspension such as biological systems where cells are to be circulated in the liquid phase. A low liquid velocity would imply a higher chance of cell settlement which will be bad for the cultivation system. On the other hand, at a very large A_d/A_r, the appearance of a strong liquid velocity can support the gas-liquid mixing due to turbulence in the movement and thus improving the k_La. At the end, it is difficult to state the optimal level of A_d/A_r as the selection of this parameter depends markedly on the purposes of application.

4.3 Influence of salinity on airlift contactor performance

The application of airlift bioreactor in aquaculture industry can involve the use of seawater with various salinity levels. Salinity affects the physical properties of the liquid and, hence, can have significant influences on airlift performance. Therefore it is important that the effects of salinity on the system behavior is fully understood.

The aim of this section is to examine the influence of salinity on gas holdup, liquid velocity, and overall volumetric mass transfer coefficient. The airlift system using the mixture of tap water and seawater at salinity of 15, 30, 45 part per thousand (ppt) were investigated. All experiments were performed in the 170L airlift contactor with four 20 cm i.d. internal draft tubes where A_d/A_r was fixed at 2.03. In the hereafter discussion, "SW" is defined as seawater and the number following "SW" indicated the level of salinity in the unit of ppt, e.g. SW15 = seawater at salinity of 15 ppt. The details for salinity used in this work are shown in Table 3.3 (Chapter3).

4.3.1 Effect of salinity on gas holdups

Figure 4.14 illustrates gas holdups in the airlift contactor at different locations in four salinity levels (all at u_{sg} = 2 cm/s). It was obvious that seawater played a significant role in enhancing the overall gas holdup and it was shown that the system running with fresh tap water always had the lowest level of gas holdups. However, gas holdups in the seawater were not found to be strongly affected by the level of salinity and the little change was discovered.

Salinity changed the physical property of the liquid by changing the surface tension, viscosity and density where higher salinity levels always result in higher levels of such parameters. The surface tension strongly affected the bubble size in the system (Limpanuphab, 2003). High surface tension at high salinity level indicated stronger bubbles surface force, and therefore a lower level of bubble coalescence became apparent. This was reflected in the photos of the bubbles in the systems running with solutions with different salinity levels (Figure 4.15), i.e. bubble size in the system with tap water was in the range of 2-4 mm whereas that in the system with SW15 was about 0.5-1 mm, SW30 0.3-1 mm, and SW45 0.25-1 mm. Note that in this experiment, gas injected through the sparger was fast which did not allow the formation of large bubble.

As stated above, in the system with fresh tap water, coalescence seemed to take place more extensively as a result of bubble-bubble interaction. This resulted in a larger bubble size (Figure 4.15 (a)). Large bubble moved upwards rapidly due to its high buoyancy force and caused a poor recirculation of bubbles within the system. This phenomenon is shown as a photograph of the actual system in Figure 4.16 (a) and schematically in Figure 4.17 (a). This loss of bubbles reduced the total gas volume which was reflected in the low overall gas holdup.

The overall gas holdups in the airlift contactors operating at the various levels of salinity were found to increase with enhancing salinity level. Experiments revealed that the system with SW45 accommodated a slightly higher downcomer and riser gas holdup than the system with SW30 and SW15, respectively. This was because the slight lowest of bubble size in SW 45 facilitated the inducement of gas bubbles into the downcomer and within the system. According to approximate the same downcomer liquid velocity in all seawater levels (Section 4.3.2), the small bubbles in SW45 also provided the best bubbles recircuration to the riser Figure 4.17 (d) which improved the fraction of gas in the riser zone. Moreover, this smaller bubble size increased the bubble residence time and also led to the higher riser gas holdup.

4.3.2 Effect of salinity on liquid velocity

Figure 4.18 illustrates the effect of salinity on the liquid velocities. It was observed that both riser and downcomer liquid velocities in the system with tap water were slightly higher than that obtained in the airlift with seawater. This was because the system with tap water was operated with larger bubble size. The larger bubble moved at the faster speed than the smaller one due to its high buoyancy force and therefore induced, through a momentum and energy transfer, a higher liquid movement. However, in this experiment, the different in seawater levels (15, 30, and 45 ppt) were not found influence on liquid velocities.

4.3.3 Effect of salinity on overall volumetric mass transfer coefficient

The overall volumetric mass transfer coefficient, k_La, was clearly shown to be more superior in the system operated with seawater at high salinity (see Figure 4.19). Previous discussion demonstrated that liquid velocities and gas holdups were not significantly affected by the salinity. Therefore it was expected that k_La would not have been markedly influenced by salinity neither. Higher k_La was, in fact, due to the effect of bubble size which was altered as a result of changes in salinity. At high salinity, bubble size became small and this increased the interfacial area between gas and liquid. This meant that the specific surface area, "*a*", which is one of the main components in k_La increased with salinity. As a matter of fact, "k_L" was regulated by the difference between the liquid and bubble velocities and therefore the bubble size would also have effects on this parameter. In other words, larger bubbles would move at faster speed, and as the liquid velocity was not changed with salinity, the system with larger bubbles would have had a larger difference in bubble and liquid velocities. This led to an increase in "k_L". The apparent k_La was therefore a result of these two effects, and this experiment proved that the effect of salinity on "*a*" was more significant than that on "k_L".

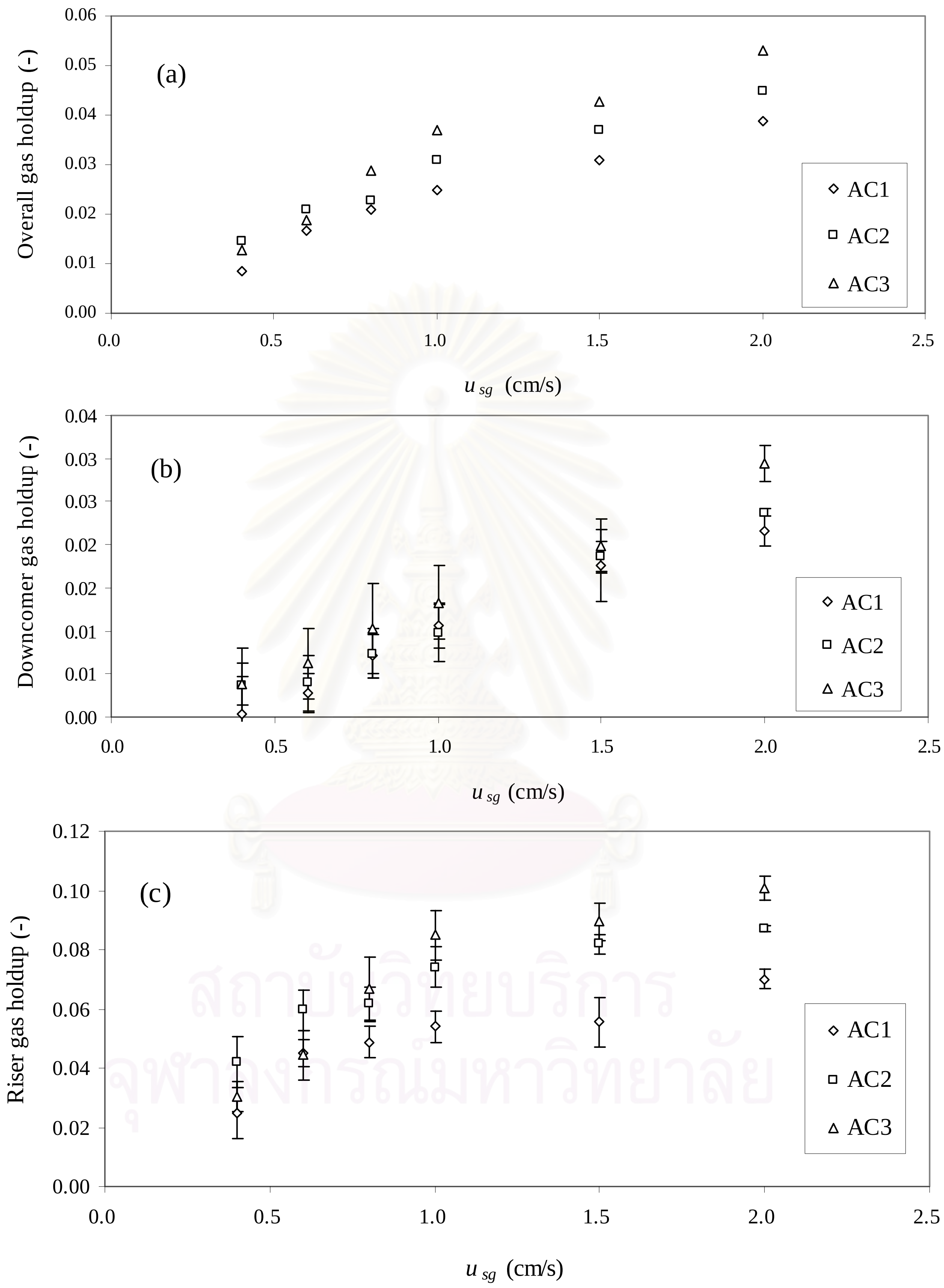
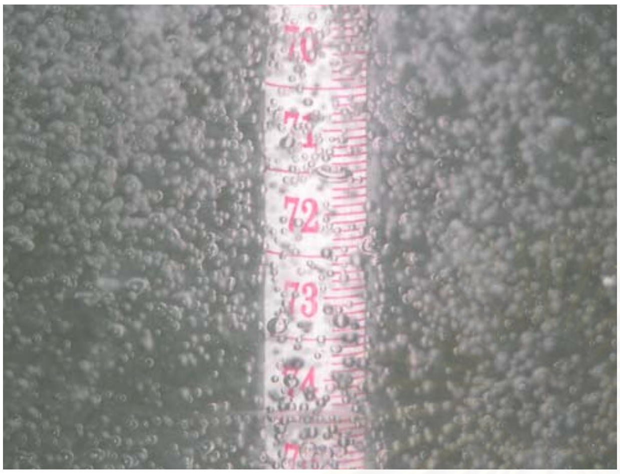
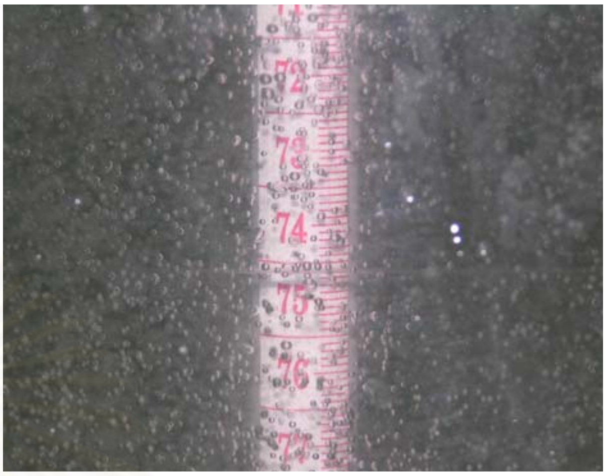


Figure 4.1 Effect of airlift configurations on gas holdups (A_d/A_r=2.03, SW30)

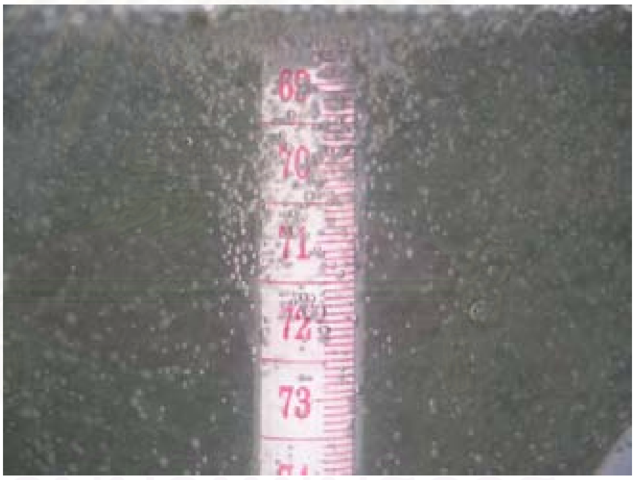
(note that: AC1=airlift configuration#1, AC2=configuration#2 and AC3=airlift configuration#3)



(a) AC1



(b) AC2



(c) AC3

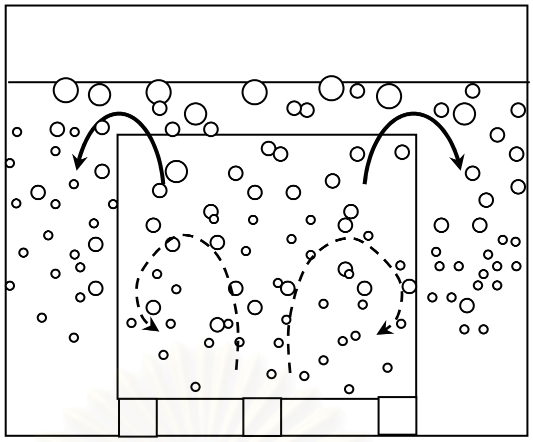
Figure 4.2 Bubble sizes obtained from the system with different airlift configurations (A_d/A_r=2.03, SW30)

(a) AC1

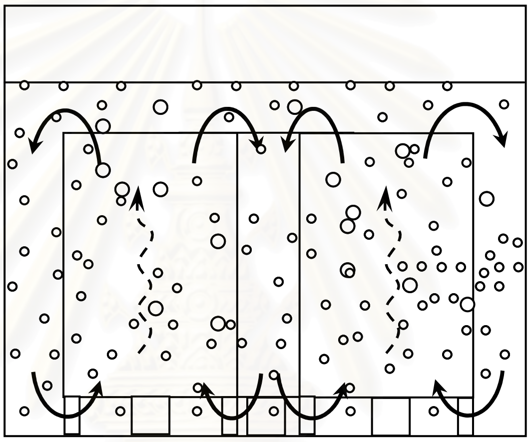
(b) AC2

(c) AC3

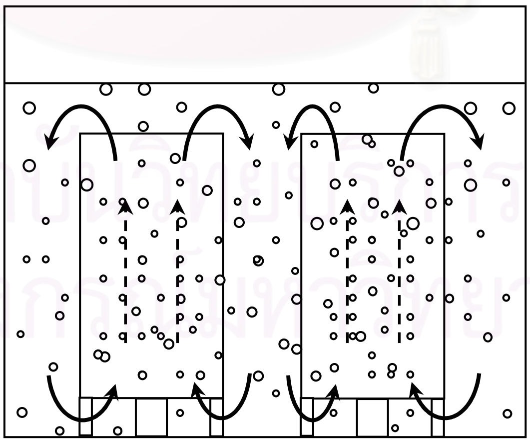
Figure 4.3 Entrainment of gas bubbles in the system with different airlift configurations (A_d/A_r =2.03, SW30)



(a) AC1 (1 draft tube)



(b) AC2 (3 draft tubes)



(c) AC3 (4 draft tubes)

Figure 4.4 Schematics of bubble entrainment in the system with different airlift configurations (A_d/A_r=2.03, SW30)

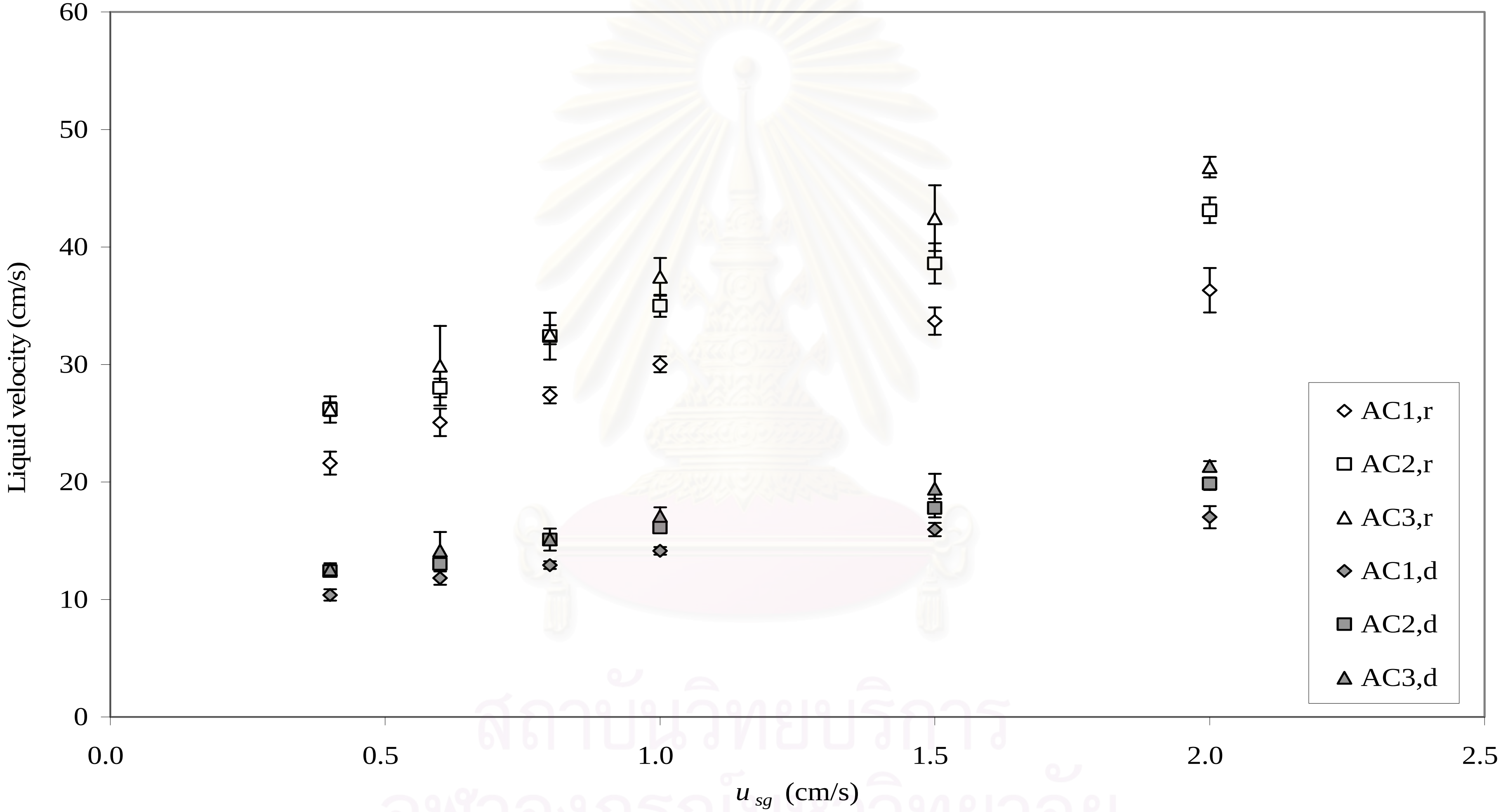


Figure 4.5 Effect of airlift configurations on liquid velocity (A_d/A_r=2.03, SW30)
(note that: subscipt r=riser and subscript d=downcomer)

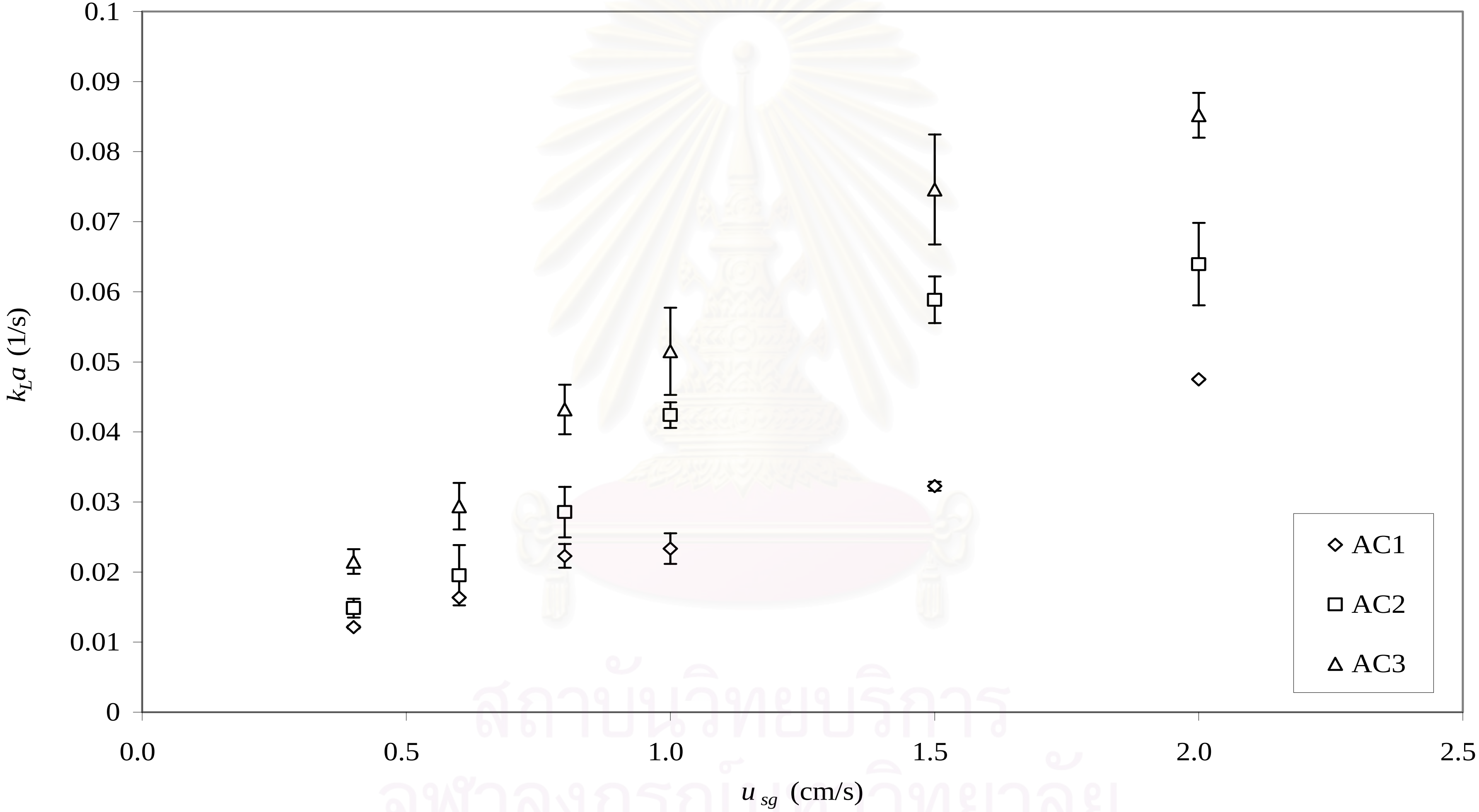


Figure 4.6 Effect of airlift configurations on overall volumertic mass transfer coefficient (A_d/A_r=2.03, SW30)

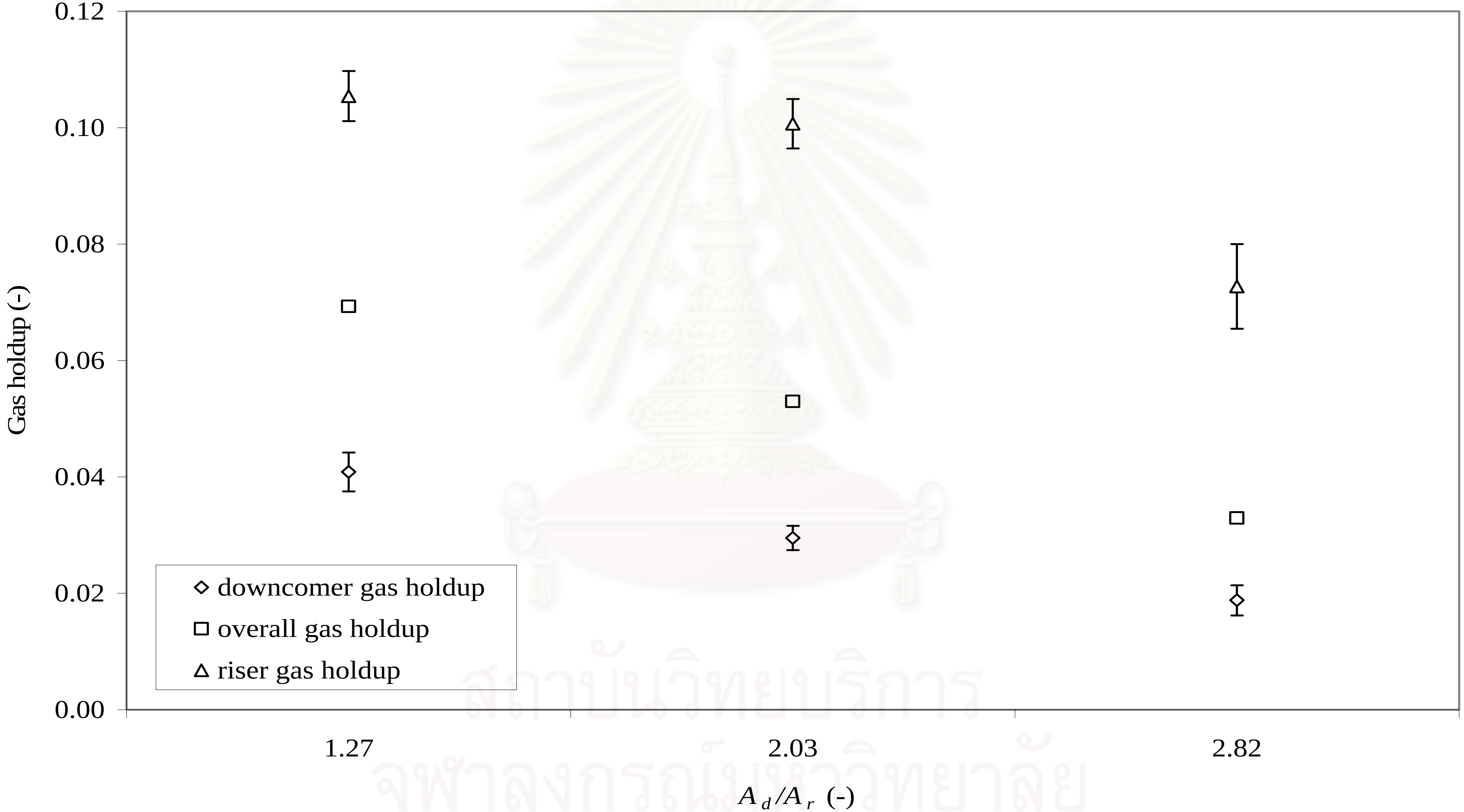
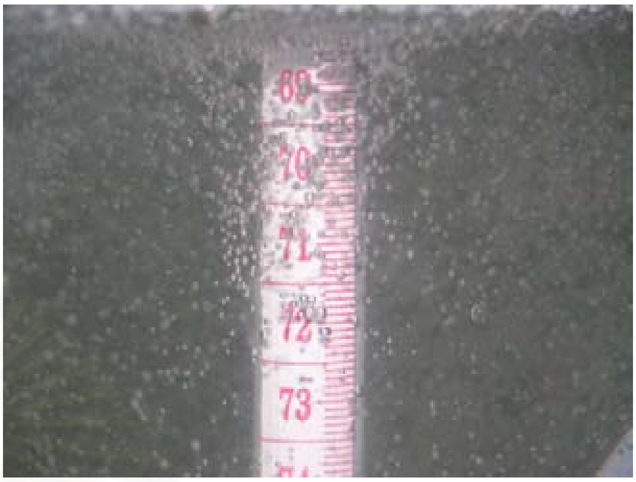
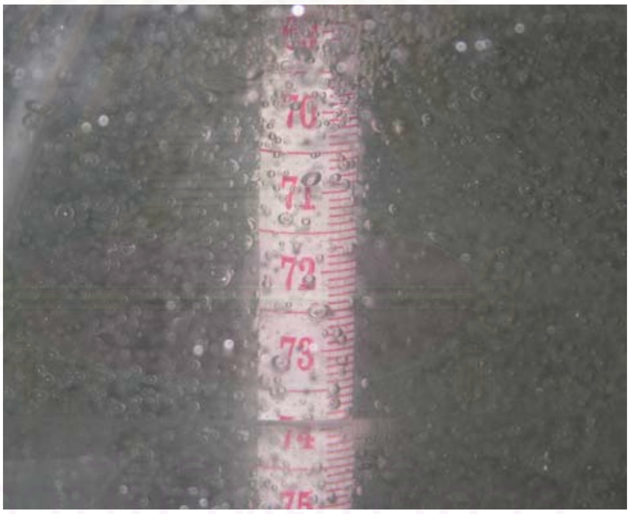


Figure 4.7 Effect of A_d/A_r on gas holdups (airlift configuration#3, SW30, u_{sg} =2.0 cm/s)

(a) A_d/A_r=1.27



(b) A_d/A_r=2.03



(c) A_d/A_r=2.82

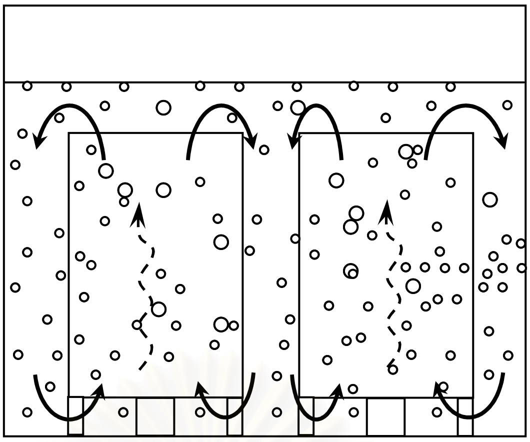
Figure 4.8 Bubble sizes obtained from the system with different A_d/A_r (airlift configuration#3, SW30)

(a) A_d/A_r=1.27

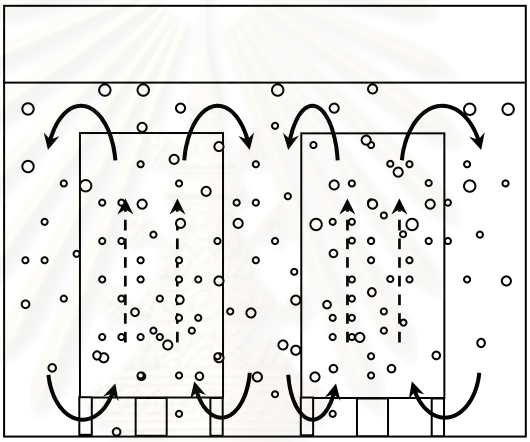
(b) A_d/A_r=2.03

(c) A_d/A_r=2.82

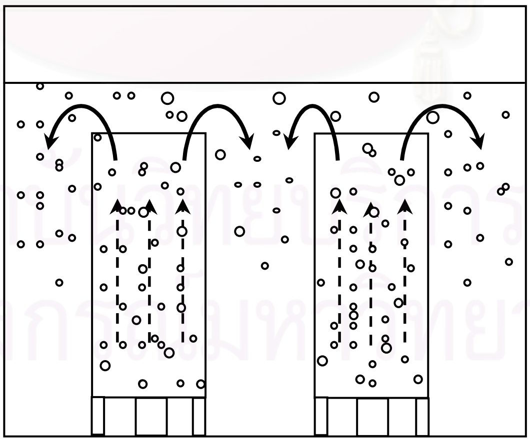
Figure 4.9 Entrainment of gas bubbles in the system with different A_d/A_r (airlift configuration#3, SW30)



(a) A_d/A_r = 1.27



(b) A_d/A_r = 2.03



(c) A_d/A_r = 2.82

Figure 4.10 Schematics of bubble entrainment in the system with different A_d/A_r (airlift configuration#3, SW30)

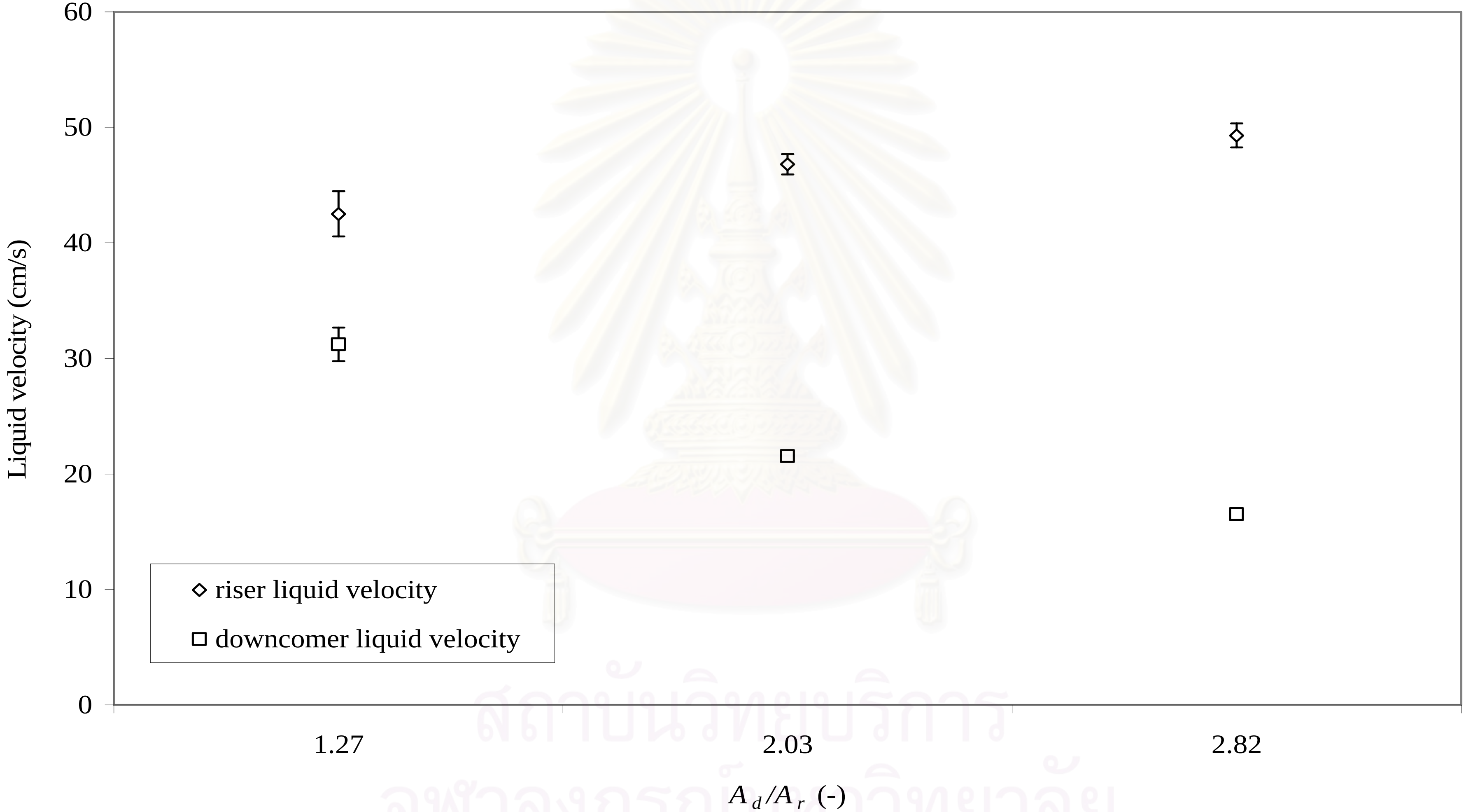


Figure 4.11 Effect of A_d/A_r on liquid velocity (airlift configuration#3, SW30, u_{sg} =2.0 cm/s)

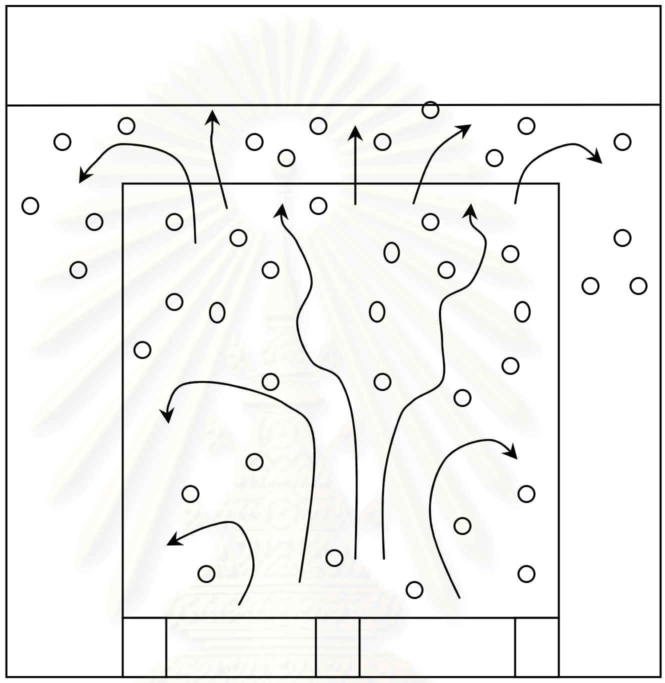


Figure 4.12 Schematic diagram of internal liquid circulation in the airlift system with large A_d/A_r

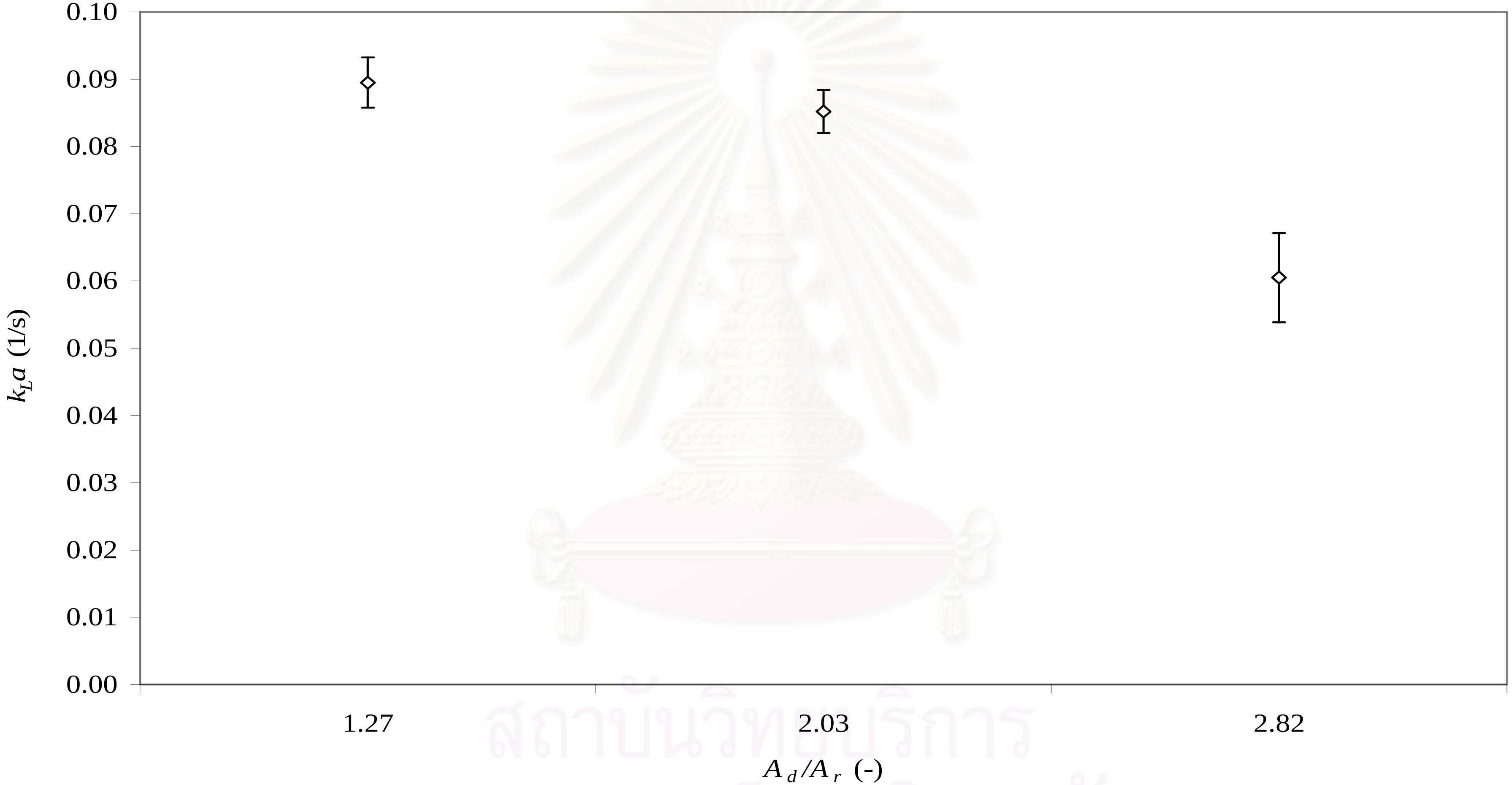


Figure 4.13 Effect of A_d/A_r on overall volumetric mass transfer coefficient (airlift configuration#3, SW30, u_{sg} =2.0 cm/s)

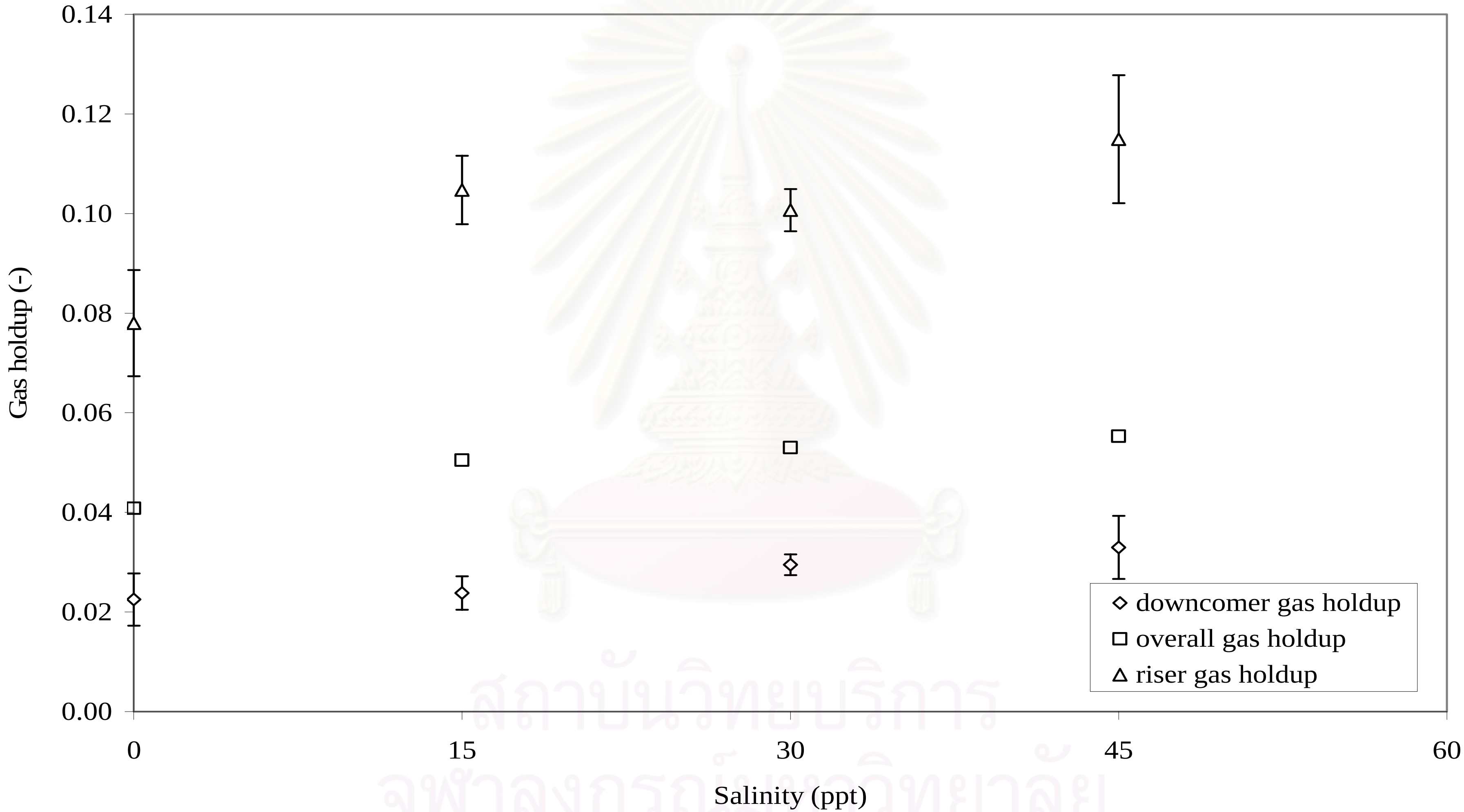
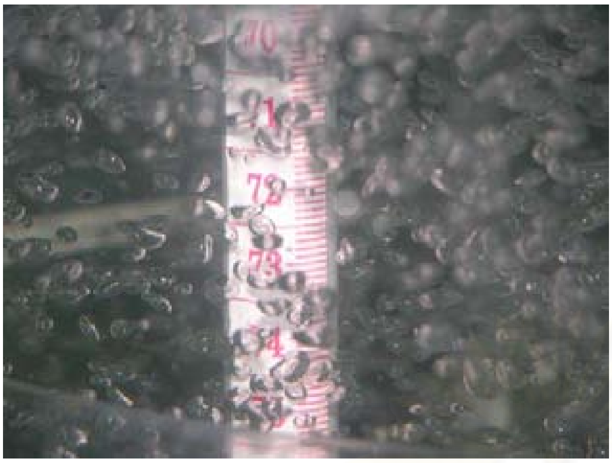
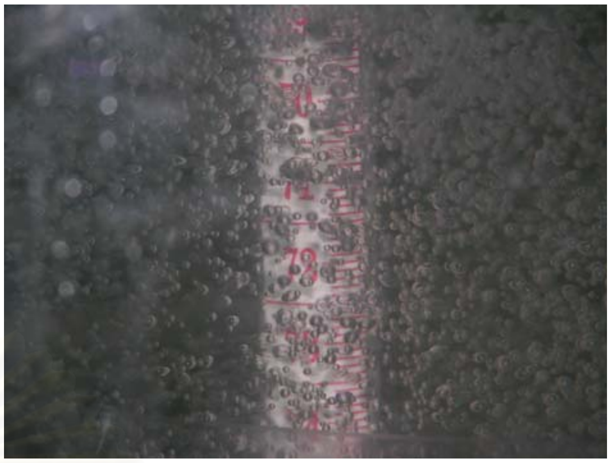


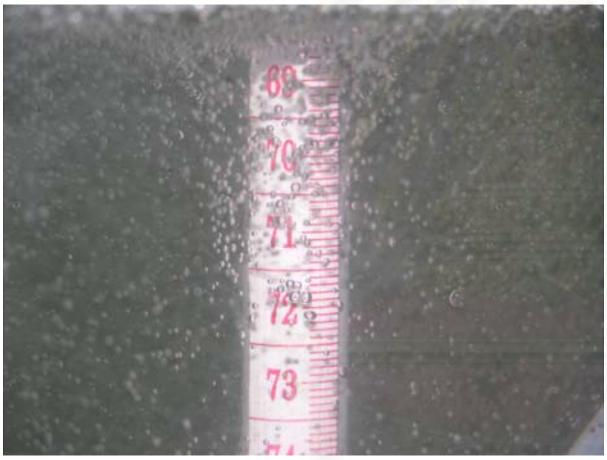
Figure 4.14 Effect of salinity on gas holdups (airlift configuration#3, A_d/A_r =2.03, u_{sg} =2.0 cm/s)



(a) Tap water



(b) SW15



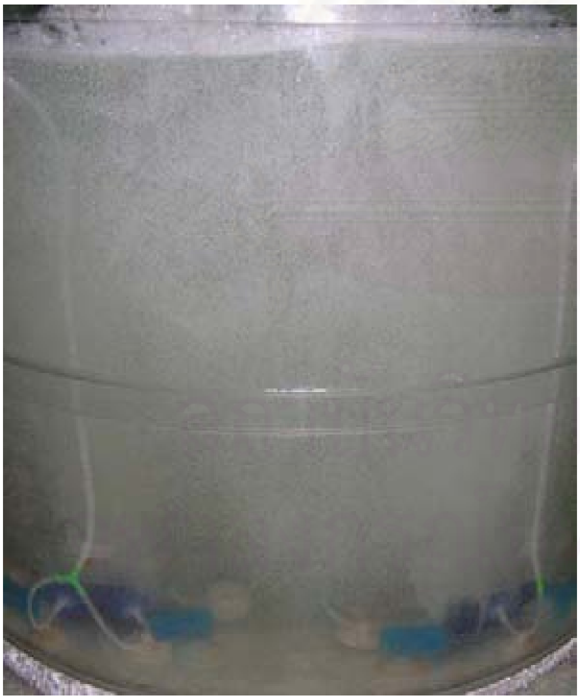
(c) SW30

(d) SW45

Figure 4.15 Bubble sizes obtained from the system with different levels of salinity (airlift configuration#3, A_d/A_r =2.03)

(a) Tap water

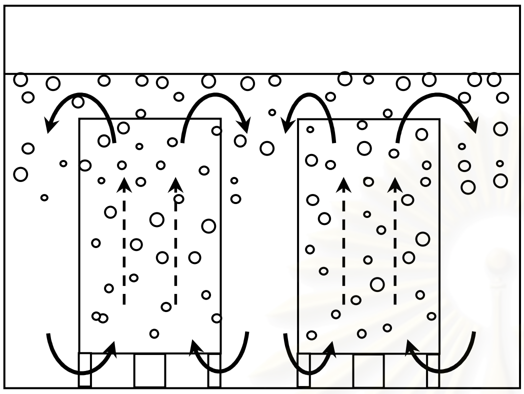
(b) SW15



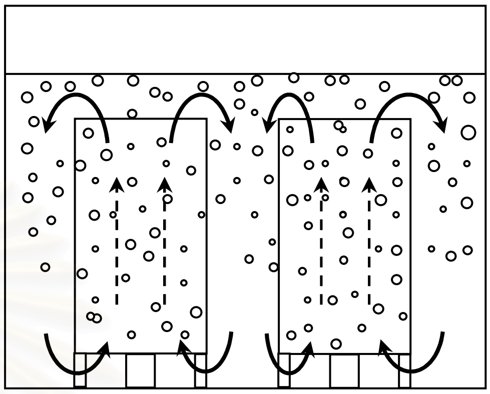
(c) SW30

(d) SW45

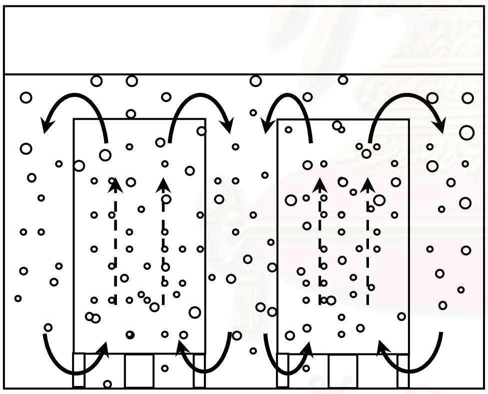
Figure 4.16 Entrainment of gas bubbles in the system with different levels of salinity (airlift configuration#3, A_d/A_r =2.03)



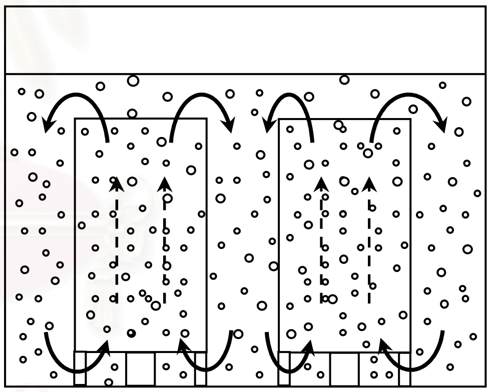
(a) Tap water



(b) SW15



(c) SW30



(d) SW45

Figure 4.17 Schematics of bubble entrainment in the system with different levels of salinity (airlift configuration#3, A_d/A_r =2.03)

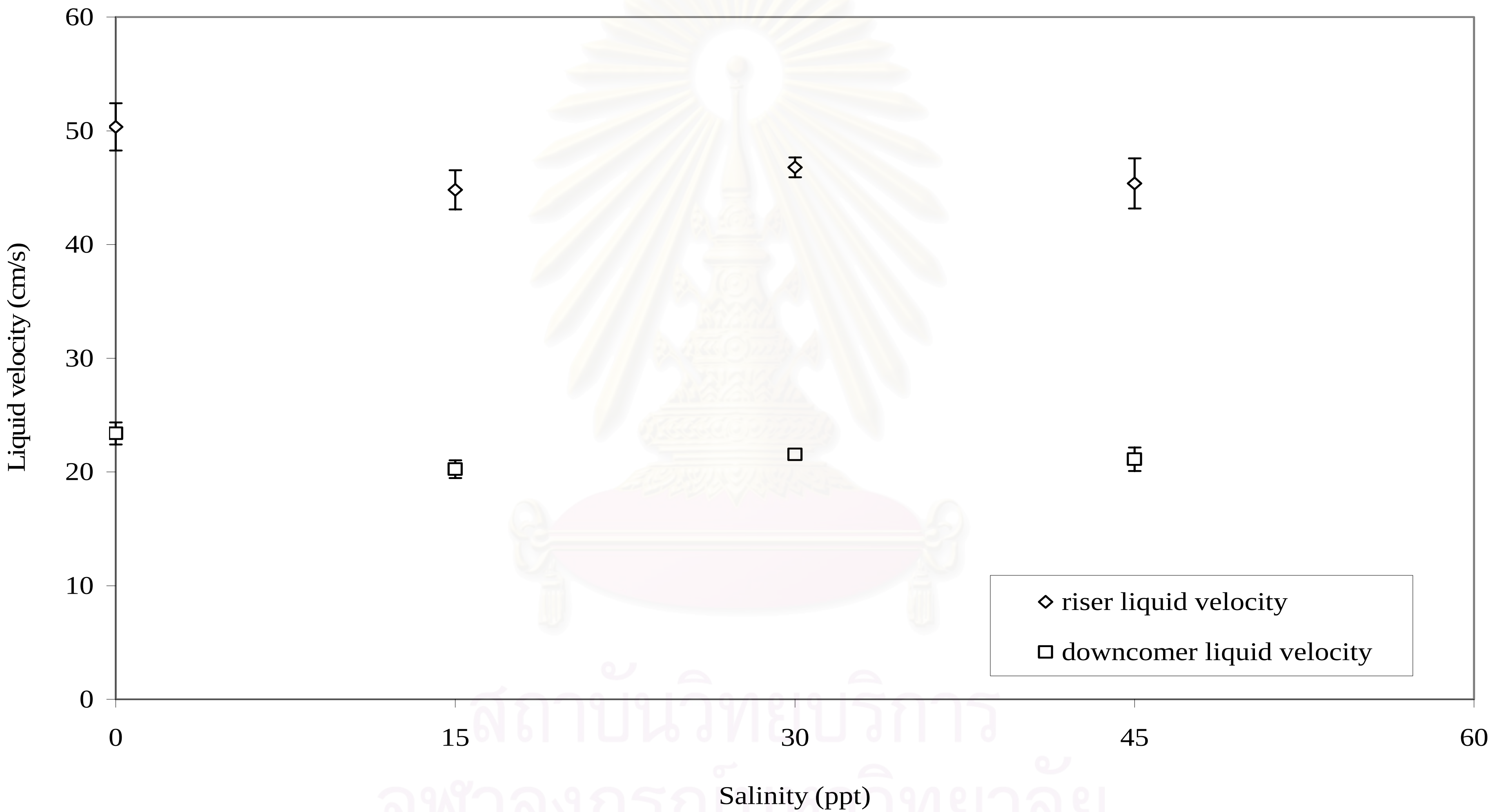


Figure 4.18 Effect of salinity on liquid velocity (airlift configuration#3, A_d/A_r =2.03, u_{sg} =2.0 cm/s)

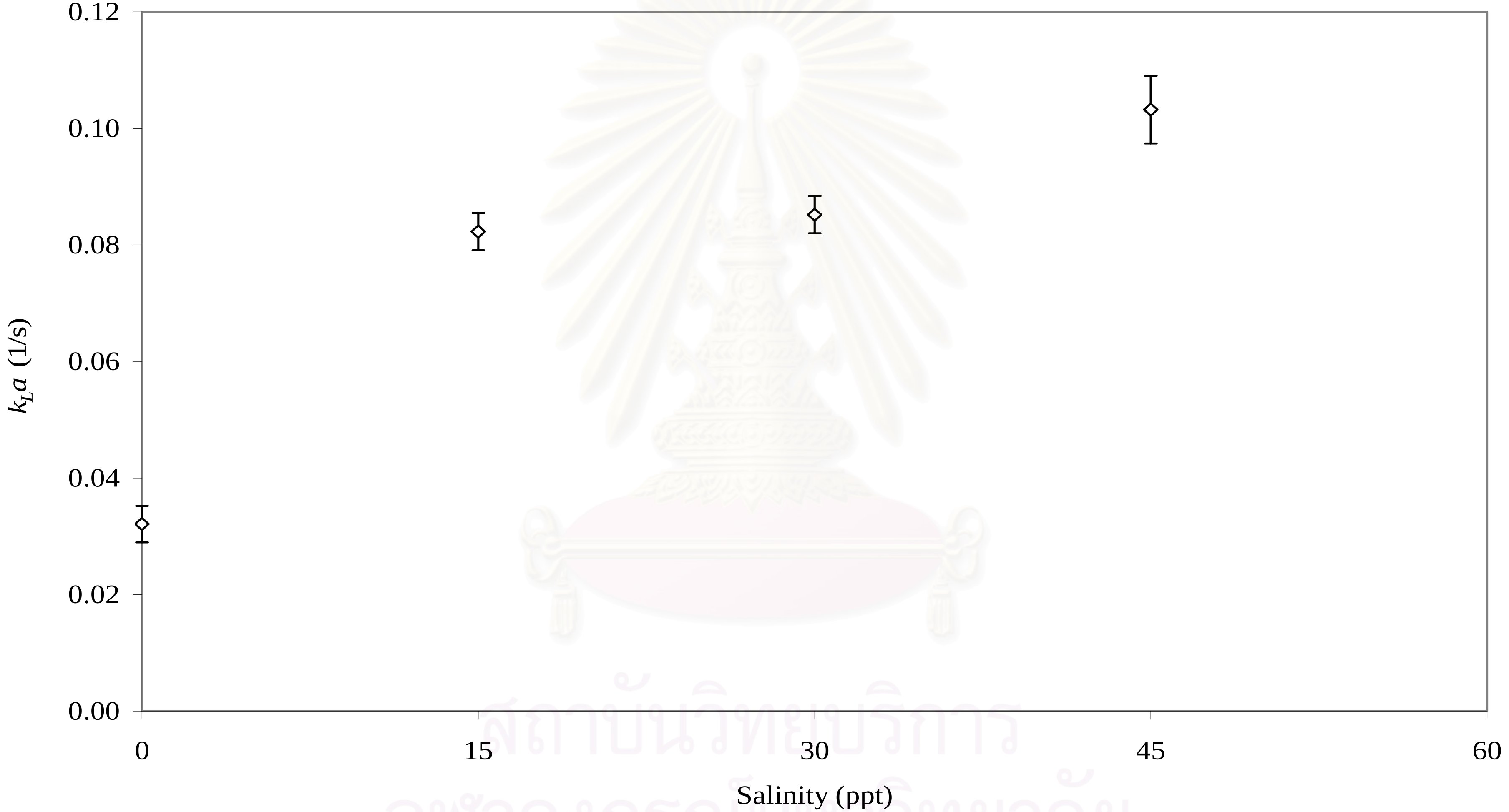


Figure 4.19 Effect of salinity on overall volumetric mass transfer coefficient (airlift configuration#3, A_d/A_r=2.03, u_{sg}=2.0 cm/s)

CHAPTER V

CONCLUSIONS

5.1 Achievements

This work was completed with the following main achievements:

1. In the case of a large cross sectional area airlift contactor, the use of conventional one large draft tube configuration exhibited the local recirculation of liquid and gas bubbles. This behavior approached that which was taken place in the bubble column which caused inferior hydrodynamics and mass transfer data. The application of multiple draft tubes, which enhanced the contacting surface between riser and downcomer parts, demonstrated to be a preferable configuration as an improved system performance in terms of gas-liquid mass transfer could be achieved. It was concluded that the liquid velocities both in riser and downcomer increased as the numbers of draft tubes increased. The faster liquid motion provided a better liquid and gas entrainment to the downcomer (small loss of gas out of the system) and increased the overall and downcomer gas holdups. Therefore a larger number of draft tubes implied a higher gas-liquid interfacial area required for mass transfer which led to a higher k_La.

2. The downcomer to riser cross sectional areas ratio (A_d/A_r) was proven to be one of the most significant parameters that influenced the multiple draft tube system performance. The higher A_d/A_r, or equivalent to the system with a small riser area, demonstrated a higher riser liquid velocity but lower downcomer liquid velocity. This condition led to a lower overall and downcomer gas holdups as a result of low liquid recirculating velocity which was inadequate to entrain gas bubbles into the downcomer and cause the circulation within the system. Furthermore, the riser gas holdup was also found to decrease with an increase in A_d/A_r as the faster liquid velocity reduced the retention time of bubbles in the system. As there was a large disengagement of gas bubbles at

high A_d/A_r, a poorer gas-liquid mass transfer area was resulted and thus a low gas-liquid mass transfer rate.

3. High salinity contributed to a high surface tension. The high surface tension led to a generation of smaller bubble because strong surface force interrupted the bubble coalescence. Since the bubble interfacial areas played a significant role on controlling the overall rate of mass transfer in the system, a high salinity system resulted in a higher gas-liquid mass transfer area and therefore became more favorable in terms of inducing high gas-liquid mass transfer rate. However, the effect of salinity on liquid velocity was not well observed from this work. Gas holdups were found to increase with salinity for the reason that small bubble size generated from high salinity condition moved more slowly and therefore spent more time in the system.

5.2 Contributions

Although a large number of investigations on airlift systems have been reported, the study of the performance of the airlift system with a multiple draft tube configuration was not found. This novel new configuration was proven to be appropriate for the system with large cross sectional area. Therefore, this work contributed greatly to the basic knowledge on the future design of the airlift system, note that hydrodynamics and mass transfer could now be related to the variety in geometrical structure. In addition, the analysis of air-seawater system with large scale multiple draft tube airlift contactor as presented in this work will be a good starting point for the design of the novel aquacultural system which should be one of the main research streams in Thailand.

5.3 Recommendations

It is still difficult, from the data revealed in this work, to conclude that the configuration with four draft tubes was the optimal for the design of large scale airlift contacting systems. This is because four draft tubes were at the edge of the scope of the work. It is therefore possible that if the system is larger, one would probably like to have a system with more draft tubes. However, the effect of wall friction can be serious in such systems and this aspect is not included at all in this work. It is therefore recommended that the future work should be conducted to investigate the effect of wall effect on the performance of this large scale, multiple draft tube, airlift contactor. This is not to mention the increasing fabricating cost if the number of draft tubes increases. This point is therefore also opened for further discussion.

Furthermore, the effects of salinity on liquid velocity were still unclear. Further studies should also be considered to verify this point. In addition, bubble size distribution in this large scale system would be ideal for the examination of the gas-liquid mass transfer behavior in such system. This should also be considered as a future work.

The design of sparger was also an interesting aspect that should be taken seriously into consideration, particularly in large scale systems. The differences in sparger types and the sparger orifices also caused the variation of bubbles size generated which is crucial for the evaluation of the interfacial area for gas-liquid mass transfer.

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BIOGRAPHY

Miss Nalinee Tanthikul was born on 1st July, 1980 in Chonburi. She finished her higher secondary course from Benchama Rat Rungsarit School Chachoengsao in May 1999. Later on, she studied in the major of Chemical engineering in Faculty of Engineering at Kasetsart University. In 2003, she participated in the Biochemical Engineering research group at Chulalongkorn University and achieved her Master's degree in April 2005.