

# CHAPTER 3

## Experiment

### 3.1 Experimental Apparatus

The gas-liquid contacting apparatus employed in this work is made of clear acrylic plastic in which various phenomena can be well observed. A series of measuring ports are attached along the column height with a vertical space between each port of 10 cm. These ports are employed for the pressure drop measurement and also are used as injection points of color tracer for the measurement of liquid velocities (riser and downcomer). Figure 3.1.1 shows the experimental setup of this work where the dimensions of the apparatus are detailed in Figure 3.1.2.

During the operation of the contactor, air is sparged centrally through a porous sparger at the contactor base, and gas volumetric flowrate is controlled by a calibrated rotameter with minimum and maximum  $U_{sg}$  of 1.88 and 8.43 cm/s respectively. A dissolved oxygen (DO) meter (JENWAY model 9300) is used to measure dissolved oxygen in the dispersion for the estimation of mass transfer rate.

Three schematic sketches of gas-liquid contactors investigated in this study are shown in Figure 3.1.3. The first type (Figure 3.1.3 (a)) represents a bubble column which has the same dimensions as the outer column of the ALC. A normal concentric tube ALC is illustrated in Figure 3.1.3 (b) where a cylindrical draft tube of 207 cm. length with 8 cm. diameter is placed centrally in the outer column. Similarly, Figure 3.1.3 (c) depicts the concentric ALC with the same dimensions with ALC in Figure 3.1.3 (b), but the last one, the ALC-P, has two perforated plates inserted perpendicular to the direction of liquid flow in the draft tube. Each plate is 7.4 cm. in diameter and is perforated with variable numbers of holes. Details of plates geometry are shown in Figure 3.1.4.

It is noted that the ALC in Figure 3.1.3 (c) contains two perforated plates, but the number of the plates is variable.

## 3.2 Experimental Methods

### 3.2.1 *Experimental Preparation*

1. Calibrate the rotameter by a simple, conventional method, i.e. the replacement of air in water.
2. Fill each column with water up to the level of 220 cm. In the case of ALC and ALC with perforated plates, this level is 7 cm. above the draft tube.
3. Sparge air through a porous sparger at the contactor base. A rotameter is used to adjust the Superficial gas velocity,  $U_{sg}$ , and also to keep it constant at the decided values, e.g. 1.88 cm/s. Before any measurement, the system will be left running until no further changes in bubble distribution, nor dispersed volume is observed. This usually takes a few seconds.

### 3.2.2 *Measurement of overall gas holdup*

1. Read the value of liquid dispersion height and unaerated liquid height.
2. Determine the overall gas holdup according to the calculation in Section 3.3.1 (Equation 3.4).

### 3.2.3 *Measurement of gas holdups in downcomer and gas separator*

1. Connect one end of the manometer to one of the measuring ports in the downcomer of the contactor (choose the lowest port 135 cm from the base of the contactor) while the other end of the manometer is open to the atmosphere, measure the pressure difference.
2. Calculate the gas holdup in this section which is the summation of holdups in downcomer and gas separator,  $\varepsilon_{g+d}$ . (see Equation 3.13, Section 3.3.3 for detailed calculation)

3. Disconnect the port from the manometer and connect it again, this time at the top of the downcomer (205 cm from the base of the contactor), read the pressure difference.
4. Calculate the gas holdup in this section which is the holdup in the gas separator,  $\varepsilon_g$  (See Equation 3.12, Section 3.3.2 for detailed calculation)
5. Determine the downcomer gas holdup from Equation 3.15, Section 3.3.3.

#### ***3.2.4 Calculation of riser gas holdup***

Since riser gas holdup cannot be measured directly due to experimental limitation, it is calculated from the continuity equation (Equation 3.18 in Section 3.3.4) using the information of the overall, gas separator, and downcomer gas holdups determined a priori.

#### ***3.2.5 Measurement of liquid velocity***

1. Inject color tracer directly into the measuring port, 185 cm., from the base of the column,
2. Measure the time required for the color tracer to flow along a fixed distance in downcomer, i.e. 130 cm. Tracer is also injected via the lowest port to determine riser liquid velocity.
3. Calculate riser and downcomer liquid velocity by using Equations 3.19 and 3.20 in Section 3.3.5.

#### ***3.2.6 Measurement of volumetric mass transfer coefficient***

1. Immerse a dissolved oxygen probe into the gas separator, the completely mixed region of each column.
2. Purge pure nitrogen into the system to remove all dissolved oxygen and wait until the DO meter indicates 0% saturation of DO in water.
3. Stop the nitrogen flow, and immediately sparge the compressed air at designed volumetric flowrates (detailed later) and read the DO value at every 5 seconds until the value becomes constant.

4. Calculate the volumetric mass transfer coefficient from Equation 3.22 in Section 3.3.6.

### 3.2.7 *Experimental repetition*

1. Repeat every experiment at various  $U_{sg}$ , i.e. 2.83, 3.76, 4.70, 5.64, 6.58, 7.52 and 8.45 cm/s.
2. Repeat experiment with all designs of gas-liquid contacting system.

## 3.3 Calculations

### 3.3.1 *Calculation of overall gas holdup*

The overall gas holdup is determined by the volume expansion method. The expanded dispersion volume represents the volume of gas in the system according to the following equation:

$$V_G = V_D - V_L \quad (3.1)$$

where

$V_G$  = expanded gas volume or overall gas volume [cm<sup>3</sup>]

$V_D$  = dispersed liquid volume [cm<sup>3</sup>]

$V_L$  = unaerated liquid volume [cm<sup>3</sup>]

The fluid volume in the system can be calculated from the product between cross sectional area ( $A$ ) and fluid height ( $H$ ):

$$V = AH \quad (3.2a)$$

hence, 
$$V_D = A H_D \quad (3.2b)$$

and 
$$V_L = A H_L \quad (3.2c)$$

where

$A$  = cross sectional area of the column [cm<sup>2</sup>]

$H_D$  = dispersion height [cm]

$H_L$  = unaerated liquid height [cm]

If  $\varepsilon_o$  is the gas fraction in the expanded fluid volume in the contactor, one can calculate the overall gas holdup by:

$$V_G = \varepsilon_o A H_D \quad (3.2.d)$$

Combining Equations 3.1, 3.2b, 3.2c and 3.2d yields:

$$\varepsilon_o A H_D = A H_D - A H_L \quad (3.3)$$

$$\varepsilon_o = \frac{(H_D - H_L)}{H_D} \quad (3.4)$$

The unaerated liquid height and dispersion height can be measured (Section 3.2.2) and hence, the overall gas holdup can be calculated accordingly.

### 3.3.2 Calculation of gas holdup in the gas separator

Downcomer gas holdup,  $\varepsilon_d$ , together with gas holdup in both gas separator and downcomer,  $\varepsilon_{g+d}$ , can be estimated from hydrostatic pressure differences between column and manometer measured according to the procedure in Section 3.2.3.

For gas holdup in the gas separator :

$$\Delta P_{column} = \Delta P_{manometer} \quad (3.5)$$

where  $\Delta P_{manometer}$  is the pressure difference read from the manometer when one end of the manometer is attached to the column at the height of 205 cm from the bottom. Equation 3.5 can be transformed into the following:

$$\rho g (H_D - H_L) = \rho_L g \Delta Z \quad (3.6)$$

where  $\rho$  on the left hand side represents the density of the dispersion:

$$(\rho_L \varepsilon_L + \rho_g \varepsilon_g)g(H_D - H_I) = \rho_L g \Delta Z \quad (3.7)$$

Since  $\rho_g \ll \rho_L$ , it is reasonable to neglect the second term in the first bracket on the left hand side of Equation 3.7 and this leads to:

$$\rho_L \varepsilon_L g(H_D - H_I) = \rho_L g \Delta Z \quad (3.8)$$

$$\varepsilon_L (H_D - H_I) = \Delta Z \quad (3.9)$$

since

$$\varepsilon_L = 1 - \varepsilon_g \quad (3.10)$$

Equation 3.9 becomes

$$(1 - \varepsilon_g)(H_D - H_I) = \Delta Z \quad (3.11)$$

This leads to an expression for the gas holdup in the gas separator:

$$\varepsilon_g = 1 - \frac{\Delta Z_I}{(H_D - H_I)} \quad (3.12)$$

where

$\varepsilon_g$  = gas fraction in gas separator (gas separator gas holdup) [-]

$\varepsilon_L$  = liquid fraction in gas separator [-]

$\rho_L$  = liquid density [g/cm<sup>3</sup>]

$\rho_g$  = gas density [g/cm<sup>3</sup>]

$\Delta z_I$  = difference of liquid height in manometer, measuring at  
point  $H_I$  [cm]

$H_I$  = height of measuring port in gas separator at 205 cm. from  
the bottom of the column [cm]

$g$  = gravitational acceleration [cm/s<sup>2</sup>]

### 3.3.3 Calculation of downcomer gas holdup

In this work the downcomer and gas separator gas holdup,  $\varepsilon_{g+d}$ , is estimated from:

$$\varepsilon_{g+d} = 1 - \frac{\Delta Z_2}{(H_D - H_2)} \quad (3.13)$$

where

$\Delta Z_2$  = difference of liquid height in manometer measuring  
at  $H_2$  [cm]

$H_2$  = height of measuring port in downcomer at the height of  
135 cm from the bottom of the column [cm]

The volume of gas in both downcomer and gas separator is the summation of each individual gas volume:

$$\left[ \begin{array}{c} \text{Total volume of gas in} \\ \text{gas separator and downcomer} \end{array} \right] = \left[ \begin{array}{c} \text{Volume of gas in} \\ \text{gas separator} \end{array} \right] + \left[ \begin{array}{c} \text{Volume of gas} \\ \text{in downcomer} \end{array} \right]$$

$$\varepsilon_{g+d}[(A_d + A_r)(H_D - H_{DT}) + A_D(H_{DT} - H_2)] = \varepsilon_g(A_D + A_r)(H_D - H_{DT}) + \varepsilon_d A_d(H_{DT} - H_2) \quad (3.14)$$

Rearrange this equation gives the equation for the estimation of downcomer gas holdup:

$$\varepsilon_d = \frac{\varepsilon_{g+d}[(A_d + A_r)(H_D - H_{DT}) + A_D(H_{DT} - H_2)] - \varepsilon_g(A_d + A_r)(H_D - H_{DT})}{A_d(H_{DT} - H_2)} \quad (3.15)$$

where

$\varepsilon_d$  = downcomer gas holdup [-]

$A_r$  = riser cross sectional area [cm<sup>2</sup>]

$A_d$  = downcomer cross sectional area [cm<sup>2</sup>]

$H_{DT}$  = height of draft tube [cm]

### 3.3.4 Calculation of riser gas holdup

The summation of the amount of gas in riser, downcomer, and gas separator is the overall gas holdup :

$$\varepsilon_o V_T = \varepsilon_r V_r + \varepsilon_d V_d + \varepsilon_g V_g \quad (3.16)$$

$$\varepsilon_o H_D (A_d + A_r) = \varepsilon_r A_r H_{DT} + \varepsilon_d A_d H_{DT} + \varepsilon_g (A_d + A_r) (H_D - H_{DT}) \quad (3.17)$$

Rearrange this equation to give:

$$\varepsilon_r = \frac{\varepsilon_o H_D (A_D + A_r) - \varepsilon_d A_d H_{DT} - \varepsilon_g (A_d + A_r) (H_D - H_{DT})}{A_r H_{DT}} \quad (3.18)$$

where

$$V_T = \text{total volume of fluid in the column [cm}^3\text{]}$$

Equation 3.18 is used to calculate the riser gas holdup.

### 3.3.5 Calculation of liquid velocity

Once the average time that tracer needs to travel along a fixed distance in riser,  $t_r$ , and downcomer,  $t_d$ , is measured, the riser and downcomer liquid velocities can consequently be calculated as follows:

$$v_{Lr} = \frac{L_r}{t_r} \quad (3.19)$$

$$v_{Ld} = \frac{L_d}{t_d} \quad (3.20)$$

where

$v_{Lr}$  = riser liquid velocity in [cm/s]

$v_{Ld}$  = downcomer liquid velocity [cm/s]

$L_r$  = a fixed distance tracer travel along in riser [cm]

$L_d$  = a fixed distance tracer travel along in downcomer [cm]



$t_r$  = the time tracer needs to flow a distance  $L_r$  [s]

$t_d$  = the time tracer needs to flow a distance  $L_d$  [s]

### 3.3.6 Calculation of volumetric mass transfer coefficient

The oxygen mass transfer is measured using a dynamic method. (Bandyopadhyay *et al.*, 1967; Van't Riet, 1979; and Sobotka *et al.*, 1982) The dissolved oxygen probe is submerged above the draft tube to measure changes in dissolved oxygen concentration in the dispersion, and the  $k_L a$  is determined by:

$$V \frac{dC}{dt} = V k_L a (C^* - C) \quad (3.21)$$

where

$C$  = bulk concentration of dissolved oxygen [ $\text{g}/\text{cm}^3$ ]

$C^*$  = equilibrium oxygen concentration with the gas above the dispersion [ $\text{g}/\text{cm}^3$ ]

$k_L a$  = mass transfer coefficient [1/s]

Assuming that  $C^*$  is constant for small scale systems, Equation 3.21 can be integrated to

$$\ln(1 - \bar{C}) = -k_L a t \quad (3.22)$$

where

$$\bar{C} = \frac{C - C_o}{C^* - C_o} \quad (3.23)$$

and

$C_o$  = initial concentration of dissolved oxygen [ $\text{g}/\text{cm}^3$ ]

### 3.3.7 Calculation of Sauter mean diameter

The measurement of bubble size is performed using the digitally photographic technique where all equipments are assembled according to the arrangement shown in Figure 3.5. The digital video-recorder employed in this work is SONY Mini Digital Video Cassette Model DCR-TRV 20E.

The bubbles are captured in a “still” mode using an appropriate “image processing software”. Sauter mean diameter is then calculated by measuring gas bubble diameters (as depicted in Figure 3.6) and using the following correlation: (see also Figure 3.6)

$$d = \sqrt[3]{a^2 \times b} \quad (3.24)$$

where

$a, b$  = bubble dimensions illustrated in Figure 3.6

In fact, this calculation results in a “equivalent” mean diameter where the surface area of the bubble will be equal to the spherical bubble. However, if the number of sampling bubbles is not extremely high, this diameter can be used as a Sauter mean diameter.

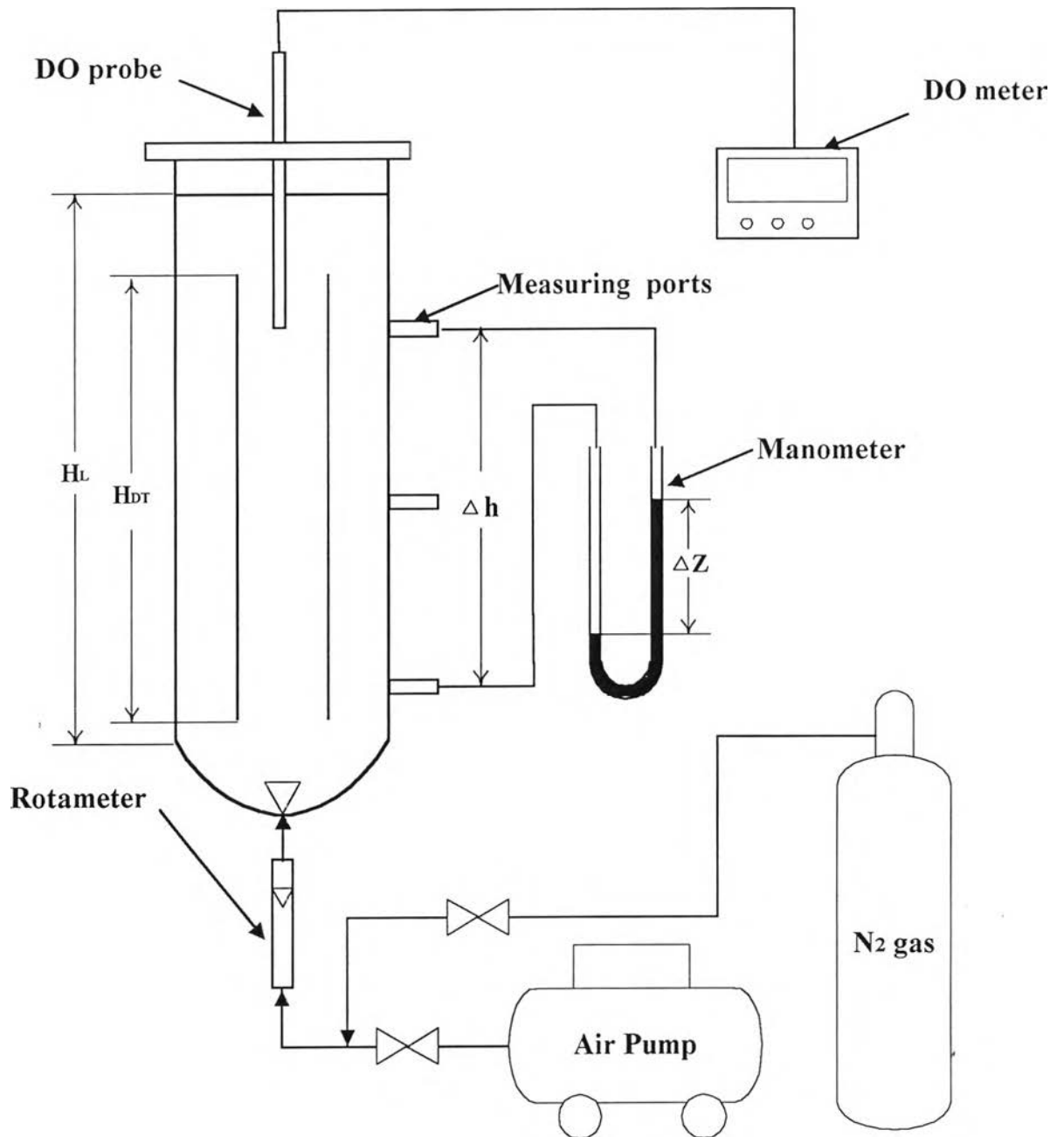


Figure 3.1 Experimental setup

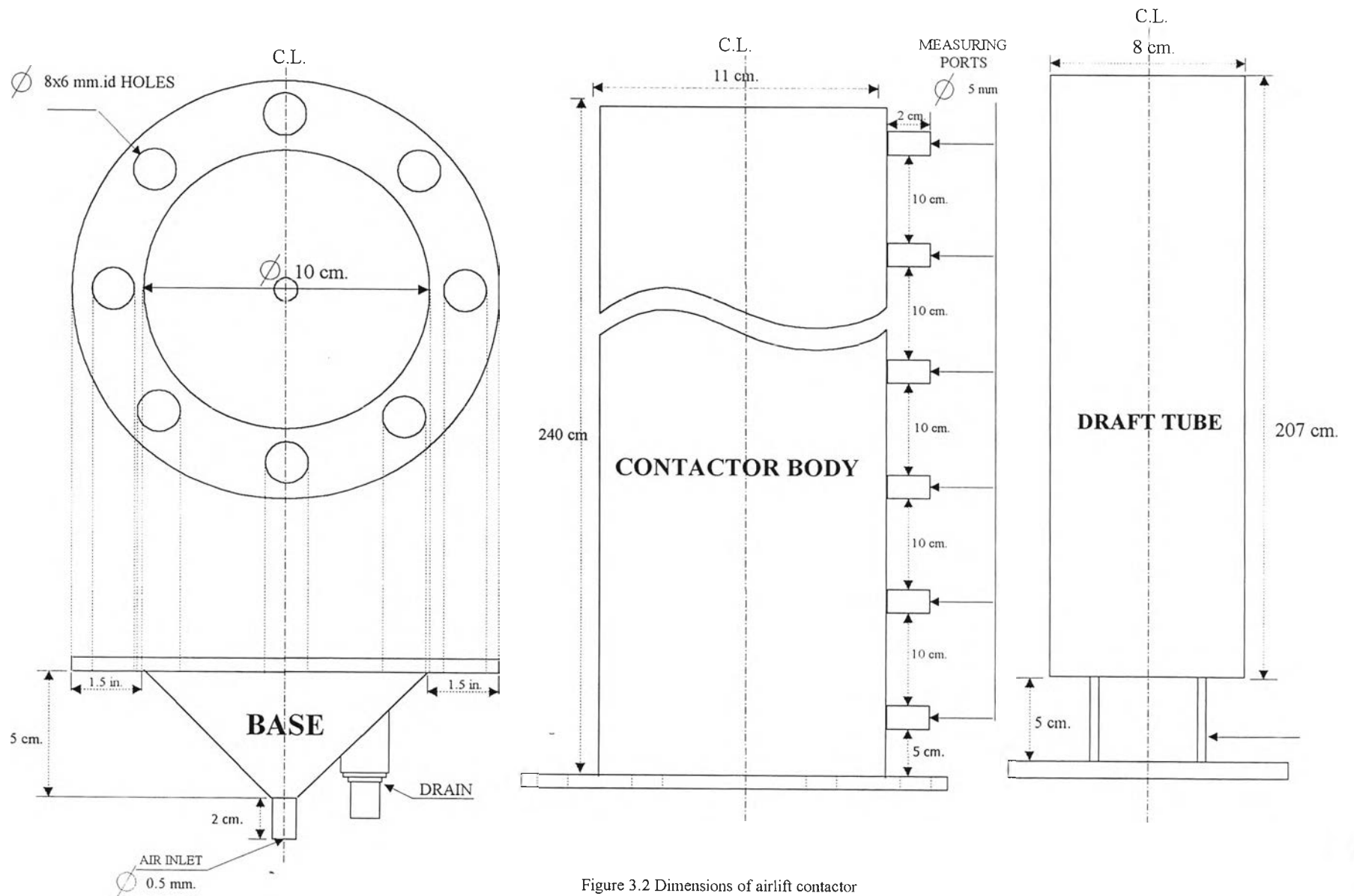
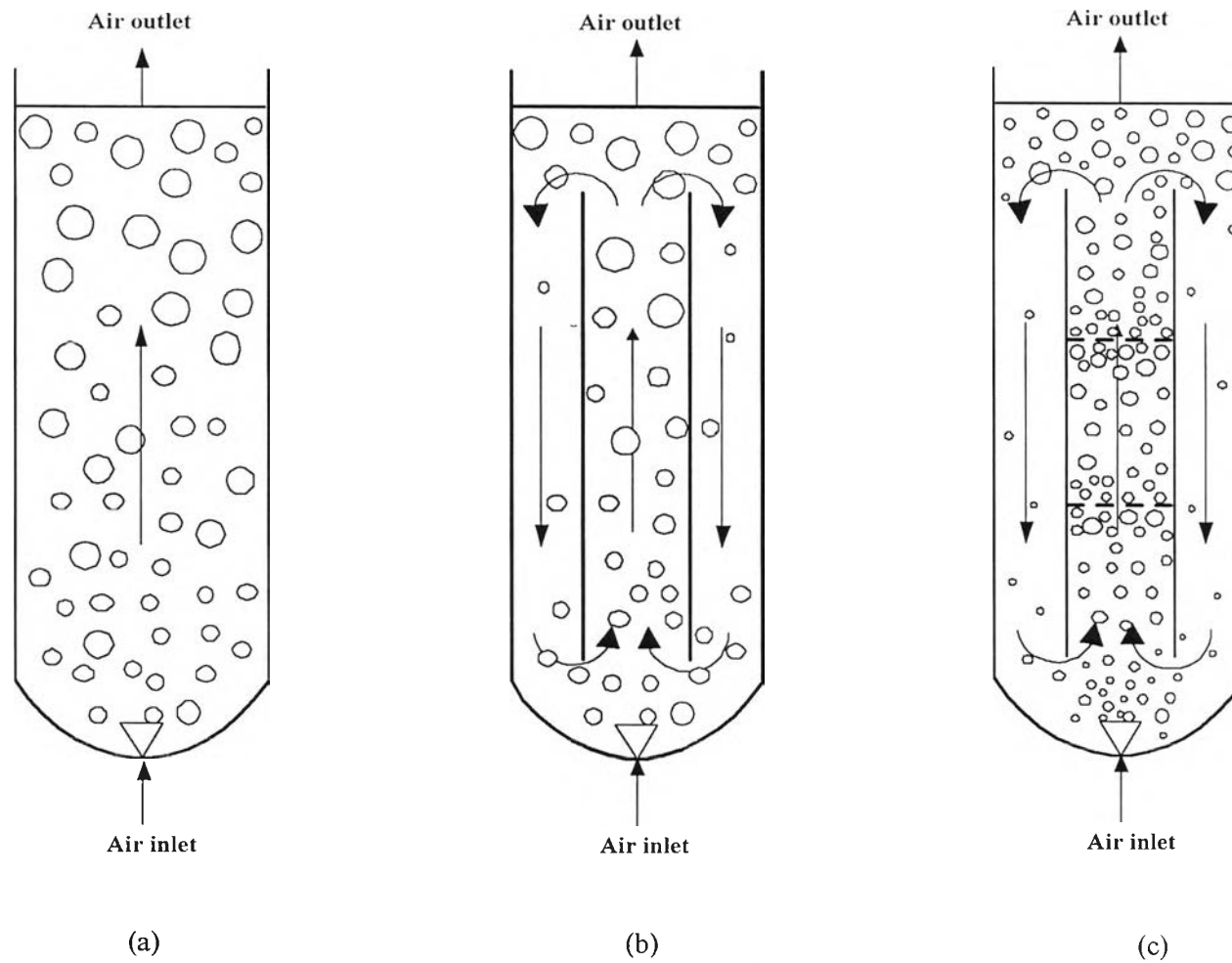


Figure 3.2 Dimensions of airlift contactor



**Figure 3.3** Gas-liquid contactors employed in this work. (a) Bubble column.  
 (b) Concentric ALC (c) Concentric ALC with baffle plate

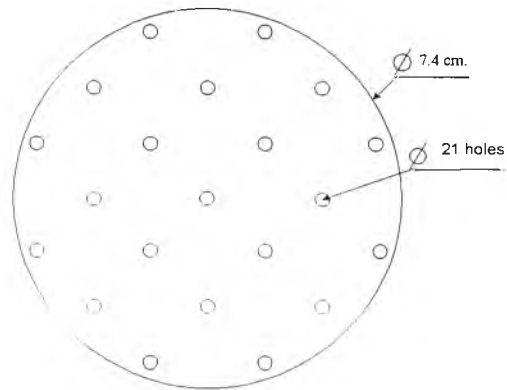
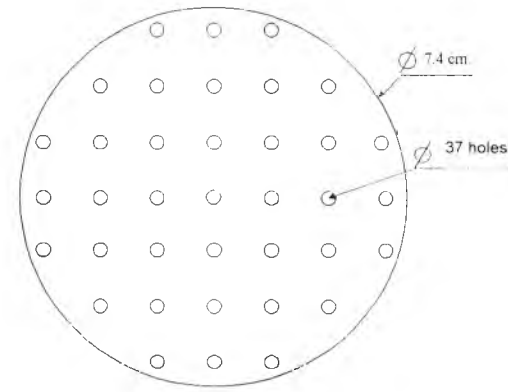
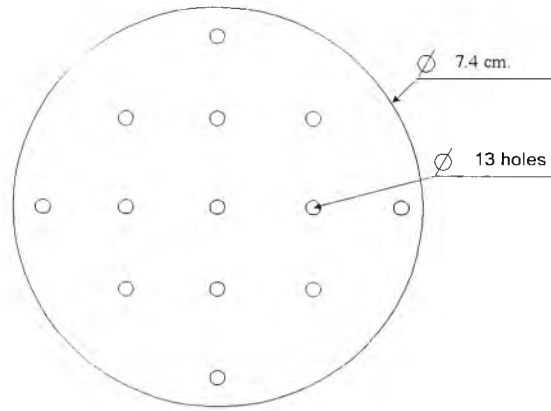
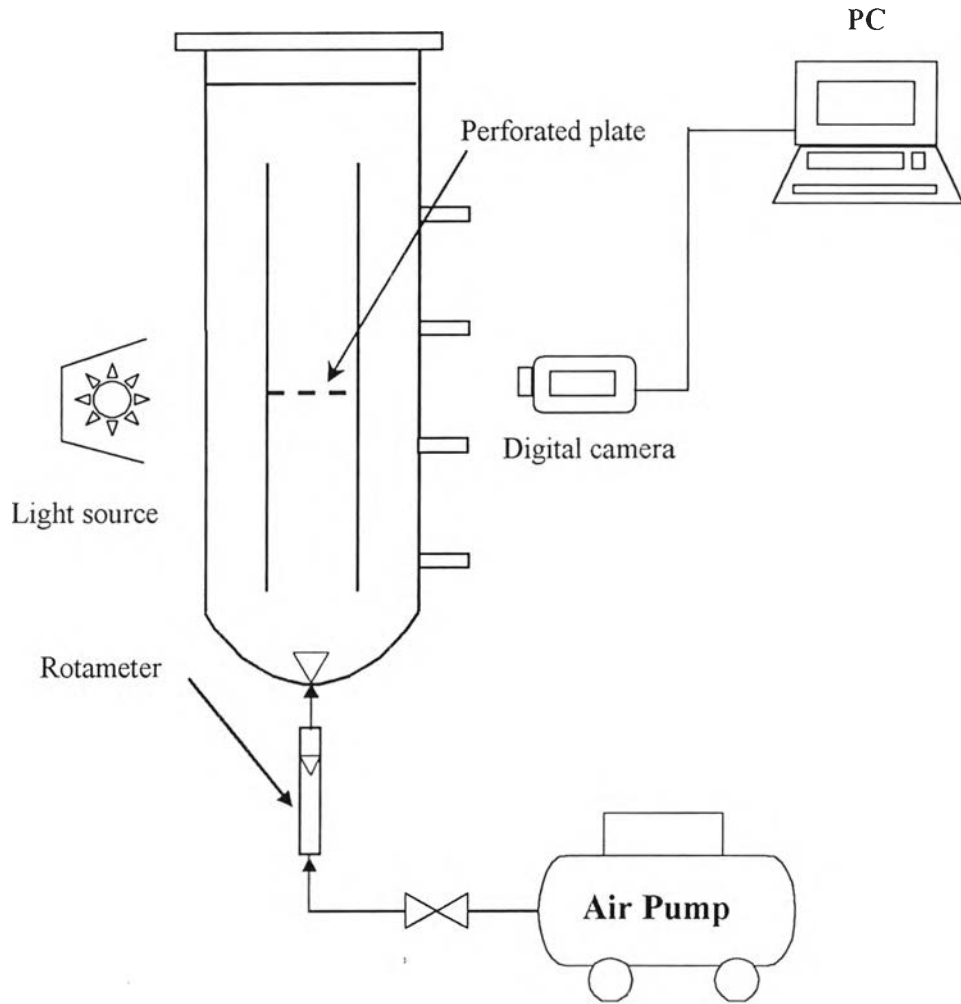
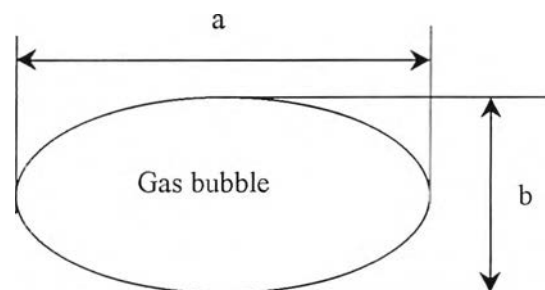


Plate	Holes size diameter (mm)	Number of holes
A-1	3	13
A-2	3	21
A-3	3	37
B-4	4	13
B-5	4	21
B-6	4	37
C-7	5	13
C-8	5	21
C-9	5	37

Figure 3.4 Perforated plates geometry



**Figure 3.5** Experimental setup for the digital record of bubble diameter



**Figure 3.6** Gas bubble dimensions for the calculation of Sauter mean diameter