CHAPTER 2

BACKGROUNDS AND LITERATURE REVIEWS

2.1 Backgrounds: Airlift contactor

2.1.1 General concepts of airlift contactors

Airlift contactors (ALCs) consist of a liquid pooi divided into two distinct zones and only one of these is sparged by gas. The different gas holdups in the gassed and ungassed zones result in different bulk densities of the fluid in these regions and cause circulation of the fluid in the reactor. The part of the reactor containing the gas-liquid upflow is called "riser" and the region containing the downflow fluid is called "downcomer". *(See Fig. 2.1) (Chisti, 1989)*

2.1.2 Classification of airlift contactors

ALCs can be mainly classified into two types. Firstly, the internal loop airlift contactor is a simple bubble column splited into riser and downcomer by a cylindrical tube or a internal baffle plate *(Fig. 2.2, (a),(b))* and the external or outer loop airlift contactors *(Fig. 2.2, (d))* where the riser and downcomer are two separate columns connected by horizontal sections near the top and the bottom.

2.2 Backgrounds: Hydrodynamics

The main hydrodynamic parameters of interest in design of ALCs are the overall gas holdup, gas holdups in riser and in downcomer and the liquid circulation in the contactor.

2.2.1 Gas holdup

The overall gas holdup (ε_o) is the volume fraction or the gas void fraction of gas phase in the gas-liquid dispersion:

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

where V_G and V_L are gas and liquid volumes in the contactor, respectively.

In airlift contactors, individual riser and downcomer gas holdups *(ε_r and ε_d),* can also be identified and are related to the overall gas holdup through the following equation:

$$\varepsilon_o = \frac{A_r\varepsilon_r + A_d\varepsilon_d}{A_r + A_d} \tag{2.2}$$

Eq.(2.2) is derived for contactors with uniform cross-sections of the riser and the downcomer. This equation is exact for internal loop airlifts and it is applicable also to external loop when the dispersion heights in the riser and the downcomer are nearly the same. Moreover, calculation for gas holdup can be estimated by using information on superficial gas velocity and cross-section area ratio. Wongsuchoto (2002) summarized the empirical correlations proposed by various researchers on the estimation on gas holdups in ALCs.

2.2.2 Liquid circulation

The liquid circulation in airlift contactors originates from the difference in the bulk densities of the fluids in the riser and the downcomer. The fluid circulates along a well defined path upflow in the riser, downflow in the downcomer. A mean circulation velocity *(U_{Lc})* is defined by:

$$U_{Lc} = \frac{L_c}{t_c} \tag{2.3}$$

where L_c is the circulation path length and t_c the average time for one complete recirculation.

There are theoretical backgrounds in determining velocities of liquid circulation in the airlift contactors based on the rule of energy conservation and consideration of energy loss. For more detail, a review by Wongsuchoto (2002) should be consulted.

2.3 Backgrounds: Oxygen transfer

Dissolved oxygen (DO) is essential for most forms of living overtures. Solubility of oxygen is approximately 7 ppm in most aqueous systems at ambient temperatures and this is often not adequate for a mass production of microbial cells. Oxygen transfer capacity is therefore significant in the operation of the biological processes.

One of the most common methods to determine the rate of oxygen transfer in a bioreactor is a dynamic approach of oxygen measurement. This is based on an oxygen balance performed across an aerated bioreactor in which a living culture is actively growing. A material balance gives:

$$\frac{dC_L}{dt} = k_L a(C_L^* - C_L) - r_{o_2} \qquad (2.4)$$

where C_L is dissolved oxygen concentration, C_L^* dissolved oxygen concentration in equilibrium with partial pressure of oxygen in the air, $k_L a$ the overall volumetric oxygen transfer coefficient and r_{O_2} the specific oxygen consumption rate.

By turning on the air flow again after a brief period of zero dissolved oxygen level without starving the cells, dissolved oxygen will increase according to Eq. (2.4). Rearrangement of Eq. (2.4) can produce the following linear relationship:

$$C_L = -\frac{1}{k_{La}}\left(\frac{dC_L}{dt} + r_{o_2}\right) + C_L^* \qquad (2.5)$$

A C_L vs. $(\frac{dC_L}{dt} + r_{O_2})$ curve should produce a straight line with a slope of a reciprocal of the overall volumetric oxygen mass transfer coefficient.

For systems with gas-liquid oxygen transfer only, i.e. with-out cell consumption, Eq. (2.4) becomes:

$$\frac{dC_L}{dt} = k_L a(C_L^* - C_L) \qquad (2.6)$$

The rate at which gas-liquid mass transfer takes place in ALCs is usually involved with operating conditions and geometrical parameters such as downcomer/riser cross-sectional area ratio, column height, column diameter, etc. The summaries of work done on gas-liquid mass transfer can be found in Krichnavaruk, 2000.

2.4 The effect of liquid properties in airlift reactor

Table 2.2 summarizes the work on performance of ALCs with various types of properties of liquid that could strongly influence the contactors behavior including viscosity, surface tension and other physical chemical identification such as conductivity, impurity content, etc.

One of the most important properties of liquid that influences the reactor performance is viscosity. (*Al-Masry, 1999*) In addition, liquid viscosity was reported to affect bubble characteristics in the column such that highly viscous liquids promoted bubble coalescence causing the bubble size to progressively increase and the interfacial area for mass transfer to gradually decrease. As a result, gas holdup, gas-liquid mass transfer rates and liquid velocity decreased. (*Chisti, 1987; Snape, 1992*) However, liquid viscosity in the range of 0.3 to 1.26 Pa.s was reported to hardly affected gas holdup. (*Zhao, 1994*)

Other parameters were also reported to have influence on ALC. Surface tension is one of these factors. The addition of surface-active agents (aqueous solutions of *n*-hexanol and *n*-octanal, Nissan Disfoam) was reported to destabilize the foams by acting as hydrophobic bridges between two film surfaces which caused collapse of the foam structure. This, on the other hand, could also favor the coalescence of bubbles in the body of liquid and resulted in an increase in the mean bubble diameter, and consequently reduction in gas holdup. Both of these effects led to a smaller the specific interfacial area available for mass transfer. (*Al-Masry, 1998; 1999*) Antifoam agent is among other additives commonly used in bioreactors. The antifoam agent is surface-active agent which acts like surfactant. There were many investigations on the effect of antifoam on system performance. However, there are substantial discrepancies among the published data. In 1987, Schugerl et al. found that the addition of an antifoam agent increased the bubble size thereby decreasing gas holdup and gas-liquid mass transfer coefficient at high gas flow rate. However, at low gas flow rate, this addition of antifoam agent increased gas holdup and gas-liquid mass transfer coefficient. In 1974 Yagi and Yoshida found that addition of antifoam agent caused decreased in the gas holdup and mass transfer coefficient in the whole range of gas flow rate used in their work. On the other hand, there was also a report that the addition of surfactants reduced the surface tension and therefore caused the bubble size to decrease. This led to a larger gas holdup and better gas-liquid mass transfer rate. *(Al-Masry, 1998)* The effect of surfactant or antifoam therefore still could not be unambiguously concluded but it seems that the type of antifoams might affect the system performance considerably.

Physical properties of liquid phase were also reported to influence hydrodynamics and mass transfer. An increase in sugar solution concentration was reported to augment density and viscosity, but the surface tension decreased slightly. In particular, the level of sugar concentration seemed to have influence on system performance. An increase in sugar at the low concentration range (<8%wt) was found to give an increase in gas holdup, but at higher concentrations (>8%wt), further increase in sugar level led to a lower gas holdup. Increases in the concentration of various electrolyte solution (NaCl, $CaCl_2$, KCl, Na_2SO_4, $MgSO_4$) was reported to increase gas holdup. In their work, however, the effect of liquid properties on gas-liquid mass transfer was not reported. *(Snape, 1992*)

Table 2.2 Review on the investigation of liquid properties on the performance of ALCs

No.	Authors	Summary	Experimental conditions
1.	Al-Masry (1999)	$\epsilon_{silicone} < \epsilon_{water}$ $U_{l,\ silicone} < U_{l,water}$ $K_La_{\ silicone} < k_La_{\ water}$	External loop airlift reactor $A_d/A_r = 0.25, 1$ System : Air - water Antifoam agent : silicone polymer $0.036 < \sigma < 0.046$ N/m $0 < U_{sg} < 25$ cm/s Methods: Gas holdup: using a differential pressure cell and u-tube manometer Liquid velocity: electromagnetic flowmeter K_La : DO meter
2.	Al-Masry et al. (1998)	Xantan gum : $\epsilon_r = 0.9856\,(U_{sg})^{0.8747}\,(\eta_{eff})^{0.0577}$ $k_La = 0.0032\,(U_{sg})^{0.7271}\,(\eta_{eff})^{-0.5282}$	External loop airlift reactor $A_d/A_r = 1$

No.	Authors	Summary	Experimental conditions
		CMC : $\epsilon_r = 0.3245\,(U_{sg})^{0.9032}\,(\eta_{eff})^{-0.0925}$ $k_La = 0.0032\,(U_{sg})^{0.8797}\,(\eta_{eff})^{-0.6966}$ Adding antifoam; $\epsilon_{\text{xanthan gum solution}} > \epsilon_{\text{water}}$ $D_{b,\text{xanthan gum solution}} < D_{b,\text{water}}$ $U_{l,\text{xanthan gum solution}} < U_{l,\text{water}}$ $k_La_{\text{ xanthan gum solution}} < k_La_{\text{ water}}$ Air - cmc system : $\epsilon_{cmc} < \epsilon_{water}$ $U_{l,cmc} < U_{l,water}$	System : Air - Non newtonian fluid (xanthan gum and CMC) Antifoam agent : silicone polymer $0.0663 < \sigma_{\text{xanthan gum}} < 0.0696$ N/m $0.0590 < \sigma_{CMC} < 0.0688$ N/m $0.2 < U_{sg} < 6$ cm/s Methods: Gas holdup: using a differential pressure cell and u-tube manometer Liquid velocity: eletromagnetic flowmeter K_La : DO meter both riser and downcomer (bigger bubbles)
3.	Pironti et al. (1995)	$\epsilon_{\text{high siliceous sand}} < \xi_{\text{low siliceous sand}}$	Internal loop airlift reactor , central sparger

No.	Authors	Summary	Experimental conditions
			$A_d/A_r = 3.44$
			System : Air - slurry (siliceous sand)
			$121 < C_{siliceous\ sand} < 230$ Kg/m^3
			$0 < U_{sg} < 25$ cm/s
			Methods:
			Gas holdup: pressure transmitters connected to a data acquisition system
4.	Zhao et al. (1994)	$k_La_{air\ lift} < k_La_{bubble\ column}$	Bubble column , Internal loop airlift reactor, inner sparger
		$\epsilon_{air\ lift} < \varepsilon_{bubble\ column}$	$A_d/A_r = 1.8$
			gas - fluid
		$k_La_{liquid} > k_La_{highly\ viscous\ liquid}$	fluid : water, sugar (40%,97%), olive oil, SAE (20,40,50), castor oil, CMC (0.1%,3.5%, 0.75%, 1.5%)
		$\varepsilon_{liquid} > \varepsilon_{highly\ viscous\ liquid}$	
			$0.78 < U_{sg} < 6.5$ cm/s
			$0.001 < \eta < 1.26$ Pa.s or Pa.s^n

No.	Authors	Summary	Experimental conditions
			$0.03 < \sigma < 0.07$ N/m
5.	Snape et al. (1992)	Aqueous sugar solutions;	External loop airlift reactor
		$\varepsilon_{lower\ concentration} > \varepsilon_{higher\ concentration}$	v = 65 dm^3, $A_d/A_r = 1.33$
		$U_{l,lower\ concentration} > U_{l,higher\ concentration}$	$15.7 < U_{sg} < 22$ cm/s
			$0.000887 < \eta_{electrolyte} < 0.000962$ Pa.s or Pa.s^n
		Aqueous electrolyte solutions;	$0.00101 < \eta_{sucrose\ solution} < 0.00141$ Pa.s or Pa.s^n
		$\epsilon_{lower\ concentration} < \varepsilon_{higher\ concentration}$	$57.3 < \sigma_{electrolyte} < 69.8$ N/m
			$60.5 < \sigma_{sucrose\ solution} < 69.5$ N/m
			Air - aqueous electrolyte system
			(Nacl,KCl,Na_2SO_4,$MgSO_4$,$CaCl_2$) 0.01- 0.2 M
			Air - sugar solution system (0.5-8 % v/w)
			Methods:
			gas holdup: visual observation

No.	Authors	Summary	Experimental conditions
			liquid velocity: conductivity pulse technique using KCl
6.	Philip et al. (1990)	For viscous newtonian liquids;	Internal loop reactor , inner sparger
		$\varepsilon_{lower\ viscosity}$ < $\varepsilon_{higher\ viscosity}$	circle cross section: $A_d/A_r = 1.78$
		$U_{lD,water}$ > $U_{lD,viscous\ newtonian\ liquid}$	square cross section: $A_d/A_r = 3$
		For non newtonian liquids;	gas - fluid (olive oil, SAE,castor oil, sugar syrup,
		No trend for gas hold up	CMC, xanthan solution)
		$U_{lD,water}$ > $U_{lD,viscous\ newtonian\ liquid}$	$1.5 < U_{sg} < 11.7$ cm/s
			$0.115 < \eta < 2.85$ Pa.s or Pa.s^n
			$0.03 < \sigma < 0.08$ N/m
			Methods :
			Gas holdup: visual observation
			Liquid velocity: metal detectors
7.	Popovic, et al. (1989)	$k_La = 2.14 \times 10^{-3} (U_{sg})^{0.52} [1+A_d/A_r]^{-0.85} (\eta_{eff})^{-0.89}$	External loop airlift reactor

No.	Authors	Summary	Experimental conditions
			System : Air - Non newtonian fluid and Viscous newtonian
		Or	$0 < A_d/A_r < 0.44$
		$k_La = 0.5 \times 10^{-2} (U_{sg})^{0.52} (D_L)^{0.5} [1+A_d/A_r]^{-0.85} (\eta_{eff})^{-0.89} (\rho_L)^{1.03} (\sigma_L)^{-0.75}$	CMC: $0.02 < \eta_{eff} < 0.5$ Pa.s
			Sucrose: $\eta = 0.019$ Pa.s
			$2.0 < U_{sg} < 26$ cm/s
			$0.33 < D_L \times 10^9 < 2.53$ m^2/s
			$59 < \sigma_L \times 10^3 < 79$ N/m
8.	Popovic et al. (1988)	$\epsilon_r = 0.465 (U_{sg})^{0.65} [1+A_d/A_r]^{-1.06} (\eta_{eff})^{-0.103}$	External loop airlift reactor
			System : Air - Non newtonian fluid and Viscous newtonian
		$U_l = 0.23 (U_{sg})^{0.32} [A_d/A_r]^{0.97} (\eta_{eff})^{-0.39}$	$0.11 < A_d/A_r < 0.44$
			$0.02 < \eta_{eff} < 0.5$ Pa.s
			$2.0 < U_{sg} < 26$ cm/s
9.	Chisti, et al. (1987)	Bubble column:	Bubble column , Internal loop airlift reactor,annulus sparger

No.	Authors	Summary	Experimental conditions
		$\epsilon_{0.15\,M\,NaCl} > \epsilon_{water} > \epsilon_{1\%\,SF\,sol.} > \epsilon_{2\%\,SF\,sol.} > \epsilon_{3\%\,SF\,sol.}$	Rectangular: $A_d/A_r = 0.614$
		$K_La_{0.15M\,Nacl} = K_La_{1\%\,SF\,sol.} > K_La_{2\%\,SF\,sol.} > K_La_{3\%\,SF\,sol.}$	gas - liquid or slurries (Nacl, Solka Floc cellulose fiber)
			$0 < U_{sg} < 30$ cm/s
		Air lift:	$0.17 < \eta < 9.06$ Pa.s or Pa.s^n
		$\epsilon_{0.15\,M\,NaCl} > \epsilon_{1\%\,SF\,sol.} > \epsilon_{2\%\,SF\,sol.}$	Methods :
		$K_La_{0.15M\,Nacl} > K_La_{1\%\,SF\,sol.} > K_La_{2\%\,SF\,sol.}$	Gas holdup: volume expansion or manometer
			K_La : DO meter

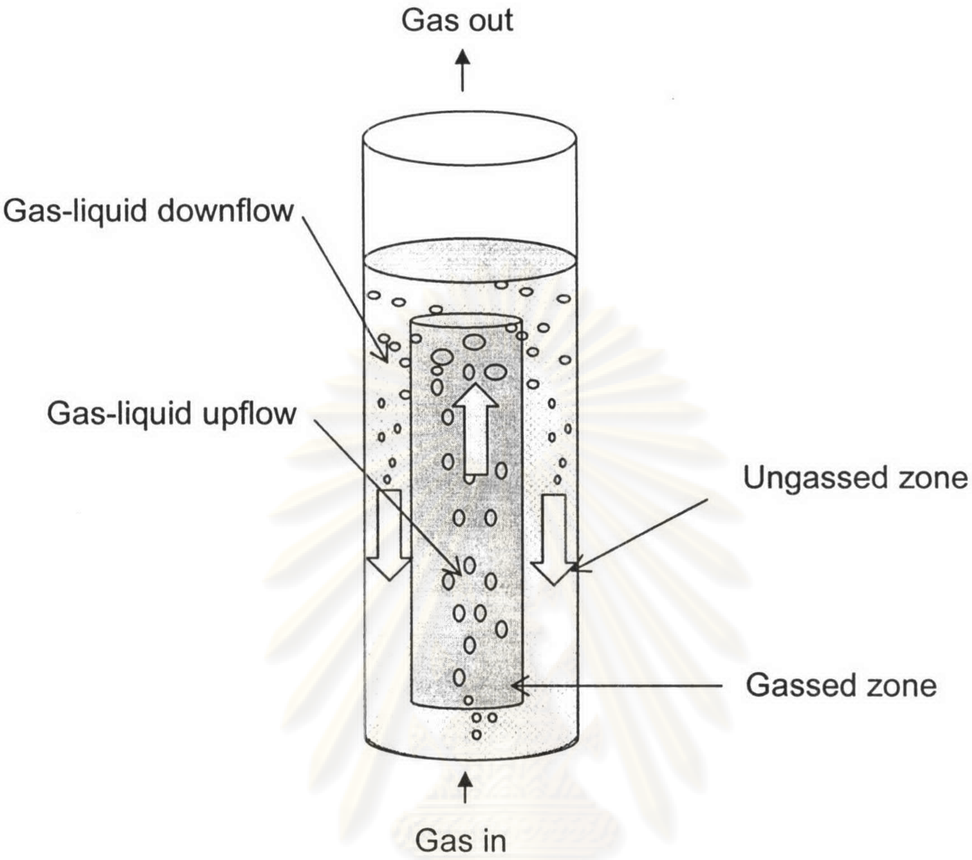

Figure 2.1 Schematic of airlift contactor

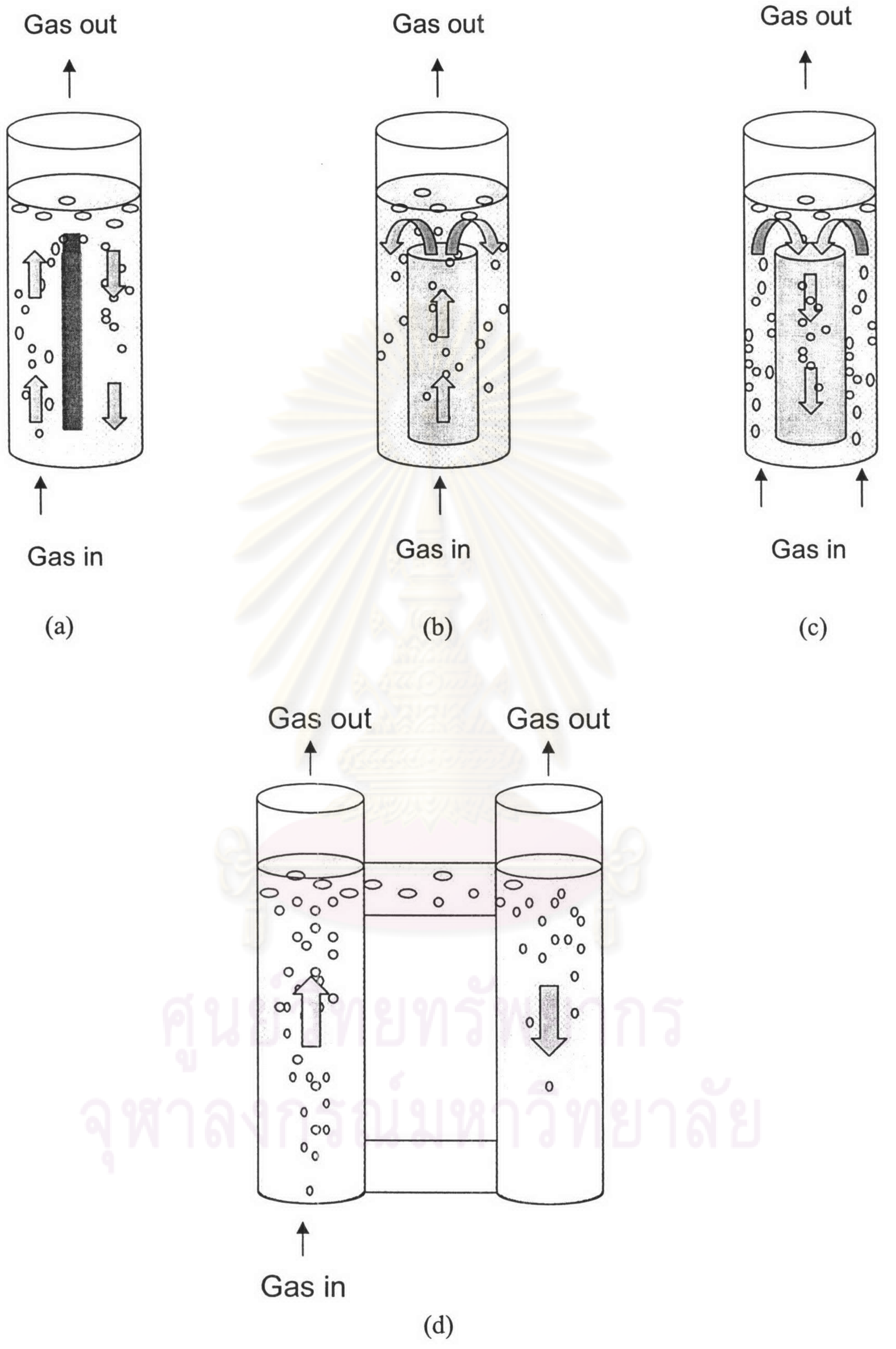

Figure 2.2 Two configurations of ALCs: (a) split cylinder internal loop ALC, (b) concentric tube ALC (c) external loop ALC