International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 5, July - 2012

Hydrodynamics of Multi-Stage Air Lift Reactor (MSALR)

Nikhil K. Gajbhiye[1*], Jagdish. B Khadse[2*] and S. D. Dawande[3]

Department of chemical Engineering
Laxminarayan Institute of Technology
Nagpur University, Nagpur-440033 INDIA.

Abstract :- Gas hold-up, Liquid side mass transfer coefficient (K_La) and scale up studies have been investigated for the constant head of fluid, counter-current flow of liquid in the draft tube, co-current & counter-current flow of liquid in the annular portion with respect to the gas flow rate in the multi-stage air lift reactor(MSALR). At higher gas flow rate, the gas hold-up was significantly higher for each stage in the counter current flow of liquid in the draft tube as compared to others flow conditions. Similarly the liquid side mass transfer coefficient K_La was significantly higher for the counter-current flow of liquid with respect to gas flow rate. The power input per unit volume of liquid has also been studied for the scale up of MSALR.

Key words: airlift reactor, hydrodynamics, mass transfer, scale-up, Gas Hold-up, Air lift reactor.

INTRODUCTION: - Gas holdup and liquid circulation velocity are the most widely studied parameters in airlift reactors. The difference in gas holdup between the riser and the downcomer in an airlift reactor determines the magnitude of the induced liquid circulation velocity which in turn influences the bubble rise velocity, and the gas holdup [1]. The holdup and the liquid circulation velocity together affect the mixing behavior, mass and heat transfer, the prevailing shear rate, and the ability of the reactor to suspend solids [7]. Clearly, all aspects of performance of airlift systems are influenced by gas holdup and liquid circulation. The relationship between the gas holdups in the riser and the downcomer is useful for performance evaluation [4, 5]. Air lift reactors are basically modified bubble column reactors, which help in mixing, suspending solids, heat transfer and mass operations. In comparison with mechanical agitated fermenters, air lift reactor system is more productive in terms of specific power demands and commercial-scale effectiveness [2, 5]. The primary purpose of multi-stage air lift bioreactor is to provide favorable environmental conditions to the microorganisms so that they will carry out the desired biodegradation or transformation optimally [6]. In aerobic bioreactor, the critical environment is the oxygen mass transfer, as a consequence media. Hence, the volumetric mass transfer coefficient (K_La), which is normally used to characterize the mass transfer performance, plays an important role in the performance of bioreactor [9, 2]. Ideally, a reactor should have a maximum mass transfer rate, efficient mixing and minimum energy input. The advantages of air lift reactors (ALR) are low energy input, efficient mixing, avoiding destruction in shear sensitive organisms, simple construction, good heat transfer and easier scale up. Based on the configuration of the geometry, airlift reactors are generally classified into two main categories[3, 2]: (1) The internal loop (IL-ALR) which is a simple bubble column split into a riser and a downcomer by an internal baffle; and (2) The external loop (EL-ALR) reactors where the riser and the

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 5, July - 2012

downcomer are two separate tubes connected by horizontal sections near the top and bottom.

Experimental Setup & Procedure: -

The experimental setup consists of the annular portion and the draft tube portion. The annular portion of the MSALR made up of acrylic material with the diameter of 10.4 cm and the total length is 114 cm. The draft tube is also of acrylic material with a diameter of 3.8 cm and the length 67 cm. The multi stage is provided in such a way that the draft is divided into number of stages. The experiments were carried out in two stage air lift reactor .Draft tube is fitted within the annular portion, in such a manner that the draft tube is concentric to the annular portion of the multi-stage air lift reactor. The draft tube is divided into two portions having equal length of 31 cm each and 5cm gap is provided between each stage. An inverted U-tube manometer was used for measuring the pressure drop across the MSALR [3]. The experimental setup is shown in fig.1.

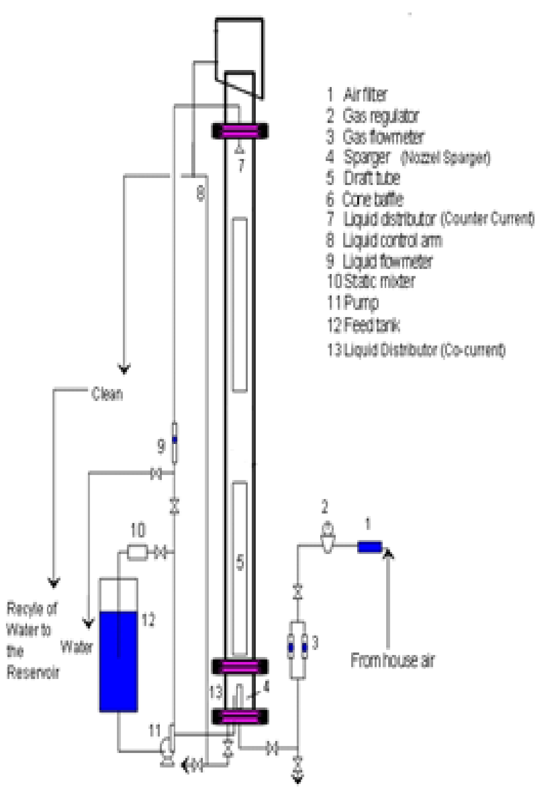

Figure No. 1. Multi-Stage Air Lift Reactor (MSALR)

Procedure:-

The experiments were performed with four flow conditions:

1) Maintaining the constant head of liquid in the reactor and passing the air from the bottom of MSALR.

2) Continuous counter-current circulation of the liquid in the draft tube (V_L= 6 LPM) and passing the air from the bottom of the reactor.

3) Continuous counter-current circulation of the liquid in the annular portion (V_L= 6LPM) and passing the air from the bottom of MSALR.

4) Continuous co-current circulation of the liquid in the annuls portion (V_L= 6LPM) and passing the air from the bottom of the reactor.

Various systems are used in the MSALR and their properties are shown in Table1.

Property of various system				
Sr. No	Systems	Density (kg/m3)	Viscosity (N -sec/ m2)	Surface tension (pa -sec)
1	Air-Water	995.68	0.001	0.072
2	Air- Salt solution (13.15 wt/Vol%)	1024	0.00154	0.067
3	Air- Salt solution (26.315 wt/Vol%)	1039	0.00299	0.0623
4	Air- Salt solution (52.63 wt/Vol%)	1058	0.0195	0.0579
5	Air - (Butanol +Water)	1086	0.02137	0.0535
6	Air- (Acetone +water)	1098	0.03312	0.04915

Table.1 Properties of various Systems

1. Gas Holdup Measurement

Gas holdup is an important parameter affecting the various operations such as mass transfer. Local gas holdup determines the liquid circulation velocity and local interfacial area 'a' was reported by author [4]. U tube manometer is used to the measures the overall gas hold up and inverted U tube manometer is employed to measures the local gas holdup in the riser and downcomer. The following equations are used to calculate the overall gas holdup and local gas holdup [2].

$$\varepsilon_{Overall} = \frac{H_B - (\rho_m/\rho_w) H m - H w}{H_B} \quad (1)$$

$$\varepsilon_{local} = \frac{H_m}{H_L} \quad (2)$$

Where Hm denotes the manometer reading; H_B is the liquid surface height; H_L is the distance between two pressure taps; Hw denotes the head of water in manometer; ρ_w and ρ_m are the density of water and indicating fluid respectively. The overall gas hold-up is difficult to measure accurately and will not be considered in this work.

2. Mass transfer Coefficient: - The volumetric mass transfer coefficients K_La were measured by using chemical method. The concentration of the dissolved oxygen in the liquid was measured by volumetric titration; the same was reported by M.M, Sharma & J.S. Gopal [9, 8].

The amount of oxygen transferred per unit volume of reactor (Q_{O2}) is defined as,

$$N_{O2} = K_La\,(C^*_L - C_L) \quad (3)$$

Where 'a' is the gas-liquid interfacial area per unit of volume and K_La represents the volumetric mass transfer coefficient [10]. The dissolved oxygen concentration variation with time is equal to the molar flux defined in equation (3).

$$\frac{dC}{dt} = = K_La\,(C^*_L - C_L) \quad (4)$$

Equation (4) expresses the oxygen mass balance in the liquid phase. Considering the liquid phase homogeneous and C^0_L the dissolved oxygen concentration at t = 0, the integration of the last equation leads to:

$$\ln (C^*_L - C_L) = \ln (C^*_L - C^0_L) - K_La \times t \quad (5)$$

If C^o_L and C^*_L (oxygen solubility) are known, then the volumetric mass transfer coefficient can be determined by plotting ln (C^*_L - C_L) against time [6, 11].

3. Process Scale Up:

The development of any commercial process with scale up investigation on fundamental issue in order to understand the various phenomena taking place. Once the system is fully characterized and the most important design parameters identified, the next steps should include scale on these critical parameters [11]. This quantity can be easily calculated using the equation as follows:

$$\frac{P_G}{V_L} = \frac{\rho_L g U_{sg}}{1 + (A_d/A_r)} \quad (6)$$

4. Pressure Drop (ΔP):

The pressure drop plays an important role in the MSALR. Pressure drop at a given liquid density, the two-phase pressure drop increases with gas and liquid mass fluxes, superficial velocities and liquid viscosity. Liquid holdup increases with liquid mass flux and superficial velocity, and liquid Viscosity [11].

Hydrodynamic hysteresis may occur at high pressure for the two component system however, for single-component liquids or liquid mixtures consisting of similar components, hysteresis is not detected at high pressure [3]. The effect of pressure increases with increased liquid density, liquid viscosity and surface tension. Hence, high-pressure operation can be successfully simulated with liquid of higher molecular weight at lower pressures.

The pressure drop in each stage of down comer and riser of the MSALR are calculated by using the given correlation as shown as below.

$$\Delta P = (1-\varepsilon)(\rho_w - \rho_g)\, g \times H \quad (7)$$

Where ρ_w = Density of the liquid systems = 995.96 kg/m^3.

ρg = Density of the gas = 1.137 kg/m^3.

ε = Gas holdup in each section of the MSALR.

H = Head in the manometer of MSALR for each stage of riser and down comer.

g = acceleration due to gravity.

RESULTS AND DISCUSSION

1. Gas hold-up

Amongst all hydrodynamic properties, gas hold-up is the most widely studied parameter because of its importance in design. It directly affects mass transfer through a combination of gas residence time and bubble sizes [11].

The effects of both superficial gas velocity and liquid feed rate on local gas hold up were experimentally determined, for different flow conditions. The effects of density, viscosity and surface tension on local gas hold up were also studied. Fig.2 shows the value of local gas holdup as a function of superficial gas velocity for counter-current flow of liquid in draft tube with respect to gas flow rate, for air-water system. It is seen that, local gas holdup in each stage increase linearly with increasing gas velocity. Fig. 3, 4 & 5 show a relationship between the local gas hold-up and superficial gas velocity for constant head of liquid, counter-current and co-current flow of liquid in the annular portion respectively.

Local gas hold-up in each stage for counter-current flow of liquid in draft tube is higher than constant head of liquid as well as for co-current and counter-current flow of liquid in the annular portion. The linear relationships between downcomer and riser of stage have been determined by the regression analysis, for different flow conditions as shown in Table. 2

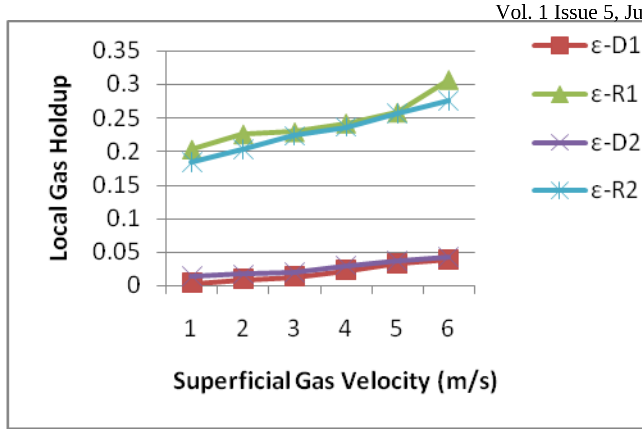

Fig.2. Gas holdup at counter-current flow of liquid (6Lpm) in the draft tube with respect to gas flow rate

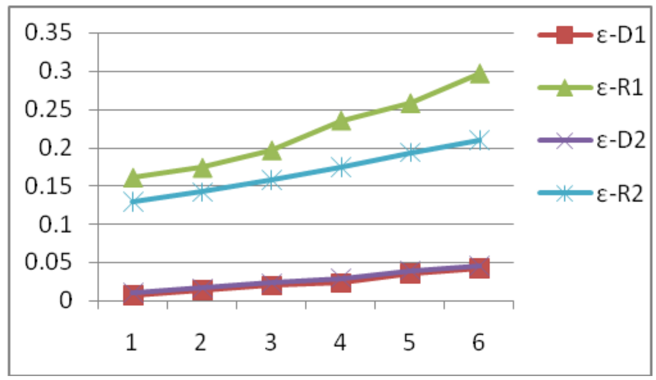

Fig.3. Gas holdup at constant Head of Liquid

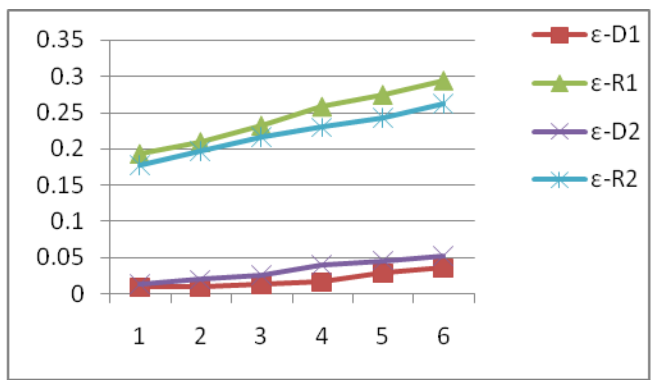

Fig.4. Gas holdup at counter-current flow of liquid (6Lpm) in the annular portion with respect to gas flow rate

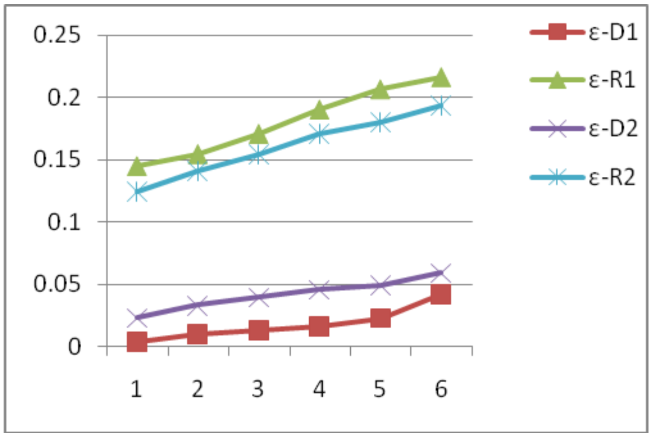

Fig.5. Gas holdup at co-current flow of liquid (6Lpm) in the annular portion with respect to gas flow rate

As varying the density, viscosity & surface tension of the liquid for various system it is experimentally found that, counter current flow of liquid in the annular portion gives the uniform mixing and higher gas hold up as compare to other flow conditions. Gas holdup increases as liquid viscosity, gas-liquid surface tension and density increases.

Higher gas hold up and uniform mixing in the counter-current flow of liquid with respect to gas flow rate which is due to higher residence / retentions of the gas in MSALR. Particularly counter-current flow of liquid gives the additional resistance to the gases and increases the liquid circulation of the gases, which breaks the larger bubbles into smaller bubbles leads to increase the higher gas hold up.

2. Mass transfer Coefficient: The value of dissolved oxygen concentration were measured experimentally by volumetric titration method, for constant head of liquid, counter-current and co-current flow of liquid in annular and draft tube portion. Dissolved oxygen concentration increases with increasing superficial gas velocity. Dissolved oxygen concentration is used to measure the value of K_La [7, 8].

Fig.6 shows the value of K_La as a function of superficial gas velocity, with different flow conditions for air-water systems. It can be seen from the plot, a linear relationship is obtained between the gas velocity and liquid side mass transfer coefficient (K_La).

It is experimentally found that the liquid side mass transfer coefficient for counter-current flow of liquid in draft tube is greater as compare to other flow conditions.The higher value of K_La is due to the coalescence of bubble with each other in the draft tube portion. This results in increasing the retention time of bubble and liquid circulation.

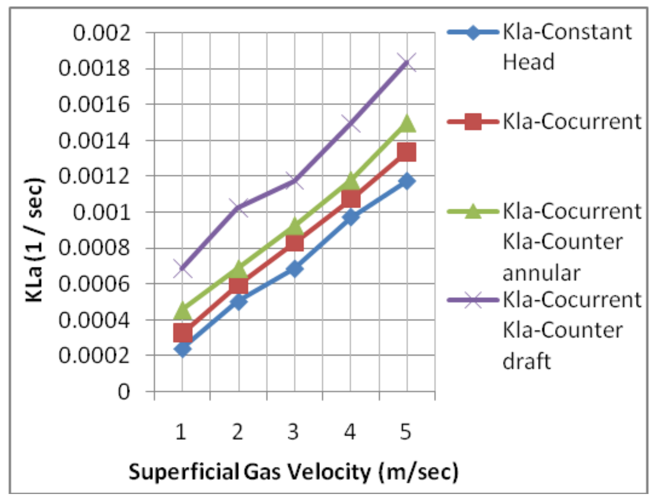

Fig.6. Mass transfer coefficient with respect to U_{sg} with different flow condition for air-water system.

For various systems of different density, viscosity & surface tension of the liquid it is experimentally proved that, counter current flow of liquid in the annular portion gives the higher liquid side mass transfer coefficients as compare to other flow conditions.

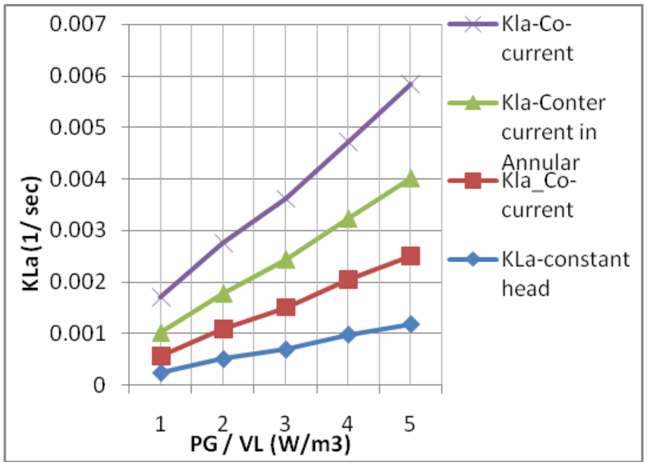

Fig.7. Graph for K_La and (P_G / V_L) with various flow condition for air-water system.

3. Scale-up studies: -

The aeration efficiency of MSALR is usually reported in terms of power input per unit volume of liquid (P_G/V_L). This quantity can be easily calculated using the equation as follows:

$$\frac{P_G}{V_L} = \frac{\rho_L g U_{sg}}{1+ (A_d/A_r)} \quad (7)$$

Due to the differing hydrodynamic conditions described for the different flow condition, it would be of necessary to consider the aeration efficiency for scale-up study. From fig 7 shows value K_La as a function of P_G/V_L, for constant head of liquid, counter-current flow of liquid in draft tube and annular portion and co-current flow of liquid. It is clear that P_G/V_L is linear function of K_La.

For the same power input per unit volume of liquid(P_G/V_L), mass transfer coefficient for counter-current flow of liquid in draft tube is more in comparison with co-current of liquid in annular portion, constant head of liquid and counter-current of liquid in annular portion . So the counter-current flow of liquid in draft tube is more efficient in terms of aeration efficiency, this is clearly seen in Fig.7

The experimental k_La data can be fitted to the widely reported relationship:

$$K_La = a\,(P_G/V_L)^{\alpha} - \beta \quad (8)$$

From the above plot, the linear relationships between K_La and P_G/V_L have been determined by the regression analysis, for different flow conditions for various systems as shown in Table 3. For various systems of different viscosity, surface tensions & liquid density of the liquid, it is experimentally found that, counter-current flow of liquid in the annular portion gives the higher side mass transfer coefficient as compare to other flow condition.

4. Pressure Drop:

For the MSALR pressure drop in each stage gives the effect on gas holdup, liquid side mass transfer coefficient and power input per unit volume of the liquid. The pressure drop in each stage of MSALR gives the linear relationship with respect to superficial gas velocity as shown the below figure. From fig.9 it is clear that counter-current flow of liquid in the annular portion gives the uniform pressure drop in each stage of MSALR for air water system. For the Air-Water system it is found that the pressure drop increases linearly for each stage of MSALR as shown in the below figure.

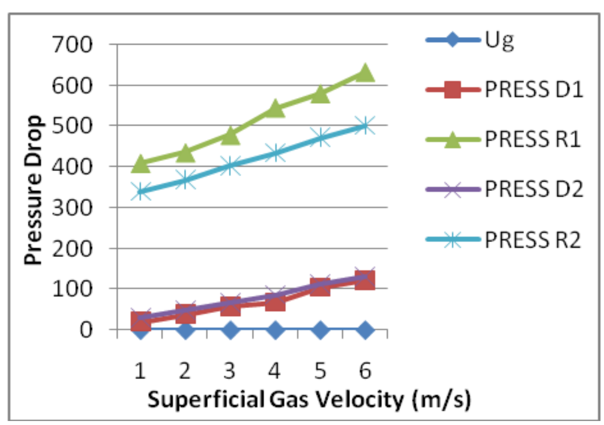

Fig.8. Fig of Constant Head of Liquid

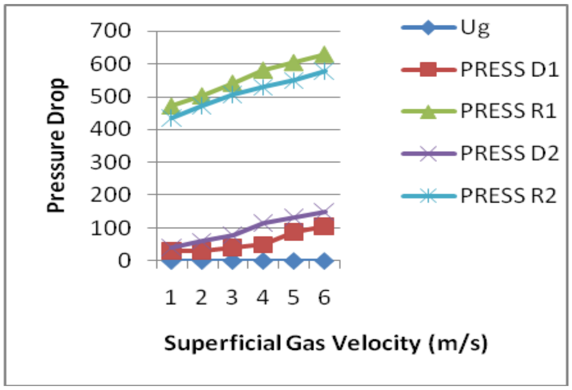

Fig.9. Fig of counter-current flow of liquid in Annular portion.

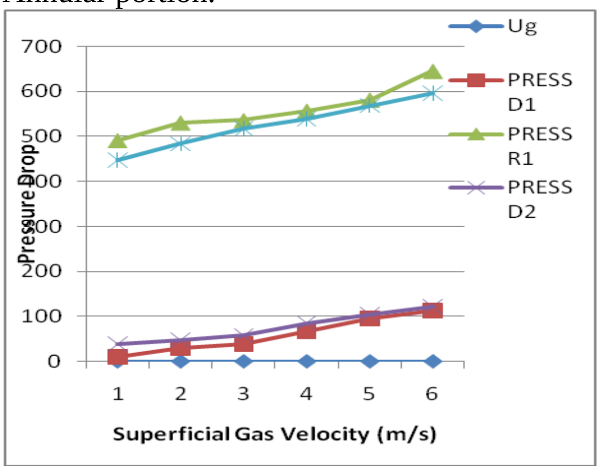

Fig.10. Fig of counter-current flow of liquid in draft tube

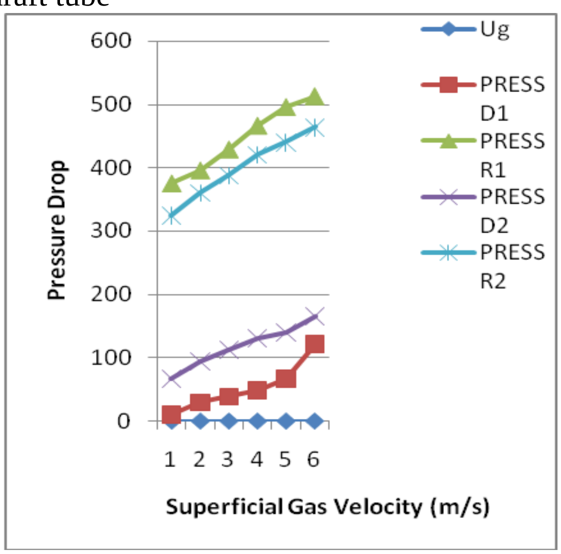

Fig.11. Fig of co-current flow of liquid in annular portion

Form fig 8, 9, 10 & 11 it shows that with increase in superficial gas velocity pressure drop increase linearly in each stage of MSALR. With varying the properties of the liquid system the pressure drop in each stage increase linearly and deviation in the pressure drop of various systems is found very less from that it is clear that the experiments performance is very good.

Conclusion: -

Hydrodynamics and mass transfer experiments have been carried out in MSALR for different flow condition with the various systems (varying the density). Based on the continuity principle, the gas holdup in the riser and downcomer of airlift reactor are related by the equation:

$$\varepsilon_d = \alpha \varepsilon_r - \beta \qquad (9)$$

In many cases α & β do not vary with gas flow; hence the linear dependence is observed. The holdup in the downcomer is always lower than the value in the riser. As the gas flow rate is increased, gas hold-up and mass transfer coefficient is found to be higher in the counter-current flow of liquid in the draft tube portion with respect to gas flow rate. At higher gas flow rate, a vortex above the sparger plane caused air bubble which collide against the tube wall and break up into many smaller bubbles. Thus counter current flow of liquid significantly increases the interfacial area and ultimately increase the mass transfer coefficient (K_La).

For the same power input per unit volume of liquid, the counter - current flow of liquid, gives higher value of mass transfer coefficient in draft tube as compared to co-current flow of liquid, constant head of liquid and counter current flow of liquid in the annular portion.

For the pressure drop of each stage of MSALR, it experimentally found that the pressure drop in the counter-current flow of liquid in the annular portion with respect to gas flow rate gives the uniform pressure drop as compare to other flow conditions. It is also clear that the pressure drop increase linearly with increase in density, viscosity and surface tension of the liquid with respect to superficial gas velocity.

Table.2.The various correlations had derived by using the Multiple Regression Analysis Method (polynomial Method): -

S. N	Constant Head of Liquid		Counter current of Liquid to the draft tube portion		Counter current of Liquid to the Annular portion		Co-Current of liquid		Systems
	1st Stage	2nd Stage	1st Stage	2nd Stage	1st Stage	2nd Stage	1st Stage	2nd Stage	
1	$\varepsilon_{d1} = 0.2517\ \varepsilon_{r1} - 0.0324$	$\varepsilon_{d2} = 0.4455\varepsilon_{r2} - 0.0474$	$\varepsilon_{d1} = 0.3658\ \varepsilon_{r1} - 0.0694$	$\varepsilon_{d2} = 1.00\ \varepsilon_{r2}$	$\varepsilon_{d1} = 0.2613\ \varepsilon_{r1} - 0.0448$	$\varepsilon_{d2} = 0.4938\ \varepsilon_{r2} - 0.0763$	$\varepsilon_{d1} = 0.4303\ \varepsilon_{r1} - 0.060$	$\varepsilon_{d2} = 0.4935\ \varepsilon_{r2} - 0.0378$	Air-Water
2	$\varepsilon_{d1} = 0.4761\ \varepsilon_{r2} - 0.0536$	$\varepsilon_{d2} = 0.4076\ \varepsilon_{r2} - 0.0651$	$\varepsilon_{d1} = 0.5091\ \varepsilon_{r1} - 0.0560$	$\varepsilon_{d2} = 0.0198\ \varepsilon_{r2} - 0.0644$	$\varepsilon_{d1} = 0.2269\ \varepsilon_{r1} - 0.0119$	$\varepsilon_{d2} = 0.7845\ \varepsilon_{r2} - 0.01089$	$\varepsilon_{d1} = 0.5490\ \varepsilon_{r1} - 0.0829$	$\varepsilon_{d2} = 0.4754\ \varepsilon_{r2} - 0.0359$	Air-(13.15%) Salt solution (wt/vol) %
3	$\varepsilon_{d2} = 0.3516\ \varepsilon_{r2} - 0.0573$	$\varepsilon_{d2} = 1.1397\ \varepsilon_{r2} - 0.1967$	$\varepsilon_{d1} = 0.5788\ \varepsilon_{r1} - 0.0757$	$\varepsilon_{d2} = 0.5401\ \varepsilon_{r2} - 0.0462$	$\varepsilon_{d1} = 0.4080\ \varepsilon_{r2} - 0.0657$	$\varepsilon_{d2} = 0.5652\ \varepsilon_{r2} - 0.0844$	$\varepsilon_{d1} = 0.5712\ \varepsilon_{r1} - 0.0900$	$\varepsilon_{d2} = 0.5067\ \varepsilon_{r2} - 0.0449$	Air-(26.315 %) Salt solution (wt/vol) %
4	$\varepsilon_{d2} = 0.3174\ \varepsilon_{r2} - 0.0540$	$\varepsilon_{d2} = 0.44\varepsilon_{r2} - 0.0282$	$\varepsilon_{d1} = 0.7492\ \varepsilon_{r1} - 0.1485$	$\varepsilon_{d2} = 0.6237\ \varepsilon_{r2} - 0.0810$	$\varepsilon_{d1} = 0.3393\ \varepsilon_{r1} - 0.0590$	$\varepsilon_{d2} = 0.6333\ \varepsilon_{r2} - 0.0765$	$\varepsilon_{d1} = 0.6975\ \varepsilon_{r1} - 0.1255$	$\varepsilon_{d2} = 0.5067\ \varepsilon_{r2} - 0.0532$	Air-(52.63 %) Salt solution (wt/vol) %
5	$\varepsilon_{d2} = 0.4516\ \varepsilon_{r2} - 0.079$	$\varepsilon_{d2} = 0.5607\ \varepsilon_{r2} - 0.0654$	$\varepsilon_{d1} = 0.4384\ \varepsilon_{r1} - 0.0876$	$\varepsilon_{d2} = 0.3885\ \varepsilon_{r2} - 0.00566$	$\varepsilon_{d1} = 0.3227\ \varepsilon_{r1} - 0.0759$	$\varepsilon_{d2} = 0.4112\ \varepsilon_{r2} - 0.0634$	$\varepsilon_{d1} = 0.4491\ \varepsilon_{r1} - 0.0696$	$\varepsilon_{d2} = 0.4526\ \varepsilon_{r2} - 0.0546$	Air-(Butanol +Water)
6	$\varepsilon_{d2} = 0.4834\ \varepsilon_{r2} - 0.1013$	$\varepsilon_{d2} = 0.6333\ \varepsilon_{r2} - 0.0765$	$\varepsilon_{d1} = 0.7873\ \varepsilon_{r1} - 0.1575$	$\varepsilon_{d2} = 0.5667\ \varepsilon_{r2} - 0.0880$	$\varepsilon_{d1} = 0.2269\ \varepsilon_{r1} - 0.0119$	$\varepsilon_{d2} = 0.4077\ \varepsilon_{r2} - 0.0651$	$\varepsilon_{d1} = 0.5295\ \varepsilon_{r1} - 0.0950$	$\varepsilon_{d2} = 0.5833\ \varepsilon_{r2} - 0.0735$	Air-(Aceton+water)

Table.3.The various correlations had derived by using the Multiple Regression Analysis Method (polynomial Method): -

S.N	Constant Head of Liquid	Counter current of Liquid to the Annular portion	Co-Current of liquid to the Annular portion	Counter current of Liquid to the Draft tube portion
1	$K_La = 0.0010(P_G/V_L) - 0.0009$	$K_La = 0.0422(P_G/V_L) - 0.0039$	$K_La = 0.0470(P_G/V_L) - 0.0040$	$K_La = 0.0125\ (P_G/V_L) - 0.0011$
2	$K_La = 0.0058(P_G/V_L) - 0.0004$	$K_La = 0.02437(P_G/V_L) - 0.0019$	$K_La = 0.0272(P_G/V_L) - 0.0020$	$K_La = 0.0066\ (P_G/V_L) - 0.0004$
3	$K_La = 0.0037(P_G/V_L) - 0.0002$	$K_La = 0.0218(P_G/V_L) - 0.0017$	$K_La = 0.0247(P_G/V_L) - 0.0019$	$K_La = 0.0073\ (P_G/V_L) - 0.0005$
4	$K_La = 0.0030(P_G/V_L) - 0.0001$	$K_La = 0.00212(P_G/V_L) - 0.0018$	$K_La = 0.0256(P_G/V_L) - 0.002$	$K_La = 0.0035\ (P_G/V_L) - 0.0001$
5	$K_La = 0.0025\ ((P_G/V_L) - 0.0006$	$K_La = 0.0100(P_G/V_L) - 0.000$	$K_La = 0.0249((P_G/V_L) - 0.0018$	$K_La = 0.0034\ (P_G/V_L) - 0.0002$

ISSN: 2278-0181
Vol. 1 Issue 5, July - 2012

NOMENCLATURE

a	*Gas* phase interfacial area per unit bioreactor volume.
e_d	Downcomer gas Hold-up
e_R	Riser gas Hold-up
K_La	Liquid side mass-transfer coefficient
(P_G/V_L)	Power per unit volume of liquid
A_d	Area of downcomer
A_r	Area of Riser
ρ_L	Density of Liquid (kg/m3).
g	Acceleration due to gravity
U_{sg}	Superficial gas velocity (m/sec)
C^*_L	Equilibrium concentration (mg/ltr)
C_L	Final concentration (mg/ltr)

ε_{R1}, ε_{D1} $\varepsilon_{R2,}$ ε_{D2} Gas hold up in the riser, downcomer of stage 1 and 2 respectively.

Reference

1. Pedro Miguel Pacheco Neves Carteado Mena, " Mass transfer and hydrodynamics in multiphase systems", Phd thesis Universidade do Porto Porto, Portugal, pp. 1-218, November. 2005.
2. Aseel Abd Aljabbar, "HYDRODYNAMICS OF A CONCENTRIC TUBES AIRLIFT REACTOR", Engineering Scientific Conference College of Engineering–University of Diyala Vol.22-23, pp. 427-444 December 2010.
3. M. Tobajas, E. GarcoAa-Calvo, "Comparison of experimental methods for determination of the volumetric mass transfer coefficient in fermentation processes", Heat and Mass Transfer Vol.36 (2000) 201-207 @ Springer-Verlag 2000.
4. Deify Law, "COMPUTATIONAL MODELING AND SIMULATIONS OF HYDRODYANMICS FOR AIR-WATER EXTERNAL LOOP AIRLIFT REACTORS" , Phd thesis, Blacksburg, Virginia May 27, 2010.
5. Carla freitas, Jose A. Teixeria, "Oxygen mass transfer in a high solid loading three-phase internal-loop airlift reactor", Chemical engineering journal 84 57-61. (2001)
6. Perry R.H. and Green D.W., Perry's chemical engineering handbook, 7th ed., 23 (15-23), McGraw-Hill, New York, N.Y., U.S.A. (1997)
7. SHERIF H. EISSA and K. SCHUGERL, "Holdup and Back mixing Investigation in counter and concurrent Bubble column", Chemical Engineering Science, Vol. 30. pp. 1251-1256. (1975)
8. P.C. Mena, M.N. Pons, J. A. Texeira, F.A. Rocha, "Using image analysis in the study of multiphase gas absorption, Chemical Engineering science 60 ,5144-5150.(2005)
9. M.M. Sharma and J.S. Gopal, "Mass Transfer characteristics of low H/D Bubble column", Canadian Journal of chemical Engineering, Vol 61, August (1983).
10. Bhim charan meikap, Gautam kundu & Mahindra Nath Biswas, "Mass Transfer characteristics of a counter current Multi-Stage air lift scrubber", Journal of chemical engineering Japan, vol.37. No.19. pp. 1185-1193, 2004.
11. Sanchez Oscar , Guio Felipe , Garcia Diana , Silva Edelberto , Caicedo Luis, "Oxygen transfer, mixing time and gas holdup characterization in a hybrid bioreactor", Proceedings of European Congress of Chemical Engineering, Copenhagen, 16-20 September 2007.