INTRODUCTION

- *airlift reactor (ALR) covers a wide range of gas–liquid or gas–liquid–solid pneumatic contacting devices that are characterized by fluid circulation in a defined cyclic pattern*

- Role of gas stream
- Difference between ALRs and bubble columns

Airlift reactors on the basis of their structure

- 1) external loop vessels
- 2) baffled (or internal-loop) vessels
All ALRs comprise four distinct sections

- *Riser*
- *Downcomer*
- *Base*
- *Gas separator*

**Advantages of Airlift Bioreactors**

- energy dissipation
- heat transfer
- shear
Gas injected to the Airlift reactors

the difference in gas holdup between the riser and the downcomer

\[ \Delta P_b = \rho_L g (\psi_r - \psi_d) \]  

(1)

where \( \Delta P_b \) is the pressure difference, \( \rho_L \) is the density of the liquid (the density of the gas is considered to be negligible), \( g \) is the gravitational constant, and \( \psi_r \) and \( \psi_d \) are the fractional gas holdup of the riser and downcomer.

energy input

unit volume of reactor

\[ \text{Aeration efficiency as a function of pneumatic power of gas input per unit volume in a straightbaffleALR} \]
• Energy economy

• The advantages counterbalance the obvious disadvantage of ALRs

**FLUID DYNAMICS**

• **Design variables**: reactor height, riser-to-downcomer area ratio, geometrical design of gas separator, and the bottom clearance

• **Operating variables**: gas input rate, top clearance

liquid velocity in the ALR
Flow Configuration

• Riser

• 1. Homogeneous bubbly flow regime
• 2. Churn-turbulent regime

• Downcomer.

• Cross-sectional area ratio of the riser to the downcomer

• Gas Separator.

• Gas Holdup

\[ \phi_i = \frac{V_G}{V_L + V_G + V_S} \quad (2) \]

where the subindexes L, G, and S indicate liquid, gas, and solid, and \( i \) indicates the region in which the holdup is considered.
Importance of the holdup

1. The value of the holdup gives an indication of the potential for mass transfer.

2. The difference in holdup between the riser and the downcomer generates the driving force for liquid circulation.

Gas Holdup in Internal Airlift Reactors.

\[ \varphi_r = a(J_G)\alpha \left( \frac{A_d}{A_r} \right)^\beta (\mu_{ap})^\gamma \]  

\( J_G \) is the superficial gas velocity, \( \mu_{ap} \) is the effective viscosity of the liquid, and \( \alpha, \beta, \gamma, \) and \( a \) are constants.
\[ J_{G,\text{true}} = \left( \frac{Q_{in} + Q_d}{A_r} \right) \] (4)

\( Q_{in} \) is the freshly injected gas, \( Q_d \) is the recirculated gas.

Some correlations proposed for prediction of gas holdup in the riser of internal-loop ALRs.
External-Loop Airlift Reactors.

- By using Drift flux model
  \[ J = J_G + J_L \]  

- Drift velocities of the gas and liquid phases
  \[ J_G = U_G - J \]  
  \[ J_L = U_L - J \]

\[ U_G = \frac{J_G}{\phi} = C_0 J + \frac{1}{A} \int \phi (U_G - J) dA \]  
\[ = \frac{1}{A} \int \phi \cdot dA \]

where \( A \) is cross-sectional area, \( C_0 \) is distribution parameter, \( J \) is superficial velocity, \( J_G \) is superficial gas velocity, \( U_G \) linear gas velocity, and \( \phi \) is gas holdup

\[ C_0 = \frac{1}{A} \int \phi J \cdot dA \]  
\[ \frac{1}{A} \int J \cdot dA \frac{1}{A} \int \phi \cdot dA \]
• The value of $C_0$ depends mainly on the radial profile of the gas holdup

• $C_0 = 1$ for a flat profile and $C_0 = 1.5$ for a parabolic profile

• $C_0 = 1.03–1.2$ for upflow,

• $C_0 = 1.0–1.16$ for downflow

\[ U_{GI} = U_G - J \]  

(10)

Drift velocity of a swarm of bubbles

\[ U_{2J} = 1.53 \cdot \left(\frac{\sigma g \Delta \rho}{\rho_L^2}\right)^{0.25} \cdot (1 - \varphi)^{1.5} \]  

(11)

Where $U_{2J}$ is the velocity of the swarm of bubbles, $\Delta \rho$ is the density difference, $\sigma$ is the surface tension difference between holdup, $\varphi$, and the flowing volumetric concentration ($\beta$)

\[ \beta = \frac{Q_G}{Q_G + Q_L} = \frac{J_G}{J} \]  

(12)
connection between the gas holdup and $\beta$

$$\frac{\beta}{\varphi} = C_0 + \frac{U_{b\infty}}{J}$$  \hspace{1cm} (13)

$J$ is the superficial velocity, $U_{b\infty}$ is the terminal gas velocity

For riser

$$U_G > U_L; \varphi < \beta$$  \hspace{1cm} (14)

For downcomer

$$U_G < U_L; \varphi > \beta$$  \hspace{1cm} (15)

Gas flow holdup ($\phi$) vs. flowing volumetric concentration ($\beta$). The different zones in the plane $\phi$-$\beta$ identify the two phase flow.
Dependence of the riser gas holdup in a 4-m high external-loop ALR with a multiple-orifice sparger (solid lines) and a single-orifice sparger (broken lines).

Gas holdup in the riser

\[ \varphi_r = \alpha J_G^\beta \]  

(16)

where the constant \( \alpha \) depends on the friction losses in the loop, and \( \beta \) is usually a value between 0.6 and 0.7

Gas holdup reported by various sources for the riser of airlift reactors under conditions of little or no gas recirculation. The data correspond to different Ad/Ar ratios.
Some correlations proposed for prediction of gas holdup in the riser of external ALRs. The gas holdup is presented as a function of the superficial gas velocity.

**Effects of Liquid Rheology.**

- Effects
  - superficial gas velocity and the global shear rate have direct Proportionality:

\[
\gamma = 5000 \cdot J_C \quad (J_C > 0.04 \text{m/s}) \quad (17)
\]

Where $\gamma$ is global shear rate

$\gamma$ is used $\rightarrow$ global viscosity

\[
\gamma = \left[ \frac{\tau}{K} \right]^{1/m}
\]
L_b is an effective length that represents the mean circulation path of a bubble in the system considered, \( P \) is the power input, \( S_{ab} \) is the total surface of all of bubbles, and \( \tau \) is the shear stress

\[
\gamma = \left[ \frac{p_1 J_{\text{c}} \ln \left( \frac{p_1}{p_2} \right)}{\alpha L_b \kappa} \right]^{1/n}
\]

where the subindexes 1 and 2 represent the two extremes of the section considered.

**Effect of Liquid Level.**

Riser and downcomer gas holdup in an internal-loop ALR for two different top clearances and two liquids.
Gas holdup in the riser of an external-loop ALR for several top clearances

Gas Recirculation

Gas recirculation in a split-cylinder ALR. The level indicated corresponds to no-aeration conditions.
The mathematical expression that gives this maximal gas recirculation is:

\[ Q_d = \frac{Q_1(P_2 - P_3) + Q_L \rho_L g h - \frac{1}{2} \rho_L C_d A_d (1 - \varphi_d) U_L^2}{P_4 \ln\left(\frac{P_3}{P_2}\right)} \]  

(20)

where \( Q_d \) is the gas flow rate in the downcomer, \( Q_1 \) is the liquid circulation flow rate, \( P_i \) is pressure at point \( i \) of the reactor (1 is top of the riser, 2 is top of the downcomer, 3 is bottom of the downcomer, 4 is bottom of the riser), \( C_d \) is the hydraulic resistance coefficient, \( U_L \) is the linear liquid velocity

**Liquid Velocity**

- affects the gas holdup in the riser and downcomer, the mixing time, the mean residence time of the gas phase, the interfacial area, and the mass and heat transfer coefficients.

\[ U_L = \frac{\text{liquid volume}}{\bar{e} \times A \times (1 - \varphi)} \]  

(21)
Modeling of Liquid Flow.

- Two main methods for the modeling of two-phase flow in ALRs
  - energy balances and momentum balances
  - expression for the average superficial liquid velocity based on energy balance:

\[
U_{lf} = \left( \frac{2gH_d(\varphi_l - \varphi_d)}{K_t \left(1 - \varphi_t\right)^2 + K_b \left(\frac{A_t^2}{A_d}\right) \left(1 - \varphi_t\right)^2} \right)^{0.5} \tag{22}
\]

where \(K_b, K_t\) are the hydraulic pressure loss coefficients

Authors assume that \(K_t\), the friction coefficient at the top of the loop, is negligible in concentric-tube type reactors and that in external-loop reactors \(K_t\) can be taken as equal to \(K_b\), the friction coefficient for the bottom of the loop.

empirical correlation for \(K_b\)

\[
K_b = 11.402 \cdot \left(\frac{A_d}{A_b}\right)^{0.789} \tag{23}
\]

where \(A_b\) is the minimal cross section at the bottom of the airlift reactor.
the riser-to-downcomer cross-sectional area ratio and the reactor height are the main parameters that affect the superficial liquid velocity at constant superficial gas velocity.

Liquid velocity predicted by some of the proposed correlations

\[
U_{Lr} = \frac{J_{Gr} \left( \frac{1}{\phi_r} - C_0 \right)}{C_0 (1 - \phi_r)} - U_{GJ} \quad (24)
\]

Liquid Mixing

- \( t_m \)
- degree of homogeneity (\( I \)):

\[
I = \frac{C - C_{m_{\text{III}}}}{C_m} \quad (25)
\]

where \( C \) is the maximum local concentration and \( C_m \) is the mean concentration of tracer at complete mixing.
• Study of the residence time distribution (RTD)

• The axial dispersion model

$$\frac{\partial C}{\partial \tau} = D_z \frac{\partial^2 C}{\partial Z^2} + U_z \frac{\partial C}{\partial Z}$$  \hspace{1cm} (26)

where \( C \) is the concentration of a tracer

Bodenstein number \((Bo)\), which is used to describe the mixing in the reactor:

$$Bo = \frac{U_z L}{D_z}$$  \hspace{1cm} (27)

where \( L \) is the characteristic length

Bo $\longrightarrow \infty$ the mixing conditions are similar to those of a plug-flow reactor

Low Bo no. the reactor can be considered as well-mixed

$$t_m = MBo$$  \hspace{1cm} (28)

where \( M \) is a constant equal to 0.093 or to 0.089

for \( Bo > 50 \) and a degree of inhomogeneity \( l = 0.05 \)
where $D_z$ is the dispersion coefficient and $D$ is the column diameter

$$D_z = 0.678 \cdot D^{1.4} \cdot J_C^{0.3}$$  \hspace{1cm} (29)

Where $J_L$ is the superficial liquid velocity and $U_c$ is the cell circulation velocity given by:

$$U_C = 1.31 \left[ gD \left( J_c - \frac{\phi_G}{1 - \phi_G} J_L - \phi_G U_{b_{\infty}} \right) \right] \hspace{1cm} (31)$$

Where $U_{b_{\infty}}$ is the terminal bubble velocity

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**Mixing in the Gas Phase**

**Energy Dissipation and Shear Rate in Airlift Reactors**

Extended to mass transfer proposed the expression:

$$\gamma = 5000 \cdot J_C$$  \hspace{1cm} (32)
The general energy balance

\[ \Delta(PQ) + \Delta E_p + E_D = W_S \]  \hspace{1cm} (33)

**Riser**

\[ (E_d)_R = Q_L(P_4 - P_3) - Q_A P_4 gh - Q_A P_4 \ln \left( \frac{P_3}{P_4} \right) \]  \hspace{1cm} (34)

**Gas separator**

\[ (E_d)_S = Q_L(P_3 - P_2) - Q_A P_3 \ln \left( \frac{P_2}{P_3} \right) - Q_A P_4 \ln \left( \frac{P_3}{P_5} \right) \]  \hspace{1cm} (35)

**Downcomer**

\[ (E_d)_d = Q_L(P_2 - P_3) - Q_A P_3 gh - Q_A P_4 \ln \left( \frac{P_3}{P_2} \right) \]  \hspace{1cm} (36)

**Bottom**

\[ (E_d)_b = Q_L(P_3 - P_4) - Q_A P_4 \ln \left( \frac{P_4}{P_3} \right) \]  \hspace{1cm} (37)

Schematic description of the variables in the thermodynamic model for energy dissipation distribution in an ALR.
The shear stress in the liquid of each region of the reactor can be defined as the energy dissipated divided by the mean path of circulation in the region and by the sum of the areas of all the bubbles.

For the region \( i \) in the ALR

where \( t_i \) is the residence time of the liquid, \( h_i \) is the effective length, and \( a_i \) is the specific interfacial area, in the region \( i \).

A global shear rate \( \gamma_i \) can be calculated for each region \( i \) as

\[
\gamma_i = \frac{t_i}{\mu}
\]  
(39)

**MASS TRANSFER**

- 1) *static properties of the liquid*
- 2) *dynamic properties of the liquid*
- 3) *liquid dynamics.*

**Mass Transfer Rate Measurements:**

- steady-state and nonsteady-state methods

\[
\text{OTR} = k_i a (C^* - C)
\]  
(40)

valid only for perfectly mixed systems

\[
t_c \cdot k_i a < 0.5
\]  
(41)
Bubble Size and Interfacial Area

• in a population of homogeneous bubble size

\[ a = \frac{6\varphi}{d_s} \]  \hspace{1cm} (42)

where the Sauter mean diameter \((d_s)\) is given by

\[ d_s = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \]  \hspace{1cm} (43)

Influence of the superficial gas velocity on overall \(k_{i,a}\) and on the \(k_{i,a}\) in each of the regions of an ALR.
for the volumetric mean diameter of the bubbles in the riser of a concentric-tube ALR

\[ \bar{d} \left( \frac{g_{\mu L}}{\pi d_o} \right)^{1/3} = f(N_w) \]  
(44)

where \( d_o \) is the diameter of the sparger orifice

\[ N_w = \frac{We}{Fr^{0.5}} \]  
(45)

and the function \( f(N_w) \) is different for each range of \( N_w \)

\[
\begin{align*}
  f(N_w) &= 2.9 & & N_w < 1 \\
  f(N_w) &= 2.9N_w^{0.188} & & 1 < N_w < 2 \\
  f(N_w) &= 2.9N_w^{0.5} & & 2 < N_w < 4 \\
  f(N_w) &= 3.6 & & 4 < N_w
\end{align*}
\]  
(46)

Data Correlations for Mass Transfer Rate

- Hydrodynamic
- Thermodynamic

Influence of the superficial gas velocity on overall \( k_{L_a} \) and on the \( k_{L_a} \) in each of the regions of an ALR
AIRLIFT REACTOR—SELECTION AND DESIGN

Scale-up of Airlift Bioreactors

• purposes
• problems

Results for a scaled-up bioreactor with a constant oxygen transfer rate
Schematic representation of the scale-down method

Influence of residence time in the poorly aerated downcomer on the production of *A. pullulans*.
Design Improvements

- Mechanical stirrer
  - Gas output
  - Gas input
  - Marine propeller

- Static stirrer
  - Gas output
  - Gas input
  - Static mixer

- Perforated draft tube
  - Gas output
  - Gas input