Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

# Experimental investigations of hydrodynamic characteristics of a hybrid fluidized bed airlift reactor with external liquid circulation

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ARTICLE INFO

*Article history:*
Received 8 March 2017
Received in revised form 4 August 2017
Accepted 30 August 2017
Available online 7 September 2017

*Keywords:*
External loop airlift
Fluidized bed
Gas holdup
Liquid circulation velocity
Momentum balance

ABSTRACT

The paper presents a simple analytical model of the hydrodynamics of a hybrid airlift apparatus with an external liquid circulation loop. The apparatus consists of two sections: a two-phase fluidization column and a barbotage section. The advantage of such a configuration is that there is no contact between the gas phase and the solid phase, which is relevant in case of processes involving a biofilm immobilization on fine carrier particles. Then, the shear stresses produced by passing bubbles do not damage the surface of a biofilm. The proposed model was derived based on the global momentum balance. It allows to determine basic hydrodynamic parameters of the apparatus including liquid and gas velocity, gas hold-up, and porosity and height of the fluidized bed. The model was verified experimentally and the hydrodynamics of the selected zones of the apparatus was simulated using Computational Fluid Dynamics (CFD).


## 1. Introduction

Three-phase fluidized-bed reactors; thanks to many advantages such as higher biomass concentration, better contact between liquid and solid phases and low washout of microorganisms compared to conventional tank reactor (Wisecarver and Fan, 1989) are commonly used for aerobic microbiological processes (Tang et al., 1987; Wisecarver and Fan, 1989). Immobilization of the biomass on a fine carrier particles, where solid particles act as a carrier for biofilm, permits to obtain a significant increase in its overall concentration in the reaction environment (Fan et al., 1987). Moreover, fluidization allows for easy bed replacement and prevents particles agglomeration and clogging of the pores, which is a serious issue for fixed beds (Iliuta and Larachi, 2004). Aeration of the liquid, i.e. is the process by which air is dissolved in a liquid, has two functions. Apart from providing oxygen for the reaction, the barbotage enhances mixing. In the airlift reactor the aeration has got an additional function – supply of the air into the barbotage zone leads to the reduction of the average density of a gas–liquid mixture in relation to the liquid density. The difference in the average density of the aerated and non-aerated zone acts as a driving force for the liquid circulation.

However, in case of a three-phase fluidized bed, flowing gas bubbles induce a shear stress which may damage a delicate biofilm deposited on the carrier surface, which may lead to complete degradation of biofilm (Henzler, 2000). The possible solution to this problem is to separate the barbotage zone from the fluidized-bed zone. Dunn et al. (1983) introduced an apparatus composed of a fluidized-bed reactor and an aerator connected by a recirculation loop. According to the authors such a configuration permits to eliminate contact of the gas bubbles with the biofilm immobilized on the solid particles. Guo et al. (1997) proposed a modification of the three-phase airlift reactor with external liquid circulation, in which the barbotage section is located above the fluidized-bed section, thus there is no mixing of the solid phase and gas. An additional advantage is that such a configuration does not require a circulator pump. For an appropriate level of aeration the pressure difference enables to achieve the liquid velocity necessary to fluidize the bed.

Olivieri et al. (2010) introduced their own design of a hybrid airlift bioreactor. The authors proposed an apparatus with the internal liquid circulation loop having more compact design than the apparatus with the external liquid circulation. An analytical model of the

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http://dx.doi.org/10.1016/j.cherd.2017.08.028
0263-8762/

**Nomenclature**

| | |
|---|---|
| $d$ | Diameter, m |
| $F_V$ | Volumetric flow rate, $m^3/s$ |
| $g$ | Gravitational acceleration, $m/s^2$ |
| $H$ | Height, m |
| $m$ | Mass, kg |
| $n$ | Exponent in the Richardsona and Zaki model, – |
| $\Delta p$ | Pressure drop, Pa |
| Re | Reynolds number, – |
| $S$ | Cross section, $m^2$ |
| $u$ | Velocity, m/s |

*Greek symbols*

| | |
|---|---|
| $\varepsilon_1$ | Bed porosity, – |
| $\varepsilon_2$ | Gas holdup, – |
| $\eta$ | Dynamic viscosity coefficient, kg/(m s) |
| $\lambda$ | Flow friction coefficient, – |
| $\xi$ | Local friction coefficient, – |
| $\rho$ | Density, $kg/m^3$ |
| $\sigma$ | Surface tension, N/m |
| $\upsilon$ | Gas bubble rise velocity, m/s |
| $\phi$ | Shape factor, – |

*Subscripts*

| | |
|---|---|
| 0 | Value related to the cross section of the apparatus |
| 1–5 | Zones of the apparatus (Fig. 1) |
| E | Refers to local friction factor of the bend |
| *f* | Refers to fluidized bed |
| *feed* | Refers to feed flow |
| *g* | Gas phase |
| *I* | Refers to local friction factor of the upper vessel inlet |
| *l* | Liquid phase |
| *mf* | Minimum fluidization conditions |
| N | Refers to local friction factor of the mesh |
| O | Refers to local friction factor of the upper vessel outlet |
| s | Solid phase |
| S | Refers to mesh |
| SE | Refers to local friction factor of the sudden expansion |
| t | Refers to terminal velocity of the particle |

hydordynamics of the loop apparatus with the internal liquid circulation was then formulated by Tabiś et al. (2014). Fig. 1 shows two different configurations of the apparatus, i.e. with the external (Fig. 1a) and internal (Fig. 1b) liquid circulation. Five zones can be distinguished in both configurations. As shown in Fig. 1 these zones are: fluidization zone "1", barbotage zone "2", downcomer "3", degassing zone "4" and bottom zone "5".

Description of the hydrodynamics of the hybrid fluidized-bed reactor is a rather complex problem. Due to the presence of the gas phase such an apparatus may operate, like a traditional airlift reactor, in three hydrodynamic regimes characterized by: complete degassing of the liquid in the upper vessel, partial degassing of the liquid in the downcomer or gas circulation through all zones of the reactor. Depending on the liquid circulation velocity the bed of solid particles may operate as: a fixed bed resting on the bottom mesh, a fluidized bed or a fixed bed resting under the upper mesh. The combinations of operating regimes of the hybrid apparatus listed above are presented graphically in Fig. 2.

Despite the variety of theoretically possible operating regimes of the hybrid apparatuses shown in Fig. 2, own experimental studies con-

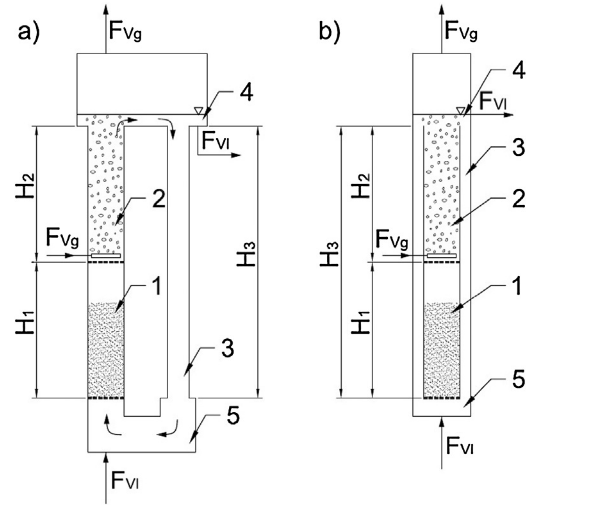


**Fig. 1 – Hybrid fluidized-bed apparatuses (a) with external liquid circulation, (b) with internal liquid circulation; 1 – fluidization zone, 2 – barbotage zone, 3 – downcomer, 4 – degassing zone, 5 – bottom zone.**

firmed complete degassing of the liquid in zone "4" (Fig. 1a). Therefore, the only possible operating modes are regimes I, IV and VII (Fig. 2) corresponding to the complete liquid degassing. On the other hand, a technologically attractive operating mode of the bed of solid particles corresponds to the regimes IV, V and VI (Fig. 2), i.e. conditions at which the bed is in a fluidized state. Thus, only the regime IV fulfils both conditions of the hybrid apparatus.

The paper presents an analytical hydrodynamic model of a hybrid airlift apparatus with an external liquid circulation that provides design guidelines and allows to select optimal operating conditions. The proposed model is verified experimentally and the results obtained from the model are further compared with Computational Fluid Dynamics (CFD) simulations in order to adjust the values of local friction coefficients.

## 2. Experimental setup

The experimental apparatus is shown in Fig. 3. It is equipped with an external circulation tube and is made of transparent tubes and plates made of poly methyl methacrylate (PMMA). A fluidized-bed section "1" (Fig. 1a) is located in the lower part of the riser. A wire mesh with the openings of 1 mm and made of wire having a diameter of 0.5 mm is mounted under the fluidization zone. To prevent entrainment of the particles from the fluidization zone, an identical mesh is disposed in the upper part of this section. Directly above this, a barbotage section is located. Air is supplied to the barbotage zone by means of a cross-shaped metal distributor. At the top of the gas distributor, 25 equally spaced holes (one hole in the centre and six holes on every branch) with diameter of 1 mm and at distance of 5 mm apart were drilled. The liquid leaving the barbotage section enters the upper vessel "4" and then it flows into the downcomer "3" (Fig. 1a). The design of the apparatus allows to mount circulation tubes of different diameters. The riser and the downcomer are connected in the bottom by means of a connector which creates a bottom section "5".

The air supplying the apparatus is first compressed by means of a compressor. Then it flows through a gas mass flow controller (MFC) allowing for the adjustment of the volumetric flow rate and enters the air distributor. The measurements were carried out for several values of the gas flow rate. The minimum gas flow rate coincided to the minimum fluidization conditions of the solid particles, whereas the highest corre-