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Enhanced hydrodynamics in a novel external-loop airlift reactor with self-agitated impellers

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ABSTRACT

In the present work, self-agitated impellers, as a novel type of internals, have been proposed for improving hydrodynamic and mass transfer characteristics of external-loop airlift reactors. The influence of inserted self-agitated impellers, in the riser section, in various liquid phases and with different sparger types, on main hydrodynamic parameters, was studied. The results show that the insertion of impellers led to significant bubble breakage and decrease in mean bubble size, particularly in pseudoplastic liquid. Obtained riser gas holdup values were up to 47% higher, in comparison to the configuration without impellers. Higher improvements were obtained with single orifice, given that this is the least effective gas distributor. Even though impellers represent an obstacle to the flow, relatively low reduction (about 10%) in downcomer liquid velocity was observed, for all investigated cases. Having this in mind, the benefit of inserting self-agitated impellers for improving the performance of external-loop airlift reactors was apparent.

1. Introduction

As a result of simple construction without moving parts, low shear rate, good mixing and low energy requirements, external-loop airlift reactors (EL-ALR) are extensively employed in many biochemical and pharmaceutical applications. Their performance is notably affected by complex interrelationships between hydrodynamic parameters, transport phenomena, design and operating variables, microbial survival and production kinetics [1,2]. One of the key factors in determining their productivity is the gas-liquid mass transfer. Improved mass transfer and thereby higher productivity are achieved by increasing either the specific gas-liquid interfacial area, a, or mass transfer coefficient, k_L. Smaller bubble diameter, higher and more uniform radial holdup profiles initiate an increase in the interfacial area and hence the more intimate contact between phases is achieved [3]. Intensified turbulence promotes higher mass transfer by increasing mass transfer coefficient, destabilizing large bubbles and increasing surface renewal frequency of bubbles [4]. Nevertheless, with an increase in liquid velocity rates, the residence time of the gas phase shortens and thus a decrease in the gas holdup is obtained. Because of the important influence of hydrodynamics on mass transfer rate, detailed characterization of hydrodynamic parameters, such as gas holdup, liquid velocity rate and bubble behavior, is fundamental for the assessment of EL-ALR operation.

Hydrodynamics and mass transfer in EL-ALRs are largely affected by liquid phase properties, such as rheological behavior and surface tension, and sparger design. Most of the commercial fermentation processes involve viscous non-Newtonian media thus instigating numerous studies, regarding their behavior in EL-ALRs. Carboxymethylcellulose (CMC) is mainly employed as a model fluid because it has properties that highly resemble fermentation media. The effect of CMC on hydrodynamics is greatly dependent upon the apparent viscosity of the solution. Wu et al. [5] observed that in CMC solutions with lower viscosities bubble coalescence was prevented. As a result, higher riser gas holdup values were achieved. However, in highly viscous CMC solutions very large irregular-shaped and spherical-cap bubbles, with high rise velocities, are accompanied by very small bubbles [6]. Since larger bubbles have higher rise velocities, lower gas holdup values are obtained. Considering that an increase in mean diameter of the bubbles reduces a, whereas k_L decreases because of lower diffusivity, mass transfer is highly diminished in viscous non-Newtonian liquids [7]. In some fermentation applications non-coalescing media are involved. Alcohols, as surface active liquids, supress bubble coalescence and thus have a huge impact on hydrodynamics and mass transfer characteristics and hence, are used to simulate the behavior of non-coalescing media. The addition of small amounts of aliphatic alcohols decreases the mean size of bubbles and reduces bubble

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Nomenclature

Notation

A	cross-sectional area, m^2
a	specific gas-liquid interfacial area, 1/m
D	diameter, m
d_b	bubble diameter, m
g	gravitational acceleration, m/s^2
H	height, m
HI	improvement of riser gas holdup
K	flow consistency index, $Pa\cdot s^n$
K_f	overall friction coefficient
k_L	mass transfer coefficient, m/s
k_La	volumetric mass transfer coefficient, 1/s
L_{12}	distance between two conductivity electrodes, m
LVR	reduction of downcomer liquid velocity
n	flow behavior index
t	time, s
U_G	superficial gas velocity, m/s
W_L	liquid velocity, m/s

Greek letters

$\varepsilon_{GR,v}$	riser gas holdup measured with volume expansion technique
ε_{GR}	riser gas holdup
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

c	circulation
D	downcomer
DT	draft tube
i	impeller
m	mixing
R	riser

Abbreviations

CMC	carboxymethylcellulose
DT-ALR	draft tube airlift reactor
EL-ALR	external-loop airlift reactor
EL-ALRI	external-loop airlift reactor with self-agitated impellers
EL-ALRoX	external-loop airlift reactor with restriction orifice (*X* denotes orifice free area)
SO	single orifice
SP	sinter plate

rise velocities which lead to increased gas holdup [8,9]. In EL-ALRs, the type of gas sparger influences hydrodynamics only through initial bubble size [10]. The impact of sparger type is more pronounced at lower gas throughputs, *i.e.* bubbly flow or transition flow, in which the size of bubbles in the dispersion is determined by the bubble size at formation [11]. In the case of heterogeneous flow, the influence of sparger type is lessened due to strong bubble coalescence. Hence, sparger type influence is even more emphasized in systems with inhibited coalescence, like alcohol solutions.

Various modifications of both internal- and external-loop airlift reactors have been developed as a result of increasing demand for improved yield and productivity. Some of them have inserted internals like baffles [12,13], perforated plates [3,7,14], static mixers [15–17], mechanically driven impellers [18–20], packed beds [21–23] or custom designed internals [4,24,25], which obstruct fluid flow and intensify mixing and mass transfer. Summarized in Table 1 are listed characteristics of modified EL-ALR with the details of used internals.

Table 1
Review of investigated types of internals in external-loop airlift reactors.

Reference	Internal type	EL-ALR characteristics (mm)	Investigated parameters	HI †	LVR ‡
Lin et al. [12]	Slanted baffles	$D_R = 150$, $D_D = 50$, $H = 3000$	k_La, t_m, t_c	–	–
Nikakhtari and Hill [22]	Woven stainless steel mesh packing	$D_R = 89$, $D_D = 47$, $H_R = 1810$	k_La, ε_{GR}, U_{LR}, bubble size	20–130%	54–76%
Nikakhtari and Hill [26]	Woven nylon mesh packing	$D_R = 89$, $D_D = 47$, $H_R = 1810$	k_La	–	–
Meng et al. [23]	Woven nylon packing	$D_R = 89$, $D_D = 47$, $H_R = 1810$	ε_{GR}, U_{LR}, axial dispersion, bubble size distribution	21–35%	9–24%
Hamood-ur-Rehman et al. [21]	Two rolls of fiberglass packing	$D_R = 248$, $D_D = 102$, $H = 1996$	t_m, U_{LR}	–	17–29%
Hamood-ur-Rehman et al. [27]	Two rolls of fiberglass packing	$D_R = 248$, $D_D = 102$, $H = 1996$	ε_{GR}	5–15%	–
Goto and Gaspillo [15]	Static mixer	$D_R = 27$, $D_D = 61$, $H_R = 585$, $H_D = 390$	U_{LR}, $U_{G,min}$, k_La	–	23–37%
Zhang et al. [4]	Perforated baffles (45° angle between baffle and vertical axis)	$D_R = 230$, $D_D = 190$, $H = 4800$	Local ε_{GR}, U_{LR}, bubble rise velocity, d_b	–	–
Mohanty et al. [24]	7 internals (4 contraction and 3 expansion discs)	$D_R = 219.9$, $H = 1820$	ε_{GR}, U_{Lc}	–	–
Chisti et al. [16]	SMV-12 static mixer elements	$D_R = 50$, $D_D = 75$	k_La	–	–
Gavrilescu et al. [17]	Sulzer type static mixer	$A_D/A_R = 0.1225$	U_{LR}, ε_{GR}	–	–
This paper	9 self-agitated impellers	$D_R = 93$, $D_D = 54$, $H = 2360$	ε_{GR}, W_{LD}	11–36%	3–18%

† Relative improvement of riser gas holdup (water as a liquid phase).
‡ Relative reduction of liquid velocity (water as a liquid phase).