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Gas suction and mass transfer in gas-liquid up-flow ejector loop reactors. Effect of nozzle and ejector geometry

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HIGHLIGHTS

- Correlations more of 700 m_G and of k_La data are presented for air-water system.
- Effect of nozzle geometry is described by the nozzle pressure loss coefficients.
- Energy of inner turbulence and kinetic energy of liquid jet is considered separate.
- High accuracies of the correlations, deviations lower than 8%, are so obtained.

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ABSTRACT

The aim is to develop a method for the design of up-flow ejector loop reactors for coalescent systems respecting the different energy dissipation and mechanism of interfacial mass transfer in the ejector and in the holding vessel. Measurements and correlations of gas entrainment rate (m_G/m_L) and of oxygen volumetric mass transfer coefficient (k_La) are reported describing their dependencies on operating conditions for various geometries of the ejector. The results show that the energy supplied into the ejector must be expressed as a two independent parts: one representing the energy of inner turbulence of the liquid jet leaving the nozzle and the one representing the kinetic energy of axial liquid flow entering the suction chamber. Turbulent transverse motion generated in the nozzle characterized by its pressure loss coefficient ς, produces a surface roughness of the jet and plays a dominant role in its ability to entrain the surrounding gas. The kinetic energy of the axial liquid flow characterized by liquid velocity in the nozzle v_n, diminished for the energy spent on gas compression is utilized in the mixing shock for dispersing of the entrained gas into the liquid. The correlations formed for a prediction of m_G/m_L and of k_La in ejector based on the more of 700 individual ejector configurations have average deviation lower than 8%. Mass transfer and gas hold-up in the holding vessel were modeled using the previously verified slip velocity concept, characterizing the mutual flow of phases in homogeneous bubble beds. An example of the application of the correlations for evaluation of mass transfer performance of Ejector Loop Reactor is shown.

1. Introduction

The ejector loop reactors (ELR) are considered as a superior alternative to the conventional stirred tank reactors due to their simpler construction and excellent mass transfer performance. Ejectors are characterised by self-priming, bringing a sufficiently large amount of gas reactant into the contact with the liquid phase, by generating microbubbles (20–60 µm) with high energy-efficiency and high throughput capacity, and with volumetric mass transfer coefficients k_La up to two orders of magnitude higher (5–50 s^{-1}) than those achieved in other types of commonly used gas-liquid contactors. This is achieved by mechanical co-location of the gas phase inflow to the point where a maximum shear of the motive liquid occurs. ELRs in the encapsulated pressurized mode are highly recommended for the following types of reactions: amination, alkylation, ethoxylation, hydrogenation, carbonization, nitration, oxidation etc. [1,2]. Although ejectors have been used in industry for decades, there are only a few papers in the open literature that provide all the information required for their reliable design and scale-up as a function of geometrical and performance parameters. Majority of them dealt only with the gas entrainment rate

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Notation

A_{col}	column cross-section area, m^2
c_G	oxygen concentration in gas phase, kmol m^{-3}
c_L	oxygen concentration in liquid phase, kmol m^{-3}
c_{Gin}	oxygen concentration in gas phase at ejector inlet, kmol m^{-3}
c_L^{*G}	liquid phase equilibrium oxygen concentration, kmol m^{-3}
c_L^{*Gair}	liquid phase equilibrium oxygen concentration with respect to air at atmospheric pressure, kmol m^{-3}
c_L^{*Gin}	liquid phase equilibrium oxygen concentration with respect to air at pressure in ejector inlet, kmol m^{-3}
d_d	diffuser diameter, m
d_m	mixing tube diameter, m
d_n	nozzle diameter, m
d_p	nozzle inlet diameter, m
d_{col}	column diameter, m
e_{Gcol}	gas hold-up in the bubble column, –
$e_{Gcol,exp}$	experimental gas hold-up in the bubble column –
g	gravitational constant, m s^{-2}
h_{col}	dispersion height in the bubble column, m
h_{ej}	ejector height, m
h_1	liquid height in the U-tube 1, m
h_4	liquid height in the U-tube 4, m
I_{air}	oxygen probe reading in liquid saturated with air at p_{air}, –
I_d	oxygen probe reading in liquid at diffuser exit, –
I_{in}	oxygen probe reading in liquid at ejector inlet, –
I_{sat}	oxygen probe reading in air at pressure of p_d, Eq. (13), –
k_La	oxygen volumetric mass transfer coefficient in ejector, s^{-1}
k_La_{col}	oxygen volumetric mass transfer coefficient in column, s^{-1}
L_d	diffuser length, m
L_m	mixing tube length, m
L_n	nozzle tip length, m
L_t	throat length, m
$L_{1,4}$	distance between the ports of U-Tube 1 and 4, m
M_{air}	molar mass of air, kg kmol^{-1}
m_G	gas mass flux, kg s^{-1}
m_L	liquid mass flux, kg s^{-1}
m_O	oxygen solubility, –
N_{col}	oxygen mass transfer rate in the column, kmol s^{-1}
N_{ELR}	oxygen mass transfer rate in the ejector loop reactor, kmol s^{-1}
N_{ej}	oxygen mass transfer rate in the ejector, kmol s^{-1}
P_{comp}	power on gas compression, W
P_{disp}	power utilized for the dispersing of phases, W
P_{in}	power of liquid in suction chamber, W
P_{out}	power at the diffuser exit, W
$P_{pump,ej}$	power supplied by centrifugal pump to ejector, W
p_{air}	atmospheric pressure, Pa
p_d	pressure at the diffuser exit, Pa
p_p	pressure in the ejector inlet pipe, Pa
p_s	pressure in the suction chamber, Pa
p^o	standard pressure, Pa
p^o_{H2O}	water saturation pressure, Pa
Q_G	gas entrainment rate expressed at pressure p^o = 101.3 kPa and temperature 25 °C, m^3 s^{-1}
Q_{Gair}	gas flow rate in suction chamber, m^3 s^{-1}
Q_{Gd}	gas flow rate at the diffuser outlet, m^3 s^{-1}
Q_L	liquid flow rate, m^3 s^{-1}
R	universal gas constant, J kmol^{-1} K^{-1}
R_{air}	specific universal gas constant, J kg^{-1} K^{-1}
T_s	temperature in suction chamber, K
V_d	diffuser volume, m^3
V_{ej}	ejector volume, m^3
V_{Lej}	liquid volume in ejector, m^3
V_{col}	dispersion volume in reactor vessel, m^3
v_d	velocity at the diffuser exit, m s^{-1}
v_n	jet velocity at the nozzle exit, m s^{-1}
v_p	liquid velocity in the ejector inlet pipe, m s^{-1}
v_{sl}	slip velocity, m s^{-1}
v_{0Gcol}	gas phase fictive velocity in the column, m s^{-1}
v_{0Lcol}	liquid phase fictive velocity in the column, m s^{-1}

Greek letters

α	nozzle contraction angle
β	diffuser opening angle
ε_{disp}	specific energy utilized for mixing of phases, J kg^{-1}
$\varepsilon_{pump,ej}$	specific energy supplied by centrifugal pump to ejector, J kg^{-1}
ρ_{Gs}	gas density at pressure p_s and temperature T_s, kg m^{-3}
ρ_{Gd}	gas density at pressure p_d and temperature T_s, kg m^{-3}
ρ_{Gcol}	gas density at mean pressure in the column, kg m^{-3}
$\rho_G{}^o$	gas density at pressure p^o and temperature 298.13 °K, kg m^{-3}
ρ_L	liquid density, kg m^{-3}
ς	pressure loss coefficient

(i.e. down-flow [3–10], horizontal-flow [11–13], up-flow [14–18]). Studies which deal with a mass transfer in the ejectors are even less available and a majority of them concerns the down-flow ejectors [19–21]. The mass transfer in the up-flow ejectors was studied by authors [22,23] who used two configurations of the ejector, and the gas entrainment rate was optimized only without considering mass transfer and by Balamurugan et al. [14] which have studied ejectors employing air as the motive fluid and water as the entrained fluid.

This work is the continuation of our earlier studies [15,22,24] devoted to the up-flow configurations with liquid as a motive fluid. This configuration provides some advantages [25]: the liquid jet produces smaller gas bubbles, the driving force for a mass transfer is enhanced by the hydrostatic pressure and thus the conversion of the gas phase can be improved, the gas passes through the holding vessel faster and thus is suitable for higher gas throughputs particularly when the gas has a high content of an inert.

In designing a gas–liquid contactor with ejector distributor, it is necessary to respect very different energy dissipation in the ejector alone and in the remaining vessel. Most of authors give overall k_La for ejector and holding vessel [2]. To our knowledge there are only few studies [19,21,22] where the authors considered mass transfer in the ejector and the holding vessel separately. Havelka et al. [22] showed that the mass transfer rate in holding vessel is proportional to the gas hold-up in the vessel. It well agree with findings of Zahradník et al. [17] who compared the mass transfer rate and gas hold-up in a bubble column equipped by an ejector gas distributor and a sieve-tray and showed that the dependence of k_La on gas hold-up ratio in the holding vessel is almost identical for both types of gas distributors. From these studies [17,22] it can be concluded, that the mass transfer in the holding vessel of the ejector loop reactors in the up-flow arrangement can be estimated by applying the methods developed for bubble columns.

Havelka et al. [22] studied the behavior of coalescent and non-coalescent batches in an ejector loop reactor similar to the one used in this work. Using different methods of k_La measurement (dynamic pressure-step, steady-state physical, classic sulfite and steady-state sulfite method) and absorption of air and pure oxygen they came to the following findings for a coalescent system: (i) values of k_La measured in