Chemical Engineering Journal 133 (2007) 293–299

Chemical Engineering Journal

www.elsevier.com/locate/cej

Influence of draft tube cross-sectional geometry on K_La and ε in jet loop bioreactors (JLB)

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Received 30 October 2006; received in revised form 31 January 2007; accepted 21 February 2007

Abstract

Due to their compactness, and high flexibility in operation, the new processes like jet loop bioreactors (JLB) show a large potential for high removal efficiency and significant cost reduction in particular for the biological treatment of highly polluted wastewater. The rate of oxygen delivery determines the efficiency of aerobic processes. A modified JLB with square cross-sectional draft tube was developed in this study. Experiments were performed to investigate the effects of cross-sectional geometry, liquid flow rate and gas flow rate on gas hold-up and K_La. The comparison of these parameters as well as K_La was carried out for two cross-sectional draft tubes geometry. The results indicated that K_La values were better by 11–13% in square draft tube. In this study, the mass transfer characteristics with the square draft tube configuration have also been studied and a model was developed for this configuration.

Keywords: Jet loop reactors; Draft tubes; Bioreactors; Gas–liquid mass transfer; Gas hold-up

1. Introduction

With growing industrialization and density of population, the selection of treatment processes has become more and more important because of the stringent discharge limits. In order to meet these limits, the existing treatment plants have to be modified or replaced with the novel reactors. In the aerobic bioprocesses, oxygen transfer is essential for the performance of the system. Any shortage of oxygen drastically affects the process performance negatively. The oxygen transfer also effects metabolic activity, process efficiency and energy cost. It is also the principal hydrodynamic parameter in the operation of bioprocess. Therefore, oxygen transfer is important and frequently a rate limiting step for aqueous bioprocesses [1]. The oxygen absorption capacity of a bioreactor is characterized in terms of the overall volumetric gas–liquid mass transfer coefficient, or K_La. The use of jet aeration systems for biological treatment of wastewaters is becoming more common by means of combining efficient oxygen transfer with high turbulent. Jet aerator systems have been used successfully to upgrade biological treatment plants to meet increased loads and ever tightened legislations [2].

There are various types of loop bioreactors such as air lift bioreactor, propeller loop bioreactor and jet loop bioreactor. The jet loop bioreactors (JLB) are reactors with high performance and extensively used in fermentation, biotechnology and wastewater treatment plants. The JLBs have many advantages such as simple construction and operation, low investment and operational costs, definitely directed circulation flow, fine gas dispersion, high mixing and mass transfer performance and relatively lower power requirements [2–4]. In addition, absence of moving parts in the bioreactor, the efficient primary dispersion of gas in gas–liquid system and efficient redispersion of gas phase during recirculation, JLBs provide high performance at the biological treatment of industrial wastewater with high organic contents [2,5–9].

The principle in this reactor type is the utilization of the kinetic energy of a high velocity liquid jet to entrain the gas phase and to create a fine dispersion of two phases. The high shear rates from the liquid jet produce very fine gas bubbles and thus very high interfacial areas and volumetric gas transfer rates are generated in this equipment. The most important parameter in multiphase systems is the generation of interfacial area, the extent of which is directly related to the gas hold-up

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1385-8947/$ – see front matter
doi:10.1016/j.cej.2007.02.022

Nomenclature

A_b	bioreactor area (cm^2)
A_d	draft tube area (cm^2)
C	oxygen concentration in liquid (mg/L)
C_i	initial oxygen concentration in liquid (mg/L)
C_s^*	saturation oxygen concentration in liquid (mg/L)
D_b	bioreactor column diameter (m)
D_c	draft tube diameter (cm)
D_i	smaller diameter in liquid annular hole in the nozzle (cm)
D_G	air hole diameter in nozzle (mm)
D_L	diffusion coefficient (m^2/s)
E/V	energy dissipation rate per unit volume ($\rho_l A_D U_L^3/2V$) (kW/m^3)
g	gravitational constant (m/s^2)
h_L	level of the clear liquid (cm)
h_D	level of the two phase dispersion (cm)
H_b	bioreactor height (m)
JLB	jet loop bioreactor
K_La	volumetric mass transfer coefficient (1/h)
L_d	height of the draft tube (cm)
ΔP	pressure drop
Q_g	gas flow rate (L/min)
Q_L	liquid flow rate (L/min)
u	linear liquid velocity based on A_D (m/s)
V	liquid volume in the bioreactor (m^3)

Greek letters

ε	gas hold-up
μ_L	liquid viscosity (mPa s)
ρ_L	liquid density (kg/m^3)

(ε). The gas hold-up in turn depends upon the physical properties of the liquid, the flow regime and bioreactor efficiency [10]. JLBs in comparison with other types of gas–liquid bioreactors produce higher surface area between the gas and liquid phases.

There are a lot of parameters that affect K_La and ε in the JLBs. Investigations of the fundamental hydrodynamic features and mass transfer characteristics in JLBs have been reported by various authors in literature [3,4,10–13]. However, no work has been reported for the effect of draft tube cross-sectional geometry on K_La and ε so far. In the present investigation, the experiments were performed to obtain the effect of draft tube cross-sectional geometry on K_La and ε in the JLBs.

2. Materials and methods

2.1. Equipment and operational procedure

A schematic diagram of experimental set-up is shown in Fig. 1. JLB consisted of a cylindrical vessel (height 140 cm, inner diameter 15 cm) with a height to diameter ratio of 10:1 and carried inside a draft tube open at both ends and a degassing tank. The apparatus was made of a Perspex flex glass tube. Other dimensions of the experimental system are given in Table 1.

Table 1
Experimental parameters for jet-loop bioreactor investigation

Description	Notation	Value
Bioreactor height (cm)	H_b	140
Bioreactor diameter (cm)	D_b	15
Draft tube diameters/length		
Circular (cm)	D_c	6.2
Square (cm)	D_s	5.5
Draft tube to bioreactor cross-section area ratio	A_d/A_b	0.19
Draft tube length (cm)	L_d	100
Distance between the lower edge of the draft tube and the impact plate (cm)	H_p	7
Distance between the impact plate and the lower edge of the bioreactor (cm)		7
Air hole diameter in nozzle (cm)	D_G	0.64
Liquid annular hole inside diameter in nozzle (cm)	D_i	1.2
Unaerated liquid height (cm)	h_L	124
Liquid height above draft-tube (cm)		10
Working volume (L)	V	35
Temperature	°C	20 ± 2
Liquid phase	Tap water	

Two-fluid nozzle consisted of two concentric tubes. The outer nozzle was made of polyester. The inner nozzle was a stainless-steel tube of 6.4 mm in diameter and 1 mm thickness. The air to the reactor was provided from an air pump through the inner stainless-steel tube via a gas flow-meter. Gas and liquid flow rates were controlled by the valves and flow-meters on their respective pipelines. The two-fluid jet nozzle located at the top of reactor created a downward directed two-phase flow inside the draft tube and at the same time dispersed the air sucked in through the gas tube located within liquid jet. The type and place of the spray nozzle has a significant effect upon the gas dispersion within the liquid phase and the extent of the jet flow momentum, which promotes the mixing of the phases. There is no contact between the liquid and gas phases within the nozzle. Due to the momentum of liquid jet, the liquid and the gas inside the draft tube were moving downwards and after reflection at the reactor bottom, rose within the annulus between the wall of the reactor and the draft tube. At the upper end of the draft tube, a part of fluid was recycled into the draft tube by sucking action of the two-phase jet resulting in a re-dispersion of the bubbles. The temperature of bioreactor content was maintained around 20 ± 2 °C by circulating tap water through a stainless steel heat exchanger immersed in the degassing tank. The recycle flow was measured by a flow-meter and air flow supplied to bioreactor was measured by an air flow-meter.

Two draft tubes with different cross-sectional geometry were used in the experiments. One was a circular and the other was square geometry. Both draft tubes had equal cross-sectional area.

All the mass transfer tests were performed with tap water while the system was running under batch mode (the broken

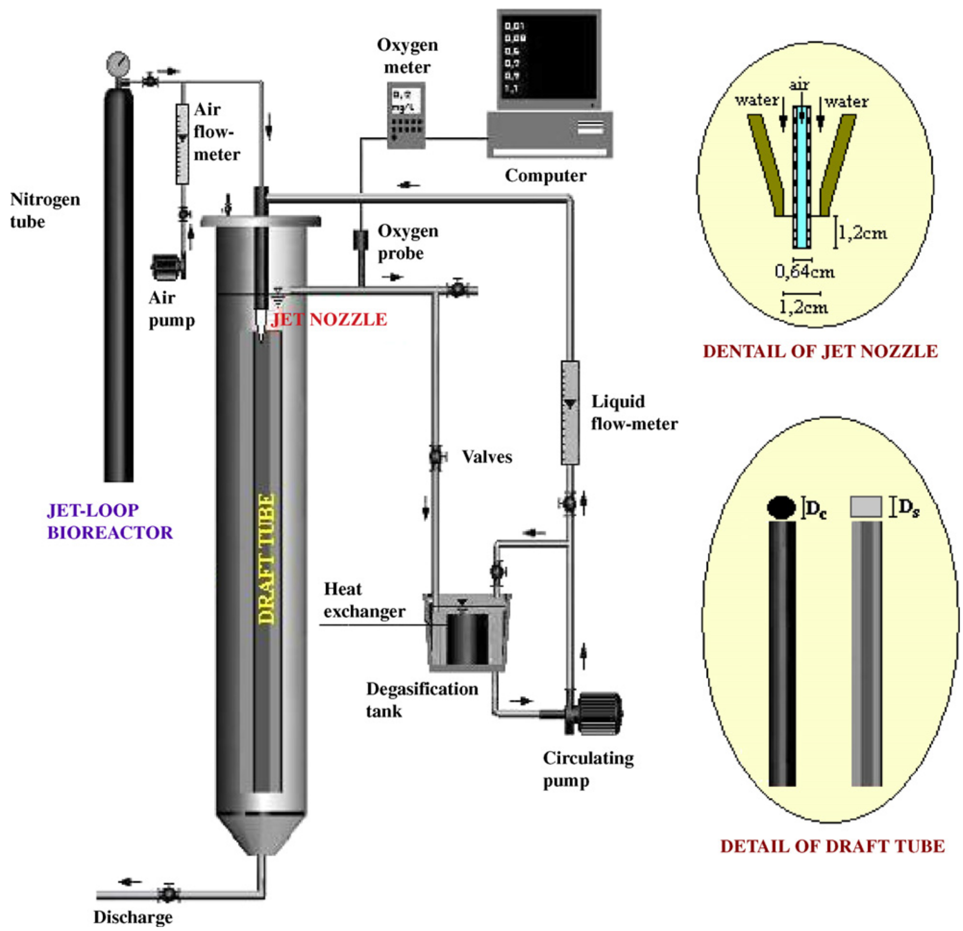

Fig. 1. Schematic diagram of the experimental set-up.

flow lines and relevant equipment excluded). Before each test, the dissolved oxygen (DO) in the water was stripped down to 0.5 mg/L by nitrogen purging. After switching over to air supply line, the concentration of oxygen was measured as a function of time using a DO meter (ORION 835 type) equipped with an oxygen probe. Also, temperature and pH were measured with the same measurement device. The DO data obtained through DO meter was sent to computer for further analysis.

2.2. Experimental procedure

The inlet water flow rates were converted to energy dissipation rate (power input), E, by using the following equation:

$$E = Q_L \, \Delta P = Q_L \left(\rho_L \frac{u^2}{2} \right) \qquad (1)$$

where Q_L is the inlet water flow rate in the jet nozzle, ΔP the pressure drop at the nozzle (which is converted to kinetic energy), u the mean water velocity at exit of the jet nozzle, and ρ_L is the density of water under the experimental conditions. E/V values were calculated by using this equation.

The inflows of air and liquid were stopped during the steady-state operation. The overall gas holdup, ε, in the reactor was determined by visual measurements of the static liquid height, h_L, and the aerated height, h_D, according to the following relationship:

$$\varepsilon = \frac{h_D - h_L}{h_D} \qquad (2)$$

It is difficult to determine the liquid–gas interfacial area available for the mass transfer when dealing with reactors of the present type. Therefore, the mass transfer is usually expressed in terms of mass transfer per unit volume of the reactor and the mass transfer coefficient as overall volumetric mass transfer coefficient [14]. K_La can be computed by using a non-linear expression:

$$C = C_s^* - \left(C_s^* - C_i\right) e^{-(K_La)t} \qquad (3)$$

where C is the DO concentration in the medium at a given time of t, C_s^* saturation and C_i is initial ($t = 0$) oxygen concentration at the experimental conditions.

3. Results and discussion

3.1. The effect of draft tube cross-sectional geometry on K_La and ε

Two different types of draft tubes (circular and square) with the same cross-sectional area were investigated. The cross-sectional area of both draft tubes was 30.2 cm^2. A_d/A_b ratio was 0.19. In the experiments, the gas (air) flow rates were varied from 4 to 16 L/min. The liquid flow rates were changed between 35 and 58 L/min. the power produced by the pump was calculated as the kinetic energy for unit volume (*E*/*V*) between 0.6 and 2.6 kW/m^3. During the experiments, it was observed that the loop was not achieved for both draft tubes configuration if the liquid flow was under 34 L/min. This was due to the low power generated by pumping at that rate.

High velocity jet produced in the jet nozzle breaks and forms smaller air bubbles. The primary reason of the high performance of JLBs is the formation of smaller bubbles. The smaller bubbles increase gas hold-up and accordingly K_La values of the JLBs. The draft tube is the key part of JLBs. The draft tube provides the long travel path and high residence time for the liquid (air–water mixture). Long residence time causes to obtain higher K_La. The length of draft tube and the ratio of draft tube diameter to reactor diameter were studied in earlier researches and found the optimal values for those parameters [4,15]. In these studies, JLBs with the cylindrical draft tubes have been used.

In the first stage of the study, the influences of *E*/*V* values on K_La and ε for different draft tubes were investigated. The jet nozzle with the 1.2 mm inner diameter was used in all experiments. The effect of *E*/*V* values on K_La and ε for two different draft tubes geometry under a given gas flow rate are shown in Figs. 2 and 3. It was observed that K_La values were increased with the increasing *E*/*V* values. The increase in K_La showed the same tendency for two draft tubes. In addition, ε increased in similar tendency with increasing *E*/*V* values for both draft tubes.

From Figs. 2 and 3, it is noticeable that higher K_La values obtained in the square draft tube than those for circular draft tube. The higher ε values obtained from the square draft tube proved the conclusions for K_La. High ε resulted when high K_La was achieved.

The effect of gas flow rates on K_La and ε at different draft tubes geometry for a given *E*/*V* and nozzle diameter are seen in Figs. 4 and 5. K_La values increased in both draft tubes with increasing Q_g. Similarly, ε increased with the increasing Q_g.

K_La was obtained higher in the square draft tube than in the circular draft tube in the entire *E*/*V* and Q_g experiments. K_La

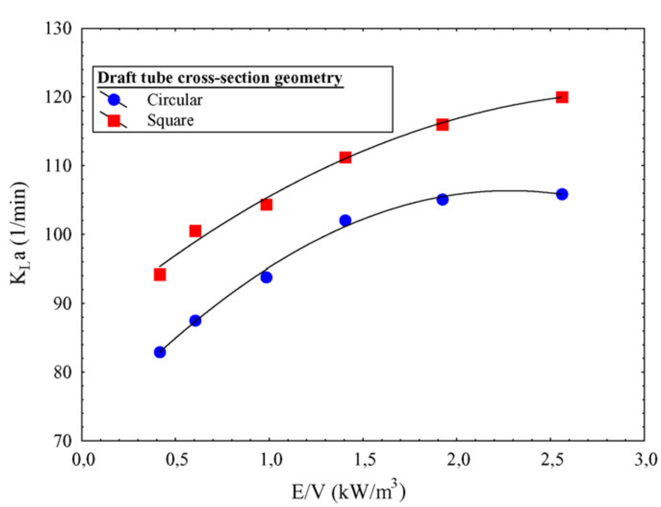

Fig. 2. Effect of *E*/*V* values on K_La at two different draft tubes geometry for a constant gas flow rate and nozzle diameter (Q_g = 6 L/min and D_i = 1.2 cm).

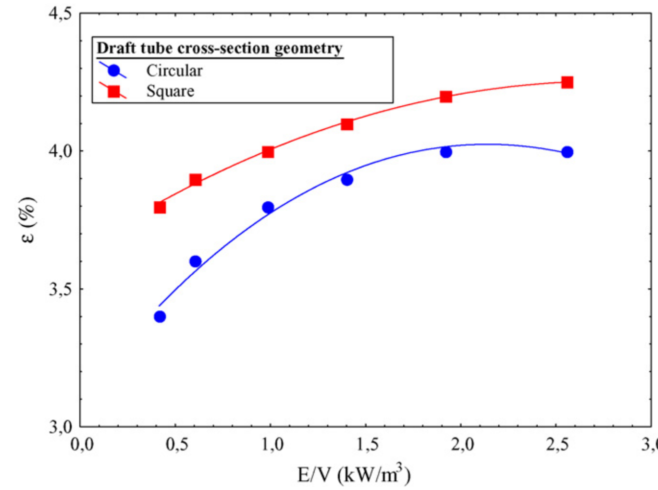

Fig. 3. Effect of *E*/*V* values on ε at two different draft tubes geometry for a constant gas flow rate and nozzle diameter (Q_g = 6 L/min and D_i = 1.2 cm).

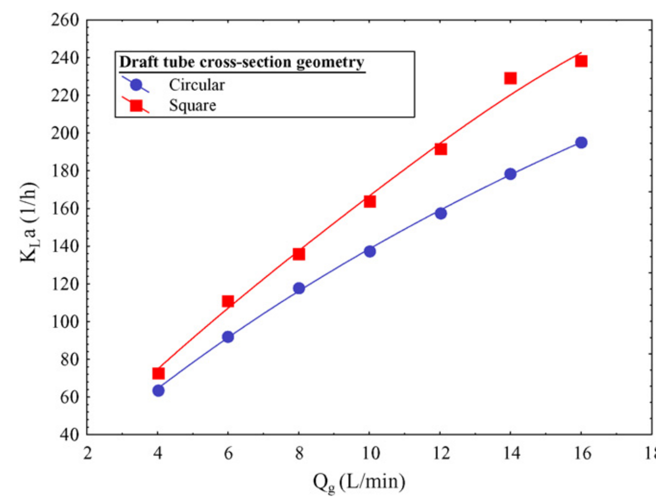

Fig. 4. Effect of gas flow rates on K_La at two different draft tubes geometry for a constant *E*/*V* and nozzle diameter (*E*/*V* = 1.9 kW/m^3 and D_i = 1.2 cm).

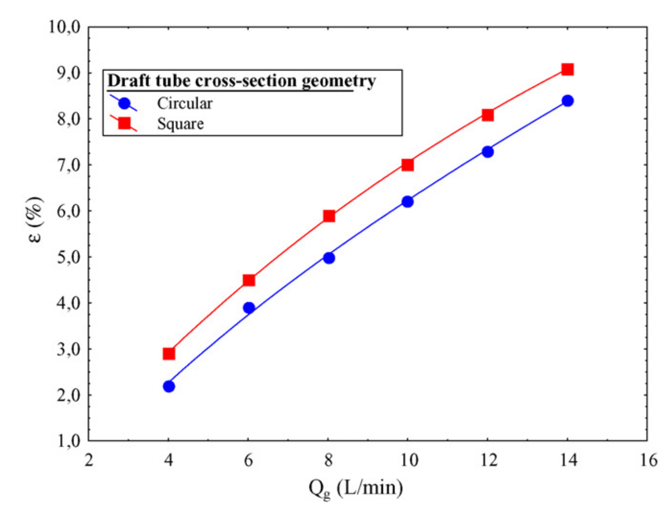

Fig. 5. Effect of gas flow rates on ε at two different draft tubes geometry for a constant *E*/*V* and nozzle diameter (*E*/*V* = 1.9 kW/m^3 and D_i = 1.2 cm).

values in the square draft tube modification were determined to be 11–13% higher than circular draft tube. This is a substantial contribution considering high K_La performance of the JLBs.

Choosing square cross-sectional draft tube, a zone with geometrically irregular cross-sectional area became between the bioreactor and draft tube. The liquid phase was forced to a macro circulation in this irregular area. This geometrically irregular region decreased the circulation velocity. Therefore, the mixing time increased. That caused an increase at circulation time in JLB. This resulted air bubbles to stay in bioreactor for a long time. Thus, the mass transfer the mass transfer between the air bubbles and water was achieved at longer time. In addition, the local liquid flow fairly differentiated in the geometrically irregular region. This circumstance caused some velocity and concentration differences (gradient) among the streamlines. Consequently, these velocity and concentration gradients promoted the overall mass transfer in the draft tube configuration with square cross-sectional area. Thus, it was assumed that obtaining higher K_La values in the square draft tube modification was the result of this irregular geometry.

Higher ε values were achieved in square cross-sectional draft tube. This could be attributed to irregular region from the square cross-section geometry. The decrease of circulation velocity in geometrically irregular region caused to decline the rising velocity of the air bubbles in this region. The air bubbles stay in the bioreactor for longer time. At the same time, due to the decrease in rising velocity of air bubbles, the jet region at the top of the draft tube could suck much more air bubbles. As result, more air bubbles were presented in the system. This caused the increase in ε.

A similar study was performed by Lu et al. with the airlift reactor system. It was stated that, when the reactor was chosen at square and the draft tube was chosen at circular cross-sectional area, a geometrically irregular region occurred between reactor and draft tube. Increases in K_La were attributed to the irregular geometrical region [16].

3.2. Determination of mass transfer characteristics of the configuration with square cross-sectional draft tube

In this stage of the study, the mass transfer characteristics of square cross-sectional draft tube configuration were investigated. A number of investigators have studied the influence of Q_g and E/V on K_La and ε in JLBs with circular cross-sectional draft tube. However, no study could have been found on JLB with square cross-sectional draft tube. The influence of liquid flow rate on K_La and ε is shown in Figs. 6 and 7 in terms of E/V for different gas flow rates. ε was found to be increasing with an increase in liquid flow rates (as shown in Fig. 8) due to the increased circulation of gas bubbles into the draft tube with the increased liquid flow. A similar trend was reported in the literature for the jet loop reactors with circular cross-sectional draft tube [4,12,13]. The effect of liquid flow rate on K_La showed an increase as presented in Fig. 6. It was observed that K_La increased with increasing E/V in the range of experienced E/V within the range of variables studied.

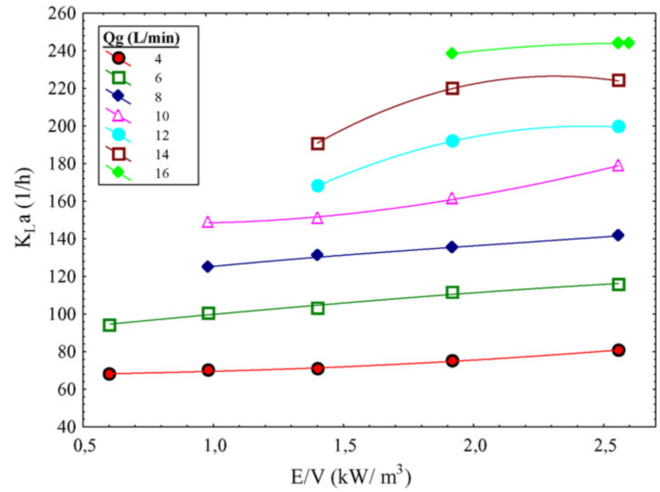

Fig. 6. Effect of energy dissipation rate per unit volume (E/V) on K_La under different gas flow rates (Q_g) in the configuration with square draft tube geometry (D_i = 1.2 cm).

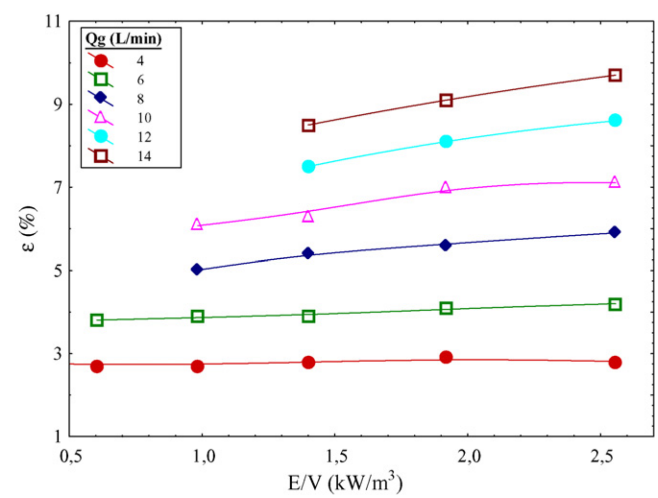

Fig. 7. Effect of E/V on ε under different gas flow rates in the configuration with square draft tube geometry (D_i = 1.2 cm).

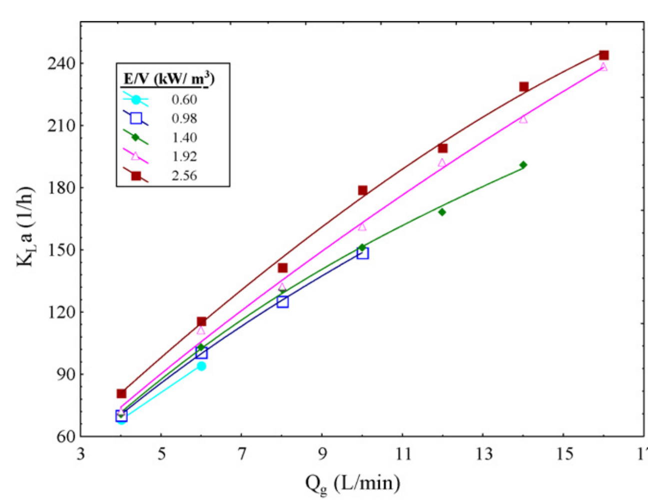

Fig. 8. Effect of Q_g on K_La under different E/V in the configuration with square draft tube geometry (D_i = 1.2 cm).

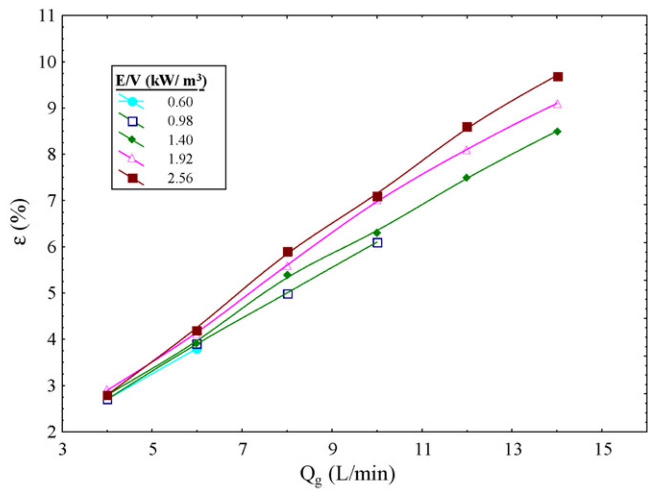

Fig. 9. Effect of Q_g on ε under different *E*/*V* in the configuration with square draft tube geometry (D_i = 1.2 cm).

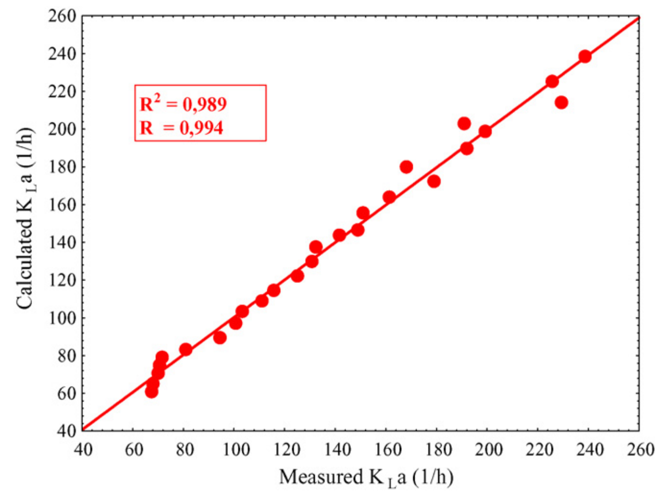

Fig. 10. Comparison of the predictions of Eq. (5) with measured values of the volumetric mass transfer coefficient.

The influence of gas flow rate on K_La and ε at different energy dissipation rates are shown in Figs. 8 and 9. The energy dissipation rates were calculated as the kinetic energy of the liquid jet based on the flow area of the nozzle. It was observed that both ε and K_La increased with an increase in gas flow rate for a given *E*/*V*. This was due to the increased gas entrainment and gas–liquid interfacial area at higher gas flow rates. From the Figs. 8 and 9, it can also be observed that the effects of *E*/*V* and Q_g on K_La were more pronounced than that of ε. Similar trends have been reported in the literature for various jet loop reactor configuration which had a circular cross-sectional draft tube [4,10,17].

Dependence of K_La on the main operational variables of liquid flow rate and aeration rate was determined. K_La values were enhanced by increasing gas and liquid flow rates. It was reported in earlier researches that the volumetric mass transfer coefficient, K_La, is related to the energy dissipation rate per volume, *E*/*V*, and gas flow rate, Q_g. This relation could be written as follows [18]:

$$K_La \approx \left(\frac{E}{V}\right)^a \left(\frac{Q_g}{A}\right)^b \tag{4}$$

If nonlinear solution of K_La changes with the *E*/*V* and Q_g values according to the Eq. (4) was made, the following equation and coefficients would be determined.

$$K_La = 23.38\left(\frac{E}{V}\right)^{0.17} (Q_g)^{0.80} \tag{5}$$

It was seen that K_La increased with the increasing *E*/*V* (kW/m^3) and Q_g (m^3). However, it was found that the influence of gas flow rate was more pronounced than that of the liquid flow rate. Therefore, the liquid flow influenced K_La mainly by affecting the bubble size and gas–liquid interfacial area *a*.

The present data was predicted by the model established in Eq. (5). Comparison plot was drawn connecting the observed volumetric mass transfer coefficient with the predicted values using the model and was shown in Fig. 10. It was seen that the predicted K_La values were highly comparable with the observed K_La (R^2 = 0.99).

4. Conclusions

The following conclusions can be made based on results of the present investigation:

1. Both overall gas hold-up and volumetric mass transfer coefficient were found to be higher in the modified JLB with the square cross-sectional draft tube than in the JLB with circular cross-sectional draft tube.
2. Higher K_La (11–13%) was achieved in the configuration with the square cross-section draft tube.
3. In the experiments of the JLB with the square cross-section draft tube, the overall gas hold-up and volumetric mass transfer coefficient increased with increased gas and liquid flow rates. The effect of gas flow rates was more pronounced than that of the liquid flow rates.
4. Based on experimental data, an empirical correlation was proposed to predict the overall volumetric mass transfer coefficient.

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