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Numerical Model of Absorption in Single Nozzle Jet Ejector (Chlorine- Aqueous $NaOH$ system)

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Abstract

High velocity jet from the nozzles entrains the gas and due to very high turbulence in the throat gas is split into bubbles. In the diffuser section partial separation of the gas and liquid may occur. The high interfacial area formed by bubbles is desirable for increasing rate of mass transfer. Different researchers, including Kuznetsov and Oratovskii (1962), Boyadzhiev (1964), Volgin et al. (1968) and Beg and Taheri (1974) attempted to simulate the operation of the jet ejectors for gas absorption. In this paper, we have made an attempt to predict mass transfer characteristics by numerical modeling. Here, we have described the mathematical model for the prediction of the amount of chlorine removed in jet ejector. The results of simulation are compared with the experimental data.

1. Introduction

Johnstone et al. (1954) reported a jet ejectors study in which SO_2 was absorbed in 0.6N NaOH solutions, and the amount of sulfur dioxide, absorbed in the liquid, was measured at various distances from the point of liquid injection. It was found that the mass transfer increased substantially as the liquid injection rate increased.

Kuznetsov and Oratovskii (1962) developed a mathematical model for predicting absorption of CO_2 by reacting with $NaOH$ solution in the throat and the divergent section of a venturi scrubber.

SO_2 removal efficiency of a jet ejector was investigated by Talaie et al. (1997) using a three-dimensional mathematical model based on a non uniform droplet concentration distribution predicted from a dispersion model in the gas flow where the gas-phase mass transfer coefficient was calculated by empirical equations.

Mandal et al (2003) studied the jet ejector followed by bubble column and developed two simple correlations of a and k_La as a function of superficial gas velocity. This correlation can be combined to calculate liquid-side mass transfer coefficient k_L.

Utomo et al. (2008) investigated the influence of operating conditions and ejector geometries on the hydrodynamics and mass transfer characteristics of the ejector by using three-dimensional CFD modeling. The CFD results were validated with experimental data.

Taheri et al. (2010) studied the three-dimensional mathematical model, based on annular two-phase flow, for the prediction of the amount of SO_2 removed in a venturi scrubber.

2. Mathematical modeling

In this study the model developed by Taheri et al. (2010) is modified to suit the jet ejector used in the present work. Taheri et al. (2010) developed a three-dimensional mathematical model based on annular two-phase flow in rectangular geometry of the venturi scrubber. They develop a model to predict interfacial area by predicting drop size and droplet concentration. Instead in this work an attempt is made to predict the bubble size and bubble concentration. Therefore, the model of this study is based on a three-dimensional dispersion of bubbles by convection and eddy diffusion.

The concentration of bubbles has been assumed uniform across the cross section of the scrubber in current study, the bubbles are of small in size and are dense in nature, which justifies using a simple Lagrangian approach for bubbles. The simple Lagrangian method is based on tracking of each individual bubble and ignoring the effect of gas turbulence on bubble movement.

The continuity equation of bubbles is solved to obtain bubble concentration distribution considering the effect of gas turbulence.

In developing the model, the pollutant concentration distribution in gas phase was obtained by the following model using mass balance:

$$\frac{d(v_g C_g)}{dx} = -N_A(\pi\, {D_b}^2)C_b \qquad (1.1)$$

Boundary conditions for Equation (1.1) are as follows:

$$x = 0;\ C_g = C_{g0} \qquad (1.2)$$

This general equation can be obtained by writing differential mass balance for pollutants over a differential control volume.

In order to evaluate the bubble concentration distribution, C_b, in the above equations, the following one-dimensional dispersion equation, expressing material balance for bubble in a differential control volume, must be solved:

$$\frac{d(v_b C_b)}{dx} = S\sqrt{n} \qquad (1.3)$$

with the boundary conditions of:

$$x = 0;\ v_b C_b = 0 \qquad (1.4)$$

In Equation (1.3), the bubbles are convected in the x direction.

It is assumed that for each nozzle the source of bubbles is limited to one element. The source strength, S , is the number of bubbles generated per unit volume per unit time. Bubbles are carried from element to element and are dispersed by convection and eddy diffusion effects. Number of bubbles per second is defined by the following equation:

$$N_b = \frac{G_{tot}}{\left(\frac{\pi}{6}\right) {D_b}^3} \qquad (1.5)$$

where G_{tot} is the total gas flow rate.

The bubble velocity can be obtained by solving the following equation. This is obtained by writing a force balance for bubbles.

$$\frac{dv_b}{dx} = \frac{3\mu_l(v_l - v_b)C_{DN}}{4\rho_l \, {D_b}^2 \, v_b} \qquad (1.6)$$

The modified drag coefficient, C_{DN}, can be calculated by using the following relations given by Hollands and Goel (Yung et al., 1977) applied for bubble:

$$C_{DN} = C_D Re_b \qquad (1.7)$$

$$C_D = C_{D1} \left(\frac{v_b}{v_l - v_b}\right)^{0.5} \qquad (1.8)$$

Here C_{D1} can be obtained by the formula given by Dickinson and Marshall (Yung et al., 1977) adopted for bubble:

$$C_{D1} = 22 + \frac{24}{Re_g}\left(1 + 0.15\, {Re_g}^{0.6}\right) \qquad (1.9)$$

The value of D_b may be estimated by using the following equation (Perry et al., 1997, pp. 14.70)

$$D_b = \left[\left(\frac{6}{\pi}\right)\left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{15(\mu/\rho)G}{2g}\right)^{3/4}\right] \qquad (1.10)$$

The value of N_A is according to Equation (1.21)

Substituting Equation (1.10) and Equation (1.21) in Equation (1.1) it will reduce to

$$\frac{d(V_g C_g)}{dx} = -k_g C_g \pi \left[\left(\frac{6}{\pi}\right)\left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{15(\mu/\rho)G}{2g}\right)^{3/4}\right]^2 C_b \qquad (1.11)$$

Substituting Equation (1.10) in Equation (1.5) it will reduce to

$$\frac{d(v_b C_b)}{dx} = \frac{G}{\left(\frac{\pi}{6}\right) {D_b}^3} = \frac{G}{\frac{\pi}{6}\left[\left(\frac{6}{\pi}\right)\left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{15(\mu/\rho)G}{2g}\right)^{3/4}\right]^3} \qquad (1.12)$$

$$\therefore \quad C_b \frac{d(v_b)}{dx} = v_b \frac{d(C_b)}{dx} = \frac{G}{\frac{\pi}{6}\left[\left(\frac{6}{\pi}\right)\left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{15(\mu/\rho)G}{2g}\right)^{3/4}\right]^3} \qquad (1.13)$$

Substituting Equation (1.7) and Equation (1.8) in the Equation (1.6) it will reduce to

$$\frac{dv_b}{dx} = \frac{3\mu_g (v_l - v_b) C_{DN}}{4\rho_l \, {D_b}^2 \, v_b} \qquad (1.14)$$

$$= \frac{3\mu_g (v_l - v_b)}{4\rho_l \, {D_b}^2 \, v_b} C_{D1} Re_b \qquad (1.15)$$

$$= \frac{3\mu_g (v_l - v_b)}{4\rho_l \, {D_b}^2 \, v_b} C_{D1} \left(\frac{V_g}{V_g - V_B}\right)^{0.5} \qquad (1.16)$$

Substituting Equation (1.9) in the Equation (1.16) will reduce to

$$\frac{dv_b}{dx} = \frac{3\mu_g (v_l - v_b)}{4\rho_l \, {D_b}^2 \, v_b}\left(22 + \frac{24}{Re_g}(1 + 0.15\, {Re_g}^{0.6})\right)\left(\frac{v_b}{v_l - v_b}\right)^{0.5} \qquad (1.17)$$

The mean bubble diameter is calculated using Boll's equation adopted for bubble (Boll et al., 1974):

$$D_b = \frac{42{,}200 + 5776\,(G/L)^{1.932}}{v_{lth}^{1.602}} \qquad (1.18)$$

The gas velocity is computed by the following equations:

$$V_g = \frac{G}{\left(\frac{G}{G + L}\right)\frac{\pi}{4} D_T^2} \qquad (1.19)$$

The mass transfer rate, N_A, in each element can be evaluated by the following relation:

$$N_A = k_l (C_g - C_{gs}) \qquad (1.20)$$

When pollutants undergo a very fast reaction into the liquid phase such as absorption of Cl_2 into aqueous $NaOH$ solution, the surface concentration in the gas phase can be considered equal to zero. Thus N_A can be evaluated by the following equation:

$$N_A = k_l C_A^* \qquad (1.21)$$

3 Results and discussions

Figure 1 is a plot of variation of gas phase concentration C_{Ag} along the axis of ejector for different values of initial gas concentration having number of nozzle 1 for laboratory scale jet ejector. For comparison of the experimental results and predicted results obtained by the proposed model are plotted in the same figure. From both the profiles shown in the figure, it is clear that the proposed model is in good agreement with experimental results.

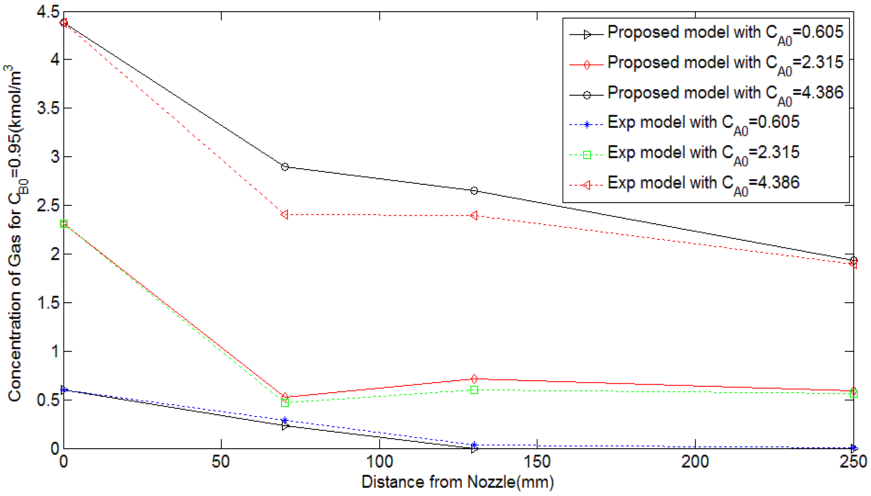

Figure 1: Variation of gas phase concentration C_{Ag} along the axis of ejector for different values of initial gas concentration $C_{Ag,in}$ at $C_{B0} = 0.95\ kmol/m^3$ (comparison between proposed model and experimental value)

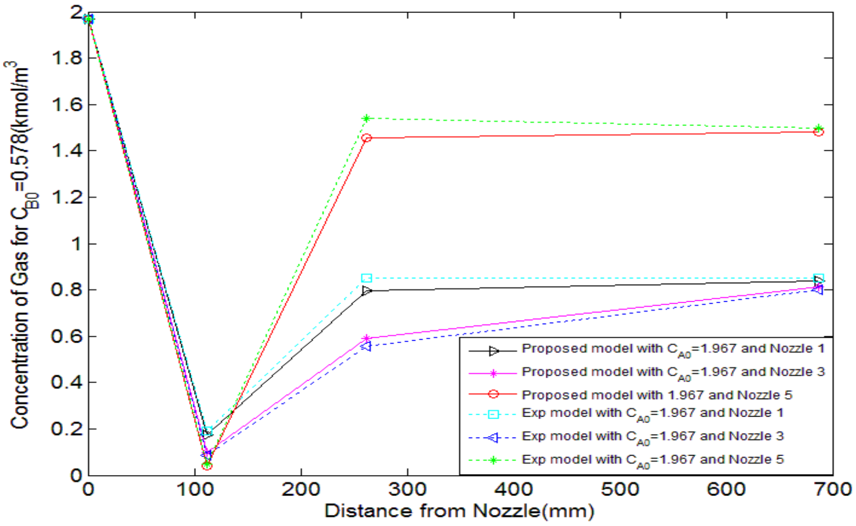

Figure 2 : Variation of gas phase concentration C_{Ag} along the axis of ejector for different setup for industry scale ejector having no. of nozzles 1, 3 and 5 at $C_{B0} = 0.578\ kmol/m^3$ and initial gas concentration $C_{Ag,in} = 1.967 \times 10^{-3}\ kmol/m^3$ (comparison between proposed model and experimental value)

Figure 2 shows the variation of gas phase concentration C_{Ag} along the axis of the ejector for different setup like number of nozzles 1, number of nozzle 3 and number of nozzle 5 for industry scale ejector. The results predicted by the model are in good agreement with the experimental results. Thus the model is applicable for multi nozzle jet ejector.

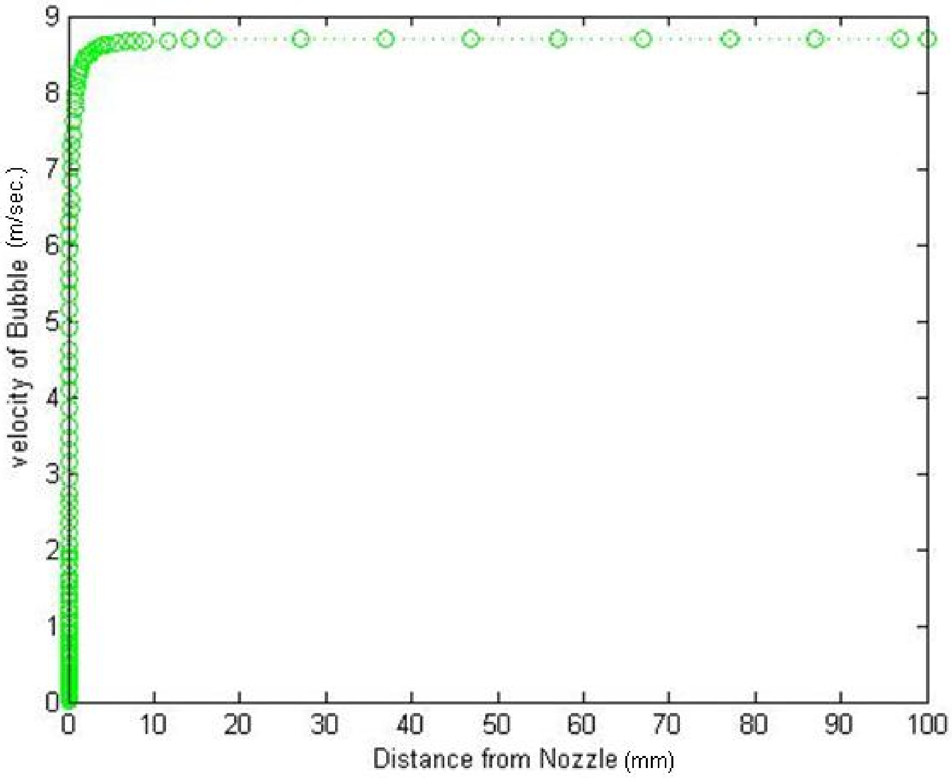

Figure 3 : Velocity profiles (m/sec.) of gas and droplet along axial direction (mm)

The figure 3 shows the variation of bubble velocity along the axis of the ejector. It indicates that the bubble velocity suddenly increases to a maximum value and then it remains constant.

Conclusion

- The proposed model is in good agreement with experimental values for single nozzle as well as for multi nozzles. Hence the proposed model may be used for designing the industrial ejectors.
- The number of nozzle (orifice) affects the gas conversion.

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Nomenclature

Latin letters

C	concentration	[kmol/m^3 or gmol/liter]
C_{A0}	concentration of A bulk of liquid/ Initial concentration in gas	[kmol/m^3 or gmol/liter]
C_D	drag coefficient	[-]
C_{DN}	modified drag coefficient	[-]
d, D	diameter	[m]
G	volumetric flow rate of gas	[m^3 s^{-1} or litre/hr]
g	acceleration due to gravity	[m s^{-2}]
N_A	rate of molar absorption with chemical reaction (flux)	[mol m^{-2} s^{-1}]
N_b	number of bubble	[-]
kg	gas sided mass transfer coefficient	[mol m^{-2} Pa^{-1} s^{-1}]
k_l	liquid sided mass transfer coefficient	[m s^{-1}]
n	number of nozzles	[-]
Re	Reynold number	[-]
v	velocity	[m s^{-1}]
x	distance along axis of ejector	[m]
Greek letters		
μ	dynamic viscosity	[Pa s]
ρ	homogeneous flow model density	[kg m^{-3}]
Subscripts		
0	fluid bulk	
A, B….	component A,B…..	
b	bubble	
G, g	gas phase	
L, l	liquid phase	
th, T	throat	
tot	total	
Superscripts		
*	Equilibrium, physical solubility	

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