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Interfacial area and mass transfer characteristics in multi nozzle jet ejector

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Abstract: The dispersion of gases in liquids in many areas like chemical engineering, biochemical engineering and waste treatment systems is of prime importance. Hence, there have been many significant contributions in recent years in the development of more efficient gas- liquid ejector. In this paper a mathematical model to predict, mass transfer coefficient and interfacial area has been proposed for multi nozzle jet ejector and it is also compared with experimental data obtained. The measured values of the interfacial area in the jet ejector are about in the range of 3000 to 13000 m²/m³ in the ejector.

I. Introduction

Because of high energy efficiency in gas dispersion, many researchers studied jet ejector and considerable amount of work has been done: (Jackson, 1964; Volmuller and Walburg, 1973; Nagel et al., 1970; Zehner, 1975; Hirner and Blenke, 1977; Pal et al., 1980; Ziegler et al., 1977).

It is important to note that the kinetic energy of a high velocity liquid jet is used for getting fine dispersion and mixing between the phases in the given gas liquid ejector. The studies in this area are listed below:

- (Zlokam, 1980) has reported that oxygen absorption efficiency is as high as 3.8 kg O₂/kwh in ejectors as compared to 0.8 kg O₂/kwh in a propeller mixer. The higher gas dispersion efficiency of the ejector type can be understood from the well known fact: "gas dispersion is possible only if the fraction of micro turbulence is high" (Schugerl, 1982).
- Radhakrishnan et al. (1984) have used a vertical column fitted with a multi jet ejector for gas-dispersion for studying the pressure drop, holdup and interfacial area.

II. New model to predict mass transfer characteristics, k_g and a

To predict mass transfer characteristics the value of k_g and a are required to be predicted. Here a mathematical model is developed to predict the value of k_g and a using chlorine-aqueous sodium hydroxide solution.

Doraiswamy and Sharma (1984) have reported that if

$$\frac{[D_A k_2 C_{OH}^0]^{1/2}}{k_L} > 3 \quad (1)$$

and

$$\frac{[D_A k_2 C_{OH}^0]^{1/2}}{k_L} \ll \frac{C_{OH}^0}{2C_A^*} \quad (2)$$

then the reaction is considered to be pseudo first order and in the fast reaction regime.

As absorption of Cl₂ in aqueous solution of NaOH studied in the present work satisfy the condition (1) and (2), it is treated as pseudo first order fast reaction.

Levenspiel (1999) presented a simplified solvable pseudo first order rate expression as a replacement for second order reaction rate equation when the value of C_{B0} is so high that it do not change appreciably, which is presented here as follows:

$$-r_A dV = \frac{1}{\frac{1}{k_g a} + \frac{H_e}{a \sqrt{D_A k_2 C_{B0}}}} p_A \cdot dV \quad (3)$$

Now,

$$-r_A = -d(G_{mo} y) = -d \left(\frac{G'_{mo} y}{1-y} \right) = \frac{G'_{mo} dy}{(1-y^2)} \quad (4)$$

and

$$p_A = H_e C_A^* = yP \quad (5)$$

Substituting equation (4) and (5) in equation (3) we have:

$$\frac{G'_{mo} dy}{(1-y^2)} = \frac{1}{\frac{1}{k_g a} + \frac{H_e}{a k_{LR}}} yP \cdot dV \quad (6)$$

where $k_{LR} = \sqrt{D_A k_2 C_{B0}}$

By rearranging equation (6) and integrating between $V = 0$ to V_R will yield the equation:

$$K_g = \frac{G'_{mo}}{PaV_R} \ln \left[\frac{1-y_0}{y_0} \frac{y_i}{1-y_i} + \frac{1}{(1-y_i)^3} - \frac{1}{(1-y_0)^3} \right] \quad (7)$$

where,

$$\frac{1}{K_g} = \frac{1}{k_g} + \frac{H_e}{k_{LR}} \quad (8)$$

Interfacial area

Sharma and Danckwerts, (1970) stated that when

$$k_g \cdot He \gg k_{LR} \quad (9)$$

Then gas phase resistance is negligible.

But for chlorine-aqueous $NaOH$ system

$$k_g \cdot He \not\gg k_{LR}$$

Hence, to predict interfacial area few experiments were carried out for CO_2 -aqueous $NaOH$ system.

CO_2 -aqueous $NaOH$ system satisfies the condition as of equation (9). Therefore gas phase resistance is negligible. Hence equation (8) will turn to

$$\frac{1}{K_g} = \frac{H_e}{k_{LR}} \quad (10)$$

And equation (7) may be written for calculating interfacial area as follows:

$$a = \frac{G'_m He}{k_{LR} P_{CO_2} V_j} \ln \left[\frac{1-y_0}{y_0} \frac{y_i}{1-y_i} + \frac{1}{(1-y_i)^3} - \frac{1}{(1-y_0)^3} \right] \quad (11)$$

True gas side mass transfer coefficient for chlorine

For Cl_2 - aqueous $NaOH$ system

$$k_g p_A \leq \frac{k_{BL} C_{B0}}{z} \quad (12)$$

Table 1: Typical range of experimental values

Interfacial area	CO_2 aqueous $NaOH$ solution	Cl_2 aqueous $NaOH$ solution	Condition required for
C_{OH}^0 kmol/m ³	0.525	0.525	
k_2 kmol/m ³ s at 300K	9.63×10^3 (Hikita, 1976)	1.7×10^9 (Eq.4.2.37)	
Heatm. ³ /kmol (Table A3.4)	32 (Patel, 2004)	19.55 (Ashour, 1996)	
k_g kmol/m ³ atms	.00037	.00037	
D_g at 303 Km ² /sec (Table A3.4)	2.05×10^{-9}	1.68×10^{-9}	
D_{NaOH} at 303 Km ² /sec	3.89×10^{-9}	3.89×10^{-9}	
C_g^* at 303K in water kmol/m ³ (Calculated from Table A3.4)	1.88×10^{-3}	1.39×10^{-3}	
$k_{LR} = [D_{g1} k_2 C_{OH}^0]^{1/2}$ m/s	0.0032	1.22	
k_{LA} m/sec apx avg (Radhakrishnan, 1984) and calculated	3.2×10^{-4}	0.009515	
$k_{LB} = k_{LA}(D_B/D_A)$ m/sec k_{LR}/k_L	6.072×10^{-4} $10 > 3$	0.022×10^{-4} $121 > 3$	Fast reaction
$C_{OH}^0/2C_g^*$ (eq. no. 5)	139 $k_{LR}/k_L \ll C_{OH}^0/2C_g^*$	188 $k_{LR}/k_L \ll C_{OH}^0/2C_g^*$	Pseudo first order
$k_g \cdot He$ (eq. no. 12)	0.01184 $\therefore k_g \cdot He > k_{LR}$	7.2×10^{-3} $\therefore k_g \cdot He \not> k_{LR}$	Gas phase resistance negligible
$k_g \cdot p_A$	—	1.09×10^{-5}	
$k_{LB} \cdot C_{B0}/z$ (eq. no. 15)	—	5.78×10^{-3} $\therefore k_g \cdot p_A \leq k_{LB} \cdot C_{B0}/z$	Gas resistance control

That implies that gas phase resistance controls the rate of reaction (Levenspiel, 1999).

Therefore the rate of absorption of Cl_2 may be written as

$$R_{Cl_2} \cdot a = k_G \cdot a \cdot p_A^* \quad (13)$$

$$k_G \cdot a = \frac{R_{Cl_2} \cdot a}{p_A^*} \quad (14)$$

The true gas side mass transfer coefficient, k_G , is given by,

$$k_G = \frac{k_G a}{a} \quad (15)$$

The model presented by the equations (7), (11) and (15) are the models to predict the value of a , k_G and $k_G a$

III. New mathematical model related to interfacial area for multi nozzle ejectors

Radhakrishnan et al. (1984) have suggested the following correlations to estimates interfacial area i.e.

$$a_{sy} = 225\chi_1^{-2.649} \text{ where } \chi_1 \text{ is liquid holdup} \quad (16)$$

Mandal et al. (2003) have suggested the following estimates for interfacial area of system i.e.

$$a = 0.38 \times 10^4 \times v_{gs}, \quad (16a)$$

where v_{gs} is gas superficial velocity

In this work a new model has been proposed for estimation of 'a'. This model is easy to apply and require minimum input data.

For that, $-r_A$ is determined experimentally and is equal to $R_A a$.

R_A can be estimated by the model developed by Agrawal (2012) :

$$N_{Cl_2} = \frac{D_1}{t_e} \int_0^{t_e} \left(\frac{\partial w_1}{\partial x} \right) (0, t) dt \quad (17)$$

Thus a can be determined by using the equation

$$R_A a = -r_A \quad (18)$$

or

$$a = \frac{R_A a}{R_A} \quad (19)$$

This mathematical model is employed for multi nozzle ejector for different set up with number of orifice 1, 3 and 5. The dimensions of multi nozzle ejector are Table 2. The results obtained with this model for multi nozzle ejector are compared with experimental data.

Table 2: Dimensions of jet ejector used for different setup

	Setup - I	Setup - II			Setup - III		
Nozzle diameter (mm)	3.28	3.28	2.0	1.50	8.2	4.7	3.7
Number of Nozzle (orifice)	1	1	3	5	1	3	5
Nozzle No.	N1	N2	N3	N4	N5	N6	N7
pitch *	--	$2D_N$			$2D_N$		
Diameter of Throat/ mixing tube (mm)	10	10			25		
Length of Throat/ mixing tube *** (mm)	60	60			150		
Length of the conical diffuser (mm)	120	120			425		
Diameter of the diffuser exit (mm)	25	25			77		
Diameter of the suction chamber (mm)	25	25			77		
Length of the suction chamber (mm)	40	45			122		
Distance between nozzle & commencement of throat (mm)	20	45			112		
Diameter of secondary gas inlet (mm)	10	10			25		
Volume of free jet (m^3)	0.75×10^{-6}	1.689×10^{-6}			26.32×10^{-6}		
Volume of throat (m^3)	4.71×10^{-6}	4.710×10^{-6}			73.6×10^{-6}		
Volume of divergence (m^3)	30.6×10^{-6}	30.600×10^{-6}			1156.78×10^{-6}		
Total ejector volume (m^3)	36.061×10^{-6}	37.000×10^{-6}			1256.7×10^{-6}		

Reference : * Panchal (1991), *** Biswas et al. (1975),

IV.

A new mathematical model has been proposed as per expression (11), (15) and (19) to predict mass transfer characteristics by determining the value of $k_G a$, k_G and a . The predicted values by using this proposed model is presented graphically in the figures 2 to 4. The figures show the effect of $C_{Ag,in}$ on predicted value of $k_G a$, k_G and a for different nozzles and different values of C_{B0} . The values of $R_A a$ is obtained experimentally (Agrawal, 2012b) and presented in figure 1.

A. Comparison of experimental results of mass transfer characteristics with simulated results

Experimental results and simulated results of mass transfer characteristics $k_G a$, a and k_G are plotted together for set up 1 in the figure 2, 3 and 4 respectively. The experimental results are based on equation 11, 14, and 15. The simulated results are based on the equation 17, 19, 14 and 15. The experimental and simulated results are in good agreement. So the model proposed is well fitted.

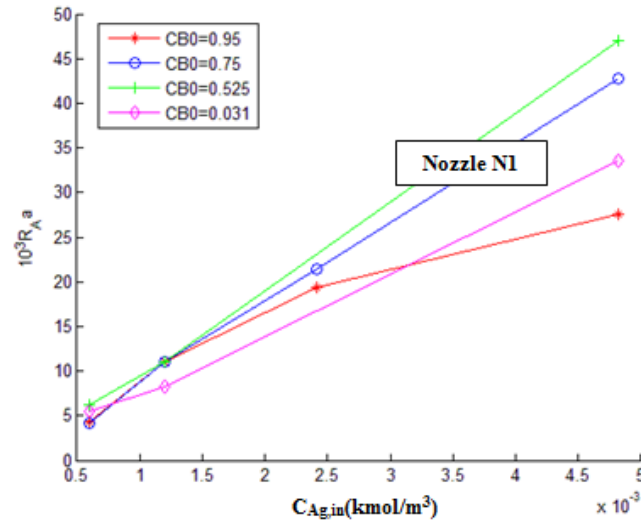


Figure 1: Effect of $C_{Ag,in}$ on $R_A a$ for different C_{B0} for setup – 1 with nozzle N1 (no. of orifice 1)

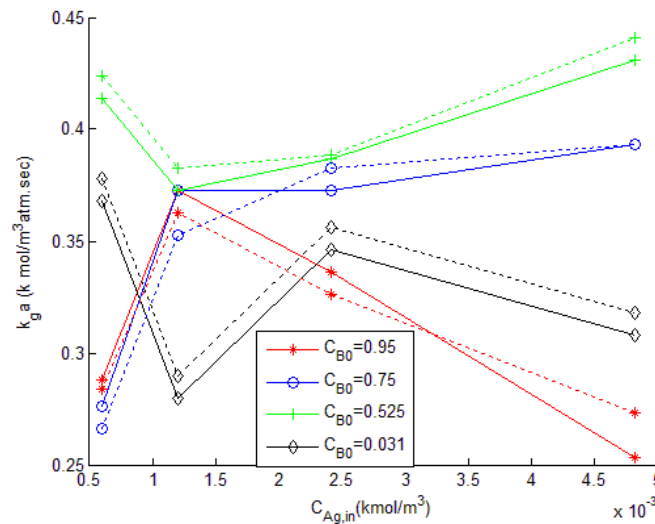


Figure 2: Effect of $C_{Ag,in}$ on $k_g a$ for different C_{B0} for setup – 1 with nozzle N1 (no. of orifice 1) (comparison of experimental results and present model)

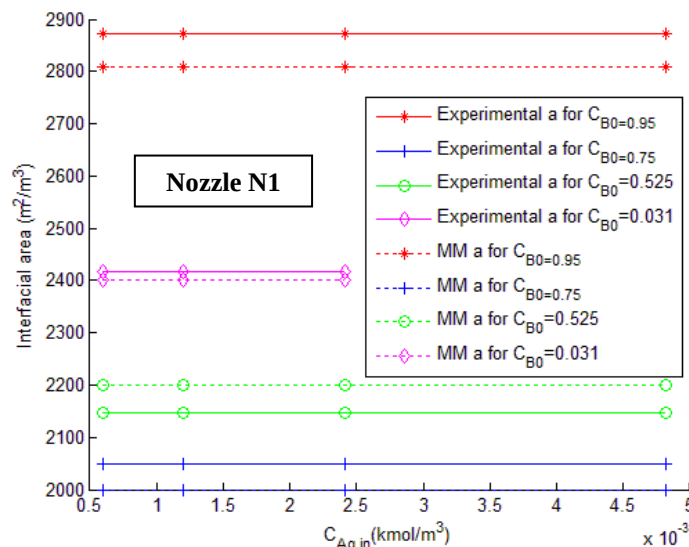


Figure 3: Effect of $C_{Ag,in}$ on interfacial area generated in jet ejector for different C_{B0} for setup – 1 with nozzle N1 (no. of orifice 1) (comparison of experimental results and present model)

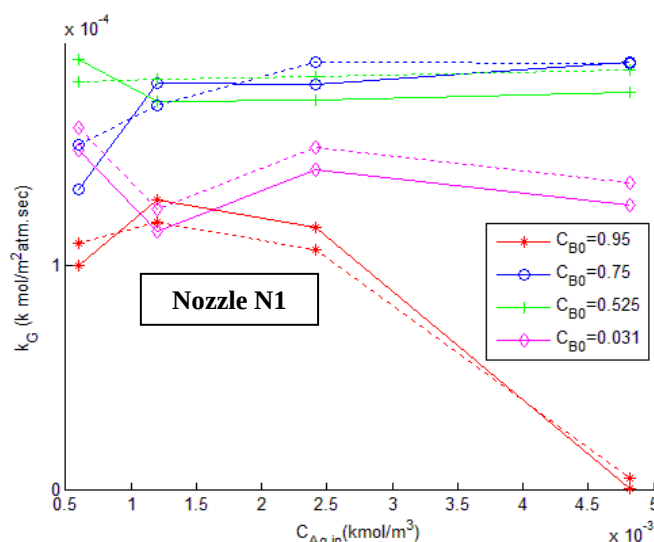


Figure 4: Effect of $C_{Ag,in}$ on k_g for different C_{B0} for setup – 1 with nozzle N1 (no. of orifice 1) (comparison of experimental results and present model)

B. Factors affecting rate of absorption ($R_A a$) in liquid jet ejector

Figure (1), (5), (9) and (13) show the effect of $C_{Ag,in}$ on $R_A a$ using different nozzles. The following conclusions can be derived from the study of the figures.

- A common trend has emerged that as $C_{Ag,in}$ increases the $R_A a$ also increases in all setups for all nozzles. This is because rate of reaction is function of concentration of both reactants i.e. chlorine ($C_{Ag,in}$) and $NaOH$ (C_{B0}).
- As C_{B0} increases the $R_A a$ decreases. The concentration of aqueous $NaOH$ solution in C_{B0} is kept high to maintain pseudo first order condition i.e. rate of reaction is independent of concentration of C_{B0} . The reduction in rate of absorption is due to (1) the increase in viscosity of aqueous $NaOH$ solution (2) reduction of physical solubility of Cl_2 (Krevelen and Hoftijzer theory, 1948) and (3) decrease in diffusivity coefficient (Stokes-Einstein equation) when concentration of $NaOH$ increases.
- $R_A a$ is higher for higher number of nozzles (figure-13). This is because the exposed outer surface of liquid jet in the free jet section is higher for more number of nozzles having same flow area. The high liquid jet exposed outer surface counters the effect of increase in viscosity of aqueous $NaOH$ solution due to increase in its concentration. But for lower concentration of C_{B0} , the value of $R_A a$ is maximum for nozzle N6 (three nozzle). The value of $R_A a$ is minimum for nozzle N5 (single nozzle).
- The maximum absorption obtained is in vertical installation in setup 3 having nozzle N6 (no. of orifice 3).

C. Effect of different parameters on mass transfer characteristics ($k_g a$, a and k_g) in jet ejectors

C1. Effect of C_{B0} on $k_g a$, a and k_g

Volumetric mass transfer coefficient ($k_g a$) predicted by proposed model versus $C_{Ag,in}$ for setup 1, 2 and 3 are shown in figure (2), (6), (10) and (14).

Interfacial area (a) predicted by proposed model versus $C_{Ag,in}$ for setup 1, 2 and 3 are presented in figure (3), (7) and (11).

True gas side mass transfer coefficient (k_g) predicted by proposed model versus $C_{Ag,in}$ for setup 1, 2 and 3 are presented in figure (4), (12) and (16).

The figures show that the interfacial area first decreases with increase in C_{B0} then it rises with increase in C_{B0} . The increase in C_{B0} has two phenomena simultaneously: (1) the viscosity increases (2) electrolyte concentration increases. By increasing viscosity the diffusivity and solubility of gas both decrease which have a negative effect on absorption. While increase in electrolytes leads to a strong hindrance on bubble coalescence. This will lead to a major decrease of the mean bubble size. Therefore interfacial area and the volumetric mass transfer coefficient both increase. (Bailer, 2001; Havelka et al., 2000; Kordac and Linek, 2008). Thus depending upon the influence of these parameters, there is a net rise or fall in $k_g a$ and k_g . In most cases the value of $k_g a$ and k_g are lower at higher C_{B0} .

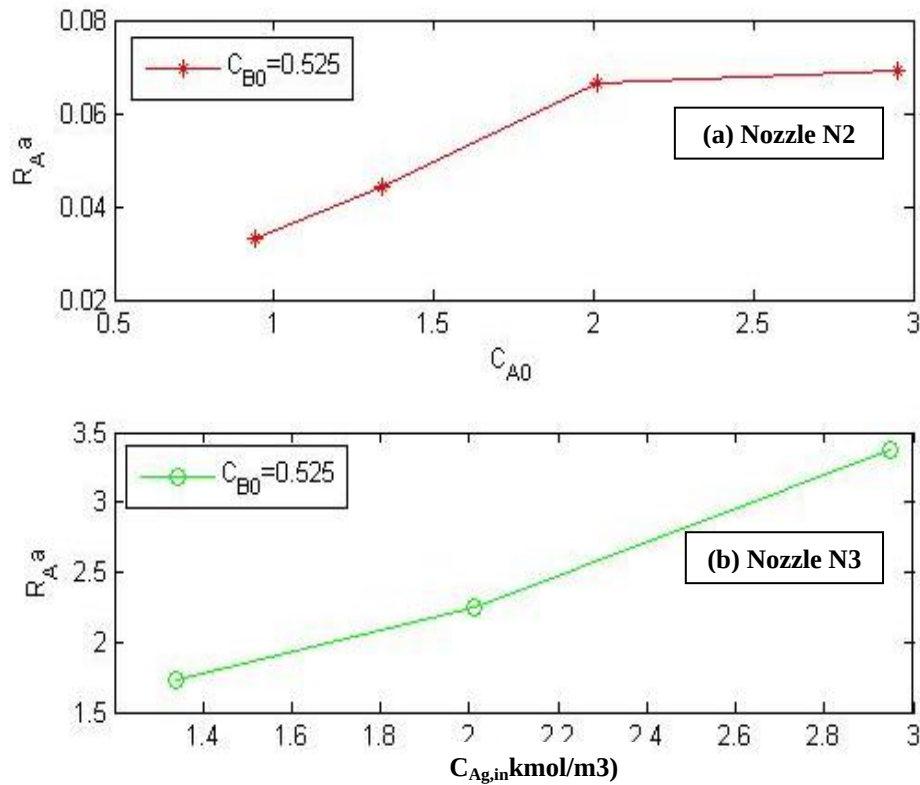


Figure 5: Effect of $C_{Ag,in}$ on R_{Aa} for $C_{B0} = 0.525$ for set up 2.
(a) with nozzle N2 (no. of orifice 1), (b) with nozzle N3 (no. of orifice 3)

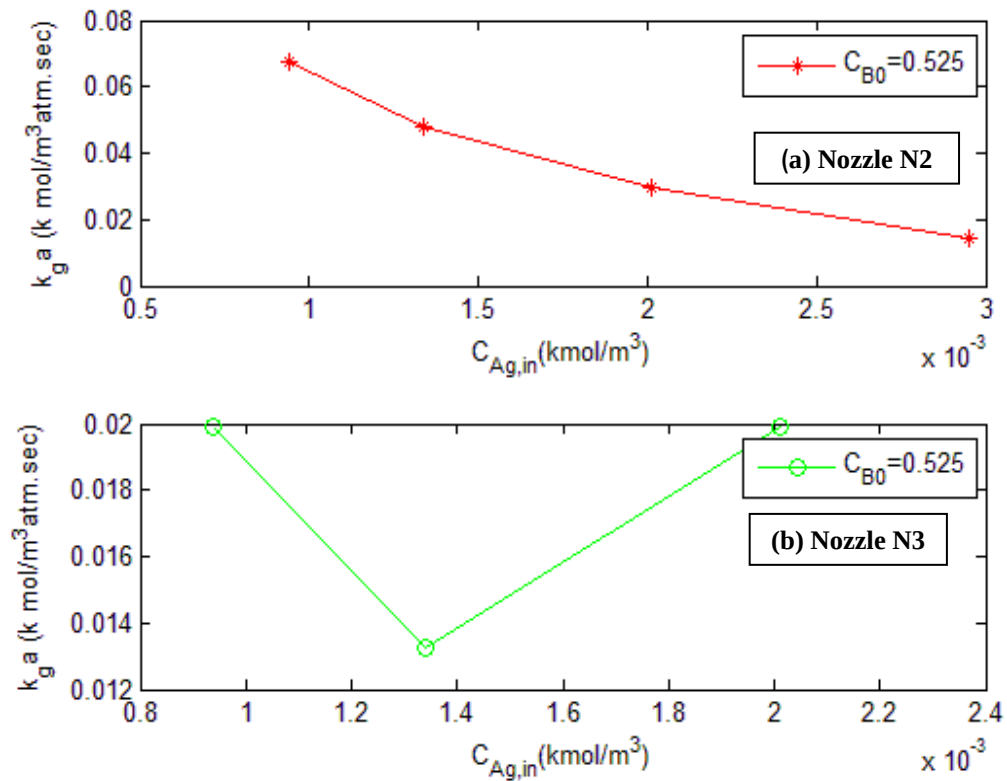


Figure 6: Effect of $C_{Ag,in}$ on k_{ga} for $C_{B0} = 0.525$ for set up 2.
(a) with nozzle N2 (no. of orifice 1), (b) with nozzle N3 (no. of orifice 3)

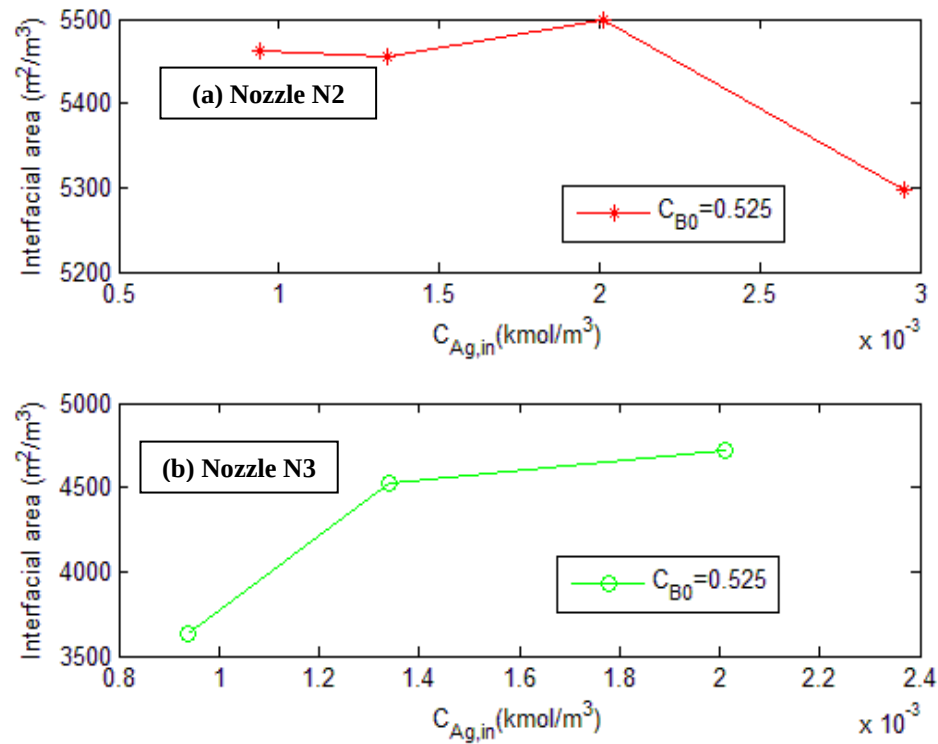


Figure 7: Effect of $C_{Ag,in}$ on interfacial area for $C_{B0} = 0.525$ for set up 2.
(a) with nozzle N2 (no. of orifice 1), (b) with nozzle N3 (no. of orifice 3)

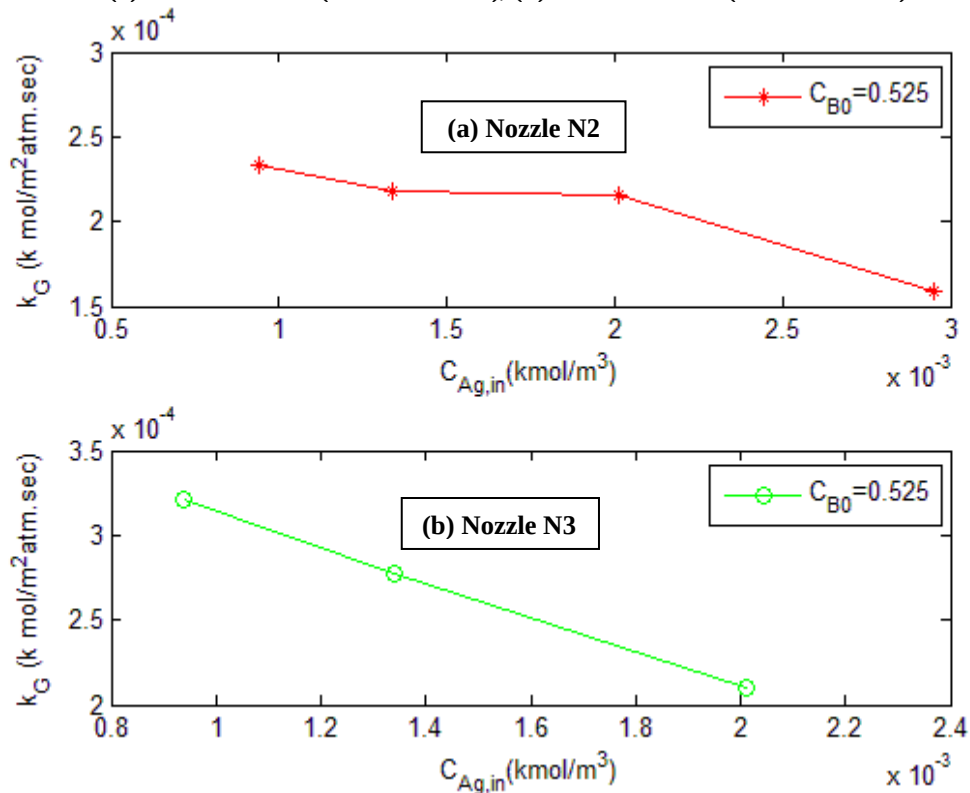


Figure 8: Effect of $C_{Ag,in}$ on k_g for $C_{B0} = 0.525$ for set up 2.
(a) with nozzle N2 (no. of orifice 1), (b) with nozzle N3 (no. of orifice 3)

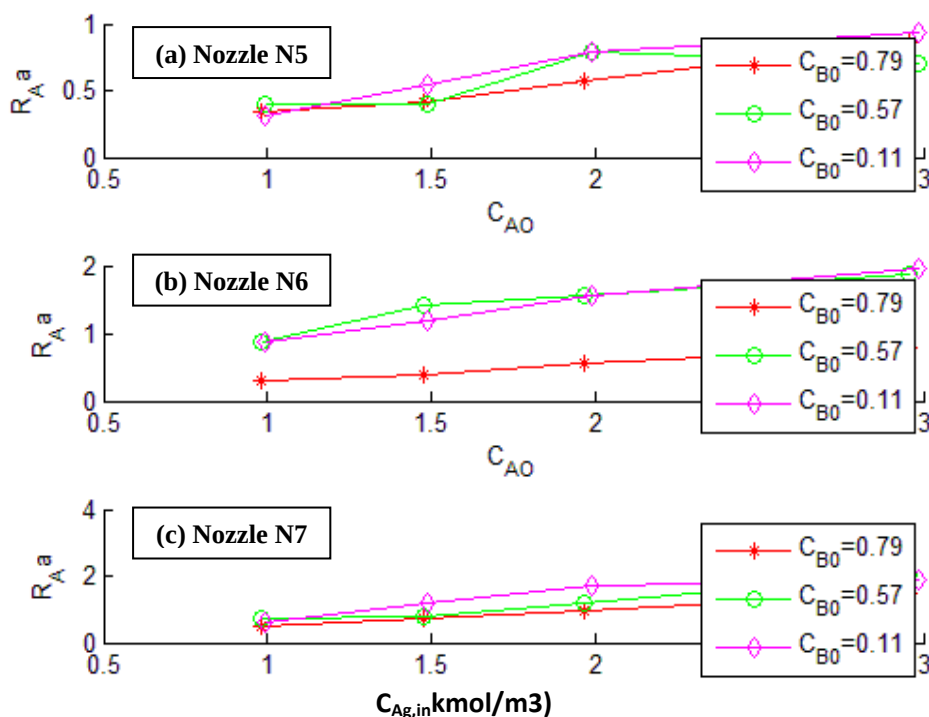


Figure 9: Effect of $C_{Ag,in}$ on R_{Aa} for different C_{B0} for set up 3.
 (a) with nozzle N5 (no. of orifice 1), (b) with nozzle N6, (no. of orifice 3),
 (c) with nozzle N7 (no. of orifice 5)

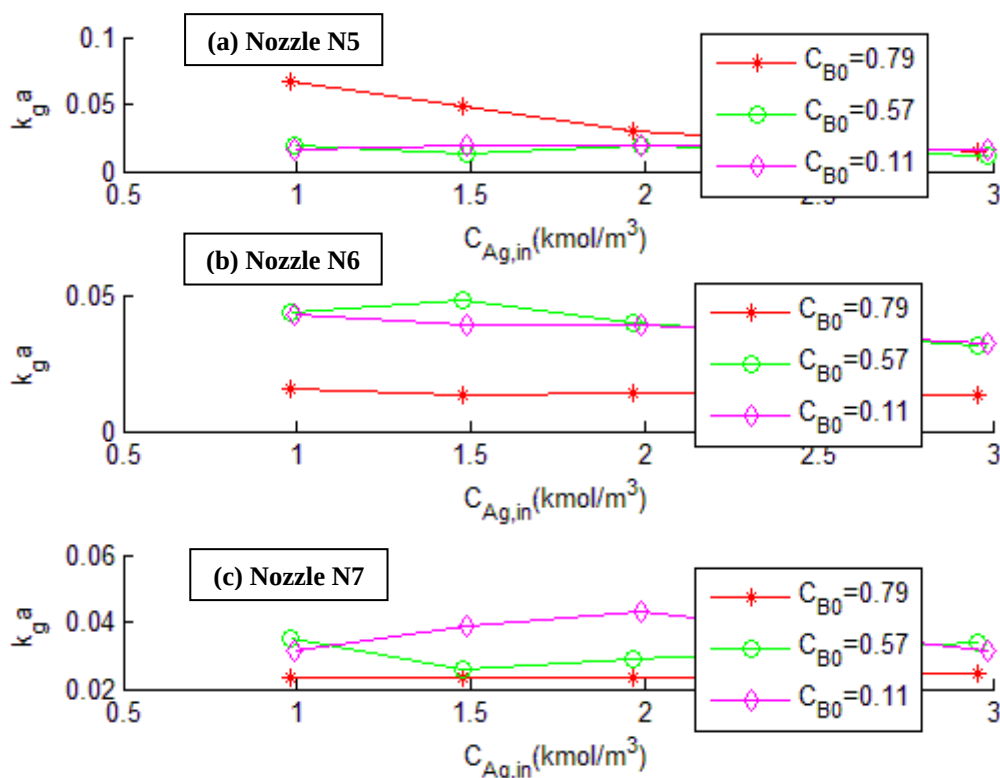


Figure 10: Effect of $C_{Ag,in}$ on k_{ga} for different C_{B0} for set up 3.
 (a) with nozzle N5 (no. of orifice 1), (b) with nozzle N6, (no. of orifice 3),
 (c) with nozzle N7 (no. of orifice 5)

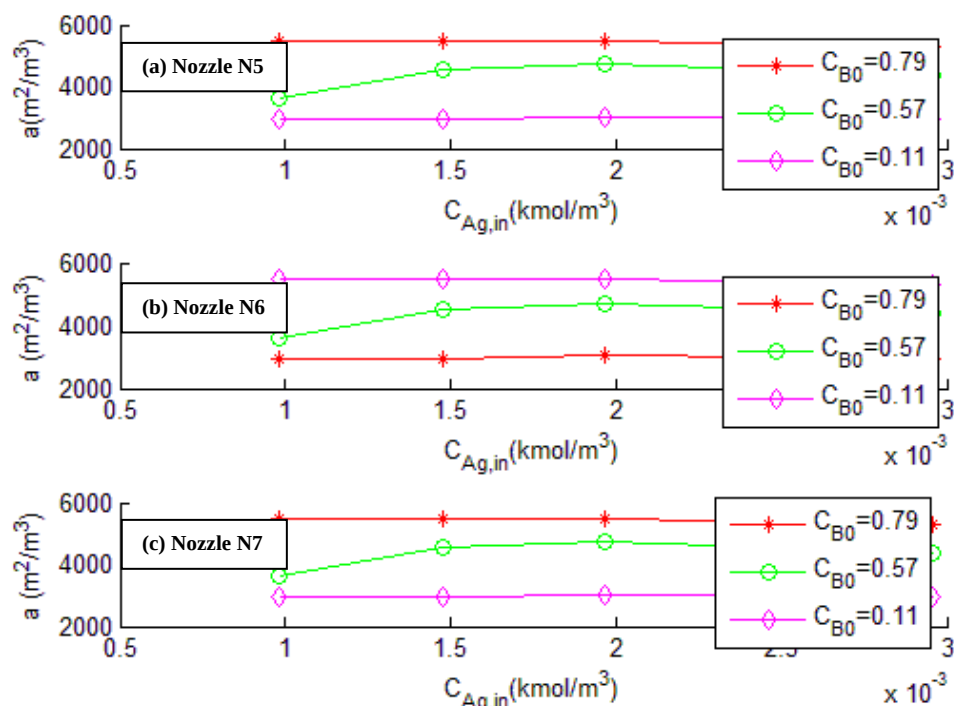


Figure 11: Effect of $C_{Ag,in}$ on interfacial area for different C_{B0} for set up 3.
 (a) with nozzle N5 (no. of orifice 1), (b) with nozzle N6, (no. of orifice 3),
 (c) with nozzle N7 (no. of orifice 5)

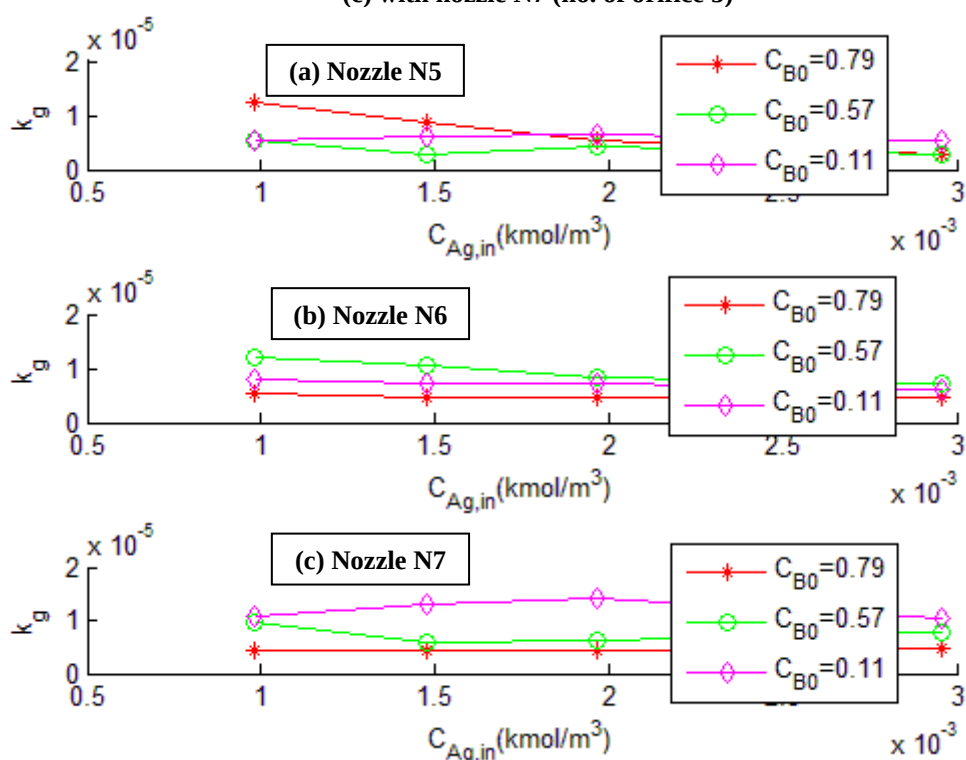


Figure 12: Effect of $C_{Ag,in}$ on k_g for different C_{B0} for set up 3.
 (a) with nozzle N5 (no. of orifice 1), (b) with nozzle N6, (no. of orifice 3),
 (c) with nozzle N7 (no. of orifice 5)

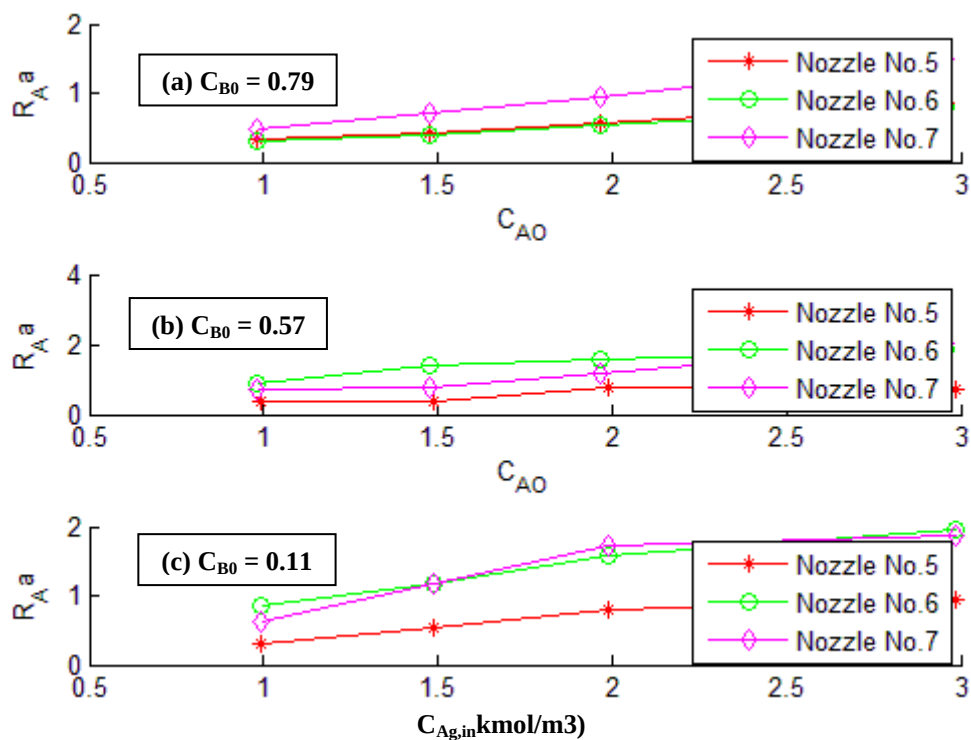


Figure 13: Effect of $C_{Ag,in}$ on R_{Aa} for different nozzle for set up 3.
(a) with $C_{B0} = 0.79$ (b) with $C_{B0} = 0.57$ (c) with $C_{B0} = 0.11$

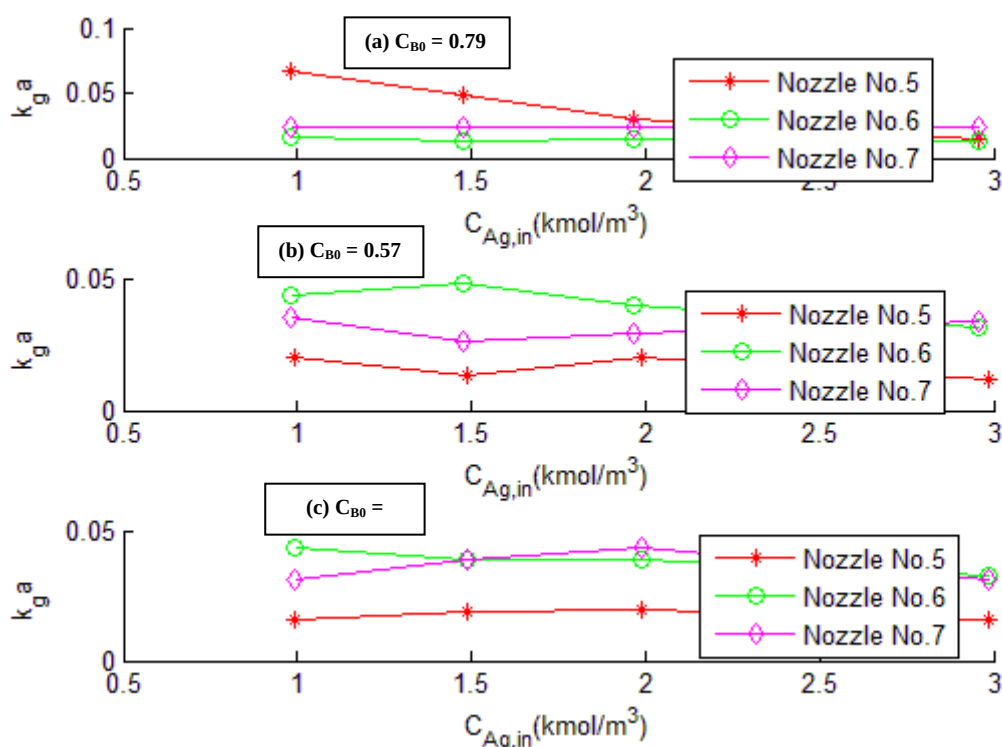


Figure 14: Effect of $C_{Ag,in}$ on k_{ga} for different nozzle for set up 3.
(a) with $C_{B0} = 0.79$ (b) with $C_{B0} = 0.57$ (c) with $C_{B0} = 0.11$

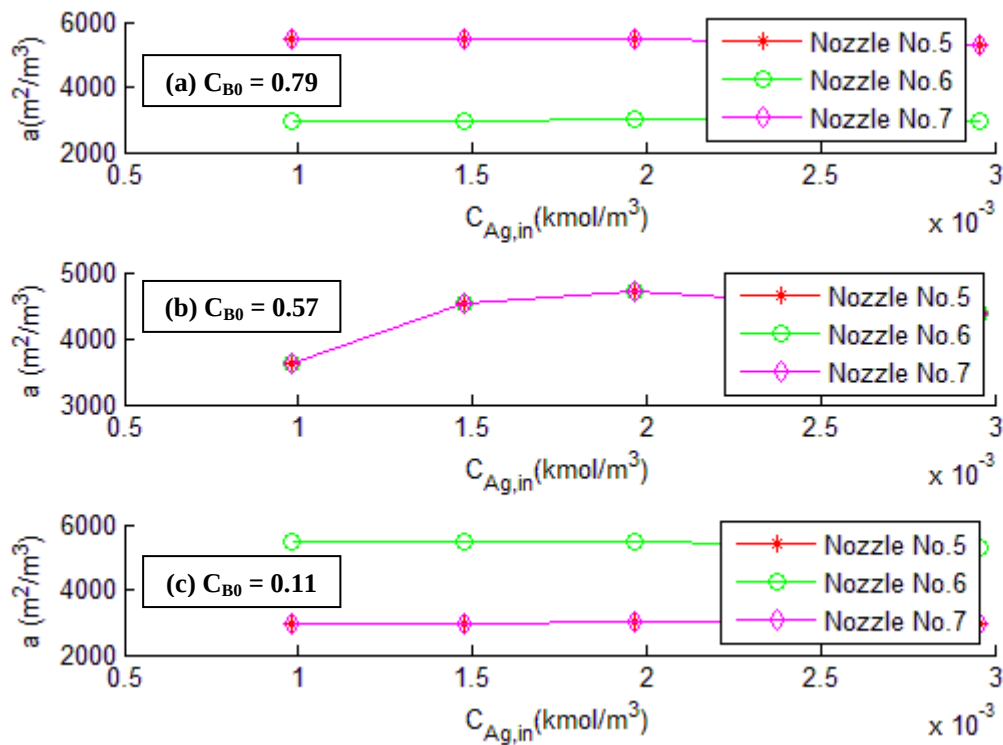


Figure 15: Effect of $C_{Ag,in}$ on interfacial area for different nozzle for set up 3.
(a) with $C_{B0} = 0.79$ (b) with $C_{B0} = 0.57$ (c) with $C_{B0} = 0.11$

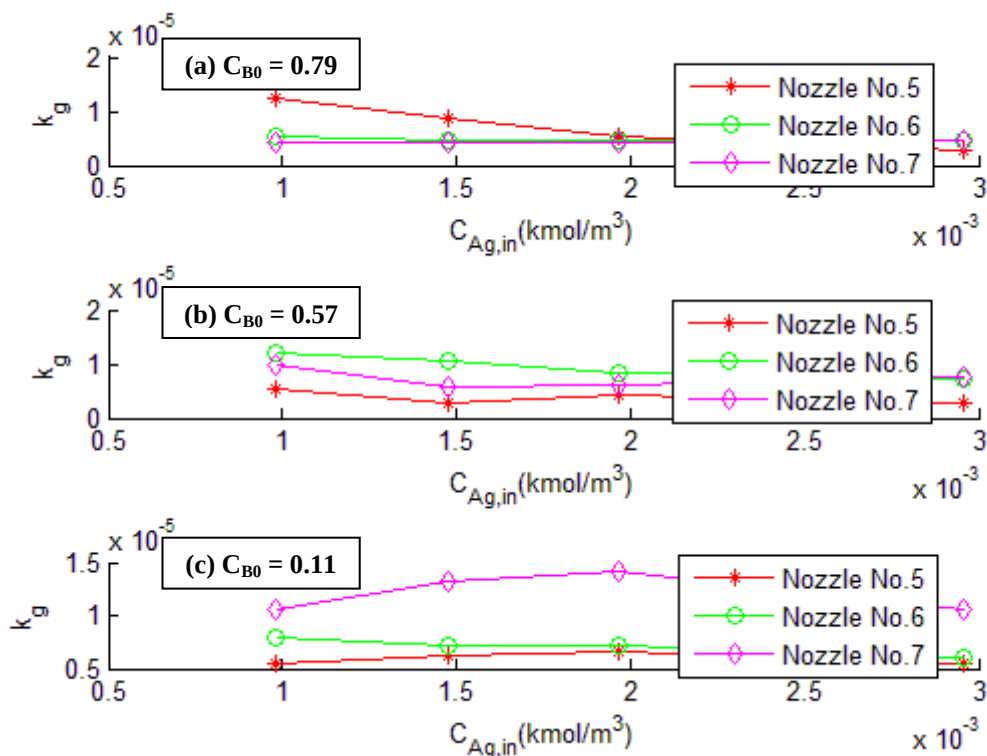


Figure 16 Effect of $C_{Ag,in}$ on k_g for different nozzle for set up 3.
(a) with $C_{B0} = 0.79$ (b) with $C_{B0} = 0.57$ (c) with $C_{B0} = 0.11$

C2 Effect of number of nozzles on $k_g a$, a and k_g

The effect of number of nozzle on volumetric mass transfer coefficient $k_g a$ predicted by proposed model with respect to $C_{Ag,in}$ at different C_{B0} are shown in figure (6) and (14). The figure (6) is a plot of the $k_g a$ vs $C_{Ag,in}$ for setup 2 at $C_{B0} = 0.527$ for nozzle N2 (having number of orifice 1) and N3 (having number of orifice 3). The figure (14) is a plot of the $k_g a$ vs $C_{Ag,in}$ for setup 3 at different C_{B0} for nozzle N5 (having number of orifice 1), N6 (having number of orifice 3) and N7 (having number of orifice 5).

The effect of number of nozzle (orifice) on interfacial area ' a ' generated are shown in the figure (7) and (15).

True gas side mass transfer coefficient (k_g) is studied in the figure (8) and (16) for different nozzles (N2, N3, N5, N6 and N7) at different C_{B0} .

It is observed that at the lower C_{B0} , the $k_g a$ and k_g are higher for nozzle N7 (no. of orifice 5) and at higher C_{B0} the $k_g a$ and k_g are higher for nozzle N5 (no. of orifice 1). Similar effect is observed for setup 2 (figure 6 and 8) where the $k_g a$ is higher for nozzle N2 (no. of orifice 1) compared to nozzle N3 (no. of orifice 3).

As numbers of nozzle (orifice) are increased the outer exposed area of free jet is more for same flow area. The higher outer exposed area makes entrainment of gas easy to the free jet. The higher C_{B0} also lead to increase in viscosity, which resist gas to enter in the liquid stream. So at higher C_{B0} the effect of higher outer exposed area is compensated and we are getting lower value of k_g and $k_g a$ for higher number of orifice.

It is also observed that at high C_{B0} (0.79 kmol/m^3) the higher interfacial area is obtained for nozzle N5 and N7 (no. of orifice 1 and 5 respectively). For intermediate C_{B0} (0.57 kmol/m^3 for setup 3 and 0.52 kmol/m^3 for setup 2) the interfacial area is almost same for all nozzle. While for lower C_{B0} (0.11 kmol/m^3) the interfacial area is more for nozzle 6 (no. of orifice 3). As number of orifice (nozzle) increases there is collision of jet at the entry of throat which has negative effect on the interfacial area. Thus the effect of more outer exposed area and collision of jet enhances the interfacial area for number of more nozzles.

C3. Effect of $C_{Ag,in}$ on $k_g a$, a and k_g

The variation in $k_g a$, a and k_g with respect to $C_{Ag,in}$ are shown in figures (1) to (16).

- **Volumetric mass transfer coefficient ($k_g a$):** The effect of $C_{Ag,in}$ on $k_g a$ by variation in C_{B0} and no. of nozzle are shown in figures (2), (6), (10) and (14). All the figures are almost similar qualitatively i.e. as the value of $C_{Ag,in}$ increases the value of $k_g a$ decreases. The decrease is very sharp at initial values of $C_{Ag,in}$. Afterwards the decrease in $k_g a$ with respect to $C_{Ag,in}$ is reduced.
- **Mass transfer coefficient (k_g):** The effect of $C_{Ag,in}$ on k_g is shown in figures (4), (8), (12) and (16). From figures it is seen that there is decrease in the value of k_g with respect to $C_{Ag,in}$ except some exception.

The trend of decrease in $k_g a$ and k_g is because of effect of reactant ratio C_{B0}/C_A^* on reaction factor. As discussed in section (4.2); the increase of reaction ratio C_{B0}/C_A^* this will lead to increase in enhancement factor. The rate of increase in enhancement factor is sharp at the lower value of C_{B0}/C_A^* ratio and then decreases and become negligible. The C_A^* is the function of $C_{Ag,in}$ as per Henry's law. Therefore as C_{A0} increases the enhancement factor also decreases. The enhancement factor is direct function of mass transfer coefficient ratio of absorption with and without chemical reaction.

C4 Interfacial area ' a '

The effect of $C_{Ag,in}$ on interfacial area for different nozzles and at different C_{B0} is shown in figures 3, 7, 11 and 15. It is observed that there is only a little variation in interfacial area with change in $C_{Ag,in}$. This is because the interfacial area generated depends on liquid to gas ratio and viscosity of the liquid. In the present experiment the liquid to gas ratio is kept constant and very low concentration of Cl_2 has been used. Under these conditions the viscosities of liquid and gas will not change significantly.

V. Conclusion

- The model to predict interfacial area is presented by the equation 11. A new model has also been proposed to predict the interfacial area a by the correlation 19. For utilizing this correlation the experimental data of the system does not required to satisfy the condition 9.
- The figures (1) to (16) are plotted on the basis of the prediction from proposed new model presented by equations 19. The behavior of $k_g a$, a and k_g are shown against different initial concentration of gases for different nozzles and C_{B0} in these figures. The results are summarized in the following table.

Table 3: Summary of analysis of results for different C_{B0} and nozzles

	C_{B0}	$C_{Ag,in}$	Number of nozzle
$R_a a$	decreases	increases	increases
$k_g a$	decreases except N5	decreases	increases except $C_{B0}=0.79$
a	decreases then increases except N1	$\approx$ constant	constant for $C_{B0}=0.57$
k_g	decreases except N5	constant except N1 at $C_{B0}=0.95$	increases except $C_{B0}=0.79$

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VII. References

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