ELSEVIER

Journal of Hazardous Materials A100 (2003) 13–25

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Simulation of an orifice scrubber performance based on Eulerian/Lagrangian method

A. Mohebbi [a,*], M. Taheri [b], J. Fathikaljahi [b], M.R. Talaie [b]

[a] *Department of Chemical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran*

[b] *Department of Chemical Engineering, Shiraz University, Shiraz, Iran*

Received 19 February 2003; received in revised form 19 February 2003; accepted 24 February 2003

Abstract

A mathematical model based on Eulerian/Lagrangian method has been developed to predict particle collection efficiency from a gas stream in an orifice scrubber. This model takes into account Eulerian approach for particle dispersion, Lagrangian approach for droplet movement and particle-source-in-cell (PSI-CELL) model for calculating droplet concentration distribution. In order to compute fluid velocity profiles, the normal $k - \varepsilon$ turbulent flow model with inclusion of body force due to drag force between fluid and droplets has been used. Experimental data of Taheri et al. [J. Air Pollut. Control Assoc. 23 (11) (1973) 963] have been used to test the results of the mathematical model. The results from the model are in good agreement with the experimental data. After validating the model the effect of operating parameters such as liquid to gas flow rate ratio, gas velocity at orifice opening, and particle diameter were obtained on the collection efficiency.

Keywords: Orifice scrubber; Venturi scrubber; Eulerian/Lagrangian method

1. Introduction

The standards for air pollution control are becoming increasingly stringent, so that there is a constant demand for more effective pollution control technologies. Many countries have developed highly elaborate regulatory programs aimed at requiring factories, and other major sources of air pollution, to install the best available control technology for removing pollutants from gaseous effluent streams released into the atmosphere. The popular choices of control equipment for the effective removal of pollutants from moving gas streams have

---

[*] Corresponding author.

E-mail address: amohebbi2002@yahoo.com (A. Mohebbi).

doi:10.1016/S0304-3894(03)00066-9

Nomenclature

C_{d}	droplets concentration (no./m^3)
C_{Df}	drag coefficient of droplet (dimensionless)
C_{P}	particulate concentration ($\mathrm{kg/m^3}$)
$\bar{d}_{\mathrm{P}}$	mean particle diameter (m)
D_{d}	mean diameter of droplets (m)
D_{P}	particle diameter (m)
E_{g}	eddy diffusivity of gas ($\mathrm{m^2/s}$)
g	acceleration of gravity ($9.8\,\mathrm{m/s^2}$)
k	turbulence kinetic energy (J/kg)
L/G	liquid to gas flow rate ratio (m^3 of liquid/$1000\,\mathrm{m}^3$ of gas)
$\dot{N}$	total number flow rate of droplets (no./s)
$\dot{N}_j$	number flow rate of droplets at starting location j (no./s)
Pe	Peclet number (dimensionless)
r	radial direction
t	time
u	gas velocity in z direction (m/s)
u'	fluctuation velocity of gas (m/s)
u_{d}	droplets velocity in z direction (m/s)
v	gas velocity in r direction (m/s)
v_{d}	droplets velocity in r direction (m/s)
V	vector of gas velocity (m/s)
$V_{\mathrm{C.V.}}$	volume of control volume (m^3)
V_{d}	vector of droplet velocity (m/s)
V_{o}	gas velocity at orifice opening (m/s)
X_j	number fraction of droplets starting at a location j (dimensionless)
z	axial direction

Greek letters

ε	turbulence dissipation rate (J/kg s)
η_{OV}	overall collection efficiency (dimensionless)
η_{t}	target efficiency (dimensionless)
μ	laminar viscosity (kg/m s)
ρ	gas density ($\mathrm{kg/m^3}$)
ρ_{d}	droplet density ($\mathrm{kg/m^3}$)
ρ_{P}	particle density ($\mathrm{kg/m^3}$)
ψ	inertial impaction parameter (dimensionless)

included devices operating on the basis of centrifugal, inertial or electrostatic principles. One of well-known types of devices for removing pollutants from a gaseous effluent stream is wet scrubber in form of venturi or orifice.

Some industries utilize the orifice type scrubber to clean the exhaust gases from particles and other pollutants. In the orifice scrubber, a gas cleaning liquid (e.g. water) is injected into an incoming particle-laden gas stream in vicinity of the orifice opening. The high velocity of the gas stream at the opening atomizes the water into fine droplets. The collection mechanisms involve primarily, collision between the pollutants and the droplets due to inertial mechanism and diffusion of very fine pollutants to the surface of the droplets. The contaminated water droplets are removed by means of a cyclone separator. The advantages of this device include simplicity in structure and operation, simplicity for altering the cross sectional area of orifice opening, lower initial costs for comparable collection, low floor requirements, removal of both gases and particulate, and capabilities to handle wet and corrosive gases. Beside the pollutant collection efficiency, the overall pressure drop associated with the operation of the system is the most significant information required for a successful design of an orifice scrubber. Momentum gained by droplets through the accelerating zone, friction losses from the eddies generated by the reexpanding jet below the vena contracta, and wall losses define the magnitude of the pressure drop. Orifice scrubber collection efficiencies range from 80 to 99%, depending upon the application and scrubber design.

Several attempts have been made on the mathematical modeling of pollutant removal in a venturi scrubber [1–9]; but no study has been published to develop a mathematical model for predicting the collection efficiency of particulates in an orifice scrubber. In the present study, a two dimensional mathematical model in cylindrical coordinates has been developed to predict the particle removal efficiency from a gas stream in an orifice scrubber. This model takes into account Eulerian approach for particle dispersion, $k-\varepsilon$ model of turbulence for predicting gas velocity profiles, Lagrangian approach for water droplet movement, and particle-source-in-cell (PSI-CELL) model [10] to calculate the droplet concentration distribution.

2. Mathematical model

In this study, under extreme operating conditions of orifice scrubber experimental data [11], the inertia of a droplet is about 300 times higher than that of a particle. This fact justifies using simple Lagrangian approach for water droplet movement and Eulerian approach for particle movement. Simple Lagrangian method is based on tracking of each individual droplet and the effect of gas turbulence on droplet movement is ignored. In Eulerian method, the continuity equation of particles is solved to obtain particle concentration distribution and the effect of gas turbulence is considered.

3. Particulate concentration

For particle loading in an orifice scrubber, continuity equation for particles based on the conventional diffusion equation can be represented as:

$$\frac{\partial}{\partial z}(uC_{\mathrm{P}})+\frac{1}{r}\frac{\partial}{\partial r}(rvC_{\mathrm{P}}) = \frac{\partial}{\partial z}\left(E_{\mathrm{g}}\frac{\partial C_{\mathrm{P}}}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(rE_{\mathrm{g}}\frac{\partial C_{\mathrm{P}}}{\partial r}\right)-\frac{\pi}{4}D_{\mathrm{d}}^{2}\eta_{\mathrm{t}}|V-V_{\mathrm{d}}|C_{\mathrm{d}}C_{\mathrm{P}} \quad (1)$$

This equation (see nomenclature) can be obtained by writing mass balance for particulate matters over a cylindrical volume element. The particles are usually very small in size; this allows us to assume that the eddy diffusion of the particles is equal to the eddy diffusion of gas. In computing Eq. (1) for predicting particulate removal efficiency, one must obtain expressions for the turbulent gas velocity, droplet concentration, water droplet velocity, gas eddy diffusivity, target collection efficiency, and droplet diameter. These variables are discussed in the following sections.

4. Gas velocity distribution

In order to predict fluid velocity distribution, the partial differential equations governing steady, incompressible turbulent flow in axisymmetric cylindrical coordinates based on standard $k-\varepsilon$ model with inclusion of body force due to drag force between fluid and droplets were used. The details of these equations are given elsewhere, Mohebbi [12] and Mohebbi et al. [13].

5. Liquid droplet velocity

The droplet velocities in the axial direction (u_d) and in the radial direction (v_d) are determined from a force balance on the droplets as follow:

$$\frac{\mathrm{d}u_\mathrm{d}}{\mathrm{d}t}=\frac{3}{4}\frac{C_\mathrm{Df}}{D_\mathrm{d}}\frac{\rho}{\rho_\mathrm{d}}(u-u_\mathrm{d})|V-V_\mathrm{d}|+g \tag{2}$$

$$\frac{\mathrm{d}v_\mathrm{d}}{\mathrm{d}t}=\frac{3}{4}\frac{C_\mathrm{Df}}{D_\mathrm{d}}\frac{\rho}{\rho_\mathrm{d}}(v-v_\mathrm{d})|V-V_\mathrm{d}| \tag{3}$$

In order to obtain droplet trajectories following equations can be used.

$$\frac{\mathrm{d}z}{\mathrm{d}t}=u_\mathrm{d} \tag{4}$$

$$\frac{\mathrm{d}r}{\mathrm{d}t}=v_\mathrm{d} \tag{5}$$

The value for C_Df is calculated using the equation [9]:

$$C_\mathrm{Df}=\frac{18.65}{Re_\mathrm{d}^{0.84}} \tag{6}$$

The droplet Reynolds number Re_d is

$$Re_\mathrm{d}=\frac{\rho|V-V_\mathrm{d}|D_\mathrm{d}}{\mu} \tag{7}$$

The mean droplet diameter is calculated using Boll's equation [14]:

$$D_\mathrm{d}=\frac{(4.22\times10^{-2})+5.776\times10^{-3}(L/G)^{1.932}}{V_\mathrm{o}^{1.602}} \tag{8}$$

where V_o is the gas velocity at the orifice opening.

6. Droplet concentration

Simple Lagrangian approach based on PSI-CELL model is used for obtaining the local number concentration of droplets. The number flow rate of spherical droplets at starting location j is given as:

$$\dot{N}_j = X_j \dot{N} \tag{9}$$

where $\dot{N}$ is the total number flow rate of droplets and X_j is the number fraction of droplets starting at a location j. It was assumed that gas velocity fluctuations do not influence the droplet movement in Lagrangian method, so that the number flow rate of droplets located at point j is constant along their trajectory. The number concentration of droplets in each control volume is determined by:

$$C_{\mathrm{d}} = \sum_{j,\,\mathrm{C.V.}} \frac{\dot{N}_j \Delta\tau}{V_{\mathrm{C.V.}}} \tag{10}$$

where $\Delta\tau$ is the residence time of droplets in the control volume and $V_{\mathrm{C.V.}}$ is the volume of control volume. The residence time $\Delta\tau$, was calculated by using the trajectories of droplets.

7. Gas eddy diffusivity

The following equation proposed by Tennekes and Lumley [15] was used to predict the gas eddy diffusivity, E_{g}:

$$E_{\mathrm{g}} = E_{\mathrm{P}} = c_1 u' l \tag{11}$$

where l is characteristic length and usually defined in terms of turbulence dissipation rate (ε), as follows [16]:

$$l = \frac{3u'^3}{2\varepsilon} \tag{12}$$

The parameter c_1 in Eq. (11) has been determined in an experiment for heat transfer by Launder [17]. It can take the values ranging from 0.2 to 0.4. Talaie et al. [18] reported a value of 0.1 for c_1 in calculating the performance of a double-stage electrostatic precipitator. In the present work, the prediction of three sets of experimental data of Taheri et al. [11] by the proposed model indicated that the values ranging from 0.1 to 0.16 for c_1 would give the best fit.

8. Target efficiency

The principal collection mechanism in a high-energy scrubber is inertial impaction. The collection efficiency (i.e. η_{t}) of particulates by a single drop can be calculated from the following equation [1,4,8,9]:

$$\eta_{\mathrm{t}} = \left(\frac{\psi_{\mathrm{c}}}{\psi_{\mathrm{c}} + 0.7}\right)^2 \tag{13}$$

in Eq. (13), ψ_c is the inertial impaction parameter and it is given by the following equation:

$$\psi_c = \frac{\rho_P D_P^2 |V - V_d|}{9\mu D_d} \tag{14}$$

In the present work another correlation for calculating drop target efficiency is introduced. This correlation is based on following mathematical series:

$$\lim_{n\to\infty} \left(\frac{n}{n+1}\right)^r = 1 \text{ for any value of } r \tag{15}$$

by using this series and a least square curve fit of Walton and Woolcock [19] data for potential flow following correlation is introduced:

$$\eta_{tm} = \left(\frac{\psi}{\psi+1}\right)^r \tag{16}$$

where r is a function of ψ:

$$r = 0.759\psi^{-0.245} \tag{17}$$

and ψ defined by following equation:

$$\psi = \frac{\rho_P D_P^2 |V - V_d|}{18\mu D_d} \tag{18}$$

by using Eq. (16) for calculating drop target efficiency the error value respect to experimental data is 5% while for Calvert Eq. (13) this error is 12%. The comparison of predicted value of target efficiency from Calvert equation and present equation with experimental data from Walton and Woolcock [19] is shown in Fig. 1.

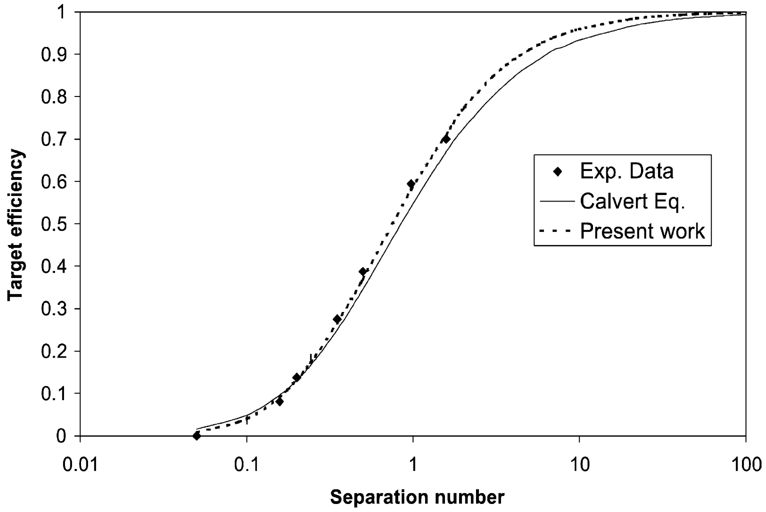

Fig. 1. Comparison target efficiency vs. separation number (ψ) for Calvert and present correlations with experimental data [19].

9. Overall collection efficiency

The overall collection efficiency is computed from the ratio of the net amount of particles captured to the total amount of input and it is given by the following equation:

$$\eta_{\mathrm{OV}} = 1 - \frac{\int_0^R rV(r,z)C_{\mathrm{P}}(r,z)\,\mathrm{d}r}{\int_0^R rV(r,0)C_{\mathrm{P}}(r,0)\,\mathrm{d}r} \tag{19}$$

10. Numerical solution procedure

The finite volume method incorporated with the power-law scheme, SIMPLE algorithm and staggered grid system [20] was employed to obtain the numerical solutions of the gas partial differential equations and Eq. (1). The numbers of stretched grid in axial and radial directions have been selected 38 and 28, respectively. With these values, the solution is independent from the grid size. Further details for calculating turbulent gas velocity, water droplet velocity, and pressure drop are given by Mohebbi [12] and Mohebbi et al. [13]. After solving Eq. (1) for particle concentration, the overall collection efficiency at any axial location in orifice scrubber is calculated by Eq. (19). In this study, the liquid jet direction is perpendicular to gas flow; it penetrates into gas stream both in radial and axial direction. Due to axial penetration, the liquid jet is atomized in the vicinity of orifice plate, so that most of droplets collide with orifice plate or symmetry line ($r = 0$) and get reatomized at orifice opening. This result is also confirmed by computer model. Therefore, it is assumed that starting locations for droplets are from orifice opening as a uniform line source.

11. Results and discussions

In order to verify the results of mathematical model, the experimental data of Taheri et al. [11] was used. Fig. 2 shows a schematic configuration of the orifice scrubber used in that experiment. Air with particles at $T = 37\,^{\circ}\mathrm{C}$ and $P_0 = 85.3\,\mathrm{kPa}$ was aspirated through

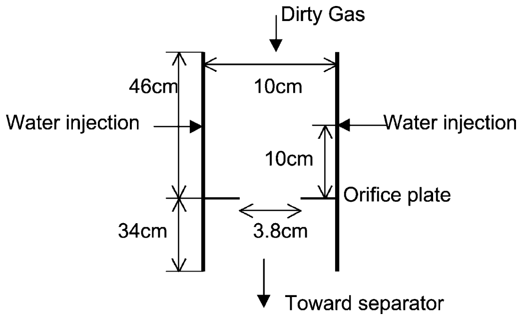

Fig. 2. Schematic configuration of the orifice scrubber in Taheri et al. [11] experiment.

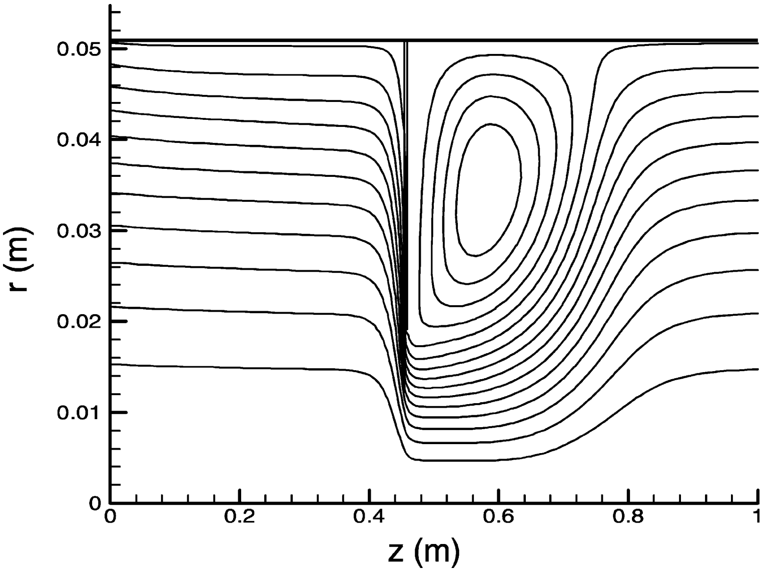

Fig. 3. Mean flow streamlines for 3.8 cm orifice.

the scrubber assembly. Particles were generated by atomizing and drying a 1% aqueous solution of methylene blue dye with a flow rate of 5 ml/min.

Fig. 3 shows the mean flow streamlines for the 3.8 cm orifice scrubber. Velocity increases sharply in the orifice opening and a recirculation zone is formed behind the orifice plate. Variation of the centerline axial velocity for droplets and gas are shown in Fig. 4 along the scrubber length. As one can see the droplet velocity in a short length increases then decreases and reaches to gas velocity after a distance. Fig. 5 shows droplet trajectories from orifice opening for 30 droplets at starting locations.

In Fig. 6 the particle collection efficiency from the present model is compared with Taheri et al. [11] experimental data for liquid to gas flow rate ratio (L/G) of 0.254, 0.51, and 0.856 m^3 of liquid/1000 m^3 of gas and particle diameters of 1.5–3.5 μm ($\bar{d}_P = 2.5$ μm). It can be seen that there is good agreement between the results of model and experimental data for a 3.8 cm orifice scrubber. This figure provides a good validation for the mathematical model and the method of solution.

After confirming the mathematical model, the effect of various parameters such as: gas velocity at orifice opening, liquid to gas flow rate ratio and particle diameter on the particle collection efficiency of the orifice scrubber were obtained. The scrubber used for this purpose has the same configuration as that used in Taheri et al. [11] experiment, which was applied for removing particulate with a diameter up to 3.5 μm from a gas stream.

Fig. 7 shows the effect of gas velocity at orifice opening (V_o) on particle collection efficiency. This figure indicates that with increasing V_o the collection efficiency increases. This is expected because as the relative velocity between gas and droplets increases, the impaction increases due to inertial effect. However increasing V_o beyond a limit will have

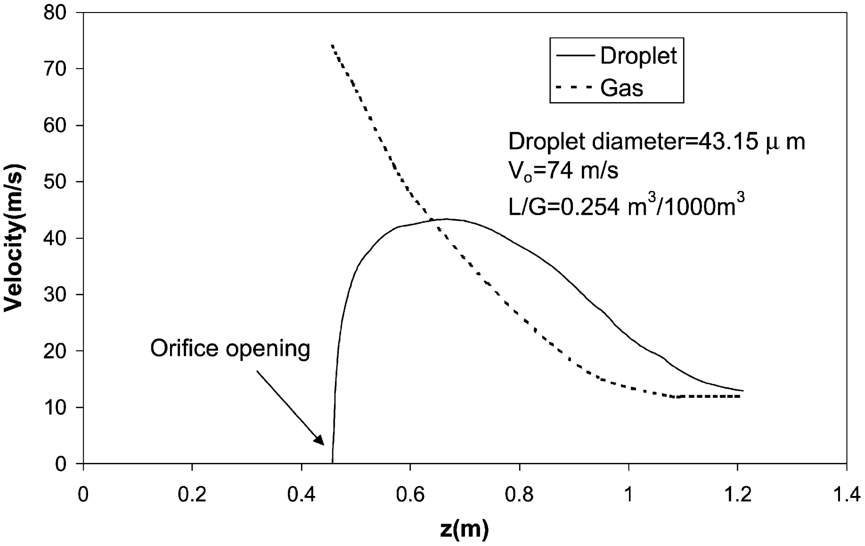

Fig. 4. Variation of the centerline axial velocity for droplets and gas along the scrubber length.

little improvement especially for large values of L/G ratio. Fig. 7 also shows that for high values of V_0, the effect of L/G ratio on collection efficiency becomes insignificant.

Fig. 8 shows how the liquid to gas flow rate ratio affects the particle collection efficiency of the scrubber. This figure indicates that increasing L/G ratio at constant V_0 increases the efficiency. Note that increasing L/G ratio will increase pressure drop; see Fig. 6. This is in accordance with the reported finding in the literature [1,3,21] that as pressure drop increases the collection efficiency increases.

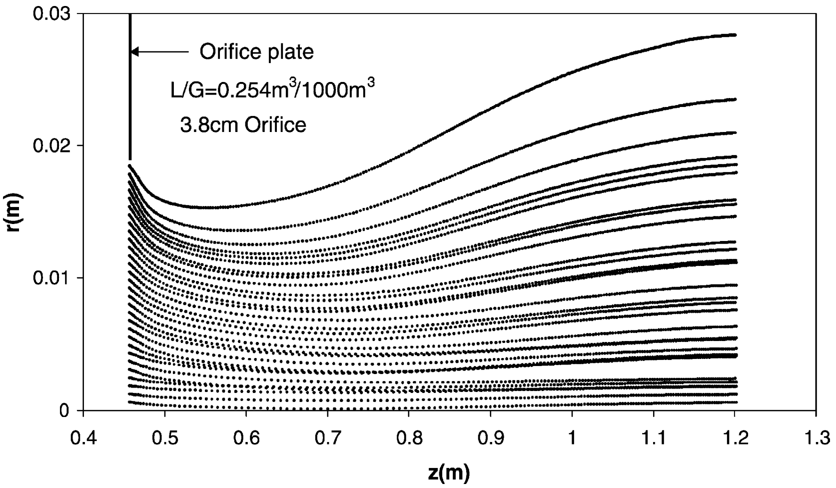

Fig. 5. Droplet trajectories from orifice opening for 30 droplets at starting locations.

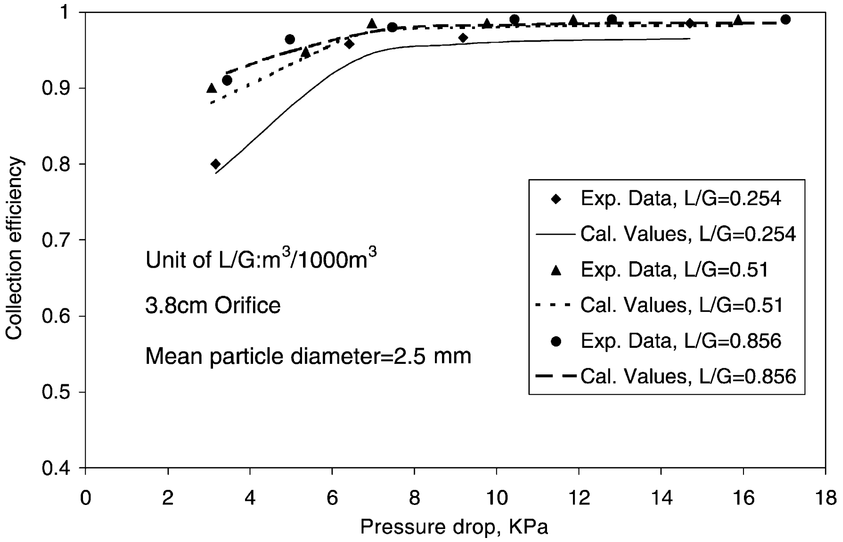

Fig. 6. Comparison between prediction of mathematical model and experimental data.

Fig. 9 shows the variation of collection efficiency with the particle diameter. From this figure, it can be observed that increasing particle diameter at constant L/G and V_o up to a certain limit will increase the collection efficiency, but increasing d_P beyond the limit will have little improvement. It may be expected that collection efficiency for larger particles

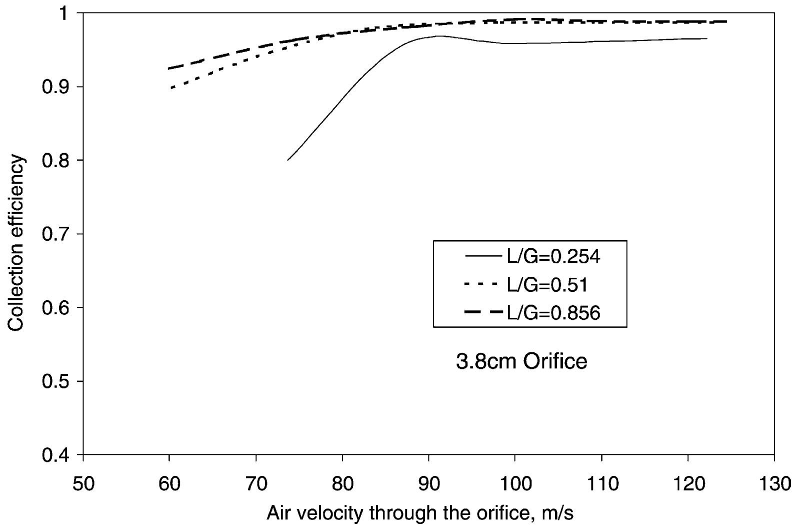

Fig. 7. Effect of gas velocity at orifice opening on particulate collection efficiency.

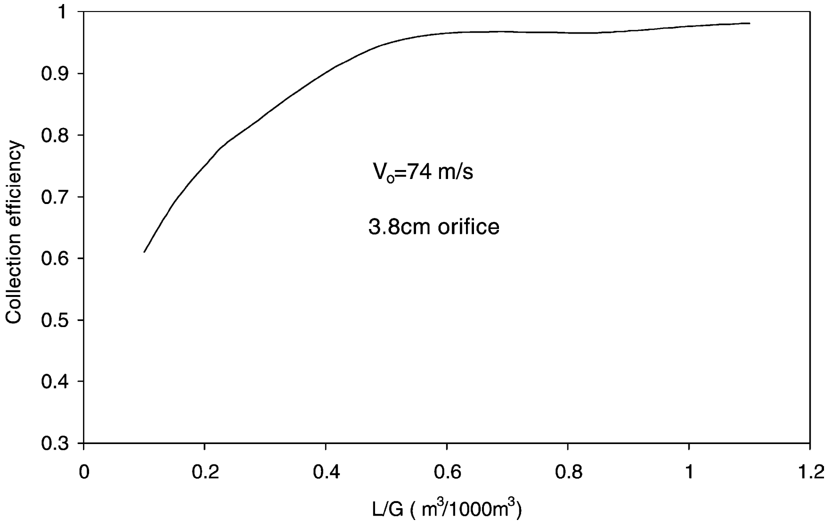

Fig. 8. Effect of liquid to gas flow rate ratio on particulate collection efficiency at constant V_o.

would approach unity. However this fact depends on L/G ratio. For low L/G ratio, the possibility of capturing particles by droplets is reduced. This is because of a non-uniform droplet distribution or low droplet concentration and partial channeling of gas stream. This behavior is predicted by the model as shown in Fig. 9 that for larger L/G ratio the collection efficiency for larger particles approaches unity.

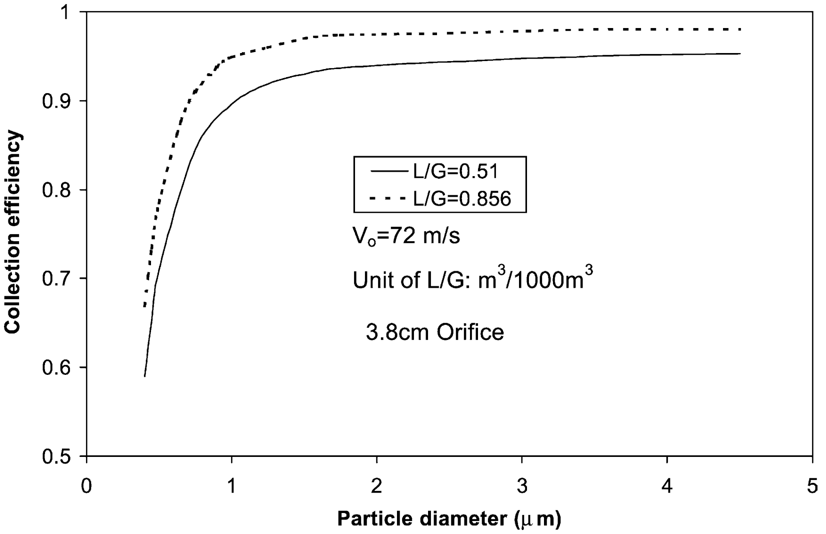

Fig. 9. Effect of particle diameter on collection efficiency at constant L/G and V_o.

12. Conclusions and recommendations

In the present study, a mathematical model based on particle dispersion model, $k-\varepsilon$ model of turbulence, and PSI-CELL model was developed to predict the particulate removal efficiency and pressure drop in an orifice scrubber. In the past calculation of droplet concentration distribution C_d, has been based on dispersion model in scrubbers, but in the present work PSI-CELL model was used. Good agreement between experimental data and simulation show that Eulerian/Lagrangian method can be a powerful model for predicting collection efficiency and pressure drop in orifice scrubber.

On the basis of the present results, it was concluded that an orifice scrubber could be used as an efficient device for gas cleaning purposes even for low L/G ratio.

In previous studies, the main difficulty with the simulation of atomizing scrubbers was in estimating the values of gas and droplet eddy diffusivities, hence the Peclet number. Different values of *Pe* number have been reported in the literature. Viswanathan et al. [6] and Fathikalajahi et al. [22] reported values of 100 and 130, respectively. Recently, Goncalves et al. [23] proposed $Pe = 70$ for the model of Fathikalajahi et al. [22] and $Pe = 30$ for their own model. Therefore, from these different values, it seems that *Pe* number is not a good parameter for estimating gas eddy diffusivity. In the present study, an alternative method based on the kinetic energy of turbulence (k) and its dissipation rate (ε) was proposed and tested for an orifice scrubber. In this method the change in gas eddy diffusivity over scrubber was considered. Finally, it is recommended that a simulation study be conducted to apply the method of this study for estimating E_g and PSI-CELL model for calculating droplet concentration in venturi scrubbers.

References

[1] S. Calvert, D. Lundgren, D.S. Mehta, Venturi scrubber performance, J. Air Pollut. Control Assoc. 22 (7) (1972) 7.

[2] S.W. Behie, J.M. Beeckmans, On the efficiency of a venturi scrubber, Can. J. Chem. Eng. 51 (1973) 430.

[3] R.H. Boll, Particle collection and pressure drop in venturi scrubber, Ind. Eng. Chem. Fundam. 12 (1973) 40.

[4] M. Taheri, C.M. Sheih, Mathematical modeling of atomizing scrubbers, AIChE J. 21 (1) (1975) 153.

[5] B.J. Azzopardi, A.H. Govan, The modeling of venturi scrubbers, Filtr. Sep. (1984) 196.

[6] S. Viswanathan, A.W. Gnyp, C.C. St. Pierre, Examination of gas liquid flow in a venturi scrubber, Ind. Eng. Chem. Fundam. 23 (3) (1984) 303.

[7] Baasel, J. Air Pollut. Control Assoc. 38 (1988) 327.

[8] J. Fathikalajahi, M. Taheri, M.R. Talaie, Theoretical study of non-uniform droplets concentration distribution on venturi scrubber performance, Part. Sci. Technol. 14 (1996) 153.

[9] N.V. Ananthanarayanan, S. Viswanathan, Estimating maximum removal efficiency in venturi scrubbers, AIChE J. 44 (11) (1998) 2549.

[10] C.T. Crowe, M.P. Sharma, D.E. Stock, The particle-source-in cell (PSI-CELL) model for gas-droplet flows, ASME J. Fluids Eng. (1977) 325.

[11] M. Taheri, S.A. Beg, M. Beizaie, The effect of scale-up on the performance of high energy scrubbers, J. Air Pollut. Control Assoc. 23 (11) (1973) 963.

[12] A. Mohebbi, Mathematical Modeling of Orifice Scrubber Performance, Ph.D. Thesis, Chemical Engineering Department, Shiraz University, Shiraz, 2002.

[13] A. Mohebbi, M. Taheri, J. Fathikaljahi, M.R. Talaie, Prediction of pressure drop in an orifice scrubber based on a Lagrangian approach, J. Air Waste Manage. Assoc. 52 (2002) 174.

[14] R.H. Boll, L.R. Flais, P.W. Maurer, W.L. Thompson, Mean drop size in a full scale venturi scrubber via transmissometer, J. Air Pollut. Control Assoc. 24 (10) (1974) 934.
[15] H. Tennekes, J.L. Lumley, A First Course in Turbulence, MIT Press, Cambridge, MA, 1972.
[16] G.L. Leonard, M. Mitchner, S.A. Self, Experimental study of the effect of turbulent diffusion on precipitator efficiency, J. Aerosol Sci. 11 (1982) 271.
[17] B.E. Launder, Topics in Applied Physics: Turbulence, Springer, Berlin, 1978.
[18] M.R. Talaie, J. Fathikaljahi, M. Taheri, Mathematical modeling of double-stage electrostatic precipitators based on a modified Eulerian approach, J. Aerosol Sci. Technol. 2001.
[19] W.H. Walton, A. Woolcock, Aerodynamic capture of particles, in: E.G. Richardson (Ed.), Pergamon Press, New York, 1960, pp. 129–153.
[20] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, McGraw-Hill, New York, 1980.
[21] S. Viswanathan, Examination of liquid film characteristics in the prediction of pressure drop in a venturi scrubber, Chem. Eng. Sci. 54 (17) (1998) 3955.
[22] J. Fathikalajahi, M.R. Talaie, M. Taheri, Theoretical study of liquid droplet dispersion in a venturi scrubber, J. Air Waste Manage. Assoc. 45 (1995) 181.
[23] J.A.S. Goncalves, M.A. Martines Costa, K.L. Serra, J.R. Coury, Droplet dispersion in a rectangular venturi scrubber, in: Proceedings of the 14th International Congress of Chemical and Process Engineering, Praha, Czech Republic, 2000.