Iranian Journal of Chemical Engineering
Vol. 6, No. 4 (Autumn), 2009, IAChE

A Simple One-Dimensional Model for Investigation of Heat and Mass Transfer Effects on Removal Efficiency of Particulate Matters in a Venturi Scrubber

A. Rahimi, A. Bakhshi*

Department of Chemical Engineering, College of Engineering, University of Isfahan, Isfahan, Iran.

Abstract

In the present study a mathematical model is developed in order to examine the effects of heat and mass transfers on removal efficiency of particulate matters in venturi type scrubbers. The governing equations including the variations of the particulate concentration, gas temperature, droplet temperature, diameter, and velocity are obtained based on the conservation laws and are solved numerically. In order to validate the model, necessary data was measured and collected in a commercial cement plant that uses these types of scrubbers in air pollution control applications. A good agreement between plant data and the model predictions is noticed in general. The results obtained from the model reveal that the existance of temperature difference between the gas and the liquid droplets decreases the overall removal efficiency of particulate matters. This is due to sudden reduction of relative velocity between the gas and droplets which is resulted from the existence of heat and mass transfers between the two fluids, especially in the throat section. In addition, the effects of various operating parameters on the extent of reduction in the removal efficiency are examined. This study confirms that in most industrial applications of venturi scrubbers it is necessary to use a direct or an indirect cooling tower in order to decrease the gas temperature before entering the venturi.

Keywords: *Venturi scrubber, Evaporation, Condensation, Mathematical model*

1- Introduction

Atomizing scrubbers have emerged as one of the most widely used pieces of equipment for removal of small particles from gas streams, primarily due to the simplicity of their operation and construction. In recent years, development of new techniques in the area of air pollution control which adapt with new allowable limits of pollutant emissions in the atmosphere have been of interest to many researchers. In order to meet these new standards, equipment with higher removal efficiencies are often required. Furthermore, increasing the number, size and complexity of new modern industries calls for new technologies or optimizing the present ones.

∗ Corresponding author: rahimi@eng.ui.ac.ir

Regarding this strategy, optimization and design of higher-efficiency venturi scrubbers, as capable devices for controlling air pollution, have been studied by many investigators. The ability of simultaneous removal of gaseous and particulate matters is an exclusive characteristic of these devices compared to the other available systems. Also, it combines the characteristics of high efficiency of particulate removal, easy maintenance, no moving parts, and low initial cost. Adequate adaptability with variation of inlet gas properties including temperature, inlet concentration of pollutants, inlet gas humidity and gas flow rate, are the other advantages of such systems. However the high pressure drop through the device and the problem of dumping the resulted sewage are some of the disadvantages of venturi scrubbers. Schematic representation of a venturi scrubber is shown in Fig. 1.

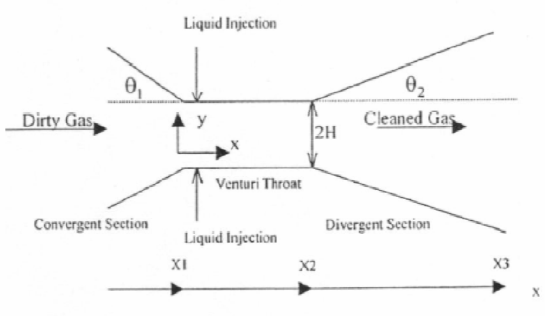

Figure 1. Schematic diagram of a venturi scrubber

In the throat section of the venturi the maximum separation rate of particles or gaseous pollutants is accomplished under affection of high relative velocity between the injected liquid and the flowing gas. Through the divergent section the particles or gaseous pollutant removal goes on due to the velocity difference between liquid and gas phases. The liquid is injected at or before the entrance of the throat section and is atomized to very fine liquid drops, causing great contact area and enhancing heat and mass transfer phenomena. It should be noted that the predominant particle separation mechanisms in a venturi scrubber are the inertial impaction and direct interception mechanisms.

The studies related to predicting or modeling the pollutants removal efficiency in venturi scrubbers have been in progress for about half a decade. At present, taking advantage of numerical methods in solving the governing equations, great improvements are achieved in the prediction of the removal efficiency. A summary of such studies is presented by Rahimi [1].

Removal efficiency through a venturi scrubber is a complex function of various parameters including the liquid-to-gas ratio, device physical dimensions, gas velocity and its variation, liquid droplet size distribution, amount of liquid film flows on the walls, particulate matter sizes and their size distribution, type of gaseous pollutant and the heat and mass transfer rates. Because of this complexity and in spite of the great number of investigations on this topic, the shortcomings of an appropriate and unique solution for predicting the removal efficiency of the venturi scrubbers may be realized. Even if there is such a solution, it may not be precise enough. Taheri and Sheih [2] developed a convective-dispersion model and investigated non-uniform distribution of liquid droplet across the venturi scrubber cross-section for the first time. Previous studies which are generally considered a uniform concentration distribution for liquid droplets may lead to various simple analytical solutions, most of which do not have appropriate preciseness for design purposes [3, 4].

Viswanathan [5, 6] studied the removal efficiency of venturi scrubbers which led to more precise relations for the prediction of the liquid film flow rate, liquid drop size distributions and drops source term in the convective-dispersion model that are relatively successful steps in the field of discovering unidentified points of the systems operation.

It should be noted that even extremely advanced existing models are not completely precise in predicting the removal efficiency and pressure drop because of using experimental or empirical correlations for calculating some key parameters. On the other hand, in the previous studies the heat and mass transfer phenomena resulted from the temperature difference between the gas and the injected liquid and gas initial humidity are not considered. It should be noted that the proposed justifications regarding the extremely short residence time inside these systems (less than 1 sec) are not reasonable. Although the residence time of gas and liquid is too short, the magnitude of the heat and mass transfers and relative velocity of the two phases are too high and significant. Outlet gas temperature and humidity measurements for an operational venturi scrubber used in Isfahan cement plant confirm the considerable differences of these parameters from the corresponding inlet values (See Table 1). As known, all of the transfer phenomena such as pollutants separation follow the same principles and their effective parameters such as high relative velocity, high gas and liquid contact area, drops size and concentration and the gradients are the same. Thus, it cannot refer on the one hand, to the high removal efficiencies to the above mentioned parameters, and on the other hand neglect the importance of the effect of the heat and mass transfers on the venturi performance.

Applying modeling principles, this study aims to investigate the behavior of a venturi scrubber in which there is a passibility of drop growth or evaporation because of the effects of the high temperature difference between the gas, the injected liquid and the gas initial humidity. Extreme gas velocity variation (therefore, the particle removal efficiency variation) are possible as well. Thus the effect of these phenomena is shown on the overall removal efficiency.

2. Mathematical Model

In the following section the governing equations of a venturi scrubber are derived by considering all effects of a significant difference between the entering gas and the liquid temperatures. In this situation, the venturi scrubber operation depends on the inlet gas humidity, droplet sizes, and temperature differences between the gas and droplets. Almost all of the heat and mass transfers occur in the liquid injection area at the entrance of the throat section. In this section the velocity gradient between the gas and droplets is at the highest value and the contact area is too extensive. The assumptions used in the modeling of the non-isothermal venturi scrubber are as follows:

- A uniform concentration distribution for liquid droplets is considered through the cross section of a venturi scrubber.
- Initial droplet velocity in the direction of gas flow is assumed to be negligible.
- Droplet and particle motions are in the direction of the venturi axis and are executed only by the convective mechanism accompanying the gas flow.
- Droplet collisions leading to size enlargement do not occur and the droplets do not break.
- Separation mechanisms only include the inertial impaction and interception.
- There is no heat transfer between the flowing gas and the surrounding (the scrubber is assumed to be adiabatic).

In the following section, on the basis of the above mentioned assumptions, the equations related to particulate concentration variation and the other effective equations are governed.

Particle Concentration Variation Equation:

Taking a differential control volume along the venturi length and using the mass conservation law for particulate matters may result in:

$$GC_p\Big|_x - GC_p\Big|_{x+\Delta x} - C_p E\,|V_r|\,L\frac{1.5D_d^2}{D_{sd}^3}\frac{\Delta x}{V_d} = 0 \quad (1)$$

in which G is the local volumetric flow rate of the gas ($G = nRT_g/P$). Eq. (1) may be summarized to:

$$\frac{d(GC_p)}{dx} = \frac{-1.5C_p E|V_r|LD_d{}^2}{D_{sd}{}^3 V_d} \quad (2)$$

Or,

$$C_p\frac{dG}{dx} + G\frac{dC_p}{dx} = \frac{-1.5C_p E|V_r|LD_d{}^2}{D_{sd}{}^3 V_d} \quad (3)$$

If the total mole and the gas pressure are constant, G may only change with temperature, namely $dG = (nR/p)\ dT_g$. Considering $dG/G = dT_g/T_g$, Eq. (3) may be finalized as below:

$$\frac{dC_p}{dx} = \frac{-1.5C_p E|V_r|LD_d{}^2}{D_{sd}{}^3 V_d G} - \frac{C_p}{T_g}\frac{dT_g}{dx} \quad (4)$$

In the above equations E is the removal efficiency of the droplets which is known as “Target” efficiency. As a definition, E is the ratio of two circular areas; the first is the cross section of a circle with a radius equal to the absorption width of a droplet and the second is the cross section area of a droplet. In this study the well-known equation proposed by Calvert et al. [7] is used for calculating E. The mentioned relation calculates a removal efficiency affected by inertial impaction and interception mechanisms.

$$E = \left(\frac{K}{K+0.7}\right)^2 \quad (5)$$

where K is the impact parameter calculated by the following equation:

$$K = \frac{\rho_p D_p |V_r|}{9\mu_g D_d} \quad (6)$$

Drop Velocity Equation:

In venturi scrubbers the drops velocity may increase or decrease in the gas direction due to gas drag force. Depending on the gas direction and scrubber positioning, other forces including gravity and buoyancy forces, act on the droplets as well. However, due to the short residence time inside the scrubber and the low density of gas, the gravity and buoyancy forces can be neglected.

Using the Newton's second law of motion the equation of drop velocity may be expressed as:

$$\frac{dV_d}{dx}=\frac{3\mu_g\left(V_g-V_d\right)}{4D_d{}^2\rho_d V_d}C_{DN} \tag{7}$$

where C_{DN} is the modified drag coefficient.

$$C_{DN}=C_D\,\mathrm{Re}_d \tag{8}$$

Eq. (4) indicates that for accurate determination of C_p variation along the venturi length and in consequence for the calculation of removal efficiency, the local values of drop diameters, gas temperature and relative velocity of gas and droplets should be known. Due to the fact that the contact surface area of gas and droplets is very high and the extent of mass and heat transfer is considerable, all mentioned parameters will be changed, so for accurate prediction of the concentration variation, it is necessary to develop the variation equations of each parameter.

Heat and Mass Transfer Equations

In many natural and industrial processes the mass and heat transfers take place between gas and drops. In industrial processes where the temperature is high, the drop evaporation is very important. Therefore in such a surrounding, mass transfer from or to a drop is the main subject of many theoretical and experimental investigations. As mentioned previously, in most of the cases, the venturi scrubbers perform in high temperature situations, so the mass and heat transfers have an important effect on the performance of these systems. In these cases, evaporation/condensation has a significant effect on the removal efficiency, gas pressure drop and pollutant collection. The drop diameter in contact with a hot gas may increase or decrease depending on water evaporation or condensation. This subject influences the removal efficiency directly, because the drop diameter is an important parameter in the equation of the removal efficiency (Eq. (6)). So the ability of the prediction of the temperature variation and mass and velocity of the droplets floating in hot gas are very important. In the following, the relevant equations for all parameters varying with mass and heat transfer processes are derived and discussed in detail.

Drop Diameter Variation Equation

Change of drop diameter along the venturi length may be expressed by a mass balance equation. If vapor partial pressure in the gas bulk is more than that of in the drop surface, the drops diameter increases due to condensation. But if the vapor partial pressure in gas is less than the second one mentioned, the drops become smaller due to evaporation. The following equation is defined for expressing drop size changes along the venturi length [1]:

$$\frac{dD_d}{dx}=\frac{2K_j M_v\left(P_b-P_{sat}\right)}{\rho_d V_d} \tag{9}$$

Drop Temperature Variation Equation

The internal energy of the drops may be changed because of the heat and mass transfers with the gas. The temperature variation equation of the droplet can be expressed as follows:

$$\frac{dT_d}{dx}=\frac{6h\left(T_g-T_d\right)}{\rho_d C_{pd} D_d V_d}-\frac{6N_A M_v}{C_{pd}\rho_d D_d V_d}\left[\lambda-C_{pd}\left(T_g-T_{ref}\right)\right] \quad (10)$$

Gas Temperature Variation Equation

In spray systems gas temperature may change as a result of heat transfer to drops and drop evaporations. Furthermore, a portion of gas energy is consumed for increasing the resulted vapor temperature from the drop surface temperature to the gas temperature. By using conservation of energy equation for constant flow through differential control volume at any point of venturi scrubber, the following equation for gas temperature variations may be derived:

$$-n_d h\pi D_d^{\,2}\left(T_g-T_d\right)-n_d N_A M_v C_{pv}\pi D_d^{\,2}\left(T_g-T_{ref}\right)=\frac{d}{dt}\left[\dot{m}_g C_{pg}\left[\left(T_g-T_{ref}\right)\right]\right] \quad (11)$$

where n_d is the number of liquid drops per unit time which is calculated by using the injected liquid flow rate and initial drops diameter. N_A is the mass transfer flux. Substituting equations related to these two parameters into Eq. (11), the following equation can be finalized:

$$\frac{dT_g}{dx}=\frac{-6LD_d^{\,2}}{D_{sd}^{\,3}\dot{m}_g C_{pg} V_d}\left[h\left(T_g-T_d\right)+K_y M_v C_{pv}\left(Y_b-Y^{sat}\right)\left(T_g-T_{ref}\right)\right] \quad (12)$$

Note that Eq. (12) is obtained from Eq. (11) by considering $V_d\ dT_g/dx = dT_g/dt$. Heat and mass transfer coefficients are calculated by the use of modified Ranz and Marshall's correlations [8] which are optimized by Downing [9] for use in such systems. Also, the equation presented by Boll [10] is used for calculating the initial diameter of liquid drops:

$$D_{sd}=\left[\left(\frac{5000}{V_g-V_d}\right)+29\left(\frac{1000L}{G}\right)^{1.5}\right]\left(10^{-6}\right) \quad (13)$$

Regarding the physical structure shown in Fig. 1, the cross-section area of the venturi scrubber at any point is determined by using the following equations.

$$\begin{cases} A=2W\left(H+(x_1-x)\tan\theta_1\right) & x\le x_1 \\ A=2WH & x=x_1 \\ A=2W\left(H+(x-x_2)\tan\theta_2\right) & x\ge x_2 \end{cases} \quad (14)$$

The so-called equations are not independent and are comprised of pollutant concentration variations, gas temperature, drop temperature, drop diameter and velocity that can be found by using numerical methods. These equations are solved simultaneously using forth-order Range–Kutta method.

3. Result and Discussion

Having solved the governing equations the accuracy of the model in predicting the values of some outlet parameters is checked by comparison of the model results with the operating values of a sample venturi scrubber taken in the Isfahan cement plant. These measurements are for the outlet and inlet gas dry and wet bulb temperatures, inlet and outlet gas humidity and overall removal efficiency of particulate matters. The operational conditions of this industrial sample are listed in Table 1. It should be noted that generally limited experimental and operational data are available in the field of venturi scrubber performance. The lack of information about the parameters used for the model verification is more critical, and includes the drops size, gas temperature, drop temperature, local efficiency along the venturi length and so many other useful parameters. For this purpose, the inspection of this model outcome and the trend of parameter changes resulted both quantitatively and qualitatively from the model show the precision, and declare the model's relative integrity.

Fig. 2 shows variations of the removal efficiency along the venturi length in the presence and in the absence of the heat and mass transfer phenomena. As seen, by absence of the mass and heat transfer effects, the removal efficiency gets much higher than the actual predicted value. Also, in Fig. 2 the results of the two mentioned cases are compared with the overall measured removal efficiency for 5μm particles. It is clear that the results of a model in which heat and mass transfer effects are considered is much closer to the actual efficiency value. It should be noted that the existing deviation between the model result and the measured value may be due to the effect of liquid droplet concentration distribution, which is not implemented in this study. This effect is studied in detail by Taheri and Sheih [2], Fathikalajahi et al., [11] and Viswanathan [6].

Table 1. Operational considerations and physical characteristics of the venturi scrubber used in Isfahan cement plant (2002).

Gas flow rate	16.54 m^3/s	Convergent section length	1.9 m
Inlet gas temperature	473 K	Throat section length	0.45 m
Outlet gas temperature	350 K	Divergent section length	2.65 m
Liquid-to-gas ratio	0.00034 m^3/ m^3	Initial humidity of gas	0.48 kg/kg dry air
Throat section width	0.45 m	Convergent on angle	21.9
Venturi length in depth	0.356 m	Divergent angle	5.4

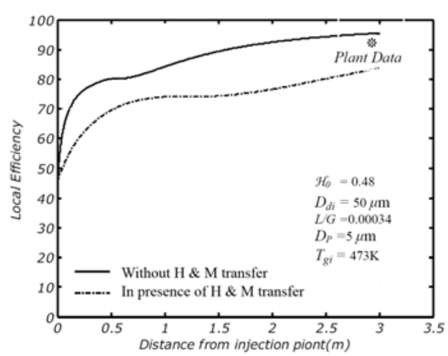

Figure 2. Removal efficiency along the venturi length in the presence and absence of the heat and mass transfer and comparison with plant data

Fig. 3 illustrates variations of the target efficiency of a single droplet along the venturi length. The heat and mass transfer decrease the drops target efficiency and reduce the overall efficiency referring to Fig.2. For a better explanation of the reasons for differences in Figs. 2 and 3, the gas and drop velocity variations along the venturi length are shown in Fig. 4 for both of the previous cases. It can be seen that the heat transfer between gas and droplets and the mass transfer resulted from evaporation or condensation suddenly reduce the gas velocity along the throat length. The result is to decrease the gas and drop relative velocity through the throat. As the target efficiency depends on the relative velocity, the value of this parameter and consequently the overall efficiency decrease. Fig. 3 shows that target efficiency reduction occurs with a much sharper slope and closer to the fluid injection point.

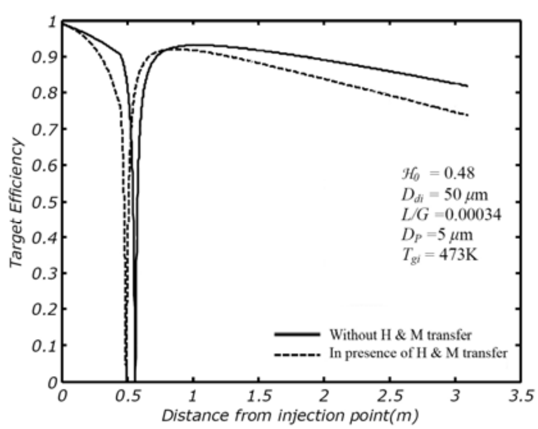

Figure 3. Target efficiency along the venturi length in the presence and absence of the heat and mass transfer

In Fig. 4 an interesting comparison is made between gas and drop velocities for the two above mentioned cases. In the absence of the heat and mass transfer phenomena, the velocity difference between the gas and drops is considerable and essentially higher efficiency is possible. In Fig. 5 the gas and drop temperature variations are shown along the scrubber length. It is shown that through the throat, gas temperature suddenly decreases as a result of the convective heat transfer and the cooling effects of the evaporation. The reason is the existance of a large exchange area, and also high heat and mass transfer coefficients caused by significant relative velocity between the gas and droplets. As seen in the previous figure, droplet final temperature is equal to the adiabatic temperature of inlet gas, corresponding to its initial temperature and humidity. Fig. 5 determines that the predicted drop temperature is too close to the measured values, which may confirm the precision of the model results. Also, according to the mentioned value in Table 1 for outlet gas temperature, it is exactly the same as the model predicted value in Fig. 5.

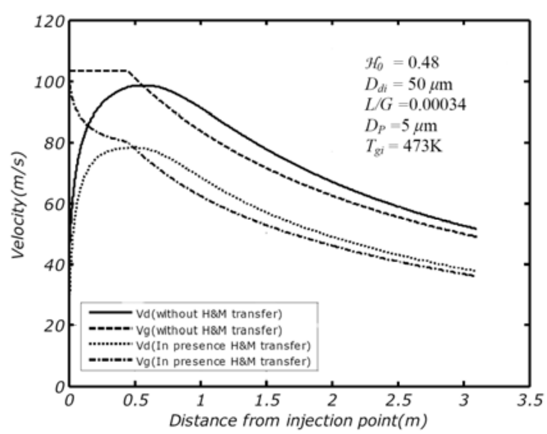

Figure 4. Gas and liquid droplet velocities along the venturi length in the presence and absence of the heat and mass transfer

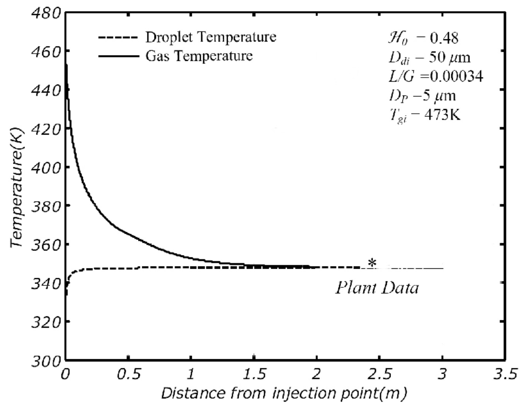

Figure 5. Variations of gas and droplet temperatures along the venturi length and comparison with plant data

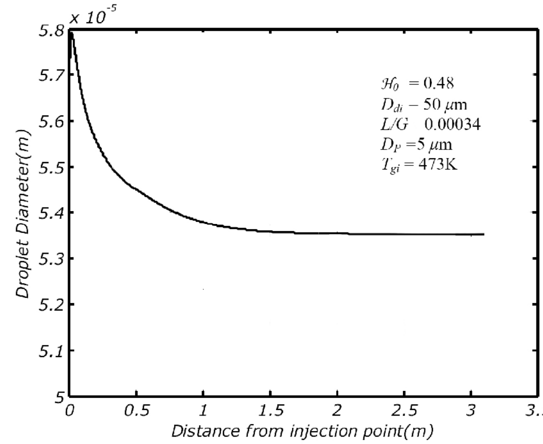

Figure 6. Variations of droplet diameter along the venturi length

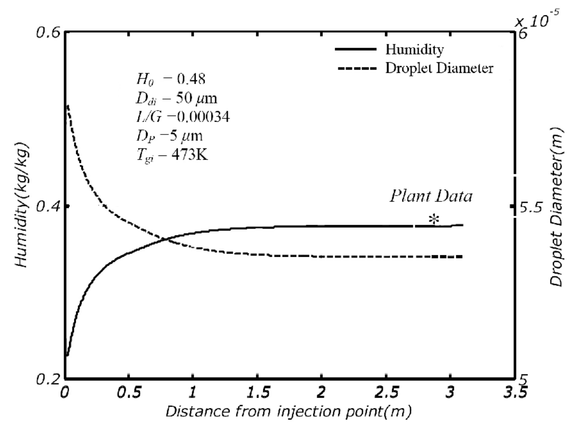

Figure 7. Variations of droplet diameter and gas humidity along the venturi length and comparison with plant data

Fig. 6 illustrates the variations of the drop diameter along the venturi length. At the start point, vapor partial pressure in the gas phase is more than that of on the drop surface due to the high inlet gas humidity. Therefore, drop diameter increases due to condensation. After a period of time, the drop diameter starts decreasing as a result of temperature increasing of the drops and consequently increasing of the vapor partial pressure on the drop surface. Since the target efficiency of the droplets is a function of drop sizes, these changes are very important. In Fig. 7 the variations of the gas humidity and the drop diameter are compared along the venturi length. As seen, the behavior of the drop diameter and the gas humidity are conversely related together. Drop diameter increases as humidity decreases which occurs due to condensation. Also, the results shown in the figure indicate that the model prediction for the outlet gas humidity is exactly equal to the measured one (according to the wet and dry bulb temperature of inlet gas) taken from the operational unit. This fact again confirms the accuracy of the model results.

In order to investigate the effect of inlet gas humidity on the drop growth or evaporation, Fig. 8 shows the drops diameter variations along the venturi length. It reveals that at higher inlet humidities, condensation occurs and the drops grow up because of the sudden cooling of the gas caused by the convective heat transfer on the one hand, and a higher vapor partial pressure on the other hand. The droplets then evaporate due to the increase in their temperature. Fig. 8 also shows that at lower initial humidities, the drop diameter only decreases.

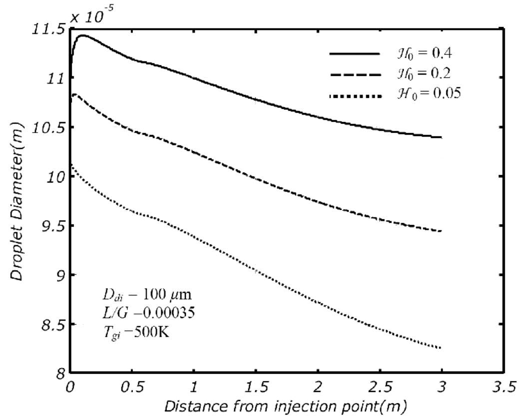

Figure 8. Variations of droplet diameter along the venturi length for different values of initial humidity

Fig. 9 depicts the effect of the gas inlet humidity on the gas and drop temperatures. It is seen that at environments with higher humidity, the drops and gas final temperatures are higher. This is due to the higher adiabatic saturation temperature of inlet gas that limits the maximum cooling possible during the contacting time. At higher humidities, the rate of gas and drops temperature variations are higher due to simultaneous condensation and convective heat transfer.

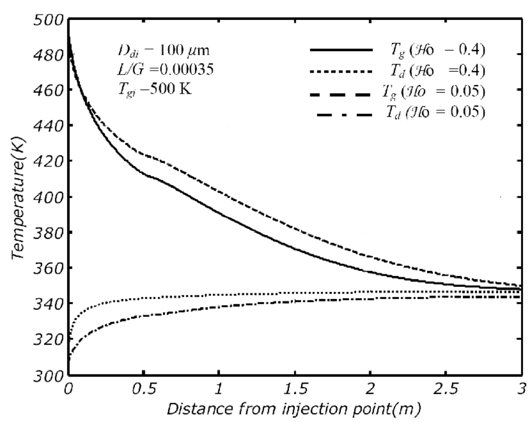

Figure 9. Variations of gas and droplet temperature along the venturi length for different values of initial humidity

The variations of the drop temperature are shown in Fig. 10. The aim of proposing such a figure is to study the effects of the initial size of the droplets on their temperature variation rate. It can be seen that, smaller droplets reach a constant temperature too, much sooner than larger drops and then, the temperature gets a constant value along the scrubber length. It is interesting to note that the final temperature of all droplets apart from the initial diameter is almost the same and equal. In Fig. 11 the effect of the inlet injected fluid temperature is shown on the drop size variation rate and consequently on the target efficiency change and the overall removal efficiency. In the figure, the inlet gas humidity is assumed 0.4, which is a high value. According to the obtained results, the inlet fluid temperature has a significant effect on the drop growth or evaporation, especially at the entrance of the throat. At this section, in spite of high initial gas humidity and the possibility of condensation, the high temperature of the droplets prevents condensation occurrence. For the inlet temperature of 350 K, drops become smaller through the venturi length. It should be noted that the presented results in Fig. 11 and the previous figures do not really confirm the necessity of cooling or warming the injected fluid. This means that, due to the effects of different factors one cannot clearly say that the drops growth or evaporation causes removal efficiency increase or decrease.

In Fig. 12 the effect of inlet gas temperature is shown on the removal efficiency. As inlet gas temperature increases the removal efficiency decreases. The reason is the increasing heat transfer between the gas and drops which occurs due to higher driving force for the heat transfer and faster reduction of gas velocity in venturi throat. Referring to the figure, one can clearly say the presence of a gas cooling tower located before the venturi scrubber may have an effective role in improvement of the venturi performance. Even so, this reality is possible in most industrial applications of venturi scrubbers.

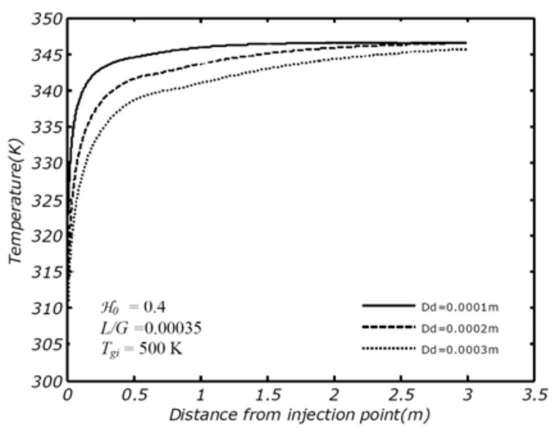

Figure 10. Variations of droplet temperature along the venturi length for different values of droplet diameter

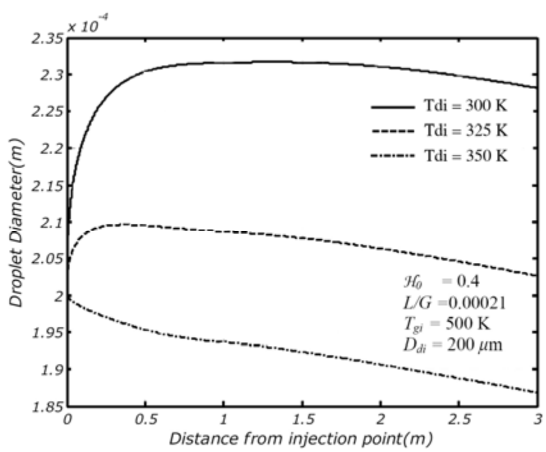

Figure 11. Variations of droplet diameter along the venturi length for different values of droplet temperature

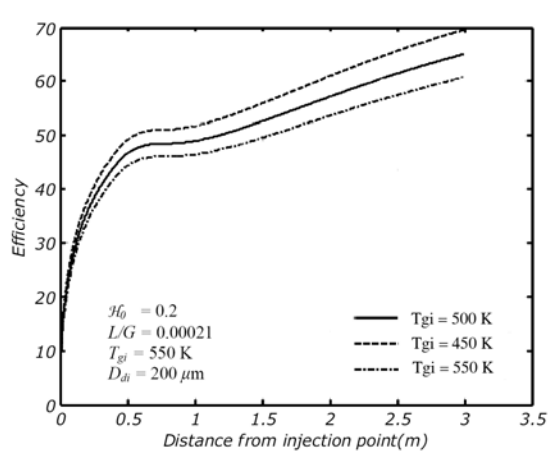

Figure 12. Variation of removal efficiency along the venturi length for different values of inlet gas temperature

4. Conclusion

Developing a comprehensive one-dimensional model, the effects of the simultaneous heat and mass transfer phenomena are analyzed on the performance of venturi scrubbers. The effects of various operating parameters are studied on the intensity of the mentioned phenomena in detail. The results show that neglecting the undeniable effects of droplet growth or condensation and reduction of their velocity as the result of convective heat transfer may lead to large errors in predicting the removal efficiency. Furthermore, according to the obtained results, introducing a cooling tower before the venturi scrubber in order to decrease the gas temperature may decrease the undesirable effects of the heat and mass transfers on the removal efficiency.

Nomenclature

A	Cross-sectional flow area, (m^2)
C_D	Drag coefficient, (dimensional)
C_p	Particulate concentration

C_{pg}	Heat capacity of gas, (J/Kg.K)
C_{pv}	Heat capacity of vapor, (J/Kg.K)
D_d	Diameter of droplet, (m)
D_{sd}	Drop initial droplet, (m)
G	Volumetric flow rate of gas, (m^3/s)
H	Half of venturi length, (m)
h	Convective heat transfer coefficient, (W/m^2.K)
K_j, K_y	Convective mass transfer coefficient, (Kmole/N.s)
L	Volumetric flow rate of liquid, (m^3/s)
M_v	Molecular weight of vapor, (kg/kgmole)
$\dot{m}_g$	Mass flow rate of gas, (kg/s)
$\dot{m}_d$	Mass flow rate of droplets, (kg/s)
P_b	Partial pressure of water vapor in the gas bulk, (Pa)
P^{sat}	Partial pressure at the drop surface,(Pa)
Re	Reynolds number, (dimensional)
t	Time, (sec)
T_d	Droplet temperature, (K)
T_g	Gas temperature, (K)
V_g	Gas velocity, (m/s)
V_d	Droplet velocity, (m/s)
V_r	Relative velocity (m/s)
W	Width of venturi, (m)
x	Distance measured along x-axis, (m)
ρ_l	Liquid density, (kg/m^3)
ρ_g	Gas density, (kg/m^3)
μ_g	Gas viscosity, (kg/m.s)
μ_l	Liquid velocity, (kg/m.s)
λ	Heat of vaporization, (J/kg)
η	Efficiency

References

[1] Rahimi, A., "Simulation of air pollutants removal in a non-isothermal Venturi scrubber", Ph.D. Thesis, Chemical Engineering Department, University of Shiraz, Shiraz, Iran,(2002).

[2] Taheri, M., and Sheih, Ch., "Mathematical modeling of atomizing scrubber", AIChE. J., 21-153 (1975).

[3] Boll, R. H., "Particle collection and pressure drop in Venturi scrubbers", Ind. Eng. Chem. Fundam. 12-40, (1973).

[4] Calvert, S., "Venturi and other atomization scrubbers", AIChE J., 16-392-396,(1970).

[5] Viswanathan, S., Gnyp, W. A., St. Plerre, C. "Examination of gas liquid in a Venturi scrubber", Ind. Eng. Chem. Fundam. *23*, 303-308, **(**1984).

[6] Viswanathan, S., "Modeling of Venturi scrubber performance", Industrial and Engineering Chemistry Research., 36.

[7] Calvert, S., Lundgern, D., Mehta, D., "Venturi scrubber performance", J. Air Pollut. Control Assoc., 22- 529, (1972).

[8] Ranz, W.E., Marshall, W.R., "Evaporation from drops", J. Chem. Eng. Prog. *48*, 141-173.(1952).

[9] Downing, C. G. "The evaporation of drops of pure liquids at elevated temperature", AIChE. J. *12*,760-766, (1966).

[10] Boll, R. H., Flais, L. R., Maurer, P. W., Thompson, W. L, "Mean drop size in a full size venturi scrubber via transmissometer", J. Air. Pollution Control Association**,** 24, 934-938.

[11] Fathikalajahi, J., Taheri, M., Talaie, M. R., "Theoretical study of non-uniform droplet concentration distribution on venturi scrubber performance", Part. Sci. Tech**.**. 14-153,(1996).