# Mathematical Modelling of Venturi Scrubber for Ammonia Absorption

S.Mousavian, D.Ashouri, M.abdolahi, M.H.Vakili and Y.Rahnama

*Abstract*—In this study, the dispersed model is used to predict gas phase concentration, liquid drop concentration. The venturi scrubber efficiency is calculated by gas phase concentration. The modified model has been validated with available experimental data of Johnstone, Field and Tasler for a range of throat gas velocities, liquid to gas ratios and particle diameters and is used to study the effect of some design parameters on collection efficiency.

*Keywords*—Ammonia, Modelling, Purge gas, Removal efficiency, Venturi scrubber

## I. INTRODUCTION

SEVERAL options are available for the control of particulate matter from flue gases such as cyclones, settling chambers, fabric filters, electrostatic precipitators, and various types of wet scrubbers. Amongst the wet scrubbers, the venturi scrubber is unique in that it is not only very efficient for the collection of particulates but can also function as a gas absorber.

The venturi scrubber is a special design of venturi-based absorbers. The main characteristic is the liquid injection mechanism, based on a mechanical atomization system. In this study, a pressure-swirl atomizer was used. The principle of operation involves a jet effect created by the water (or aqueous solution) spray nozzle. This spray nozzle is located on the top of the jet scrubber and creates a full cone-shaped spray. This is a relatively narrow-angle spray, which contacts the wall of the jet scrubber at a point above the throat. The result is an induced airflow through the scrubber. The gas and liquid enter the throat, where extreme turbulence is encountered, and continue through the diffuser section where partial separation of the gas and liquid occurs. The concurrent nature of this scrubber requires a separation device to be used to separate the gas completely from the liquid. Mechanical devices such as blowers are used when high gas flow rates are desired.

The scrubbing mechanism includes the cross-flow effect of the air being entrained through the spray plus the turbulence, which occurs at the throat area.

While the efficiency of venturi scrubbers for the removal of particulate matter has been extensively studied, only a few papers on gas pollutants absorption have been reported. Johnstone et al. [1] found that efficiencies for SO2 removal by alkaline solutions in venturi scrubbers were proportional to the specific surface area of the droplets; they also found that the gas mass transfer coefficient increased substantially as the liquid injection rate increased. In the Russian literature,

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several papers related to venturi scrubbers can be found, most of them theoretical approaches (Kuznetsov and Oratovskii [2], Boyadzhiev [3], Elenkov and Boyadzhiev [4] and Volgin et al. [5]). The first paper related to complete venturi scrubber modelling was published by Uchida and Wen [6]. These authors performed mass, heat and momentum balances for SO2 removal in an industrial scale venturi scrubber pilot plant. For mass transfer, they developed material balances in the droplet without chemical reaction. They solved the equation analytically and obtained the rate of physical absorption. Chemical reaction was applied as an enhancement factor derived from film theory.

## II. MATHEMATICAL MODELLING

A generalized expression for the efficiency of a venturi scrubber can be developed through a material balance on a differential volume element in the venturi scrubber and is given by:

$$\eta_{rem_g} = \frac{C_{g_0} - C_{g_f}}{C_{g_0}}$$

Where $C_{g_0}$ and $C_{g_f}$ are gas concentration at entrance and end of venturi scrubber. In order to apply this generalized relationship it is necessary to develop expressions for the gas concentration as a function of contactor geometry and for the droplet velocity as a function of axial position and liquid drop concentration.

### A. Liquid drop concentration

The dispersed model of Fathikalajahi et al[7] is used to predict liquid drop concentration profile. Figure 1 shows control volume of the model. Material balance for liquid drops in the control volume gives the following equation

$$\Delta y \, \Delta z \left[ \left( V_{d_x} C_d - E_d \frac{\partial C_d}{\partial x} \right)\bigg|_{x+\Delta x} - \left( V_{d_x} C_d - E_d \frac{\partial C_d}{\partial x} \right)\bigg|_x \right]$$

$$+ \Delta x \, \Delta z \left[ \left( V_{d_y} C_d - E_d \frac{\partial C_d}{\partial y} \right)\bigg|_{y+\Delta y} - \left( V_{d_y} C_d - E_d \frac{\partial C_d}{\partial y} \right)\bigg|_y \right]$$

$$+ \Delta y \, \Delta x \left[ \left( V_{d_z} C_d - E_d \frac{\partial C_d}{\partial z} \right)\bigg|_{z+\Delta z} - \left( V_{d_z} C_d - E_d \frac{\partial C_d}{\partial z} \right)\bigg|_z \right]$$
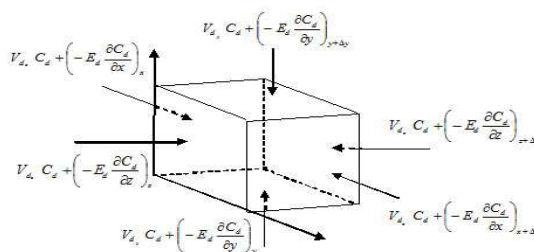
$$+ S \, \Delta x \, \Delta y \, \Delta z = 0$$



Fig. 1 Control volume for dispersed model

In order to cut off size of control volume, the pervious equation is divided by volume of control volume and gives:

$$\frac{\partial(V_{d_x} C_d)}{\partial x} + \frac{\partial(V_{d_y} C_d)}{\partial y} + \frac{\partial(V_{d_z} C_d)}{\partial z} =$$

$$\frac{\partial\left(E_d \frac{\partial C_d}{\partial x}\right)}{\partial x} + \frac{\partial\left(E_d \frac{\partial C_d}{\partial y}\right)}{\partial y} + \frac{\partial\left(E_d \frac{\partial C_d}{\partial z}\right)}{\partial z} + S$$

By neglecting liquid drop velocity in y and z coordinate, this model is reduced to one dimensional model

$$\frac{\partial(V_{d_x} C_d)}{\partial x} = E_d\left(\frac{\partial^2 C_d}{\partial y^2} + \frac{\partial^2 C_d}{\partial z^2}\right) + S$$

The following boundary condition should be used to solve this model

$$At \quad x = 0, \quad V_d C_d = 0$$

$$At \quad y = 0, y = H \qquad \frac{\partial C_d}{\partial y} = 0$$

$$At \quad z = 0, z = W \qquad \frac{\partial C_d}{\partial z} = 0$$

Dimensionless form of the model and it's boundary conditions is shown by the following equation

$$\left(\frac{N_{Pe} L}{D_H}\right)\frac{\partial(U_d f)}{\partial x} = \frac{E_d}{E_g}\left(\frac{L^2}{H^2}\frac{\partial^2 f}{\partial y^2} + \frac{L^2}{W^2}\frac{\partial^2 f}{\partial z^2}\right) + \frac{U_d S L\left(\frac{N_{pe} L}{D_H}\right)}{\left(\frac{L_0}{A}\frac{\pi}{6}D_d^3\right)}$$

$$At \quad x = 0, \quad f = 0$$

$$At \quad y = 0, y = 1 \qquad \frac{\partial f}{\partial y} = 0$$

$$At \quad z = 0, z = 1 \qquad \frac{\partial f}{\partial z} = 0$$

The diffusion length $(h)$ is calculated by Viswanathan equation

$$h = 0.1145 \frac{V_j \rho_j}{V_g \rho_g}\left(\frac{P_j}{P_\infty}\right)^{1/2}$$

### B. Velocity of drop liquid

Velocity of drop liquid can be obtained by writing force balance on moving drop liquid

$$\rho_L\left(\frac{\pi D_d^3}{6}\right)\frac{dV_d}{dt} = C_{Df}\frac{\pi D_d^2}{4}\frac{\rho_g}{2}(V_g - V_d)^2 + \rho_L\left(\frac{\pi D_d^3}{6}\right)g$$

$dt$ can be replaced by $\frac{dx}{V_d}$ and the previous equation can be written

$$\frac{dV_d}{dx} = \frac{3}{4}\frac{C_{Df}}{D_d}\frac{\rho_g}{\rho_L}\frac{(V_g - V_d)^2}{V_d} + \frac{g}{V_d}$$

The boundary condition of this equation is

$$At \quad x = 0, \quad V_d = 0$$

### C. Gas phase concentration

The dispersed model is used to predict liquid drop concentration profile.

$$\Delta y \Delta z\left[\left(V_{g_x} C_d - E_g \frac{\partial C_g}{\partial x}\right)_{x+\Delta x} - \left(V_{g_x} C_d - E_g \frac{\partial C_g}{\partial x}\right)_x\right]$$

$$+\Delta x \Delta z\left[\left(V_{g_y} C_d - E_g \frac{\partial C_g}{\partial y}\right)_{y+\Delta y} - \left(V_{g_y} C_d - E_g \frac{\partial C_g}{\partial y}\right)_y\right]$$

$$+\Delta x \Delta y\left[\left(V_{g_z} C_d - E_g \frac{\partial C_g}{\partial z}\right)_{z+\Delta z} - \left(V_{g_z} C_d - E_g \frac{\partial C_g}{\partial z}\right)_z\right] + N_A \pi D_d^2 C_d \Delta x \Delta y \Delta z = 0$$

In order to cut off size of control volume, the pervious equation is divided by volume of control volume and gives:

$$\frac{\partial(V_{g_x} C_g)}{\partial x} + \frac{\partial(V_{g_y} C_g)}{\partial y} + \frac{\partial(V_{g_z} C_g)}{\partial z} =$$

$$\frac{\partial\left(E_g \frac{\partial C_g}{\partial x}\right)}{\partial x} + \frac{\partial\left(E_g \frac{\partial C_g}{\partial y}\right)}{\partial y} + \frac{\partial\left(E_g \frac{\partial C_g}{\partial z}\right)}{\partial z} + N_A \pi D_d^2 C_d$$

By neglecting gas velocity in y and z coordinate, this model is reduced to one dimensional model

$$\frac{\partial(V_{g_x} C_g)}{\partial x} = E_g\left(\frac{\partial^2 C_g}{\partial y^2} + \frac{\partial^2 C_g}{\partial z^2}\right) - N_A \pi D_d^2 C_d$$

Rate of mass transfer can be liquid phase controlled or gas phase controlled and is calculated by the following equation

$$N_A = K_g\left(C_g - C_{g_s}\right)$$

$C_{g_s}$ is gas phase concentration that is in equilibrium with liquid

$$C_{g_s} = f_{eq}(C_L)$$

### D. Liquid phase concentration

Liquid phase concentration can be obtained by material balance on liquid in control volume

$$\left(\frac{\pi}{6}D_d^3\right)\Delta x \Delta z\left[\left(-E_d \frac{\partial C_d}{\partial y} C_L\right)_{y+\Delta y} - \left(-E_d \frac{\partial C_d}{\partial y} C_L\right)_y\right]$$

$$+\left(\frac{\pi}{6}D_d^3\right)\Delta x \Delta y\left[\left(-E_d \frac{\partial C_d}{\partial z} C_L\right)_{z+\Delta z} - \left(-E_d \frac{\partial C_d}{\partial z} C_L\right)_z\right] =$$

$$\left(\frac{\pi}{6}D_d^3\right)\Delta x \Delta z\left[(V_d C_d C_L)_{x+\Delta x} - (V_d C_d C_L)_x\right] - \pi D_d^2 C_d N_A$$

In order to cut off size of control volume, the pervious equation is divided by volume of control volume and gives:

$$\frac{\pi}{6}D_d^3\frac{\partial(V_d C_d C_L)}{\partial x} = \frac{\pi}{6}D_d^3\frac{\partial\left(E_d \frac{\partial C_d}{\partial y} C_L\right)}{\partial y}$$

$$+\frac{\pi}{6}D_d^3\frac{\partial\left(E_d \frac{\partial C_d}{\partial z} C_L\right)}{\partial z} + \pi D_d^2 C_d N_A$$

By neglecting liquid drop velocity in y and z coordinate, this model is reduced to one dimensional model

$$\frac{\pi}{6}D_d^3\frac{\partial(V_d C_d C_L)}{\partial x} = \pi D_d^2 C_d N_A$$

### III. RESULTS AND DISCUSSIONS

Governing equations in the previous section were solved using the fourth-order Runge–Kutta method.

### A. Model validation

Experimental data of Johnstone, Field and Tasler[1] is used to compare with result of model. In this model $SO_2$ absorbed from gas phase by $NaOH$ solution that concentration is 0.6N. Figure 2 and 3 show the cumulative mass transfer along the venturi scrubber.
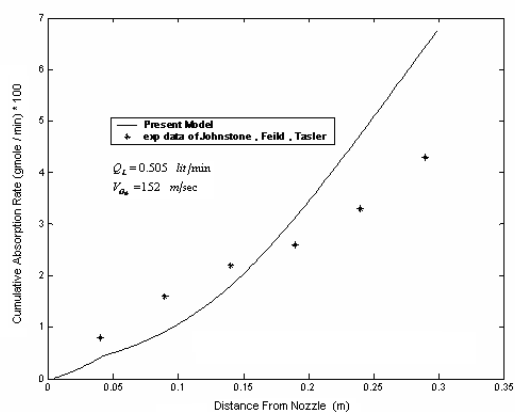
Fig. 2 Cumulative absorption of $So_2$ along the venturi scrubber
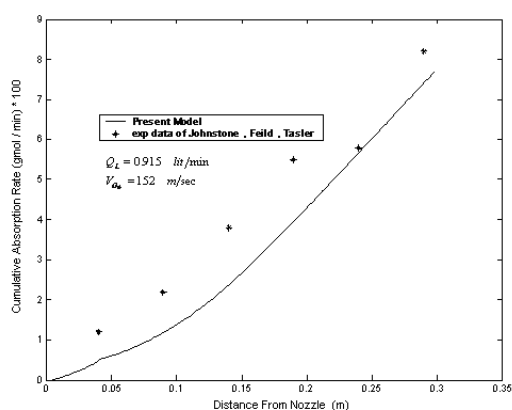


Fig. 3 Cumulative absorption of $So_2$ along the venturi scrubber

These figure show that this combined mathematical modelling have good agreement with experimental data.

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