Asian Journal of Water, Environment and Pollution, Vol. 6, No. 2, pp. 7-13.

Performance of A Venturi Scrubbers in Intermediate Drop Reynolds Number Regime for Small Particles at Different Throat Length and Throat Gas Velocity

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Received November 8, 2007; revised and accepted September 30, 2008

Abstract: Venturi scrubbers are devices where particle-laden gas (air) is cleaned of particles by capture on water drops. A high relative velocity at throat between drops and particles moving with gas enhances capture of particles. The present model estimates penetration (fraction of un-collected particles) of small particles (less than 3 mm) in intermediate drop Reynolds number ($1 < Re_D < 1000$). In this model of venturi scrubber where intermediate drop Reynolds number effects are accounted for show reasonably good agreement with available experimental data. Venturi scrubber is found to be effective in capture of such small particles at high throat gas velocities (80 m/s and higher).

Key words: Particle capture, penetration, venturi scrubber, wet scrubbing, inertial impaction.

Introduction

Suspended particulate matter in ambient air is recognized as an important environmental concern due to fatal effect on human bodies. Particulate matter in ambient air originates from a variety of sources, viz., industries, mining, and automobile emissions; their presence in the atmosphere, often in excess of permissible limits, causes adverse health effects and affects the performance of many machines and processes. There are two broad categories of scrubbing devices, viz. dry scrubbers and wet scrubbers. Venturi scrubbers are wet scrubbers that are widely used in mining and several process industries. It consists of a converging section, throat and a diverging section as shown in Figure 1. A very high gas velocity (up to 150 m/s) is generated at the throat where water is introduced just before the throat, either as a sheet of liquid (wet approach type) or atomized spray. A high relative velocity between drops and particles moving with gas enhances capture of all sizes.

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$$\eta = \frac{n_0 - n}{n_0} \tag{1}$$

The effectiveness of capture of particles in a device is measured in terms of penetration (P) defined as

$$P = \frac{n}{n_0} \tag{2}$$

The extent of capture on a single target (drop) is expressed as isolated single target efficiency defined as ratio of cross-sectional area for upstream of target from which particles are removed to the projected area of the

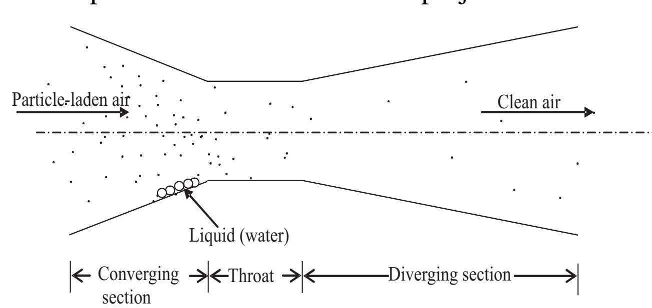

Figure 1: Schematic diagram of a venturi scrubber.

target normal to the direction of flow. Inertial impaction is the major capture mechanism for particles greater than 1 μm diameter.

For spherical and cylindrical targets, inertial impaction efficiency depends upon the Reynolds number and/or Stokes number.

$$\mathrm{Re}_\mathrm{D} = \frac{D V_\mathrm{r}}{\nu_\mathrm{f}} \tag{3}$$

$$St = \frac{C \rho_\mathrm{p} d^2 V_\mathrm{r}}{9 \mu_\mathrm{f} D} \tag{4}$$

Literature Review

Much research has been done to predict the pressure drop and collection efficiency of venturi scrubbers. Work on theoretical and experimental models are discussed in various literatures. Yung et al. (1978) obtained an analytical expression for penetration, for performance prediction of venturi scrubbers assuming one-dimensional motion of uniformly distributed drops and capture in the throat region by inertial impaction. Placek and Peters (1981) numerically solved the differential equations for particle concentration and pressure gradient and presented their collection efficiency data against a parameter L (St) $^{0.5}$. In another study, Placek and Peters (1982) analyzed the effect of heat and mass transfer from the drops on the capture efficiency of venturi scrubber by inertial, interception and diffusiophoresis capture mechanisms.

Crowder et al. (1982) used the drag correlation for decelerating motion of drops and non-zero initial velocity for liquid drops. Oliveira and Coury (1996) conducted experiments and developed a theoretical model adding terms to account for the diffusion effects on particle capture. They observed that the collection efficiency for particle size of 0.75 μm exhibits minima with increasing liquid flow rate.

Pulley (1997) developed a model for dust collection in the entire venturi length by inertial impaction and validated it against extensive experimental data of pressure drop and particle collection for wetted approach and throat injection type venturi scrubbers. Ananthanarayanan and Vishwanathan (1998) employed two-dimensional, steady state continuity equation for drop motion and transport of particulate matter, neglecting longitudinal diffusion. Azzopardi et al. (1991) and Gamisans et al. (2002) conducted studies on pressure drop in venturi scrubbers.

Modelling of Venturi Scrubbers

Most of the mathematical models of venturi scrubbers are based on many assumptions, notably potential flow about the drop, dilute particle and drop loadings, uniform homogeneous particle distribution, and rapid transverse mixing of un-captured particles. In the present work, assumption of potential flow about the drop is relaxed and its effect on penetration of small particles (less than 3 μm) through the venturi is investigated.

The assumption of potential flow about drops cannot be entirely justified. Flow about the drop can be said to be potential if drop Reynolds number is 1000 or higher

Nomenclature

- C Cunningham correction
- C_D drag coefficient
- D drop diameter (m)
- d diameter of particle (m)
- f ratio of actual drop drag coefficient and Stokesian drag coefficient
- G air flow rate (m^3/s)
- L volumetric liquid to gas flow rate (m^3/s)
- m mass of the particle (kg)
- n number of particles leaving the device
- n_0 number of particles entering the device
- P penetration
- Q_LG liquid to gas flow rate
- Re_D Reynolds number of drop
- St Stokes number
- V velocity (m/s)
- V_D absolute velocity of drop in the tower vertically downwards (m/s)
- V_{pj} terminal settling velocity (m/s)
- V_r drop velocity relative to gas (m/s)
- We_m modified Weber number

Greek Symbols

- η capture efficiency
- η_Tj single drop capture efficiency
- η_tp efficiency potential flow
- η_tv efficiency viscous flow
- ρ density (kg/m^3)
- σ surface tension of water (N/m)
- μ dynamic viscosity (N-s/m^2)
- ν kinematic viscosity (m^2/s)
- λ Taylor length scale (m)

Subscripts

- D drop
- f.g gas/fluid
- j 'j' grade
- l liquid
- o undisturbed/infinity
- p particle
- r relative
- T total
- v viscous
- x,y,z coordinate directions

(Michael and Norey, 1969; Pulley and Walters, 1990). In venturi scrubbers the drop size is of the order of 60 µm or less. Even for a relative velocity of 100 m/s at the start of throat section, drop Reynolds number as given by Eq. 3 is about 350. The drop Reynolds number decreases sharply as drops are accelerated along the flow direction. These drop Reynolds numbers lie between 1 and 1000, a range known as intermediate drop Reynolds numbers. The resulting flow regime about the drop has both potential and viscous effects. The viscous effects tend to reduce capture of particles. Thus, a realistic model of venturi scrubber should account for the combined effects of viscous and potential flow about the drop.

In a venturi scrubber water drops and particle-laden gas flow horizontally (co-current configuration). In typical simulation, the motion of drops through an elemental control volume is tracked during which they capture particles. Such an approach has been extensively applied to venturi scrubbers by Yung et al. (1978), Placek and Peters (1981 and 1982) and Pulley (1997). The particle conservation equation for an elemental volume of the venturi scrubber can be summarised as:

$$\begin{pmatrix}\text{Rate of particles}\\ \text{in flow}\end{pmatrix} - \begin{pmatrix}\text{Rate of particles}\\ \text{outflow}\end{pmatrix} + \begin{pmatrix}\text{Rate of accumulation}\\ \text{of particles in C.V.}\end{pmatrix} = \begin{pmatrix}\text{Rate of capture}\\ \text{of particles}\end{pmatrix}$$

The drop concentration per unit volume of gas is sufficiently dilute so that each drop is regarded as acting independently. Particles are modelled as rigid mono-disperse spheres and a particle that touches the drop is considered to be captured. Uncollected particles behind the drop are assumed to mix laterally to produce a uniform concentration that is then experienced by the next drop. The model described below is based on Licht (1988) for drops travelling at their terminal velocity in a counter-flow configuration. The same was then modified for venturi scrubber by Kumar (2002).

For particles of 'j' grade size, d_j, capture on a drop is the product of the number of particles present in its swept volume and the corresponding single drop capture efficiency. Estimating capture on a drop and accounting for the number of drops present in the section and simplifying with the assumption of no accumulation of particles in the control volume, the particle conservation equation becomes:

$$dn_{\rm j} = 1.5(Q_{\rm LG})\eta_{\rm Tj}\, n_{\rm j}(V_{\rm r} - V_{\rm pj})\frac{dz}{DV_{\rm D}} \tag{5}$$

where dn_j is change in number of particles, Eq. (5) represents change in particle concentration per unit gas flow or the capture of particles per unit area in the elemental volume. The total 'j' grade capture in the tower can be obtained by integrating Eq. (5):

$$\int dn_{\rm j} = \int 1.5\,(Q_{\rm LG})\, n_{\rm j}\,\eta_{\rm Tj}\left(V_{\rm r} - V_{\rm pj}\right)\frac{dz}{DV_{\rm D}} \tag{6}$$

Equation 6 has been used in the present formulation to estimate change (capture) of particles in venturi scrubber and penetration has been, then, calculated from Eq. 2.

Drop Velocity

The drop velocity and the distances travelled in a cross-flow gravity tower are determined by numerically solving the equation of two-dimensional motion of a drop through air. The two components of the equation of motion of the drop after simplification are given by:

$$\frac{dV_{\rm DX}}{dt} = \frac{C}{A}\left[C_{\rm D}(V_{\rm r})(V_{\rm fX} - V_{\rm DX})\,V_{\rm r}\right] \tag{7}$$

$$V_{\rm DX} = \frac{dX}{dt} \tag{8}$$

$$\frac{dV_{\rm DZ}}{dt} = \frac{1}{A}\left[-B + C\,C_{\rm D}(V_{\rm r})(V_{\rm fZ} - V_{\rm DZ})V_{\rm r}\right] \tag{9}$$

$$V_{\rm DZ} = \frac{dz}{dt} \tag{10}$$

where A, B and C are constants defined by:

$$\text{A} = 1 + 0.5(\rho_f/\rho_D) \tag{11a}$$

$$\text{B} = (1 - \rho_f/\rho_D)gd \tag{11b}$$

$$\text{C} = 3(\rho_f/\rho_D)/4\text{D} \tag{11c}$$

These equations are solved by fourth-order Runge-Kutta method to determine the velocity and position of the drop with time.

Drag (C_D - Re_D) Relation

In the present work drag relation given by Loth (2000) has been used

$$C_{\rm D} = \frac{24}{\text{Re}_{\rm D}} \qquad \text{Re}_{\rm D} << 1 \tag{12a}$$

For higher drop Reynolds number the relationship is of the form

$$C_{\rm D} = f\,\frac{24}{\text{Re}_{\rm D}} \tag{12b}$$

where f is the ratio of actual drop drag coefficient and Stokesian drag coefficient. For a solid sphere in incompressible quiescent flow, f is given by following relations.

$$f = 1 + \frac{3}{16}\mathrm{Re_D} \qquad \mathrm{Re_D} < 1 \qquad (12c)$$

$$f = 1 + 0.1935\mathrm{Re_D}^{0.6305} \qquad 1 < \mathrm{Re_D} < 285 \qquad (12d)$$

$$f = 1 + 0.15\mathrm{Re_D} + 0.2283\mathrm{Re_D}^{0.427} \qquad 285 < \mathrm{Re_D} < 2000 \qquad (12e)$$

Drop Size

The drop size was obtained by the relation used by Pulley (1997) for wetted approach type venturi scrubber:

$$D = 5.4\lambda\, We_{\mathrm{m}}^{-0.58} + \frac{3.5\lambda\, \rho_g\, L}{\rho_l\, G} \qquad (13)$$

Taylor length scale and modified Weber number are defined as follows:

$$\lambda = \sqrt{\frac{\sigma}{\rho_l g}} \qquad (14)$$

$$We_{\mathrm{m}} = \frac{\lambda\, \rho_l\, v_f^{\,2}}{\sigma} \qquad (15)$$

Modelling for Intermediate Drop Reynolds Number Effects

All the correlations for single isolated drop capture efficiency given in literature are valid for either potential or viscous flow about the drop. Thus, they do not account for the transition effect in the intermediate drop Reynolds number range. Langmuir (1948) proposed an interpolation relation to account for transition from viscous to potential flow. This interpolation formula is based on the assumption that at drop Reynolds number 60, the inertial impaction efficiency of an isolated drop is the arithmetic mean of the efficiencies in potential and viscous flows:

$$\eta_{\mathrm{Tj}} = \frac{\eta_{\mathrm{tv}} + \eta_{\mathrm{tp}}(\mathrm{Re_D}/60)}{(1 + \mathrm{Re_D}/60)} \qquad (16)$$

The inertial impaction efficiencies for viscous and potential flow respectively are calculated from the following relations proposed by Langmuir (1948).

$$\eta_{\mathrm{tp}} = \left[\frac{St}{St + 0.5}\right]^2 \qquad (17)$$

$$\eta_{\mathrm{tv}} = \left[1 + \frac{0.75\ln(2St)}{St - 1.214}\right]^{-2} \qquad (18)$$

Thus, the single drop capture efficiency in intermediate drop Reynolds number range is a function of Stokes and drop Reynolds numbers.

Results and Discussions

The model developed in the present work was used to simulate capture in a venturi scrubber and penetration values were calculated for particles of size in the range of 0.5 to 3.0 μm for the geometry used by Rudnick et al. (1986).

Figure 2 presents the model predictions and experimental results for a venturi of 0.051 m throat length and velocity at throat is 50 m/s; the liquid to gas ratio is 1.36 L/m^3. In this case, the present model predictions and the experimental values exhibit same trend for penetration for the entire range of particle size. The difference in the values is also small and does not exceed 10% even for smallest particle size of 0.5 μm. On the contrary, there is significant variation in model results of Boll (1973) and the experimental results of Rudnick et al. (1986). The present model exhibits better agreement with the experimental data for smaller particles in comparison to those from Pulley (1997) and Yung et al. (1978).

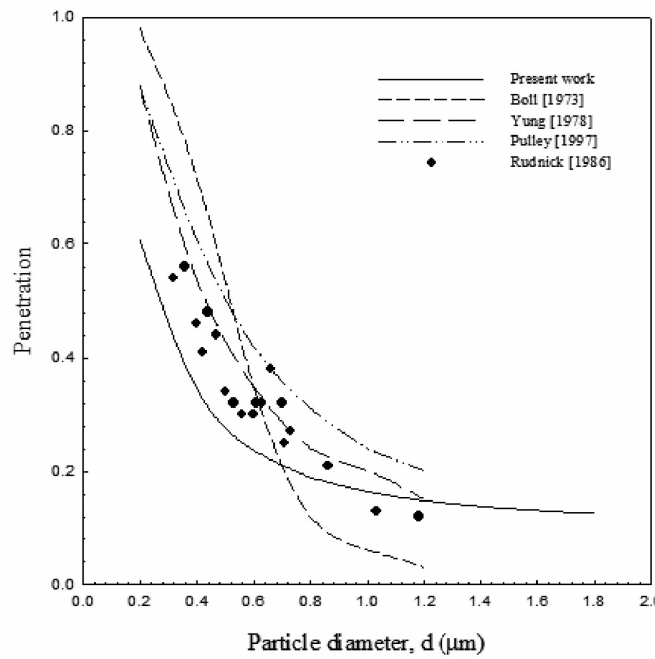

Figure 2: Variation of penetration with particle size in a medium venturi scrubber (Q_{LG} = 1.36 L/m^3, V_t = 50 m/s, TL = 0.051 m).

A similar trend is observed for the results for a smaller throat length of 0.032 m with higher throat velocity of 60 m/s (Figure 3). At such high gas velocity, higher capture efficiency and lower penetration is obtained. Thus, we observe that even for particles of 1 μm size, penetration is only about 20%. The model results from

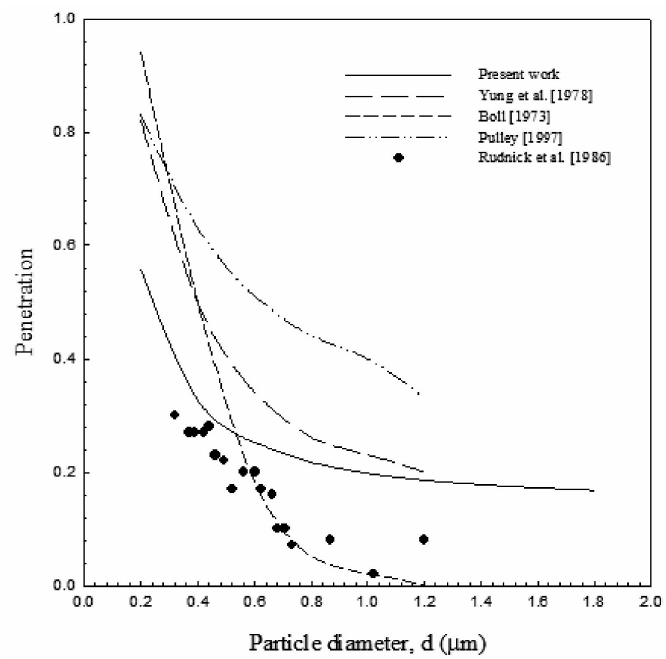

Figure 3: Variation of penetration with particle size in a small venturi scrubber (Q_{LG} = 1.25 L/m^3, V_t = 60 m/s, TL = 0.032 m).

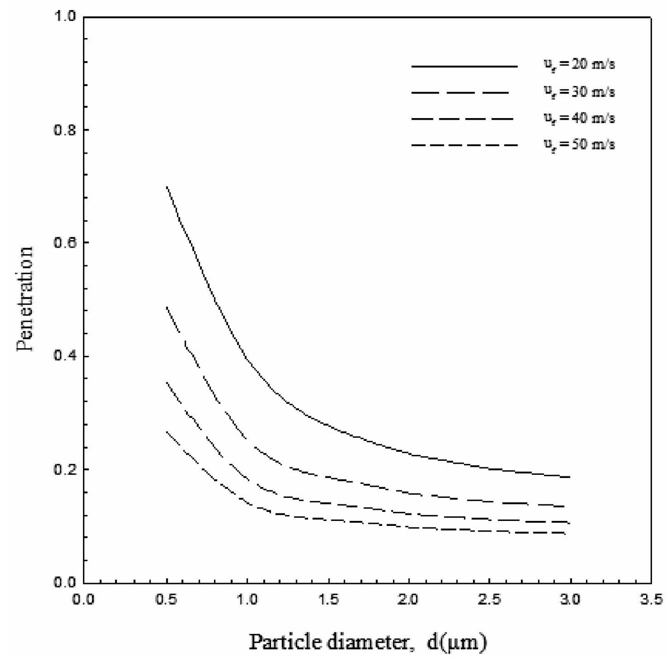

Figure 4: Variation of penetration with particle size at moderate throat velocity in venturi scrubber (Q_{LG} = 1.36 L/m^3, TL = 0.076 m).

present work match the experimental results satisfactorily. The present model shows better agreement with experimental data in comparison to those of Yung et al. (1978) and Pulley (1997) for the entire range of particle diameter.

Figure 4 depicts the effect of low to moderate air velocity at throat on penetration. The throat length under consideration is 0.076 m and liquid-to-gas flow rate ratio is 1.36 L/m^3. It is observed that penetration value decreases for particles of all sizes as the throat velocity is increased. Penetration for 0.5 μm particles is about 0.7 for throat velocity of 20 m/s that decreases progressively with increasing velocity to about 0.27 at 50 m/s. However, for larger particles (3 μm), corresponding decrease in penetration is from about 0.19 to 0.08.

When high throat gas velocity is employed, penetration of even small particles decreases significantly (Figure 5). It can be seen that when gas velocity is 100 m/s, penetration for smallest size particles is about 0.1, i.e., particle capture efficiency improves dramatically with throat gas velocity. At such velocities, particles of 2-3 mm size are entirely removed from air, as can be seen from very low values of penetration (about 0.05).

Such significant change in penetration with increasing throat gas velocity is due to large relative velocity between particles travelling with gas and water drops in

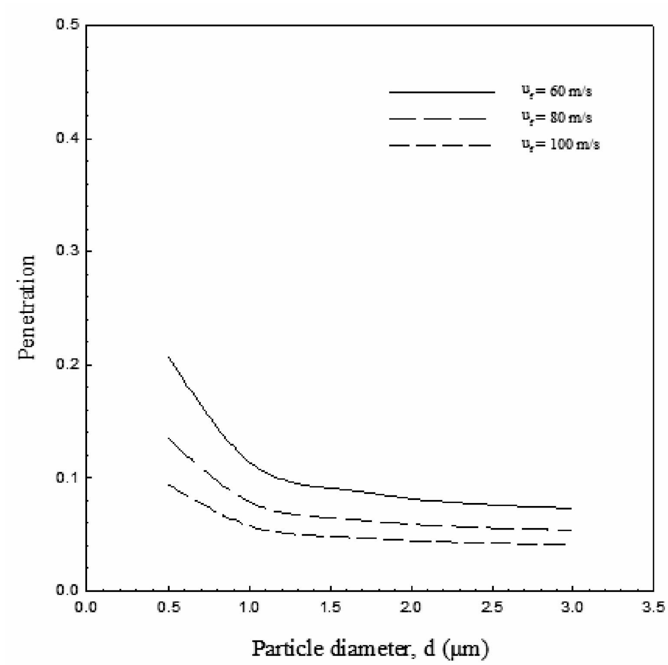

Figure 5: Variation of penetration with particle size at high throat gas velocity in venturi scrubber (Q_{LG} = 1.36 L/m^3, TL = 0.076 m).

the throat region. A large relative velocity results in greater Stokes number (Eq. 4) and isolated single target capture efficiency. Moreover, drop Reynolds number values are also high, reducing the viscous effects that

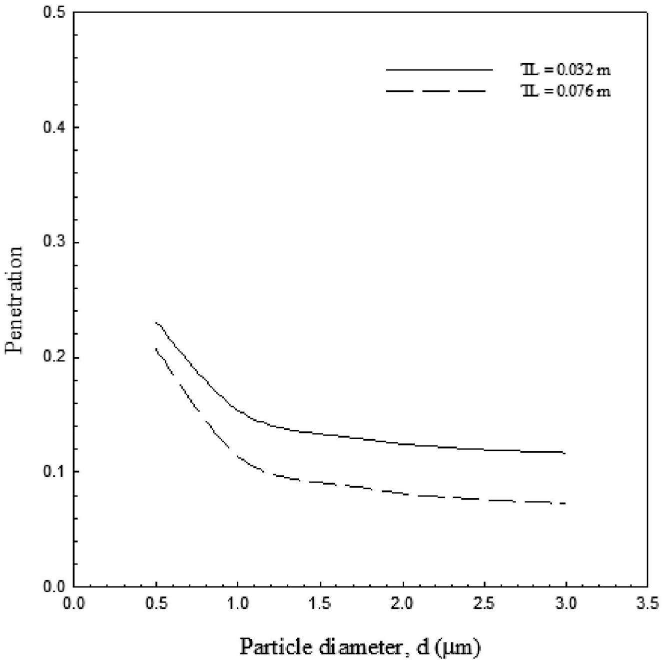

Figure 6: Variation of penetration with particle size at different throat length (Q_{LG} = 1.36 L/m^3, V_t = 60 m/s).

adversely affects the capture process increasing penetration. At high throat velocity drop size given by Eq. 13 is small and for same liquid-to-gas flow rate ratio, the number of drops increases in the cross-section; this reduces penetration. Such trends were also observed by Placek and Peters (1981) who found that throat velocity improves capture and is one of the most important operating parameter in venturi scrubbers.

Figure 6 shows the effect of throat length on penetration of particles through venturi scrubber. Two throat lengths of 0.032 and 0.076 m are considered for comparison. The throat gas velocity is 60 m/s for both throat lengths. Increase in throat length from 0.032 to 0.076 (more than 100%) does not reflect in a very significant decrease in particle penetration. The decrease in penetration is about 4-6% for the entire range of particle sizes. This signifies that capture of particles takes place mainly at initial section of throat length. The drops that start from rest at throat are dragged by the high speed gas, and at a short distance the drop and gas travel at nearly the same velocity reducing the relative velocity to a very low value. As this condition is reached, very limited additional capture does take place.

Conclusions

Venturi scrubbers are found to be quite effective in capturing of small particles, especially when throat gas velocity is high. The present model of venturi scrubber where intermediate drop Reynolds number effects are accounted for shows reasonably good agreement with available literature and experimental data. The gas velocity at throat is an important parameter affecting penetration of particles, penetration of particles decreases sharply with increasing gas velocity. At a throat velocity of 100 m/s, penetration for 0.5 µm particles is about 0.1. This signifies a high degree of particle capture in venturi. However, increasing throat length does not improve effectiveness of particle capture significantly.

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Asian Journal of Water, Environment and Pollution

Volume 5 Number 3 **July – September, 2008**

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