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Simulation Study on Liquid Droplet Size Measurement inside Venturi Scrubber

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ABSTRACT

Droplet distribution is an importance factor to observe scrubber's performance as uniform droplets distribution improved the particle's collection efficiency at minimal liquid usage. Yet, the optimization problem typically involves complicated model functions to predict particle's collection efficiency and pressure drop. Since the interaction between liquid droplets and gas phase is complex and difficult to solve by an experimental approach. Thus in this study, the prediction of liquid droplet's behavior in the venturi scrubber was observed by using computational fluid dynamic. The liquid was injected through two orifices on the throat wall. The droplet size at different position was observed at various range of a gas velocity from 70 to 100 m/s and the ratio of liquid to gas of 0.07 to 2.0 L/m^3 to determine the optimum absorption rate. The droplet's breakup in the venturi scrubber was observed using ANSYS© simulation where two-fluid model Eulerian-Eulerian approach was applied. It shows as the gas passes through the throat section, the velocity increases gradually and as it passes through the divergent section, it decreases causing the droplet diameter to increase. Typically, the gas velocity in the throat section is between 30-120 m/s, however in this simulation, the gas velocity of 70-105 m/s shown an adequate to achieve the optimum absorption rate. Besides, the liquid to gas ratio less than 0.06 was insufficient to cover the throat, and by increasing it up to 1.0 does not significantly improve the particle collection efficiency as the velocity at the scrubber's throat drops which a larger droplets diameter was formed.

Keywords: Droplet distribution; venturi scrubber; ANSYS© CFX; phase separation; gas velocity

INTRODUCTION

Micron-sized dust particles are known to have a fatal effect on human bodies, especially the heart and lungs. These fine particles are mainly generated from the internal combustion engines of cars or other motor vehicles, fuel burned at stationary sources for example power-generating plants, and numerous industrial processes. A lot of venturi scrubbers have been used in the industrial plants since 1940s, to remove the harmful particles and dust in the range of 0.5~10 µm (Green Fact, 2001). Thus, the venturi scrubber has been widely used in the industry as a gas cleaning devices to control pollution emissions, due to high collection efficiency, simple structure, low cost and implementation (Ahmad and Talaie, 2010).

In a venturi scrubber, the droplet distribution is an importance factor to observe the performance of a scrubber where a uniform droplets distribution can improve the particle's collection efficiency at a minimal liquid usage. Yet, the optimization problem typically involves the complicated model functions, both operating and design parameters like gas velocity, liquid to gas ratio, throat's length, nozzle's diameter and throat aspect ratio (ratio of depth to width) in order to predict the particle's collection efficiency and pressure drop (Pulley, 1997, Viswanathan, 1998, Mussatti, 2002 & Ravi et al., 2003). Since the interaction between the liquid droplets and gas phase is a complex problem and difficult to solve by experimental approach (Fernández et al., 2001), thus the prediction of a multiphase dynamic behavior in the industrial equipment with a computational fluid dynamics (CFD) has gain more attention (Guerra et al. 2012, Sharifi et al. 2013 & Othman et al. 2018). Therefore, in this study, a *Pease-Anthony* type of venturi scrubber was developed using ANSYS© software in order to observe a liquid droplet's behavior and to determine the optimum absorption rate. Also, to ensure the CFD analysis is acceptable, this numerical simulation need to be verified with the experimental data in order to evaluate their feasibility.

MATHEMATICAL MODELLING

The equations of solid and gas phases are developed based on the Eulerian-Eulerian model, using averaging approach (Argyropoulos et al. 2015). The system of governing equations used in this simulation is summarized as below.

Conservation of mass,

$$\frac{\delta}{\delta t}(\alpha_q \rho_g) + \nabla.(\alpha_q \rho_q \overrightarrow{v_q}) = \sum_{p=0}^{n}(\dot{m}_{pq} - \dot{m}_{qp}) + S_q \tag{1}$$

Conservation of momentum,

$$\frac{\delta}{\delta t}(\varepsilon_s \rho_s) + \nabla.(\varepsilon_s \rho_s v_s) = 0 \tag{2}$$

i) For gas phase,

$$\frac{\delta}{\delta t}(\varepsilon_g \rho_g v_g) + \nabla.(\varepsilon_g \rho_g v_g v_g) = -\varepsilon_g \nabla p + \nabla \overline{\overline{\tau_g}} + \varepsilon_g \rho_g g + K_{gs}(\overrightarrow{v_g} - \overrightarrow{v_s}) \tag{3}$$

ii) For solid phase,

$$\frac{\delta}{\delta t}(\varepsilon_s \rho_s v_s) + \nabla.(\varepsilon_s \rho_s v_s v_s) = -\varepsilon_s \nabla p + \nabla p_s + \nabla \overline{\overline{\tau_s}} + \varepsilon_s \rho_s g + K_{sg}(\overrightarrow{v_g} - \overrightarrow{v_s}) \tag{4}$$

Continuity equation for solid phase,

$$\frac{\delta}{\delta t}(\varepsilon_s \rho_s) + \nabla.(\varepsilon_s \rho_s v_s) = 0 \tag{5}$$

Conservation of Energy

i) For gas phase,

$$\frac{\delta}{\delta t}(\varepsilon_g \rho_g h_g) + \nabla.(\varepsilon_g \rho_g v_g h_g) = -\varepsilon_g \frac{\delta p_g}{\delta t} + \overline{\overline{\tau_g}} : \nabla \overrightarrow{v_g} - \nabla \vec{q}_g + Q_{sg} + \dot{m}\Delta H_{vap} \tag{6}$$

ii) For solid phase,

$$\frac{\delta}{\delta t}(\varepsilon_s \rho_s h_s) + \nabla.(\varepsilon_s \rho_s u_s h_g) = -\varepsilon_s \frac{\delta p_s}{\delta t} + \overline{\overline{\tau_s}} : \nabla \vec{u}_s - \nabla \vec{q}_s + Q_{gs} - \dot{m}\Delta H_{vap} \tag{7}$$

The equations (1) to (7) were used to solve and predict the multiphase dynamic behavior in the venturi scrubber where v is a velocity, τ is a shear stress tensor, ρ is a density, p is a pressure, g is a gravity, v_q is a velocity for q phase, $\dot{m}_{pq}$ is a mass transfer from p to q phase, $\dot{m}_{qp}$ is a mass transfer from q to p phase, h is a heat transfer coefficient, q is a heat flux, Q is a heat transfer rate, H is a latent heat and K is a drag coefficient.

METHODOLOGY

Design Model and Specification

Generally, the *Pease-Anthony* type of the scrubber consists of three segments: convergent, throat and divergent section (Pulley, 1997 & Schick 1997). In the convergent section, the gas flow has been accelerated due to a reduction in a cross-section area, hence reducing a static pressure. Meanwhile, in the divergent section, the gas velocity has been reduced due to an increasing of the cross section area and the pressure regain occurred.

In this study, the design model of the venturi scrubber is based on studied by Ananthanarayanan et al., 1999. Table 1 shows the details dimension and geometry of the scrubber's model with the total length of the scrubber (convergent, throat and divergent section) is 198.2 mm with the diameter of inlet gas is 48.26 mm. The appropriate scrubber's type and suitable dimension was chosen by ensure the angle of converging and diverging can allow the gas to accelerate at its highest potential.

The *Space Claim* software was used to design the *Pease-Anthony* type of venturi scrubber and the particle distribution was observed by using CFD tool; ANSYS© 18.2 academic version (Ansys Inc., 2013). The 3D design of the venturi scrubber was developed using ANSYS© is shown in a Figure 1.

TABLE 1. Design specification of venturi scrubber

Specifications	Size
Diameter of orifice	2.108 mm
Diameter of throat	15.24 cm
Gas inlet diameter	48.26 cm
Gas outlet diameter	19.12 cm
Length of throat	26.7 cm
Length of convergent section	77.5 cm
Length of divergent section	94 cm
Converging section angle	30°
Diverging section angle	7°

Source: Ananthanarayanan, 1999

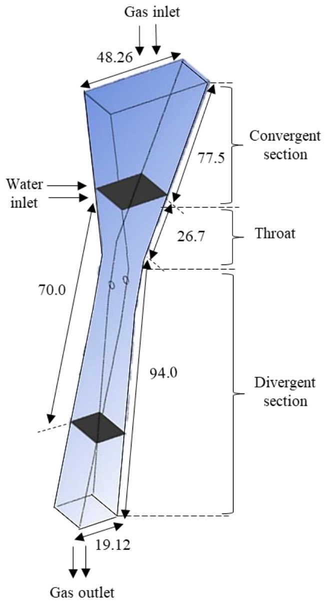

FIGURE 1. 3D design of venturi scrubber with dimensions and three segments; convergent, throat and divergent section.

Boundary Condition and Parameters

Once the scrubber’s model was developed, the meshing was generated by ANSYS© Mesh. The local meshing is performed at three points; inlet, outlet and the main body of scrubber. This is to ensure the developed mesh was refined enough at these positions before the global mesh is generated. The generated mesh has a good quality with the value of the skewness is 0.14939 and the value of the orthogonal is 0.98812 which is a good quality.

The boundary condition was defined as three parts which is the inlet air, water inlet and outlet. Table 2 shows the details parameter and ANSYS© Fluent setting for operating and boundary conditions specified in this simulation study. The scrubbing liquid used is water and the gas flows from the top of the scrubber whereas the liquid is injected using an orifice at the throat. The velocity and the ratio of liquid to gas (L/G) was manipulated as its plays a significant role for determining the liquid’s breakup of droplet size and the size distribution. In addition, a high gas velocity increases the droplet breakup; hence more surface area is obtained to absorb the dust particle.

TABLE 2. ANSYS© Fluent Setting

Input setting	Parameters in ANSYS©	
Physics	Multiphase, Species Transport	
Turbulent model	k-ε (Realizable)	
Iteration	100	
Phase type	Primary	Air
	Secondary	Water
Time based study	Transient	
Solver scheme	Phase-coupled SIMPLE	
Boundary conditions	Turbulent intensity	5 %
	Wall condition	No Slip
Operating conditions	L/G ratio	0.07-2.0 L/m^3
	Air velocity	70-100 ms^{-1}
Time step	600	

In this simulation, a Eulerian–Eulerian model was applied since it gives better opportunities to observe the phase interactions and phase separation. In the venturi scrubber, the gas is in a continuous and liquid water is a dispersed phase. The flow inside the scrubber was considered as an isothermal, turbulent, incompressible and steady-state. In order to calculate a drag coefficient, Schiller-Nauman model is used (Nukiyama, 1938 & Boll et al. 2012). To determine the effect of a droplet size in the scrubber, the inlet gas velocity was injected through the scrubber’s throat at 70 to 105 m/s and at the liquid to gas ratio of 0.07-2.0. These parameters were chosen as the air-blast atomization inside the scrubbers was depend on these two parameter and it produces a large distribution of droplet sizes.

As well, to determine the formation of droplet size, the Sauter mean diameter (D_{32}) is used where it is defined as the average ratio between the volume and the surface area of the droplets. This D_{32} is the most appropriate mean diameter to represent the droplet size distribution in the venturi scrubber. Two correlations have been frequently used to estimate the droplet size in the venturi scrubber; the classic correlation proposed by Nukiyama and Tanasawa (1938) and the correlation of Boll et al. (2012). The equation (8) was used to determine the mean diameter (Boll et al., 2012) where the term Q_l and Q_g are a liquid and a gas volumetric flow rate, respectively.

$$D_{32} = \frac{4.22 \times 10^{-2} + 5.77 \times 10^{-3} \left(\frac{1000\ Q_l}{Q_g} \right)^{1.932}}{v_r^{1.602}} \qquad (8)$$

RESULTS AND DISCUSSION

Effect of Liquid to Gas Ratio on Velocity Distribution

The ratio of the inlet liquid to the gas (L/G) on the velocity distribution in the scrubber’s throat plays an enormous role in order to determine the droplet breakup size. By changing the exact amount of a mass flow rate of the gas and liquid, the interaction and flow of the gas and liquid become more dynamic at the scrubber’s throat area. Figure 2 shows a 3D flow profile and a cross-sectional view of the velocity distribution at the scrubber’s throat at different ratio of L/G; 0.07-1.30. The color bar contour in the left side shows the water velocity where the red color in the velocity contour represent the highest velocity distribution with the value of 120 m/s, while the blue color represents the lowest velocity distribution with the value of nearly to zero.

By changing the L/G, the velocity distribution variation at a particular position which is at 14 cm below the throat area was observed. As the overall, the simulation result shows at the low ratio; L/G=0.07, the minimum velocity was indicated at the center area of scrubber’s throat with the value below than 60 m/s. however, its slightly increasing up as the L/G was increased where the velocity at near to the throat’s scrubber area is comparatively higher compare to the scrubber’s convergent and divergent section. It is occurred as the water was injected and sprayed through the nozzle, the interaction and collision between the gas-liquid molecules occurred in the scrubber that reduce the movement of the gas velocity. It shows the mixing process was occurred between the gas and water droplets.

At a high ratio; L/G=0.5-1.30, the maximum velocity distribution was observed. It shows as the ratio of L/G increases; the gas velocity also increases linearly until it reaches a maximum point; 120 m/s. It is due to the liquid-injection rate also affects the particle collection. The proper amount of liquid must be injected to provide adequate liquid coverage over the throat area and avoid for any evaporation losses. In the case where there is an insufficient liquid, then there will not be enough liquid targets to provide the required capture efficiency.

Typically, the gas velocity in the throat section was reported between 30-120 m/s, however, in this simulation a velocity ranges of 70-135 m/s has shown an adequate to achieve the optimum absorption rate. Besides, the L/G ratio less than 0.06 are usually not sufficient to cover the throat, and by increasing the L/G up to 1.0 does not significantly improve the particle's collection efficiency as the velocity at the scrubber's throat drops and will creating a larger droplets diameter.

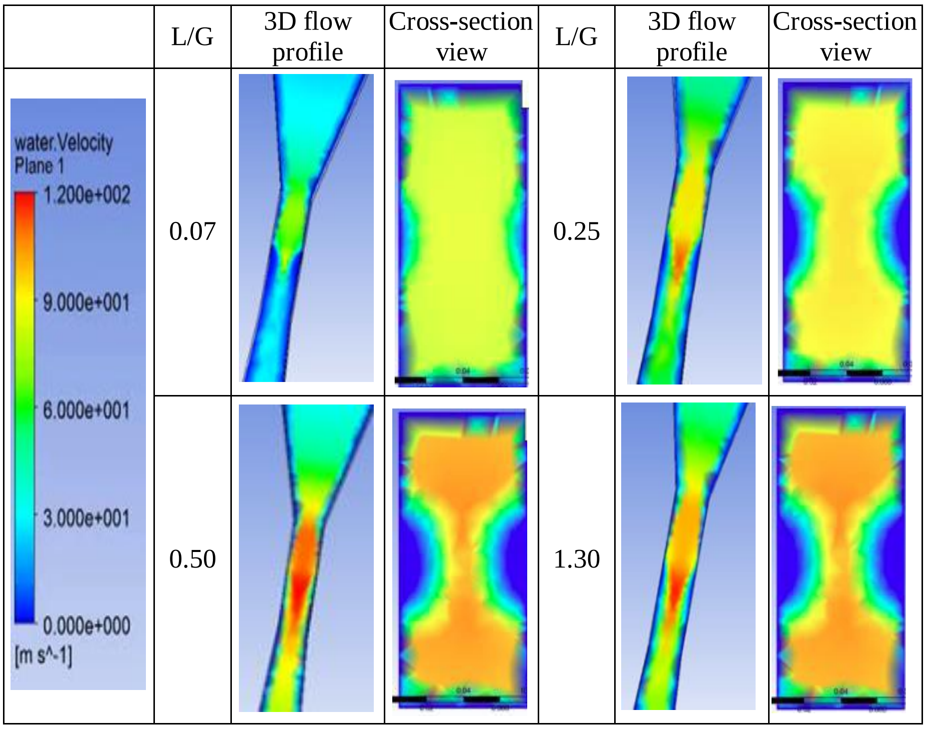

FIGURE 2. Velocity distribution and a cross-section view at the scrubber's throat at different ratio of liquid to the gas.

Mean Droplet Size in Venturi Scrubber

Figure 3 shows the effect of L/G on the velocity distribution and Sauter diameter of liquid droplets in the venturi scrubber. The Sauter diameter of droplets was calculated from the equation (8). As the ratio of L/G increases, both of the velocity and the droplet's diameter also increases. However, at the high L/G; L/G>1.0, the velocity distribution shows unsteady reduction as the liquid droplet doesn't have enough break up time for atomization process to happen within the gas. As a result, it will produce a smaller size droplet breakup. While, by increasing of the loading ratio, more droplets collide with each other and the Sauter mean diameter increases by the means of the coalescence. Besides, this result shows as a similar pattern trend on the velocity flow profile with the Boll correlation (Boll et al., 2012).

From the Figure 3, the ratio of L/G=0.8 was chose as the optimum condition to determine the droplet diameter as it shows the maximum value of the velocity distribution in the scrubber. As the gas passes into the throat section, the velocity increases gradually and the when the gas atomize with liquid it increases rapidly. Then, as it passes through the divergent section, it decreases causing the droplet diameter to decrease.

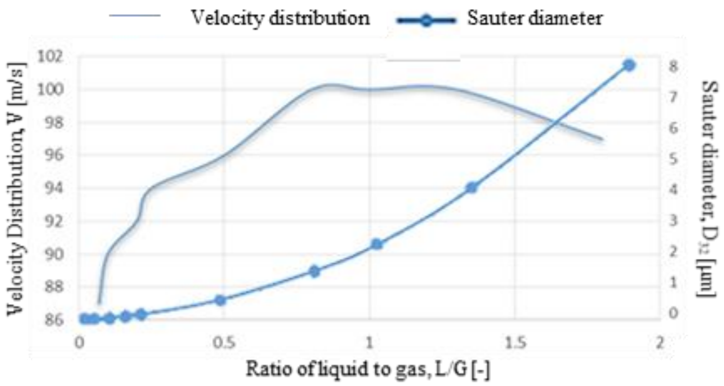

FIGURE 3. Effect of the ratio of liquid to gas (L/G) on the velocity distribution and Sauter diameter of droplets.

Cross-Section View of the Velocity Distribution at Different Distance in Venturi Scrubber

Venturi scrubber has an ability to absorb smaller particles which is less than 1 µm. To determine the diameter of the droplets in the scrubber at different velocities, eight different positions were observed at L/G=0.8. As show in the Figure 1, the position distance before the throat to the diagonal portion at the position of *x*=70 cm was observed to study the interaction between the gas phase and liquid in order to determine the liquid droplet size diameter along the venturi scrubber flow.

Figure 4 shows a cross-sectional plane view of the velocity distribution at the scrubber's throat area at different position; *x*=10-50 cm at the same L/G=0.8. The red color represents the highest velocity distribution with the value of 120 m/s while, the blue color represents the lowest velocity distribution with the value of nearly to zero. Before entering the throat area at position of *x*=10 cm, there is no interaction between the phase as there is no fluid orifice injection; only the gas flow exists. Thus, the yellow color contour only covers the observation area. However, the gas velocity increases due to the effect of the venturi design through the reducing of the cross-section area. But, there is no interaction between the gas phase and the liquid as well.

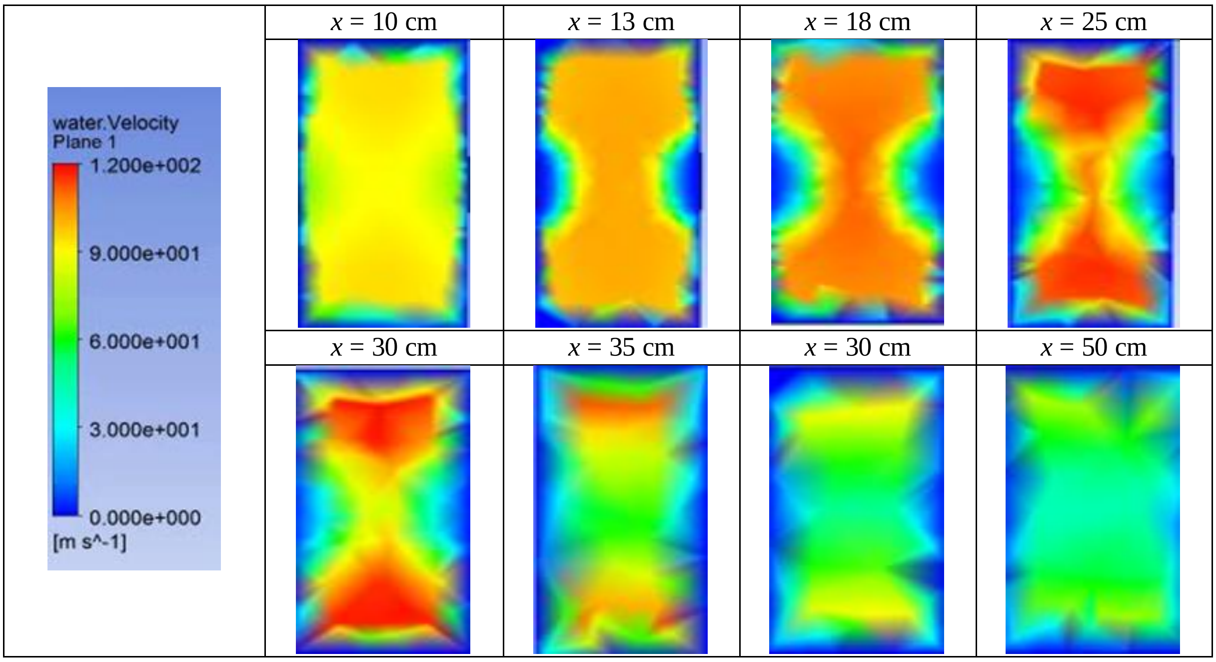
x = 10 cm
x = 13 cm
x = 18 cm
x = 25 cm
x = 30 cm
x = 35 cm
x = 30 cm
x = 50 cm

FIGURE 4. Cross-sectional plane view of the velocity distribution at the scrubber's throat area at different *x*-axis position; *x*=10-50 cm at L/G=0.8.

Once the water was injected through the orifice, the velocity increases in the throat section. With increasing of the time interval, the mixing process occurred where the velocity increases in the throat area as compared to the orifices at the initial position due to their interaction with the gas phase. As compared to the position of x=18 and x=25 cm, the red contours are more prominent at the position of x=25 cm. The orifice surface is closer to the position of x=18 than x=25cm, however the velocity at the position of x=25 cm is higher and increases in the interval time.

The velocity is increased as the water has been injected at the high concentrations at the scrubber's wall and after the injection, the distribution of fluid flux becomes more uniform to the downward divergence section due to the inertia momentum and the devastation of drops of agitation (Pak and Chang 2006). As it passing through the divergent section, the velocity is decreased. At the position of x=30 cm, it was observed that the red contour is decreased as it moves towards the divergent section. The diameter of the divergent area grows increasingly downward, causing the gas to slow down as the cross-sectional area increases. The green color contour was observed at x=60 cm, shown the lowest velocity distribution. This is occurred due to some of the kinetic energy from the liquid droplets shifts back to the gas stream, causing a partial recovery of the energy required to accelerate the gas velocity.

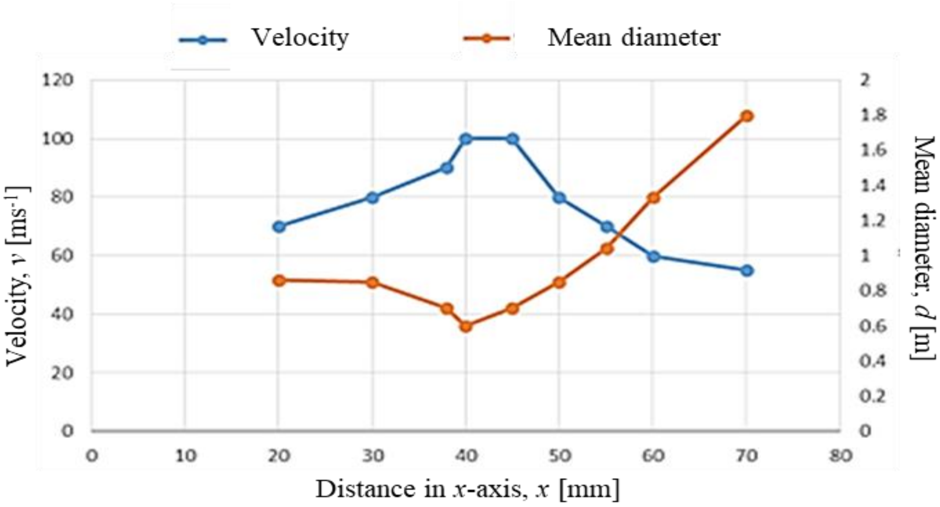

FIGURE 5. Effect of the distance on the velocity distribution and Sauter diameter of droplets.

Figure 5 shows the effect of the distance in the x-axis of the throat section area on the velocity distribution and Sauter diameter of droplets in the venturi scrubber. It was observed that the maximum velocity is achieved in the case of the orifice is placed on the converging section. The gas velocity is increased through the converging section area until it reaches the maximum value at the throat where the pressure is negative and at the end, the pressure is recovered as the velocity decreased through the diverging section.

In addition, higher velocity will accelerate the momentum of air carrying the droplets out of the scrubber. The higher velocity means more turbulent flow hence; an efficient droplet generation will take place. Movement along the distance in the venturi scrubber droplet size distribution can be observed, indicating an increase in the size of the droplets. The same behavior was reported by Guerra et al. (2012) for a cylindrical venturi scrubber. A combination of various factors including preferential deposition (by the turbulent diffusion) of the smaller droplets, evaporation/condensation, and coalescence of the droplets may contribute to this phenomenon.

Validation of the simulation result

This simulation result was compared with the others previous studies and simulation works (Guerra et al., 2012, Qamar, 2016, & Zerwas, 2017). They found the gas velocity highly increases up to the maximum level of the throat area as the center point of scrubber experience high turbulence, thus the fluid suction efficiency will occur (Qamar 2016). Figure 6 shows the comparison results of the Qamar studied and this work where its shows the similar trend on the velocity pattern at the scrubber's throat area. In this study, the simulation result on the velocity is slightly higher as compared to the previous studied where the maximum velocity of 100 m/s was obtained, while the others researcher was 85 m/s. This is due to the selection of venturi type and geometry as well as the throat's diameter.

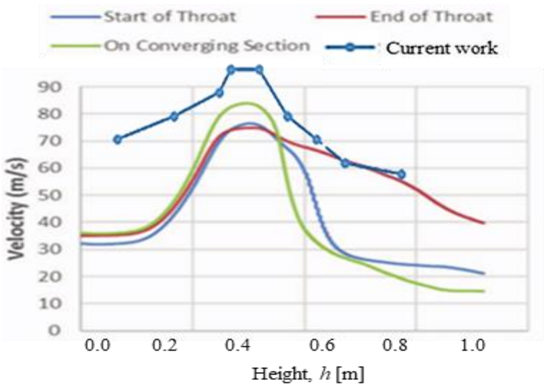

FIGURE 6. Result comparison with the previous studies on the effect of the distance on the velocity distribution

According to Qamar (2016), as the orifice is placed in the throat area, the highest velocity was observed at the throat area, where it's very important condition to achieve an efficient dissipation between gas and liquid phases. When the gas is accelerated, the pressure in the gas stream decreases in the throat area. Thus, the gas velocity flow begins to decrease at the gas outlet, causing the pressure to rise and reaching a lower level than the pressure at the inlet.

CONCLUSION

The gas velocity plays a major variable influencing in order to determine the droplet size in the venturi scrubber. Typically, the gas velocity in the throat section is 30-120 m/s, but in this simulation, velocity of 70-105 m/s shown an adequate to achieve the optimum absorption rate. As the gas passes through the throat section, the velocity increases gradually and as it passes through the divergent section, it decreases causing the droplet diameter to increase. Besides, the droplet size increased with the throat's distance as the liquid injection point becomer far from the initial point. The droplet size distribution slightly shifts towards larger size and becomes wider as it flows along the venturi scrubber. It also can be applied for predicting the collection efficiency in the venturi scrubber.

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