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Effects of the Nozzle Location on Hydrodynamic Properties of a Venturi-Type Scrubber

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Abstract – This study reports the hydrodynamic properties of a wetted venture-type scrubber by injecting the liquid (water) into the mixture (air) flowing inside the venture. Venturies are used in various engineering applications such as in the chemical industry for the removal of dust and aerosols, waste combustion installations, gasification process, glass industry, and metallurgy for several types of degasses and marine industry for cleaning the gas from the unwanted harmful emissions such as SO_2, H_2S, and dust. The Computational Fluid Dynamics (CFD) technique is used for unsteady and turbulent flow of mixture in the venture. The Ansys Fluent, a commercially available CFD package is used for this two-phase flow. Before proceeding further, the numerical model is validated successfully with the data found in the open literature and then the parametric studies are performed in a systematic manner. For this purpose, the location of the nozzle(s) used for water injection into the venture scrubber is changed from the wall of the convergence section of the venture to the throat where the gas accelerates. The flow field is visualized with the pressure, and velocity contours, and the pressure and velocity distributions are shown along with the pressure drop in the venturi to assess the more suitable location of the nozzle.

Keywords – Scrubber, Separation, Venturi, Mixture, Computational Fluid Dynamics (CFD)

I. INTRODUCTION

Better cleaning systems must be employed to eliminate dangerous impurities including SO_2, H_2S, and dust in the gases before to be discharged into the atmosphere as a result of the significantly increased rate of industrialization. The equipment used to purify the gases at this point is called a scrubber. Scrubbers come in a variety of kinds for a variety of uses, including ultrasonic [1], vortex [2], packed bed tower [3], and venture [4]. Venture scrubbers stand out among them for their straightforward design and outstanding productivity.

Due to such advantages, it can be regarded as one of the most important types of wet scrubber. In the wetted venture scrubber the liquid is introduced as a film on the wall just before the convergent section, most of the liquid is atomized at the throat by the shearing action of the gas flow. Another type of venture scrubber is known as the Pearce-Anthony type where the liquid is introduced through nozzles at the throat [4]. Venturi scrubbers work in two modes such as self-priming and force feed mode. In the force feed scrubber, water is supplied to the throat or converging section via a pump from a water reservoir. However, in the self-priming type, the water automatically enters the throat via orifices due to the pressure gradient between the hydrostatic pressure of a liquid and the static pressure of the gas at the throat of the venture [5]. The design of the venture scrubber causes the separation of contaminants from the gas using the liquid sent to the scrubber as a jet. It consists of convergent in which gas accelerates to its maximum velocity, throat which is between the convergent and divergent sections where gas and liquid interact with each other, and diffuser where the fluid decelerates for pressure recovery.

There are several parameters that affect the venture performance such as the pressure drop, droplet and particle sizes, liquid droplet distribution, gas and liquid flow rate and the liquid injection system. Up to now, these parameters have been the subject of many experimental [6]-[8] and numerical studies [9]-[11].

As revealed by the previous literature survey, several factors affect venture performance have been investigated so far, however the studies on the location of the injection nozzle is quite rare. Therefore, in the present paper, it is aimed to numerically investigate the influence of the injection nozzle location on the velocity distribution and pressure drop in the venture.

II. MATERIALS AND METHOD

The hydrodynamic properties such as the velocity and pressure distributions in a wetted venture scrubber are obtained by means of the Computational Fluid Dynamics (CFD) method. Unsteady flow of phases (air and water) if solved with Volume of Fluid (VOF) with SST k-omega turbulence model. Pressure and velocity is coupled and for the spatial discretization of pressure, momentum, volume fraction, turbulence kinetic energy and its dissipation PRESTO and second order upwind scheme are used, respectively.

The venture used by Khadra et al., 2022 is used for parametric study (1). The venture scrubbers is a combination of convergence, throat and divergence sections. While the gas flows in the venturi the water is sent to the gas flow as a jet.

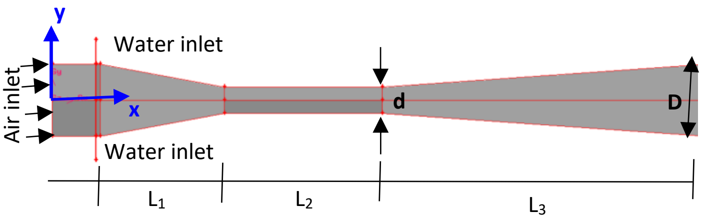

Fig. 1 Investigated wetted venturi scrubber

The diameters and lengths of the throat, convergence and divergences are given precisely in Table 1. It must be noted that the present venture investigated here was designed by Khadran et al., 2022.

Table 1. Dimensions of the venturi

Inlet diameter	250
Throat diameter	122.5
Convergence length, L_1	230
Throat length, L_2	300
Divergence length, L_3	740
Convergence angle (α_0)	17°
Divergence angle (α_0)	5°

The computational domain was discretized into several small areas called grid for numerical calculations. Different numbers of grids are generated and their outputs are compared with each other to ensure that the results are grid-independent. During the grid generation special care is given to the locations in which sharp gradients are expected. The denser grid elements are used in such regions while coarser grids are used away from the intersections of the venturi.

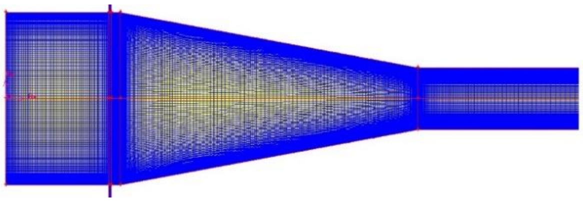

Fig. 2 Mesh structure applied to the scrubber

For the sake of grid independence study, five different grids (Mesh-1 – Mesh 5) were generated. The number for mesh elements starts from 40,351 to 2,570,750 are shown in Table 1 for each mesh.

Table 2. The number of mesh elements used for mesh independence study

Mesh title	Number of mesh elements
Mesh-1	40,351
Mesh-2	644,400
Mesh-3	1,142,681
Mesh-4	1,645,280
Mesh-5	2,570,750

The change in the axial velocity profile from the inlet to the outlet of the venture is used for mesh independence study as shown in Fig.3. It is evaluated that, except the Mesh-1, increasing the number of mesh elements from 644,400 does not affect the velocity change through the venture, therefore, all the remaining calculations were done on Mesh-2 with 644,400 elements.

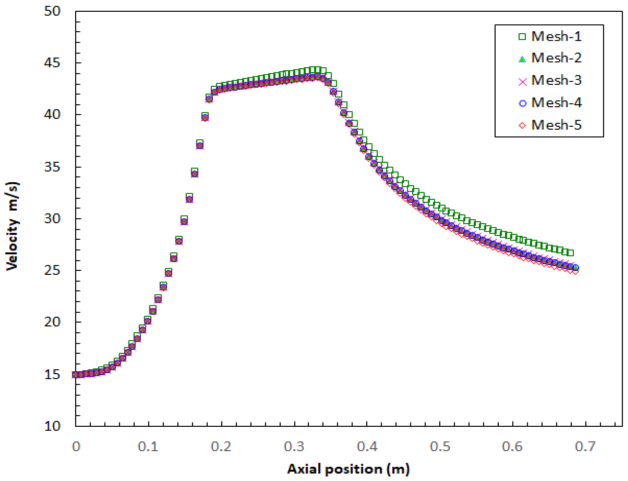

Fig. 3 Grid independency results, u_{gas}=15 m/s, $\dot{m}_{water} = 0.02\ kg/s$,

The governing flow equations of the mixture flowing inside the venture are the continuity and momentum equations (Eq. 1- Eq.3).

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0 \tag{Eq.1}$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{Eq.2}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + v\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{Eq.3}$$

The unsteady and turbulent flow of the mixture consisting of water and air through the venture is solved with the mixture model which is one of the homogeneous models in Ansys Fluent. The turbulence was taken into account with the Renormalization Group (RNG) k-epsilon turbulence model [12]-[14] with standard wall function. Transport equations of RNG k-epsilon turbulence model are shown in Eq. 4 and 5 for turbulence kinetic energy (k) and its dissipation (ε), respectively.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) \tag{Eq.4}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) \tag{Eq.5}$$

III. RESULTS

Prior to the parametric studies, the validation of the model is done with available data [15] found in the open literature. The comparisons made for velocity and pressure distributions found by Ref. [15] are shown in Fig.3 and 4, respectively for two different gas velocities (10 and 15 m/s) and one mass flow rate of liquid of 0.02 kg/s. A close agreement between the present CFD study and the literature can be seen for the single (gas only) and two-phase (gas and liquid) flows.

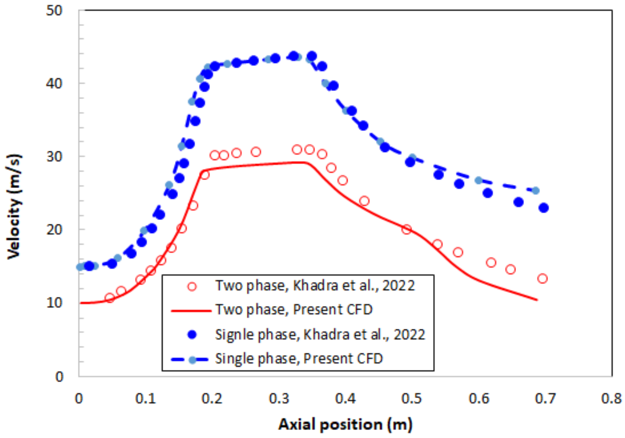

Fig. 4 Velocity profiles for single phase (15 m/s) and two-phase flow (10 m/s) in the venturi, $\dot{m}_{water} = 0.02\ kg/s$,

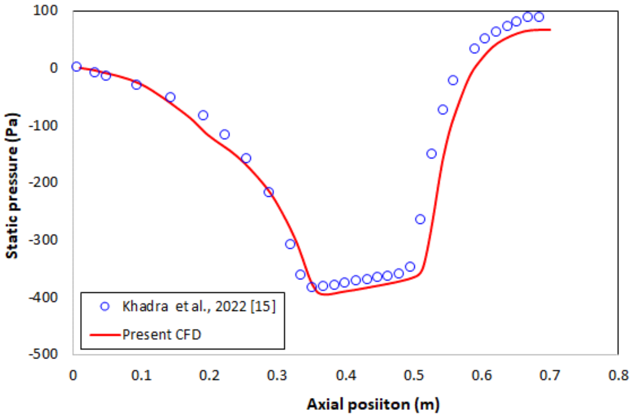

Fig. 5 Pressure distribution in the venturi, u_{gas}=10 m/s, $\dot{m}_{water} = 0.02\ kg/s$,

The venturies rely on the high kinetic energy of the accelerated gas flow in the throat. The relationship between velocity and pressure requires that a minimum specific pressure drop is maintained in the venturi for better cleaning efficiency. In this context, the location of the nozzle used for liquid (water) injection is investigated to assess the change in velocity change and the pressure drop in the venturi. For this purpose, the nozzle was located in four different stations; at the intersection of the main pipe and the convergence called Station-1, in the middle of the convergence (Station-2), at the intersection of the convergence (Station-3) and at the throat and finally in the center of the throat (Station-4).

The simulations were conducted for the nozzle in turn in the specified positions and results are presented in Fig.5 and 6 in terms of velocity and static pressure distributions, respectively. As seen in Fig.5 the gas accelerates from the inlet velocity of 10 m/s to 28 m/s in the convergence and decelerates in the divergence section. It reaches the maximum velocity in the throat section since this is the smallest cross-sectional area of the venturi. It is observed in both figures that the position of the nozzle affects both the velocity and pressure accordingly in the throat section. Since the Station-3 and 4 are close to each other the difference between the velocity distributions in the divergence section are quite similar while this is the case for Station-1 and 2. It should be noted that Station -1 and 2 provide higher exit velocities. In the throat section, Station-4 gives the lowest velocity of the gas flow while Station-1 causes the highest.

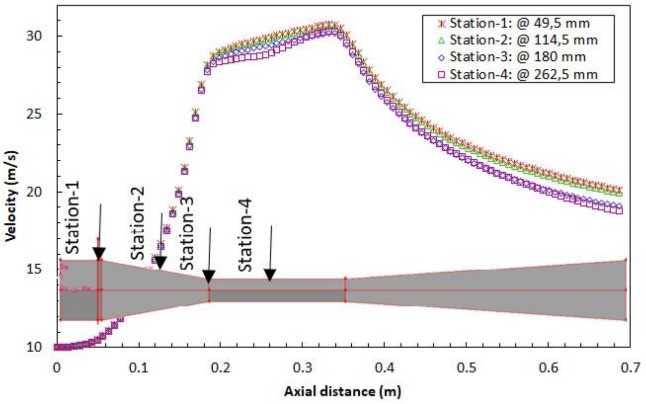

Fig. 6 Velocity distribution in the venturi, u_{gas}=10 m/s, $\dot{m}_{water} = 0.02$ kg/s,

The change in velocity affects the pressure in the throat section and this relationship is seen in Fig.6. Since the velocity is the lowest for Station-1, the pressure distribution is higher than that of the other stations in the throat. The pressure drop between the inlet and outlet of the venturi seems highest for Station-1 and -2 and the lowest for Station-4 and -3.

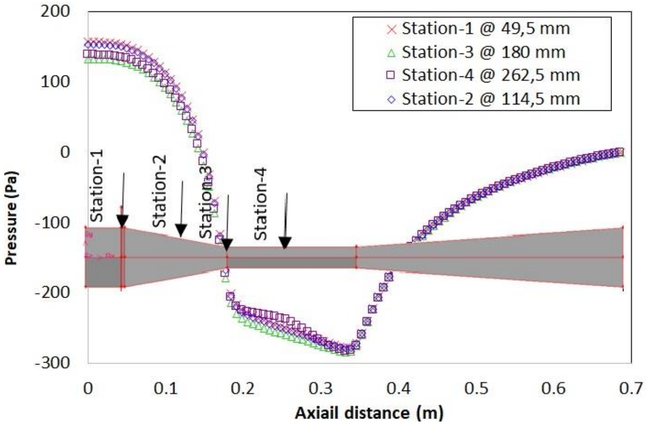

Fig. 7 Pressure distribution in the venturi, u_{gas}=10 m/s, $\dot{m}_{water} = 0.02$ kg/s,

IV. DISCUSSION

The pressure drop is one of the important factors that requires special attention in venturi design. It is taken into account as the difference in the static pressure measured at the inlet and outlet of the scrubber. Correct measurement or calculation of the pressure drop helps in the selection of the appropriate venturi for a particular system. It occurs due to energy loss arising from the friction gas flow even if water is not injected into the venturi.

The higher gas velocity at the throat is always required because higher gas velocity provides higher collection and cleaning efficiency of the venturi. According to the Bernoulli equation, the pressure must be lowest at a point where velocity is the maximum. Therefore, the pressure becomes smallest in the throat section causing a vacuum. As shown in Fig.6, it decreases in the convergent and throat sections and then it is recovered in the divergent part.

It can be concluded that the lowest pressure and highest velocity can be obtained in the throat by placing the nozzle at the intersection of the convergence and throat sections while the highest pressure drop can be obtained by placing the nozzle upstream of the convergence section for efficient venturi performance. The gas friction in the throat is the only parameter that contributes to the pressure drop. Although some parts of this pressure loss are then recovered in the divergent section, a small amount of pressure loss is lost by friction and pressure drop occurs in the venturi.

V. CONCLUSION

The gas (air) and liquid (water) flow in a wetted venturi-type scrubber are investigated numerically in the present study. The paper focuses on the location of the nozzle used in venturies for liquid injection. The nozzle is placed in the course at four different stations from the intersection point between the main pipe and the convergence section to the center point of the throat in which the gas flow accelerates due to the special design of the throat. A series of simulations revealed that the maximum pressure drop which affects the cleaning efficiency of the venturi is obtained when the nozzle is placed upstream of the convergence section.

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