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Analysis of Pressure and Velocity at the Throat of Self-Priming Venturi Scrubber

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Abstract : *The filtered vented containment system (FVCS) containing venturi scrubber is being installed in order to prevent the particulate matter and gaseous pollutant entering the environment due to severe accidents in nuclear power plant. In the present work three - dimensional modeling is done, in order to analyze pressure and velocity of fluid at the throat of self priming venturi scrubber. A commercial software "ANSYS WORKBENCH" tool has been selected for this research work. The velocity field of gas flow is determined by using K-Є turbulence model, while Gas velocity distribution is calculated using equations derived from momentum conservation principle. The Euler-Euler approach is used to understand behavior of fluid dynamics inside the venturi scrubber. Gas and liquid interact with each other in the throat section of venturi scrubber, hence the pressure, velocity of fluid at the throat and pressure drop across venturi scrubber are the key factors to interpret the performance of venturi scrubber. Three - dimensional model of venturi scrubber is considered having throat length of 0.038 m and diameter 0.019 m. The Mass flow rates of the gases are 0.0321 kg/s, 0.03727 kg/s, 0.04236 kg/s and 0.05252 kg/s respectively. The results from present investigation and simulation are helpful to improve the venturi design.*

1. INTRODUCTION

In recent years due to growing air pollution problems which are an inevitable result of industry development numerous efforts have been made to develop new air pollution control technologies and to improve the old ones. venturi scrubber is one of the most popular choices for engineers and scientist from 20th century for cleaning the exhaust gas industries and power plant. The venturi scrubber is one of the most prominent wet scrubbers due to their simple structure and easy application. This kind of scrubber uses an appropriate liquid (commonly water) to capture particulate matter and gaseous pollutant which is suspended in a gas stream [1]. A venturi scrubber consists of mainly three parts: a convergent, a throat, and a diffuser. In Convergent section accelerates the gas to its maximum velocity. The liquid is introduced at the throat or at the entrance of convergent section in jet, film or spray form. The gas and liquid comes in contact with each other at throat portion of venturi scrubber. High gas velocity scrubs the liquid into a huge number of minute droplets. In diffuser part, the droplets accelerate and gas decelerates [2]. The Source liquid is supply in to venturi scrubber in two ways; force feed method and self priming method, in the present work self priming method is used. In order to understand the hydrodynamics of two-phase flow inside the venturi scrubber, it is important to evaluate how liquid and gas is distributed inside it. For this aim, "ANSYS FLUENT" software is used to understand the complex phenomenon inside the venturi scrubber. The "ANSYS FLUENT" software solves the fluid dynamic transport equations numerically by using the finite-volume approach. Two basic approaches are available in modeling the liquid-gas flows in venturi scrubber based on the volume-averaged Navier–Stokes equations, the Euler–Euler approach and the Euler–Lagrangian approach. The Euler–Euler approach treats both the dispersed and the continuous phases as meanwhile, whereas, the motion of two phases is analyzed using the Euler–Lagrangian approach in which each individual particle is tracked. In Euler–Lagrangian approach, the continuous phase is treated in the similar way as in the Euler–Euler approach, while the dispersed phase is tracked by solving the equations of motion. Since a very large number of discrete droplets had to be tracked, therefore, it requires large computer memory, computer time as well as computational cost is very expensive in the Euler–Lagrangian approach [3-4]. The main aim of this study is to evaluate numerically the pressure and velocity at the throat and fluid dynamics inside the venturi scrubber based on Euler-Euler approach with the help of "ANSYS FLUENT".

2. SELF-PRIMING VENTURI SCRUBBER

This study deals with performance of a venturi scrubber in self-priming operation. Usually washing liquid is injected into the throat by means of pump in force feed method; in such way that amount of liquid added per cubic meter of gas is adjustable independent from the gas flow rate. In contrast to this kind of design, the venturi scrubber used works via a self priming operation. In self-priming method, pressure difference composed of hydrostatic pressure of the liquid in the tank and static pressure of the flowing gas in venturi scrubber [5-6]. Figure1 Shows that the venturi scrubber is surrounded by scrubbing liquid and this liquid gets enter through orifices at venturi throat because of pressure difference.

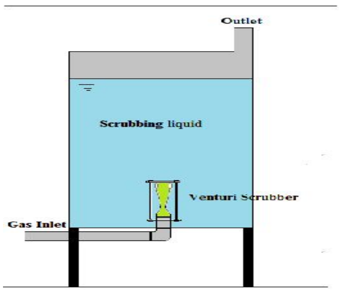

Figure 1. Venturi scrubber inside the scrubber tank

3. MATHEMATICAL MODEL

In this work, an Euler-Euler regime based on two-phase flow is employed [2]. The pressure field in the domain is assumed to be shared by the two phases in proportion of the volume fraction. The assumption of no mass transfer has been taken. The motion of each phase is governed by respective mass and momentum conservation equations can be written as follows [2]:

3.1. Continuity Equation :

$$\frac{\partial r_\alpha \rho_\alpha}{\partial t} + \nabla.(r_\alpha \rho_\alpha U_\alpha) = 0 \qquad (1)$$

The right hand term of continuity equation is zero since, the total mass is conserved. The equation (1) doesn't contain a term describing the turbulent diffusion due to concentration gradient. This is a consequence of mass weighted averaging, which removes all the fluctuation correlation of second term in continuity equation. Mixture continuity equation can be written as,

$$\frac{\partial \rho_m}{\partial t} + \nabla.(\rho_m U_m) = 0 \qquad (2)$$

Here, the mixture density (ρ_m) and mixture velocity (U_m) are defined as follows:

$$\rho_m = \sum_{\alpha=1}^{n} r_\alpha \rho_\alpha \text{ And } U_m = \left(\frac{1}{\rho_m}\right) \sum_{\alpha=1}^{n} r_\alpha \rho_\alpha U_\alpha$$

Where 'n' is number of phases, in the present study n=2

In the numerical simulation, volume fraction of the two phases satisfies the following condition:

$$r_1 + r_g = 1 \qquad (3)$$

3.2. Momentum Equation:

The general form of the momentum equation is as follows,

Rate of momentum accumulation = Rate of momentum in – Rate of momentum out + Sum of the forces acting on the system.

$$\frac{\partial r_\alpha \rho_\alpha U_\alpha}{\partial t} + \nabla.(r_\alpha \rho_\alpha U_\alpha U_\alpha)$$

$$= -\nabla P_\alpha + \nabla.\{r_\alpha \mu_t[(\nabla.U_\alpha)+]\} + S_{M\alpha} + M_\alpha \qquad (4)$$

3.3. K-Є Turbulence Model:

The K-Є turbulence model is one of the most common turbulence models which include two extra transport equations to represent the turbulence properties of flow.

The first transported variable is turbulent kinetic energy (K) whereas; the second transported variable is the turbulent dissipation (Є), which are explained by the following equations: Turbulence characteristics k and ε can be used to evaluate the gas eddy diffusivity throughout the Venturi scrubber.

$$\frac{\partial r_\alpha \rho_\alpha U_\alpha}{\partial t} + \nabla.\left\{ r_\alpha \left[(\rho_\alpha U_\alpha k_\alpha) - \left(\mu + \frac{\mu_{r\alpha}}{\sigma_k} \right) \nabla k_\alpha \right] \right\}$$

$$= r_\alpha (P_\alpha - \rho_\alpha \epsilon_\alpha) \qquad (5)$$

$$\frac{\partial r_\alpha \rho_\alpha \epsilon_\alpha}{\partial t} + \nabla.\{[(r_\alpha \rho_\alpha U_\alpha \in_\alpha) - (\mu + \frac{\mu_{r\alpha}}{\sigma_\epsilon}) \nabla \in_\alpha]\}$$
$$= r_\alpha \frac{\in_\alpha}{k_\alpha} [C_{\in 1} P_\alpha - C_{\in 2} \rho_\alpha \in_\alpha] \qquad (6)$$

Where, Cε1 and Cε2 are k-ε turbulence model constant.

3.4. Schilller Nauman Drag Model:

In the self priming operation of venturi scrubber, the drag force acts on the particle. The drag is due to velocity relative to the fluid which is mainly a function of Reynolds number and the drag coefficient is given by,

$$C_D = \max\left(\frac{24}{Re}(1 + 0.15Re^{0.687}), 0.4\right) \qquad (7)$$

4. Numerical Simulation

The 3D model and meshing of a circular cross-section venturi scrubber used in this study is shown in figure 2 and figure 3 respectively. The mesh is generated in "ANSYS WORKBENCH" with 21,97,766 elements. Maximum cell skewness is 0.79 on the scale from 0 to 1 based on "ANSYS WORKBENCH" mesh quality criteria and maximum aspect ratio is 10.61 [7].

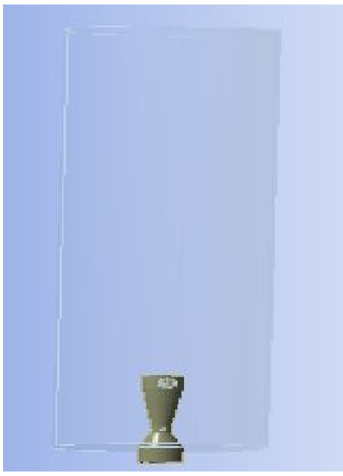

Figure 2. Geometry of venturi scrubber tank

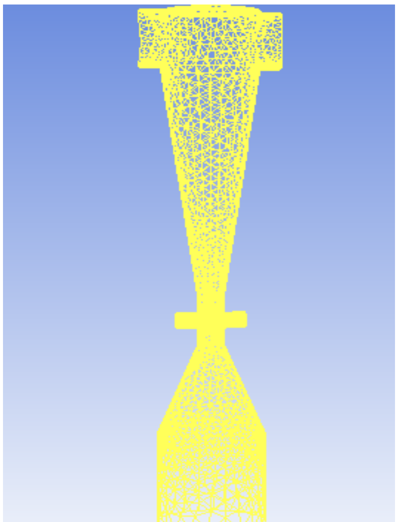

Figure 3. Meshing of venturi scrubber

Analysis of this model is done in "ANSYS FLUENT" software while computation is carried out in the steady state. The gas (air) is treated as continuous field and liquid (water) as dispersed fluid in the domain. k–ε model is used for gas and dispersed phase zero equation model is used for liquid. Upwind discretization scheme is applied, which accounts for accuracy and stability. The discretized equations are solved using the advanced coupled multi-grid solver, where pressure velocity coupling is based on the Rhie Chow algorithm of fourth order is used. The convergence criterion of 1.0e–06 is set for all the numerical simulations. Boundary conditions for the CFD model are defined as follows: At the inlet, the mass flow rate of the air and water is specified. The direction of the flow is defined normal to the boundary. At the outlet of venturi scrubber tank, the pressure boundary condition is applied. At all the walls, a no-slip boundary condition is imposed for both liquid and gas. The standard near wall function is used in the near wall treatment. For the selection of appropriate mesh for analysis, a grid independency is checked.

5. RESULTS AND DISCUSSIONS

Performance in self-priming process:
The cleaning efficiency of venturi scrubber can be improved in two different ways: (i) the amount of liquid added per volume of gas and (ii) by increasing gas velocity at the throat. As described in section 2 above, the scrubber worked in self - priming mode whereby the liquid flow rate was not adjustable independently from the gas flow rate. This flow rate is function of gas velocity at throat and liquid level inside the scrubber tank. So following parameters were studied.

5.1. Gas Velocity:

The gas first accelerates in convergent section and attains maximum velocity in throat section and then it start decelerating in diffuser section. The maximum throat gas velocity are 122 m/s,145m/s,162 m/s and 196m/s for mass flow rate of gases are 0.0321, 0.03727, 0.0423 and 0.05252 kg/s respectively. The snapshot of contours of gas velocity at mass flow rate of gas 0.03727kg/sec is shown in figure 4.

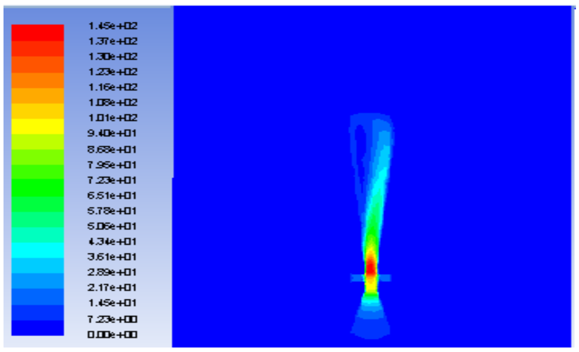

Figure 4. Snapshot of contours of gas velocity at mass flow rate of gas = 0.03727kg/s

The graph of gas velocity at different mass flow rates are shown in figure 5. This graph shows that as mass flow rate of gas increases the velocity at throat also increases.

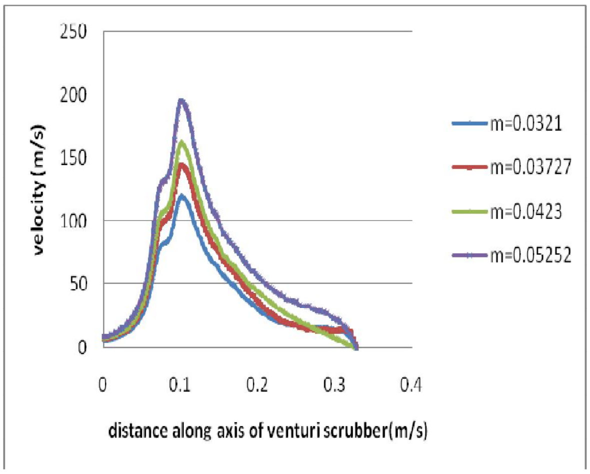

Figure 5. Graph of gas velocity along the axis of venturi scrubber.

5.2. Gas Pressure:

The velocity accelerates in the convergent section as a result pressure decreases in convergent part, according to Bernoulli's principle. Due to the lower pressure in throat section, a vacuum is created. Here, according to Bernoulli's principle velocity decreases in diffuser part and pressure recovery is done, as shown in the figure 6.

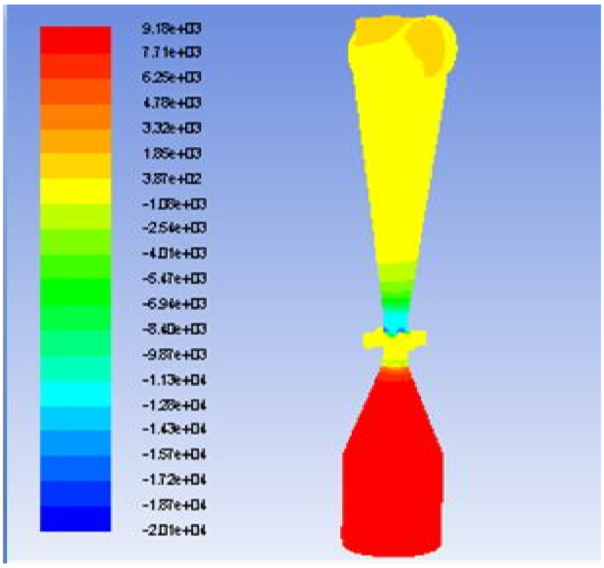

Figure 6. Snapshot of contours of static Pressure at mass flow rate of gas= 0.03727 kg/sec

The graph of static pressure at different mass flow rates of the gas are shown in figure 7. This graph shows that as mass flow rate of gas increases the pressure at throat of venturi scrubber decreases.

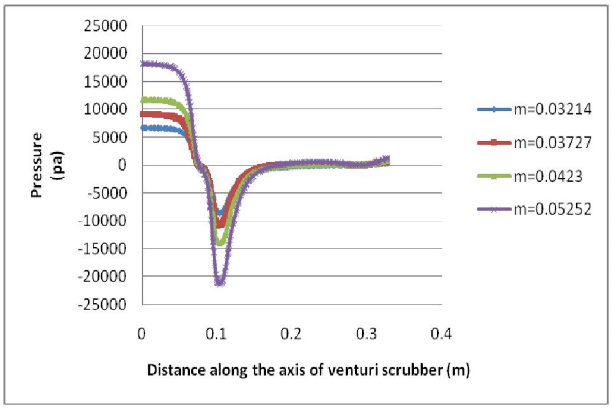

Figure 7. Graph of Pressure along the axis of venturi Scrubber.

5.3. Pressure drop across venturi scrubber:

Variation for the mass flow rate of gas in throat significantly influences the pressure drop across the venturi scrubber. The variation of pressure drop with respect to mass flow rates of gases are shown in figure 8.

Figure 8 reveals that pressure drop across the venturi scrubber increases with increase in mass flow rate of gas.

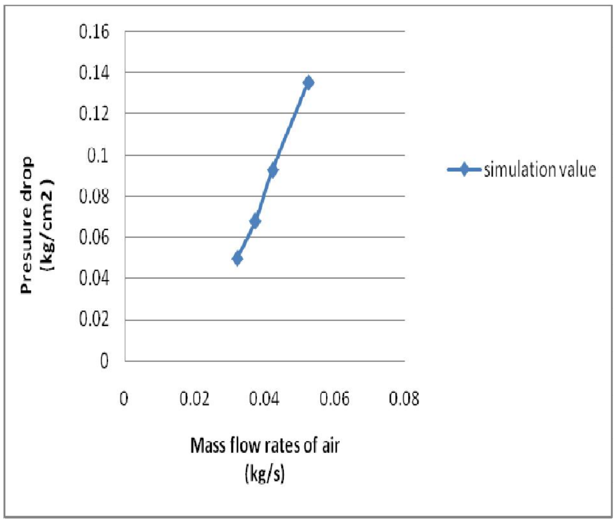

Figure 8. Pressure drop across venturi scrubber at different mass flow rates of gas by simulation.

6. CONCLUSION

CFD analysis of self priming venturi scrubber is done for the study of hydrodynamics of gas-liquid inside the venturi scrubber by using Euler-Euler approach. Study reveals that as mass flow rate of gas increases the pressure drop also increase. The pressure at throat helps to understand volumetric liquid to gas ratio inside venturi scrubber. This work is helpful to improve the venturi design for good performance.

7. ACKNOWLEDGMENT

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Abbreviations

Latin letters

n	number of phases [dimensionless]
U_m	low velocity of mixture [m/s]
Re	Reynolds number [dimensionless]
D	diffusion coefficient [m^2/s]
C_D	drag coefficient [dimensionless]
U_α	low velocity of phases (liquid or gas) [m/s]
r_α	volume fraction of phase (liquid or gas)[m/s]
ρ_α	density of phase (liquid or gas) [kg/m^3]
ρ_m	density of mixture [kg/m^3]
r_l and r_g	volume fraction of liquid and gas respectively [Dimensionless number]
∇P_α	pressure gradient term for phases [N/m]
S_{tk}	stokes number [dimensionless number]
k_α	kinetic energy of phase [J]
p_α	phase pressure [N/m^2]
P_m	mixture pressure [N/m^2]

Greek letters

α	phases index
μ	dynamic viscosity [$N.s/m^2$]
ρ	material density [kg/m^3]
$\boldsymbol{\tau}$	stress tensor [N/m^2]
μ_t	eddy viscosity [$N.s/m^2$]
τ^p	relaxation time of the particle [sec]
ε	turbulent dissipation rate [J/kg.s]

Subscripts

T	Turbulent
D	diffusion
F	fluctuating component
L/G	liquid to gas ratio

Other symbols

Δ	difference
∇	gradient operator

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