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Numerical Modelling of Flow through Perforated Plates Applied to Electrostatic Precipitator

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Abstract: The main aim of this study is to simulate numerically the flow through perforated plates in Electrostatic precipitator and compare the obtained results with the one obtained experimentally. Better flow distribution in the collection chamber of electrostatic precipitator was obtained with two perforated plates of porosity 50%, one plate located just upstream of the diffuser exit and other at some distance downstream of the diffuser entrance. Perforated plates of higher porosity do not have the capability to spread out the flow, whereas plates of low porosity lead to excessive pressure drop. Mean velocity of flow at diffuser exit obtained numerically was 4.5 m $\sec^{-1}$ while velocity obtained experimentally at diffuser exit was 3.75 m $\sec^{-1}$, with about 16% deviation. Numerical investigation of flow through perforated plates and velocity distribution in the collection chamber of an Electrostatic Precipitator was carried out using a Computational Fluid Dynamics code namely FLUENT. The effect of porosity and perforated plate location on flow uniformity and turbulence were studied and the results were compared with experimental data.

Key words: Electrostatic precipitator, source term, porosity, CFD, flow distribution, turbulence

INTRODUCTION

An Electrostatic Precipitator (ESP) is being used to capture particles suspended in the flue gas stream of a coal based power plant. The gas stream consists of polydisperse particles. The particles get ionised due to the applied electric field in the gas flow path and gets deposited on the collector electrode from where it is rapped off periodically. A schematic of an ESP is shown in Fig. 1. It consists of a positively charged electrode (collector plate) and a negatively charged electrode (discharge electrode) separated by a small distance through which the gas suspended with particles flow. Electrostatic precipitators are widely used in coal based power plants, copper smelting, phosphoric acid manufacture and electrostatic spray painting applications.

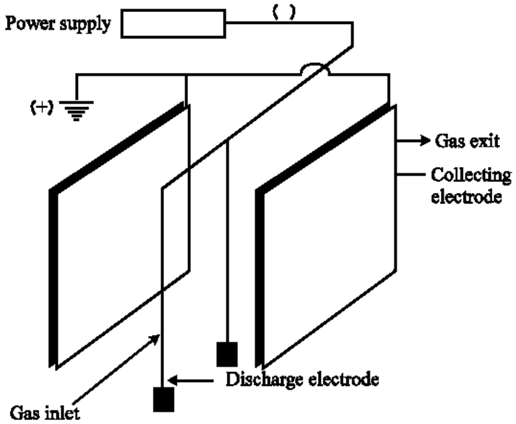

Fig. 1: Schematic of a wire plate ESP

Uniform distribution of flue gas in the collection region is necessary for efficient operation of the ESP. The flow through Electrostatic precipitator is turbulent as Reynolds number based on hydraulic diameter is high (greater than 10^5) (Munson *et al*., 2002). Also, turbulence in the collecting region is affected by the flow distribution. Poor distribution leads to non uniform turbulence in the collection region, which directly affects particle collection. Distribution of flue gas in the collection region is achieved by installing a diffuser upstream of collection chamber with multiple perforated plates. Location and porosity of the perforated plates greatly affect the distribution of flow and turbulence in the collection region. Flow distribution in ESP should satisfy ICAC EP-7 (Institute of Clean Air Companies) standard for efficient collection of particles. The ICAC EP -7 standard requires that, the local velocity distribution over the cross section of the collection chamber should have a minimum 85% of the readings within 1.15 times the mean velocity and 99% of the readings not more than 1.4 times of mean velocity (White, 1963). Perforated plates of low porosity tend to diverge the flow, causing the flow to accumulate near the walls. Perforated plates of high porosity have poor flow distribution and high velocities

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are expected in the vicinity of the axis. Placing the perforated plates in close proximity will not improve flow distribution; rather enhance flow non-uniformity. Fixing a perforated plate at the exit of the diffuser is not recommended, as the flow has to travel some distance before it is able to adjust itself and smoothen the eddies formed downstream of the perforated plate.

Varonos *et al.* (2002) numerically simulated the cleaning efficiency of an ESP using CFD. Dumont and Mudry (2003) analysed CFD model of an industrial ESP and found that gas distribution was not uniform which lead to poor collection efficiency. Sahin and Ward-Smith (1987) conducted experiments with wide angle diffuser with perforated plates. They found that plate with medium porosity gives better flow distribution than plates with higher and lower porosity. Sahin and Ward-Smith (1991) studied the pressure drop characteristics of flow from exit of a diffuser with three perforated plates. Gan and Riffat (1997) conducted experiments of different geometries of perforated plates and studied their exit pattern. Skodras *et al.* (2006) analysed a 2D model of a wire plate ESP using CFD for different particle sizes. Kallio and Stock (1990) performed a flow visualisation study using smoke as flow tracer and illumination with a laser beam. They found that at high cross flow velocity there is ionic wind which is detrimental to the collection of particles in ESP. Schwab and Johnson (1994) studied flow improvement methods in industrial ESP s and deduced new design methods. Kim and Lee (1999) performed experiments on a laboratory scale single stage ESP by modifying the ESP geometry parameters like wire to plate spacing, channel width, applied voltage, gas velocity and turbulence intensity. Shah *et al.* (2007) conducted experiments on a laboratory scale precipitator and compared numerically simulated data with measured data. Shah *et al.* (2009a) investigated the effect of inlet velocity profile on velocity distribution inside the ESP. A laboratory scale ESP was modelled in three dimension using GAMBIT and analysed using FLUENT.

Stringent emission norms and improvement in ambient air quality requires better insight on parameters affecting collection efficiency of an Electrostatic Precipitator. The current study analyses numerically the effect of perforated plate location and porosity on flow distribution in the collection chamber of Electrostatic Precipitator using a Computational Fluid Dynamics code namely FLUENT.

MATERIALS AND METHODS

A three dimensional model of the ESP system used by Sahin and Ward-Smith (1987) was modelled using GAMBIT pre-processor, with the same dimensions of the experimental setup and analysed using FLUENT code. The flow through the perforated plate was modelled as porous region and porous jump boundary condition was used. Eight numbers of perforated plates were modelled with a distance of 60 mm between each. In each case only two plates will act as plate with porosity and other plates will allow flow through them completely. The 3D model of the Electrostatic precipitator without hoppers is represented in Fig. 2.

The mesh or the computational domain for the simulation consists of about 2,45,000 cells of tetrahedral shape. The mesh size is quite adequate for simulation and grid independent tests carried out to ensure the required mesh size. The mesh is shown in Fig. 3.

The dimensions of the model are shown in Fig. 4 (not to scale). The length of the diffuser is 425 mm, the length of the collection chamber is 1300 mm and the length of the outlet evase is 425 mm. The diffuser is a wide angle pyramidal diffuser, the angles are $2\gamma = 97°$ horizontally and $2\alpha = 67°$ vertically. The working section is the collection chamber of the ESP.

The position of the plates and measuring locations in diffuser are indicated in Fig. 5. The plates are located at the entrance of the diffuser, then after every 60 mm a

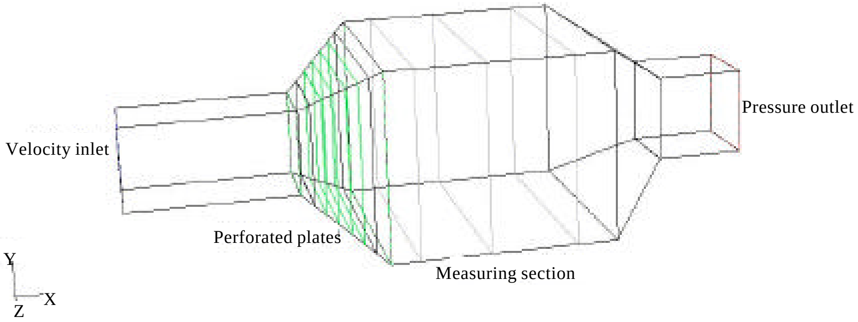

Fig. 2: 3D model of the electrostatic precipitator

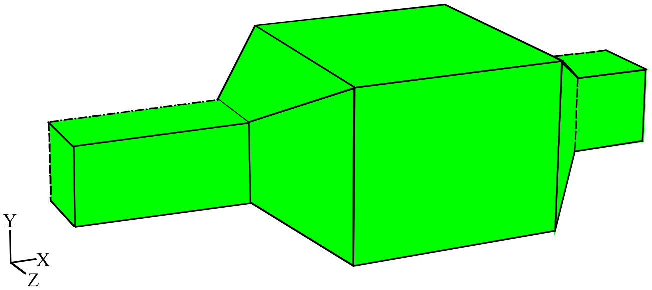

Fig. 3: Mesh for the simulation

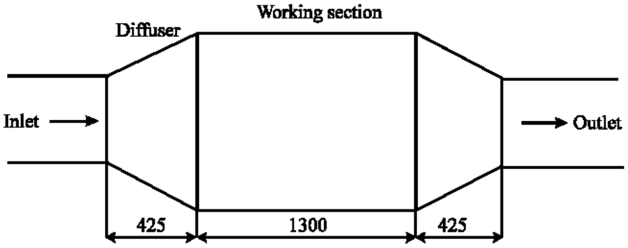

Fig. 4: Dimensions of the model in mm (not to scale)

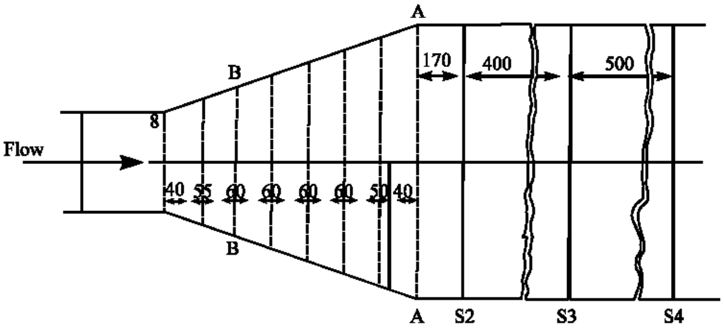

Fig. 5: Location of plates and measuring planes (measured in mm)

perforated plate is placed and the last plate at the diffuser exit is placed at 65 mm from the previous plate. The location of the plates is indicated by the dashed lines. The measuring locations are indicated by the numerals above the arrows.

The flow through the ESP is turbulent flow and turbulence is taken care by standard k-ε turbulence model. FLUENT solves the continuity, Navier-Stokes and k-ε turbulence model equations which are represented as Eq. 1-4, respectively. The porous jump boundary condition is solved using Eq. 5 (Idelchik, 1994). The equations are solved using a second order scheme and SIMPLE algorithm. Air is treated as the gas flowing through without particles and modelled as isothermal flow (Fluent 6.3, 2006).

Governing equations:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + U.\nabla U = -\frac{\nabla P}{\rho} + \nu \nabla^2 U + g \tag{2}$$

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho k U) = \nabla.\left(\frac{\mu_t}{\sigma_k}\nabla k\right) + 2\mu_t E_{ij}, E_{ij} - \rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho\varepsilon U) = \nabla.\left(\frac{\mu_t}{\sigma_k}\nabla\varepsilon\right) + C_{1\varepsilon}\frac{\varepsilon}{K}2\mu_t E_{ij}, E_{ij} - C_{2\varepsilon}\frac{\varepsilon^2}{K} \tag{4}$$

$$\nabla p = -\left(\frac{\mu}{\alpha}U + C_2\frac{1}{2}\rho U^2\right)\Delta m \tag{5}$$

The boundary conditions are given in Table 1. Shah *et al*. (2009b) showed that pressure drop across perforated plate is mainly due to inertial term (second term in Eq. 5 and that losses due to viscous effects are negligible. As such the viscous term was neglected. The simulations were repeated with plates of porosity 58% and also by varying perforated plate locations in the diffuser. The simulation results compared with experimental results and are in good agreement.

Table 1: Boundary conditions

Location	Values
Inlet	Velocity = 25 m sec^{-1}
Perforated plate 1	Porosity (β)= 50%
Perforated plate 1 and 2 permeability	α = 7.153 e-7 m^2
Perforated plate 2	Porosity (β) = 50%
Turbulent Intensity at inlet	5%
Turbulent Intensity at outlet	8%
Outlet	Pressure = 1×10^5 Pa
Pressure jump value	C_2= 1933 m^{-1}
Thickness of perforated plate	0.0015 m

RESULTS AND DISCUSSION

The velocity distribution in the collection chamber, before and after the perforated plates was presented as a contour plot. Figure 6 shows the velocity variation at diffuser exit. It shows an average exit velocity value of 4.5 m sec^{-1}, while experimental value was 3.75 m sec^{-1}, which is satisfactory with about 16.7% deviation. Also, the velocity distribution is uniform as the perforated plate is kept some distance before the diffuser exit. This ensures that the flow is able to adjust itself from the effect of the recirculation downstream of the hole.

Velocity variation at plane S2 is shown in Fig. 7, which shows a better flow distribution compared with diffuser exit. As the flow from the exit travels some distance before reaching plane S2, the stream can readjust itself and so it shows a more uniformity than at diffuser exit.

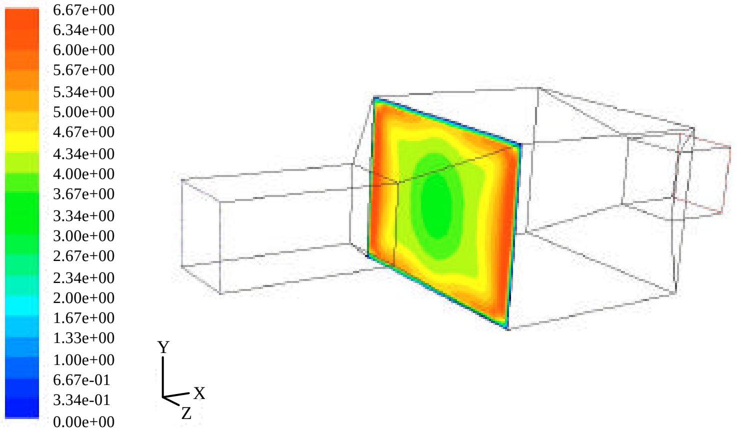

Fig. 6: Velocity distribution at diffuser exit in m sec^{-1}

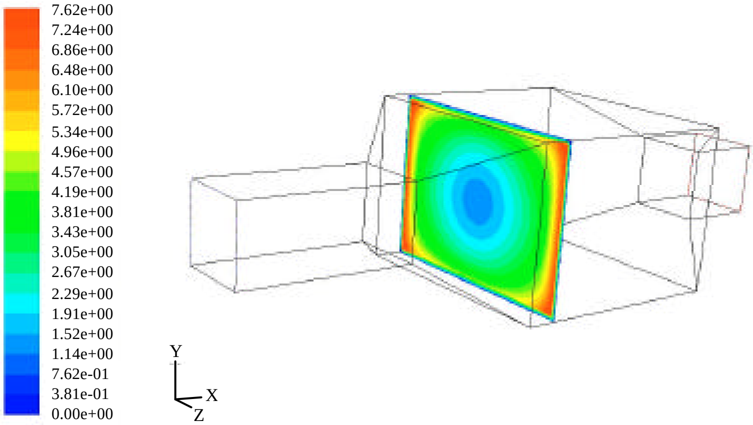

Fig. 7: Velocity distribution at location S2 in m sec^{-1}

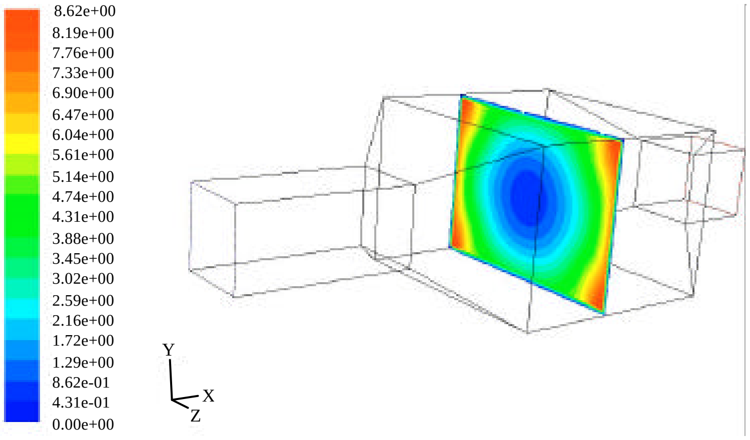

Fig. 8: Velocity distribution at location S3 in m sec^{-1}

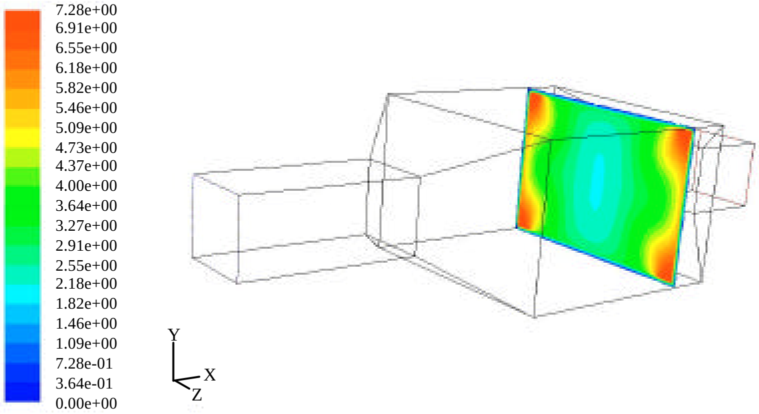

Fig. 9: Velocity distribution at location S4 in m sec^{-1}

Figure 8 shows the velocity distribution at measuring plane S3. The central region shows a much slower stream than at location S2 and an average velocity of 3.45 m sec^{-1}. As the flow approaches the solid wall the flow streamlines tend to diverge and then finally become nearly normal to the original direction.

Factors of this kind explain the ability of a perforated plate of the appropriate porosity to spread the action of the axial jet more widely over the cross-section of the diffuser, thereby reducing the scale of any separated flow region. The accumulation of flow in close proximity of the walls will cause a retarded flow region in the vicinity of the axis. Perforated plates with higher porosity provide insufficient spreading action and create high velocities in central region. As the flow is undisturbed the region near wall tends to have higher velocity and as such Fig. 9 shows higher velocities near the wall.

Figure 10 shows the velocity distribution upstream of the perforated plate of porosity 50%. It can be seen that there exists a region of high velocity close to walls, due to combined action of spreading action of the diffuser and also due to the lesser momentum loss near the walls.

Figure 11 shows the variation in velocity at diffuser exit between the simulated values and the experimental data. The variation is about 5% near the walls and almost negligible at the centre and as such simulated results match very close with experimental data.

Figure 12 shows the variation in velocity at measuring plane S2 between the simulated values and experimental data. In both Fig. 11 and 12 the simulated values of velocity are higher than that of experimental data, as local disturbances might reduce the flow velocity. As such flow uniformity downstream of spreading diffuser in an Electrostatic Precipitator can be obtained by installing two perforated plates of 50% porosity, with one perforated plate just downstream of diffuser entry and the other just upstream of diffuser exit.

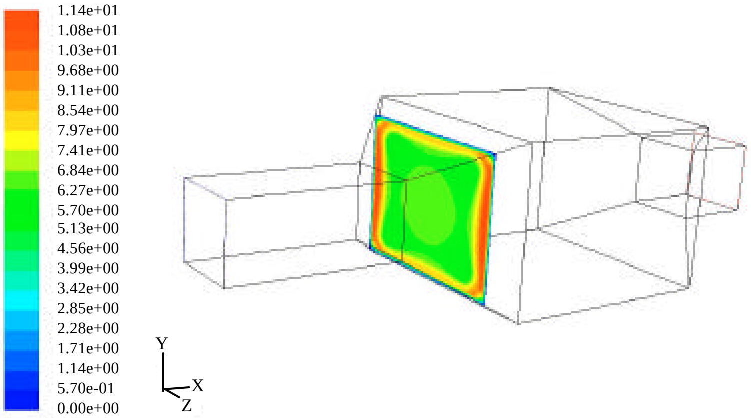

Fig. 10: Velocity distribution upstream of second perforated plate in m sec^{-1}

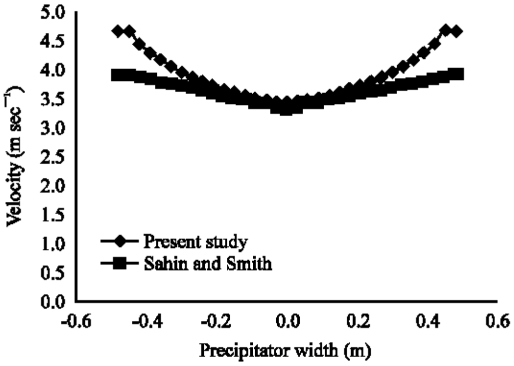

Fig. 11: Comparison between experimental and simulated values of velocity

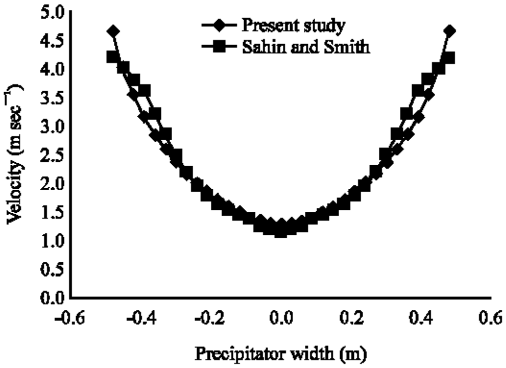

Fig. 12: Comparison between experimental and simulated values of velocity

CONCLUSION

Simulation of flow through perforated plate applied to electrostatic precipitator using CFD showed that multiple perforated plates are necessary to distribute flow uniformly in the collection chamber and that flow distribution depends very much on perforated plate porosity and location. Plates of higher porosity do not have the ability to distribute the flow and that plates of low porosity slows down the flow and cause excessive pressure drop.

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NOMENCLATURE

u = Fluid velocity (m sec^{-1})
D_h = Hydraulic diameter (m)
Δm = Thickness of perforated plate (m)
C_2 = Pressure jump coefficient m^{-1}
k = Turbulent kinetic energy (m^2 sec^{-2})
p = Pressure (Pa)
S2 = Measuring plane (mm)
S3 = Measuring plane (mm)
S4 = Measuring plane (mm)

Greek symbols

ρ = Fluid density (kg m^{-3})
β = Porosity (%)

ν = Kinematic viscosity ($m^2\ sec^{-1}$)
ε = Turbulence dissipation rate ($m^2\ sec^{-3}$)
α = Permeability of perforated plate (m^2)
μ = Absolute viscosity ($kg\ msec^{-1}$)

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