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APPLICATION OF MULTI-SCALE APPROACH IN THE GAS FLOW SIMULATION THROUGH ELECTROSTATIC PRECIPITATORS

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ABSTRACT

The gas flow distribution significantly affects the collecting performance of an Electrostatic Precipitators (ESP) system. Computational Fluid Dynamic (CFD) method and a multi-scale approach are used to study the gas flow through the ESP system at different scale. Firstly, numerical experiments are conducted at an orifice scale and ESP unit scale (unit cell and collection unit study) respectively, to determine the parameters of the perforated plates and ESP unit, such as the pressure drop coefficient. Flow distribution in the large scale ESP system is then simulated and adjusted based on a simplified method. The simulation results and experiment data match very well both in trend and value. The study shows that multi-scale approach in CFD simulation can be used to predict the gas flow within ESP system accurately and conveniently.

NOMENCLATURE

C_2	pressure loss coefficient per unit thickness
c	flow contraction factor
d	orifice diameter of perforated plate
f	plate porosity
P, p	pressure
S	source
u,v	velocity
ρ	density
μ	dynamic viscosity
ξ	pressure drop coefficient
α	permeability of the perforated plate
Δm	thickness of the porous media.

INTRODUCTION

Electrostatic precipitator (ESP) system device is widely used in power plants for removing particulate matters from flue gas generated in coal fired boilers (Varonos et al, 2002). Its complex structure, as shown in Figure 1, comprises diffuser, collection chamber, ductwork, electrical system, rapping system and solid transport system, etc. So far, ESP unit or such a large system is the most common, effective and reliable particulate control device due to the merit of handling large gas volumes with a wide range of operation conditions, e.g., temperature, pressure, particle loading and chemical composition. The distribution of gas flow significantly affects the collecting performance of the ESP system. Traditionally, trial-and-error physical experiment was relied on to adjust the gas flow by installing guide baffles in the upstream pipework and distribution devices within the diffuser with little understanding of the reason. With the development of computer technology and further improvement of Computational Fluid Dynamic (CFD) technique, commercial CFD softwares are increasingly applied to the gas flow prediction within the ESP.

Haque et al. (2006,2007,2009) studied the flue gas flow through the ESP in a laboratory model and one in a local power station using the CFD code Fluent, and compared the flow behavior with experimental and on-site data supplied by the power plant respectively. Hou et al. (2009) divided the large scale simulation into three steps, viz. unit cell, ESP unit, and entire ESP system. Swamination and Mahalakshmi (2010) numerically studied the flow through perorated plate in a ESP diffuser. The simulation results were compared with experimental data and showed that the flow uniformity in the collection chamber depends on the location and porosity of the perforated plates. A too high porosity does not distribute the flow uniformly, whereas a low porosity will slow down the flow and cause excessive pressure drop. Bhasker (2011) studied the flow numerically in ESP ducts with turning vanes by several different flow solvers such as CFX-TASCFLOW, FLUENT, CFX, and STAR-CD. The simulation results suggest that flow distribution can be improved by placing more turning vanes in the inlet duct.

However, most of parameters used for perforated plates during the simulations were obtained from an empirical coefficient. In the current paper, a multi-scale approach is applied for the modeling of an ESP system, where the coefficients for the perforated plates are determined by so-called unit cell modeling at a single orifice scale, combined with an ESP collection unit simulation. Finally a large ESP system (a network of four parallel ESP units) is considered, where the flow distribution is adjusted for optimization purpose based on a simplified numerical simulation.

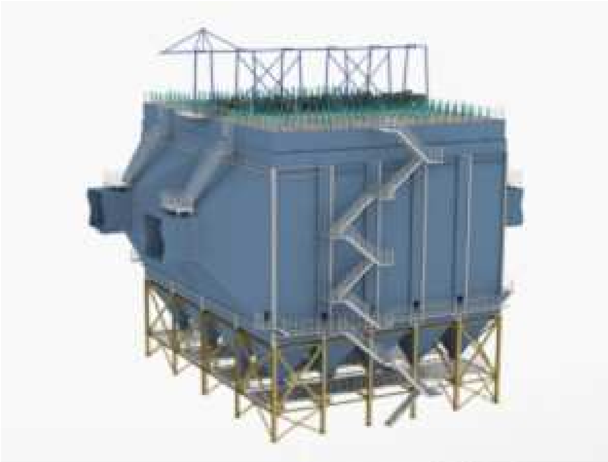

Figure 1: Typical structure of ESP

Governing Equations and Numerical Method

The flue gas is assumed as incompressible and Newtonian fluid. The governing equations include the conservation equations of mass, momentum and energy, which are given as,

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j} - \overline{\rho u_i' u_j'}\right) + S_i \tag{2}$$

The realizable $k-\varepsilon$ model was selected to simulate the turbulence (ANSYS, 2009).

Both of the perforated plates and channel plates are treated as a thin porous media with a finite thickness and directional permeability. The pressure drop of the perforated plates and channel plates is expressed as the sum of viscous loss term and inertial loss term in the form,

$$\Delta P = -\left(\frac{\mu}{\alpha}v + C_2\frac{1}{2}\rho v^2\right)\Delta m \tag{3}$$

where ν is the normal velocity component to the plate face.

The full scale geometry of a ESP system is so complicated that it is difficult to implement all the details exactly in a single CFD model under the current computational capability, particularly for an ESP system with several collection chamber units, perforated plates with thousands of holes (in the diffuser), and channel plates with thousands of individual cells (placed near the exit after the electric fields). By a so-called multi-scale approach, the simulation of a complete ESP system is considered at four basic length scales: (a) microscopic scale, such as the flow around a single orifice on the perforated plate, (b) small scale at local parts, (c) intermediate scale operation units and (d) large scale full system. The large-scale systematic modeling requires development of simplified local models dedicated to some specific regions (e.g., porous media model for the perforated plates and channel plate).These local models will be developed through microscopic flow simulations at each specific part, and the microscopic flow characteristics are transformed into macroscopic model parameters.

RESULTS AND DISCUSSION

Unit Cell Study and Coefficient of Perforated Plate

The perforated plates inside the inlet diffuser divide the large area of flow into small areas and suppress the turbulence by increased resistance, so that the gas flow through the collection region becomes more uniform. Proper treatment of perforated plates, as shown in Figure 2, is crucial to the modeling of the whole system. Figure 3 shows typical streamlines around a single orifice obtained through the unit cell study. Both the velocity and pressure change with the distance in the bulk flow direction.

Figure 4 shows the static and total pressures (normalized by the dynamic pressure at the inlet) as the function of stream-wise distance (normalized by the orifice diameter) along the centre line, for different inlet velocities (corresponding to different Reynolds numbers). The reference point is located on the front face of the plate. At a very low velocity, pressure is lost within a short distance of 1*d*. At a high velocity, the static pressure generally starts to drop at 1*d* upstream of the front face, to zero pressure around the back face, and further down to a negative pressure until a minimum at 1d after the plate. Then it starts to rise until 5-6*d* downstream. The total pressure does not change much before 2.5*d* downstream. Then it decreases with distance in the range 2.5-8*d*.

The unit cell is regarded as the micro-scale of the whole ESP system, while the perforated plates are usually treated as homogeneous in simulation, where the pressure drop can be calculated according to Eq. 3. Normally the first term on the right side is much smaller than the second term. The values for α and C_2 vary in literature, for example α is assumed arbitrarily as one in the study by Tu et al. (2004). The pressure drop coefficient of the perforated plate $\xi = C_2\Delta m$ is usually obtained from experiment at high Reynolds number. For example, some engineers use a simple empirical correlation

$$\xi = 1/\left(f \times c\right)^2 - 1 \tag{4}$$

where *f* is the porosity and *c*=0.85 taking account of flow contraction at the entrance to the orifice. Here, we select the unit cell simulation method proposed by Hou et al. (2009). Numerical experiments are conducted for different variables such as velocity, orifice diameter, thickness and porosity to determine the parameters α and C_2, which are given by

$$\alpha = \frac{2d}{b_1 f}\Delta m \tag{5}$$

$$C_2 = b_2\frac{1}{\Delta m} \tag{6}$$

where, b_1 and b_2 are parameters largely dependent on the porosity. In order to validate the unit cell simulation method, the simulated loss coefficient is compared to the results given by Idelchik (1996), the simple empirical correlation and our own experiment respectively, as listed in Table 1. The simulated loss coefficient is shown qualitatively consistent with the literature and test result, and more accurate than the empirical correlation mentioned above.

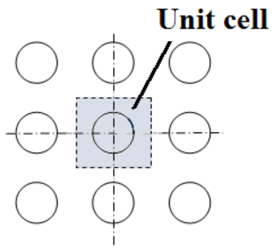

Figure 2: Unit cell definition.

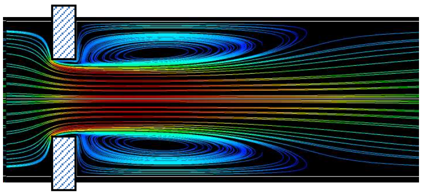

Figure 3: Flow stream line through a unit cell orifice

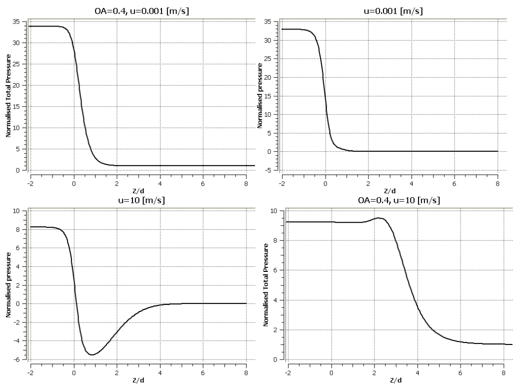

Figure 4: Streamwise distribution of pressure along the centreline for different inlet velocities (f=0.4).

Table 1: Comparison of pressure loss coefficient

Porosity, f（%）		30	40	50
Simulation	Δm/d=0.1	18.32	8.20	4.19
	Δm/d=0.3	16.83	7.45	3.90
Idelchik (1996)	Δm/d=0.1	18.21	8.21	4.24
	Δm/d=0.3	18.07	8.15	4.22
Experiment	Δm/d=0.1	18.25	7.36	4.18
	Δm/d=0.3	16.01	7.00	3.51

Validation of Velocity Distribution in a Base Model

An experimental test rig, so-called the “base ESP chamber model” (Figure 5), is set up to validate the numerical model for the perforated plate. The test planes in the 1st and 2nd electric fields are located at 122mm and 647mm from the start of the rectangular chamber. A hot-wire anemometer is used to measure the velocity at each of 12x10 test points shown in Figure 6. The computational domain is defined as a symmetric half of the chamber. The origin of the coordinates is located at the centre of the start of the expansion section. The comparison of the velocity distribution, total pressure loss between simulation and measurement is shown in Figure 7, Figure 8 and Table 2 respectively. The error bars indicate the standard deviation of multiple data points obtained by repeated measurements on both symmetrical sides. It is evident that the parameters obtained from the unit cell study are very useful to accurately predict the flow profile in the base ESP chamber model. The relative deviation and pressure drop also match very well between the simulation and experiment.

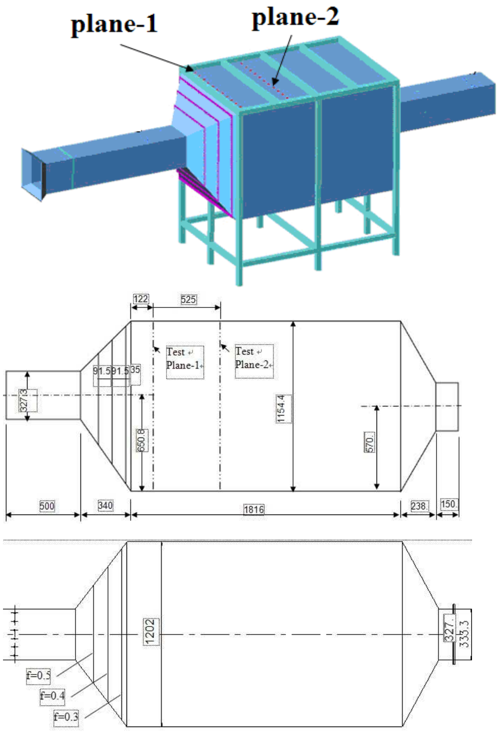

Figure 5: Base ESP chamber model and dimensions

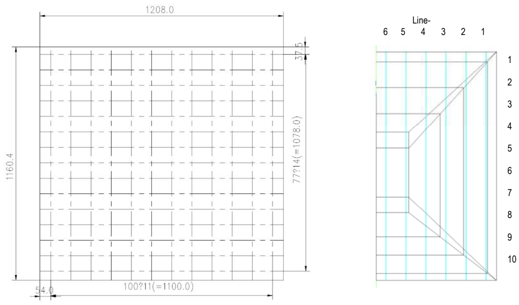

Figure 6: Measurement points

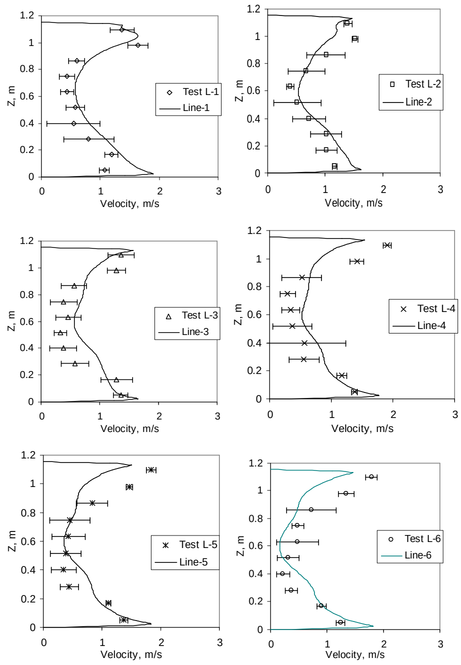

Figure 7: Comparison of velocity profiles at Plane-1 (for case with three perforated plates and collection plates)

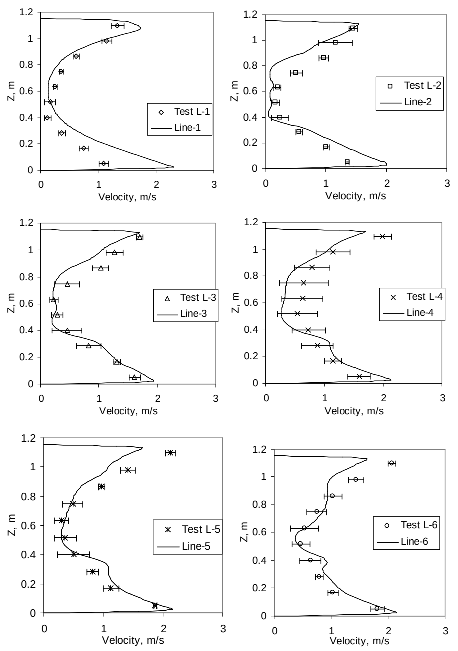

Figure 8: Comparison of velocity profiles in Plane-2 (for case with three perforated plates)

Table 2: Comparison of velocity deviation and pressure drop between simulation and measurement

	velocity deviation		Pressure drop
	Plane-1	Plane-2	(Pa)
Experiment	0.567	0.828	182
Simulation	0.576	0.854	180

Simulations of Industrial Scale ESP System

Most of industrial scale ESP systems comprise more than one the same units operating in parallel, which are connected by the inlet and outlet ductwork. The main purpose of the simulation is to optimize the entire system so that both the flow rate to each chamber and velocity distribution over the cross section of the electric field are uniform. A case study of gas flow optimized by multi-scale approach simulation is summarized as follows.

Figure 9 shows a typical layout of large scale ESP system for a 3×660MW power plant. The applied structure features double rows, four chambers, and horizontal air inlet/outlet. The two rows of ESPs and the respective flue gas rates at inlet and outlet are carefully arranged around the central line of the boiler.

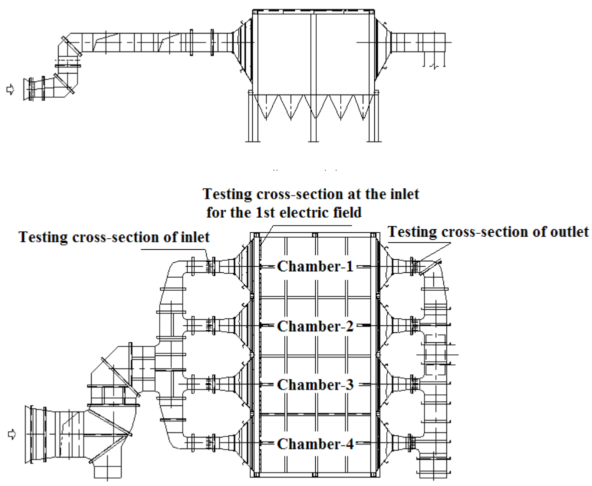

Figure 9: The schematic drawing of the general layout

Simulation Procedure

The entire system will be simulated by the procedure outlined in Figure 10. Firstly, the unit cell study of perforated plates is conducted to determine their resistance coefficients. By regression, the coefficient can be conveniently expressed as Eq.3. Secondly, the coefficients obtained from the first step will be used in ESP unit simulation, and the pressure drop coefficient for an ESP unit will be determined. Thirdly, apply the coefficient obtained from the second step to the system model to predict the inlet cross-sectional velocity profile and the flow rate to each ESP unit. Next, install appropriate guide plates in the main duct to adjust the individual branch flow rate. Finally, treat the velocity profile as the inlet velocity condition of ESP unit and recalculate flow field in the chamber.

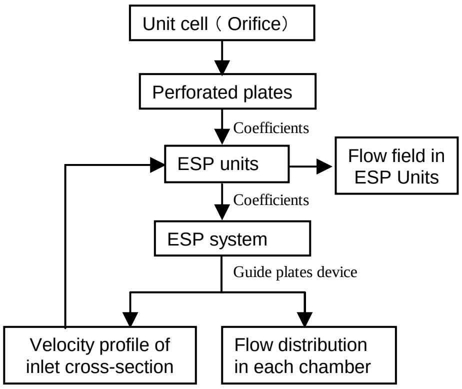

Figure 10: Simulation procedure of ESP system

Pressure Drop Coefficients of ESP Unit

ESP unit configuration is shown in Figure 11. From the smaller end to the large opening of the diffuser, the perforated distribution plates are numbered as the first, second and the third, corresponding to 50%, 40% and 30% in area porosity. The parameter determined in the unit cell studies can be implemented into porous media boundaries for perforated plates installed in ESP unit.

Figure 12 shows the overall pressure drop and pressure drop coefficient of the ESP unit with different velocity at the inlet. The pressure drop coefficient of ESP unit is found to decrease and approach a constant as the velocity increases.

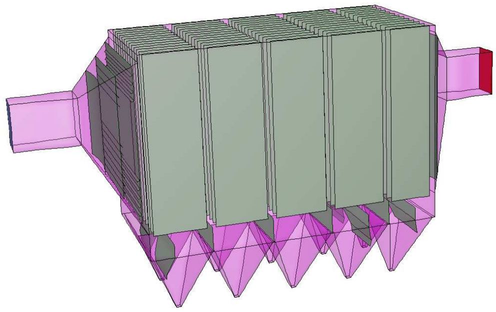

Figure 11: ESP unit configuration

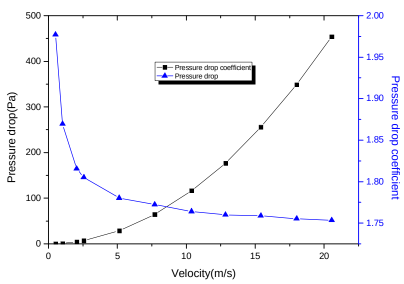

Figure 12: Overall pressure drop character through the ESP unit with different velocity

Flow Distribution in the Branch Duct

To meet the design requirement in the relative flow deviation (generally <5% in each branch), a guide plates device is installed and adjusted by changing the location and direction. In the modelling, each ESP unit is represented as a “black box” with known pressure-velocity characteristics typical of uniform porous media. The final design of guide plate device is shown in Figure 13. The inlet cross-section velocity profile and mean velocity through the branches before and after the adjustment are given in Figure 14 and Table 3. The result shows significant decrease in relative flow deviation. Here, excellent consistency of mean velocity through the branches between simulation and test is achieved.

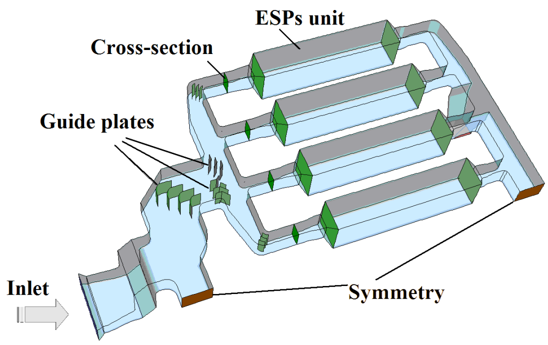

Figure 13: Configuration of whole system for flow distribution simulation

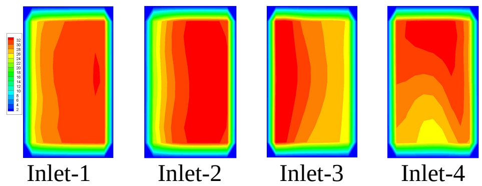

Figure 14: Inlet cross-section velocity profile

Table 3: Mean velocity in inlet cross-section (m/s)

	Inlet	1	2	3	4
Without guide plates device	Simulation	26.6	29.6	36.6	25.0
With guide plates device adjusted	Simulation	29.8	30.3	29.4	29.6
	Experiment	29.7	29.6	29.8	30.0

Velocity Distribution in ESP Chamber

The inlet cross-section velocity profile in Figure 14 is used as the inlet boundary condition of ESP unit simulation, and the flow field in chambers is recalculated accordingly. Table 4 compares simulation and experimental statistics with respect to mean velocity and relative deviation before the first electrical field. This demonstrates that the flow field in the chamber has been accurately predicted to the design requirement in velocity deviation.

Table 4: Mean velocity and deviation at the cross-section before first electrical field

Chamber		1	2	3	4
Mean velocity (m/s)	Simulation	1.567	1.548	1.554	1.594
	Experiment	1.565	1.562	1.567	1.569
	Deviation (%)	0.13	-0.90	-0.83	1.59
Relative Deviation	Simulation	0.183	0.191	0.180	0.187
	Experiment	0.188	0.198	0.178	0.192
	Deviation (%)	-2.66	3.54	1.12	-2.60

CONCLUSIONS

Gas flow through an ESP system is modelled using CFD and a multi-scale approach. Pressure drop coefficient of the perforated plates and ESP unit are obtained by extensive numerical experiments on perforated plate orifice scale and ESP unit scale respectively. The parameters are compared with the literature and experiment results, and validated in a base ESP chamber model test rig.

A large scale ESP system with several coupled parallel collection units is considered. Unequal flow rate to each branch and biased velocity profiles in the inlet duct are found. However, overall flow distribution is improved by a proposed adjustment to the guide plates, and qualitative/quantitative consistency is achieved between simulation and experiment. Therefore the multi-scale approach can be applied to the gas flow prediction within ESP system accurately and conveniently. The present work also presents a practical example of CFD being used for optimizing design of the ESP system.

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