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MODELLING OF FLUID DYNAMICS IN AN ELECTROSTATIC PRECIPITATOR

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ABSTRACT

FLUENT software was used to model the pilot-plant electrostatic precipitator (ESP) rig at CSIRO Division of Coal & Energy Technology in North Ryde, N.S.W. In 1991, a set of five louvres, or splitter plates, was installed in the inlet diffuser to divide the flow into six equal cross-sections. Modelling indicated reversed flows, boundary layers from velocity profiles, contours of flow variables and particle trajectories. Various flow-turning designs were evaluated for improving gas distribution, with minimum pressure losses, and subsequently improving the particle collection efficiency. Since electrostatic forces were ignored, only low-speed gas and inert particle dynamics were considered.

INTRODUCTION

An average pulverised-coal boiler produces about 25 tonnes of flyash per hour or approximately 200,000 tonnes per year. If this ash were deposited at sea level, in four years it would immerse the Sydney Harbour Bridge (Paulson, 1991).

In Australia, fabric filters (only in N.S.W.) and ESPS are used to collect flyash before it enters the stack. Dust collection must be trouble-free, operate continuously and perform at high efficiency. Electricity generating authorities typically specify the maximum outlet dust loading to be 0.1g m^{-3}. If the inlet dust loading is 20g m^{-3}, the dust collector must operate at 99.5% efficiency (Paulson, 1991).

ESPs have high investment costs. Due to their low cost of US$5,000-$7,000/MW, flue gas conditioning and pulsed power supplies are the preferred (Preston, 1986) options for upgrading existing ESPs. If satisfactory performance cannot be achieved by either of these two options, Preston (1986) states that the cost of enlarging or rebuilding an ESP would be US$20,000-$50,000 per installed MW. Since Australia has an installed base of 18,500MW for black coal, it is imperative that the most effective techniques are used to improve ESP performance (Vale, 1991).

RELEVANCE

The movement of flue gas, and the flyash particles conveyed with it, are of fundamental importance to the performance of an ESP. Figure 1 shows that there are three distinct areas in an ESP where gas/solid distribution is important: the precipitator inlet; the main precipitator; and the precipitator outlet.

An imbalance in the dust burden entering any two adjoining precipitators causes a marked deterioration in performance. For example, if there are two passes designed to received 50% each of the flow rate and the flow rate changes to 65% and 35%, the emission rate is doubled (Vale, 1991).

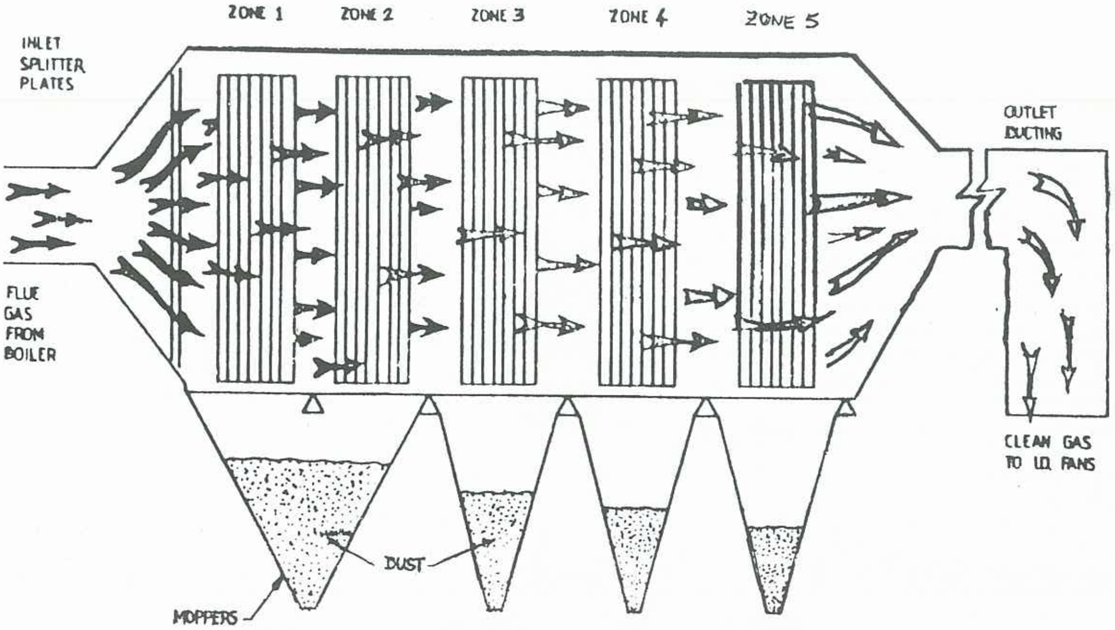

Figure 1 Schematic diagram of electrostatic precipitator.

Since the location of an opacity monitor in the duct should be where its measurement will best represent that of the entire duct, the distribution of dust in the gas steam leaving the precipitator is also of interest.

The re-entrainment of ash during rapping cycles, used to remove the ash from the plates, is widely regarded (Rumpf, 1990) as one of the major causes for ESPs not reaching their theoretical performance levels. The degradation in performance attributed to high re-entrainment levels may cause emission to become 50% to five times higher than normal. The major component of the re-entrainment occurs when the dislodged ash falls through the moving gas stream. Ash re-entrainment may be followed by re-collection or emission. Note that as soon as a particle is discharged, there is no electrical field to enhance its cohesion and it easily becomes re-entrained into the gas stream.

METHOD

FLUENT is a finite volume, fluid-flow modeling software package specifically developed for chemical, aeronautical and mechanical engineering applications. Built-in three-dimensional colour graphics allow the display of any calculated variable in terms of velocity vectors, profiles, contours and streamlines.

Of particular relevance to this project, FLUENT has the capability to model a dispersed second phase such as particles. Lagrangian trajectory computations are performed for groups of particles based on the computed continuous gas phase flow field. The effect of turbulence on the particle trajectories is modelled by a built-in stochastic tracing capability, which takes into account the local turbulence characteristics as the particle traverses the flow field. FLUENT also accounts for the exchange of momentum, heat and mass transfer between the particles and the continuous gas phase.

An important limitation of the second phase model is that the particles must be less than 10% by volume of the total fluid phase. This limitation arises from the following assumptions: (1) the volume of a computational cell is not adjusted for the presence of particles within it; and (2) there are no particle-particle interaction forces. The last assumption precludes collisions, agglomeration, coalescence, etc..

FLUENT version 3.03 was used for this paper; unfortunately, stepped cells were needed to approximate inclined planes. Version 4.1, which has a CAD-type pre-processor for body-fitting coordinates, was released in mid 1992. The manuscript deadline precluded use of version 4.1 graphics in this paper. The new version has just been received.

PASSIVE FLOW-CONTROL DEVICES

Passive flow control/stablisation devices have been studied since the end of World War II. The simplest flow-straightening device is the wire-mesh screen (Schubauer and Spangenberg, 1949). Kmonicek (1956 in Czech., 1974 translation) experimented with screens, rods, cones, single and triple rings and single and triple star-shaped flow control devices for improving diffuser operation. Welsh et al (1976) successfully used star devices to improve flow stability in straight-walled annular exhaust diffusers. Welsh (1976) also obtained good results when using a star flow-control device in wide-angled conical diffusers. None of the above flow-control devices are suitable for collecting *and removing* particles from a gas stream.

Aerodynamic flow-turning devices can settle out large particles, but not the small dust-like particles. Large particles help the total ash collection process by reducing the flow resistance of neighbouring particles (Rumpf, 1990), as well as by agglomeration.

The use of vanes to improve the performance of straight-walled subsonic diffusers is best reported by Feil (1964). The resultant design is essentially vertical splitter plates of the same length and throat spacing. This design would be suitable for use with flows with particulates. Note that the splitter plates installed in the CSIRO pilot-plant ESP are horizontally oriented. If these plates are constructed from louvres, which can rotate to allow collected particles to fall off them, then this orientation is acceptable for operational ESPs.

PILOT-PLANT ESP CHARACTERISTICS

The CSIRO experimental ESP rig at North Ryde receives dust-laden (approximately 10 ppm by volume) air from 0.15m diameter pipe and discharges air with ash at approximately 1 ppm by volume to a similar size outlet pipe. The body of the ESP is 2.4m long, 1.0m high and 0.2m wide. The inlet diffuser changes shape from the circular pipe inlet to the narrow rectangular ESP body. The top and bottom diffuser walls slope at nominally 25 degrees from a horizontal datum plane. The diffuser side walls slope at nominally 12 degrees. The convergent outlet has identical dimensions to the diffuser, except the shape changes from rectangular to circular. Two 2.4m x 1.0m electrostatic plates are situated next to the vertical side walls of the ESP body; they are 0.20m apart. The side walls are heated and lagged with insulation material to prevent heat loss.

The ESP nominally operates at 130°C and -5kPa (gauge) pressure. The density of the gas is 1.3 kg m^{-3}; the flyash density is 2,200 kg m^{-3}. Total gas flowrate varies from 500 to 900 m^{3}hr^{-1}. The particle diameter varies from 0.1 to 100 microns with a mass median diameter (MMD) of 20-25 microns. The gas stream is sampled in the 0.15m inlet pipe about 1.8m upstream of the start of the diffuser. A resistance anemometer has measured flow velocity in the middle of the ESP to be of the order of 1ms^{-1}.

FLOW MODELLING

Initially a three-dimensional (3D) geometry with a 45 degree diffuser, without splitter plates, was examined. Figure 2 illustrates the jet effect that occurred without flow turning devices; the addition of a 45 degree outlet section reduced the jet effect.

The necessity of using stepped cells to approximate inclined planes, such as the shallow-angled splitter plates, required a large computational grid. Full (1/4 symmetry) 3D geometry would require 112x36x6 cells. Since the body of the ESP was rectangular, it was decided to proceed with 1/2 symmetry, 2D geometry. Figure 3 represents the first 2D version of an ESP with straight splitter plates.

Figure 4 is a close-up of the diffuser and the start of the rectangular ESP body. There is a third splitter plate on the axis which extends to the start of the rectangular ESP body. When the ESP is mirrored in the vertical direction, there is a total of five splitter plates, including the one on the horizontal centreline. Note the boundary layer growth on all plates in the diffuser. The angles are correct, but the inlet and outlet planes are too large relative to the ESP body.

Although it is easy to reduce the ESP outlet plane, the only way to reduce the diffuser inlet plane with FLUENT version 3.03 is to adjust the computational grid in that area. The first attempt produced relatively steep, double-sloped splitter plates. Figure 5 shows the second attempt where both splitter plates begin with a 5 degree slope; the more shallow plate changes to a 10 degree slope; and the steeper plate changes to a 18 degree slope. Flow velocity near the centreline of the ESP body is 1-3 ms^{-1}, which is acceptable for operational ESP. The velocity profiles are disturbed along and immediately following the splitter plates. Then the velocity profiles become relatively flat.

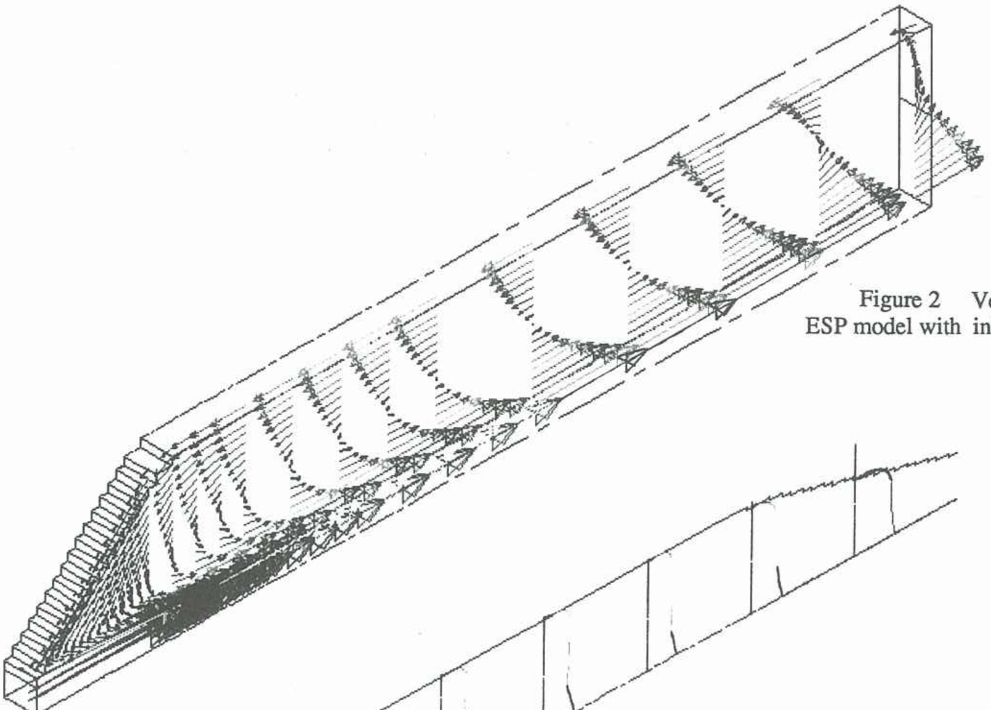

Figure 2 Velocity vectors in primitive ESP model with inlet flow velocity of 10 m/s.

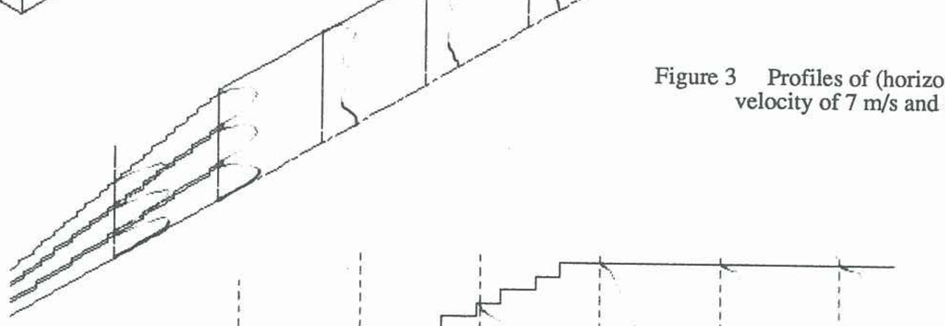

Figure 3 Profiles of (horizontal) U-velocity with an inlet velocity of 7 m/s and a maximum of 9m/s.

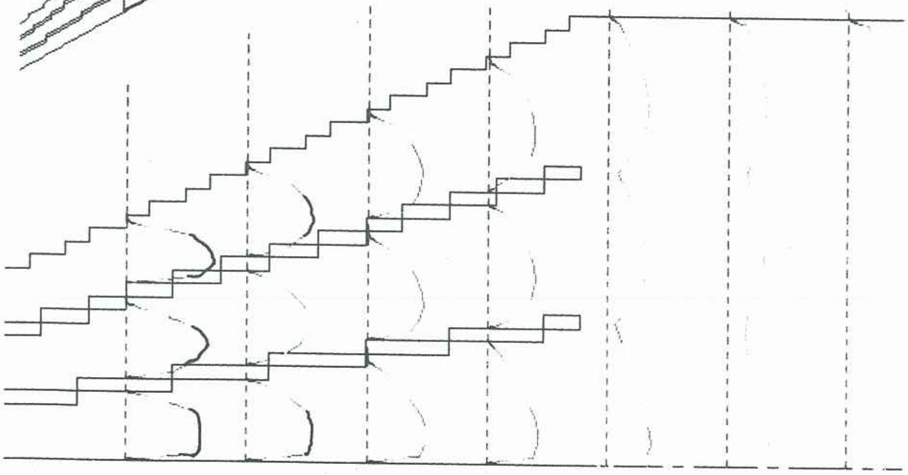

Figure 4 Enlarged diffuser section of Figure 3.

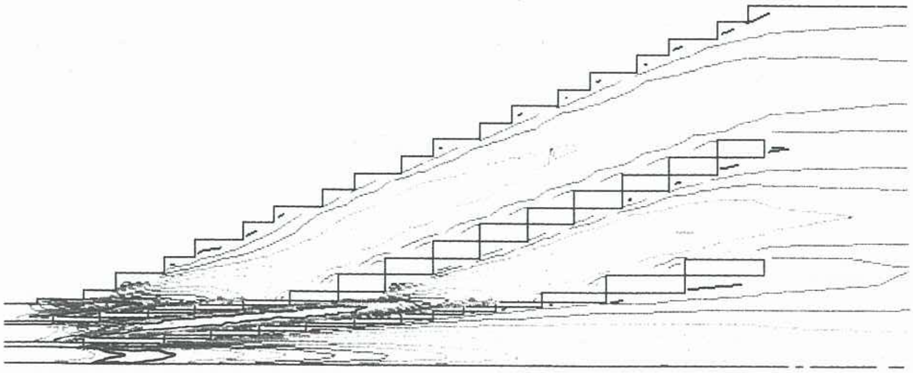

Figure 5 Contours of U-velocity with identical velocities as Figure 3.

It is possible to have 10 particle injection points. Each of these injections may have up to 10 particles emitted from them. The maximum was used with this study. Only the mean particle tracks will be presented here. Figure 6 shows the 20 micron mean particle tracks for the diffuser with correct inlet and outlet size. Figure 7 illustrates the effect of removing the first part of the two inclined splitters and of using the actual 130°C operating temperature. Note the bunching of the lower and middle particle tracks.

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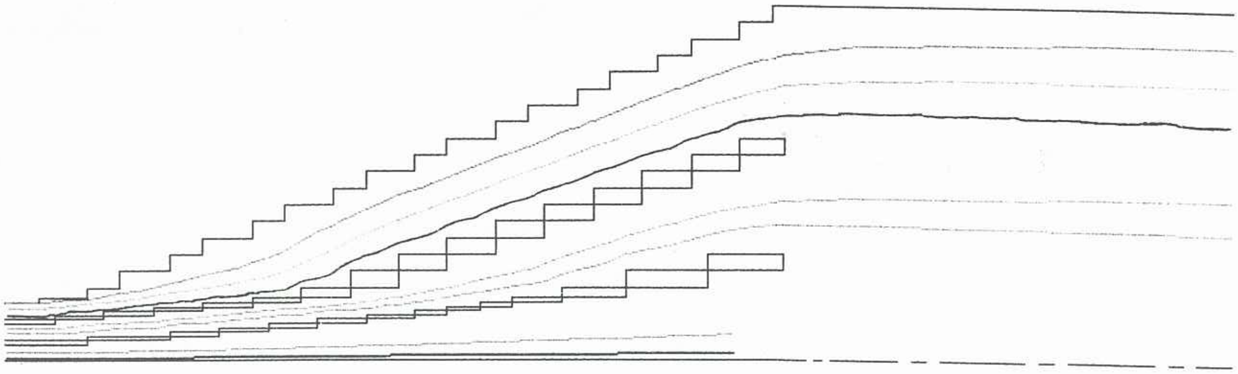

Figure 6 Mean particle tracks for 273K operation.

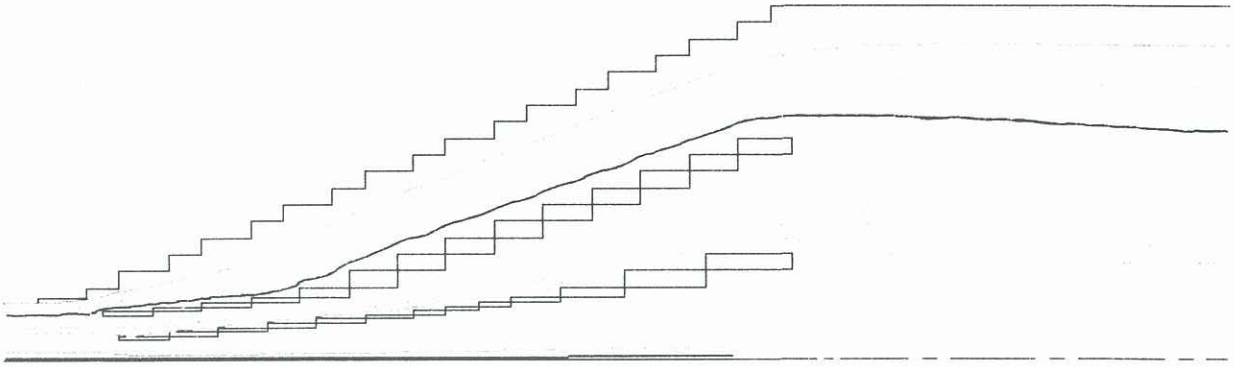

Figure 7 Mean particle tracks for 400K operation.

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