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Evaluation of Large Particle Ash Screen Designs for SCRs Using CFD

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ABSTRACT

The power industry is facing increased challenges in the operation and performance of selective catalytic reduction (SCR) systems on pulverized coal boilers because of large particle ash (LPA) also called "popcorn" ash transport through the system. LPA can cause significant catalyst plugging and erosion. At the same time, ash buildup will decrease the flow area of the SCR reactor and as a result will increase the catalyst deactivation rate. Modifications to both the ash removal systems as well as the economizer hoppers can help mitigate these issues.

This paper describes Riley Power Inc.'s (RPI) approach to LPA screen design and its use of CFD modeling in the design and implementation of LPA mitigation methods in SCR reactors. The initial design stage consisted of modifications to the economizer outlet with the primary focus placed on the orientation and location of the large particle ash screens to prevent the carryover of ash particles. The computational modeling examined the velocity profiles within the economizer outlet for various economizer and screen configurations. Once the economizer hopper and screen designs were selected, an additional optimization study was conducted on the screen top design in order to compare the approach velocities and ash particle loading. The final design solution and the benefits of the CFD modeling process are discussed.

INTRODUCTION

Large Particle Ash Mitigation Methods

Typically there are two approaches to preventing LPA from entering an SCR reactor. The first approach, commonly referred to as an aerodynamic approach, utilizes baffles, plates, or other flow distribution devices to divert LPA into the existing economizer hopper area. The second approach utilizes perforated plate or wire mesh screens to prevent particles above a certain size from exiting the economizer outlet. For the utility boiler application discussed here a screen solution has been implemented. Typically screens experience much lower gas-side pressure drop and additionally, the designs are much less dependent on the physical properties of the LPA (i.e. density, size distribution, etc.) than the aerodynamic approach. This translates to lower operating costs and greater confidence in final screen design. Wire screens with screen openings on the order of 4-5 mm are typically employed and can be very effective if maintenance issues are addressed.

Large Particle Ash Screen Design Considerations

The economizer outlet's lower relative gas velocities and torturous flow path, in addition to an existing ash removal system, make it the most favorable location for fly ash removal. Depending on the particular hopper design, a significant fraction of the popcorn ash can be captured in the existing economizer hopper. Larger particles fall out of the flow easily as the flow makes a 90 deg. turn. The aerodynamic capture rate decreases with the decrease in size of the particle and is influenced by the economizer outlet and hopper geometry. Ash particles which are not captured aerodynamically are physically blocked by a wire mesh screen. The effectiveness and life of the screen is influenced by many factors. The LPA screen will be placed at the economizer outlet section. The openings in the screen are made slightly smaller than the catalyst openings. It is necessary to ensure that flue gas velocity across the screen is lower than prescribed limits to limit erosion rates. The screens are subjected to particle laden flue gas flow in an acidic environment. This is more of a concern in cases where the fuels produce fly ash with highly erosive characteristics. The erosion rate is most sensitive to the flue gas velocity and generally can be expressed as: E=CMVn, where C=constant; M=ash particle loading (lb/ft3); V=flue gas velocity and n=velocity exponent 2.25.

The screen material choice and wire thickness affect the screen life and pressure drop. Thicker wires make the screen more robust but reduce the amount of free area and increase pressure drop. With respect to screen orientation it is advantageous to have the screen slope backwards over the hoppers. This increases the aerodynamic capture efficiency of the popcorn ash in the hoppers. The screen slope is often obtained by attaching the screen to a suitably angled short flat plate. The plate serves the additional purpose of preventing direct impingement on the screen. For the utility boiler application described in this paper a more advanced moveable screen construction was considered. The screen would periodically rap to clean the screen and thus prevent screen plugging. The screen consists of panels and each panel could make use of different screen material and design.

Large Particle Ash Characterization

CFD simulations of particle-laden flow require inputs regarding the dispersed phase properties. Typically, key LPA properties governing entrainment or separation from flow, such as particle size, shape, density, and coefficients of restitution, are determined experimentally. To measure the aerodynamic properties, samples of ash are collected from the economizer hopper. Typical properties of interest are as follows:

(i) Density — The apparent density of the popcorn ash particles can be measured by different techniques. For this study the specific gravity is assumed to vary between 0.6 and 1.3.

(ii) Sphericity — The aerodynamic drag on the popcorn ash particles depends on the size and shape. The popcorn ash particles are not perfect spheres and as such, the drag expression needs to be modified, typically by incorporating sphericity in the drag expression. A sphericity of 0.8 has been assumed for all particles in this study.

(iii) Coefficients of restitution — The particle-laden flow modeling requires information on what happens to particles after they hit the wall. This is characterized by normal and tangential coefficients of restitution. In general this varies widely between particles and with each collision. In this engineering study a constant coefficient of restitution has been assumed in the normal and tangential direction.

(iv) Particle size distribution — Particle size distribution is estimated by doing a sieve test on the collected ash sample. Popcorn ash particles can grow up to 1 in size and collected samples show a wide variation in sizes.

With the exception of particle size, the pertinent LPA properties were selected based on Riley Power's past experience and practices [1-2].

SCREEN DESIGN EVALUATION & OPTIMIZATION USING CFD

Scope of CFD Modeling

The primary objective for the CFD modeling was to determine approach and through velocities for the current screen and hopper design. It is desirable that the peak velocities across the screen be lower than the specified maximum for a given screen material choice. Also, for the given hopper design the aerodynamic capture efficiency was estimated as a function of particle diameter. The CFD model included the economizer outlet section just above the lowest existing economizer header to a location sufficiently downstream of the economizer outlet. Riley Power Inc. has used the commercial CFD code FLUENT for this study. A generalized schematic indicating the CFD model boundaries is shown below in Figure 1 where the scope of the study area is highlighted in red.

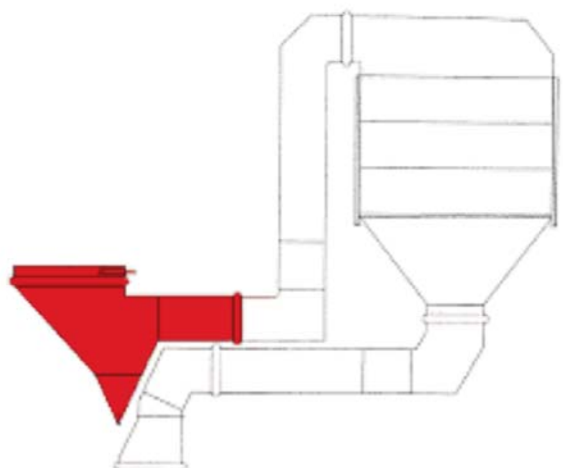

Figure 1: Scope of the CFD Model

The CFD analyses were conducted in two phases. In the first phase, a series of 2-D simulations were run followed by the second phase, in which several 3-D simulations were run to establish confidence in the use of 2-D approximation as a design tool and also to evaluate screen top designs.

The following simulations were conducted:

(a) 2-D computational models for evaluating the hopper design alternatives
(b) 2-D particle laden flow simulation to estimate aerodynamic capture efficiency
(c) 3-D computational model to study flue gas flow and validate the 2-D results
(d) 3-D particle laden flow simulation to verify and compare to 2-D model results
(e) Evaluation of screen top design options

CFD Model Assumptions and Boundary Conditions

The flow analysis solved for incompressible isothermal flow. Typical flow rates and pertinent LPA properties assumed in the model are listed below in Table 1.

Table 1

Typical Operating Conditions and LPA Properties used in CFD Modeling

Parameter	Units	Value
Flue Gas Flow per reactor	pph	Approx. 3,000,000
Flue Gas Temperature	°F	650
Flue Gas Density	lb/ft3	0.035434
Selected LPA Particle sizes	mm	0.50, 1.00, 3.35, 4.75
LPA Sphericity	--	0.8
LPA Coefficient of Normal Restitution	--	0.44
LPA Coefficient of Tangential Restitution	--	0.70

The 2-D model corresponds to a cut through the deepest point of the hopper and assumes that the flow is primarily in plane. The CFD model of the economizer outlet and hopper with the screen installed is shown in Figure 2.

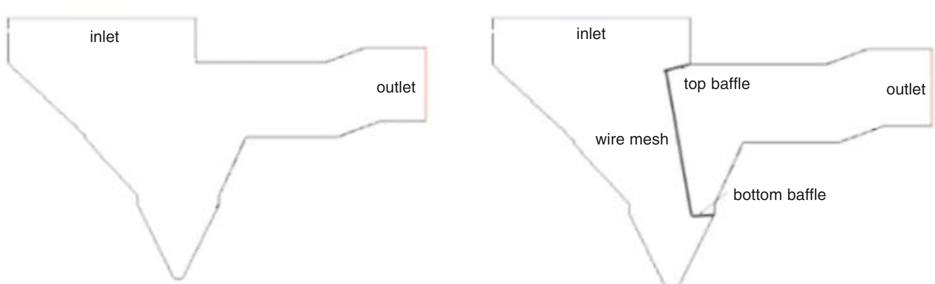

Figure 2. Schematic of the 2-D CFD Model (a) without screen and (b) with screen

The 3-D model geometry includes half of the economizer with three hoppers and is illustrated in Figure 3. Highlighted in the same figure is the moveable-type LPA screen selected for this study.

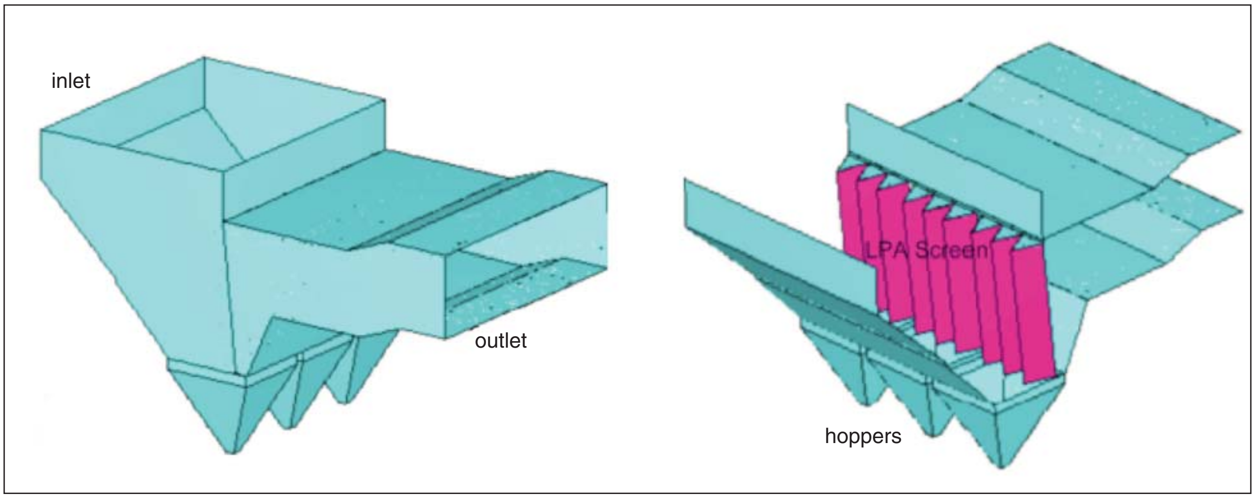

Figure 3. Geometry of 3-D CFD Model and details of the 3-D wire mesh screen

2-D Flue Gas and Particle Laden Flow Simulations

First, several hopper design concepts were compared by simulating flue gas flow without the screen and ash particles. The current and previous outlet and hopper cross-sections are shown below in Figure 4. It can be seen that the current design reduced the area of high velocity present at the economizer outlet.

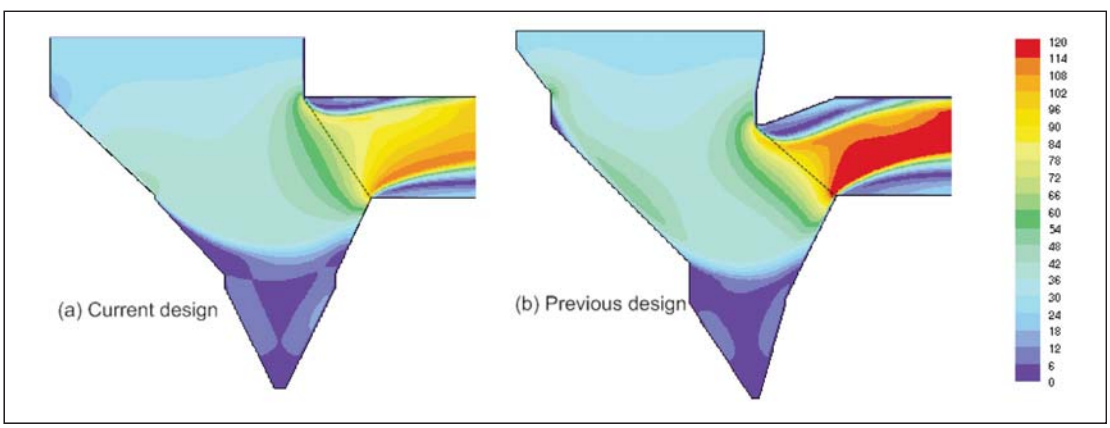

Figure 4. Velocity contours from 2-D CFD analysis of economizer outlet and hopper design

Once the hopper design was selected, LPA particles were added to the incoming flue gas stream to estimate the aerodynamic capture efficiency as a function of the particle diameter. The aerodynamic LPA capture efficiency is compared between the two different hopper designs from 2-D simulations in Figure 5. The variation of aerodynamic capture rate of ash particles with particle size for the current and previous designs is shown in Figure 6. It can be seen that the current design has almost identical aerodynamic ash capture rate compared to the previous design. The current and previous designs experience high rate of particle impingement and re-entrainment on the hopper front wall. The particles impinging on the front wall can also be deflected towards the hopper by a baffle plate placed at the bottom of the screen.

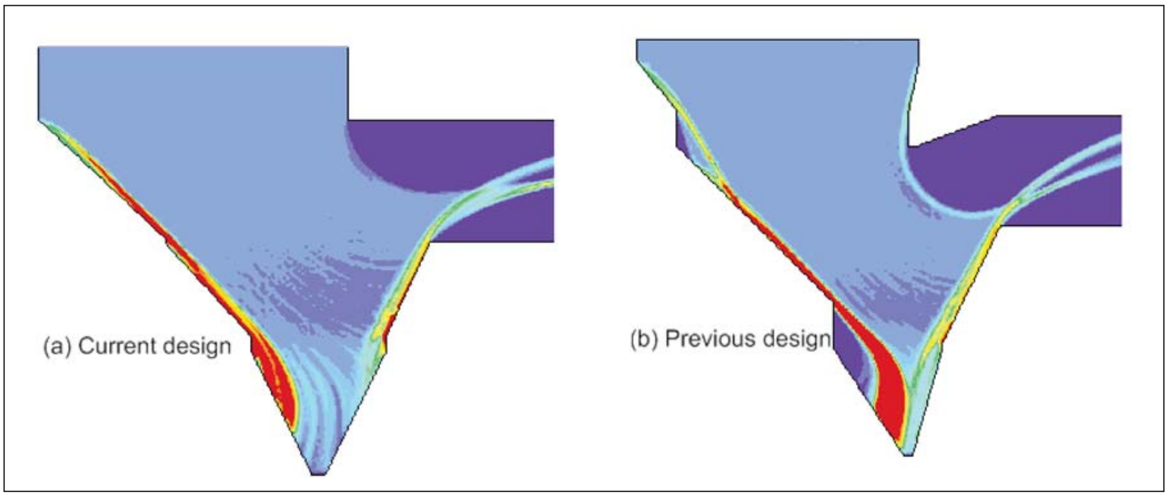

Figure 5. Contours of ash particle concentration for a particle diameter of 1m specific gravity 0.6 and sphericity of 0.8

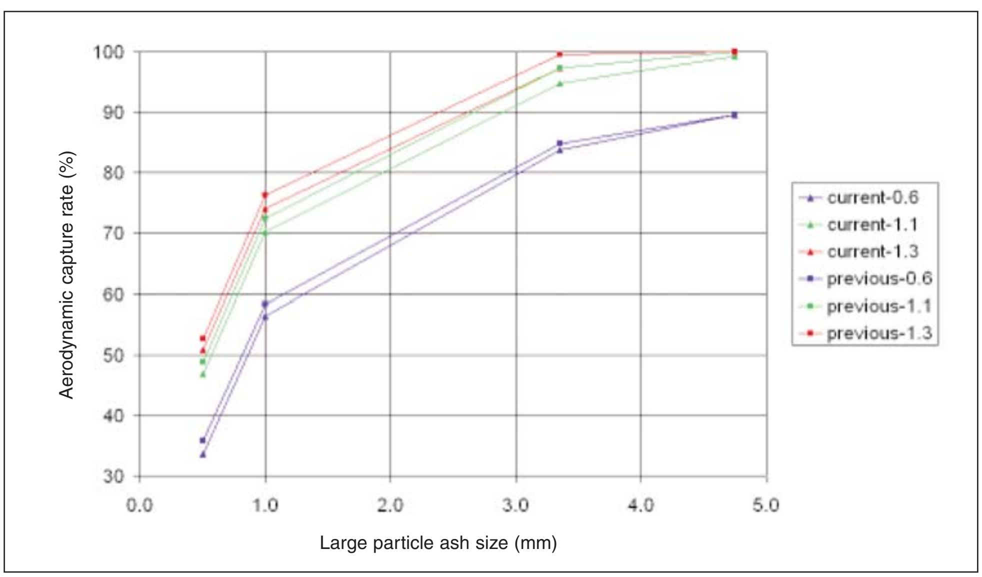

Figure 6. Aerodynamic capture rate of ash particles vs. size for current and previous designs

As expected, the particle laden flow simulations show that, large ash particles fall downwards and are easily collected in the hopper, while, a significant portion of particles which are 1 mm in diameter or smaller can be expected to be carried with the flow as the flow makes a 90 degree turn.

3-D CFD Simulation of Flow in Economizer outlet and Hopper

To verify the results from the 2-D simulations, a series of 3-D models were completed. The flow field solutions were evaluated and compared and then ash particles with a diameter of 1 mm, sphericity of 0.8 and specific gravity 0.6 were introduced into the 3-D model. The velocity field in the x-y plane at two sections passing through the 3-D model is compared to the velocity field obtained from 2-D simulations in Figure 7. Additionally, the ash particle concentration plots for the 2-D and two different planes for the 3-D simulation are also compared in Figure 7. The velocity field and ash particle distribution were nearly identical for the 3-D model sections and the 2-D CFD predictions, which showed that a 2-D model is a reasonable approximation for the flow solution and an indicator for the areas of interest for the particle-laden flow. From the complete 3-D simulations with a uniform economizer outlet velocity profile, the maximum approach and through velocities associated with the screen were estimated at 50.0 ft/s and 75.0 ft/s respectively. Skewing the economizer outlet velocity profile changed the maximum expected approach velocities associated with the screen. Biasing the flow towards the right hand side increased the maximum velocities while biasing the flow towards the left hand side had the opposite effect, i.e. reduced maximum velocities.

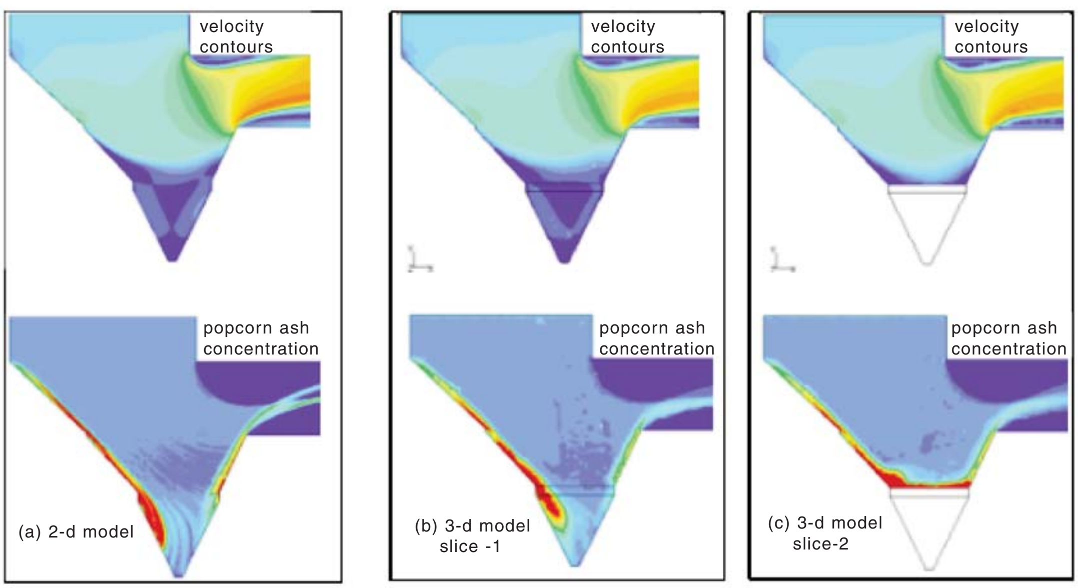

Figure 7. Velocity magnitude and popcorn ash concentration contours (a) 2-D model (b) 3-D model — plane through deepest point of the hopper (c) 3-D model — plane through shallowest point of the hopper

The 3-D simulations incorporating actual measured ash particle distribution revealed that between 36 % and 49 % of incoming LPA mass will escape aerodynamic collection in the hopper. This consisted mainly of particles with spherical diameters < 1mm.

Screen Top Design Evaluation

The next step in screen optimization was to compare the three possible design alternatives for the screen top and evaluate their effect on the flue gas velocity and solids flux across the screen face. The three screen top designs considered were triangular, flat plate and tetrahedral cap and are shown in Figure 8.

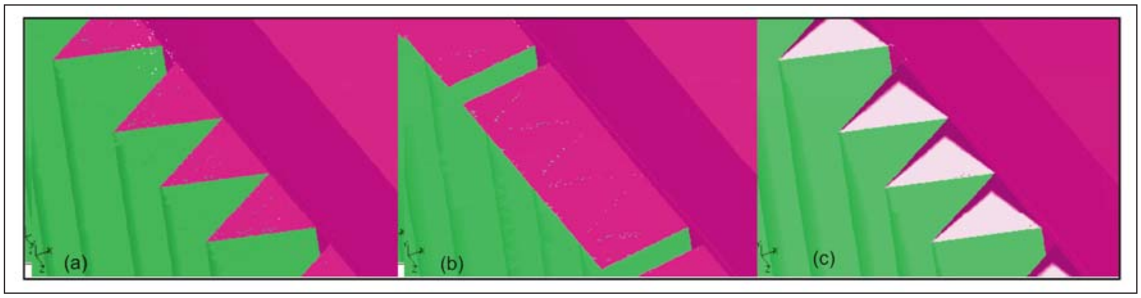

Figure 8. Screen top design options (a) triangular (b) flat plate, and (c) tetrahedral cap

The 3-D CFD model was run with flue gas flow and ash particle flow mentioned in Table 1. All ash particles were assumed to have specific gravity, 1.1 and sphericity 0.8. The particle size distribution was obtained from sieve analysis of collected ash samples [3]. The velocity magnitudes and solid flux distribution across the screen face for the three top design options are shown in Figure 9.

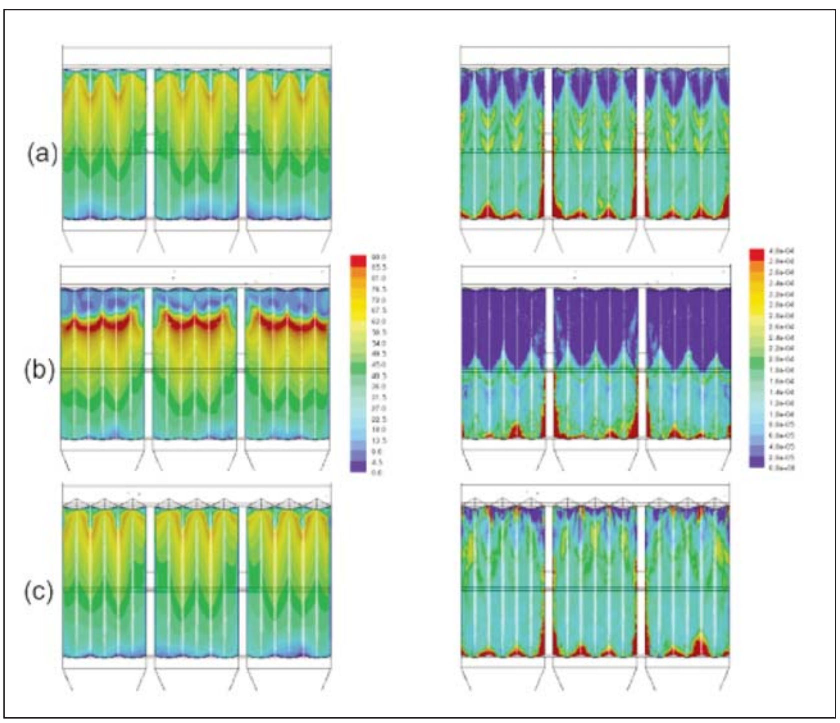

Figure 9. Flue gas velocity (left) and ash particle concentration (right) contours at the screen inlet for (a) triangular top (b) flat plate top and (c) tetrahedral top

The results showed that the flat plate top design is most unfavorable in terms of non-uniformity of velocity and solids flux distribution across the screen. The triangular top and the tetrahedral top designs resulted in more uniform flue gas velocity and solids flux distribution.

Out of the three screen top designs evaluated, the flat plate top reduced the gas flow over the top section of the LPA screen. The peak velocity across the screen was highest for this design at 93.4 ft/s. The triangular top and tetrahedral cap top designs produced a similar flow distribution across the screen face with peak velocities at 89.9 and 92.0 ft/s respectively. The normal operating conditions indicate that the durability of the screen depends on the flue gas velocity across the screen and additionally, manufacturer's warranty requires that peak velocities be lower than the prescribed limit. The particle laden flow simulations show that the screen top design choice changes the LPA particle loading across the screen as illustrated in Figure 9. The flat plate design leads to much lower LPA particle loading at the top of the screen. In contrast, the tetrahedral cap top design leads to most uniform LPA distribution across the height of the screen and therefore is the preferred choice over the triangular cap design.

CONCLUSIONS

The efficient operation of SCR units requires good ash removal systems in place to deal with large particle ash. A CFD flow simulation study like the one described in this paper can confirm that hopper design, screen choice and placement are appropriate and optimum. Through CFD simulation, we have ensured that the velocity in the economizer outlet, hopper and LPA screen region are kept as low as possible and that the chosen outlet and hopper design produces a high aerodynamic capture rate for the popcorn ash particles. For the utility boiler considered here the screen is made up of panels and based on the flow simulation results the screen panels near the top experience high velocity flue gas flow and more prone to erosion. A different material choice for these sections of the screen will ensure the screen has adequate life.

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