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Computer Modeling of Flow, Thermal Condition and Ash Deposition in a Hot-Gas Filtration Device

Keywords: Hot-Gas Filtration, Computer Simulation, Ash Deposition, Filter Vessel

Objectives and Approach

The objective of the present study is to develop a computational model for simulating the gas flow, thermal condition and ash transport and deposition pattern in the hot-gas filtration systems. The computational model is to provide a virtual tool for design and operation modifications. Particular attention is given to the Particle Control Device (PCD) at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. For evaluation of gas velocity and temperature field in the vessel, the FLUENT^{TM} commercial CFD computer code is used. Ash particle transport and deposition pattern was analyzed with the Largrangian particle tracking approach.

Introduction:

Developing clean coal technology for electric power generation is a major goal of the U.S. Department of Energy as well as power industry. As a result advanced highly efficient Pressurized Fluidized Bed Combustors (PFBC) and Integrated Gasification Combined Cycle (IGCC) are developed and are being tested. These advanced coal-fired systems require effective removal of particulate matter from high-temperature, high-pressure gas streams produced from coal combustion and/or gasification. Effective removal of particulate matter from the hot-gas is essential for protecting the downstream gas turbines components from damages due to fouling and erosion. In addition the gas need to be cleaned to meet particulate emission requirements.

Currently the effort for hot-gas cleaning of coal-fired advanced energy systems is focused on the use of ceramic candle filters due to high efficiency and the capability to operate at high temperatures. Ceramic candle filters typically have a diameter of about 6 cm and a length of 1 to 1.5 m, and with the wall thickness of about 1 cm. An industrial unit normally contains a large number of candle filters. During the operation of the filter vessel, the clean hot-gas pass through the porous walls of the ceramic filters. The ash particles form deposit on the outside of the candle filter and form a filter cake. As the thickness of the filter cake builds up and the filter pressure drop increases. To avoid the excessive pressure drop, groups of candle filters are periodically cleaned by a rapid backpulse procedure.

A number of pilot and demonstration scales hot-gas filtration systems were developed and tested in the past. Under ideal operating conditions, the hot-gas filtration systems effectively remove fine particles and deliver essentially particulate-free hot gases that meet turbine engineering requirements and regulatory standards for power-plant emissions, while produce stable (design) pressure drop across the filtration system (Lippert et al., 1995; Radian, 1994). In this case, the cyclic cleaning pulse removes the transient cake from each filter leaving only a rather stable residual cake. The routine logging pressure drop across the tubesheets then shows saw tooth variation with stable peaks.

On occasions, however, the pressure drop across the tube sheet may not reach a steady state value, but increases continuously. When ash-deposits build up in a filter vessel, the pressure drops across the tubesheet provides an indication of an operating problem. Monotonically increasing pressure drops imply that particulate cakes are building up on and/or around the filters. “Ash bridging” occurs when all of the space between adjacent filter surfaces has been filled by particles. This normally lead to disruption of the filtration process due to candle filter failure and/or excessive pressure drop. The details of the mechanism for ash bridging are not known. The incomplete filter cleaning during backpulse, in which within each cycle the amount of cake removed is slightly less than the amount of new cake formed was suggested as a potential mechanism. In this case the average filter-cake radius slowly expands until cakes on adjacent filters meet. Among other hypotheses it was suggested that the “ash bridging” is caused by particle depositing on solid surfaces (tubesheets and central post) that have no cleaning mechanisms (Ahmadi and Smith, 1998).

To make hot-gas filtration process effective and reliable, it is important to identify the mechanisms that control ash bridging under various operating conditions. Thus, understanding the ash deposition process in the filter vessel as well as the spatial distribution of the particle deposition pattern is critical to ash bridging mitigation. The model of Smith et al. (1998) and the data of Dahlin et al. (1998) and Kono et al. (1998) provided information concerning the time dependence of the filter cake thickness. The analysis of the operating data by Smith et al. (1997b), the model of Ferer and Smith (1998) also provided insight into the process of incomplete cleaning.

To design reliable hot-gas cleaning filtration systems, a fundamental understanding of the particle transport and deposition in the filter vessels is needed. Due to extreme high temperature and toxicity, direct experimentation of the ash transport during the operation of the industrial scale filter vessel is not feasible. On the other hand computer simulation provides an effective and economical tool for analyzing the transport processes in complex passages. Therefore, computational modeling of gas flow and particle transport and deposition in filter vessel is a cost-effective technique available for advancing our knowledge on the mechanism by which particle deposits begin and grow.

PARTICLE code developed by Ahmadi and co-workers (Li et al., 1994; He and Ahmadi, 1999) has been used for predicting particle transport and deposition patterns in complex regions. Ahmadi and Smith (1998a,b) have reported computer simulations of the hot-gas filtration process including the gas flow and particle deposition in the hot-gas filter vessel at Tidd 70 MWE PFBC Demonstration Power Plant. Ahmadi and Zhang (2000) and Zhang and Ahmadi (2001) reported the results of their computer simulations of the hot-gas filter vessel at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama, under isothermal conditions using a low-resolution model. Recently Mazarei et al (2001) developed a high-resolution isothermal computational model for analyzing the filtration process.

Temperature variations, however, have been reported in the hot-gas filter vessel at Wilsonville (Davidson et al, 1999; Guan, 2000) with higher temperatures at the upper portion of the vessel and cooler near the cone. These experimental findings have motivated Gamwo et al. (2001a,b) to study the temperature variation in the vessel using a temperature-dependent low-resolution model.

In this study, a high-resolution grid and the FLUENT^{TM} code is used and the gas flows and the thermal condition in the particle Control Device (PCD) at the Power Systems Development Facility (PSDF) are studied. The computer simulation results for the mean gas flow and temperature distribution are presented and discussed. The simulation results show strong rotating flow pattern in the gap between the shroud and the refractory liner and in the body of the vessel. The computed temperature distribution in the vessel shows qualitative agreement with the observation of the demonstration scale PCD at the PSDF.

Power Systems Development Facility

The schematics of the advanced coal-fired electricity generating systems at demonstration-scale Power Systems Development Facility (PSDF) in Wilsonville, Alabama are shown in Figure 1. The PSDF can operates in both Integrated Gasification Combined Cycle (IGCC) (Figure 1, upper part), as well as Pressurized Fluidized Bed Combustors (PFBC) (Figure 1, lower part).

U.S coals normally have moderate to high level of sulfur and require addition of a sorbent like limestone in order to remove SO_x emission. In the Integrated Gasification Combined Cycle (IGCC) system (Figure 1, upper part) based on the transport reactor, ground coal and limestone are injected into a circulating-transport gasifier/combustor where combustion occurs. The hot gases and entrained fine particles of ash and sulfur pass through a cyclone, which removes large particles. The finer particles that remain then are removed in the filter vessel, so that the cleaning gas could be sent directly to a fuel cell. In the Advanced Pressurized Fluidized Bed Combustor (APFBC) system (Figure 1, lower part), coal is introduced into a carbonizer, which converts the coal into char and hot combustible gases. As in the second-generation PFBC, fine particles are removed from the hot gases by a cyclone and filtration unit, the char then is fed into a pressurized combustor, and particles are removed from the hot combustor gases by a second cyclone and a filter vessel. The clean gas exiting from the filter vessels is sent through a hot-gas turbine. As illustrated in Figure 1, three filter vessels are present at the PSDF site. At the current time, however, only on the filter is under investigation.

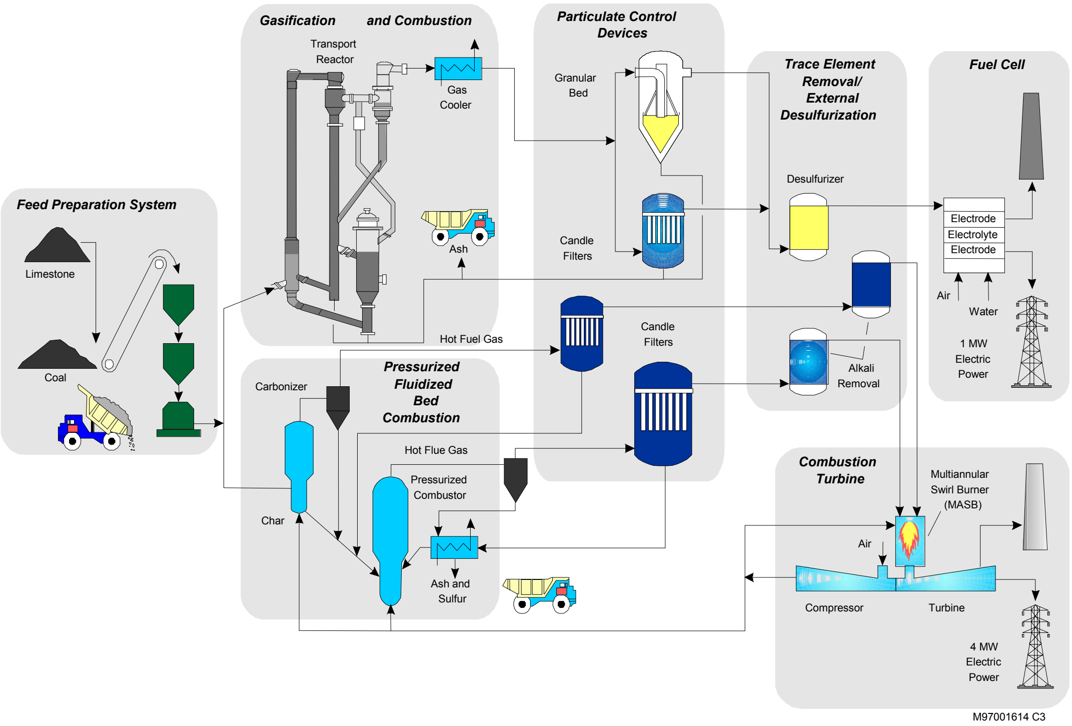


Figure 1. Schematic of the Integrated Gasification Combined Cycle (IGCC) and Advanced Pressurized Fluidized Bed Combustor (APFBC) System at the Power Systems Development Facility in Wilsonville, Alabama.

Particle Control Device

The Particle Control Device (PCD) at Wilsonville, Alabama accommodates 91 candle filters arranged in two plenums. The upper plenum has 36 and the lower has 55 candle filters. The ceramic candle filters are about 6 cm (2.36 in.) outer diameter and 1.5 m (4.92 ft) long. The gas enters the vessel tangentially into the shroud. Ash particles are collected on the external surface of the candle filter and form the filter cake during the normal operation of the vessel. The filter cake is removed from groups of filters by a high pressure reverse-flow, compressed air, backpulse process. A schematic diagram of the PCD filter vessel is shown in Figure 2. Additional details of the PCD may be found in the work of Davidson et al. (1999) and Zhang and Ahmadi (2001).

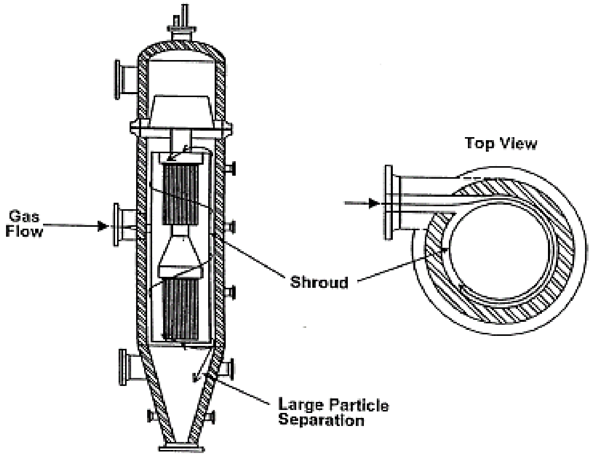


Figure 2. Schematic of the Particle Control Device (PCD) vessel.

Simulation Conditions

To make the computational effort manageable, the group of candle filters in the upper plenum is replaced by six effective filters and the lower cluster of filters is replaced by seven effective filters. Each effective filter has an outer diameter of 27.9 cm (11 in.) and an inner diameter of 23.9 cm (9.4 in.). The exception is the center equivalent filter in the lower tier that has an outer diameter of 40.6 cm (16 in.) and an inner diameter of 34.3 cm (13.5 in.). The permeabilities for the 11 and the 16 in equivalent filters are, respectively, $2.033\times10^{-12}m^2$ and $3.05\times10^{-12}m^2$ (Mazaheri et al., 2002). A schematic of the modeled PCD vessel is shown in Figure 3.

The inlet gas enters the PCD vessel tangentially into the gap between the shroud and the vessel refractory with a superficial velocity of 9.82 m/s at a temperature of 760 ^{0}C (1033 K). The inlet turbulence intensity is assumed to be 5% and an air density, viscosity, and heat capacity of, respectively, 4.53 kg/m^3, 3.7×10^{-5} kg/m.s, 1006.4 J/kg K for an operating pressure of 1344 kPa are used. A temperature of 600 K for the vessel wall is assumed in the simulation.

Computational Model

The hot-gas flow in the Particle Control Device is in a state of turbulence motion. We used the Reynolds Stress Transport Model (RSTM) of the FLUENT code for analyzing the hot-gas flow and heat transfer in the vessel. The RSTM accounts for the evolution of individual turbulent stress components, and therefore, is well suited for handling anisotropic turbulence fluctuations in the vessel.

Results and Discussion

Figure 4 shows the grid generated by GAMBIT code and is used in the present simulation. The grid is unstructured and contains 1,371,262 cells. This figure shows the grid for the tubesheet and the equivalent upper and lower filters, and the connecting post inside the PCD vessel. In addition, the details of the grid at the mid-section of the vessel

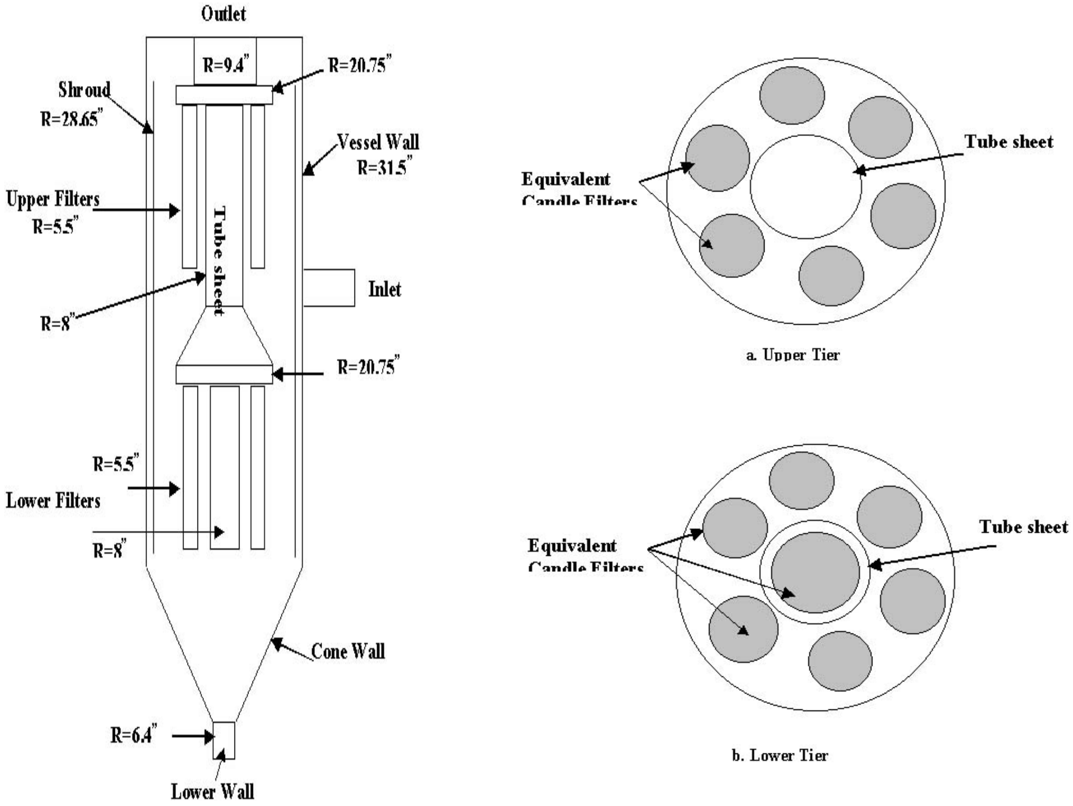


Figure 3. Schematic of the modeled PCD vessel.

are shown in Figure 4. It is seen that the grid near the shroud is further refined.

As stated before, the Reynolds Stress Transport turbulence model in addition to the heat transfer equation were used in these computations. In the simulation, the origin of the coordinate system is set in the center of the circle on top of the vessel. The z-axis is in the vertical direction (gravitational direction) and the x-axis is along the inlet flow direction.

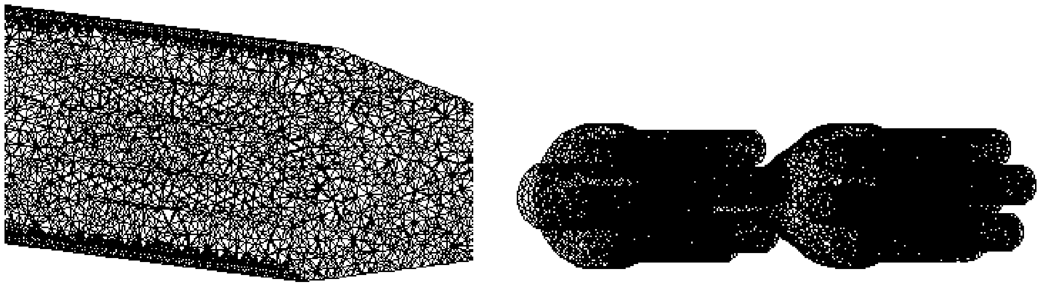


Figure 4. Schematics of the grid used in the simulation.

The gas temperature variation in the PCD vessel is shown in Figure 5. Figure 5a shows the temperature contours at the mid-section of the vessel and three planes across the vessel. This figure shows that the temperature in the inlet region and in the gap between the vessel wall and the shroud is at 1033 K. The temperature is cooler near the conical section in the lower part of the vessel and is higher at the outlet. This trend is in qualitative agreement with the observation at the PSDF (Guan, 2000). Figure 5b shows the gas temperature variation inside the PCD vessel including the filter assembly. It is seen that the temperature in the vessel is roughly uniform with the temperature near the lower filters being slightly lower than that near the upper filters.

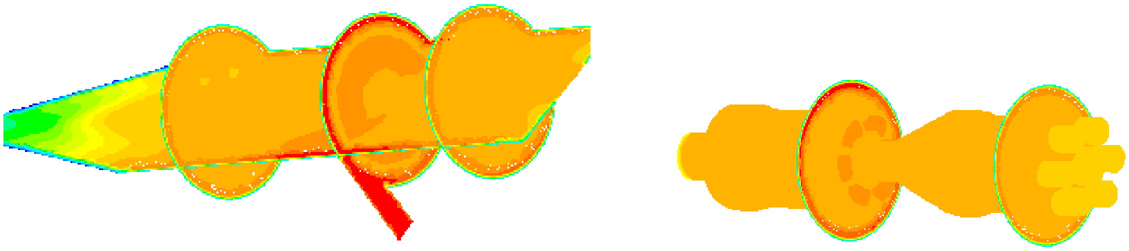


Figure 5. Temperature variations in the PCD vessel.

Variations of the static pressure in the PCD vessel are shown in Figure 6. This figure shows a perspective view of the pressure variations at several sections across the vessel, and at the filter assembly. It is seen that the pressure is uniform inside the filter vessel. The main pressure drop occurs across the candle filter walls and that the pressure is constant in the filter cavity and in the outlet pipe. These observations are in agreement with the earlier results of Zhang and Ahmadi (2001), Mazaheri et al. (2002) and Gamwo et al. (2001a,b).

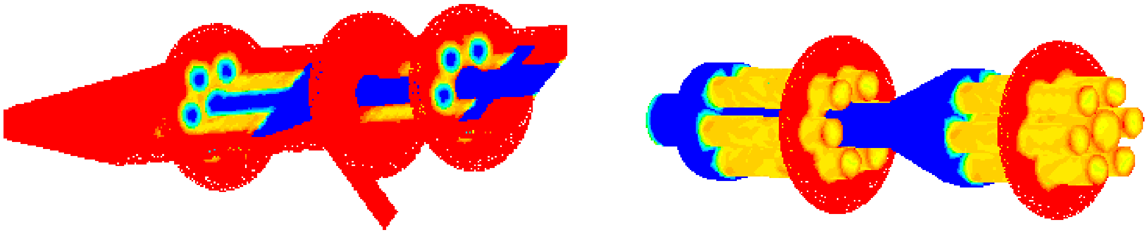


Figure 6. Pressure variations in the PCD vessel.

Figure 7 shows the velocity vector fields in several planes across the PCD filter vessel. The plane in the middle crosses through the inlet of the PCD vessel. It is seen that the velocity is quite high in the gap between the shroud and the vessel wall near the inlet, but rather low inside the vessel. This figure shows that the flow in the gap between the shroud and the vessel wall is rotating at high speed. This is as expected due the tangential inlet design of the PCD at PSDF. The rotating flow pattern persists inside the body of the vessel. It is perhaps of interest to note that the helical ash deposition pattern was observed at the Power System Development Facility (Guan, 2000; Zhang and Ahmadi, 2001).

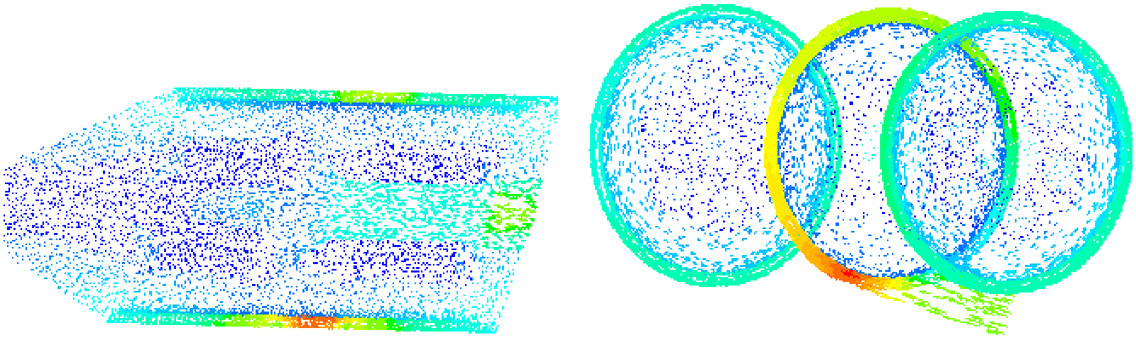
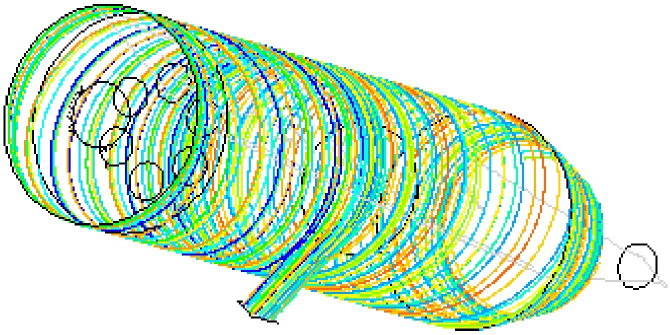


Figure 7. Velocity vector variations in the PCD vessel.

Sample 1μm particle trajectories are shown in Figure 8. It is seen that the particle follows a spiral path in the gap between the shroud and the vessel wall. The high-speed tangential flow in the gap moves the particles on spiral paths both up ward and down ward along the shroud. Additional details of the trajectory analysis and the particle deposition rate for the case of isothermal flows were discussed by Mazaheri et al. (2002).



Conclusions

The hot-gas flow and temperature variations in the PCD vessel at PSDF at Wilsonville, Alabama were studied. The Reynolds Stress Transport Model and the momentum and the energy transport equations of the FLUENT code were used to simulate the turbulent gas flow and thermal conditions in the vessel. The simulated temperature distributions in the vessel show nonisothermal conditions with higher temperature in the upper part of the PCD and lower temperature near the lower cone of the vessel. The computed temperature variation in the vessel is in qualitatively agreement with the field observation at the PSDF. Strong rotating flow regions were also predicted inside the filter vessel near the upper and lower parts, which are also in agreement with the field observations. The pressure was found to be roughly uniform inside the filter vessel with the main pressure drop occurring across the candle filter vessel walls.

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