CFD modeling of stripper ash cooler of circulating fluidized bed boiler

Ravi Inder Singh, Karan Ghule*

Birla Institute of Technology and Science, Pilani, India

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KEYWORDS
Computational fluid dynamics; Ash cooler; Power plant; Eulerian–Eulerian

Summary  The stable operation of a bottom ash cooler is vital for the operation of the circulating fluidized bed boiler. To assess, the stability of the ash cooler, it is important to have a thorough understanding of the flow behaviour. Although, many experimental results have been reported in literature, CFD modelling of the ash cooler has not been carried out. In this paper, the transient computational analysis of a novel stripper ash cooler has been carried out using the Eulerian–Eulerian multiphase approach. The phase coupled SIMPLE algorithm has been used to solve the multiphase equations and the Gidaspow drag model has been employed to model the interaction between the fluidized air and ash. Two cases have been analysed in this paper. In the first case, the filling of the ash in the cooler has been analysed and in the second case, the phenomenon of fluidized bed bubbling in the ash cooler has been simulated. The study the of flow characteristics of hot ash has been studied. The contours of temperature, phase volume and bubbling have been analyzed in this paper. © 2016 Published by Elsevier GmbH. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

The circulating fluidised bed combustion of biomass offers advantages such as high heat transfer rate, high carbon utilisation efficiency, fuel flexibilities and effective NOx control Guo et al., 2006. While the boiler combusts the low-calorie fuel, the ash content is normally more than 40% and the physical heat loss is approximately 3% if the bottom ash is discharged without cooling Singh, 2016. The red-hot bottom ash has a temperature of 850 °C and is not suitable for mechanized handling as the upper limit temperature that can be handled by the ash handling machinery is 200 °C. A bottom ash cooler (BAC) is often used to cool the high temperature bottom ash and also to reclaim the useful heat by passing fine particles back to the boiler along with the fluidisation air. Thus the BAC has a direct influence on the secure and economic operation of the boiler.

In this study, CFD analysis of a novel stripper ash cooler has been conducted. The fluidisation regime in this stripper ash cooler is bubbling bed. Bed Ash flows out of the bottom of the boiler into the stripper cooler where it is stripped of fine particles that are re-injected into the boiler. The remaining

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heavier particles are cooled with air. The aim of the study is to understand the flow pattern inside the stripper ash cooler.

**Literature review**

Lu and Li 2000 were among the earliest authors to carry out experiments on ash coolers. They investigated various operating characteristics, such as the effect of fluidization velocity on the bed height, the relationship between pressure drop and fluidization velocity and the effect of section area of the revertering area on the bed height.

Thite and Ingole 2014 proposed a one dimensional transient heat transfer model of the fluidised bed ash cooler. They used finite difference numerical method to solve the mathematical model of ash cooler. They discussed the effect of particle size on the heat transfer coefficient between ash and air.

Man et al. 2010 studied the performance of a fluidized bed ash cool using a cold test rig. Air flow rate, particle size of the solids and air distributor type were the parameters considered for the study. They suggested that the amount of fluidization and the conveying of ash have a quadratic relationship. They found out that the acceptable particle size for stable operation must be less than 450 µm.

Zeng et al. 2011 proposed a novel bottom ash cooler (BAC) called compound fluidized bed ash cooler (CFBAC). The CFBAC combined the major technical features of spouted bed and bubbling bed, and needed a smaller quantity of fluidizing air to work in the bubbling bed regime. They conducted experiments on a cold test rig and showed that the new ash cooler had an excellent adaptability on the bottomash, a good cooling effect and a large ash discharge capacity over 30 t/h. It was also showed that the CFBAC had better energy efficiency as compared to a water cooled BAC.

**Computational model**

The computational model of the novel stripper ash cooler is shown in Fig. 1.

The primary air, supplied by a blower is directed into the ash cooler with the help of the inclined nozzles. The primary air is responsible for fluidizing the ash. Ash is directed to the cooler through the hopper with the help of secondary air. The ash cooler has a vent (not depicted in the figure) on the top surface and is exposed to the atmosphere. This vent serves as an outlet for the air and also for the finer ash particles. The transient model was created in commercial CFD software, FLUENT 15.0 using a multiphase Eulerian—Eulerian method Gavi et al., 2010. The time step used for the computation was 0.001 s and the simulation was run for 10 s of real time. The phase coupled SIMPLE algorithm with second order upwind scheme has been used to solve the transport equations. Drag model proposed by Gidaspow has been employed to set up the interaction between phases. In the first case, the filling of the ash in the cooler has been analysed and in the second case, the phenomenon of fluidised bed bubbling in the ash cooler has been simulated.

**Governing equations**

**Continuity equation**

The following equations ensure the continuity of the gas and solid phase respectively.

\[
\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{v}_g) = 0; \quad \varepsilon_g + \varepsilon_s = 1
\]

**Momentum equation**

The following are the momentum equation for the gas and solid phase, respectively.

\[
\frac{\partial}{\partial t}(\varepsilon_g \rho_g \vec{v}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{v}_g \vec{v}_g) = -\varepsilon_g \nabla P_g + \nabla T_g + \varepsilon_g \rho_g g + \beta (\vec{v}_s - \vec{v}_g)
\]

\[
\frac{\partial}{\partial t}(\varepsilon_s \rho_s \vec{v}_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{v}_s \vec{v}_s) = -\varepsilon_s \nabla P_s + \nabla T_s + \varepsilon_s \rho_s g
\]

\[ - \beta (\vec{v}_s - \vec{v}_g) \]

**Boundary conditions**

The following boundary conditions were used to analyse the transient filling of the ash in the cooler (Table 1).

<table>
<thead>
<tr>
<th>Name of boundary</th>
<th>Type of boundary</th>
<th>Boundary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air inlet</td>
<td>Velocity inlet</td>
<td>Velocity of primary air = 8 m/s</td>
</tr>
<tr>
<td>Ash inlet</td>
<td>Velocity inlet</td>
<td>Velocity of secondary air = 8 m/s; velocity of ash = 0.1 m/s; volume fraction of ash = 0.4</td>
</tr>
<tr>
<td>Ash outlet</td>
<td>Pressure outlet</td>
<td>Gauge pressure = 0</td>
</tr>
<tr>
<td>Top vent</td>
<td>Pressure outlet</td>
<td>Gauge pressure = 0</td>
</tr>
</tbody>
</table>
The phenomena of bubbling occurs when the ash cooler is completely filled along its length. Bed height of 100 mm has been used to simulate the bubbling phenomena and the primary air velocity has been taken as 8 m/s.

**Computational specification**

The simulation was run on a workstation having a configuration of XENON Quad Core Processor, 3.7 MHz, 32 GB RAM.
Parallel processing (6 modes) was used so as to reduce the computational time and make optimum use of computational resources. The computation is highly intensive and it takes about 110 h of real time for a simulation time of 10 s.

Results

Transient filling of the ash cooler

Hot ash enters the ash cooler with the help of the secondary air and is fluidised by the incoming primary air. Fig. 2 illustrates the distribution of ash as a function of time. The temperature contours of ash as a function of time are presented in Fig. 3. As time passes the primary air cools the incoming hot ash. The average temperature of ash at the mid plane of the ash cooler reduces from 807.6 K to 587.4 K in a span of 6 s. The high cooling rate thus advocates the suitability of the ash cooler in real time application.

Phenomena of bubbling

The vertical section of the ash cooler is depicted in Fig. 4. The contours of volume fraction of air which depict the phenomenon of bubbling have been presented above. It is observed that initially the bed is stationary and bubble formation begins to take place after about three seconds. As time elapses, the bed enters the fluidized regime. It has also been observed that the porosity of the bed is reduced significantly upon fluidization and the diameter of the bubbles is observed to be 18.33 mm. The bubble size is also calculated using standard correlations and there is a satisfactory agreement between the values.

Conclusion

In this paper, results of the transient CFD analysis of a novel stripper ash cooler have been presented. The distribution of ash particles has been predicted along with time and temperature history using the Eulerian–Eulerian approach. The temperature plots indicate that as time passes the incoming hot ash is cooled by the primary air and the rate of cooling is sufficiently high for the ash cooler to be utilised in real time application. The operation of the proposed ash cooler is in the bubbling bed regime and this is supported by the simulation results which depict the bubbling phenomena. The diameter of the bubbles is observed to be 18.33 mm that agrees with the empirical relationship given by Werther and thus validates the proposed model. The results show that the ash cooler has a stable operation and hence it augments the efficiency of the entire power plant.

References


