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Gas-Solid Heat Transfer Analysis of Bubbling Fluidized Bed at Bottom Ash Cooler

바닥재 냉각기 기포유동층의 기체-고체 연전달 분석

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Abstract

In this study we investigated the gas to solid heat transfer of bubbling fluidized bed bottom ash cooler installed at the Donghae power plant in South Korea. Several different analyses are done through 1-D calculations and 3-D CFD simulation to predict the bottom ash exit temperatures when it exits the ash cooler. Three different cases are set up to have consideration of unburnt carbon in the bottom ash. Sensible heat comparison and heat transfer calculation between the fluidization air and the bottom ash are conducted and 3-D CFD analysis is done on three cases. We have obtained the results that the bottom ash with unburnt carbon is exiting the ash cooler, exceeding the targeted temperature from both 1-D calculation and 3-D CFD simulation.

Keywords: Gas-solid heat transfer, Bubbling fluidized bed, Ash cooler, CFD simulation

I. Introduction

Donghae power plant is utilizing circulating fluidized bed(CFB) technology in firing anthracite coal, having 400 MWe power generation capacity, located in South Korea. It has fluidized bottom ash coolers(FBACs) for processing extracted high temperature bottom ash particles from CFB boilers' furnaces. FBACs are bubbling fluidized bed heat exchangers(HXs), using fluidized air, feed water and closed cooling water (CCW) system as cooling medium. Donghae plant has been suffering from FBAC operation troubles mainly about tube wear and damages, which even leads to boiler emergency stop since it has in-bed HX tubes filled with boiler feed water directly connected to boiler water/steam system. In order to solve out this problem, tubes extraction have been suggested as trouble shooting plan. In this matter, the analysis on one big question is needed to see if bottom ash from the furnace could be cooled only with fluidization air without in-bed heat exchanger tubes. Several different approaches have been applied in order to conduct this analysis such as 1-D calculation and 3-D computational particle fluid dynamic (CPFD), predicting heat transfer between gas and solid particles in bubbling fluidized bed heat exchangers. In first, heat capacity and heat transfer have been computed and compared on heat exchange of gas-solid through 1-D calculation. Then 3-D computational particle fluid dynamic analysis is conducted having identical 3-D modelled FBAC and its same operation condition.

II. 1-D Calculation

Prior to three-dimensional computational particle fluid dynamic analysis, one-dimensional calculation has been conducted to see if the bottom ash from the furnace can be cooled down to the targeted temperature degree (150 C) only with fluidization air. 1-D calculation is composed of two parts, which are the comparison on heat capacities of fluidization air and bottom ash and then the computation of the amount of heat transfer between fluidization air and bottom ash.

The heat capacities of bottom ash and fluidization air can be written down as below:

Bottom ash heat capacity:

$$Q_{BA} = Cp_{BA} \times \dot{m}_{BA} \times (T_{BA\ inlet} - T_{BA\ outlet})$$

Fluidization air heat capacity:

$$Q_{FA} = \dot{m}_{FA} \times (H_{FA\ outlet} - H_{FA\ inlet})$$

The bottom ash from the furnace enters the FBAC with temperature of 900-Celsius degree and the FBAC is designed to have 150-Celsius degree of ash outlet temperature. The mass flow of the bottom ash from the furnace is calculated as 10.8 ton/hr. The sensible heat amount of the bottom ash is computed as 1.91 MWth and, corresponding to this value, the fluidization air temperature after

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heat exchange between air and ash has been turned out to be 204-Celsius degree with the inlet air temperature of 90-Celsius degree. For cooling the bottom ash, mass flow of 16.5 kg/s fluidization air is inputted through air nozzles installed at the bottom of the FBAC, which has fluidization velocity of 0.5 m/s in the FBAC. This means air temperature does not exceed the inlet ash temperature(900 C) after passing through the bed consisted of bottom ash from the furnace, having enough heat capacity to cool down the bottom ash temperature from 900 to 150 C. The additional consideration, however, has to be made regarding unburnt carbon(UBC), which accompanies with bottom ash from the furnace, having heat amount of approximately 0.5 to 1.5 MWth. In order to take it account, additional heat from UBC is added in the form of higher inlet temperature of the ash entering the FBAC, which has originally the value of 900 C. The heat capacity comparison results have been summarized in the table 1. By simple sensible heat comparison, it seems that fluidization has enough heat capacity for cooling hot bottom ash flowing from the furnace.

In order to have more precise heat exchange rate between fluidization air and bottom ash, the gas-solid heat transfer coefficient is calculated. The correlation has been adopted from bubbling bed heat transfer formula[1]. The particle diameter of bottom ash, which is needed for the calculation of Reynolds number and Nusselt number, has been inputted as 800 micro-meter, an average value of the bottom ash particle size distribution(PSD). The Reynolds number and Nusselt number of fluidization air are calculated as 27.9 and 2.28, respectively. The heat transfer coefficient between gas-solid in packed bubbling fluidized bed can be written as follows,

$$H_{gas\ to\ solid} = Nu_{bed} \cdot \kappa \cdot d_p$$

and we got 86.62 W/m² C for the value. Based on this heat transfer coefficient, we have calculated the amount of heat transfer between fluidization air and bottom ash, dividing the FBAC into 10 spatial bed regions according to temperature gradient order. The heat transfer amount of gas-solid in FABC and the heat capacity of fluidization air can be expressed as below,

Heat transfer of gas-solid:

$$Q_{bed\ to\ air} = h_{gas\ to\ solid} \times A \times (T_{bed} - T_{FA})$$

Heat capacity of fluidization air(gas):

$$Q_{FA} = \sum_{i=1}^{10} Cp_{FA} \times \dot{m}_{FA} \times (T_{FA\ out,i} - T_{FA\ in,i})$$

The Fig. 1 shows the FBAC structure and ten(10) special bed temperature(Tbed) gradient for the calculation and the average temperature value of each spatial region in the case of no UBC consideration case. In order to estimate the heat transfer area (A) between gas and solid, the average diameter of bubbles and the velocity of bubbles in the bed are assumed as approximately 0.5 m and 1.5 m/s, respectively. In table 2, each heat transfer amount in individual ten(10) spatial region have been stressed out. In addition to it, outlet temperatures of fluidization air are calculated to meet the computed heat transfer amount between gas and solid particles in each region.

III. 3-D CPFD analysis

Besides 1-D calculation, 3-D CPFD analysis has been conducted through the commercially available CFD program Barracuda Virtual Reactor®, adopting 3D multiphase particle-in-cell(3D-MP-PIC) numerical method for gas-solid hydrodynamics calculation[2-3]. The time required for cooling the bottom ash from the furnace has the

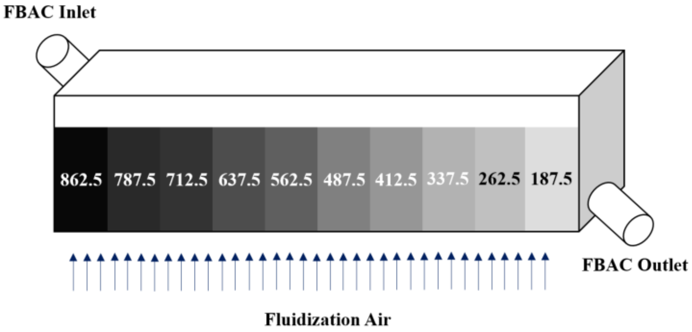


Fig. 1. Schematic drawing of the FBAC with ten (10) spatial bed temperature(℃) gradients for Case 1 calculation

TABLE 1
Sensible heat comparison between bottom ash and fluidization air

Description	Unit	Value		
Solid Side		Case 1	Case 2	Case 3
Inlet Temperature	℃	900	1,095	1,487
Outlet Temperature	℃	150	150	150
UBC Consideration	MWth	0	0.5	1.5
Air Side				
Inlet Temperature	℃	90	90	90
Outlet Temperature	℃	204	233	292

TABLE 2
The particle size distribution of the bottom ash

Cumulative (%)		Particle diameter
0	mm	0
0.03		0.075
0.03		0.425
19.98		2.8
64.08		5.63
88.12		8
100		12

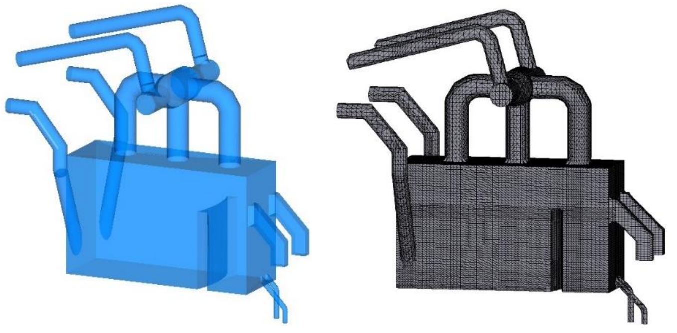

(a) 3D CAD model (b) 3D grid model for the simulation

Fig. 2. 3D models of FBAC

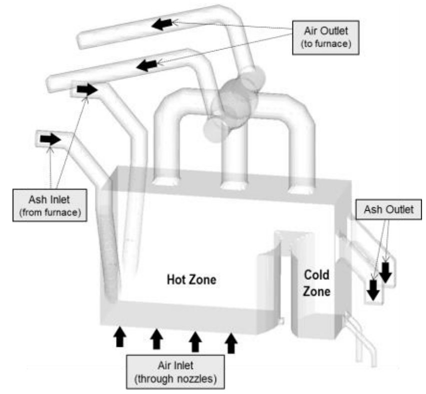


Fig. 3. The inlet and outlet of the FBAC's mass balance specification

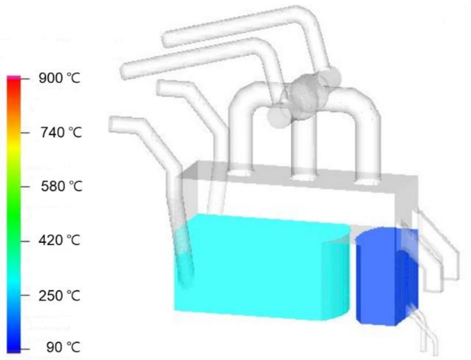


Figure 4. The initial filling of the bottom ash in the FBAC at the beginning of the simulation

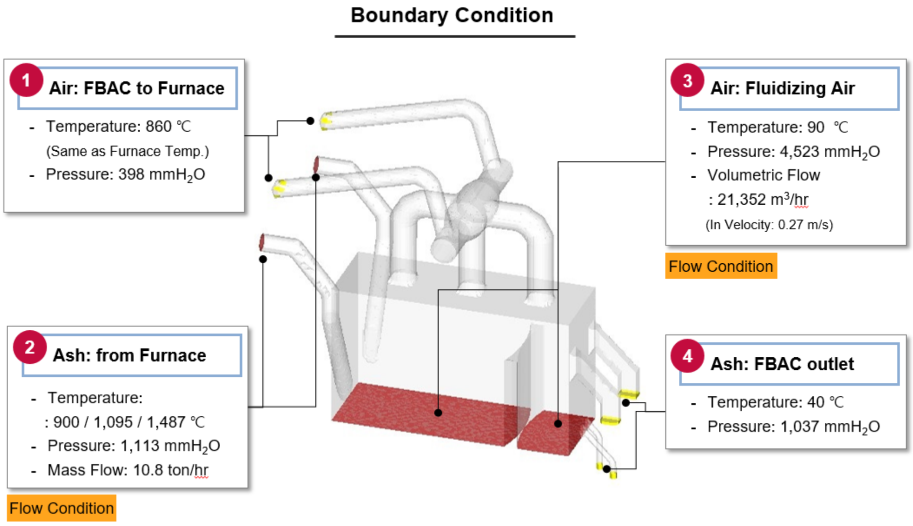
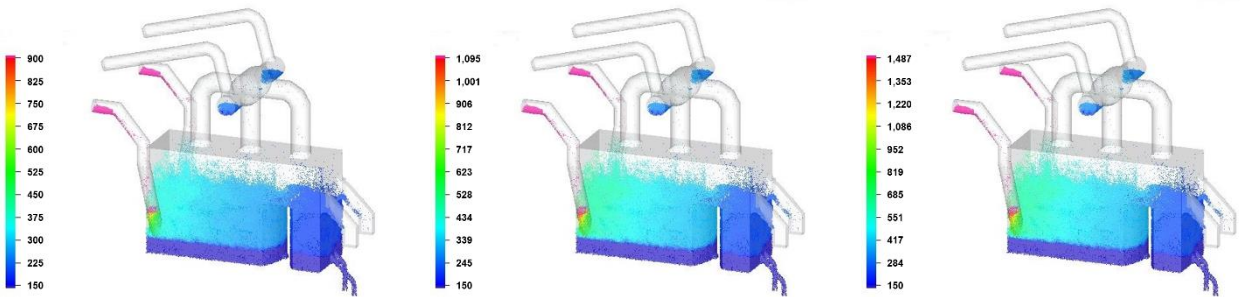


Fig. 5. The boundary condition at the inlet and outlet of the FBAC



(a) Case 1. 7,056 (b) Case 2. 7,488 (c) Case 3. 7,668

Fig. 6. The simulation results of particle temperature

limited condition, which is the exit temperature(150 Celsius degree) of the ash when it exits the FBAC and the residence time of the bottom ash in the FBAC. From the moment the bottom ash enters the FBAC, it has 4 hours and 41 minutes till it leaves the cooler with its mass flow of 10.8 ton/hr. The 1-D calculation has no consideration of time aspect, therefore, the 3-D model is created for the CFD analysis as in Fig. 2. The 3-D grid model is consisted of total 578,656 cells and has the same dimension with the actual FBAC at Donghae power plant. The intuitive explanation of each part of the FBAC is shown in Fig.3 about inlets and outlets of the mass balance of the FBAC. The FBAC has two chambers of so called hot and cold zones, left and right chambers in the Fig. 3, respectively. The initial bed temperature of those chambers are set as 300 and 150 degree Celsius for hot and cold zones, respectively as in Fig. 4, for demonstrating the equilibrium state like in the middle of the FBAC operation since it would take long simulation time to fill the FBAC from the beginning with the bottom ash as actual operation. The boundary condition of the simulation is elaborated in the Fig. 5. All the simulation condition is demonstrating the actual operation data, which is collected from pressure, temperature transmitters attached to the FBAC in the plant. The particle size distribution(PSD) of the bottom ash is inputted into the simulation and shown in table 2. For the drag model, Wen-Yu-

TABLE 3
Simulation results of bottom ash exit temperatures and convergence times for temperature stabilization

Description	Unit	Simulation Results		
Simulation Case		Case 1	Case 2	Case 3
Ash Exit Temperature	℃	153	232	298
Time for Temperature Convergence	hr	1.96	2.08	2.13

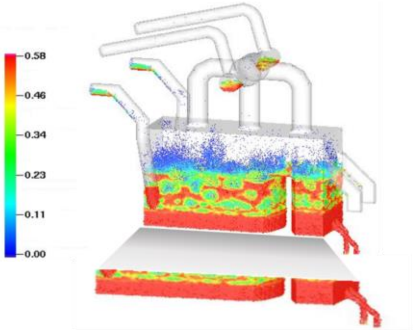


Fig. 7. The simulation results of particle volume fraction of Case 1 at 7,056 seconds with enlarged bottom part of FBAC with coarse sizes particles, having diameter of 7.8 mm above

Ergun is applied to demonstrate the particle behavior in the bed[4-5]. Three(3) different cases are run for the CFD analysis depending on the UBC heat capacities of 0, 0.5 and 1.5 MWth which are case 1, 2 and 3, respectively. The simulation results are elaborated in the Fig. 6 and 7 for the particle temperatures and the particle volume fraction, respectively. The temperature of the bottom ash at the FBAC outlet is summarized in the table 3 with the cooling time till the bottom ash temperature stabilization in other word, reaching the convergence value.

IV. Results and Discussion

In 1-D Calculation, we conducted two comparisons: the first thing is heat capacities of the bottom ash and the fluidization air, and the second thing is heat transfer amount between solid(bottom ash) & gas(fluidization air) and the bottom ash heat capacity. In the first part, we wanted to make projections of possibility if the fluidization air has enough heat capacity to cool the bottom ash travelled from the furnace in terms of air mass flow and its inlet temperature, and in all three simulation cases of 0, 0.5 and 1.5 MWth UBC, the fluidization air have larger room of sensible heat capacities as in the table 1. From this ground of simple comparison results, we moved on to heat transfer coefficient calculation between gas to solid in bubbling fluidized bed. In table 4, we obtained the results that, in case 2 and 3, heat transfer amounts between bottom ash particle(solid) and gas(fluidization air) are smaller than bottom ash sensible heat amounts which mean that case 2 and 3 have higher bottom ash exit temperatures than 150 C(targeted value). In addition to the 1-D calculation results, 3-D CPFD is conducted to have time aspect and to see other unexpected bed particle hydrodynamics behaviors. As written in the table. 3, the simulation results are showing similar phenomena like 1-D heat transfer calculation. Only case 1 simulation has shown the bottom ash is cooled down to the targeted temperature while case 2 and 3 are exceeding it with the temperatures of 232 and 298 C. All three cases of 3-D simulation reached to the converged temperatures within the residence time of bottom from the moment of entering to the exit of the FBAC as in the table 3. Besides the ash temperature, from the simulation results, we could see relatively coarse sizes particles are building up in the bottom of the FBAC from the particle volume fraction results as shown in the Fig. 7. It indicates the fact the already cooled down bottom ash particles with large sizes in diameters are taking up the space of the FBAC and it interrupts mixing of particles in entire FBAC space and reduces the residence time, resulting not enough time for cooling (contacting) between gas and solid.

TABLE 4
1-D calculation results

Description	Unit	Calculation Results		
Simulation Case		Case 1	Case 2	Case 3
Bottom Ash Sensible Heat amount	MWth	1.91	2.41	3.41
Heat transfer amount between Gas & Solid	MWth	1.92	2.35	3.22
Average Outlet temperature of fluidization air	℃	197	221	270

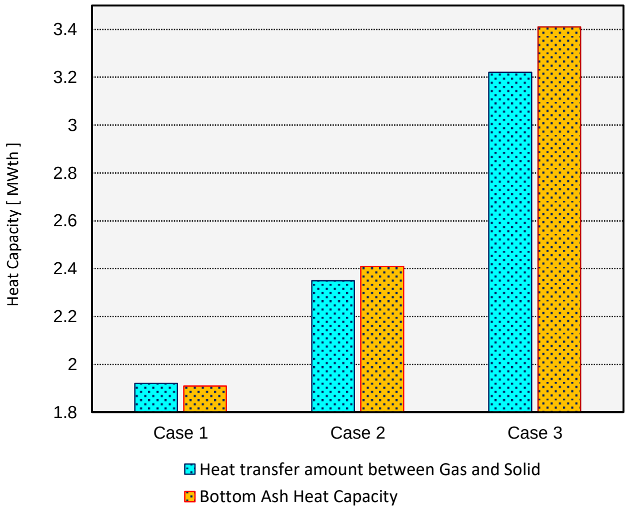


Fig. 8. The 1-D calculation result of comparison on heat transfer between gas & solid and the bottom ash heat capacity from the furnace

V. Conclusion

Various approaches have been conducted to see if the FBAC could function well only with the fluidization air without heat exchanger tubes in it. From simple comparison on the sensible heat of gas and solid, we checked the fluidization air has enough heat capacities to cool down the bottom ash in all three (3) calculation cases. In actual heat transfer calculation, we found out the case 1 which has no UBC in the bottom ash is the only case that the FBAC can cool down the bottom ash to the targeted temperature while other cases do not meet the temperature requirement. From 3-D CPFD simulation, we could have similar conclusion that only case 1 simulation meets the bottom ash exit temperature limit. Additionally, we could see the phenomena that coarse sizes bottom ash particles are building up in the bottom area of the FBAC, affecting negatively on the FBAC performance in terms of the residence time of the bottom ash.

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