Prediction of Slag Occurrence in a Lignite-Fired Utility Boiler

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Abstract: - Lignite from Mae Moh mine is the largest source of solid fuel for electricity generation in Thailand. It is used in pulverized coal-fired boilers of a 2400 MW thermal power plant. Its high CaO content in ash is a major concern that can affect severe slagging. In this paper, potential of slag occurrence in the power plant was investigated by numerical simulation. The FactSage thermochemical package was used to predict ash and slag behaviour, as well as ash fusion temperature. A commercial CFD package was also employed to simulate gas velocity and temperature distribution, particle trajectory and temperature, and wall heat flux in a utility boiler of the power plant. The results were found to show good quantitatively and qualitatively prediction of slag formation. They can be applied to predict slag deposition inside the boiler effectively.

Key-Words: - slag, lignite, pulverized coal-fired boiler, coal combustion, FactSage simulation, CFD simulation

1 Introduction

Coal is one of the main natural resources that contains energetic materials for combustion. It is widely used in electricity generation [1]. Lignite is typically brown, soft, and friable, containing high moisture, low carbon, hence low energy density. Higher rank coals (bituminous and anthracite) are generally black, hard, and strong, having low moisture, high carbon, high energy content, and often used in cement and steel industries [2].

In Thailand, about 17 million tons of the lignite from Mae Moh mine was used annually for Mae Moh power plant under management of Electricity Generating Authority of Thailand (EGAT). The Mae Moh plant consists of 10 pulverized coal-fired boilers with a total capacity of 2,400 MW, accounting for about 12% of the national electricity consumption. The lignite is usually of poor quality and has different properties at various mining areas. The lignite is usually blended to meet the power plant requirement [3]. However, the recent survey of remaining lignite showed that they are of lower quality. High CaO in ash of the lignite is that main issue that can affect severe slag in future operation of the boilers. It is a major challenge faced by EGAT engineers [4].

Slag is waste products from lignite incineration. Main products are fly ash and bottom ash [5]. Slag is caused by many factors, such as the coal organic properties, coal mineral matter properties, mineral transformation and decomposition, temperature of the boiler furnace, the fluid dynamic, ash transport, vaporization and condensation of the ash species, deposit chemistry-specie migration and reaction etc. [6-7]. Slag consists of fused deposits or a re-solidfied molten material that forms primarily on the walls of the furnace or on other surfaces predominately exposed to the radiant heat or excessively high gas temperature [8]. When the slag occurs, the soot blowers are normally put in operation to remove it from the wall. However, if slag in the boiler becomes excessive, the soot blowers may not be able to handle it. The built-up slag will bring about a loss in radiation heat transfer, leading to lower overall boiler efficiency. Subsequent problems associated with slag such as loss of heat, loss of capacity, boiler equipment damage, loss of time and money in maintenance boiler will also occur.

Although EGAT attempted to solve the slag problem, but it seemed that so far there was no good practical solution. Potential of slag (combined effect of the slag liquid formation, ash flow distribution, and temperature profiles) in a pulverized coal-fired boiler remains to be a great interest.

2 Methodology

The properties of Mae Moh lignite were analyzed for proximate and ultimate composition, as well as its heating value. Results are shown in Table 1 [9]. Additionally, its ash composition and ash fusibility temperatures (AFT) were analyzed and the results are shown in Table 2 [10-15]. These properties were prepared for use in the software programs.

Table 1 Lignite properties

Proximate analysis (%w/w, as-received basis)	
Moisture content	35.07
Volatile matter	28.17
Fixed carbon	25.86
Ash	10.91
Ultimate analysis (%w/w, dry basis)	
Carbon	58.54
Hydrogen	3.00
Nitrogen	1.89
Oxygen	12.88
Sulfur	5.49
Heating value (MJ/kg dry basis)	
HHV	22.80
LHV	22.15

Table 2 Ash properties

Ash composition (%w/w)	
SiO_2	21.28
Al_2O_3	13.43
TiO_2	0.24
CaO	11.08
Fe_2O_3	28.03
Na_2O	1.87
MgO	4.02
K_2O	1.31
SO_3	18.64
P_2O_5	0.07
MnO_2	0.04
Ash fusion temperature (°C)	
IT	1235
ST	1305
HT	1340
FT	1480

2.1 Ash Melting Point Prediction

The FACTSAGE program has been developed as an efficient predictive tool prediction of liquidus temperature, proportions of solids, mineral formation, and phase equilibria of ash samples [11-18]. FactSage is the fusion of two well-known software F*A*C*T/FACT-Win and ChemSage and it is the largest thermochemical package and database available for inorganic solid and slag in the field of computational thermochemistry. The package runs on a PC operating under Microsoft Windows [10].

The Equilib module (thermodynamic application calculations) and Phase Diagram module (phase diagram calculations) are used to incorporate the FactSage Gibbs energy minimize [19]. It calculates the concentrations of chemical species when specific elements or compounds reacted or partially reacted, in order to reach a state of chemical equilibrium [20]. In this study, these modules (supported by ETII, the University of Leeds) were used to predict the ash behaviour and the ash fusion temperature.

2.2 CFD Simulation

Computational fluid dynamics (CFD) has been used to simulate the firing of coal combustion under different operating conditions extensively [21-26]. In this work, a commercial CFD package, ANSYS FLUENT, was used to predict gas flow, temperature distribution and particle trajectory that can adapt to predict slagging behavior [21-25, 27].

In general, coal combustion in CFD models is used to solve for fluid flow, turbulence, particle trajectory, heat transfer, chemical reactions of the fuel, and the formation of pollutants [28]. In this study, FLUENT version 13.0 was used to predict the temperature and flow distribution inside a boiler. The wall heat flux was evaluated for comparison with real operating parameters. The information was combined with those from the previous FactSage method to predict deposition of slag in the boiler furnace. All numerical simulation was performed at ETII, the University of Leeds.

A Mae Moh boiler is of 300 MWe capacity and tangentially fired type. The geometry is shown in Fig. 1. The dimensions are 13.8 m in width and 15.3 m in depth. The height from the lowest at hopper to the highest point at superheater and reheater is 54.3 m. On the walls, there are four windboxes for four corners to generate tangential fireballs. There are four secondary air panels, five panels for mixing of primary air and coal powder, an overfire air panel, a bottom air panel, and a warmup oil panel in one windbox.

The boiler was generated into 3-D geometry using ICEM CFD. The furnace geometry used approximately 470,000 computational grid cells with 4 blocks, shown in Fig. 2. The properties of coal particle were set at: as-received HHV = 14.82 MJ/kg, volatile molecular weight = 30 kg/kmol, CO/CO_2 = 1 split in reaction products, high temperature volatile yield = 1.5, fraction of N in char = 0.7, and dry density = 800 kg/m^3. Coal particles are assumed to be spherical with mean diameter of 74 µm and temperature of 333 K. The particle properties were used in the discrete phase particle trajectory technique. The boundary conditions used for the CFD model were taken from the real operating condition in the power plant.

The standard k-ε model was used for the turbulent flow calculation [29]. The discrete ordinate (DO) radiation model was commonly used in coal combustion. Although the DO model demands on computational time, the model offers more detail and better accuracy [30]. The combustion model used is the eddy dissipation [22, 26]. The chemical equations for coal burned with oxygen, in a two-step reaction, are given below:

$$C + H + O + N + S + O_2 \Rightarrow CO + 0.5H_2O + 0.5N_2 + SO_2 \quad (1)$$

$$2CO + O_2 \Rightarrow 2CO_2 \quad (2)$$

The inlet boundary condition was set to velocity inlet. The outlet boundary condition was set to outflow at the top of geometry. The wall boundary condition was divided into two parts; the bottom outlet was set to escape wall, all wall surface was set to no-slip condition, 4.57 mm thick with temperature = 673 K, internal emissivity = 0.8, and thermal conductivity of material = 1.5 W/m-K. The partial overall admittance factor is set as a constant value of 333 W/m^2K [22].

3 Results and Discussion

3.1 Slag Formation

Predicted mineral transformation, slag-liquid formation, and compositions of the sample coal are shown in Table 3. It was found that as the temperature increases to 950°C, slag-liquid starts to form. The main solids at 800°C are hematite, anhydrite, and high-albite. They decrease at higher temperatures. Unlike the main solid, the slag-liquid increase at higher temperatures. Fig. 3 presents total slag formation. The equilib model can be used to predict quantity and identify the details of slag-liquid formed and its composition at operating temperature, which can be applied to design operating temperature in the boiler furnace.

3.2 Ash Melting Temperature

The main compositions (SiO_2, Al_2O_3, CaO, and Fe_2O_3) of ash in the blended coal were chosen to plot against fusion temperature in ternery phase diagram. Fig. 4 presents the ash melting temperature predicted by the phase diagram. The lines show ash melting temperature for different compositions. The melting point of this coal is estimated to be 1440°C, which was in good agreement with measured AFT.

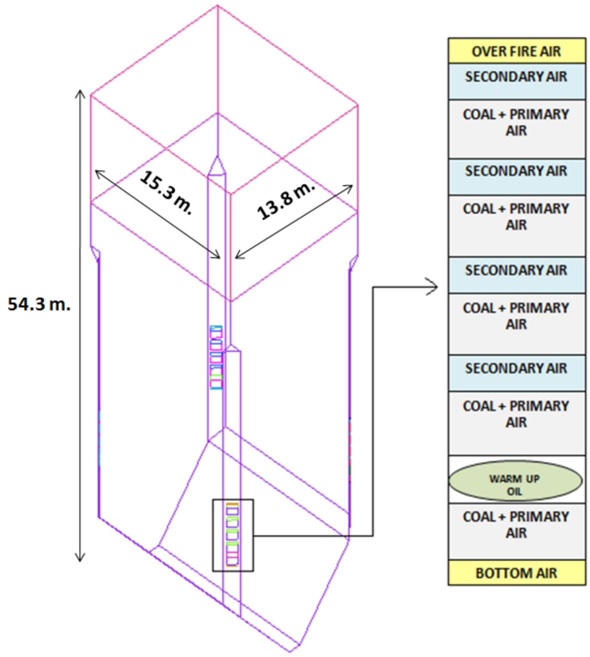

Fig. 1 Geometry of the Mae Moh boiler

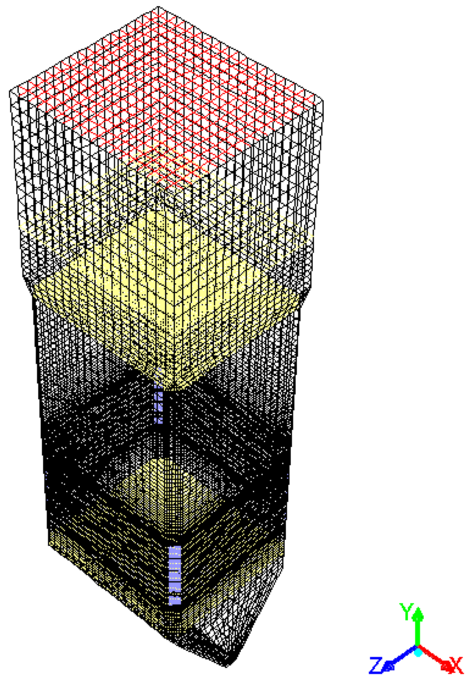

Fig. 2 Computational grid cells

The superimpose function in FactSage was used in the quaternery diagram. The possible reason for the behavior shown in Fig. 4 is that the combined effect of CaO, Fe_2O_3, SiO_2, and Al_2O_3 may be significant.

Table 3 Solid product from the FactSage Equilib model

Solid product (g/100 g of lignite)	Temperature (°C)								
	800	900	1000	1100	1200	1300	1400	1500	1600
Slag	0	0	0.7	5.4	8.7	10.6	14.2	14.4	14.3
composition									
Na_2O	0	0	0.4	0.6	0.4	0.3	0.2	0.3	0.4
K_2O	0	0	0.1	0.9	0.8	0.7	0.5	0.5	0.3
Al_2O_3	0	0	1.1	9.7	14.3	16.4	13.1	13.7	14.3
SiO_2	0	0	51.5	42.1	38.4	33.1	25.9	26.9	27.1
$NaAlO_2$	0	0	33.7	15.0	9.4	7.6	5.6	5.2	4.5
CaO	0	0	6.1	24.4	23.1	18.6	14.2	14.0	14.1
FeO	0	0	0.1	0.3	1.2	3.7	8.9	12.4	15.9
Fe_2O_3	0	0	0.2	1.6	5.2	12.4	26.0	21.6	18.0
MgO	0	0	5.2	4.6	6.5	6.8	5.1	5.1	5.1
MnO	0	0	1.1	0.1	0.1	0.1	0	0	0
TiO_2	0	0	0.3	0.7	0.5	0.4	0.3	0.3	0.3
Fe_2O_3 (Hematite)	5.1	5.1	5.1	5.0	4.5	3.1	0.0	0.0	0.0
$CaSO_4$ (Anhydrite)	4.9	4.9	2.5	0.0	0.0	0.0	0.0	0.0	0.0
$NaAlSi_3O_8$ (High-Albite)	2.9	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Mg_2Al_4Si_5O_{18}$ (Cordierite)	1.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Mg_4Al_{10}Si_2O_{23}$ (Sapphirine)	1.5	1.5	0.0	1.4	0.8	0.0	0.0	0.0	0.0
$KAlSi_2O_6$ (Leucite(RHF)-B)	1.1	1.1	1.1	0.8	0.8	0.6	0.4	0.0	0.0
Mg_2SiO_4 (Forsterite)	0.3	0.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0
$CaAl_2Si_2O_8$ (Anorthite)	0.0	0.0	4.4	0.8	0.0	0.0	0.0	0.0	0.0
$NaAlSiO_4$ (Nepheline)	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
$CaTiO_3$ (Perovskite-A)	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
$Ca_2MgSi_2O_7$ (Akermanite(melilite))	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0
$CaMg_2Al_{16}O_{27}$ (Solid)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

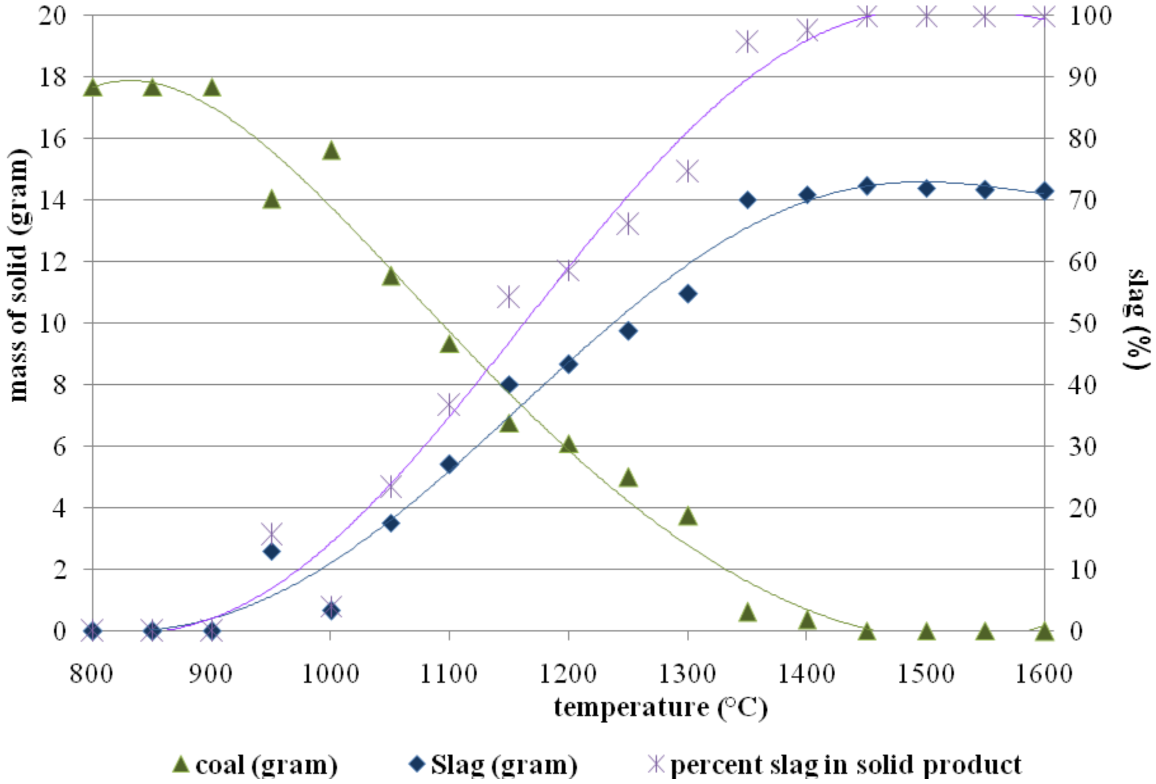

Fig. 3 Trend of slag formation

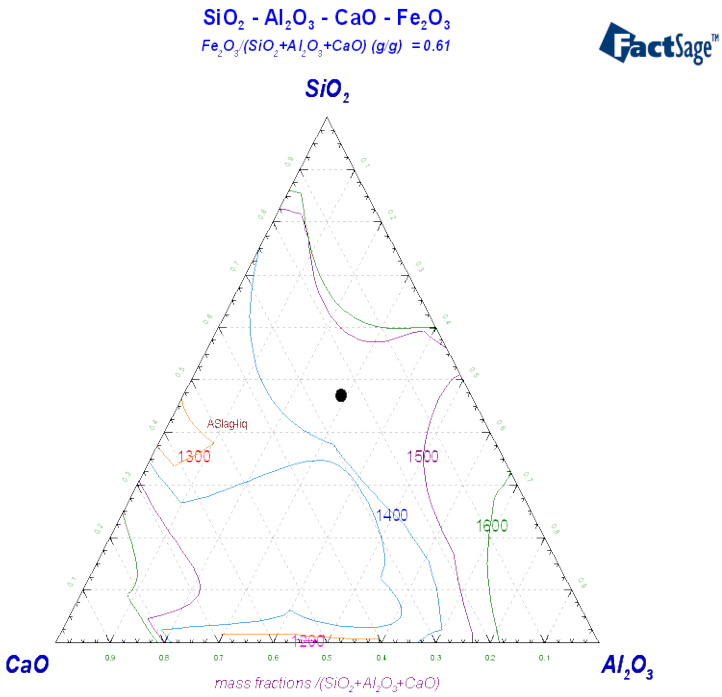

Fig. 4 Predicted ash melting point of the SiO_2-Al_2O_3- CaO,- Fe_2O_3 system

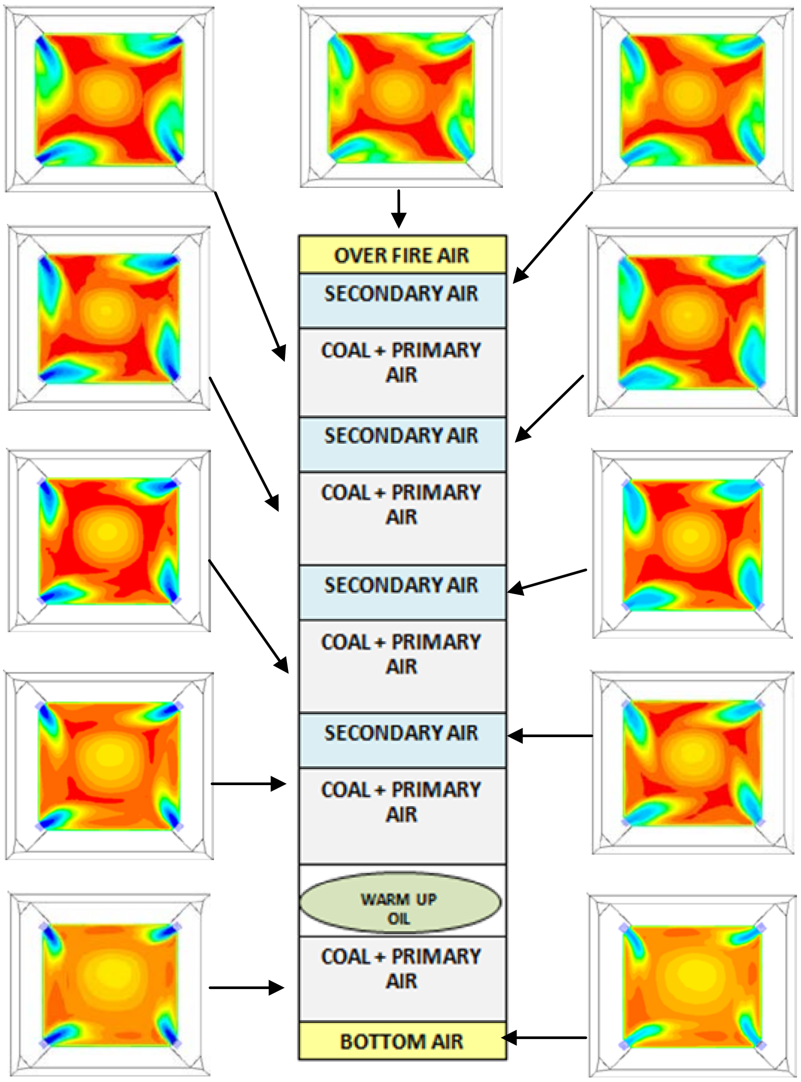

Fig. 5 Temperature distribution (in K) during coal combustion

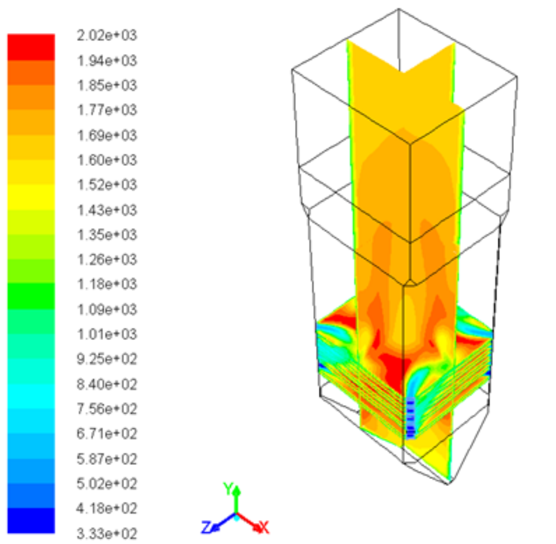

Fig. 6 Temperature distribution isosurface (K)

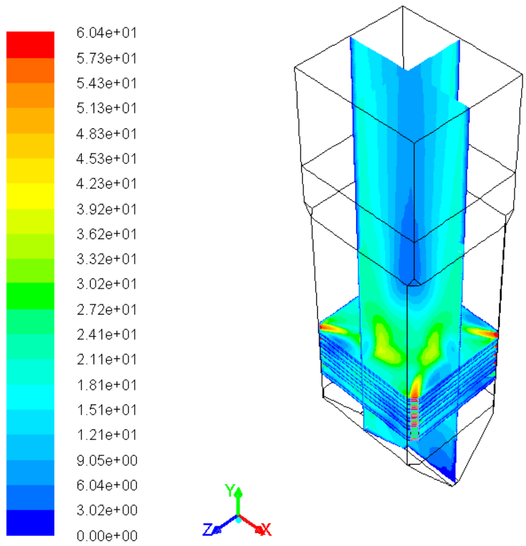

Fig. 7 Velocity distribution isosurface (m/s)

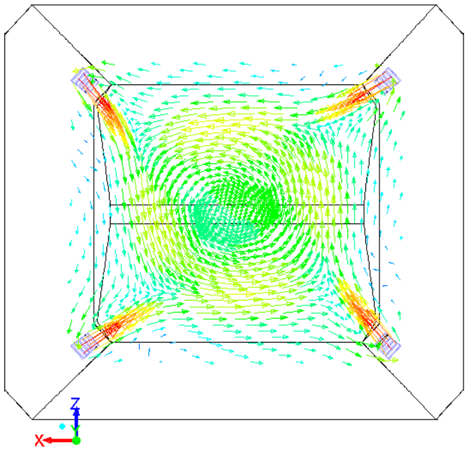

Fig. 8 Velocity vector in a cross section (m/s)

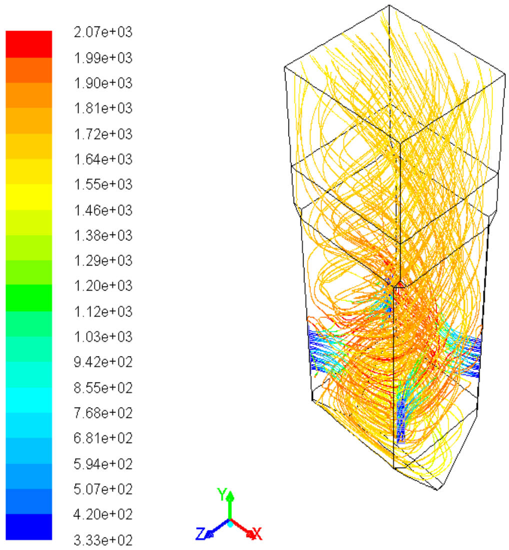

Fig. 9 Particle trajectory and temperature (K)

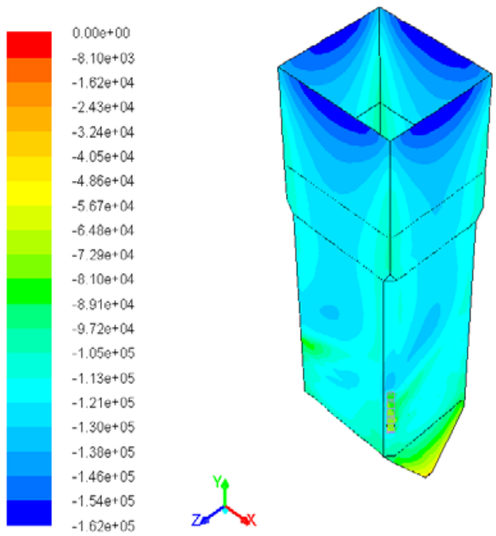

Fig. 10 Wall heat flux (W/m^2)

3.3 Potential Occurrence of Slag

The ANSYS CFD package has been used to calculate coal combustion in one of the Mae Moh boilers. Figs. 5 and 6 show the temperature distributions at different cross sections of the boiler furnace. Maximum temperature is located on the top of the windbox. The contour and direction of fireball velocity are shown in Figs. 7 and 8. Trajectory and tempeture of the coal particles are presented in Fig. 9. The distribution of wall heat flux is shown in Fig. 10. These results are used to predict deposition potential of slag inside the boiler furnace. The CFD simulation was conducted using the real operation information (coal properties and real operation) and it will be useful for comparison with the measured heat flux and flue gas outlet.

4 Conclusion

The equilibrium and phase diagram models were found to be useful in identifying composition of slag and predicting ash fusion temperature. The results from FactSage simulation can be used to compare with subsequent slag and ash fusion temperature experiments. The computational results of gas temperature distribution, flow fields, temperature and trajectory of particle, and surface heat flux appeared to show possibility of slagging deposition. The results of CFD simulation can be used to compare against wall heat flux and flue gas of EGAT measurements. This simulation is useful for predicting potential of slag in boiler and addressing future slag problem effectively.

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