CFD Modeling of Co-Firing Wood Chips with Coal for UI Power Plant Boiler 10

Partial Final Report To
Utilities Group
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Executive Summary

This report presents a preliminary study of co-firing wood chips with chunk coal in a stoker boiler using a comprehensive numerical model, which is first validated with experimental data for pure coal combustion. In this CFD simulation, a one dimensional steady state fuel bed model is employed to describe the combustion process on the bed. The simulation is then used to study the combustion behavior when different quantities of wood chips are co-fired with coal at a constant total heating value. Due to the lower carbon content of wood chips, the peak temperature inside boiler drops with increasing wood chips ratio, which is helpful for reducing the level of NOx. Another finding is that a more oxygen rich environment is created for the co-firing cases due to wood chips having more oxygen content than coal. This tends to both improve combustion efficiency and necessitates a smaller working load on air supply system. Therefore substituting coal with wood chips can increase both the energy and economy efficiency of the boiler.

Background

Renewable energy, together with fossil energy and fissile energy are the main energy sources on the earth. Although fossil energy sources (petroleum, coal, natural gas, bitumen, oil shale, and tar sands) still hold a dominating role in supplying over 80% of world’s total energy, the availability of these sources is finite. These energy sources also produce high quantities of greenhouse gases and atmospheric pollutants. Against the backdrop of increasing energy use and increasing environmental concerns, the utilization of renewable energy is becoming more and more attractive. It has been widely recognized for its sustainability, low emissions, and low cost. For those reasons, it is regarded as one of the primary sources of future energy.

Renewable energy exists in varies forms including biomass, solar, wind, geothermal, and hydro-power. It provides 14% of the total world energy demand. Currently, biomass use accounts for 4% of total energy consumption in the USA. Biomass includes organic matter produced during the photosynthesis process in which green plants convert sunlight into plant material. It normally refers to all land- and water-based vegetation like wood, short rotation woody crops, agricultural wastes, short-rotation herbaceous species, wood wastes, bagasse and all animal wastes. Due to its formation, biomass has a unique property in that it is neutral for carbon dioxide production. Moreover, the content of sulfur and nitrogen in a large number of biomass fuels is lower than fossil fuels, which can further decrease pollution which results in acid rain. These virtues make biomass fuel an attractive substitute for fossil fuels.

The various types of biomass have significantly different forms, structures and properties, which results in a wide range of conversion technologies. Their corresponded
Conversion processes include physical, chemical and biological conversion, through which biomass is converted into liquid, solid or gaseous fuels. These technologies have varying degrees of complexity, with direct combustion of biomass considered to be the most convenient and economical way to utilize biomass energy. It is responsible for over 97% of the world's bio-energy production.

The Power Plant/Facilities Group of the University of Iowa have worked closely with the university’s Mechanical and Industrial Engineering department to conduct research on biomass combustion. The research spans a broad range of activities including a basic scientific study on the gasification of different biomass material, computational modeling of biomass combustion, and the technical design and optimization of facilities. This collaboration has borne fruit in terms of both theoretical understanding and industrial applications. The work has assessed a variety of biomass, including examinations in the lab, inclusion in numerical models, and testing in full-scale facilities.

One of the most common sources of biomass for power plant is wood chips. Various studies have shown that the UI power plant can receive abundant quantities of wood chips for the purpose of utilizing them as a renewable energy fuel. In general, wood chips can be regarded as a biomass fuel with great potential in US Midwest. With current technology, the primary method of using wood chips is by co-firing them with coal. However, due to significantly different material properties between wood chips and coal, a strongly changed and varied pattern of combustion behavior is reasonably expected. This dictates some necessary technical improvement and process revisions for existing facilities.

CFD is an efficient tool to investigate the combustion of biomass for the university’s stoker boiler, boiler 10, as it can not only reveal more detail, including temperature variance, gaseous species dispersion, and pollutant production during the combustion process, it can also greatly reduce the technical difficulties and cost incurred for actual tests and implementation. This report presents the results of co-firing wood chips based on the computational modeling. The corresponded changes of the pattern of combustion behavior are discussed and the potential of substituting a portion of the coal flow by wood chips is assessed.

**CFD Model**

The comprehensive CFD model of boiler 10 used in this research is constructed in the commercial code Fluent, version 6.12, and is shown in Fig. 1. A realizable $k-\varepsilon$ model is used for the turbulence closure, the eddy dissipation model is applied to the combustion model, and P1 radiation model is chosen for calculating radiation heat transfer in the furnace. The grid
employed contains a total number of 842,761 tetrahedral cells. Its main components include a heat source volume representing the grate bed, geometry representing the coal feed system, oat hull injection nozzles, a secondary air system, and a heat sink zone modeling the heat exchanger. This model is validated by comparison to the pure coal combustion case and has been previously applied to study co-firing of oat hulls and NOx emissions. The validation is made by comparing to the temperature data collected for 155 klb/hr and 120 klb/hr steam flow-rates. The measurements were performed through the observation windows of the boiler, shown in Fig 2. A 12 ft long pole carrying the thermocouple was inserted into the boiler through each window, and the temperature data was collected at one foot intervals.

Figure 1 Grid of Unit 10
Results

1. Pure coal combustion

In the case of pure coal combustion, the boiler was run with a steam flow rate of 155 klb/hr. Fig. 3 shows the computed temperature contour for a vertical cross-section inside the furnace for identical model conditions. Since the majority of the coal chunks reside on the bed during combustion, a high temperature zone located directly above the grate was detected as expected. The temperature is shown to continuously decrease as the flow proceeds upwards, with significant cooling occurring in the heat exchanger. Fig. 4 shows the mass concentration of oxygen in the same cross-section. The low concentration above the coal bed indicates strong oxygen depletion. This problematic aspect was later improved by use of the proposed secondary air system.
**Figure 3** Temperature contour of pure coal combustion (155 klb/hr steam)

**Figure 4** Mass fraction of O₂ of pure coal combustion (155 klb/hr steam)

Fig. 5, 6 and 7 show the comparison between the comprehensive model prediction of this and the experimental data (whose accuracy is ±1.5%). For the comparison at window N2 (where the peak temperature area located), a good agreement is observed. The average deviation is less than 1.1%, indicating an excellent predication of temperature for the central
area for the furnace. The comparisons at window S2, which is symmetric to N2, also showed very close agreement, with the averaged deviation being less than 0.9%.

As for the behavior at window N3, the access window is located close to the back wall where the secondary air enters the system. This proximity to both the back wall and the secondary air induces a pattern of fluctuations in the temperature data. The predictions in the comprehensive model tended to be a little higher than the experimental data but maintain the same pattern seen in the experiments. Except for the significant difference at the first location (most likely caused by the access window being open), a good agreement was achieved with an averaged deviation of less than 3.6%.

Figure 5 Comparison of predicted results with measurement data of window N2
Figure 6 Comparison of predicted results with measurement data of window N3

Figure 7 Comparison of predicted results with measurement data of window S2
2. Co-firing wood chips with coal

Tables 1 and 2 show the basic chemical analysis for wood chips, alongside that for coal. These are the chemical properties used in the numerical model to describe wood chip and coal fuel properties. The tables show wood chips contain a much lower content of fixed carbon than coal, meaning most of the carbon in wood chip exists in the form of volatiles. This would indicate that the combustion temperature above the coal bed for boiler 10 should decrease with wood co-firing due to the drop in the amount of fixed carbon. The oxygen content of wood chips is also much higher than coal, indicating a more oxygen-rich atmosphere inside the boiler.

**Table 1.** Proximate analysis of fuels

<table>
<thead>
<tr>
<th></th>
<th>Wood Chips Proximate Analysis wt%</th>
<th>Coal Proximate Analysis wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>29.41</td>
<td>5.85</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>56.70</td>
<td>35.61</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>11.65</td>
<td>47.94</td>
</tr>
<tr>
<td>Ash</td>
<td>2.24</td>
<td>10.6</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>HHC [Kj/Kg]</td>
<td>12840</td>
<td>28470</td>
</tr>
</tbody>
</table>

**Table 2.** Ultimate analysis of fuels

<table>
<thead>
<tr>
<th></th>
<th>Wood Chips Ultimate Analysis (daf) wt%</th>
<th>Coal Ultimate Analysis (daf) wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>49.76</td>
<td>72.4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.6</td>
<td>5.07</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.23</td>
<td>1.64</td>
</tr>
<tr>
<td>Oxygen</td>
<td>44.39</td>
<td>8.26</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

It is assumed that the wood chips are being co-fed with the coal, and are hence being thrown in with the coal chunks from the feeders on the front wall. This would result in a wood chip distribution similar to that of coal, with corresponding similarity in heating and gaseous fluxes released by the wood chips. Based on the published literature, the composition of volatile gases released from the wood chips was taken to be 22.81% C₂H₄, 38.2% CO₂, and 38.99% H₂O.

The wood chips are co-fed with coal at various percentages of the total heating value: 5%, 10%, and 15%. Figures 8, 9, and 10 show the temperature of the center plane of boiler for 5%, 10%, and 15% respectively. A deceased peak temperature, locating on the coal bed, was predicted, validating the initial assumptions about overall combustion behavior. Since the heat
source on the bed was unchanged, the temperature drop is not large. The amount of change increased with increasing wood chip percentage. The results also show a shortened flame zone above the coal bed. This phenomenon can be explained by the significant amount of oxygen content carried by wood chips, which can react with most of the combustion species right above the bed. This feature of co-firing wood chips means the possibility of reducing air flow pumped into the boiler and a higher overall/economic efficiency.

Figures 11, 12, and 13 show how the O2 concentrations inside the boiler changed with increasing wood chip use. The average of oxygen left inside the boiler is increased and the oxygen depletion zone (represented by the blue zones) shrank when the ratio of wood chips increased.

Figure 8 Temperature contour (5% wood chips)
Figure 9 Temperature contour (10% wood chips)

Figure 10 Temperature contour (15% wood chips)
Figure 11 Mass concentration of O$_2$ (5% wood chips)

Figure 12 Mass concentration of O$_2$ (10% wood chips)
Conclusions

This research based on CFD modeling has shown the feasibility of co-firing wood chips in the stoker boiler, unit 10, of the UI power plant. Due to the lower carbon content of wood chips, the peak temperature inside boiler drops as the co-firing ratio increases. This reduction also reduces NOₓ levels in the boiler. The amount of air needed by the boiler also decreases because wood chips contain significant amounts of bound oxygen. The more oxygen-rich environment is not only beneficial for achieving higher combustion efficiencies, but also aids overall efficiency through the smaller working load on air system.