Computational Fluid Dynamics Modeling for Evaluating Design and Operational Issues for Biomass Cofiring in Coal-Fired Boilers

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This paper reports on the development and validation of comprehensive combustion submodels for biomass fuels, with emphasis on cofiring synergies in coal-fired applications. Because coal-fired boilers are a significant source of power generation in the U.S. and abroad, cofiring at levels of 2-15% (heat basis) could provide a significant increase in bioenergy utilization while taking advantage of the existing utility infrastructure. This applied research is focused on developing strategies for biomass cofiring, including enhanced NO_x reduction techniques, such as biomass reburning, that take advantage of the high volatility of biofuels in combustion zones, such as those found in pulverized coal boilers. Minimizing unburned carbon loss while achieving NO_x reductions are important factors in evaluating biomass fuels for cofiring as well as in specifying appropriate biomass handling/injection schemes for utility boilers.

Computational fluid dynamics (CFD) modeling routines for biomass cofiring are being developed using available experimental data and first principles that provide accurate estimations of kinetic and model parameters of devolatilization and diffusion-controlled char burnout. Two sets of drying functions include the effect of moisture on particle surfaces and embedded in the char. In the commercial CFD code, FLUENT™, gas flow is described by time-averaged equations of global mass, momentum, enthalpy, and species mass fractions. The standard k-? turbulence closure, finite rate chemistry, and the Discrete Ordinate radiation models are used for the gas phase. Coal and biomass devolatilization is incorporated using an Arrhenius-type, first order kinetic rate model. Coal-char oxidation is described with the char burnout kinetics (CBK) model [1] controlled surface reaction while biomass char oxidation is controlled by diffusion-limited surface reaction, and is modeled as a constant density process. The standard FLUENT code is updated with the modified char oxidation submodels for coal and biomass via an externally defined function. In addition to solving transport equations for the continuous phase, a discrete second phase is solved in the Lagrangian frame of reference. The trajectories and heat and mass transfer for these discrete particles are coupled with the continuous phase. The detailed equations, previous developmental work, and comparisons to bench-scale experimental data, are published elsewhere [2].

In this paper, further CFD modeling development, validation, and simulations are presented for a pilot-scale combustor as well as full-scale utility boilers. While some utilities have had success when cofiring 6-mm (1/4-inch) topsize biomass at full load, CFD modeling can provide insight on the behavior of the 6-mm particles as opposed to the smaller sizes. For example, Table 1 illustrates the complex behavior when cofiring a dry switchgrass in a 150 MWe tangentially-fired pulverized coal utility boiler with four burner levels (A, B, C, D; where D is the lowest level near bottom ash, and A is the uppermost level). Using an eastern bituminous low sulfur coal in this CFD simulation, switchgrass is evenly distributed among the burners at a total 10% energy basis cofiring level, using a broad size distribution of about 5% plus 6-mm, 14% plus 4-mm, 37% plus 2-mm, 60% plus 1-mm, and 23% minus 0.5-mm with a mean particle size of 2-mm. Table 1 presents the fate of biomass particles - whether particles distribute to the fly ash or bottom ash, their effective biomass particle residence time (from burner injection level to either the convective section entrance or bottom ash hopper), and combustion efficiency (CE) – as viewed from one corner of the boiler.

Table 1. CFD Biomass Particle Size Impacts - Residence Time, Combustion Efficiency (CE), and Fly Ash/Bottom Ash Partitioning for 10% Switchgrass Cofiring at Full Load in a 4-Level Burner 150 MWe Tangentially-Fired Boiler

Burner Level	0.5 mm Switchgrass	1 mm Switchgrass	3 mm Switchgrass	4 mm Switchgrass	5 mm Switchgrass	6 mm Switchgrass
A Upper	2.1 sec no sparklers 99.9% CE All Fly Ash	1.5 sec few sparklers 99.9% CE All Fly Ash	6.4 sec sparklers 97% CE All Fly Ash	8.1 sec sparklers 96.3% CE 90% Fly Ash	3.2 sec sparklers 95.3% CE Bottom Ash	2.5 sec sparklers 95.4% CE Bottom Ash
B	2.6 sec no sparklers 99.9% CE All Fly Ash	3.4 sec few sparklers 99.9% CE All Fly Ash	3.4 sec sparklers 97.2% CE 6% Fly Ash	2.8 sec sparklers 95.5% CE Bottom Ash	2.3 sec sparklers 95.2% CE Bottom Ash	1.9 sec sparklers 95.2% CE Bottom Ash
C	3.1 sec no sparklers 99.9% CE All Fly Ash	2.1 sec few sparklers 99.9% CE All Fly Ash	2.8 sec sparklers 95.7% CE Bottom Ash	2.2 sec sparklers 95.3% CE Bottom Ash	1.9 sec sparklers 95.1% CE Bottom Ash	1.7 sec sparklers 95.1% CE Bottom Ash
D Lower	7.2 sec no sparklers 99.9% CE 39% Fly Ash	7.6 sec few sparklers 99.2% CE 28% Fly Ash	1.4 sec sparklers 95.2% CE Bottom Ash	1.2 sec sparklers 95.1% CE Bottom Ash	1.2 sec sparklers 95% CE Bottom Ash	1.2 sec sparklers 95.1% CE Bottom Ash

In this CFD simulation, pulverized coal and switchgrass achieve an average residence time of over 3 sec and 4 sec, respectively, with average combustion efficiencies of 99.9% and 99.3%, respectively. Although switchgrass particles are an order of magnitude larger than pulverized coal, they achieve high combustion efficiencies due to their high volatile content along with residence time enhancements. Table 1 shows that the smallest switchgrass particles behave in an expected fashion, with longer residence times observed for particles injected in the lower furnace, with essentially complete burnout as particles enter the convective pass and report to fly ash. However, the larger switchgrass particles behave quite differently as the relative contributions of gravity, buoyancy, and drag forces alter particle trajectories and effective residence times inside the turbulent flow field of the t-fired boiler. This can be seen by the presence of still-burning sparklers entering the convective pass for intermediate particle sizes, and at larger sizes, still-burning sparklers that simply drop into the bottom ash. While the overall combustion efficiency of 99.3% for switchgrass is very good, the presence of still-burning sparklers could be an issue from the standpoint of boiler operations and bottom ash handling.

While Table 1 presents just one simulation result, important sensitivities include varying switchgrass moisture, particle size, and aspect ratio that impacts the choice of biomass handling/milling equipment, as well as other biofuels with different volatile/char characteristics that might be available near the utility station. In addition, consideration of boiler variables, such as varying load, injection location and velocity, and possible burner tilting are important in considering site-specific cofiring design and operational issues. In this paper, multiple data sets and CFD simulations will be presented to highlight synergies in biomass cofiring.

References

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