A Performance Analysis and Simulation of a Wood Pellet Boiler in terms of Tar Existence on Heating Surface

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Abstract

This study compares Computational Fluid Dynamics (CFD) simulation of thermal behavior and boiler efficiency with actual wood pellet boiler operation to consider tar yields on the heating surface and to see if a more accurate simulation can be utilized. A model has been developed to predict the thermal behavior of gas and water in a wood pellet boiler by using the conservation of mass, momentums, and energy equation. The fuel used for the experiment is 1st grade wood pellets and their tar yields are compared. The effects of the tar yields in a combustion chamber have been investigated, and the simulated results for tar scaling were in good agreement with measured values. The results showed that the thermal efficiency of the wood pellet boiler is predicted to improve if tar is eliminated. From this work, the research and development of wood pellet boiler should be carried out aiming at improving their overall thermal efficiency.

Keywords: CFD, Simulation, Wood pellet boiler, Wood pellet, Tar,

1 Introduction

Globally, the interest in the use of new and renewable energy is growing. Especially biomass fuel as a carbon neutral energy which has the effect of absorbing carbon dioxide by photosynthesis. When wood pellets are burned, the emission of nitrogen oxides (NOx) and sulfur oxides (SOx) is about 8.3%, the yield of carbon dioxide is approximately 3.7% compared to the burning of oil, respectively. Wood pellets are a fuel earning three times more profits than wood sawdust, due to reduced volume and consequently reduced transport costs. The heating value of pellets is greater than sawdust and the manufacturing, packaging, and supplying of pellets is improved because of its smaller retail shape. These wood pellets are produced from sawdust and waste wood after crushing, smashing, and compression. The characteristics of wood pellets include a heating value of more than 4,040 kcal/kg, moisture content of less than 15%, apparent density of more than 500 kg/m³.

Wood pellets are suitable for transport, storage, and use in a heating system. Despite these advantages, wood of logging residues has a non-uniform moisture content after the field process, high yields of tar, ash, and clinker upon combustion due to the high ash content.
Consequently problems include emission of harmful exhaust gas, decrease in boiler efficiency, and the occurrence of system operating errors [Euh et al, 2012]. One of the major problems of product gas utilization after burning is the production of condensable hydrocarbons, known as tar, during pyrolysis, gasification, and combustion [2]. Tar is an extremely complex mixture of organic compounds and condensable hydrocarbons, which may be composed of 1-5 aromatic ring compounds along with other oxygen-containing hydrocarbons and complex poly cyclic aromatic hydrocarbons (PAH). The formation of tar is highly dependent on the reaction conditions [Diana et al, 2010].

The studies on the thermal characteristics of wood pellet boilers, simulation of thermal energy use, and development of technologies for improving efficiency have been insufficient. Related research is needed to improve boiler efficiency. In this study, the performance test looking at tar existence on heating surfaces of the combustion chamber in the wood pellet boiler using the 1st grade wood pellet, the simulation verification, thermal behavior, and heat transfer characteristics were investigated.

2 Materials and methods

2.1 The mechanism of tar formation and fouling

In the present model tar products are grouped into three classes: Tar 1 (low molecular weight) released by evaporation, Tar 2 (average molecular weight), released by evaporation simultaneously reacts giving rise to both gaseous and heavier compounds and Tar 3 (high molecular weight) undergo a cross-linking reaction and form gases and char [Ahuja et al, 1996, Bradbary et al, 1979]. According to the adopted reaction scheme, the mathematical model results in a set of material balance equations – one for each “component”. The reactions were all considered as first-order reactions of Arrhenius type [Enrico et al, 2011].

(a) “Tar 1” component

\[ R_1 = \dot{m}_1 \]

\[ \dot{R}_1 : \text{transformation rate of wood to Tar 1 (kg/s)} \]

\[ \dot{m}_1 : \text{production rate of Tar 1 (kg/s)} \]

(b) “Tar 2” component

\[ (R_2 - R_{23} - R_{2g}) = \dot{m}_{2, ev} + \frac{dm_2}{dt} \]

\[ \dot{R}_2 : \text{transformation rate of wood to Tar 2 (kg/s)} \]

\[ R_{2c} : \text{transformation rate of Tar 2 to Tar 3 (kg/s)} \]

\[ R_{2g} : \text{transformation rate of Tar 2 in gas (kg/s)} \]

\[ \dot{m}_{2, ev} : \text{evaporation rate of Tar 2 (kg/s)} \]

\[ m_2 : \text{mass of Tar 2 in the sample (kg)} \]

(c) “Tar 3” component

\[ (R_3 + R_{23} - R_4 - R_{3g}) = \frac{dm_3}{dt} \]

\[ \dot{R}_3 : \text{transformation rate of wood to Tar 3 (kg/s)} \]

\[ R_{3c} : \text{transformation rate of Tar 2 to Tar 3 (kg/s)} \]

\[ R_4 : \text{transformation rate of Tar 3 to char (kg/s)} \]

\[ R_{3g} : \text{transformation rate of Tar 3 to gas (kg/s)} \]

\[ m_3 : \text{mass of Tar 3 in the sample (kg)} \]
2.2 Configuration and methods of the experimental system

The output of the wood pellet boiler is about 20,000 kcal/h and the structure is the 3PASS stand flue type. First, the generated combustion gas from the burner in the combustion chamber (1st PASS) according to combustion of air and wood pellet moves into upper region of the 1st PASS, and then enters the 2nd PASS through baffles. The flue gas is controlled by a 16 mm separation plate and is exhausted by a ventilator installed above the 3rd PASS. Throughout this flow process, heat from of the combustion gas is absorbed by a fluid circulating around the outer heating surface. This heated fluid flows out of the boiler above the 1st PASS and heat is removed at the thermal load spot. The circulating fluid is returned by a circulating pump (PW-200SMA, WILO CO. LTD., GERMANY) into a water hole underneath the 3rd PASS. The schematic of combustion gas flow in a wood pellet boiler is shown in figure 1.

The simulation results using CFD in terms of the wood pellet boiler were compared with the performance experiment by referring to the heat balancing method of land boilers (standard No. KS B 6205, 2008.12.19.) of Korean Agency for Technology and Standards (KATS). The results of the performance test considering tar existence on the heating surface of the combustion chamber in the wood pellet boiler using 1st grade wood pellet were compared to each simulation for verification. Thermal behavior and heat transfer at the heating surface were also evaluated. The 1st grade wood pellets are used for the performance test.

The 1st grade wood pellet is composed of 80% larch and 20% oak. The total operating time of the wood pellet boiler to generate the tar for the performance test in terms of the tar formation on heating surfaces was carried out for 27.33 hours and the total operating number was 70.

2.3 Model development

The wood pellet boiler includes a burner, a combustion chamber, flues, baffles, a water tank, a frame, working fluid (water), combustion gas, feeding entrance of wood pellet, and the inlets and outlets of air and water (Fig. 2). FLUENT (13.0 ANSYS Inc, USA) was used for simulation using Computational Fluid Dynamics (CFD). The generated mesh is expressed in Fig. 3.

The behavior of fluid in the system was configured as steady, compressible, incompressible, and turbulent, and the heat transfer is considered as conduction, convection, and radiation. The models of Turbulent Standard k-ε, Discrete Ordinate, Species Transport (Non-premixed combustion) and Discrete Phase were applied for the simulation. Excess air ratio is approx. 1.87.

3 Results and Discussion

3.1 Verification of performance test and simulation of the wood pellet boiler

The performance test (KS B 6205, KATS, KOREA, 2008) using the 1st grade wood pellet of wood pellet boiler was performed at steady state for more than 2 hour (primary test: 5, Oct, 2013., secondary test: 22, Oct, 2013), and the results were compared with the simulation. The velocity vectors and temperature distribution by simulation are expressed by Fig. 4, and the simulation results including the water and gas outlet temperature compared to performance test are shown in table 1.

The water outlet temperature and combustion gas outlet temperature in the performance testing were 70.12°C and 115.00 °C, while simulation results were 84.73°C and 114.59°C, respectively. The deviations between experiment and simulation are 14.61°C and 0.41°C, respectively.

The outlet temperature of the combustion gas based on the simulation is 0.41°C lower, and the water temperature is 14.61°C higher due to tar yields on the heating surface and the inner surface of flues in the experiment results.
The velocity vectors and temperature distribution results by simulation with tar existence condition (Approx. 1mm-thick) by Fig. 5, and the simulation results including the water and gas outlet temperature compared to performance test are shown in table 2.

Water outlet temperature and combustion gas outlet temperature from the performance testing were 69.43°C and 117.00 °C, while the simulation results are 73.65°C and 114.30°C, respectively. The differences between the experimental results and the simulation results are 3.22°C and 2.70°C, respectively.

4 Conclusions

In this study, analysis of a boiler where tar collected while burning wood pellets and simulations using CFD both with and without tar considerations of a wood pellet boiler was performed. The 1st grade wood pellets were used and results were compared to evaluate the impact of tar on the effectiveness of the boiler.

Compared to actual results from the performance test using the 1st grade wood pellet, simulation results with no tar were different (outlet temperature of combustion gas decreased 0.41°C, and water temperature increased by 14.61°C) showing the impact of tar yields on the heating surface and inner surface of flues. The actual performance test results are affected by tar formation as well as heat loss caused by a lack of insulation at the burner inlet and side inlet frames with windows to observe the flame. Modeling simulation considering tar existence comes closer to the actual test results than the original condition model.

Comparing wood pellet grades on the production of tar and boiler efficiency we found the efficiency of 1st grade wood pellets was 93.65%. Efficiency decreased by 7.26% when tar had accumulated. The boiler efficiency is reduced when tar accumulates because of the lowering of the total heat transfer rate because of the low heat transfer coefficient of tar. The conductive heat transfer coefficient of tar is 0.15 W/m·K while that of the heating surface (frame and flue) is 60.5 W/m·K at 300K.

Further research on the mechanism of tar formation and measures that will reduce tar sticking to the heating surface with combustion in a wood pellet boiler is needed.

5 Acknowledgements

This study was supported by 2013 Research fund from Korea Forest Research Institute.

6 References


Fig. 1. Combustion gas flow in a wood pellet boiler [1]

Fig. 2. Geometry of the wood pellet boiler
Fig. 3. Mesh of the wood pellet boiler

Fig. 4. Velocity vectors (left) and temperature volume rendering (right) of combustion gas in the wood pellet boiler with the original condition
Fig. 5. Velocity vectors (left) and temperature volume rendering (right) of combustion gas in the wood pellet boiler with the tar existence condition

<table>
<thead>
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<th>Water inlet Temp. (°C)</th>
<th>45.71</th>
<th>45.71</th>
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<td>Water outlet Temp. (°C)</td>
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<td>84.73</td>
<td>14.61</td>
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<tr>
<td>Gas outlet Temp. (°C)</td>
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<td>114.59</td>
<td>0.41</td>
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Table 1. Comparison with the experiment and simulation results with the original condition

<table>
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<th>Water inlet Temp. (°C)</th>
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<th>45.99</th>
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<tbody>
<tr>
<td>Water outlet Temp. (°C)</td>
<td>69.43</td>
<td>72.65</td>
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<tr>
<td>Gas outlet Temp. (°C)</td>
<td>117.00</td>
<td>114.30</td>
<td>2.70</td>
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Table 2. Comparison with the experiment and simulation results in the tar 1 mm condition