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A study on the effect of tar fouled on thermal efficiency of a wood pellet boiler: A performance analysis and simulation using Computation Fluid Dynamics

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ABSTRACT

The high yield and fouling of tar reduces thermal efficiency of the wood pellet boiler. In order to achieve better performance of wood pellet boiler, the effect of tar fouled on thermal efficiency should be investigated. This study presents CFD (Computation Fluid Dynamics) simulation of thermal behavior of the boiler and analysis the thermal efficiency affected by tar fouling on the heating surface of the combustion chamber. A model has been developed to predict the thermal behavior of the combustion gas and heating water in the boiler using the conservation of mass, momentum and energy equations. To investigate the effect of tar fouling on thermal efficiency, the experiments were performed by combusting the 1st and the 3rd grade wood pellets, and compared with the simulations. By about 1 mm tar fouling in heating surface of the boiler the thermal efficiency dropped by 7.26%p and 9.19%p in the 1st and the 3rd grade wood pellets, respectively. Compared to experiment using the 1st grade wood pellet, simulation results were relatively deviated, the outlet water temperature increased by 0.53 K in non-tar condition and decreased by 0.02 K in tar-existence condition. This study can be used to improve the overall performance of the boiler.

1. Introduction

Globally, the interest in the use of new and renewable energy is growing, especially biomass fuel due to its carbon neutral properties [1]. Solid biofuel, pellets, is gaining global interest [2,3] due to its homogeneity quality regarding particle density, MC (moisture contents), and uniform shape and size [4]. The wood pellets produce from sawdust and waste wood after crushing, drying, and compression. The characteristics of wood pellets include a LHV (lower heating value) of more than 4040 kcal kg^{-1}, MC (moisture contents) of less than 15%, and apparent density of more than 500 kg m^{-3} [5]. Wood pellets are suitable for transport, storage, and use in a heating system. Despite these advantages of wood pellet, wood of logging residues has non-uniform MC after the field process [6], which results high yields of tar, ash, and clinker due to the high ash content in the fuel [7]. Consequently, problems include emissions of harmful gas, decrease in thermal efficiency of the boiler, and the occurrence of system operating errors [8–12].

Tar is an extremely complex mixture of organic compounds and condensable hydrocarbons; it may compose of 1–5 aromatic ring compounds along with other oxygen-containing hydrocarbons and complex PAH (polycyclic aromatic hydrocarbons). The formation of tar is highly dependent on the reaction conditions [13].

In the pyrolysis stage of biomass burning, temperature range from 473 K to 773 K, the primary tar produce by breakdown of cellulose, hemicellulose and lignin. The further increase in temperature convert primary tar into secondary tar in the temperature range 973 K–1173 K. Primary and secondary tar compounds contain oxygen and are therefore reactive and relatively easy to destroy. The secondary tar converts into the high order tertiary tar on further increase in temperature; the tertiary tars are relatively stable and have high dew point tertiary tar. The tertiary products is further subdivided into ‘alkyl tertiary products’, like methylnaphthalene, toluene and indene, and the ‘condensed tertiary products’, which include the PAH [13].

The Morf et al., 2002 concluded that during homogeneous reaction, gravimetric tar decreases with increasing temperature,

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Abbreviations

CFD	Computational Fluid Dynamics
C_p	specific heat of heating water (kcal kg^{-1} K^{-1})
G	The feed rate of wood pellets (kg h^{-1})
G_h	quantity of supply water (kg s^{-1})
H	hydrogen mass fraction of wood pellet
H_l	lower heating value of wood pellet (kcal kg^{-1})
H_h	higher heating value of wood pellet (kcal kg^{-1})
LHV	lower heating value
MC	moisture contents (%)
$\dot{m}_1$	production rate of Tar 1 (kg s^{-1})
m_2	mass of Tar 2 in the sample (kg)
m_3	mass of Tar 3 in the sample, (kg)
$\dot{m}_{2,ev}$	evaporation rate of Tar 2 (kg s^{-1})
PAH	polycyclic aromatic hydrocarbons
Q_i	Total inflow calorific value (kcal)
Qo	Total outflow calorific value (kcal)
R_1	transformation rate of wood to Tar 1 (kg s^{-1})
R_2	transformation rate of wood to Tar 2 (kg s^{-1})
R_{23}	transformation rate of Tar 2 to Tar 3 (kg s^{-1})
R_3	transformation rate of wood to Tar 3 (kg s^{-1})
R_4	transformation rate of Tar 3 to char (kg s^{-1})
R_{g2}	transformation rate of Tar 2 in gas (kg s^{-1})
R_{g3}	transformation rate of Tar 3 to gas (kg s^{-1})
Greek symbol	
ρ	density (kg m^{-3})
η	thermal efficiency of wood pellet boiler (%)

carbon monoxide is the major product from tar conversion, acetol is the major tar compound measured in the primary tar and naphthalene measured higher in tertiary tar, and the thermal behavior of all PAH compounds showed similar.

A number of researches have been performed on the materials fouling (e.g. calcium sulfate: $CaSO_4$, potassium sulfate: K_2SO_4, potassium chloride: KCl, etc.) in biomass fired boilers [8,9,14] and performance analysis of the wood pellet boiler [4,15–26]. 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 thermal efficiency. In this study, the performance tests for the effect of tar fouled on thermal efficiency of wood pellet boiler using different wood pellets, and the CFD (Computation Fluid Dynamics) simulation for thermal behavior of the wood pellet boiler were investigated.

2. Materials and methods

2.1. The mechanism of tar formation and fouling

In this study, the kinetic model was adopted from the Grieco & Baldi, 2011 study [27]. The 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) undergoes a cross-linking reaction and form gases and char [27–29]. The mathematical model results in a set of material balance equations, one for each ‘component’ in the adopted reaction scheme, which is considered as first-order Arrhenius type [27].

(a) “Tar 1” component

$$R_1 = \dot{m}_1 \tag{1}$$

where, R_1 is transformation rate of wood to Tar 1 (kg s^{-1}) and $\dot{m}_1$ is production rate of Tar 1 (kg s^{-1}).

(b) “Tar 2” component

$$(R_2 - R_{23} - R_{g2}) = \dot{m}_{2,ev} + \frac{dm_2}{dt} \tag{2}$$

where, R_2 is transformation rate of wood to Tar 2 (kg s^{-1}), R_{23} is transformation rate of Tar 2 to Tar 3 (kg s^{-1}), R_{g2} is transformation rate of Tar 2 in gas (kg s^{-1}), $\dot{m}_{2,ev}$ is evaporation rate of Tar 2 (kg s^{-1}), and m_2 is mass of Tar 2 in the sample (kg).

(c) “Tar 3” component

$$(R_3 + R_{23} - R_4 - R_{g3}) = \frac{dm_3}{dt} \tag{3}$$

where, R_3 is transformation rate of wood to Tar 3 (kg s^{-1}), R_4 is transformation rate of Tar 3 to char (kg s^{-1}), R_{g3} is transformation rate of Tar 3 to gas (kg s^{-1}), and m_3 is mass of Tar 3 in the sample (kg).

When the combustion gas temperature cools below the dew point of tar, it is condensed and caused fouling and blocking the equipment. The temperature at which partial pressure and saturation pressure of tar equals is called dew point of tar. If there is no condensation of the combustion gas, it is called over-saturated [30,31]. The tar dew point is important to know the tar formation and fouling mechanism on the heating surface of the combustion chamber in wood pellet boiler. At dew point temperature, the tar condensation begins with cooling of combustion gas.

2.2. Configuration and methods of the experimental system

In this study, the 3-pass stand heating pipes wood pellet boiler with the heat output capacity 20,000 kcal h^{-1} was used. First, the combustion gas from the burner moves into upper region of combustion chamber (the 1st Pass), and then enters into the 2nd Pass through baffles and then it is exhausted by a ventilator (TB-115F, InnoTech Co. Ltd., Republic of Korea) installed above the 3rd Pass. Throughout this flow process, the fluid circulating around the outer heating surface absorbs heat from the combustion gas. The heat transfer from hot gas to water follows radiation, conduction and convection process. This heated fluid flows out of the boiler above the 1st Pass and it returns 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 Fig. 1.

The heating pipes (carbon steel; 828 mm of length, 42 mm of inner diameter, and 3.3 mm of thickness) in the wood pellet boiler are installed as 2 rows and 5 columns, and the baffles are disposed in each heating tube. The baffle is carbon steel, spring type, and 503.1 mm of length.

The simulation results using CFD were compared with the performance test by referring to the heat balancing method of land boilers (standard No. KS B 6205, 2008.12.19.) of KATS (Korean