Effect of Staged Air Combustion on the Temperature of A 5 MW$_{th}$ Wood Pellet Stove

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Biomass pellet is an important source of renewable energy and plays a key role in the circular economy of the fuel industry. In this study, the oxidation characteristics of the wood pellet were firstly investigated and the combustion control strategy of a 5 MW$_{th}$ pellet stove was determined accordingly. Then, the relationship between the excess air ratios and the average temperatures of the main combustion chamber ($T_{ave,main}$) was explored. The results depicted that the primary and secondary air supply dominated the gas temperature of the main combustion chamber, the criteria to control the mean gas temperature under the initial deformation temperature, i.e. 1200°C, was to control the excess air level of less than 31%. In addition, when the primary to secondary air ratio ($A_{pri/sec}$) was controlled under 2, $T_{ave,main}$, decreased with an increase in $A_{pri/sec}$ under the sub-stoichiometric combustion condition of $\lambda_{exar,main} < 0.81$.   Whereas, it increased with an increase in $A_{pri/sec}$ when the wood pellet combustion took place under the over-stoichiometric conditions of $\lambda_{exar,main} > 1.31$.

Keywords: Staged air combustion, Wood pellet, Grate firing stove

1. INTRODUCTION

Biomass pellet is an important source of renewable energy and plays a key role in the circular economy of the fuel industry. In accordance with the life cycle assessment (LCA), waste wood pellets can create GHG savings of 93% in comparison with coal based upon an energy-content basis[1]. With the increasing demand for greenhouse gas (GHG) emissions reduction, it has become an alternative to fossil fuel and introduced in industrial processes, and 27 million tons of pellets were produced in the year 2014[2].

Biomass pellet combustion is a thermo–chemical process that can convert solid fuel to energy in a safe and stable way. Basically, the combustion behaviors[3] of the biomass pellet could be described by ignition, flame combustion and char oxidation processes. However, the variety of the biomass and the manufacturing processes led to different combustion characteristics. Therefore, the characters of various kinds of biomass pellets were investigated by different approaches to explore their corresponding combustion behaviors. Among these researches, García et al[4] conducted a comprehensive study which included the proximate analysis, the ultimate analysis(C, H, N, S and O composition) and the calorimetry of more than 200 different biomass fuels to characterize their properties. The results showed that both N and S contents were low in most samples, giving biomass low emissions of NOx and SO$_2$.

Rhe´n et al.[5] investigated the effect of raw material composition in woody biomass pellets on combustion characteristics, the results depicted that pellets made of bark had up to a 50% longer char combustion time compared to that of stem wood pellets. The main reason could be attributed to the differences in char yield. On the other hand, pellets made of pine and spruce sawdust were found to have small differences in combustion characteristics. M.V. Gil et al.[6] also founded the biomass/biomass blends of pine, chestnut and eucalyptus sawdust, cellulose residue, coffee husks and grape waste presented similar combustion profiles to those of the individual raw materials. Biswas et al.[3] studied the effect of pelletizing conditions on fuel conversion behaviors by burning a single pine pellet in a laboratory scale combustion furnace. The results indicated that the time required for single pellet combustion generally increased with both the increase of pelletizing temperature as well as the moisture content of the biomass.

Jenkins et al.[7] reviewed the properties of biomass relevant to combustion, and indicated that alkali and alkaline earth metals, in combination with silica, sulfur, and chlorine, were responsible for many undesirable phenomena such as fouling occurring in combustion furnaces. By leaching the above-mentioned elements from the fuel could yield remarkable improvements in ash fusion temperatures.

Regarding the combustion control[8], the relevant research indicated that the best excess air ratio for wood combustion ranged from 1.4 to 1.6. Although some guidelines for biomass combustion had been given, the detailed control philosophy and temperature control

technology in different kinds of stoves should be established in more detail. However, it has seldom been discussed. Therefore, the main purposes of this study were to explore the combustion characteristics of the biomass pellet and the effect of staged air combustion on pellet stove temperature control. In this study, the oxidation characteristics of the wood pellet were firstly investigated and the combustion control strategy was determined in accordance with these characteristics. Finally, the relationship between the excess air ratios determined in the staged air combustion scenarios and the mean gas temperatures of the main combustion chamber was explored.

2. EXPERIMENTAL

2.1 Characterization of the material

The wood pellet was adopted in this study to investigate the combustion characteristics of the grate type stove. Table 1 lists the test results of the proximate analysis, heating value and the bulk density of the wood pellets, and the ash content of the wood pellets are displayed in Table 2. In order to get more insight into their

combustion characteristics for the determination of the combustion control parameters, a non-isothermal thermogravimetric analyser (PYRIS Diamond) was used to carry out the thermogravimetric analyses of a wood pellet. In the thermogravimetric experiments, air was served as the carrier gas to explore the thermogravimetric characteristics of the wood pellet. Based on the thermogravimetric data, the oxidation kinetic parameters were analysed in accordance with the mathematical model described as follows. In the mathematical model, the rate equation [9][10] for solid fuel decomposition was expressed by:

$$\frac{dX}{dt} = k(1-X)^n \quad \text{.......................................(1)}$$

In Eq. (1), the reaction rate k can be expressed in Arrhenius form,

$$k = A\exp\left[-E_a/(RT)\right] \quad \text{.......................................(2)}$$

Table 1　Essential properties of the wood pellets

	Sample	1	2	3
Proximate analysis	Volatile matter (D.B.*, wt %)	84.55	85.51	85.08
	Ash(D.B.*, wt %)	0.67	0.69	0.62
	Fixed carbon(D.B.*, wt %)	14.78	13.8	14.3
	Moisture(A.R.*, wt %)	8.24	7.8	8.02
Gross heating value(kcal//kg)		4422	4463	4513
Heating value (D.B.*, kcal//kg)		4876	4893	4957
Bulk density (kg/m³)		650	641	649

* D.B.－Dry basis; A.R.－As receive.

Table 2　Ash content of the wood pellets

Sample	1	2	3
Fe_2O_3	0.99	0.834	3.683
CaO	57.556	57.414	53.953
MgO	13.53	13.345	10.546
Na_2O	1.682	1.52	2.092
K_2O	3.819	5.468	6.123
P_2O_5	6.54	6.439	5.129
SiO_2	4.43	3.09	2.8
Al_2O_3	2.097	2.044	1.948
TiO_2	0.616	0.724	0.238

Where, n is the order of reaction, A is the pre-exponential frequency factor(1/s), Ea(kJ/mol) is the activation energy of the reaction, T (K) is the temperature, R represents the universal gas constant (8.3143 kJ/K-mol), and X denotes the decomposition fraction of the fuel at a given time t,

$$X = (W_i - W_t)/(W_i - W_f)$$ .... (3)

Substitute Eq. (2) and Eq. (3) into Eq. (1), we get:

$$\frac{dX}{dt} = A\exp(-\frac{E_a}{RT})(1 - X)^n$$ .... (4)

Considering the constant heating rate condition, i.e. β=(dT/dt)=constant, and making the separation of variables, then the solid fuel decomposition equation can be expressed as follows:

$$\frac{dX}{(1 - X)^n} = (\frac{A}{\beta})\exp(-\frac{E_a}{RT})dT$$ .... (5)

There is no exact solution for Eq. (5). The integral method developed by Coats and Redfern[9] was adopted in this study to establish the mathematical model of the solid fuel pyrolysis and combustion. By taking the approximation, and assume n=1, the integration of Eq. (5) can be expressed as follows.

$$\ln[\frac{-\ln(1 - X)}{T^2}] = \ln\frac{AR}{\beta E}\left[1 - \frac{2RT}{E_a}\right] - \frac{E_a}{RT}$$ .... (6)

For most reactions, 2RT/E <<1 , so $\ln\frac{AR}{\beta E_a}\left[1 - \frac{2RT}{E_a}\right]$ can be regarded as a constant. Therefore, the relation of $\ln[-\ln(1-X)/T^2]$ with 1/T becomes a linear line. By substituting TGA data into Eq. (6), the apparent activation energy Ea and frequency factor A can be determined through the slope and intercept derived from linear regression, respectively.

2.2 Equipment

This study conducted the experiments on a grate stove. Basically, the stove was designed to supply heat to the milling process, and it is operated under a pellet feeding rate of around 1 t/h. The heat release rate was estimated as 5MW$_{th}$. Fig.1 illustrates the process flow diagram of the experiments, the picture of the combustion system is shown on Fig.2.

The stove was mainly composed of a feeding system, the diesel igniter, the main combustion chamber which is equipped with a primary and secondary air supply system, and the external cylindrical combustion
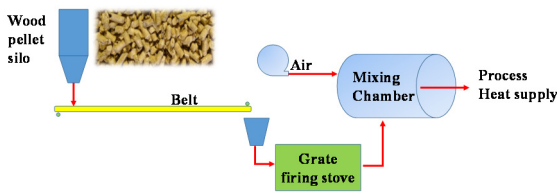

Fig.1. Sketch of the process design.

Main combustion chamber

Fig.2. Grate firing system of the wood pellet.

chamber which is designed with a 3rd independent air supply system. The walls of the combustion chamber were built with refractory materials and the fixed grates were designed at the bottom of the main combustion chamber which was connected to a primary air supply chamber located underneath. As a result, the primary air supply was provided up through the grates. In addition, the secondary air was supplied to the main combustion chamber by 36 holes located in the surrounding walls, and the outlet direction of the secondary air was perpendicular to the primary air supply.

3. RESULTS AND DISCUSSIONS

The experiments were performed in the grate firing system under an average feeding rate of 925.9kg/h with a standard deviation of 0.07kg/h. The corresponding average heat release rate was approximately 4.8 MW. The oxidation characteristics of the wood pellet and the effect of staged air combustion on the mean temperature of the wood pellet stove are described as follows.

3.1 Oxidation characteristics of the wood pellet and the combustion control strategy

In the thermogravimetric experiments, air was served as the carrier gas and its flow rate was controlled at 100 ml/min. The initial sample weight was 8.2 mg. The heating rate of the system was controlled at 10°C /min with an initial temperature of around 30°C. The results of the thermogravimetric analyses of the wood pellet are displayed in Fig.3. As a whole, the curves can be divided into (I) heating up stage; (II) main pyrolysis and combustion stage; and (III) final decarburization stage. A similar pattern was also found in the oxidation process of coal and biomass blends[11]. For the powder derived from the wood pellet, the heating up stage was located between room temperature and 234.2°C. In this stage, the weight loss of the tested sample was 8.38 wt%,
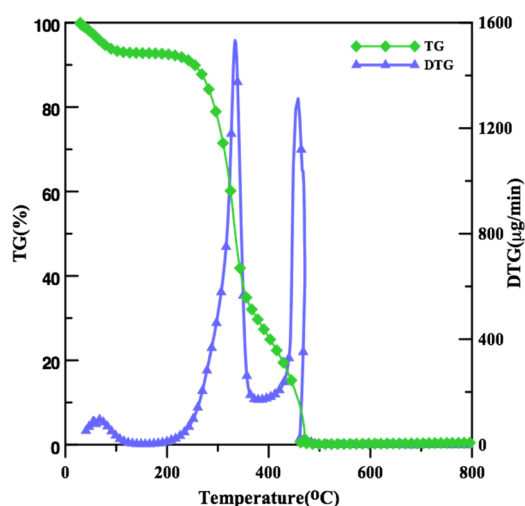
Fig.3. Non-isothermal thermogravimetric curves of the wood pellet.

which was approximately the value of the moisture content of the wood pellet as depicted in Table 1, implicating that the main reactions occurred in stage (I) were the drying procedure and the release of some light volatiles.

The main pyrolysis and combustion stage came after stage (I), where a significant drop in weight was observed. To get more insight into the thermal decomposition and combustion behaviors of the wood pellet, the initial decomposition temperature (IDT), ignition temperature (IT) and the burnout temperature (BT) were defined in this study, and the definition of IDT was the temperature at which the mass loss rate reached 3% of the maximum mass loss rate of the entire process of continuous growth. The ignition temperature (IT) was determined from two tangent lines of the TG curve. The first tangent line passed through the intersection of the TG

curve and the vertical line that pass through the IDT. The second tangent line passed through the intersection of a vertical line derived from the peak of the DTG curve and the TG curve. The burnout temperature (BT) was defined as the temperature where the mass loss rate of the tested sample went down to less than 0.5 wt%/min of the original weight. In accordance with the above-mentioned definitions, the wood pellet initial decomposition, ignition and burnout temperatures were 234°C, 296°C and 501°C, respectively. The ignition temperature was used to be as the environment temperature criteria to judge when the diesel igniter could be turned off in the initial ignition process.

In stage(II), the maximum mass loss rate was 1533 µg/min and the corresponding temperature for the maximum mass loss rate was 333°C. In this stage, the weight loss of the wood powder was 90.8 wt%. After the burnout point, the whole oxidation process came into the final decarburization stage, the burning rates decreased significantly and the residual weight was 0.147 wt%. The low residual weight could be attributed to the low ash content of the wood pellet.

The corresponding kinetic data derived from the TG experiments is shown in Table 3. In addition, the oxidation process of the wood pellet was evaluated in a comprehensive way by combustion characteristics index (CCI) [12][13] defined in Eq. (7), in which, $(dw/dt)_{max}$ and $(dw/dt)_{mean}$ represented the max mass loss rate (%/min) and average mass loss rate (%/min) detected during the thermogravimetric experiments, respectively. Besides, the ignition temperature was denoted as $T_{ignition}$, and $T_{burnout}$ represented the burnout temperature. Both of them were expressed by the Kelvin temperature scale. The calculated result of CCI for the wood pellet was

Table 3　Essential properties of the wood pellets

	Item	
Thermogravimetric	IDT (°C)	234.2
analysIs	IT (°C)	296
	BT (°C)	461.5
	CCI	1.87×10^{-7}
	Ea (kJ mol^{-1})	40.63
Oxidation kinetic	A(min^{-1})	2.17×10^{2}
	R^2	0.9469
	Initial deformation temperature (IDT; ℃)	1200
Ash fusibility	Sphere temperature (ST; ℃)	1350
	Hemisphere temperature (HT; ℃)	1355
	Flow temperature (FT℃; ℃)	1360

1.87·10[-7], which was higher than that of the Sub-Bituminous Coal (SBC). This implicated that the wood pellet would show better combustion characteristics than that of the SBC under the same combustion condition.

$$CCI = \frac{(dW/dt)_{max} \cdot (dW/dt)_{mean}}{T_{ignition} \cdot T_{burnout}} \quad \text{............................ (7)}$$

Another evaluation for the wood pellet was the ash melting characteristics. The initial deformation temperature(IDT), sphere temperature(ST), hemisphere temperature(HT) and flow temperature(FT) were determined in the oxidizing environment in accordance with ASTM D1857-03. The IDT, ST, HT and FT were 1200 °C, 1350°C, 1355°C and 1360°C, respectively. Accordingly, the upper limit for the combustion control of the average gas temperature in the main combustion chamber was set to be 1200°C, which was chosen in accordance with the test result of the initial deformation temperature. By controlling the average temperature under 1200°C, we hope to diminish the formation of ash melting phenomena during the test, and facilitate stable operation.

3.2 Effect of excess air ratio on the main combustion chamber temperature
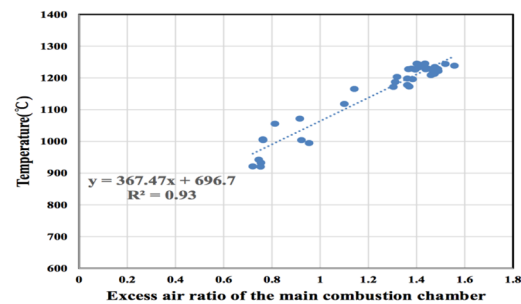
The effect of excess air ratio on the main combustion chamber temperature was explored in this section. The excess air ratio was defined herein as the ratio of air inert to the combustion system and the stoichiometric air required for the complete combustion of the wood pellet. The results presented in Fig.4 indicated the average temperature of the main combustion chamber ($T_{ave,main}$) increased with an increase in system excess air ratio (λ) when $\lambda<1.97$. When λ reached 1.97, the $T_{ave,main}$ reached 1200°C. Thereafter, the average temperature fluctuated under different air supply rates, Between the region of 1.97 δ λ ≤ 2.2, the highest value of $T_{ave,main}$ was 1245°C when the excess air ratio was controlled at 2.1. The above-mentioned $T_{ave,main}$ were the averaged measurement results of the gas temperature by 3 thermocouples. The locations of the thermocouples were near the central of the side wall with different heights, and the heights for thermocouple 1, 2 and 3 were 15cm, 65cm and 80cm above the grate, respectively.

The air supplied to the main combustion chamber was inserted by the primary and secondary air supply systems. Fig.5 depicted the relationship between the excess air ratios and the mean temperatures of the main combustion chamber, and the similar pattern was found as that presented in Fig.4. As presented in Fig. 5, $T_{ave,main}$ increased with an increase in excess air ratio for the sub-stoichiometric cases. It is because the absence of oxygen stops oxidation reactions from taking place and the heat release rate of the combustibles was limited mainly by
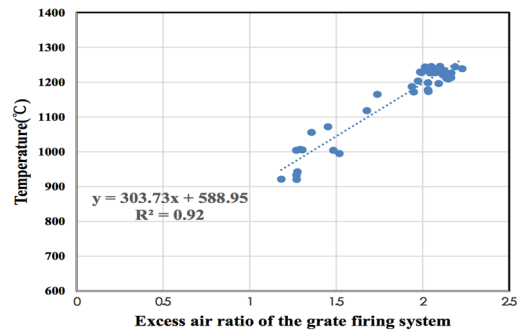
Fig.4. Relationship between the temperatures of the main combustion chamber and the excess air ratios of the grate firing system.

the diffusion of oxygen to the surface of the solid phase. The criteria to control $T_{ave,main} < 1200$ ℃ was to control $\lambda_{exar,main} < 1.31$. By the comparison of Fig.4 and Fig.5, it also demonstrated that the air supply to the main combustion chamber dominated the gas temperature of the main combustion chamber. Moreover, $T_{ave,main}$ could be linearly predicted by the excess air ratio of the main combustion chamber ($\lambda_{exar,main}$) by the following equation (8) with the R^2 of 0.93.

Fig.5. Relationship between the temperatures and the excess air ratios of the main combustion chamber.

$$T_{ave,main} = 367.47\, \lambda_{exar,main} + 696.7 \quad \text{......................(8)}$$

Regarding the effect of staged air control on the mean gas temperature of the main combustor chamber, Fig.6 depicts that, as a whole, there was no strong relationship existing between them. However, when the primary to secondary air ratio was limited to under 2, $T_{ave,main}$ decreased with an increase in primary to secondary air ratio under the sub-stoichiometric combustion condition of $\lambda_{exar,main} < 0.81$. For the group of $\lambda_{exar,main} > 1.31$, in which $T_{ave,main} > 1200$°C, $T_{ave,main}$ increased with an increase in primary to secondary air ratio. This implied the primary and secondary air played different roles in sub-stoichiometric and over-stoichiometric cases, and the effect of staged air combustion on the average temperature of the main combustion depended on the competition result of the heat release of the chemical reactions and the temperature dilution effect of the air.
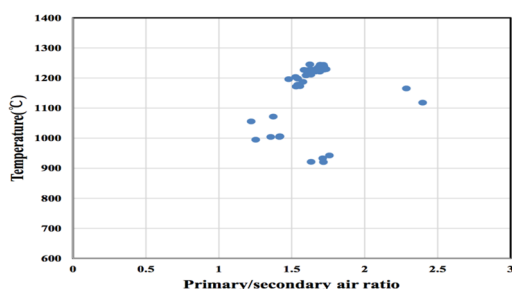
Fig.6. Relationship between the temperatures and the primary to secondary air ratios of the main combustion chamber.

4. CONCLUSIONS

The main purpose of this study was to investigate the combustion characteristics of the wood pellet and to explore the effect of excess air ratios on pellet stove temperatures. From the experiments carried out in the present work, the following conclusions could be drawn: (1) the analysis via thermogravimetric method depicted that the pyrolysis and combustion processes of the wood evolved the heating up stage, main pyrolysis, combustion stage and the final decarburization stage. The initial decomposition, ignition, burnout and initial deformation temperatures of the wood pellet were 234°C, 296°C, 501°C and 1200°C, respectively. Among them, the ignition temperature and the initial deformation temperature were used as the reference temperatures for process control. (2) For the three stage air combustion system, the air supply to the main combustion chamber (the primary and secondary air) dominated the level of the mean gas temperature, the criteria to control the mean gas temperature of the main combustion chamber under the initial deformation temperature, i.e. 1200°C, was $\lambda_{exar,main}$ <1.31. The experiments also demonstrated that the primary and secondary air played different roles in sub-stoichiometric and over-stoichiometric combustion conditions. For $\lambda_{exar,main} < 0.81$, the average temperature of the main combustion chamber decreased with the increase in primary to secondary air ratio. Whereas, it increased with the increase in primary to secondary air ratio when $\lambda_{exar,main} > 1.31$.

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