

Performance of Torrefaction Based Co-firing Power Plant: The Roles of Torrefaction

Degree and Biomass Substitution Ratio

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Abstract

Torrefaction changes the elementary composition of biomass and moves it towards bituminous coal, and accordingly, torrefaction based co-firing system in a pulverized coal boiler have been proved as a promising option for direct co-firing with a large percentage of biomass. This work investigated the performance of torrefaction based co-firing power plant, especially, discussed the roles of torrefaction degree and biomass co-firing ratio in a 220MWe pulverized-fuel power plant. Biomass torrefaction tests were performed at temperature of 200°C, 250°C, 270°C, and 300°C, respectively, and each case was kept same residence time of 30 minutes. A series of analyses were carried out to understand the impacts of torrefaction degree and biomass co-firing ratio on CO₂ emission, process operation, and electricity efficiency. According to the results, it is concluded that CO₂ and CO are the main components of torrefied gases. Averagely, CO₂ and CO account 79% and 18% of total gases in volume fraction in four studied cases. From an energy saving perspective, a deep torrefaction is not recommended, because the energy saved from biomass grinding is less than that consumed by the extra torrefaction process. The results also showed that the electrical efficiency reduced with increasing of either torrefaction degree or substitution ratio of biomass.

Key words: Torrefaction; Biomass; Co-firing; Power generation

1 Introduction

The EU has a clear framework to steer its energy and climate policies up to 2020. These policy objectives are delivered by three headline targets for GHG emission reductions, renewable energy and energy savings [1]. In the year of 2011, EU confirmed the objective of greenhouse gas reduction by 80-95 % by 2050 compared to 1990 [2]. To achieve such ambitious target, one promising option is to increase the sharing of biomass energy, because bioenergy accounts for more than two thirds of total renewable energy in the EU and the amount of CO₂ taken out of the atmosphere by plants is roughly equivalent to the amount put into the atmosphere by respiration [3]. Co-firing has an enormous potential in increasing the share of biomass and renewable sources in the global energy mix and reducing greenhouse gases emission [4]. For example, the substitution of 10% of coal in the currently installed coal-fired electrical capacity would result in about 150 GW biomass power, which is 2.5 times higher than the current globally installed biomass power capacity [4]. Pulverized fuel plant comprises the largest installed capacity for coal use in the world [5]. Therefore, pulverized coal installations represent a largest potential market for co-firing [5]. Despite the significant work that have been undertaken on co-firing of coal and biomass/waste, a number of technical issues require further work on reliable handling systems for biomass.

Biomass for energy is mainly provided by forestry, agriculture and organic waste, in which forestry provides half of the EU's renewable energy [6], bioenergy can thus be produced constantly and is a reliable source of energy. Biomass is able to penetrate all energy sector markets, but economic constraints still limit its general deployment [7]. However, the economics of biomass co-firing are significantly impacted by the twin factors of deregulation and environmental requirement. The inherent problems with raw biomass materials compared to fossil fuel resources, such as low bulk density, low energy density, and high moisture content, make biomass transportation expensive, and potentially, have negative impacts during energy

conversion such as lower combustion efficiencies[8]. Moreover, raw biomass can absorb moisture during storage and may rot as well.

In order to address those problems, enhancement of biomass properties is advisable not only is to improve its inferior characteristics, also to make it as suitable alternative for fossil fuel such as coal. Recently, torrefaction, one of a biomass pretreatment technologies, is widely acknowledged as a promising method on a large scale to increase biomass energy content, break fibrous structure of biomass making it's grinding easy, promote its flowability featuring a good fluidization behavior, and also uniform the product quality[9-14]. And accordingly, torrefaction based co-firing system in a pulverized coal boiler have been proved as a co-firing option with the aim of high percentage of fuel switching[15, 16].

However, further study is required for commercial application of the torrefaction based co-firing system. This paper mainly studied the effects of co-firing ratio of torrefied biomass and torrefaction degree on electricity efficiency in power plants, because the additional energy are required for torrefaction process, biomass grinding when compared to a traditional coal power plant. Typically, an enhanced torrefaction consumes more energy for biomass pretreatment process but less energy on biomass grinding. In this work, a series of analyses were performed to understand the impacts of torrefaction degree and biomass substitution ratio on CO₂ emission, process operation, and electricity efficiency in a torrefaction based co-firing plant.

2 Torrefaction tests and fuel preparation

In this study, a horizontal rotary furnace was used for biomass torrefaction. The rotating furnace is equipped electrical heating unit. In order to assure a perfect thermal insulation, the refractory fibers are used in a form of a ceramic blanket surrounding the inner tube. Change of the speed within the range from 2-12 rpm and additional adjustment of the tilt angle from the horizontal level up to 20°, which allows selecting an optimum control of the process efficiency

and the residence time, as well as elimination of material accumulation risk. In this work, the selected biomass material is Palm Kernel Shell (PKS).

PKS torrefaction tests were performed at temperature of 200°C, 250°C, 270°C, and 300°C, respectively, and each case was kept same residence time of 30 minutes. To assure the largest output and the longest residence time of the material, the biomass feeding flow rate was kept 6 kg/h with a tilt of 2°. For the analysis of gas from torrefaction, constituents were analyzed with SERVOMEX analyzer within the range 0-100% for CH₄, CO₂, CO, H₂; while heavy hydrocarbon tars were determined by using FTIR GASMET CX 4000. Torrefied samples collected after torrefaction were delivered to a detailed chemical analysis of the composition and grinding effectiveness.

3 System description and modeling

The study of torrefaction based co-firing system is based on a 220MWe coal-fired power plant in Ostrołęka, Poland. The overall process of torrefaction based co-firing plant was modeled by using Aspen Plus. In which, biomass torrefaction, biomass/coal grinding, biomass/coal devolatilization, volatile and chars combustion, heat exchangers, and steam turbine were modeled in details. The specific instructions of each unit are presented in Table 1.

<Table 1>

3.1 Biomass drying

Raw PKS is passed through a dryer firstly. The dryer is maintained at a temperature high enough to guarantee the drying medium does not become saturated, but low enough that mild volatilization of the biomass is minimal. Typical temperature is 105 °C when the flue gas extract from a boiler is used. For simplify, the moisture content of raw PKS will be released completely, and thus the dry biomass is on dry basis in this study.

3.2 Torrefaction process

Dried biomass is then fed into a directly-heated torrefaction reactor. In this reactor, the temperature is controlled in the range of 200 to 300 °C. At a given temperature, a portion of the volatiles matter is released off in the form of the light gases, and few amount of condensable organic compounds, which are called torrefied gases, as shown in Figure 1. Loss of the tenacious nature of the biomass is mainly coupled to the breakdown of hemicellulose matrix, which bonds the cellulose fibers in biomass, and decrease the length of these fibers during depolymerisation process[17]. The remaining solid material contains less volatile matter, and increased fixed carbon content.

<Figure 1>

According to the experimental results, the released gases are mainly CO₂, CO, CH₄, H₂, and tars (i.e. C₄H₁₀, C₅H₁₂, C₆H₁₄, and C₇₊ et al.). Due to the total volume fraction of tars was detected less than 2%, thus, tar is not considered in this simulation work. After torrefaction process, the majority of the torrefied gases are feed into boiler as re-burning species. Finally, the torrefaction process is governed by the following reaction:



The torrefaction process can be evaluated by a parameter called as torrefaction degree, which is defined as the loss volatiles mass divided by the total volatiles in the raw material. In this work, the torrefaction processes of biomass were carried out at temperatures of 200 °C, 250 °C, 270 °C and 300 °C, and for the residence time of 30 minutes. The yield of released gases is varying with the torrefaction degree, which typically determined by both torrefaction temperature and residence time. Due to the same residence time was carried out for all cases; it is, therefore,

possible to simulate the mass loss of raw biomass is only determined by temperature. The torrefaction degree of PKS is expressed by the following equation:

$$\eta_{TOR} = A \exp(-B/T)$$

Where η_{TOR} is the torrefaction degree; constants $A=65$, and $B=2596$ are estimated based on the experimental results; T is the torrefaction temperature in K, validated ranges in $473 \text{ K} \leq T \leq 573 \text{ K}$.

3.3 Mill modeling

Solid fuel particles sizes are required to be reduced in to a specified limit value when burning in pulverized fuel boilers, to ensure an intense and complete combustion process. Typical fineness criteria for coal powders are 70% wt.% below 75 μm . The power plant milling system is required to implement when switching a coal-fired boiler to co-firing application. The potential problems of grinding biomass in an existing coal mill have been identified in previous studies. The majority of such problems can be summarized as the physical differences between coal and biomass particles, because biomass is fibrous in nature and tenacious to be grinded into desired particle sizes and this requires high energy input. It is difficult to accomplish a perfect combustion, thus, finely powdered biomass is required. Consequently, prior to grinding, the selected biomass (PKS) is torrefied with varying torrefaction degrees, since it has a good grindability compared its parent material.

Accordingly, the torrefied biomasses are supposed to be grinded by the existing coal-mill system. To get more accuracy prediction results of torrefaction based co-firing system, the following equation determines the power requirement for mill:

$$q = \frac{0.01\dot{m}(\sqrt{X_F} - \sqrt{X_P}) \cdot \frac{435}{HGI^{0.91}}}{\sqrt{X_F \cdot X_P}}$$

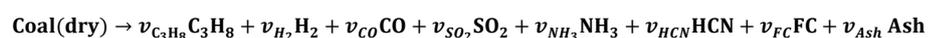
here q is the required power, W; $(X_F)^{0.5}$ refers to diameter larger than 75% of feed particle mass, m; $(X_p)^{0.5}$ refers to diameter larger than 75% of product particle mass, m; \dot{m} is the total solids mass flow rate, kg/s. In addition, Hardgrove grindability index (HGI) indicates the difficulty of grinding coal/biomass based on physical properties such as hardness, fracture, and tensile strength.

According to the above equation, HGI is a key parameter to calculate the power requirement of mill system, thus, to get an accuracy data of HGI becomes significantly important. Several empirical expressions have been reported to estimate the HGI value for various coal, which is mainly related either with the moisture, volatile, and fixed carbon contents or ash content of coal[18-20], but its normally a constant HGI value of 40 for coals. While for torrefied biomass, the HGI were rarely reported. Recently, Ibrahim et al. investigated grindability properties of the several torrefied materials, such as hard wood and soft wood[21]. Due to the studied PKS is type of hard wood, therefore, Ibrahim et al. experimental HGI data are summarized and employed in this work[21], as shown in Figure 2.

<Figure 2>

3.3 Devolatilization and combustion modeling

After torrefaction, torrefied PKS was milled and then injected into boiler furnace for combustion, including devolatilization, volatile and char combustion. In this work, detailed mechanisms for torrefied PKS and coal devolatilization have been adopted, as expressed in following reaction and calculating the devolatilization products in Aspen Plus by FORTRAN codes. During devolatilization process, biomass and coal are separately converted into its constituting components, which include intermediate species, residues of char, and ash by two separate reactors, as shown in following reactions:



In this model, it is assumed that all Fuel-N was converted into volatiles-N completely, since char-N conversion chemistry is complicated[22, 23]. For the biomass, it is assumed that 90% of the nitrogen from the volatile will be converted to NH_3 , and the rest will form HCN[24]. While for coal, oppositely, 90% of HCN and 10% of NH_3 were derived from the volatile-N[25]. Furthermore, hydrogen and oxygen are assumed to be totally released as volatiles, and there is no fixed carbon is released as volatile during the devolatilization process. For biomass cases, the ratios of each species changed for different torrefied PKS samples, because the proximate and ultimate data would be modified after torrefaction at varying torrefaction temperatures.

After devolatilization, the streams of biomass and coal as the mixture phase were feed into the next reactor, 'primary combustion zone', where most combustion reactions occurs, as shown in Figure 3. After primary combustion, the stream was feed into the continuing reactor, 'Re-burning zone', where reactions occurs under a reduction atmosphere, which is a typical NO_x -reduction technology. Unburned combustibles are complete combusted in the 'Complete combustion zone', where excess air ratio is larger than 1. After secondary combustion, hot flue gas flow continually into backpass of boiler for heat exchanging in Super-heaters, Economizers and Air-preheater etc.

<Figure 3>

3.4 Heat exchanges and steam turbine modeling

Figure 4 shows the schematic details of heat exchangers and steam turbine system in the studied pulverized fuel power plant. By modeling in heat exchangers located in the backpass of boiler into 7 sections (3-stage Super-heaters, 2-stage attemperators, Economizer, and Air-preheater), the detailed calculations of heat transfer from flue gas side to steam were conducted to simulate energy performance of the unit as precise as possible. The feed-water from the regeneration subsystem is feed to Economizer, and then heated through membrane wall, and then continually upgrades the steam parameters by SH1 and SH2 before introduced into HPT.

After HPT, the main steam is further upgraded in SH3 and then introduced into IPT and LPT. Two-stage attemperators (AT1 and AT2) are used to constant the parameters of main steam before entering HTP and IPT, respectively. The main steam expands through stages of HPT, IPT, and LPT to generate electricity. After complete shaft work, the final exhausted steam is condensed in the unit of condenser. To increase the total thermal efficiency of the steam cycle, part of expanded steam is extracted at different locations of the turbine to heat up the feedwater in regeneration subsystem, as shown in Figure 4.

<Figure 4>

4 Results and discussions

4.1 Experimental results

4.1.1 Fuel properties of torrefied PKS

PKS was torrefied at temperatures of 200°C, 250°C, 270°C, and 300°C, and was kept at same residence time of 30 minutes, in order to produce four torrefied PKS with different torrefaction degree. For simplify, those four torrefied PKS are abbreviated as PKS 200, PKS 250, PKS 270, and PKS 300 respectively. The proximate and ultimate analyses data of those torrefied biomass samples are listed in Table 2, and the analyses data of studied coal is also presented for comparison.

<Table 2>

From Table 2, it is observed that torrefaction significantly reduces the volatile-fixed carbon ratio of biomass and upgrades its energy density. Table 2 shows that biomass has lower energy density than coal, however, it interestingly shows that torrefaction changes the elementary composition of biomass, and moves it towards to coal, the elementary composition of torrefied biomass is much close to coal, so that torrefied biomass is able to be grinded as the same particle sizes distributions with coal powder.

4.1.2 Mass losses characteristics of biomass during torrefaction

Figure 5 shows the mass loss properties of three main elements (Carbon, Hydrogen, and Oxygen) compared to their original masses. Obviously, torrefaction temperature enhanced the mass losses of all studied three elements. From Figure 5, oxygen losses its weight gradually with the increasing of torrefaction degree, while the mass loss of hydrogen does not have significant changes when the torrefaction temperature over 250 °C, and similarly, the mass loss of hydrogen does not have significant changes when the torrefaction temperature over 275 °C.

<Figure 5>

Furthermore, the main gas species were detected during the biomass torrefaction process, as represented in Figure 6. It is obvious that CO₂ is the main component of torrefied gases, which volume fraction is higher than 69% in total gases, and CO₂ concentrations reduced with torrefaction temperature increasing, especially, the CO₂ mole fraction was up to 91.27% at the torrefaction temperature of 200°C. Oppositely, the CO concentrations gradually rose with torrefaction temperature increasing. Beside, big jump of CO concentrations was observed when the torrefaction temperature switched from 200 °C to above 250°C; they are 3.6% at torrefaction temperature of 200°C and 19.89% at 250°C. In average, CO₂ and CO account 79% and 18% of total gases in volume fraction in four studied cases. Compared to CO₂ and CO, traces of hydrogen and methane is also detected in non-condensable products, and their volume fractions are no more than 2% in total torrefied gases, and the fluctuate results probably are caused by the unstable errors of measuring instrument when detecting such small amount of gases.

When considering the mass losses of C, H, and O elements together with torrefied gases results, it could be concluded that the ratio of CO and CO₂ increased with increasing of torrefaction temperature. The formation of CO₂ may be explained by decarboxylation of acid groups in biomass and other herbaceous biomass; while the increased CO formation is probably

caused by the reaction of CO₂ and steam with porous char. The similar results were reviewed by Tumuluru et al. in 2011[26].

<Figure 6>

4.2 Validation of torrefaction model

The torrefaction process was modeled comprehensively by considering the changes of the amount of released gases under different torrefaction temperatures. To ensure the accuracy solid products with the adapted torrefaction model, the predicted H/C and O/C are compared to the measured data under varying temperatures, as shown in Figure 7. From Figure 7, it is clear that the predicted values of H/C and O/C ratios show a good agreement with the experimental data. The maximum H/C ratio error was observed less than 10% for the case of 270 °C torrefaction; however, it could be acceptable for further studies, because the trends of both H/C and O/C ratios varying with torrefaction temperature were clear enough.

<Figure 7>

On the other hand, the concentrations of main torrefied gaseous species, CO₂ and CO, are also able to be compared for further model validation. Figure 8 shows that the predicted the concentrations of two main gas species have a very good agreement with the measured values, apart from the measured CO concentration is slightly higher than the predicted data, which could be caused by modeling assumptions was not considering the tar content during torrefaction process. By comparing both the yields of solid products and gases products, it could be concluded that the torrefaction model is able to be used for further discussions in this work.

<Figure 8>

4.3 Power requirements of biomass torrefaction and mill

For a torrefaction based co-firing plant, the power consumptions of biomass torrefaction and grinding of torrefied biomass are important to be investigated before its commercial application. Figure 9 shows the power requirements for biomass torrefaction and biomass mill system. Obviously, the power requirement for biomass grinding significantly reduced with the increasing of torrefaction temperature, it ranges from 64.27kWh/ton at 200°C to 17.1 kWh/ton at 300°C. Oppositely, the power requirements for biomass torrefaction increased with the increasing of torrefaction temperature, it changes from 49.03 kWh/ton at 200°C to 107.84 kWh/ton at 300°C.

Furthermore, it is obvious that less grinding energy is consumed on torrefied biomass when the parent biomass was torrefied at a relatively elevated temperature, however, additional energy is required for torrefaction process itself. For example, the energy requirement is 107.8 kWh/ton in order to heat up biomass for torrefaction process occurring at the temperature of 300°C; while the mill energy consumption is as low as 17.1 kWh/ton to grind that corresponding torrefied biomass, which is even less than that for grinding of lignite coal. From an energy saving perspective, a deep torrefaction degree is not recommended, because the energy saved from biomass grinding is less than that consumed by the extra torrefaction process. In addition, it should be pointed out that pulverized coal mill capacities are decreased by co-grinding of wood with coal, which probably limits the degree of co-firing as well [5].

<Figure 9>

4.4 CO₂ Emissions

The most important benefit of co-firing biomass is to reduce CO₂ emission, because CO₂ emission from the combustion of biomass fuel source is not assumed to increase the net atmospheric CO₂ levels [27, 28]. To understand the effects of torrefaction degree and co-firing ratio on CO₂ emissions, total CO₂ and capturable CO₂ emissions with unit of kg/MWh were compared based on the predicted data, as

shown in Table 3. The capturable CO₂ was simply calculated based on the biomass feed rate and its carbon content. Table 3 shows total CO₂ increased with increasing of biomass percentages, which is due to the increased biomass consumption. However, the torrefaction temperature does not have obvious effects on the total CO₂ emissions, because the total biomass feed rates are same and all the byproducts after torrefaction were finally burned inside boiler. Typically, a subcritical coal-fired utility plant produce 900 kgCO₂/MWh, and 750 kgCO₂/MWh for a supercritical plant[29]. When compared to the uncapturable CO₂ of 759.7 kg/MWh in the pure coal case, there are 846.5 kgCO₂/MWh can be recaptured when 100% coal substituted by the torrefied biomass.

<Table 3>

4.5 Electrical efficiency

The effects of biomass substitution ratio and the torrefaction temperature on the electrical efficiency on a torrefaction based co-firing plant have been investigated in this work, as shown in Figure 10. The maximum electrical efficiency of 38.5% was observed when the biomass substitution ratio of 20% with the torrefaction temperature of 200 °C; when compared to the measured electrical efficiency in the pure coal case, the electrical efficiency of 0.5% was sacrificed, because the additional energy was consumed for biomass torrefaction and grinding. The process of torrefaction moves the chemical and physical properties of the raw biomass close to that of bituminous coal with releasing almost all the moisture and part of volatiles, which is expected to reach higher energy efficiency. Figure 10 shows that the electrical efficiency reduced with biomass torrefaction temperature increasing, which owing to the energy requirement for biomass torrefaction is higher than that for the grinding of corresponding torrefied biomass, as similarly observed in Figure 9. The lower electrical efficiencies were observed at the torrefaction temperature of 300 °C, which are 38.13%, 38.09%, 37.97%, and 37.57% at biomass substitution ratios of 20%, 50%, 70%, and 100%, respectively.

<Figure 10>

Besides, Figure 10 also shows that the electrical efficiency reduced with biomass substitution ratio increasing, which is normally acknowledged that directly using a higher moisture biofuel, the overall

energy efficiency of the co-firing plant would be reduced unexpectedly[30]. Furthermore, It is observed that the torrefaction temperature has a significant influence on the electrical efficiency when replacing 20% biomass in the studied co-firing system, it ranges from 38.13% to 38.5%; while the influences of biomass torrefaction temperature become less critical with the biomass substitution ratio increasing, the electrical efficiency slightly ranges from 37.57% to 37.65% in the pure biomass cases. These results could be explained as the energy requirement for biomass torrefaction is much higher than that for grinding of various torrefied biomasses when co-firing a higher percentage of biomass.

5 Conclusions

This work examined and assessed various torrefaction degrees and co-firing options influencing on emissions reductions and system performances in a 200MWe pulverized-fuel power plant. Experimental of biomass torrefaction were performed at four different torrefaction temperatures, 200°C, 250°C, 270°C, and 300°C, respectively. A series of analyses were carried out to understand the impacts of torrefaction degree and biomass co-firing ratios on CO₂ emission, process operation, and electricity efficiency. According to the results, it is concluded that CO₂ and CO are the main components of torrefied gases. Averagely, CO₂ and CO account 79% and 18% of total gases in volume fraction in four studied cases. From an energy saving perspective, a deep torrefaction degree is not recommend, because the energy saved from biomass grinding is less than that consumed by the extra torrefaction process. The results also showed that the electrical efficiency reduced with increasing of either biomass torrefaction degree or biomass substitution ratios.

Although the results are reasonable, however, to full understand the torrefaction based co-firing system before commercial application, series further studies should be performed on the experimental test in the local plant. Finally, the torrefaction based co-firing provides a technical option that allows a co-firing of coal and biomass process of the 100% biomass utilization with maximum efficiency and minimum emission in power plants.

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Tables

Table 1. Description of the unit operation block in Aspen plus

Units	Functions	ASPEN blocks	Remarks
Dryer	Coal/biomass drying	RStoic	Modified by FORTIRAN subroutine
Torrefier	Biomass torrefaction	RStoic	Modified by FORTIRAN subroutine
Devolatilization	Coal/biomass devolatilization	RYield	Modified by FORTIRAN subroutine
Mill	Coal/biomass grinding	Crusher, Screen	Modified by FORTIRAN subroutine
Primary combustion, Re-burning, complete combustion	Volatiles and char combustion	RGibbs	Default model
Economizer, Air- preheater	Heat recycles from flue gas	HeatX	Default model
Super-heaters, Attemperators	Upgrade and constant the parameters of main steam	HeatX	Default model
Steam turbines	Power generation	Compr	Default model

Table 2. Proximate and ultimate analysis of torrefied biomasses and coal

Items	Units	PKS-raw	PKS 200	PKS 250	PKS 270	PKS 300	COAL
Proximate analysis							
Moisture	<i>wt%</i>	13.20	6.00	5.14	4.67	4.99	1.43
Ash (dry basis)	<i>wt%</i>	4.40	5.50	6.82	8.01	8.65	25.06
Volatile (dry basis)	<i>wt%</i>	75.00	68.91	61.45	54.72	51.11	27.85
Char (dry basis)	<i>wt%</i>	20.58	25.59	31.73	37.27	40.24	47.09
LHV	<i>kJ/kg</i>	16.52	19.65	20.27	19.83	20.57	23.30
Ultimate analysis							
C (dry basis)	<i>wt%</i>	51.83	54.96	55.70	53.91	56.31	60.26
H (dry basis)	<i>wt%</i>	6.28	5.93	5.10	5.37	5.56	3.97
O (dry basis)	<i>wt%</i>	37.03	33.01	31.78	31.82	28.70	8.33
N (dry basis)	<i>wt%</i>	0.44	0.60	0.60	0.89	0.78	1.27
S (dry basis)	<i>wt%</i>	/	/	/	/	/	1.11

Table 3. Total CO₂ and captuable CO₂ emissions (kg/MWh) at different biomass substitution ratios and different torrefaction temperatures

Torrefaction temperature	Biomass substitution ratio (thermal basis)				
	0 (Pure coal)	20%	50%	70%	100%
200 °C	759.7	780.7	807.1	822.8	844.4
250 °C		781.1	808.4	824.7	847.2
270 °C		781.2	808.6	824.9	847.6
300 °C		781.0	808.1	824.3	846.6
Captuable CO₂	0	173.7	436.7	615.6	846.5

Figure captions

Figure 1. Biomass pretreatment process and coal/biomass sizing

Figure 2. Hardgrove grindability index (HGI) data for torrefied biomass[21] and coals[18-20]

Figure 3. Biomass and coal co/firing process inside boiler furnace

Figure 4. Heat exchanges and turbine subsystem in the torrefied based co-firing plant

Figure 5. Effects of torrefaction temperature on the mass losses of carbon, hydrogen, and oxygen

Figure 6. Effects of torrefaction temperature on the main components of released gases during torrefaction process

Figure 7. Comparison of prediction data and experimental data after 30min torrefaction at different temperatures (a. H/C; b. O/C)

Figure 8. Comparison of prediction data and experimental data after 30min torrefaction at different temperatures (a. CO₂; b. CO)

Figure 9. Energy requirements for biomass torrefaction and biomass mill

Figure 10. Effects of torrefaction temperature and biomass substitution ratio on electrical efficiency