Cogasification of Blended Coal-Biomass in an Air/Steam BFB Gasifier: Experimental Investigation and Model Validation

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A series of cogasification experiments were performed at a 100 kW bubbling fluidized bed (BFB) gasifier to gasify the blended pellets made from two types of coals and woody biomass, with biomass-to-fuel mass ratios of 0–30%. In the cogasification, a mixture of air and steam was fed from the BFB gasifier bottom as gasification agent and the blended biomass-coal pellets were fed into the bed layer. Impacts of biomass mass fraction in the binary pellets and gasification operation temperature on producer gas composition were experimentally investigated. The experimental results have been used to validate a mathematical model developed in this study. From both experimental observation and model prediction, it was found that adding biomass into coal has overall negative impact on producer gas quality in terms of combustible substance contents, and the extents of the blending effect were different among fuel types which have different properties. © 2015 American Institute of Chemical Engineers *AIChE J*, 61: 1639–1647, 2015
Keywords: bubbling fluidized bed, cogasification, blended biomass and coal, producer gas, synthesis gas

Introduction

Gasification is an effective technology to convert carbonaceous solid fuel to synthesis gas which can then be processed for liquid fuels or chemicals. The gasification technology was originally developed for coals as the feedstock; however, it has been used in recent years for gasification of biomass and biosolid wastes. With people being more and more concerned with depletion of fossil fuel reserves and greenhouse gas emissions, biomass as a renewable energy source has attracted great interests both from the research community and from industry. Cogasification of blended biomass and coal is regarded as one of the medium term pathways for reducing reliance on fossil fuels, which has economic, environmental, and technical advantages over utilisation of a pure solid fuel.

Extensive studies have been performed on gasification of either pure coal or pure biomass. However, there are few studies reported in literature on cogasification of blended biomass and coal. There is an apparent lack of fundamental understanding of interactive effects of coal and biomass during the cogasification. Due to the differences in blending ratio and diversity in fuel properties (biomass and coal), the mechanism of cogasification of the blend is complicated and the effects of the blending ratio and the fuel type on the gasification process is still unclear.[1–4]

In previous studies on cogasification of biomass and coal,[4–11] most of the tests were performed on fluidized bed reactor using air, steam, or pure oxygen as gasification agent. From those cogasification tests, it has been found that with increase in the biomass blending ratio, the blended solid fuel shows higher char reactivity, carbon conversion rate (ratio of carbon elements converted into the gas phase to total carbon in feedstock) and lower yield of tars in producer gas from the cogasification. The cold gasification efficiency also increases with the biomass blending ratio. However, the specific calorific value of the producer gas from the cogasification is reduced due to the increase in CO_2 content in the producer gas as a result of high oxygen content in the biomass.

It is well known that the gasification process consists of two stages: the initial devolatilization of the solid fuel, or fast pyrolysis, and the subsequent gasification reactions. In the initial fast pyrolysis, the fed solid fuel decomposes to generate char, volatile gases and vapours of hydrocarbons. In the subsequent gasification stage, reactions occur both between the gases and the char, and among the gases. Studies aiming to gain fundamental understanding of the cogasification have been focused on each of these two stages.

In copyrolysis of biomass and coal, most studies did not observe noticeable synergetic effect and, in this case, each fuel decomposed independently and thus the overall devolatilization rate of the blended mixture was linearly related to the blending ratio.[12–20] However, other studies have found the synergetic effects in the copyrolysis of the blended fuel in which the volatile gases generated were not linearly correlated to the blending ratio.[21] Unfortunately, the mechanisms for this synergetic effect have not been found in literature.

One of the most remarkable observations on the relationship between cogasification and the solid fuel properties is

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Table 1. Proximate Analysis Result of Raw Solid Fuels (wt %)

Fuel type	Moisture (ISO 5068)	Volatile Matter (ISO 562)	Fixed Carbon (By Difference)	Ash (ISO 1171)
Radiata pine (dried)	7.8	77.9	13.8	0.34
Eucalyptus niten (dried)	5.4	81.5	12.7	0.38
Lignite	19.1	41.9	34.1	4.9
Sub-bituminous	13.6	38.6	42.4	5.4

the synergy in cogenerated char reactivity. Some studies have shown synergic effect in the char reactivity[22–24] which is attributed to the catalytic effect of some metals in the biomass.[25,26] In other reported studies on cogasification of biomass and coal, the synergetic effect was found to be insignificant or negligible.[27–29] The gas yield and gas composition in these studies were found to be almost linearly related to the proportion of biomass and coal in the blended feedstock. The possible reason for this is that in these studies, the biomass and coal were fed into the gasifier separately or as a loose mixture, thus the biomass and the coal were segregated once entering the gasifier and then gasified separately. In most practical cogasification operations, the coal and the biomass are commonly fed into the gasifier after simple mixing. However, due to the density difference between biomass and coal, the two fuels are segregated in the fluidization phase, and thus the coal and the biomass are pyrolyzed and gasified independently. This is undesirable since the difference in mean residence time of the two fuels will limit the robustness of cogasification operation. To generate copyrolyzed char, one solution is to premix and to press the two fuels into pellets, and in this case, the gasification characteristic will differ from the intrinsic reaction rate because the effective internal mass transfer resistance can be significant where the particle dimension is greater than a certain value.[30] However, the economic feasibility of such method should be studied before implementing in practical operation so that the potential advantage of synergetic effect would not be compromised by additional pelletizing cost.

In downstream process of the gasification producer gas, flexibility in the gas composition is desirable. One significant advantage of cogasification is that the composition of the producer gas could be altered by changing the blending ratio of the biomass with coal.[3] Therefore, understanding of the effects of solid feed properties and operation conditions on gas product quality is important to cogasification operation. However, from the literature review, this has not been thoroughly investigated whereas most of the reported cogasification studies were focused on gasifier performance such as efficiency, carbon conversion, and tar yield. In the study of Alzate et al.,[31] who performed cogasification experiments in a lab scale fluidized bed gasifier using steam as gasification agent, the contents of H_2 and CO in the producer gas were generally decreased with coal proportion while the content of CO_2 was increased. However, Kumabe et al. reported that, in cogasification in a downdraft gasifier using air-steam as gasification agent, the H_2 content increased and CO_2 content decreased with the coal proportion.[28] Andre et al., who conducted a study on cogasification in a fluidized bed gasifier using air-steam as gasification agent, reported that with increase in the coal proportion, H_2 content increased and CO content decreased slightly while the CO_2 maintained relatively constant.[8] In other studies on air-steam cogasification, opposite trend was observed for CO in the producer gas but CO_2 content was increased with increasing of coal proportion.[4,10] From these studies, the effect of binary fuel blending ratio on the producer gas composition is inconsistent in the cogasification of blended biomass and coal. It appears that other factors may also play an important role such as fuel type, gasifier type, gasification agent and operation conditions. Therefore, further studies are needed to investigate the effects of solid fuel properties, blending ratio and operating condition on the producer gas composition and to gain in-depth understanding of the cogasification process.

The key objectives of this study were to experimentally investigate the operability of cogasification of pelletized coal and biomass on a coal fired gasifier, and to analyze the impact of blending biomass into coal on the producer gas composition. The significance of possible influencing factors such as pyrolysis yield, char reactivity and blending ratio on the producer gas composition will also be determined; and this can provide useful information for cogasification process optimization especially for autothermal type coal-fired gasifier. The experimental results obtained from the cogasification runs are also used to validate a mathematical model by comparing the data from model simulation with the results measured from the experiments. The validated model can then be employed to investigate the influencing factors on producer gas composition.

Experimental

Materials and feedstock preparation

Two types of coals (lignite and sub-bituminous) were received from Huntley mine in Waikato region, New Zealand, and two types of biomass in the form of chips (radiata pine and eucalyptus niten) were supplied from a local sawmill, near Lower Hutt, Wellington, New Zealand. The received coals were first ground by a knife mill to reduce the particle size from roughly 1 cm to approximately 3 mm which were then further ground by a ball mill into particles of about 500 μm in diameter. Concurrently the received fresh wood chips were dried to a moisture content of less than 8% which were then ground by the ball mill to powder form with particle size of less than 500 μm. Finally, the coal and biomass particles were blended at the designated coal-to-biomass mass ratios of 70:30, 80:20, and 100:0 (pure coal). After this, the blends were thoroughly mixed by the ball mill before the mixture was pelletized to form pellets of 7 mm (diameter) by 20 mm (length). The proximate and ultimate analysis results for each type of the raw solid fuel are given in Tables 1 and 2.

Equipment, experimental procedures, and operating conditions

The experiments were performed at a 100 kW bubbling fluidized bed (BFB) gasifier as shown in Figure 1 at CRL Energy, Lower Hutt, New Zealand. The BFB gasifier is in the autothermal category in which the necessary heat for the endothermic gasification process is provided by partial combustion of char and combustible gas generated from the solid fuel devolatilization (fast pyrolysis). The dimensions of the cylindrical chamber of the gasifier are 3.5 m in height and 0.4 m in inner diameter.

Table 2. Ultimate Analysis Result of Feedstock Materials (dry and ash free, daf)

Fuel type	C (wt %) ISO 12902	H (wt %) ISO 12902	O (wt %) By difference	N (wt %) ISO12902	S (wt %) ASTM D4239	H/C	O/C
Radiata pine	51.4	5.9	42.4	0.27	0.01	0.11	0.83
Eucalyptus niten	50.4	5.9	43.5	0.15	0.01	0.12	0.86
Lignite	66.6	4.8	27.1	0.72	0.81	0.07	0.41
Sub-bituminous	73.3	5.1	17.9	1.27	2.4	0.07	0.25

Before each run, 40 kg of silica sand, which was used as inert bed material, was loaded into the gasifier column, and this made up the fluidized bed height to be approximately 0.5 m. In the experiment, the mixture of air and steam was injected at the gasifier bottom through a gas distributor as the gasification agent and the fluidization agent. The steam feeding rate was fixed at 3 kg/h while the air feeding rate was manually adjusted depending on the target operation temperature. For example, to achieve 900°C gasification temperature, which was the standard operating condition in this study, air feeding rate of 60 Nm^3/h was required for pure lignite and 55 Nm^3/h was required for pure sub-bituminous. The solid fuel was fed at a constant rate of 19 kg/h into the bed by a feeding system which consists of two stacking hoppers to prevent the gas leaking from the feeding system. The upper one is the primary hopper used to store the solid fuel during operation. The valve underneath the upper hopper can be manually activated to control the amount of solid fuel being released to the secondary hopper which is located underneath the primary one. The bottom of the secondary hopper is connected to a feeding auger which continuously feeds the solid fuel into the fluidized bed, with the feeding rate being automatically controlled at the set point. Before each run, the secondary hopper was filled with pure coal for heat-up, thus the fuel initially stored in the secondary hopper is also used as the start-up fuel.

Before the experiment, the gasifier was preheated to a temperature of around 500°C using the built-in electrical elements on the gasifier walls. Once this temperature was reached, air was first fed into the gasifier column to fluidize the bed and then the start-up fuel was fed into the gasifier which was ignited and combusted by the air. At this stage, the gasifier was operated on combustion mode while the bed and the gasifier were further heated up to the set-point temperature. Once the target operation temperature for gasification was reached, feeding rates of air and solid fuel were fine-tuned until the bed temperature became stabilized at the set point. When the remaining start-up solid fuel in the secondary hopper was nearly running out, the valve underneath the first hopper was activated and the test fuel was fed into the secondary hopper. At this time the system was switched from the combustion mode to the gasification mode by injection of steam into the gasifier at a feeding rate of 3 kg/h. The test fuel (pellets) was now added to the feeding system and fed into bed. The air feeding rate and the solid fuel feeding rate were further fine-tuned until the bed temperature returned to the set-point value. Then data were collected for analysis.

In this study, a series of cogasification runs were performed to experimentally investigate the gasification process and to validate the developed model which will be described in next section. In the experiments, the set gasification temperatures were: 870, 900, 925, and 950°C, respectively. The

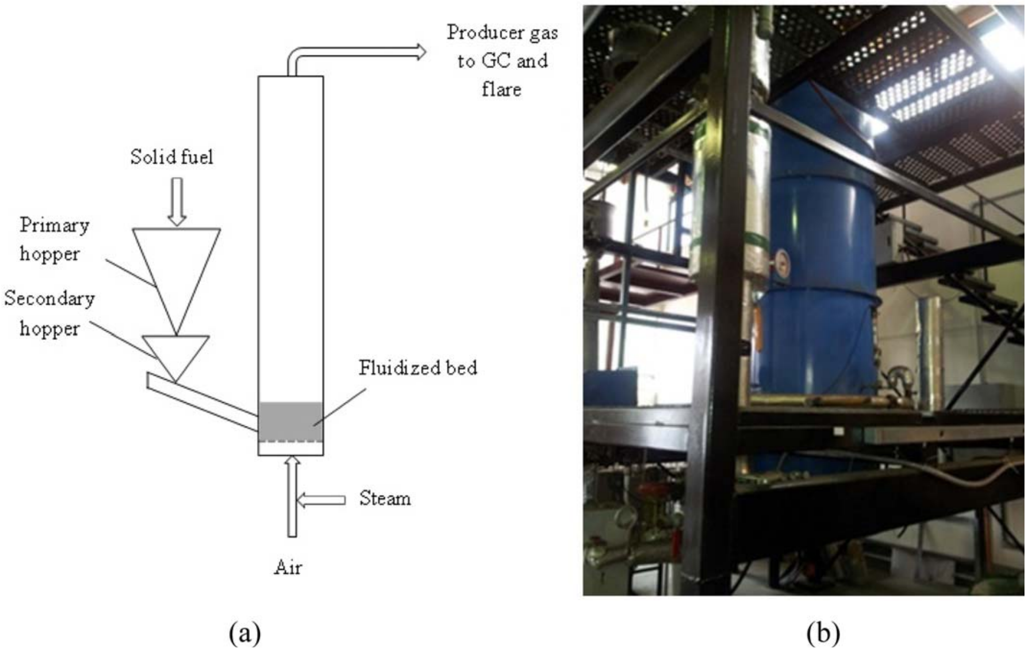

Figure 1. Flow diagram (a) and side view (b) of the bubbling fluidized bed system used for cogasification experiments in this study.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 3. Fuel Composition and Operation Conditions in Cogasification Experiments

Run number	Test fuel[a]	Operation temperature (°C)
1	100L	880–980
2	80L:20E	850–950
3	70L:30E	850–950
4	80L:20P	850–950
5	70L:30P	850–950
6	100S	880–1050
7	80S:20E	850–950
8	80S:20P	850–950
9	70S:30P	850–950

[a] *Note:* L = lignite; S = sub-bituminous; P = radiata pine; E = eucalyptus niten. The figures are the weight proportions in the blended fuel (wt %).

mass proportions of biomass in the blended pellets were: 0 wt % (pure coal), 20 wt % and 30 wt %. Higher biomass blending ratio was also tried but the set point temperature could not be achieved for gasification of feedstock pellets with biomass blending ratio higher than 30 wt %. The experimental conditions and fuel composition are given in Table 3, and for each condition two replicates were performed and the reported data are the averaged values.

The producer gas was sampled from the top of the BFB gasifier which was first cooled down through an ice bath to remove vapour and then analyzed by an online micro-GC to determine the gas composition. Since creeping was commonly encountered which was reflected in continuous change in GC readings, system was considered to reach steady state if overall shifts in GC reading were less than certain value (normally 2% for N_2 and 0.5% for other species) during 30–40 min gasification with the constant feeding rates.

Model Development

A dynamic, one dimensional mathematical model was developed to simulate the cogasification of blended biomass and coal in a bubbling fluidized bed gasifier and to predict the producer gas composition. The model considers solid fuel devolatilization, gas-char heterogeneous reactions and gaseous phase reactions involved in the gasifier process, the heat and mass transfer and essential hydrodynamics calculations of two phase model. Rates of heterogeneous reactions were calculated by effective reaction volume method[32] in which the overall char reaction rates were modified with a factor related to Thiele modulus. This enabled integration of cogenerated char reactivity calculation and conservative equations of the gasifier. The reaction kinetics for heterogeneous reactions and the properties of blended coal and biomass chars have been taken from the authors' previous studies on steam gasification of chars of blended coal and biomass.[33,34]

Results and Discussion

The results from the gasification and the cogasification experiments presented in this section will include the producer gas composition as a function of blending ratio or elapsed time. The results have been used to validate the mathematical model under the same given gasification conditions.

Producer gas composition and model validation

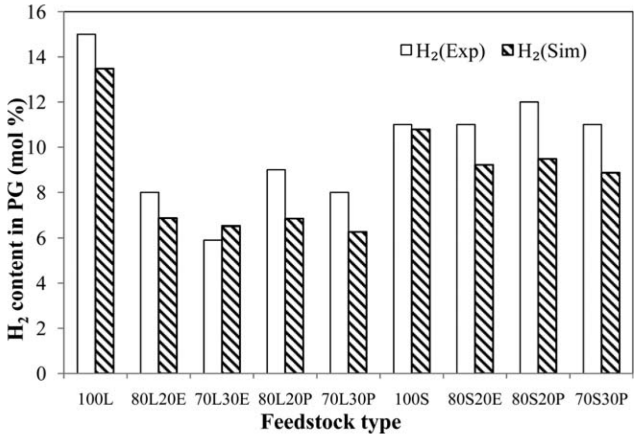

Figure 2. Experimentally measured (Exp) and model predicted (Sim) H_2 contents in producer gas (PG) in cogasification of different feedstock at steady state condition of 900°C.

Producer gas composition is the key outcome in gasification as it is the dominant factor for subsequent gas cleaning and gas application. The experimental results of producer gas compositions at steady state for operation temperature of 900°C with various blended feedstocks are shown in Figure 2 for H_2 content, in Figure 3 for CO content and in Figure 4 for CO_2 content. In these figures, model predicted values are also presented for comparison. From Figures 2–4, it can be seen that the model predicted gas compositions are in close agreement with the experimentally measured results. For all of the blending ratios, the mathematical model can predict accurately the trend of changes in gas species content for various feedstocks. The measured gas species contents are generally lower than those predicted from the model, with average discrepancy of less than 10%. This discrepancy can be raised from the experimental errors in (1) instrumental reading of air and solid fuel feed rate and (2) in measured operating conditions. For the first reason, the instrumental readings of feeding rates were used as the model input parameter; the difference between the model prediction and experimental data could be caused by the deviation between actual air and solid fuel being fed to the gasifier and the instrumental reading correlated from the revolution of the blower motor and feeding auger, respectively. Errors in air to solid fuel ratio (A/F ratio) could be tracked to errors in readings of the feeding rates. The effect of A/F ratio will be further discussed

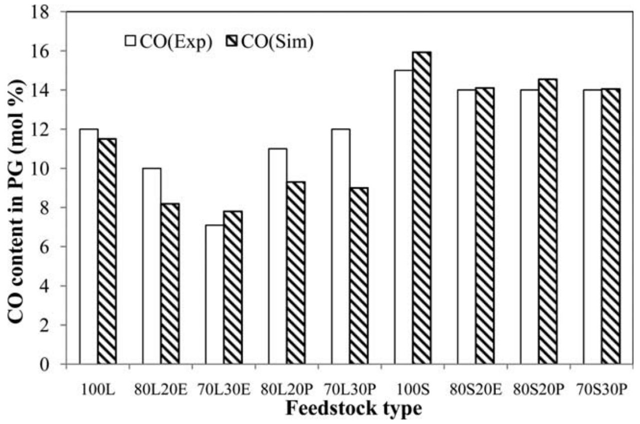

Figure 3. Experimentally measured (Exp) and model predicted (Sim) CO contents in producer gas (PG) in cogasification of different feedstock at steady state condition of 900°C.

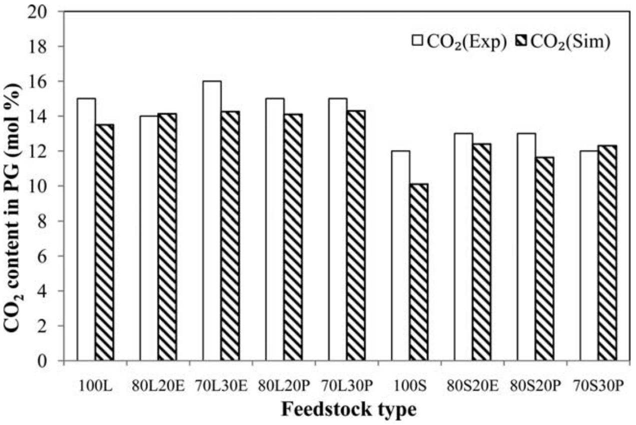

Figure 4. Experimentally measured (Exp) and model predicted (Sim) CO_2 contents in producer gas (PG) in cogasification of different feedstock at steady state condition of 900°C.

later in this section. For the second reason, the recorded operating condition of the taken sample could not truly reflect the real instantaneous operating conditions because of the continuous system creeping and response time of the micro-GC. The analysis and discussion on the effect of the feedstock will be given in the following section.

The dynamic changes in producer gas composition with time in cogasification of various feedstocks were also measured. As similar trends have been found for all of the experimental runs, dynamic gas composition changes from cogasification of blended coal (sub-bituminous) and biomass (pine) at a blending ratio of 70S:30P and operation temperature of 950°C are selected and presented in this paper as shown in Figure 5. From Figure 5, it is observed that the model simulated dynamic changes of the producer gas are in close agreement with the experimental data.

Figure 5 also shows that the model predicted CO_2 concentration initially increased sharply from 0 to 0.15 mol/mol in about 2 min and then decreased to 0.12 mol/mol after 20 minutes before it approached a steady value of 0.1 mol/mol. However, the sharp change of the CO_2 concentrations at the start of gasification could not be detected in the experiments due to the delayed response and time taken for gas sampling. For the gas species of H_2, CO, and CH_4, the concentrations increased gradually in the form of first order dynamic response to a step change. This phenomenon has been observed both from the experimental measurements and from the model predictions as shown in Figure 5.

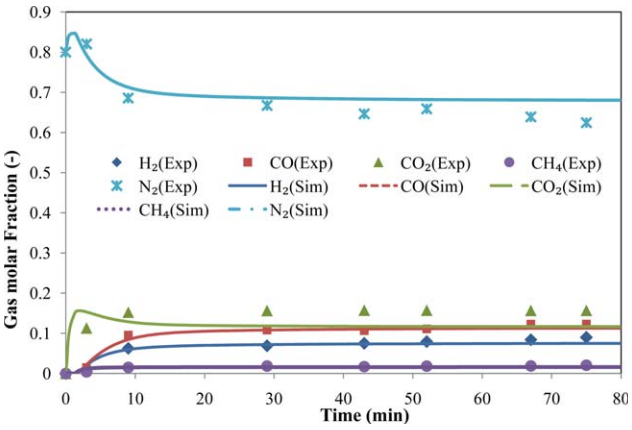

Figure 5. Experimentally measured and model predicted producer gas composition changes with time for cogasification of blended coal (sub-bituminous) and biomass (pine) at a ratio of 70S:30P at operation temperature of 950°C.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

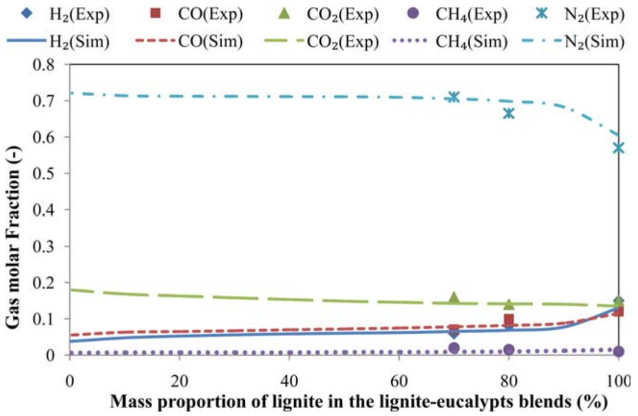

Figure 6. Model predicted and experimentally measured gas composition at steady state for cogasification of blended lignite-eucalypts pellets at 900°C.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Effect of coal-biomass blending ratio

The effect of biomass to coal blending ratio of various fuel types on producer gas composition has been investigated in this study both experimentally and by model simulations. The developed model has been run to simulate the cogasification of blended coal and biomass at coal blending ratios from 0% (pure biomass) to 100% (pure coal) for different fuels types at operating temperature ranging from 850 to 1050°C. Selected results of producer gas composition from the model simulation at operations temperature of 900°C are

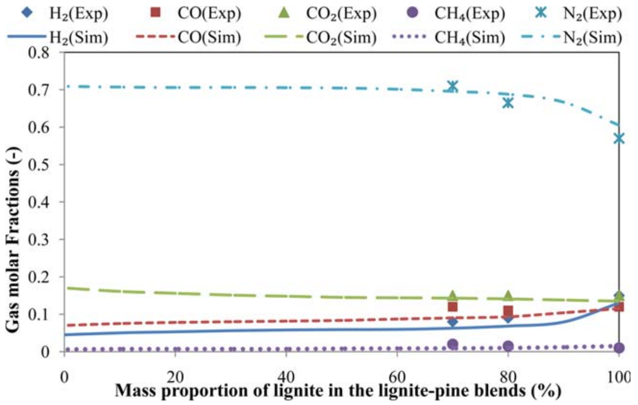

Figure 7. Model predicted and experimentally measured gas composition at steady state for cogasification of lignite-pine pellets at 900°C.

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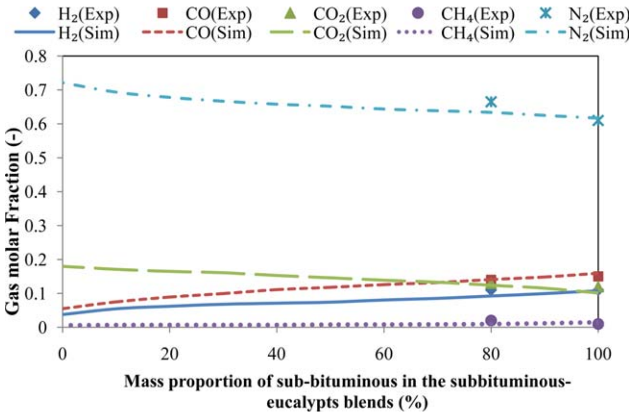

Figure 8. Model predicted and experimentally measured gas composition at steady state for cogasification of subbituminous-eucalypts pellets at 900°C.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

shown in Figures 6–9 for blended lignite and eucalyptus (Figure 6), blended lignite and pine (Figure 7), blended sub-bituminous and eucalyptus (Figure 8), and blended sub-bituminous and pine (Figure 9). In the figures, the available experimental results are also included for model validation with the coal-to-biomass ratios of 70:30, 80:20, and 100:0.

From Figures 6–9, it is found that in a general trend, the concentrations of H_2 and CO decreased with increasing biomass blending ratio (or decreasing coal blending ratio), while for CO_2 concentration, the opposite trend was observed. This was because the biomass had lower calorific value than coal, and in order to maintain the same set-point operating temperature for cogasification of feedstock with higher biomass ratio, more air was needed to promote partial combustion and hence more combustible gas species were consumed.

By comparing the producer gas compositions from cogasification of biomass and coal at various blending ratios, it is found that the impact of adding biomass to lignite was more significant than that with adding biomass to sub-bituminous. This can be related to the differences in fixed carbon, hydrogen content and calorific value of the two types of coals. From Figures 6 and 7, it can be seen that when the lignite blending ratio increased from 90% to 100% (pure lignite), the model simulated H_2 and CO concentrations in the producer gas increased rapidly from 0.08 to 0.15 mol/mol and 0.09 to 0.12 mol/mol, respectively. This is believed to be due to the increased calorific value of the blended pellets when no biomass was added to the feedstock. However for the sub-bituminous coal and biomass blends, the changes in model simulated H_2 and CO concentrations in the producer gas were increased slightly from 0.1 to 0.11 mol/mol and 0.15 to 0.16 mol/mol, respectively, and these less increases can be contributed to the fact that the sub-bituminous coal has much higher fixed carbon as well as higher calorific value compared to the lignite. Therefore, less CO and H_2 were consumed in the cogasification when 10% of biomass was added to the blended fuel. The above observations are consistent with the results presented in Figures 2 and 3.

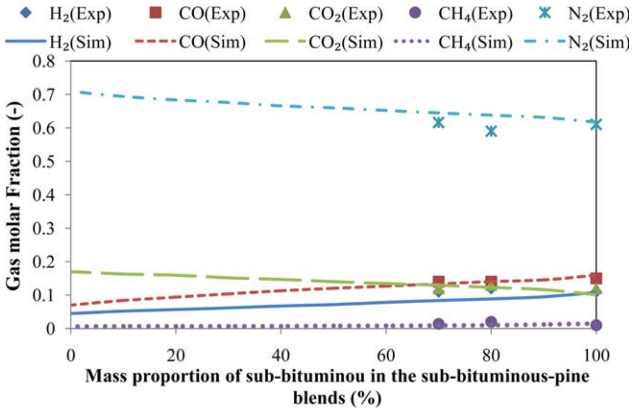

Figure 9. Model predicted and experimentally measured gas composition for cogasification of sub-bituminous-pine pellets at 900°C.

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The effect of coal type can be attributed to the difference in element composition of the coal. From the ultimate analysis (Table 2), the sub-bituminous coal contains much more carbon than the lignite while both coals have similar hydrogen content. From Figures 6–9, it can be seen that, for cogasification of sub-bituminous biomass pellets at high coal blending fractions, the CO concentration in the producer gas was higher than the CO_2 concentration while for cogasification of lignite biomass pellets, the CO concentration was always lower than the CO_2 concentration in the producer gas. For gasification of the pure coals, the CO concentration for sub-bituminous was 0.16 mol/mol which was about 0.04 mol/mol higher than that from gasification of the lignite coal, while the H_2 concentration in the producer gas for gasification of sub-bituminous (0.11 mol/mol) was about 0.03 mol/mol lower than that of pure lignite. This was because the calorific value of the sub-bituminous was higher and thus for the same gasification temperature, the required air feeding rate for sub-bituminous was lower than that for the lignite, hence overall consumption of combustible substance in the gas was less.

In cogasification of blended biomass and coal, the biomass type (pine and eucalypts) had insignificant impacts on the producer gas composition at the given blending ratios, since pine and eucalypts have very similar element composition from the ultimate analysis (Table 2). The producer gas compositions from cogasification of these two types of biomass blended with coal were similar, except for the CO concentration, which was slightly higher from cogasification of the pine-coal pellets, 0.01 mol/mol for pine-lignite blend and 0.005 mol/mol for pine-subbituminous blend, respectively. The reason for this difference is believed to be the slightly higher char yield of the pine wood. The values of other properties for the solid fuels are similar as input data for the model simulation, thus the simulation results for cogasification of blended coal and eucalypts were similar to those of blended coal and pine.

Effect of gasification temperature

The effect of operation temperature on the producer gas composition has been investigated by the experiments and the developed model. Operating temperature in this paper was defined as the mean average gas temperature through the bed at steady state. In practical operation and experiments, the mean gas temperature is commonly used as the operational control parameter, however, in the model, the

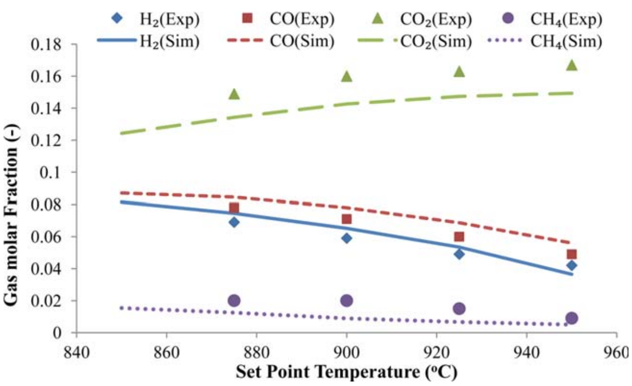

Figure 10. Model simulated results and comparison with experimental values for effect of operation temperature on producer gas composition in cogasification of blended lignite and eucalypts at a ratio of 70L:30E.

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average gas temperature in the bubbling fluidised bed is an output parameter. It has been found, both from experiments and model simulations in the present study, that the average gas temperature in the bed was strongly related to the ratio of feeding air mass flow rate to the solid fuel feeding rate. Therefore, in order to obtain different average gas temperature in the bed, the input values of solid fuel feeding rate and the feeding air mass flow rate were manipulated until average gas temperature in the bed fell into the acceptable range at steady state (normally within ±5°C from the set point). It should be noted that a similar approach was applied in the experiments in which the operation temperature was controlled at a set point by adjusting the feeding air flow rate while the solid fuel feeding rate was fixed. The selected model simulation results and the experimental data are shown in Figure 10 for cogasification of blended lignite and eucalypts at a blending ratio of 70:30. The average gas temperature in the bed was varied from 850 to 950°C in the model simulation while the temperature in the experiments was varied from 880 to 950°C.

From Figure 10, it has been found that concentrations of the combustible species of H_2, CO, and CH_4 in the producer gas decreased by 50%, 35%, and 67% as the temperature increased from 850 to 950°C. In the opposite trend, the CO_2 concentration increased by 20% with the same temperature rise. At higher operation temperatures, CO formation in carbon combustion reaction is favoured and this becomes more important at elevated temperatures.[35] This can be explained by the fact that in the experiments, for gasification temperature increase of every 1°C, approximately 0.25 m^3/h increment in air feed rate was required, therefore, more combustible substances were converted into CO_2 and water at higher gasification temperature. For cogasification of pellets with other blending ratios and other feedstock, similar trends were observed for the effect of operation temperature on the producer gas composition. Table 4 shows the details of changes in the producer gas composition with operation temperature increasing from 900 to 950°C.

Effect of solid fuel properties

The developed model has also been used to investigate the effects of solid fuel properties which are difficult or impossible to be investigated experimentally. These properties include devolatilization properties of a solid fuel (gas yield and gas composition), char yield and char reactivity. These effects could not be directly measured from gasification experiments, as factitious changing of intrinsic solid fuel properties was not feasible in this study. From the results of model simulation, it has been found that contents of combustible gaseous species in the producer gas increased with increase in combustible volatile gas species and char yield from the solid fuel devolatilzation. As the yield of combustible gas species increases, the combustion reactions are promoted at the lower part of the bed, hence less oxygen moves further up in the bed when the air feeding rate is fixed. Consequently less combustible gases are consumed in the bed above the combustion zone and the producer gas would contain more combustible gases at the gasifier exit.

The char yield has a significant effect on the producer gas as higher char yield further enhances the combustion reactions and thus more oxygen is consumed in the low part of the bed. Therefore, the combustion zone is reduced while the gasification zone is extended. Consequently H_2 and CO contents in producer gas are increased.

From the model simulations, it has also been found that the overall char reactivity has insignificant effect on the producer gas composition at the steady state. This is because for a specific operating condition, total carbon consumption rate can be automatically adjusted to a corresponding equilibrium point by accumulation of char inventory (i.e. change in char total exposed surface area in the gasifier), irrespective of the char reactivity (carbon consumption rate per unit mass of char). However, the char reactivity has significant effect on the gas composition change with time in the initial period of the gasification process. Dynamic behaviour of producer gas composition is highly dependent on the overall char reactivity as the char reactions are the slowest step among all of the processes involved in the gasification. Therefore the char accumulated in the bed takes a longer time to reach equilibrium state at which the rate of char being generated is equal to the total char consumption rate. At this point, the system has reached steady state and the producer gas composition does not change with time. Therefore the time for the gasification system to reach steady state should be comparable with the characteristic complete conversion time of a single char as examined in the previous studies on char reactivity.[33,34] This phenomenon has

Table 4. Percentage Changes in Measured Producer Gas Composition from Cogasification of Blended Coal and Biomass When the Gasification Temperature Was Increased from 900 to 950°C

Test Fuel[a]	H^2 (%)	CO (%)	CO^2 (%)	CH^2 (%)
100L	−32.1	−34.6	14.6	−53.0
80L:20E	−45.3	−43.7	13.5	−58.7
70L:30E	−28.8	−31.0	4.4	−55.5
80L:20P	−30.3	−40.1	12.7	−63.3
70L:30P	−45.5	−35.7	20.5	−36.6
100S	−21.5	−17.3	9.5	−57.6
80S:20E	−23.5	−19.3	13.8	−48.6
80S:20P	−23.8	−21.4	11.4	−61.7
70S:30P	−24.1	−23.6	12.6	−66.4
Mean ± Standard Error	−30.6±3.0	29.6±3.2	12.6±1.4	55.7±3.0

[a] *Note*: L = lignite; S = sub-bituminous; P = radiata pine; E = eucalyptus niten. The figures are the weight proportions in the blended fuel (wt %).

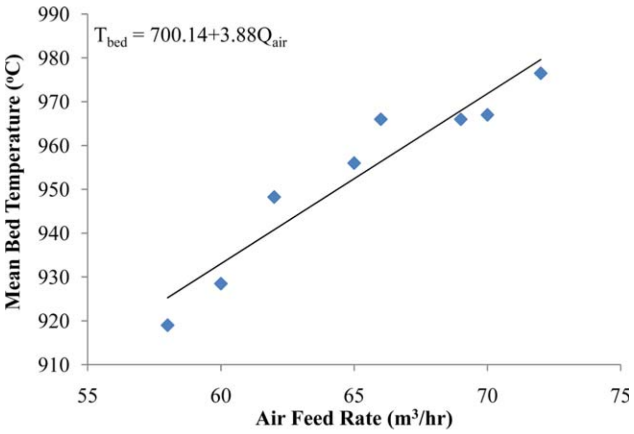

Figure 11. Recorded mean bed temperature with air feed rate with fixed solid fuel feed of 19 kg/h in cogasification of 80L:20E pellets.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

been verified by the observation of the experiments in which for a given blended solid fuel, the time for the BFB gasifier to reach steady state operation was similar to the time for a single char of the same solid fuel to accomplish the complete conversion. From experimental observation and model simulation, the pure lignite gasification reached steady state after about 35 min from start of the gasification while for cogasification of blended sub-bituminous and pine at blending ratio of 70:30, the steady state was reached after around 25 min from start of the gasification.

Although the overall char reactivity has insignificantly direct impact on the producer gas composition, the intrinsic reaction ratio between heterogeneous reactions of char with different gaseous species has significant influence on producer gas composition, especially for ratio of char combustion to water gas reaction. With increase in the char reactivity, the surface to volume area is increased thus the heterogeneous reactions are more rapid. The H_2 and CO contents increase with the increase in the intrinsic rates ratio of char combustion to gasification because more oxygen is consumed by char combustion and, consequently, more H_2 and CO are left in the producer gas.

Effect of air to solid fuel ratio

Air to solid fuel ratio (A/F) is an important variable in the gasification process since it has direct influence on the gasifier bed temperature and thus the producer gas composition. The bed temperature was controlled in the experiments by adjusting the feeding ratio of air to solid fuels. Figure 11 illustrates the linear relationship between recorded mean bed temperature and air feed rate within the operating range. In the gasification runs performed in this study, increase of every 1°C in bed temperature generally required 0.25 m^3/h air feed. At high air feeding rate, the combustion reactions were promoted as more oxygen was supplied to the system. Consequently, more combustion heat was released from the burning of combustible substances of char, H_2, CO, and CH_4. From both experimental data and model simulation, it was found the concentrations of the combustible gaseous species in the producer gas decreased while the CO_2 concentration increased with increasing the A/F ratio.

Conclusion

In this study, a series of gasification experiments were performed for cogasification of blended biomass and coal pellets in a pilot scale bubbling fluidised bed gasifier. The experimental results were used to validate a mathematical model developed in this study to predict the producer gas composition based on known solid fuel properties and operating conditions.

From comparison of the model simulation results and the experimental data, it is found that the developed model can predict the gas composition with discrepancies of less than 10% both at steady state of operation and in the initial transition period of the gasification process. Therefore, the developed mathematical model can be used for sensitivity analysis on parameters in a wider range of variation which may not be feasible for experimental investigation. The model can also be applied for better understanding of the gasification and cogasification processes of coal and biomass in bubbling fluidized bed gasifiers.

When adding biomass to lignite at biomass to fuel ratio from 0 to 100% for cogasification, H_2 content is reduced from 0.14 to 0.09 mol/mol and the CO content is decreased from 0.12 to 0.09 mol/mol while the CO_2 content is increased from 0.13 to 0.15 mol/mol. The effect of biomass to fuel blending ratio is less significant for sub-bituminous coal. With biomass ratio increasing from 0 to 100%, the producer gas composition changes are from 0.11 to 0.10 mol/mol for H_2, 0.16 to 0.14 mol/mol for CO and 0.11 to 0.13 mol/mol for CO_2. However, the biomass type has insignificant impact on the gas composition, difference between pine-coal and eucalypts-coal pellets is than 0.01 mol/mol with biomass blending ratio from 0 to 100%.

It has also been found that gasification temperature has adverse effect on the producer gas quality (reduction in concentrations of combustible gas species in the producer gas). With temperature elevated form 900 to 950°C, the H_2 and CO contents are decreased by 30%, while CO_2 content is increased by 13%. This is because the gasification temperature increase requires more the air supply at an increase rate of 0.25 m^3/h per °C. The increase in air feed consumes more combustible gas species; therefore, the producer gas quality was reduced.

From the parameter study, the gasification performance can be influenced by several factors, including char yield as well as pyrolysis gas composition during the initial devolatilization period and char reactivity. The char reactivity has the least influence on producer gas composition at the steady state operation; however, it has significant impact on the dynamic behaviour of the process. It is has been observed that in the cogasification, transition time for the operation to reach steady state is similar to that of complete conversion of char particles.

From this study, the cogasification process of blended coal and biomass is better understood and the influence of operation conditions is quantified. Based on the findings of this study, the upper limit of biomass and coal blending ratio and the gasification temperature can be determined for achieving the required producer gas composition. The developed mathematical model can be used for sensitivity analysis operating conditions, blending ratio and fuel properties.

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Literature Cited

1. Pinto F, Lopes H, Andre RN. Effect of catalysts in the quality of syngas and by-products obtained by co-gasification of coal and wastes 1. Tars and nitrogen compounds abatement. *Fuel.* 2007;86(14):2052–2063.
2. Franco C, Pinto F, Gulyurtlu I. The study of reactions influencing the biomass steam gasification process. *Fuel.* 2003;62(1):835–842.
3. Pinto F, Franco C, Andre RN. Effect of experimental conditions on co-gasification of coal, biomass and plastic wastes with air/steam mixtures in a fluidized bed system. *Fuel.* 2003;82(15):1967–1976.
4. Pan YG, Velo E, Roca X, Manya JJ, Puigjaner L. Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel.* 2000;79(11):1317–1326.
5. de Jong W, Andries J, Hein KRG. *Coal/biomass co-gasification in a pressurised fluidised bed reactor*. Paper presented at: Renewable Energy. In: Energy Efficiency, Policy and the Environment. World Renewable Energy Congress V, 20–25 Sept. 1998–1999; Florence, Italy.
6. Chmielniak T, Sciazko M. Co-gasification of biomass and coal for methanol synthesis. *Appl Energy.* 2003;74(3-4):393–403.
7. McLendon TR, Lui AP, Pineault RL, Beer SK, Richardson SW. High-pressure co-gasification of coal and biomass in a fluidized bed. *Biomass Bioenergy.* 2004;26(4):377–388.
8. Andre RN, Pinto F, Franco C, Dias M, Gulyurtlu I, Matos MAA, Cabrita I. Fluidised bed co-gasification of coal and olive oil industry wastes. *Fuel.* 2005;84(12-13):1635–1644.
9. Gani A, Morishita K, Nishikawa K, Naruse I. Characteristics of co-combustion of low-rank coal with biomass. *Energy Fuels.* 2005; 19(4):1652–1659.
10. Aznar MP, Caballero MA, Sancho JA, Frances E. Plastic waste elimination by co-gasification with coal and biomass in fluidized bed with air in pilot plant. *Fuel Process Technol.* 2006;87(5):409–420.
11. McIlveen-Wright DR, Pinto F, Armesto L, Caballero MA, Aznar MP, Cabanillas A, Huang Y, Franco C, Gulyurtlu I, McMullan JT. A comparison of circulating fluidised bed combustion and gasification power plant technologies for processing mixtures of coal, biomass and plastic waste. *Fuel Process Technol.* 2006;87(9):793–801.
12. Vuthaluru HB. Thermal behaviour of coal/biomass blends during co-pyrolysis. *Fuel Process Technol.* 2004;85(2–3):141–155.
13. Garcia-Perez M, Chaala A, Yang J, Roy C. Co-pyrolysis of sugarcane bagasse with petroleum residue. Part I: Thermogravimetric analysis. *Fuel.* 2001;80(9):1245–1258.
14. Jones JM, Kubacki M, Kubica K, Ross AB, Williams A. Devolatilisation characteristics of coal and biomass blends. *J Anal Appl Pyrolysis.* 2005;74(1-2):502–511.
15. Vamvuka D, Kastanaki E, Lasithiotakis M. Devolatilization and combustion kinetics of low-rank coal blends from dynamic measurements. *Ind Eng Chem Res.* 2003;42(20):4732–4740.
16. Vamvuka D, Pasadakis N, Kastanaki E, Grammelis P, Kakaras E. Kinetic modeling of coal/agricultural by-product blends. *Energy Fuels.* 2003;17(3):549–558.
17. Meesri C, Moghtaderi B. Lack of synergetic effects in the pyrolytic characteristics of woody biomass/coal blends under low and high heating rate regimes. *Biomass Bioenergy.* 2002;23(1):55–66.
18. Vamvuka D, Kakaras E, Kastanaki E, Grammelis P. Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite. *Fuel.* 2003;82(15–17):1949–1960.
19. Pan YG, Velo E, Puigjaner L. Pyrolysis of blends of biomass with poor coals. *Fuel.* 1996;75(4):412–418.
20. Moghtaderi B, Meesri C, Wall TF. Pyrolytic characteristics of blended coal and woody biomass. *Fuel.* 2004;83(6):745–750.
21. Haykiri-Acma H, Yaman S. Synergy in devolatilization characteristics of lignite and hazelnut shell during co-pyrolysis. *Fuel.* 2007; 86(3):373–380.
22. Sjöström K, Chen G, Yu Q, Brage C, Rosén C. Promoted reactivity of char in co-gasification of biomass and coal: synergies in the thermochemical process. *Fuel.* 1999;78(10):1189–1194.
23. Kastanaki E, Vamvuka D. A comparative reactivity and kinetic study on the combustion of coal–biomass char blends. *Fuel.* 2006;85(9): 1186–1193.
24. Howaniec N, Smoliński A. Steam co-gasification of coal and biomass—Synergy in reactivity of fuel blends chars. *Int J Hydrogen Energy.* 2013;38(36):16152–16160.
25. Zhu W, Song W, Lin W. Catalytic gasification of char from co-pyrolysis of coal and biomass. *Fuel Process Technol.* 2008;89(9): 890–896.
26. Yu JL, Strezov V, Lucas J, Liu GS, Wall T. A mechanistic study on char structure evolution during coal devolatilization—Experiments and model predictions. *Proc Combust Inst.* 2002;29(1):467–473.
27. Aigner I, Pfeifer C, Hofbauer H. Co-gasification of coal and wood in a dual fluidized bed gasifier. *Fuel.* 2011;90(7):2404–2412.
28. Kumabe K, Hanaoka T, Fujimoto S, Minowa T, Sakanishi K. Co-gasification of woody biomass and coal with air and steam. *Fuel.* 2007;86(5–6):684–689.
29. Collot AG, Zhuo Y, Dugwell DR, Kandiyoti R. Co-pyrolysis and co-gasification of coal and biomass in bench-scale fixed-bed and fluidised bed reactors. *Fuel.* 1999;78(6):667–679.
30. Paviet F, Bals O, Antonini G. The effects of diffusional resistance on wood char gasification *Process Saf Environ Protect.* 2008;86:131–140.
31. Alzate CA, Chejne F, Valdés CF, Berrio A, Cruz JDL, Londoño CA. CO-gasification of pelletized wood residues. *Fuel.* 2009;88(3): 437–445.
32. Veldsink JW, van Damme RMJ, Versteeg GF, van Swaaij WPM. The use of dusty-gas model for the description of mass transport with chemical reaction in porous media. *Chem Eng J.* 1995;57:115–125.
33. Xu Q, Pang S, Levi T. Reaction kinetics and producer gas compositions of steam gasification of coal and biomass blend chars, part 1: Experimental investigation. *Chem Eng Sci.* 2011;66(10):2141–2148.
34. Xu Q, Pang S, Levi T. Reaction kinetics and producer gas compositions of steam gasification of coal and biomass blend chars, part 2: Mathematical modelling and model validation. *Chem Eng Sci.* 2011; 66(10):2232–2240.
35. Tomeczek J. *Coal Combustion*. Malabar: Krieger, 1994.

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