

Effect of blending ratio on temperature profile and syngas composition of woody biomass co-gasification

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ABSTRACT

Co-gasification of biomass is beneficial as only relying on one type of biomass causes interruption in gasification if the feedstock supply is disrupted for any reason. Therefore, co-gasification of different biomass materials is a potential way to overcome the problem. In this work, co-gasification of wood chips (WC) and coconut fronds (CF) was carried out in a downdraft gasifier at 400 L/min airflow rate. Three blends of WC/CF of 70:30, 50:50 and 30:70 ratios were considered with a maximum particle size of 2.5-3.0 cm. The aim of this study was to investigate the effect of blending ratio on the temperature profile and syngas composition produced by the co-gasification of WC/CF blended feedstock. The results show that the temperature profile and syngas composition of 70:30 WC/CF blend was comparatively better. The average syngas composition of 70:30 WC/CF blend during steady state co-gasification operation was 20%, 12% and 3% for CO, H₂ and CH₄ respectively. Similarly, the average syngas composition of 50:50 WC/CF blend was around 21%, 8% and 0.7% for CO, H₂, and CH₄ respectively. While the 30:70 WC/CF blend encountered with bridging problem due to fibrous and low density CF. No more than 50% of fibrous and low density feedstock like CF is recommended in a blend for stable and progressive co-gasification.

Keywords: co-gasification; blending ratio; temperature profile; syngas composition.

INTRODUCTION

Fossil fuels are prime sources of energy, as energy demand is increasing day by day. The fossil fuel reserves are depleting due to over consumption to fulfil energy requirements, and as a result, there may be no more fossil fuels available in the future to satisfy the increasing energy requirement. The gap in future energy demand can be filled by renewable bioenergy sources [1-3]. According to the estimation by the International Energy Agency, 53% global energy consumption will be increasing by 2030, with 70% of the growth in demand coming from developing countries [4]. Biomass is a potential and sustainable source of non-conventional energy to reduce the dependence on fossil fuel [5]. Malaysia is richly endowed with renewable energy sources, especially bioenergy resource, for instance forestry wood, oil palm industry, rubber cultivation, and paddy crop

and many others [6-8]. The utilisation of these bioenergy resources via gasification is a promising way for energy generation. Biomass energy ranks first in power generation capacity at 263.3 MW, followed by 10.1 MW and 101.9 MW for mini-hydro and landfill gas, respectively, in Malaysia [9]. However, in many cases, gasification encounters the shortage of feedstock supply, which causes disruption in continual gasification [10, 11]. The performance of the gasification process and quality of syngas depends upon numerous factors, such as gasifying medium (air, steam and O₂) [12-18], heating rate, gasification temperature, and equivalence ratio [19, 20]. In addition, the characteristics of the feedstock, i.e. elemental composition, heating value, fixed carbon, volatile matters, moisture content, and ash content also affect on syngas composition [21, 22]. However, despite plenty of different biomass materials available around the globe, their distribution is scattered. Consequently, the collection, transportation, and delivery of biomass from the field to the gasification plant are expensive, and hence they are considered as big challenges for gasification. In addition, inconstant biomass supply and lack of developed biomass market contribute to the difficulties of the biomass collection system [23].

As Malaysia is a tropical country and has abundant natural forest, the biomass that can be obtained from these sources, such as wood from the forest and coconut fronds from the agriculture sector are potential feedstock for gasification operation. However, the problems with biomass supply are that the collection and high transportation cost could be worsened when one relies on a single source of biomass. Using a single biomass source like wood or coconut fronds for gasification may encounter problems like inconstant feedstock supply [10], storage issue and high transportation cost [24]. Thus, to avoid these problems, the co-gasification of different biomass materials is the best option as it uses a mixture of different biomass at the same locality or vicinity with different blending ratios. The aim of this study is to investigate the effect of blending ratios on temperature profile and syngas composition produced by co-gasification of wood chips (WC) and coconut fronds (CF) in downdraft gasifier.

MATERIALS AND METHODS

Characterisation of Raw Materials

Coconut fronds (CF) and wood chips (WC) are considered as feedstock for co-gasification. Coconut fronds were collected from Teluk Intan, Perak, Malaysia and wood (*acacia mangium*) was collected within the Universiti Teknologi PETRONAS campus. The raw feedstock materials were dried, ground and sieved at 250 µm particle size for characterisation. The ultimate and proximate analyses were determined according to ASTM D3176-09 and ASTM E1755-01 standard test methods by using CHNS-932 analyser and STA 6000 thermogravimetric analyser respectively [25, 26]. The higher heating value (HHV) of the feedstock materials were determined by AC-350 bomb calorimeter according to ASTM D4809-00 [27], and the characterisation results are presented in Table 1. CF and wood lumps were cut into pieces of larger dimension in the range of 2.5 to 3.0 cm for the co-gasification process as shown in Figure 1. The biomass materials were sieved according to the mentioned particle size and then dried in an oven at 105°C for 24 hours to ensure the removal of equilibrium moisture. The prepared biomass materials, WC and CF, were mixed at 70:30, 50:50 and 30:70 ratios for co-gasification experiments.

Table 1. Characterisation results of coconut fronds (CF) and wood chips (WC).

Proximate Analysis (% dry basis)	CF	WC
Volatile matter	62.37	88.07
Fixed carbon	17.76	10.77
Ash	7.92	1.16
Ultimate Analysis		
Carbon	40.02	43.54
Hydrogen	6.03	3.59
Nitrogen	0.14	1.00
Sulphur	0.54	0.16
Higher Heating Value (MJ/kg)	15.22	18.09
Moisture Content (wt. % on wet basis)	11.95	11.40



Figure 1. Prepared feedstock of (a) wood chips and (b) coconut fronds for co-gasification.

Experimental Setup

A fixed bed downdraft gasifier as shown in Figure 2 was used for the co-gasification process. Six Type-K thermocouples (T_1 - T_6) were fixed evenly on the gasifier body and the 7th thermocouple was fixed at the syngas outlet pipe to measure the temperature of released syngas. The gasifier was cleansed from ash and char produced in the previous experiment. After cleaning, the gasifier was filled up with the measured pre-mixed blend of WC/CF from the top feeding holes. The ash box and top holes were screwed after feeding. Before starting the co-gasification operation, thermocouples were plugged into a data logger and the temperature profile of the gasifier was recorded by the computer. Ignition was started through the ignition hole by using scrap paper. After the ignition was started, the ignition hole was closed and the air was supplied at a flow rate of 400 L/min. The airflow rate was regulated and measured using a rotameter and a valve. X-Stream X2GP online analyser was used to analyse the syngas composition.

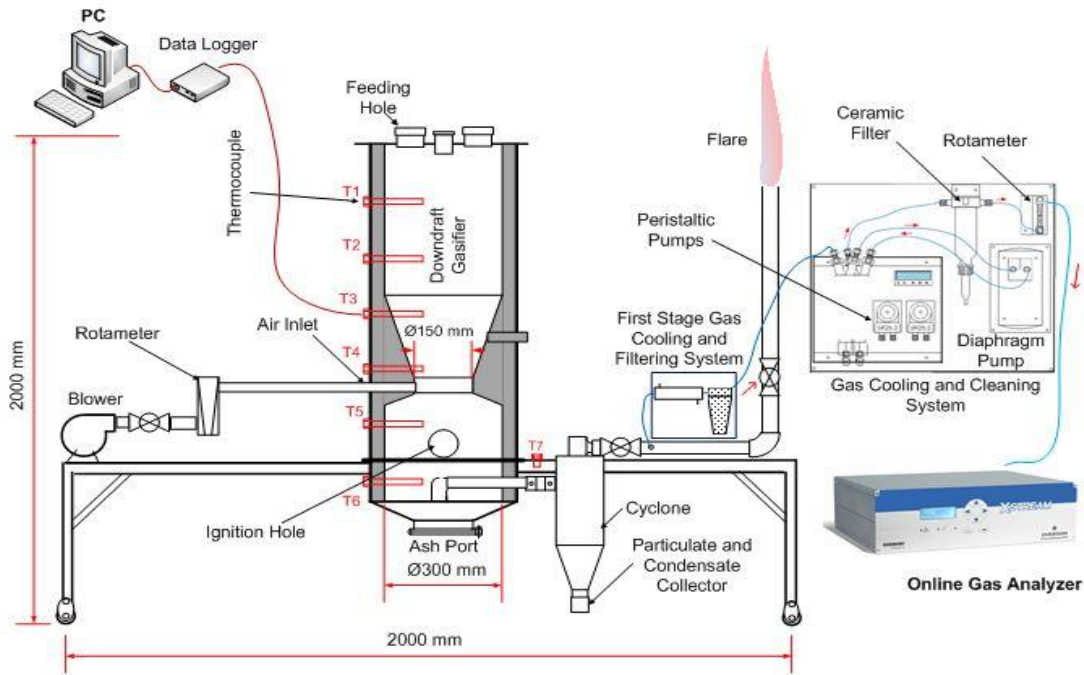


Figure 2. Experimental set-up of downdraft gasifier.

RESULTS AND DISCUSSION

The co-gasification results of syngas composition and temperature profile for 70:30 WC/CF blend are shown in Figure 3. The co-gasification process took 42 minutes to consume 14 kg of blended feedstock. Thermocouples T_1 , T_2 and T_3 measured the temperature in the drying zone, while T_4 , T_5 , and T_6 measured the pyrolysis zone, combustion zone, and reduction zone temperatures, respectively and T_7 was the syngas outlet temperature. The temperature of the combustion zone (T_5) showed a steep increase from the beginning of the experiment as shown in Figure 3(a). The flare started after 18 minutes from the ignition time, while the combustion zone temperature was recorded as 649°C. At the start of the flare, the syngas composition was recorded as 20%, 12% and 3% for CO, H₂, and CH₄ respectively. A smooth and continuous co-gasification operation was observed for 18 minutes at an average combustion zone temperature of 850°C as clearly indicated by T_5 in Figure 3(a), and syngas composition from 18-36 minutes of co-gasification as shown in Figure 3(b). During the steady state condition, the syngas composition was enriched with CO content and low CO₂ concentration. Two peaks of CO₂ at the start and end of the co-gasification revealed the combustion-dominated process as shown in Figure 3(b). As the co-gasification progressed from 18 minutes to 36 minutes, the depletion of CO₂ occurred and the lowest peak was observed in the co-gasification via Boudouard reaction ($C+CO_2 \rightleftharpoons 2CO$), the reaction was favoured by high T_5 temperature of 880°C in Figure 3(a). The Boudouard reaction is endothermic in nature and requires high temperature [28]. According to Mathieu and Dubuisson [29], Boudouard reaction only produces CO at high temperature. This seems to explain the reason of high CO% exhibited in Figure 3(b) whilst CO₂ formation was going down [30]. This implies that the Boudouard reaction dominated the co-gasification of CF/WC 70:30 blend.

The average H₂ content of the steady state co-gasification process was 11.50% which was anticipated due to water shift reaction at a reaction temperature (T_5) of 880°C as there was better air to feedstock interaction during the co-gasification of 70:30 WC/CF blend. The formation of H₂ increased from 11.8% to 13.3% with an increase of temperature from 649 to 854°C, respectively. The increase of H₂ formation was favoured by the high temperature which could be due to the combined effect of the exothermic nature of water-gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2$), which typically dominates between 500 and 600°C, and the water gas reaction ($\text{C} + \text{H}_2\text{O} \rightleftharpoons \text{CO} + \text{H}_2$) which becomes significant at a temperature of 1000°C and above [30]. It could be seen that hydrogen formation started decreasing after 32 minutes of co-gasification because the batch feedstock was almost finish.

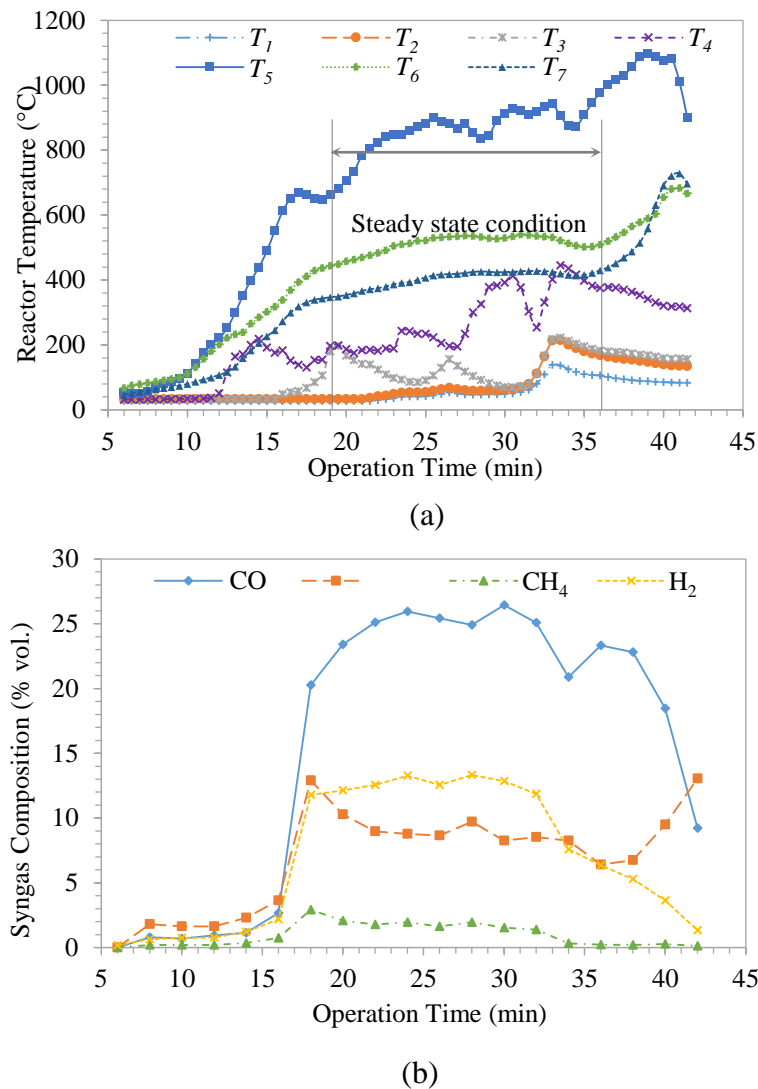


Figure 3. Temperature profile (a) and syngas composition (b) for the co-gasification of 70:30 WC/CF blend.

The reduction zone temperature T_6 was relatively stable during steady state co-gasification, while the pyrolysis temperature T_4 seemed to be fluctuating, which describes that a lot of heat is required for pyrolysis reaction. Therefore, T_4 temperature increased after a less quantity of feedstock was pyrolysed and decreased when more pyrolysis reaction occurred. In the last 6 minutes of co-gasification, the temperature of the

combustion zone increased to a peak value of 1013°C. The significant increase in the oxidation zone temperature near the end of the operation is attributed to the batch-fed nature of the gasification process, whereby most of the volatile matter components are consumed throughout the steady state operation duration, leaving combustion to be the only dominant operation in the last few minutes of the operation and causing the increase in temperature [20]. Furthermore, no bridging problem was observed.

The co-gasification results for temperature profile and syngas composition of 50:50 WC/CF blend ratio are shown in Figure 4. The co-gasification process of 50:50 WC/CF blend took 42 minutes to consume a batch of blended feedstock. The steady state temperature profile was obtained after the 18th minute of the co-gasification operation at a combustion temperature (T_5) of 650°C as shown in Figure 4(a). The syngas composition at this stage was 8%, 9%, 2% and 10% for CO, H₂, CH₄ and CO₂ respectively as shown in Figure 4(b). The H₂/CO ratio at this point was more than 1.0, which implies that syngas is suitable for use in I.C engine. The steady state co-gasification operation was observed for a period of 14 minutes between 18th to 32th minutes of operation with the average reaction temperature of the combustion zone (T_5) being 803°C.

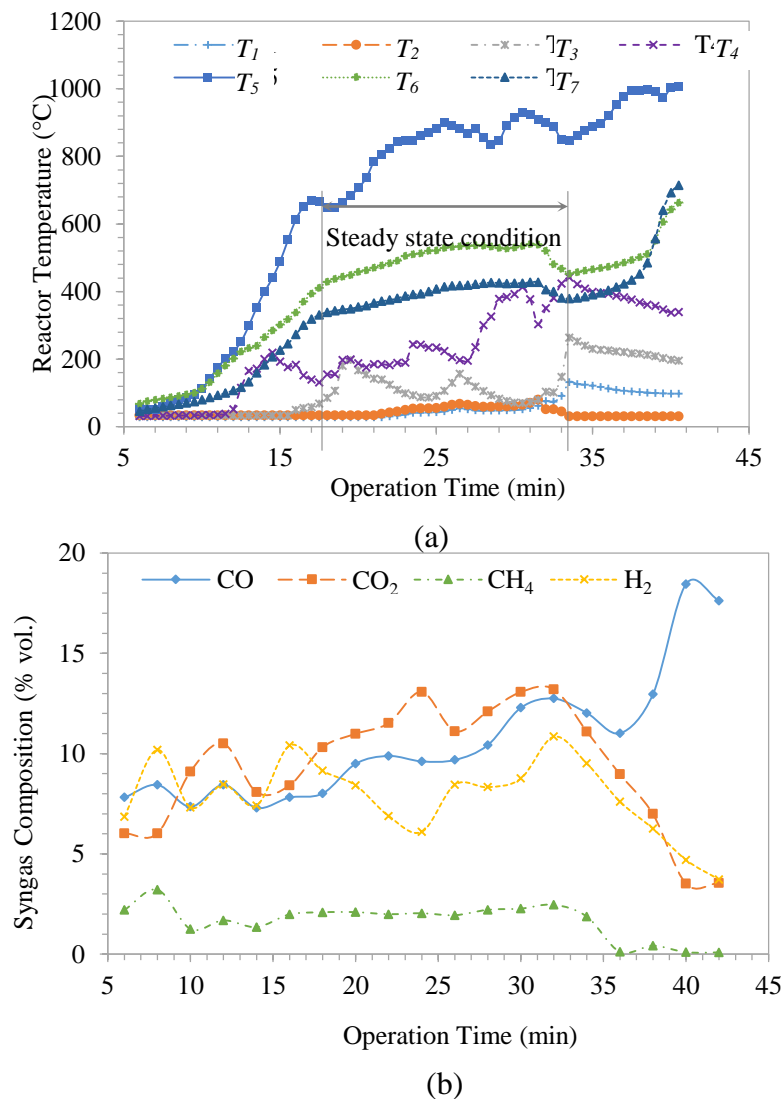


Figure 4. Temperature profile (a) and syngas composition (b) for the co-gasification of 50:50 WC/CF blend.

The syngas composition during the steady state condition was not as stable as the temperature. However, the average syngas composition during the steady state co-gasification of 50:50 WC/CF was recorded as 10.27%, 8.37%, 2.14% and 11.93% of CO, H₂, CH₄ and CO₂ respectively, which was lower than the 70:30 WC/CF blend. But it had a good H₂/CO ratio of 0.8, hence can still be used in I.C engine. After 32 minutes of co-gasification, syngas composition started declining and H₂ dropped to 4%, at the 40th minutes of the co-gasification. It was almost half of that in the steady state condition, and at this stage, the batch of feedstock was almost consumed and caused reduction in syngas composition. However, the combustion temperature T_5 increased and reached a maximum of 1007°C. The increase in temperature at the end of the process shows the batch feed nature of the downdraft gasification. The reason for this increase in temperature was the accumulation of high char on the grate and the reduction of the pyrolysis gases. The pyrolysis gases have cooling effect in the oxidation zone when these passed through the char bed because of endothermic reactions between the char and the gases. In addition, as the pyrolysis gases diminish, a large quantity of air could have a chance to react with the char instead of reacting with pyrolysis gases. At that stage of co-gasification, the oxidation process was more dominated, which could result in high CO₂ content and high temperature in the oxidation zone [31]. During the co-gasification of 70:30 WC/CF, no bridging problem was detected throughout the experiment showing that the feedstock used was suitable for this downdraft gasifier. The co-gasification results for the temperature profile and syngas composition of WC/CF blend at the ratio of 30:70 are shown in Figure 5. The successful co-gasification operation time of this blend was presented as only 16 minutes because of the recurrence of the bridging problem. At the start of co-gasification, bridging problem was observed several times. The bridging was fixed by shaking the feedstock inside the gasifier. The bridging problem is related to the downward flow of feedstock in a downdraft gasifier, especially when low density feedstock or big particle size of feedstock are used, causing the feedstock to be stuck at the throat of the gasifier. The feedstock could not smoothly flow downward and cause bridging inside the gasifier [32]. The bridging problem changed the gasification process into a combustion process in the presence of less feedstock and more air supply, consequently lower quality syngas composition was achieved.

The syngas composition after the bridging problem and at start of the steady state condition was 26.92%, 12.17%, 1.70% and 7.56% for CO, H₂, CH₄ and CO₂ respectively. The H₂/CO ratio was 0.45 in this stage, while the reaction temperature (T_5) was around 845°C as shown in Figure 5(a). After the bridging, the temperature of the combustion zone and pyrolysis zone were stable. However, gas composition slightly fluctuated due to the endothermic and exothermic nature of the reactions accruing inside the gasifier with a temperature above 800°C [30]. CO increased from 8.42% to 26.92% during 6 to 11 minutes of gasification and then decreased to 19.22%. Meanwhile, H₂ started to increase from 2.73 to 12.93% over the same period of time. CO₂ was lower than 10% and seems more stable as compared to CO and H₂. Similar gas composition and temperature profile was observed by Guangul et al. (2013) [32] during the gasification of oil palm fronds and in another work by Inayat et al. (2015) [20] during the co-gasification of wood chips, oil palm fronds and sugar cane bagasse. In this 30:70 blend of WC/CF, CF was 70% of the total feed blend. CF is fibrous in nature and low in density. Due to its fibrous nature it was very quickly consumed and its low density restricted the flow of feedstock, causing the bridging problem during co-gasification. As a result, very short operation time was achieved. Although the operation time was short, 10 minutes of steady state period was achieved, the average syngas composition of the steady state period was 21.60%,

8.60%, 0.65% and 7.50% for CO, H₂, CH₄ and CO₂ respectively as shown in Figure 5(b). The H₂/CO ratio was dropped from 0.45 to 0.40 at the start to the end of the steady state condition. The average temperature of the combustion zone during the steady state condition was 930°C. No more than 50% of fibrous and low density feedstock like CF is recommended for stable and progressive co-gasification.

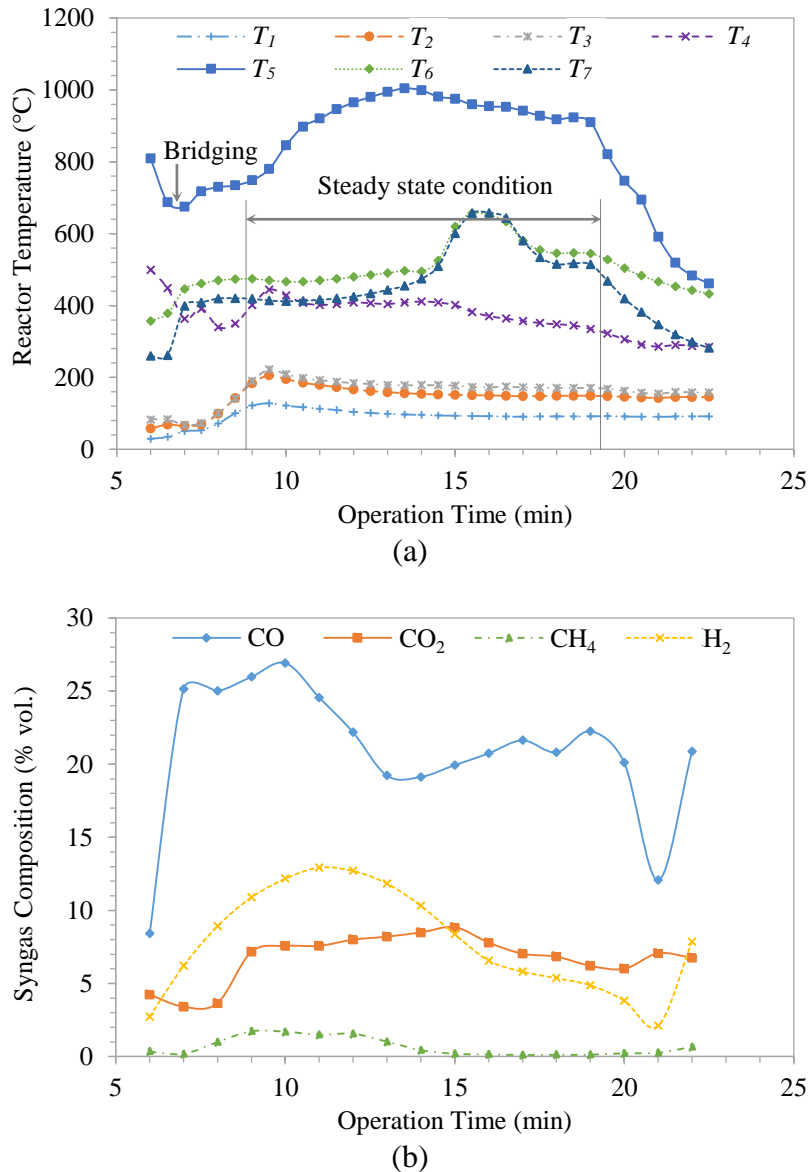


Figure 5. Temperature profile (a) and syngas composition (b) for the co-gasification of 30:70 WC/CF blend.

CONCLUSIONS

Co-gasification of WC and CF was carried out in a downdraft gasifier at a constant airflow rate with a maximum particle size of 2.5-3.0 cm. The aim of the study was to investigate the effect of blending ratio on the temperature profile and syngas composition during co-gasification. The 70:30 and 50:50 WC/CF blends were successfully co-gasified, while the

30:70 WC/CF blend encountered with bridging problem. The syngas composition of the 70:30 blend was comparatively good, followed by the 50:50 and 30:70 WC/CF blends. It was due to better reaction temperature and air to feedstock interaction of the 70:30 WC/CF blend. The syngas obtained from co-gasification WC/CF can be used in IC engine. The maximum H₂/CO ratio of more than 1.0 was obtained using the 50:50 blend, followed by 0.8 using 70:30 and 0.45 using 30:70 WC/CF blend. It is suggested that no more than 50% of fibrous and low density feedstock like CF is recommended for stable and progressive co-gasification. More co-gasification work is suggested with agricultural wastes and forestry wastes as a substitution of wood gasification.

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