Influence of Gasification Operating Parameters on Performance of the Nong Bua Dual Fluidized Bed Gasification System in Thailand

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Abstract

Keywords

biomass gasification;

dual fluidized bed gasifier;

gravimetric tar;

plant performance

Gasification system performance generally depends on feed moisture content, activity of bed material, gasifier and combustor temperatures, and scrubber media. The tar concentration and gas composition of product gas are two indicators of the gasification system performance. In this research, the effects of gasifier temperature and the activity of bed material on the tar concentration and gas composition of the product gas produced from a dual fluidized bed (DFB) gasification system power plant were investigated. The DFB gasification system power plant is located in Nong Bua district, Nakhon Sawan province, Thailand. Two periods of gasification operation were examined. These two periods were when the olivine was freshy activated and then after a period of operation. The gasifier temperature had several peaks during the operation, which caused the product gas composition to fluctuate. When the olivine had been used for a period, the percentage of hydrogen was approximately 3% higher than when the olivine had been freshly activated, and a lower heating value was observed, which was probably due to lower heating value of hydrogen. The tar concentration was substantially lower when compared with the freshly activated olivine. When the olivine was used for a period, the average tar concentration was 56±22 mg/Nm^3 (this is after 95 h continuous operating time) while the average tar concentration of the freshly activate olivine was 872±125 mg/Nm^3 (which was after 34.5 h continuous operating time). It was concluded that the average tar concentration and gas composition were influenced by the activity of the bed material and the gasification temperature

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1. Introduction

As the energy demand of the world is growing, carbon-neutral energy from biomass is considered as an attractive energy source. Biomass comes from living organisms; therefore, it is not only a carbon-neutral energy but also can be grown or raised. Thailand is considered as one of the important agricultural countries because more than half of the population are agriculturists [1]. Agricultural residue generation was estimated to be more than 130 million tons per year, of which approximately 60 million tons was consumed for energy production [2]. The remaining agricultural residue, which is equivalent to 4,000 MW electrical output, should be utilized.

Agricultural residues can be converted into energy via gasification technology. Gasification is a thermo-chemical conversion of organic matter at elevated temperature into a combustible gas. This combustible gas or product gas is primarily a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, and other combustible gases (C_2H_X, C_3H_X, C_4H_X) and compounds (char), and incombustible products (ash) [3, 4]. The lower heating value (LHV) of the product gas is generally between 4 and 20 MJ/Nm^3 and depends on the product gas composition. The product gas composition is influenced by various factors including the gasification agent. Air, pure oxygen, carbon dioxide, or steam or mixture of these gases can be used as the gasification agent [5, 6]. With steam as the gasification agent, the product gas is free of nitrogen and has a higher LHV that can be in the range of 10-18 MJ/Nm^3 [6].

Dual fluidized bed (DFB) gasification technology uses steam as the gasification agent [7]. There are two fluidized bed reactors in a DFB gasification system. One is the bubbling bed gasifier in which steam is the fluidizer and gasification agent. The other is the fast fluidized bed combustor in which air is the fluidizer and combustion agent. Both reactors are separated reactors but are connected with a loop seal and a chute [7]. The bed material is circulated between the gasifier and the combustor and functions as the heating media. The DFB gasification system was first invented and developed at the Vienna University of Technology (VUT) by a group led by Professor Hofbauer and Professor Rauch [7-9]. The technology has been successfully demonstrated on a commercial scale in Austria, with the first plants being set up in Gussing in 2001, followed by Oberwart in 2008, at 8 MW_{th} and 10 MW_{th}, respectively. In 2011, a 15 MW_{th} DFB gasification plant was operated in Villach, Austria, followed by a 15 MW_{th} plant in Senden, Germany, and a 32 MW_{th} plant in Gothenburg, Sweden [6, 9-13]. In 2017, a 3.8 MW_{th} prototype of a DFB gasification system was built and commissioned in Thailand. This plant can handle various feedstocks including woodchips and cassava rhizomes [8, 14].

Parameters that affect the product gas composition include gasification temperature and pressure, steam to biomass ratio, residence time, feedstock type and moisture contents as well as bed materials and height [15, 16]. These parameters not only affect the product gas composition but also the tar content [15, 16]. Product gas composition affects the heating value of the gas while tar can cause blockage in downstream pipes and equipment. It was reported that when the gasification temperature was increased from 790°C to 900°C, the hydrogen and carbon monoxide contents increased while the carbon dioxide and methane contents decreased [17]. Temperature changes also affect the composition of tar, which can vary in composition from highly oxygenated to high molecular tar or polyaromatic hydrocarbons [4]. Tar was reported to be reduced with increased gasification temperature and pressure [4, 18, 19]. Nevertheless, the maximum gasification temperature at which this type of plant can be operated is limited by the ash melting point, which relates to the biomass ash and the bed materials [20]. Tar can be removed from the product gas via primary and secondary methods [21]. The use of active bed material was reported as a typical primary method for the reduction of tar content in the product gas [22, 23]. The use of scrubber is considered as a secondary method for the tar reduction, which is influenced by the temperature and types of scrubbing media [24].

In this research, the influence of gasifier temperature and bed material activity on the product gas composition and tar concentration produced from the 1 MW_{el} prototype dual fluidized bed gasifier in Thailand are investigated. Two periods of operation will be compared. One after the bed material was freshly activated (hereinafter referred to as “operation period 2017”) and the other after the bed materials was used for over a period of time (hereinafter referred to as “operation period 2018”).

2. Materials and Methods

2.1 DFB gasifier and its principle

The dual fluidized bed (DFB) gasifier comprises two separated reactors, as shown in the schematic diagram (Figure 1) [11]. One is the fast fluidized bed (FFB) combustion reactor, in which air is used to fluidize the bed materials, which are the heating media, in the reactor. The other is the bubbling fluidized bed (BFB) gasification reactor, in which steam is used to fluidize the bed material and feedstock. This is where the gasification reactions occur and the product gas is obtained from this reactor. Both reactors are separate structures but are connected via a loop seal where the bed material is transferred from the combustor to supply the heat for the endothermic reactions inside the gasifier, and a chute where the residual biomass char from the gasifier is transferred with the bed materials to the combustor. Biomass char adds energy to the combustor, and hence the overall DFB gasification system. In addition, the loop seal and the chute can effectively prevent the gas crossflow between the two reactors even with high bed material and biomass char circulation rate [10, 25].

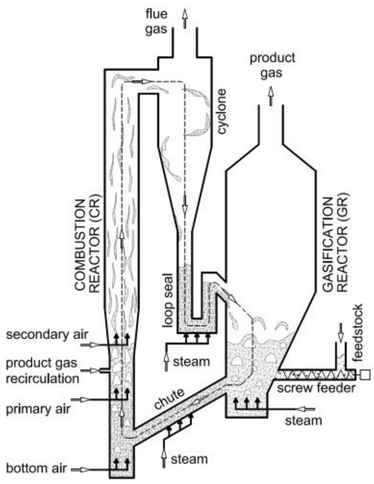

Figure 1. Schematic diagram of a DFB gasifier [11]

The operating temperatures of the combustor and gasifier are approximately 920°C and 820°C, respectively [8]. The operating temperature of both combustor and gasifier is influenced by the endothermic energy requirement for the gasification reactions, energy supplied to the combustor from char and supplementary fuel, and the bed circulation rate. The operating temperature of the gasifier can be self-stabilizing, and this depends on the amount of char and heat supplied from the combustor from char [26].

2.2 Nong Bua DFB gasification system

2.2.1 Overview of the Nong Bua gasification system

The 3.8 MW_{th} input Nong Bua DFB gasification system (hereinafter referred to as "Nong Bua Plant") is located at Nong Bua district, Nakhon Sawan province, Thailand. The gasification system is similar to the DFB gasification system. The gasifier is operated at about 820°C and the combustor is operated at about 920°C [8, 14]. The overall process of the Nong Bua plant is shown in Figure 2.

The product gas produced from the gasifier is first cooled by a heat exchanger and afterwards by a quench. The first gas cooler reduces the product gas temperature from about 820°C to 280°C. The second quench reduces the product gas temperature further to around 150-220°C through the mixing with the return flow of the cold and clean product gas after the scrubber. The cooled product gas then flows through the product gas bag filter where almost all particulates, which are mainly char, ash and fine bed material, are removed and recycled to the combustor. Before the product gas enters the gas engine to produce electricity, the product gas passes through the scrubbing system to remove all tars using biodiesel as the scrubbing media. The product gas temperature is reduced to about 40°C from the scrubbing system and compressed to 300 mbar as required for the gas engine [8].

The Nong Bua Plant was commissioned in April 2017. In this study, the operation periods of the Nong Bua Plant are in December 2017, right after the commissioning with freshly activated bed materials, and approximately a year after that in November 2018, when the Nong Bua Plant was in steady state operation with the bed materials that had been used over a period of time. The general operating conditions of the Nong Bua Plant are outlined in Table 1.

2.2.2 Feedstock

Local Thai woodchips with approximately 40% moisture content before drying was used. The local Thai woodchips, which were mainly softwood chips with a particle cross-section length in the range of 0.5-10 cm, were dried to about 15-20% moisture content before being fed into the gasifier. The proximate and ultimate analysis of woodchips were analyzed by SGS (Thailand) Limited. The results are summarized in Table 2.

2.2.3 Bed material

The bed material used was calcined olivine. The calcined olivine mainly consisted of iron and magnesium orthosilicate ($(Mg, Fe)_2SiO_4$).

2.2.4 Gasifier temperature measurement

After the start-up process of about 24 h, the biomass was first fed into the gasifier. This occurred when the system reached the steady-state condition in which the gasifier and combustor temperatures were in the range of 800-860 °C and 870-920°C, respectively. The gasifier temperature was measured at the top (free-board temperature), middle (middle-height column temperature) and bottom (in-bed temperature) of the gasifier.

2.2 Tar sampling and analysis

Tar in the product gas produced from the Nong Bua Plant was sampled for gravimetric tar analysis after it passed through the scrubbing system. The tar sampling and analysis were done based on the European Standard CEN/TS 15439: 2006 "Biomass gasification – Tar and particles in product gases – Sampling and analysis".

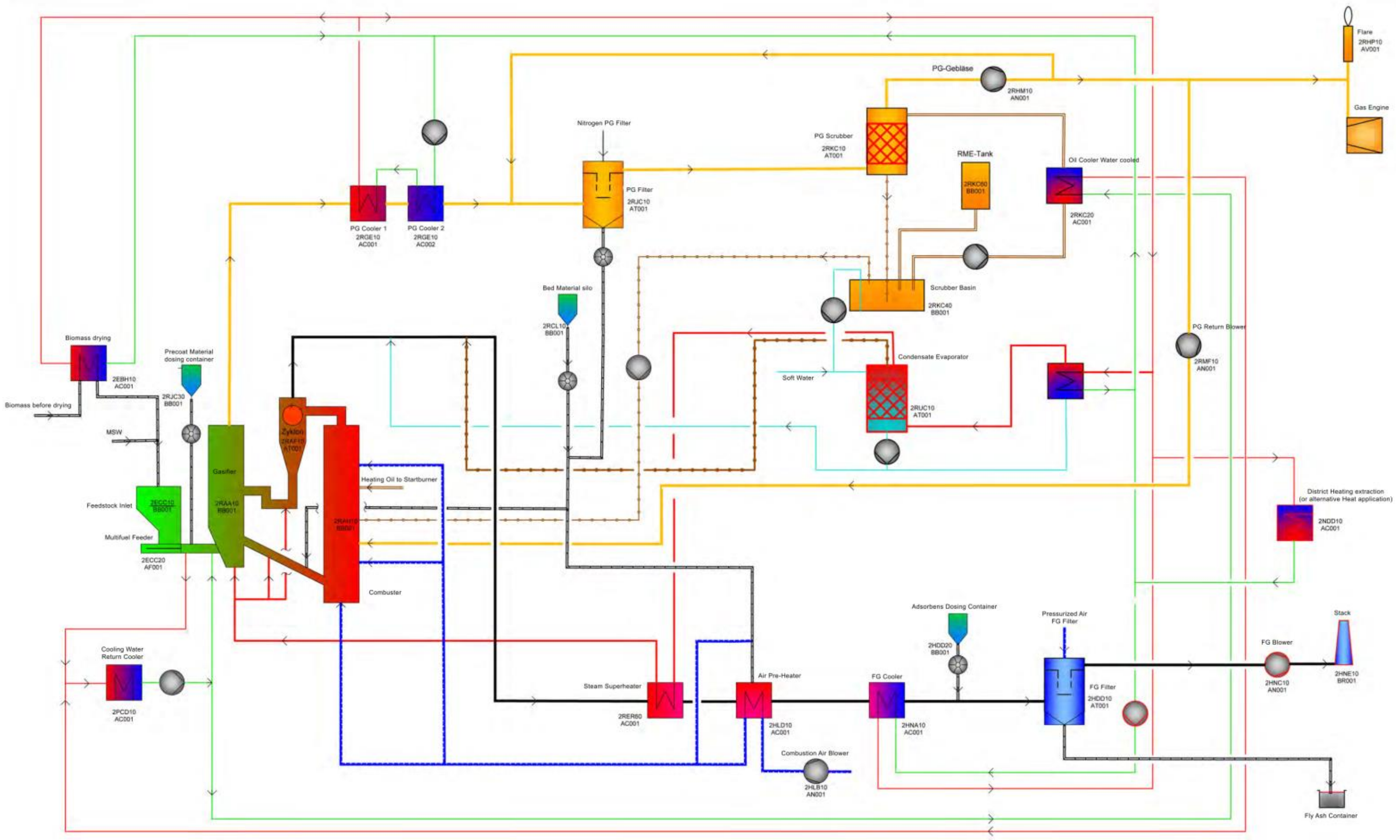

Figure 2. Schematic diagram of the DFB gasification power plant in Nong Bua district, Nakhon Sawan province, Thailand [8]. The red and green lines are hot water and cold water, respectively. The yellow, black and blue lines are product gas, flue gas and compressed air, respectively.

Table 1. Operating conditions at Nong Bua Plant

Fuel feed input (kW_{th})	3,800
Bed material type	Calcined olivine
Bed material particle size (μm)	300-800
Bed material particle density (kg/m^3)	2,800-2,900
BFB reactor temperature varied along the height (°C)	800-860
FFB reactor temperature varied along the height (°C)	870-920
Steam to fuel ratio (kg/kg_{dry})	0.5

Table 2. Proximate and ultimate analysis of wood

	Analysis (wt%)	**Method**	**Woodchips**
Proximate analysis (as received basis)	Moisture	EN 14774-1	38.74
	Ash	EN 14775	1.39
	Volatile matter	EN 15148	49.13
	Fixed carbon	By calculation	10.74
Ultimate analysis (dry and ash free, daf)	C	EN 15104	49.64
	H	EN 15104	5.98
	N	EN 15104	0.47
	S	EN 15289	0.08
	O	EN 15104	43.83
Lower heating value (MJ/kg)		EN 14918	9.89

The tar sampling port is shown in Figure 3. The product gas taken was passed through the trace heater before passing into at least four impinger bottles placed in a water bath at the temperature of 0-3°C. The trace heater prevents the tar condensation in the sampling line. Its temperature was controlled at 200°C, which is higher than the tar and water dew point, to avoid tar and water vapor condensation. The impinger bottles were filled with approximately 200 ml of solvent grade toluene per bottle. These impinger bottles condense and dissolve the tar for further gravimetric tar analysis. The last impinger bottle is empty and acts as cold trapping to directly condense the liquid in case of overflow. In addition, the last impinger bottle is connected to an ABB flow meter and a diaphragm pump to control the flow rate of the product gas. The flow meter was calibrated for this particular product gas composition.

The dissolved tar in toluene of all impinger bottles were then analyzed for gravimetric tar using the procedure developed by the research group at the College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang (KMITL) Thailand, and Gussing Renewable Energy (Thailand) company with support from Professor Rauch, Karlsruhe Institute of Technology, Germany. More detail is described by Hongrapipat *et al*. [8].

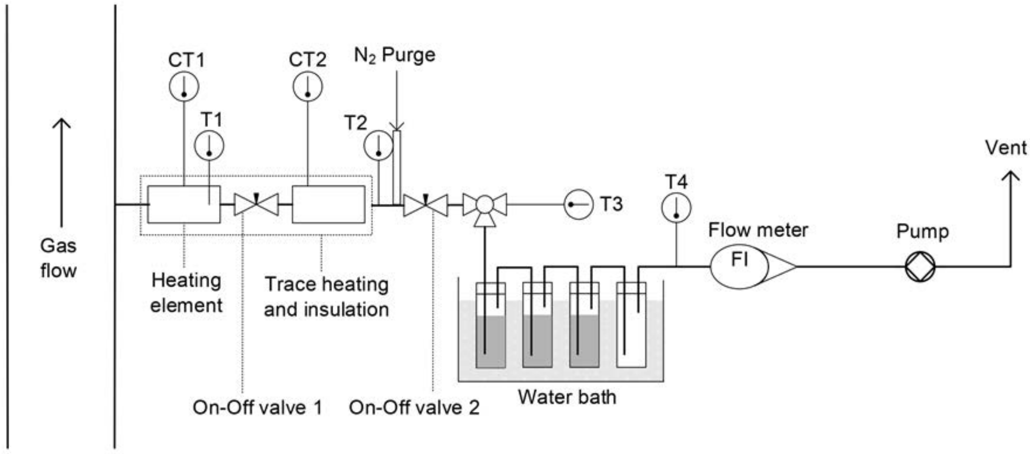

Figure 3. Schematic diagram of tar sampling port setup [8]

2.3 Product gas composition measurement and determination

The cleaned product gas, after being cooled down and scrubbed for tar, was automatically measured by the online ABB gas analyzer. The measured value presented and stored in the SCADA system were for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and oxygen (O_2). Other gases including N_2 and C_xH_y (C_2H_4, C_2H_6, C_3H_8) were estimated from previous manual product gas analyses to be 8 vol.%. The hydrogen composition was determined by calculation.

2.4 Bed material characterization

Bed materials were collected from the bottom of the gasifier of the Nong Bua Plant after both gasifier and combustor were cooled down during shutdown. The collected bed materials were cross-sectioned and analyzed for elemental composition and mapping using a Carl Zeiss EVO MA10 energy dispersive spectroscopy (EDS).

2.5 Operation period

There were two operation periods in this study, operation period 2017 and operation period 2018.

The operation period 2017 was when the Nong Bua Plant was operating in December 2017. This was when the calcined olivine used was purchased from China instead of imported from Austria and had been just activated [27]. The activation of calcined olivine was performed by the addition of biomass ash (40% CaO), calcium hydroxide ($Ca(OH)_2$) and dolomite ($CaCO_3 \cdot MgCO_3$) into the gasifier column during the operation.

The operation period 2018 was when the Nong Bua Plant was operating in November 2018. This was when the Nong Bua Plant was operating steadily using Chinese olivine, biomass ash, calcium hydroxide and dolomite.

3. Results and Discussion

3.1 Bed material characterization

The elemental composition of cross-section of the bed material collected at the bottom of the gasifier during the operation periods 2017 and 2018 are summarized in Table 3. Compositional mapping of both periods is illustrated in Figure 4. The major components detected were magnesium, silicon, calcium, and iron. Trace amounts of phosphorus and potassium were also detected. Magnesium, silicon, and iron were observed because as mentioned before the bed material mainly consists of iron and magnesium orthosilicate ($(Mg, Fe)_2SiO_4$). Calcium came from the additives such as calcium hydroxide ($Ca(OH)_2$), biomass ash (40% CaO) and dolomite ($CaCO_3{\cdot}MgCO_3$) [27].

Table 3. EDS analysis in atomic percentage (at %) of the cross-section of the bed material collected from the gasifier during the operation periods 2017 and 2018

Component	Operation Period 2017	Operation Period 2018
Mg	40.33	39.66
Si	35.86	35.60
P	0.48	0.59
K	2.60	4.31
Ca	8.78	13.53
Fe	11.95	6.31

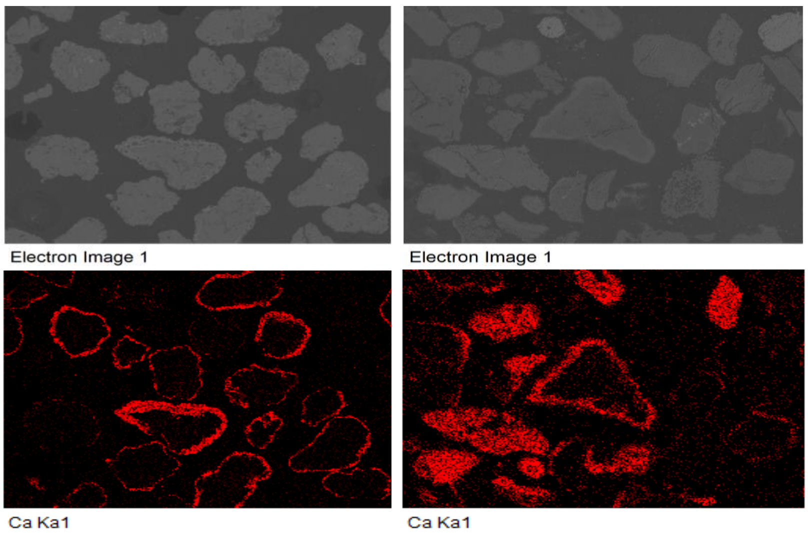

Figure 4. EDS compositional mapping of the cross-section of the bed material collected from the gasifier during the operation periods 2017 (left) and 2018 (right). The red color shows the calcium layer.

The amount of calcium and potassium in the bed material collected from the operation period 2018 is higher than that in the bed material collected from the operation period 2017. The lower amount of calcium is because calcium from additives needs time for solid-solid reaction and incorporation into the bed material [28-30]. The amount of magnesium and iron in the bed material collected from the operation period 2018 is lower than that in the bed material collected from the operation period 2017. The lower amount of magnesium and iron was from the substitution of calcium for these two elements [27-29, 31, 32].

3.2 Gasification temperature

The gasifier temperatures of both periods studied, 2017 and 2018, are shown in Figures 5 and 6. After the system had reached a steady-state, the gasifier temperatures of the periods 2017 and 2018 were 800-860°C and 790-870°C, respectively. The stable and normal operation time before shutting down in 2017 was 34.5 h and it was 95 h in 2018.

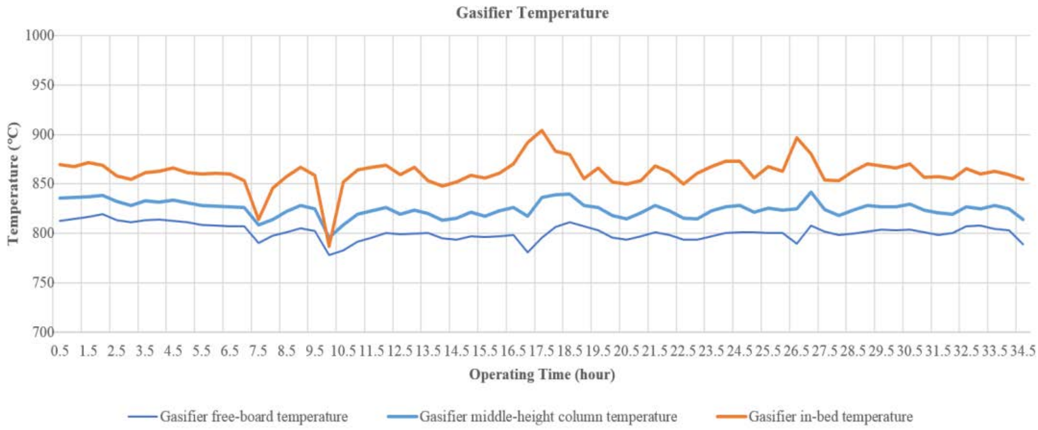

Figure 5. The gasifier temperature at different heights of the reactor over the test period 2017

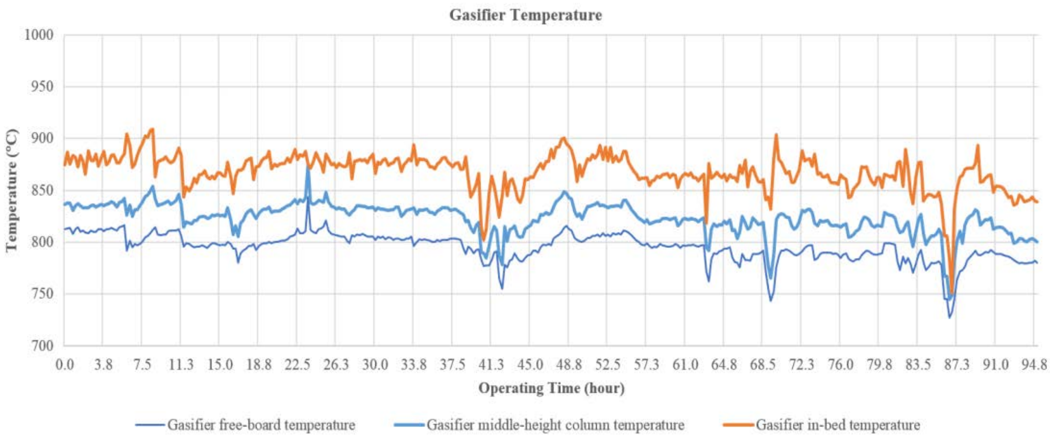

Figure 6. The gasifier temperature at different heights of the reactor over the test period 2018

The gasifier temperature was in the range of 800-860°C. Minor fluctuations were due to noise of measurement. The free-board temperature of the gasifier during the period 2018 was 10°C lower than it was in the period 2017 while the in-bed temperature of the gasifier of the period 2018 was 10°C higher than the period 2017. The gasifier temperature and operation period influence the product gas composition and tar content [4, 18-19]. However, the impact of the gasifier temperature is not as obvious as that of the active bed materials [33]. The product gas composition and tar content will be further discussed in the next section.

3.3 Product gas composition and tar concentration in the product gas

The product gas composition and calculated LHV of both operation periods and the design values are summarized in Table 4. The gas composition and the calculated LHV during each operation period are illustrated in Figures 7 and 8.

Considering the gas component during the operation period 2017, hydrogen was on the maximum threshold of the design value of 40 vol.%. Other gas components were in the range of the design value. The LHV was close to the design value of 13 MJ/Nm^3. For the gas components during the operation period 2018, hydrogen was the only gas component that was over the design value. Most of other gas components, except for carbon dioxide, were under the design value. When comparing the operation periods 2017 and 2018, hydrogen and carbon dioxide produced from the operation period 2018 were higher than those produced during the operation period 2017. However, the carbon monoxide and methane concentrations, and LHV of the operation period 2018 were lower than those of the operation period 2017. The average tar concentration in the product gas during the operation periods 2017 and 2018 were 872 ± 125 mg/Nm^3 and 56 ± 22 mg/Nm^3, respectively.

It was reported by Siriwongrungson *et al.* [27] regarding the average tar concentration in the operation period 2017 that further improvement was required to reduce the tar concentration in the product gas. The different operating parameters between the two operation periods were the activity of the bed material and the gasifier temperature. With the operating parameters in the operation period 2018, the gasification ran for the longer time (95 h) than the operation period 2017 (34.5 h).

Table 4. Average gas composition, LHV and tar concentration measured during the operation period 2017 and 2018 and the design values

Gas component /LHV	Design values	Period 2017	Period 2018
H_2 (vol.%)	37–40	40.9 ± 2.2	44.2 ± 2.1
CO (vol.%)	21–24	22.8 ± 1.2	19.6 ± 1.6
CO_2 (vol.%)	19–23	19.4 ± 1.5	21.0 ± 1.3
CH_4 (vol.%)	9–10	9.0 ± 0.5	7.2 ± 0.7
LHV (MJ/Nm^3)	13	12.7 ± 0.2	12.0 ± 0.3
Average Tar (mg/Nm^3)	50	872 ± 125	56 ± 22

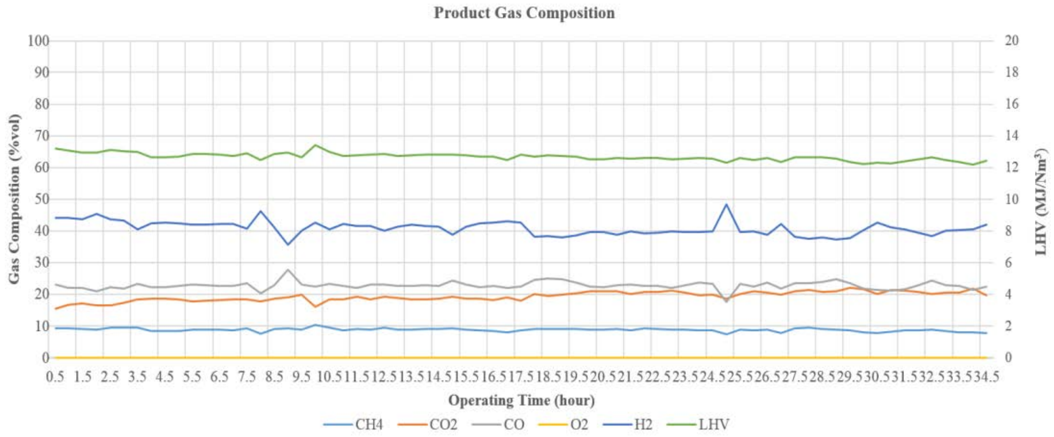

Figure 7. The product gas composition and LHV over the 34.5 hours operating time during the operation period 2017

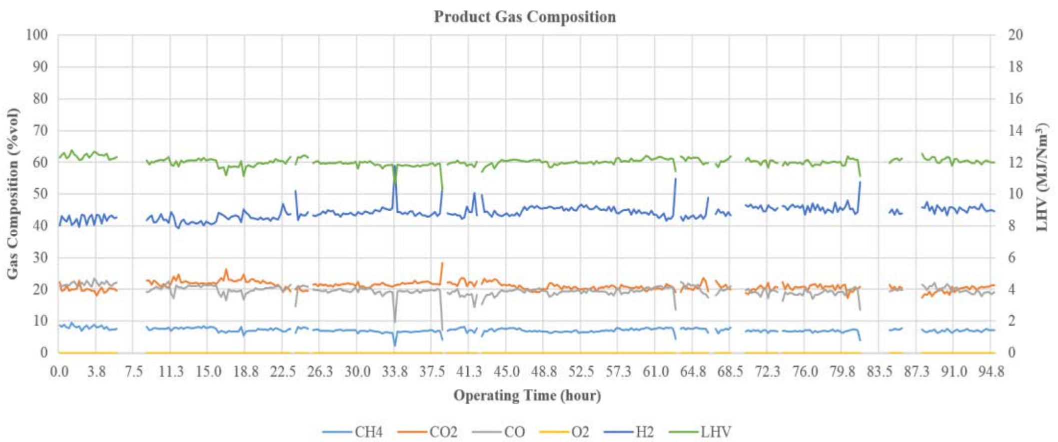

Figure 8. The product gas composition and LHV over the 95 hours operating time during the operation period 2018. The gaps are where the oxygen was present and therefore the calculated hydrogen was extremely high.

Biomass ash, calcium hydroxide and dolomite were added to the olivine during the operation periods 2017 and 2018 to increase activity of the bed material for better plant performance [27, 34]. As mentioned before, calcium, which influences the tar reduction, requires time to interact and be incorporated into the bed material. As shown in Table 3 and Figure 4, the amount of calcium in the bed material collected at the bottom of the gasifier during the operation period 2018 was higher than that collected during the operation period 2017. Therefore, average tar concentration during the operation period 2018 was lower than that for the operation period 2017 [10, 29, 35]. The effect of bed material activity combined with the gasifier temperature of the operation period 2018 resulted in higher average hydrogen and carbon dioxide concentrations with lower average carbon monoxide and methane concentrations compared to operation period 2017. This implied that the water-gas shift and steam-methane-reforming reactions occurred in the gasifier [6, 10, 27].

Considering the LHV, the LHV during the operation period 2018 was lower than it was during the operation period 2017. The LHV of the product gas is related to the LHV value of each gas and its composition in vol.% [15]. The lower the LHV of the product gas in the operation period 2018 was due to the higher hydrogen content but lower methane content.

4. Conclusions

Operating parameters of the DFB gasifier, specifically gasifier temperature and activity of bed material, of the Nong Bua Plant performance were investigated. Two operation periods, operation period 2017 and operation period 2018, were studied. The gasifier temperature ranges during the operation period 2017 and operation period 2018 were 800-860°C and 790-870°C, respectively. Higher calcium levels were detected in bed material collected from the bottom of the gasifier during the operation period 2018 compared to that collected during the operation period 2017. Higher average hydrogen concentrations and lower average methane concentrations were observed in the product gas produced during the operation period 2018 than in the operation period 2017. The bed material during the operation period 2017 was freshly activated while the bed material during 2018 had been activated for a long certain period of time, hence tar content was lower. Operating parameters were improved during the operation period 2018 and shall further be improved for much more lower tar concentration.

5. Acknowledgements

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