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Co-gasification of Cassava Rhizome and Woody Biomass in the 1 MW_{el} Prototype Dual Fluidised Bed Gasifier by Gussing Renewable Energy

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Abstract: In the current research, the effect of the mixture ratio by weight of wood chips to cassava rhizome (100%:0%, 75%:25%, and 50%:50%) was investigated on the properties of the product gas produced from the Dual Fluidised Bed gasifier power plant. The DFB gasifier power plant is located in Nongbua district, Nakhon Sawan province, Thailand. The results from this study show that the use of 100% wood chips as a fuel generates high quality product gas as designed. The mixture of wood chips and cassava rhizome in the weight ratio of 75%:25% and 50%:50% also gives satisfactory results: steady operation conditions of the whole power plant process, good quality and quantity of product gas, however, the tar content in the product gas was slightly higher than that of using wood chips alone. The researchers found that cassava rhizome can be used as a fuel mixture together with wood chips in the current DFB gasifier at site to generate heat and electricity. The outcome of this research will create the use of waste cassava rhizome, enormously available around the power plant, as well as the broad application of gasification technology using various biomass feedstock types available in Thailand.
Keywords: Biomass, cassava, gasification, dual fluidized bed gasifier, biomass power plant

1. Introduction

Gasification is the thermo-chemical conversion of any carbonaceous fuel to a combustible gas, where the fuel can be in the form of solid, liquid, and gaseous feedstocks such as coals, biomass residues, oils, and natural gases [1]. When air or oxygen is used as the gasification agent, the gasification is actually a partial oxidation process which applies heat to the feedstock at sub-stoichiometric levels of oxygen to that required for complete oxidation. However, when steam is used as the gasification agent, the gasification process is endothermic in overall and thus external heat needs to be supplied.

In this research, the gasification technology used is the Dual Fluidised Bed (DFB) gasifier system using steam (H_2O) as a gasifying agent. It has been reported that the product gas produced from the DFB gasifier primarily comprises hydrogen (34-45 vol%), carbon monoxide (20-30 vol%), carbon dioxide (15-25 vol%), and methane (8-12 vol%) [2]. The product gas is of high quality with a high calorific value of 12-14 MJ/Nm^3. This product gas can be utilised in a variety of applications: in gas turbines or engines for heat and power generation, and for further production of hydrogen gas, synthetic natural gas, synthetic liquid fuel, and various chemical products.

The biomass steam DFB gasifer was first invented and developed in a laboratory at the Vienna University of Technology (VUT) by a team of scientists and engineers led by Prof. Hermann Hofbauer and Prof. Reinhard Rauch. The first commercial combined heat and power (CHP) DFB gasification system was established in Gussing, Austria, by the contribution of several parties since 2001 [2]. The Gussing plant uses local wood chips as feedstock to generate 2.0 MW_{el} electricity to the national power grid and 4.5 MW_{th} heat to the households, and businesses of Gussing, since 2002. The Gussing plant was in operation for almost 100,000 hours and it is owned by Biomasse Kraftwerk Güssing GmbH & Co KG, which is a subsidiary of Gussing Renewable Energy International Holding GmbH, Austria.

Gussing Renewable Energy (GRE), a so-called Carbon Recycling enterprise, is the developer of the DFB gasification technology to convert biomass and organic solid wastes to usable energy in a form of high heating-value and valuable gas. The gas product can be used for electricity and heat generation (Combined Heat and Power (CHP), or for other valuable products including but not limited to pure-hydrogen gas, synthetic natural gas, synthetic liquid fuel, and chemical products (methanol, ethanol, etc.). GRE provides and supports its customers on engineering, procurement, construction (EPC), operation, training of the operators on DFB gasification process, troubleshooting, etc.

GRE has developed and constructed the 1 MW_{el} CHP DFB gasifier power plant in Nongbua district, Nakhon Sawan province, Thailand [3]. The Nongbua plant was designed to operate with various biomass resources such as wood chips, sugarcane leaf, corncob, and other biomass renewable resources. Moreover, a mixture of municipal solid waste (MSW) and biomass can also be fuelled into the 1 MW_{el} DFB gasifier [3].

Thailand is a major producer and exporter of agricultural products. The agricultural or biomass residue generation was estimated to be 134 million tons per annum, of which 53% was used for energy production and other purposes [4]. The amount of unconsumed biomass residues in Thailand is extremely large. The remaining amount of more than 60 million tons per annum is available and should be collected and used for alternative energy to generate electricity, heat or transport fuels, which is equivalent to about 4,000 MW electrical output [4]. The main unconsumed biomass includes rice straw, sugarcane leaves, corn leaves, palm leaves, empty fruit bunch, and cassava rhizome [4].

For Thailand, the use of biomass as fuel for energy production contributes to significantly reduction of reliance on foreign oil and natural gas imports. It also reduces the environmental impact since the use of biomass fuel does not increase the emission of carbon dioxide in the atmosphere (zero carbon emission), and carbon dioxide is recycled into cyclic biomass growth (carbon neutral cycle). The Ministry of Energy under the Thai government has announced and conducted "Strategic Alternative Energy Development Plan (AEDP 2015-2036)" to promote and increase the use of renewable energy in the country from 12% of total energy demand in year 2014 to 30% by the end of year 2036 [5]. Under the AEDP, the government set the target from the end of 2014 to 2036 for the use of agricultural residues or biomass to increasingly produce electricity from 2,452 MW_{el} in 2014 to 5,570 MW_{el} in 2036, to generate heat from 5,144 kTOE to 22,100 kTOE, and to generate biofuels from 1,782 kTOE to 8,712 kTOE [5].

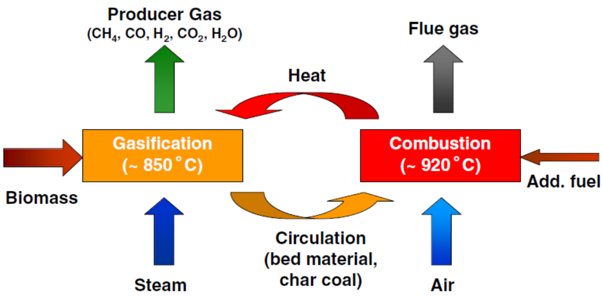
In this research project, therefore, the cassava rhizome is the main focus because it is largely available in Thailand of almost 6 million ton per annum and easily obtainable in Nakhon Sawan province where the Nongbua DFB gasifier plant is located. The cassava rhizome has never been tested or used in the DFB gasifier. It is also found that the price of cassava rhizome is much lower than wood chips and thus reducing the feedstock cost dramatically if cassava rhizome can be used. The objective of the current research, therefore, is to investigate the effect of the mixture ratio by weight of wood chips to cassava rhizome on the properties of product gas produced from the DFB gasifier for electricity generation. Results from this research can be used to determine the optimum weight ratio of wood chips to cassava rhizome for the design and improvement of gasification technology to be more efficient. The outcome of this research will create the use of waste cassava rhizome around the power plant and significantly decrease the feedstock cost. This will result to the broad application of gasification technology using various biomass feedstock types available in Thailand. In the next step, the mixture of wood chips and cassava rhizome with the weight ratio of 25%:75% and 0%:100% will be tested to discover the full replacement of cassava rhizome to wood chips as a single feedstock.

2. Experiments and materials

2.1 The DFB gasifier and its principle

The principle of the DFB gasifier is presented in figure 1 [2, 6, 7]. The basic concept is the physical separation of the gasification reaction from the combustion reaction, in order to separate the product gas from the conventional flue gas and thus obtaining a nitrogen-free product gas. The DFB steam gasifier comprises two separated chambers – a gasification reactor and a combustion reactor (figure 1 and 2). The overall steam gasification reaction is endothermic, and thus it requires energy to be supplied by the circulation of the bed material from the combustion reaction via the loop seal or siphon. Biomass is fed into the bubbling fluidised bed (BFB) gasification reactor using steam as a fluidising and gasifiying agent. Residual biomass char from the gasification reactor is flowed with the circulating bed material through the inclined chute towards the combustion reactor (see figure 2). The residual biomass char is added energy to the combustion chamber and thus the overall DFB gasifier reactor.

The combustion reactor is operated in a fast fluidised bed (FFB) regime fluidising with air and the reaction take places at about 920°C and atmospheric pressure. The two connections, namely loop seal and chute, are fluidised with steam, which effectively prevents the gas leakage between the gasification and combustion reactors and it also allows high solid circulation rate. The temperature difference between the gasification and combustion reactors is determined by the required energy and is controlled by the bed material circulation rate and additional fuel (figures 1 and 2). In the BFB gasification reactor operated at about 820°C and atmospheric pressure, the heating rate is fast and thus both pyrolysis and gasification reactions take place simultaneously, which results in low concentrations of volatiles (tars) and cleaner product gas being obtained.



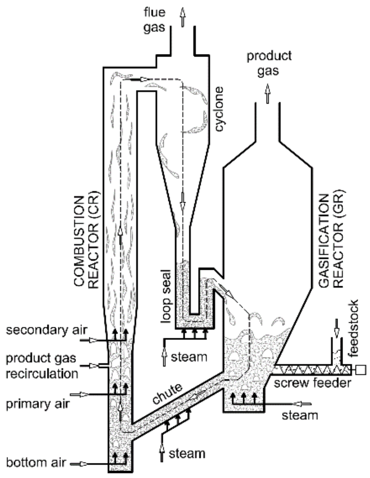


Figure 1. Principle of the DFB gasifier [2, 6, 7] **Figure 2.** The DFB steam gasifier components [8]

2.2 The Nongbua DFB gasification process

Figure 3 displays a schematic diagram of the Nongbua DFB gasifier power plant for this research project. Main components of the DFB steam gasifier are consisted of a BFB reactor for steam gasification of biomass and a fast fluidised bed (FFB) reactor for combustion of derived char transported from the BFB reactor. The BFB gasification reactor is operated at about 820°C while the FFB combustion reactor takes place at about 920°C. Figure 4 illustrates the DFB gasification power plant at Nongbua district.

The process can be described as follows. Biomass or non-biomass feedstocks are transported via a fuel handling system and then fed to the BFB gasification bed. The bed material used in the gasifier is calcined olivine sand (iron and magnesium orthosilicate, $(Mg, Fe)_2SiO_4$). The choice of olivine is justified by its hardness required for the use in the fluidised bed and its high catalytic activity in biomass steam gasification. The product gas from the DFB steam gasifier has favourable characteristics of low nitrogen content, high hydrogen content, and thus a high calorific value of about 12-14 MJ/Nm^3 is achieved. The nitrogen content originates mainly from the purge gas in the biomass feeder and product gas particle filter.

The product gas from the gasifier flows to a cooler system, a fabric PTFE filter, and a scrubber before going to the gas engine to produce electricity and heat. The product gas is first cooled by two product gas coolers to reduce temperature from about 820°C to 280°C. The temperature of the product gas is further cooled down from 280°C to 200-220°C by mixing with the return flow of the cold clean product gas after the scrubber. This novel process step was patented in Austrain Patent (österreichische patentanmeldung), published by Gussing Renewable Energy International Holding GmbH [9]. Next step, the fabric filter is used to remove almost all of the particulates (char, ash, and fine bed material) from the product gas. The particulates from the fabric filter, which contain mainly char, are transported to the combustion chamber to be used as additional fuel.

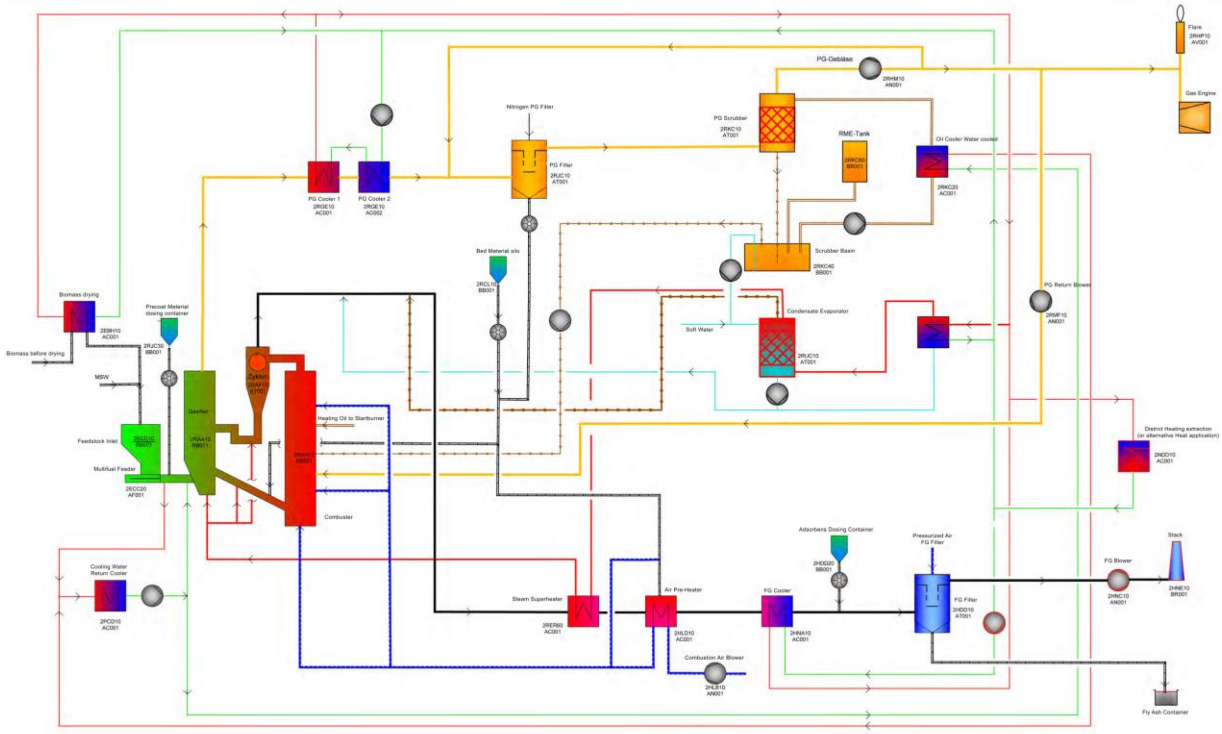


Figure 3. Schematic diagram of the CHP – DFB biomass gasifier process in Nongbua district, Nakhon Sawan province, Thailand

The last step of the gas cleaning is a scrubber to remove completely all the heavy tars and particulates from the product gas by using biodiesel (rapeseed methyl ester, RME). The scrubber also reduces further the product gas temperature from 200-220°C to about 40°C, which is then compressed to 300 mbar as required for the gas engine. The used biodiesel is used as additional fuel in the combustion zone and the condensed water in the scrubber is used for steam generation for fluidization of the gasification zone.

Finally, the clean product gas is drawn to the gas engine to generate electricity and heat. The sensible heat available in the whole process is from the product gas cooling system, the flue gas cooling system, and the flue gas and hot water from the gas engine. This waste heat can be used in various applications such as district heating system, drying, electrical generation by Organic Rankine Cycle (ORC) process, or to further use for cold water generation by absorption chiller, etc.

For the flue gas generated from the DFB gasifier, its sensible heat is used to superheat the steam and preheat air for the gasification reactor and combustion reactor, respectively. The flue gas is then further cooled down to 160-170°C before going to the fabric filter for all particulate removal and to the stack.

Figure 4. DFB gasification power plant at Nongbua district, Nakhon Sawan province, Thailand

2.3 Materials

Local Thai wood chips, mainly contain softwood, were used in the current research and it was purchased nearby the Nongbua power plant. Cassava rhizome was also purchased locally from the farmer in Nongbua district and it was chipped and sun dried at Nongbua site. The particle cross section length of the two feedstocks is in a range of 0.5-10 cm. The proximate analysis, ultimate analysis, ash fusion temperature of the wood chips and cassava rhizome was conducted by SGS (Thailand) Limited and the results are given in table 1 and table 2, respectively.

In the experiment, the mixture ratio by weight of wood chips to cassava rhizome are set at 100%:0%, 75%:25%, and 50%:50%. To control the feed of each mixture ratio, wood chips and cassava rhizome were filled into two different hoppers and two main screw driver sets, where they were designed for this purpose of multi-fuel feeding. The weight of either wood chips or cassava rhizome was set and controlled by the main screw driver control speed. The main screw driver speed was calibrated based on the fuel bulk density and was pretested beforehand.

Table 1. Proximate and ultimate analysis results of wood.

	Analysis (wt%)	Method	Wood chips	Cassava rhizome
Proximate analysis (as received basis)	Moisture	EN 14774-1	38.74	15.26
	Ash	EN 14775	1.39	5.03
	Volatile matter	EN 15148	49.13	64.54
	Fixed carbon	By calculation	10.74	15.17
Ultimate analysis (dry and ash free, daf)	C	EN 15104	49.64	50.29
	H	EN 15104	5.98	6.27
	N	EN 15104	0.47	1.58
	S	EN 15289	0.08	0.16
	O	EN 15104	43.83	41.70
Lower heating value (kcal/kg)		EN 14918	2,362	3,409

Table 2. Ash fusion temperature (Standard NEN EN 15370).

Phase	Wood chips		Cassava rhizome	
	Reducing	Oxidizing	Reducing	Oxidizing
Initial deformation temperature (°C)	1,405	1,450	1,295	1,255
Spherical temperature (°C)	1,420	1,465	1,305	1,265
Hemispherical temperature (°C)	1,430	1,484	1,310	1,280
Flow temperature (°C)	1,435	1,500	1,325	1,295

The wood chips as received with the moisture of about 38-39% was used and it was dried in a dedicated wood chips dryer to about 15% before mixing with the sun-dried cassava rhizome as received with moisture content 15%. The mixture was then fed into the bed of the BFB gasifier. The operation conditions of DFB steam gasifier are outlined in table 3.

Table 3. DFB steam gasifier operation conditions.

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

In the experiments, the steam to fuel ratio, which is defined as the ratio of mass flow rate of the feeding steam and moisture in the fuel to mass flow rate of the dry fuel feedstock, was set at 0.5 kg/kg_{dry}. The superheated steam for gasification reaction was produced from the condensation of the wet product gas which was separated from the recycled biodiesel in the sedimentation tank, placed below the tar scrubber column. The condensed and separated water from the sedimentation tank was fed to an evaporator to generate steam. This saturated steam was superheated by the recovered heat from the product gas and flue gas cooling systems. Due to the reuse of water, the fresh soft water used for the entire process is extremely low. The soft water is mainly consumed for the make-up in the cooling tower.

2.4 Product gas sampling and analysis
The clean product gas after the scrubber was automatically sampled and analysed by the ABB gas analyser, which is installed at site. The compositions of CO, CO_2, CH_4, and O_2 were online measured, presented, and stored in the SCADA system. The H_2 composition was determined by calculation.

2.5 Sampling of tar in the product gas
Tar sampling and analysis in the product gas from the gasifier process in this study was performed based on European Standard CEN/TS 15439:2006 Biomass gasification – Tar and particles in product gases – Sampling and analysis.

In the experiments, tar in the product gas was sampled at a sampling point after the product gas was removed from tar in a biodiesel scrubber. To collect the tar samples, a dedicated sampling line for tar analysis was designed and presented in figure 5. In the sampling line, the gas sample was firstly drawn through the trace heating and then through impinger bottles in water bath where tar was condensed and absorbed into the absorbing solution. The stainless steel sampling line was trace heated and insulated and was made as short as possible to avoid tar condensation in the sampling line. The controlled temperatures in the sampling line were set higher than the tar dew point and higher than the water dew point of the producer gas. The sampling line was occasionally back-flushed by N_2 gas with high flow rate for about 30 min to prevent the sampling line blockage.

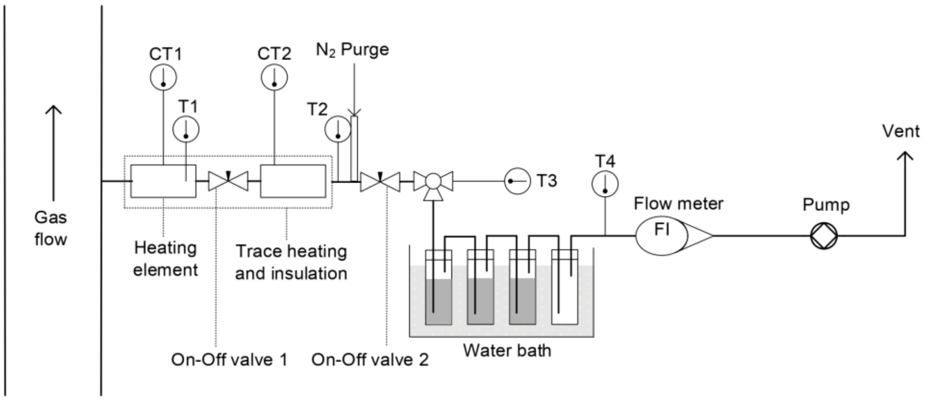


Figure 5. Schematic diagram of tar sampling port setup.

In the water bath, each of the first three impinger bottles was filled with 200 mL of pure toluene as an absorbing solution. The last bottle was empty to collect the solution in case of an overflow. The temperature of the water in the bath was maintained at 2°C. The moisture in the producer gas was condensed in toluene solution during sampling but this did not affect the measurements of tar because the total volume of the toluene and water is evaporated for tar gravimetric analysis.

The procedure and checklist for tar sampling and analysis were developed by the research group between College of Advanced Manufacturing Innovation under King Mongkut's Institute of Technology Ladkrabang (KMITL), and Gussing Renewable Energy (Thailand) company, and by the support from Prof. Reinhard Rauch from Karlsruhe Institute of Technology in Germany. Figure 6 displays tar sampling at Nongbua power plant and tar evaporation in the lab at KMITL.

Figure 6. Tar sampling at Nongbua power plant and tar evaporation in the lab at KMITL.

3. Results and Discussion

3.1 Gasifier process operation conditions

During the experiments, it was discovered that the entire gasification process was in a steady operation condition over the test period of this study when pure wood chips and the mixture of wood chips and cassava rhizome were used. As can be seen in figure 7-8, the BFB gasifier temperature was constantly operated between 800 and 860°C and its pressure drop was in a narrow range of 110-130 mbar. The FFB combustor was operated at a temperature window of 860-930°C (figure 9). The pressure at the bottom of the FFB combustor was varied in a small range from 100-160 mbar, while the pressure at the column middle was 5-30 mbar and column top was between -10 and -2 mbar (figure 10). The DFB gasifier was operating effectively with the addition of the cassava rhizome.

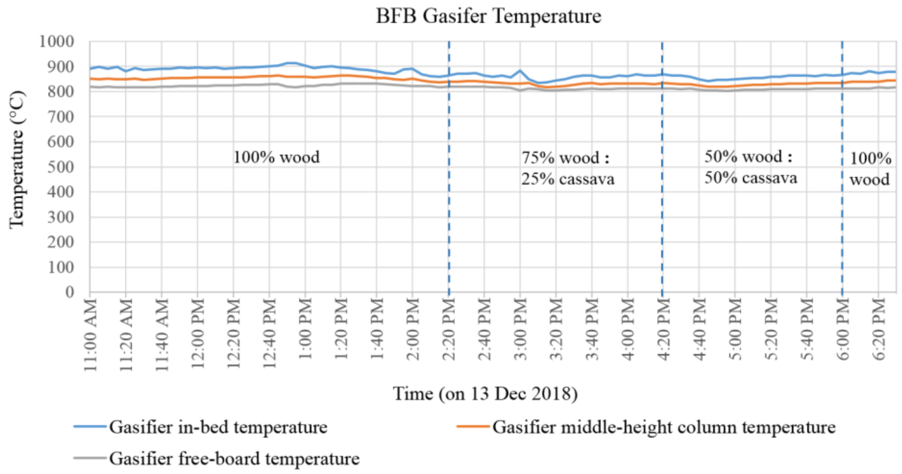


Figure 7. BFB gasifier temperature at different heights of the reactor over the test period.

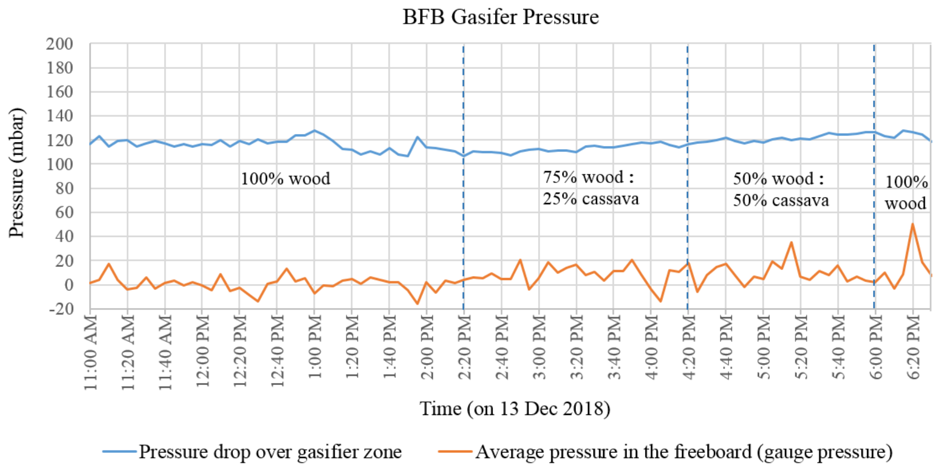


Figure 8. BFB gasifier pressure over the test period.

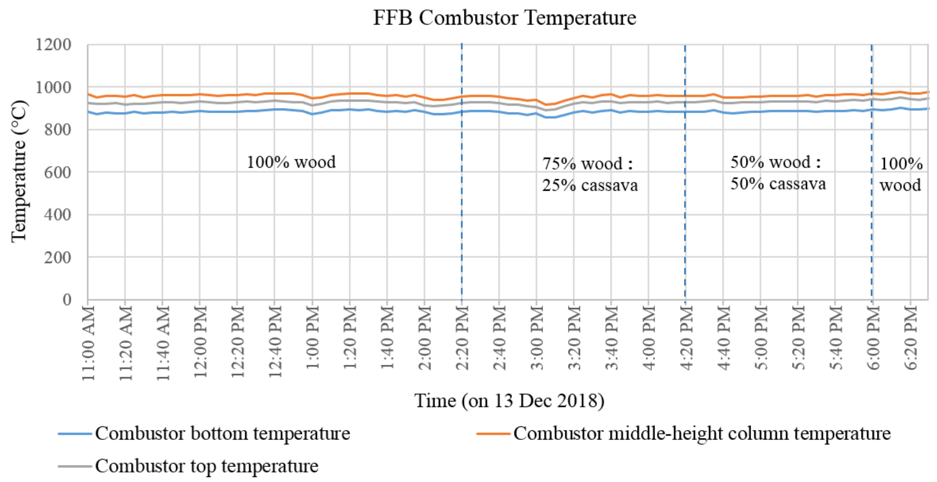


Figure 9. FFB combustor temperature at different heights of the reactor over the test period.

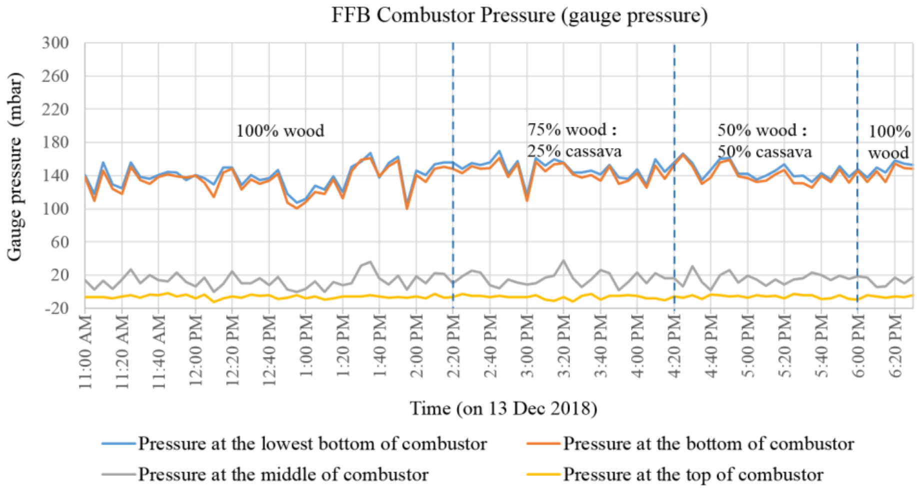


Figure 10. FFB combustor pressure at different heights of the reactor over the test period.

In figure 11-13, it was found that the operation of the product gas cooling system, the bag filter, and the scrubber was performed very well and steadily over the test period. As shown in figure 11, the product gas from the gasifier from 820°C was cooled down to 400-450°C with the first cooler among the two in the cooling system. Then, the product gas temperature was reduced to 250-280°C after the second cooler and to 200-220°C by mixing with cold recycle gas before passing through the bag filter.

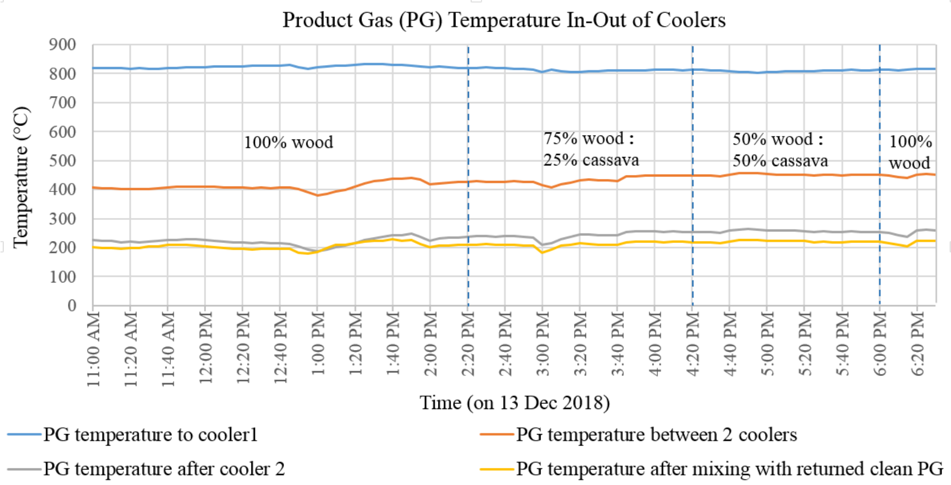


Figure 11. Product gas temperature going to cooler 1, and between 2 coolers, after cooler 2, and after mixing with returned clean product gas before passing through the bag filter.

Figure 12 and 13 show the product gas outlet temperature and pressure across the bag filter and the scrubber, respectively. These parameters are designed parameters and they need to be controlled at the set points during operation. The results proved that the bag filter and scrubber were operated well as designed.

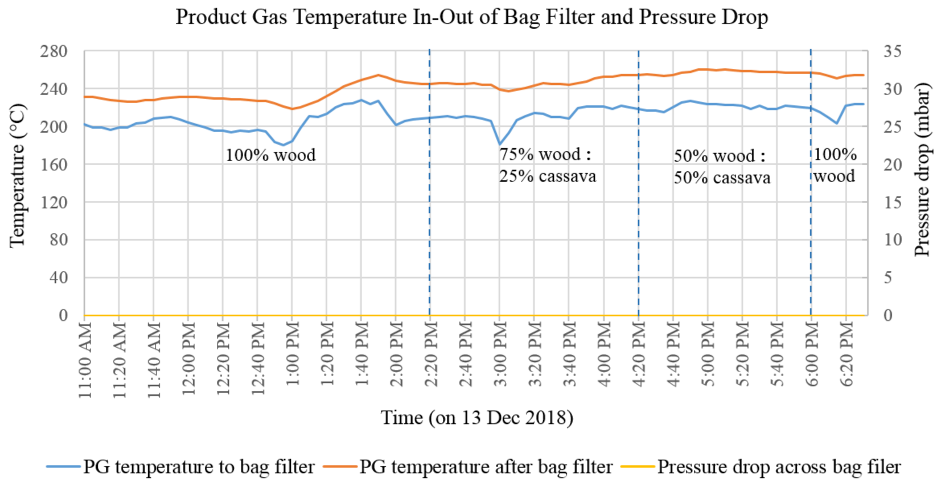


Figure 12. Product gas temperature in-out of bag filter and pressure drop across the bag filter.

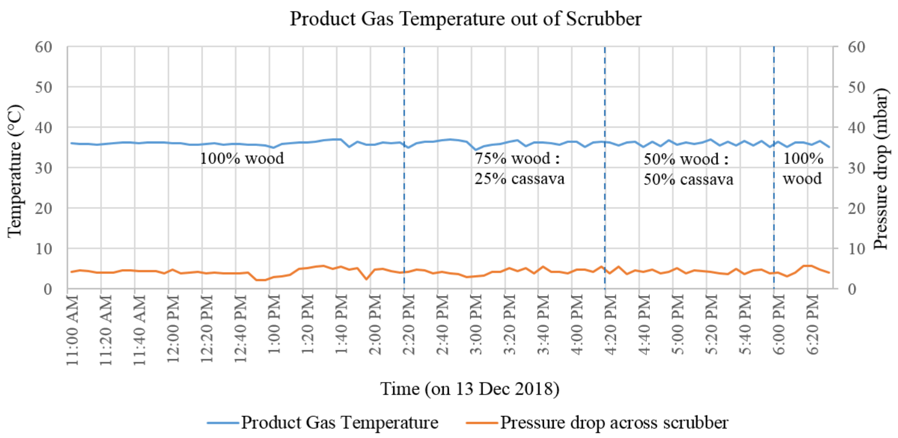


Figure 13. Product gas temperature out of scrubber and pressure drop across the scrubber.

3.2 Product gas composition

Table 4 and figure 14 show the product gas composition and its lower heating value over the whole test period. The concentrations of H_2, CO, CO_2, and CH_4 are in the same range for pure wood chips, and binary mixture of wood chips and cassava rhizome. The lower heating value of the product gas is as high as 12-13 MJ/Nm^3, which is comparable with previous studies [10]. There were some peaks of the gas compositions as shown in figure 14, which were expected to be the noise of the instrument. From these results, it is shown that binary mixtures of wood chips and cassava rhizome with the weight percent of cassava rhizome up to 50% are good feedstock in the DFB gasification process.

Table 4. Main gas composition in the clean product gas (dry basis) from all test sets.

Gas component	Measured value (%vol)
H_2 (%vol)	38 – 43
CO (%vol)	19 - 25
CO_2 (%vol)	18 – 25
CH_4 (%vol)	7 - 12
Lower Heating Value (LHV) MJ/Nm^3	12 - 13

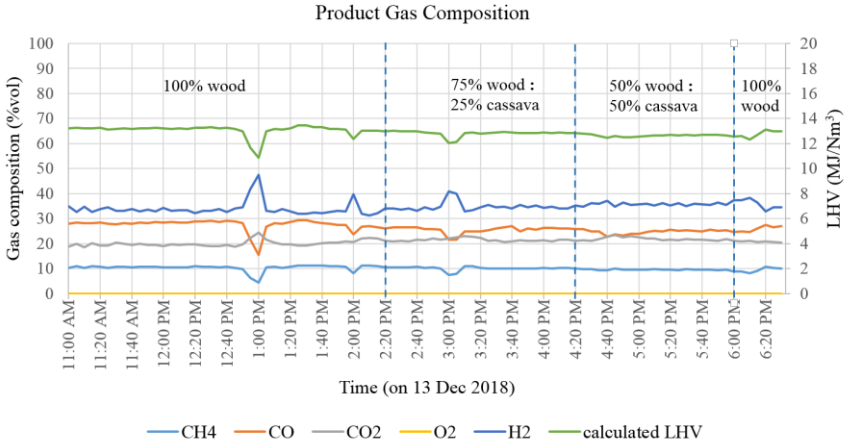


Figure 14. Main gas composition in the product gas from the feed 100%:0%, 75%:25%, 50%:50% by weight of wood chips to cassava rhizome.

3.3 Tar concentration in the product gas

The results of tar concentration in the product gas present in this study were averaged from two to four repeated measurements (see table 5 and figure 15).

Table 5. Tar concentration in the product gas from gasification of wood chips and cassava rhizome.

Tar concentration in the clean product gas	Percent by weight ratio of wood chips to cassava rhizome		
	100%:0%	75%:25%	50%:50%
Average tar value (g/Nm^3)	0.056	0.297	0.351
Standard deviation	0.0182	0.1144	0.1814

From table 5 and figure 15, it is obvious that the addition of cassava rhizome into wood chips in the feed resulted to slightly higher tar in the product gas. Increasing the feed ratio of cassava rhizome in wood chips from 25 wt% to 50 wt% did not show significant change in the tar concentration. The optimisation of the gasification process is to be performed to reduce the tar concentration.

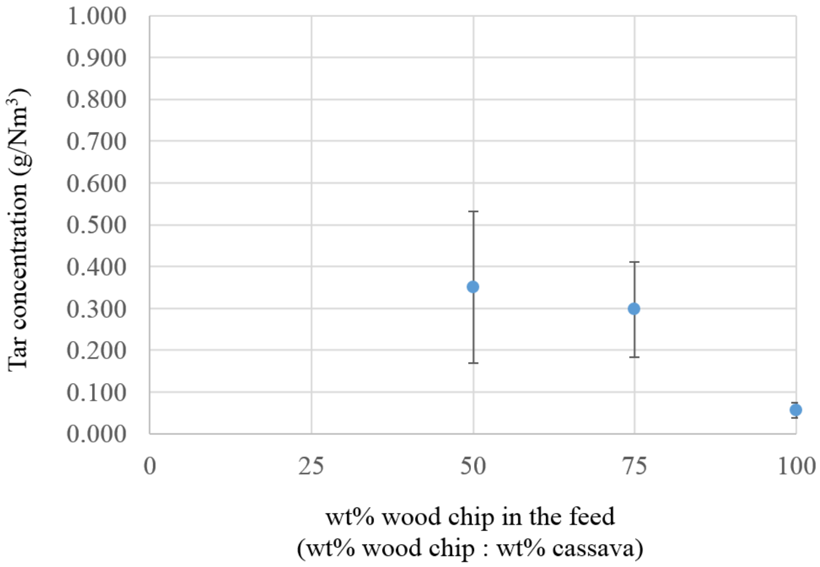


Figure 15. Tar concentration (g/Nm^3) in the product gas from gasification of wood chips and cassava rhizome

4. Conclusion

Cassava rhizome was the first time in this present work to be used in the commercial scale DFB gasifier power plant in Nongbua, Thailand. It is concluded that the addition of cassava rhizome to wood chips with the weight ratio up to 50 wt% gives satisfactory results: steady operation conditions of the whole power plant process, good quality and quantity of product gas. The cassava rhizome can be used to mix with wood chips as a binary mixture to feed to the DFB gasifier plant and the plant operates with high performance.

In the next step, the mixture of wood chips and cassava rhizome with the weight ratio of 25%:75% and 0%:100% will be tested to discover the full replacement of cassava rhizome to wood chips as a single feedstock. The optimisation of the gasification process is to be performed to reduce the tar concentration.

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