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Small-Scale Single Stage Downdraft Biomass Gasifier with Shaking Grate Mechanism

Mary Grace A. Rubio^{*1} and Kitipong Jaojaruek^{*}

Abstract – A new approach to improve the gasification process was studied through the development of an automatic shaking grate mechanism in a single stage downdraft gasifier. Tar and ash build-up are problems commonly encountered during the gasification process. This study was conducted to mechanically induce tar cracking, to prevent blockages of biomass materials at the hopper as well as to ease the removal of ashes during the gasification process. It applies the principle of increasing the effective area for tar cracking at elevated temperatures to improve the amount of combustible producer gas as well as the conditions for thermal tar cracking. Experiments were done at varying air flow rates to evaluate different gasification parameters in comparison to conventional downdraft gasifier. The study resulted to 74% reduction in tar content, 30% improvement in high heating value and 27% increase in efficiency compared to the conventional downdraft gasification at 160 Lpm air flow rate.

Keywords – downdraft gasification, gasifier, shaking grate, thermal tar cracking, thermochemical conversion.

1. INTRODUCTION

Towards the path to sustainable development, this study utilizes the renewable energy resource, biomass, for fuel conversion. Biomass materials are organic in origin. It has an easily accessible supply source, and lower harmful emissions. Prakash *et al.* [1] showed low emissions of NO, CO, and HC compared to diesel in their study regarding the performance and emissions of biodiesel and wood pyrolysis oil emulsions in diesel engines. Biomass, however, are highly erratic in nature composing of complex organic and inorganic materials varying from one species to another. The lack of homogeneity among biomass feedstock pose problems during the conversion process affecting the overall efficiency and composition of the gas produced. Conversion technologies are designed to handle biomass feedstock according to its characteristics under controlled operating conditions. There are two main ways of converting biomass into fuel and these are via biochemical and thermochemical conversion processes. The details about the biochemical conversion is outside the scope of this study. Among thermochemical conversion technologies, gasification is the most advantageous since it converts low value feedstock into highly valuable feedstock for electricity usage and for transportation fuel. It is an endothermic process which packs the energy released from the combustion of biomass into chemical bonds to yield producer gas. The process involves a sequence of steps that sometimes overlaps as it has no clear distinction from each other [2]. Among the gasifiers, downdraft is relatively easier to operate and construct making it the most suitable energy carrier producer for communities in rural areas. It

also yields producer gas with sufficiently low tar content (0.015 g/Nm³ to 0.5 g/Nm³) as compared to other gasifier technologies [3]. The four gasification stages are separated and can be more distinguishable in this type of gasifier. These includes drying, devolatilization, combustion or oxidation and char gasification or reduction. The main source of heat is at the combustion zone; this is the zone wherein a gasifying agent is supplied in the reactor and the zone with the highest temperature since it is an exothermic process. Energy from this zone generates the heat needed for chemical reactions in the other gasification process. Pyrolysis is distinguished as the layer above the combustion zone. This part requires no amount of oxygen for its processes; this zone forms gaseous fuel consisting of primarily CO₂, CO, H₂ and CH₄, higher hydrocarbons C_mH_n (m > 1), and compounds at small quantities. Tar vapors are formed at this stage. These gaseous vapors flow downward in a downdraft gasifier where reduction reaction occurs. It is an endothermic process which converts chars into permanent gases with improved components of CO, and H₂ [4]. Unlike other gasifier, downdraft gasifier has lower efficiency due to lack of internal heat exchange. Although the producer gas has lower tar content, its heating value is low since the producer gas exits the reactor at high temperature. It is also not suitable for large scale operations because it creates hot spot areas which results to non-uniform temperatures throughout the cross-area of the gasifier [5]. Several studies were done for downdraft gasifier which includes evaluation of its performance with a variety of feedstock and gasifying agents as well as employing multi-stage method to improve its gasification process. According to gasification studies of Food Agricultural Organization (FAO), temperature, residence time, and gas-solid contacting at the hot zone of volatile gases and fuel determine the complete breakdown of tars and quality of producer gas. Reaction temperature affects almost all the other parameters of the gasification process which includes gas and tar yield. One of the main contaminants in the producer gas is tar.

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It is a complex mixture of condensable hydrocarbons and is undesirable because of various problems associated with condensation, formation of tar aerosols, and polymerization causing problems in equipment using producer gas [6]. Tar removal can be done either through thermal tar cracking or catalytic gasification. Thermal tar cracking involves heating of producer gas in order to crack tar molecules to lighter gases, refractory tars (condensable tar and char) and steam. At the onset of tar cracking, significant reduction in the production of hydrocarbons was seen at approximately 650°C [7] with OH followed by CH₃ groups disappearing with increasing temperature. With regards to the effect of residence time, Rabou *et al.* [8] studied thermal tar cracking in a Bubbling Fluidized Bed (BFB) gasifier and concluded that tar concentration was reduced to 20% at 1150°C after 1 second residence time and was further reduced to 3% after 4 seconds. Significant decrease in tar formation and improved gas quality was achieved in the study of a two-stage downdraft gasification by Jaojaruek [9] supplying air with premixed gas to the pyrolysis zone. The principle applied was to widen the high temperature zone for effective thermal cracking and improved gas quality production. The results showed a decline in tar formation to 80 mg/Nm³, improved gasification rate to 30% compared to conventional two-stage gasification method, and increased H₂ production of up to 20.5%. Other studies in reducing tar content was done by using a novel approach of changing the fluid dynamic behavior of the mixture [10] which obtained up to 10 mg/m³ of tar and a lower heating value of 3.97 MJ/m³. Another parameter influencing gas quality and tar content in the gasification process is the air flow rate. Galindo *et al.* [11] studied two-stage downdraft gasification at varying air flow rates. They obtained the lowest tar formation of 54 mg/m³ at 20 m³/h air flow rate.

Most of the technologies to further reduce the amount of tar in a downdraft gasifier involves multi-stage approach. However, single stage downdraft gasifier is the easiest to fabricate and operate compared to multistage gasifier. This makes it a more attractive technology for generating power in remote rural communities. In order to improve the gasification process, reduce tar content, and improve gas quality, a shaking grate mechanism was proposed in a single stage downdraft gasifier.

The developed gasifier was studied to evaluate the effect of using an automatic shaking grate in improving the quality of producer gas using biomass feedstock in a single stage downdraft gasifier. Shaking the grate in a gasifier is a common method employed to properly disperse the fuel inside the reactor from time to time in order to avoid feeding blockage and also to shake off ash in the process. But with the vertical motion of the grate during the operation, wider dispersion of heat throughout the fuel can be done by physically allowing more portion of the fuel to become exposed in high temperature at the combustion zone. This can lead to an increased area for combustion that will generate more heat for the pyrolysis zone. Volatile gases at the pyrolysis zone will then become exposed to high

temperature inside the gasifier for a longer time before it flows out of the gasifier. This method of installing a shaking grate in the gasifier aims to improve gas quality and reduce tar content for a single stage downdraft gasifier. The result is intended to become highly useful for the research and development of generating power in far, remote rural areas.

2. METHODOLOGY

2.1 Shaking Grate Gasifier

A single-stage downdraft gasifier with a shaking grate mechanism was installed at Kasetsart University – Kamphaeng Saen, Thailand. It is a new approach developed for single-stage gasification to improve its performance, gas quality and reduce the producer gas tar content without the need to employ multistage gasification process. The gasification system is consisting of four major parts: fuel hopper, reactor, ash pit, and shaking grate along with its other accessories. For insulation purposes, a refractory cement lining was installed inside the reactor to prevent thermal stress to the gasifier during operation at high temperatures. The grate separates the reactor from the ash pit cylinder which is then connected to a motor to control the shaking mechanism. The grate moves vertically allowing the solid fuel to come in contact with the gasifying agent supplied on the sides of the reactor. This increases the area of the combustion zone as greater volume of the feedstock are exposed to high temperature. The wider length of combustion zone also provides longer time for tar vapors produced at the pyrolysis zone to be cracked as it flows down the gasifier. Moreover, the wider combustion area provides generation of more heat for chemical reactions to take place, hence, improving the quality of gas.

2.2 Biomass Feedstock Properties

In order to fully utilize the energy potential of biomass residues, these are converted further into some other form of suitable fuel which has comparable high energy value. Similar to the study of Pangavhane and Tare [12], they made briquettes from grape stalk producing 5-6 MJ/Nm³ of producer gas. In this study, however, the feedstock used are mixes of different woody biomass. The proximate and ultimate analysis of the wood feedstock were evaluated to determine the higher heating value and the chemical composition of the feedstock, respectively. ASTM D7582 and D5865 standard methods were used for the proximate analysis while ASTM D5373 and D4239 for the ultimate analysis with the former for C, H, and N analysis and the latter for S determination. The results of the proximate analysis showed the %db volatile matter, %db fixed carbon, %moisture content, and %db ash were 79.47%, 18.86%, 21.85%, and 1.67%, respectively. The composition percentage from the ultimate analysis showed C=49.52%, H=6.59%, O=41.81%, N=0.34%, and S=0.07%. The bulk density was found to be 378 kg/m³.

2.3 Gas Qualities and Thermodynamic Analysis

The gas quality of the producer gas was evaluated in terms of the HHV, tar content, and total combustible gas. The HHV of the producer gas was calculated as follows:

$$HHV_{pg} = HHV_{CO} \times Y_{CO} + HHV_{H_2} \times Y_{H_2} + HHV_{CH_4} \times Y_{CH_4} \quad (1)$$

where Y is the percentage quantity of the components CO, H₂, and CH₄ in the producer gas and HHV is the heating value of each gas species as presented in Table 1.

Table 1. Higher and lower heating values of each species.

Gas Species	Higher heating value (MJ/Nm ³)	Lower heating value (MJ/Nm ³)
CO	13.1	13.1
CH ₄	41.2	37.1
H ₂	13.2	11.2

The tar content was evaluated using the formula:

$$Tar\ content = \left[\frac{m_{tar}}{v_{sampling\ gas}} \right]_{\Delta t} \quad (2)$$

where m_{tar} is the weight of tar in a certain time Δt and $v_{sampling\ gas}$ is the gas volume in a certain time Δt . Tar content was measured using the technique performed by Brand *et al.* [13]. About 1 m³ of tar sample was taken at the sample ports then cooled down to 15°C in a condenser whereas the condensate was trapped in a flask. It is then dried at room temperature and its weight was plotted against time. Tar content was determined until the sample weight shows no further significant changes.

Total percentage of combustible gas is the sum of the obtained percentage of the actual combustible gas in the producer gas which can be calculated using Equation 3.

$$\%Total\ combustible\ gas = Y_{CO} + Y_{H_2} + Y_{CH_4} \quad (3)$$

where Y is the percentage quantity of CO, H₂, and CH₄ of the producer gas.

To evaluate the performance of the gasifier, the thermal efficiency for energy production was measured; this is termed as cold gas efficiency (CGE). It is the ratio between the chemical energy of the producer gas to the chemical energy content of the feedstock. This can be reported in terms of higher heating value as seen in the equation below:

$$\%CGE = \frac{HHV_{pg} \times v_{pg}}{HHV_f \times m_f} \times 100 \quad (4)$$

where HHV_{pg} is the higher heating value of the producer gas (kJ/m³), HHV_f is the higher heating value of the

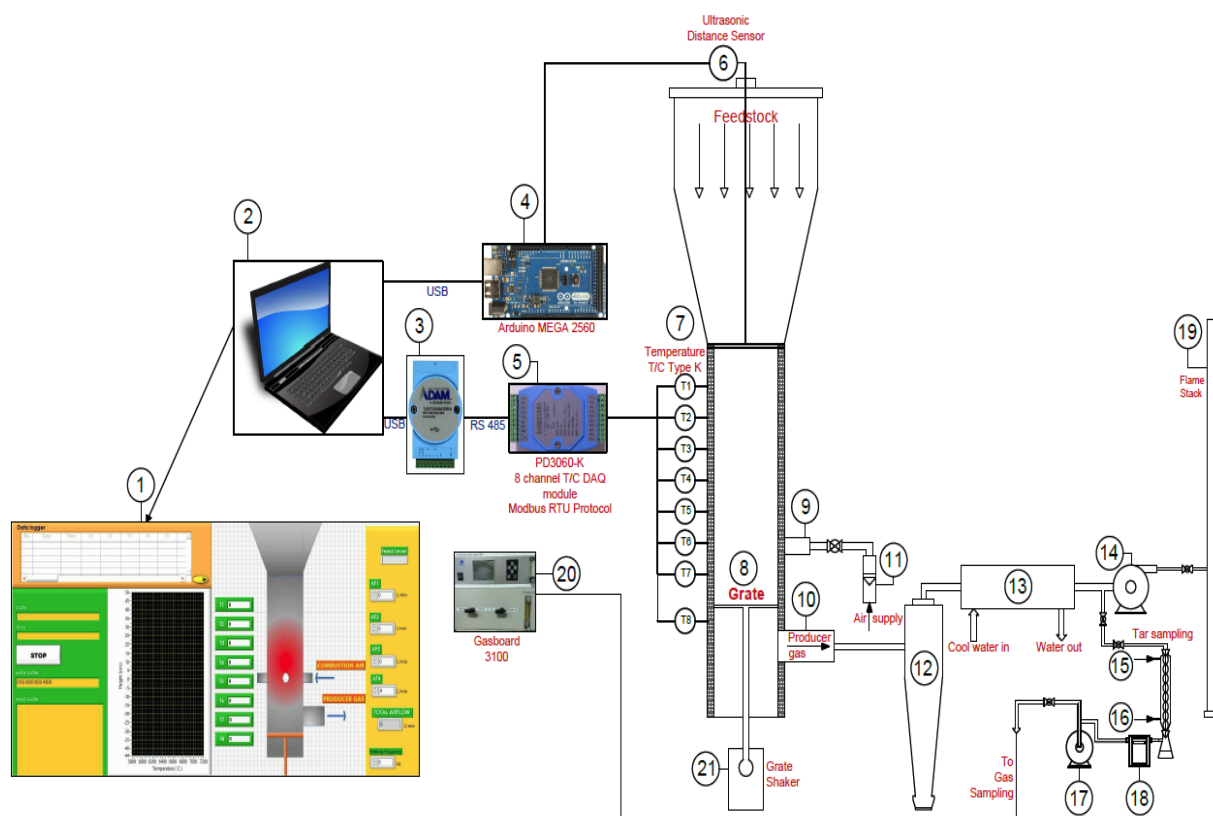
feedstock (kJ/kg), v_{pg} is the volumetric flow rate of the producer gas (m³/h), and m_f is the input mass flow rate of the biomass fuel (kg/h).

2.4 Experimental Equipment and Installation

The gasification system along with its accessories and measurement system is presented in Figure 1. The other accessories attached to the gasifier consists of cyclone, cooling tower, suction type blower, gas blow-off stack, pipes and pipe fittings, and valves. The instrumentation system installed to measure the different parameters of the gasifier consists of data acquisition (DAQ) devices, measuring instruments, communication devices, and computer. The measuring instruments are composed of a rotameter, temperature sensors (type K thermocouples), gas flow counter, ultrasonic distance sensor, and online gas analyser (Wuhan Cubic GASBOARD-3100).

The fabricated gasifier was designed with a 30.48 cm diameter and a height of 84 cm reactor that is cylindrical in shape and made of stainless steel. A conical shape fuel hopper located above the reactor is enclosed with a removable lid fitted with a gasket to prevent leakage during the operation. Four air nozzles sized 5.08 cm was positioned radially to the reactor located 20 cm from the grate while a 7.62 cm combustion hole just below the air nozzle was used to ignite the feedstock. The reactor was installed with Type-K thermocouples located at intervals of 10 cm from each other starting from the grate. Thermocouple 5 (T5), T6 and T7 are positioned approximately at the pyrolysis, combustion, and gasification zone, respectively, while T8 was installed at the producer gas exit just below the grate. The data gathered from the thermocouples are then connected to DAQ (PD3060-K Modbus RTU Protocol). Consumption rate of the gasifier was measured using an ultrasonic distance sensor connected to an Arduino board. Gasifier agent's flow rate was measured using a variable-area type flow meter (rotameter) which is manually controlled using ball valves. The percentages of the gas components of the producer gas was measured using the online gas analyser. As described by the method of Brandt *et al.* [13], the tar content of the sample gas was measured by sampling 1 m³ of gas to pass through the condenser.

Data gathered from the thermocouples and distance sensor were displayed and collected through a user interface made with LabView. Whereas the air flow rate was keyed manually and the gas composition was transmitted to the computer. The results were automatically recorded and stored as it is being transmitted to the computer which displays it in a graph and table. The method of finding the uncertainty of the measured parameters was done based from the work of Jaojaruek *et al.* [9]. Table 2 presents the accuracy of the instruments used as declared by manufacturer.



1	Interface	8	Shaking grate	15	Cooling water out
2	Computer	9	Combustion nozzle	16	Cooling water in
3	USB to RS-232/422/485 converter	10	Producer gas exit nozzle	17	Suction blower
4	Microcontroller	11	Rotameter	18	Gas flow counter
5	Thermocouple acquisition module	12	Cyclone	19	Flame stack
6	Ultrasonic distance sensor	13	Cooling tower	20	Gas flow analyser
7	Thermocouples	14	Suction blower	21	Shaking grate motor

Fig. 1. The schematic diagram of the whole experiment showing the experiment and instrument setup.

Table 2. The measuring instruments' accuracy based on the manufacturer's specifications.

Item	Parameter	Device	Range	Accuracy
1	Temperature	PD3060-K type thermocouple acquisition module 485 MODBUS RTU protocol	-100 to 1350°C	± 0.25°C
2	%CO	Wuhan Cubic GASBOARD-3100	0-50%	± 2% FS
	%CH ₄		0-15%	± 2% FS
	%CO ₂		0-50%	± 2% FS
	%H ₂		0-25%	± 2% FS
3	Feed Rate	Ultrasonic Sensor HC-SR04	2 cm to 400 cm	± 3 mm
4	Gas Flow	Displacement Type	0-250 Lpm	± 2% FS
5	Air Flow	LZM 50-G	0-600 m ³ /h	± 4%

2.5 Experimental Procedure

Two conditions were set for the experiment: 1) single stage gasification without the shaking mechanism (SS) and 2) single stage gasification with the shaking grate (SG) mechanism. For ease of reference, the conditions were written as SS and SG throughout the article. The gasifier was filled up to its full loaded feedstock capacity with charcoal preloaded 5 cm above the ignition port location. Suction blower is turned on to draw flames from the flame torch such that ember forms and combustion stabilizes. Once temperature stabilizes, tar content was measured through the tar sampling setup and gas analysis was done. Average readings from the

temperature measured was graphed to create a temperature profile. Air was the gasifying agent used in this study. The airflow was set as a control parameter varied at 130, 140, 150, and 160 Lpm for three trials each. The effects of varying air flow rate on the gas quality of the producer gas was analysed on both conditions for comparison.

3. RESULTS AND DISCUSSION

The aim of the study is to improve producer gas quality in terms of reducing tar content, and improving gas composition and efficiency as an effect of the shaking grate mechanism installed in a single stage downdraft

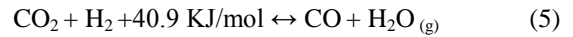
gasifier. The temperature profile, tar content, gas composition, HHV, and CGE were among the parameters determined for SS and SG gasification. Comparison of the results for the two conditions were discussed and presented in this section.

3.1 Effect on the Temperature Profile of SS and SG at Varying Air Flow Rates

The location of the thermocouples installed along the reactor height is presented in Figure 2A. The figure shows the comparison between the two conditions, SS and SG at 160 Lpm. Note the difference on the temperature change at every points of the reactor. Based on Figure 2A, the peak temperatures were found at the combustion nozzles wherein air is supplied. The temperature starts to increase at the zone 10 cm above the combustion nozzle and then reaches its peak at the combustion zone. It should be noted that pyrolysis zone is located just above the combustion zone. The temperature then gradually decreases at the zone below

the combustion nozzle towards the reactor’s producer gas exit nozzle. On the other hand, huge temperature difference was observed from the temperature profile of the two conditions at 10 cm (T5) height above the combustion nozzle wherein it increased from 318 to 623°C. With the SG condition, the maximum temperature achieved at the combustion zone (T6) was 825°C while SS condition only achieved a peak temperature of 778°C at 160 Litres per minute (Lpm).

According to Bocci *et al.* [14] high carbon conversion and low tar content occurs at temperatures above 800°C. On the other hand, water gas shift reaction (see equation 5) is favoured at temperature range of 750-900°C [15].



However, reaction rate decreases as temperature falls and at temperature lower than 700°C the water gas shift reaction proceeds much slower [3].

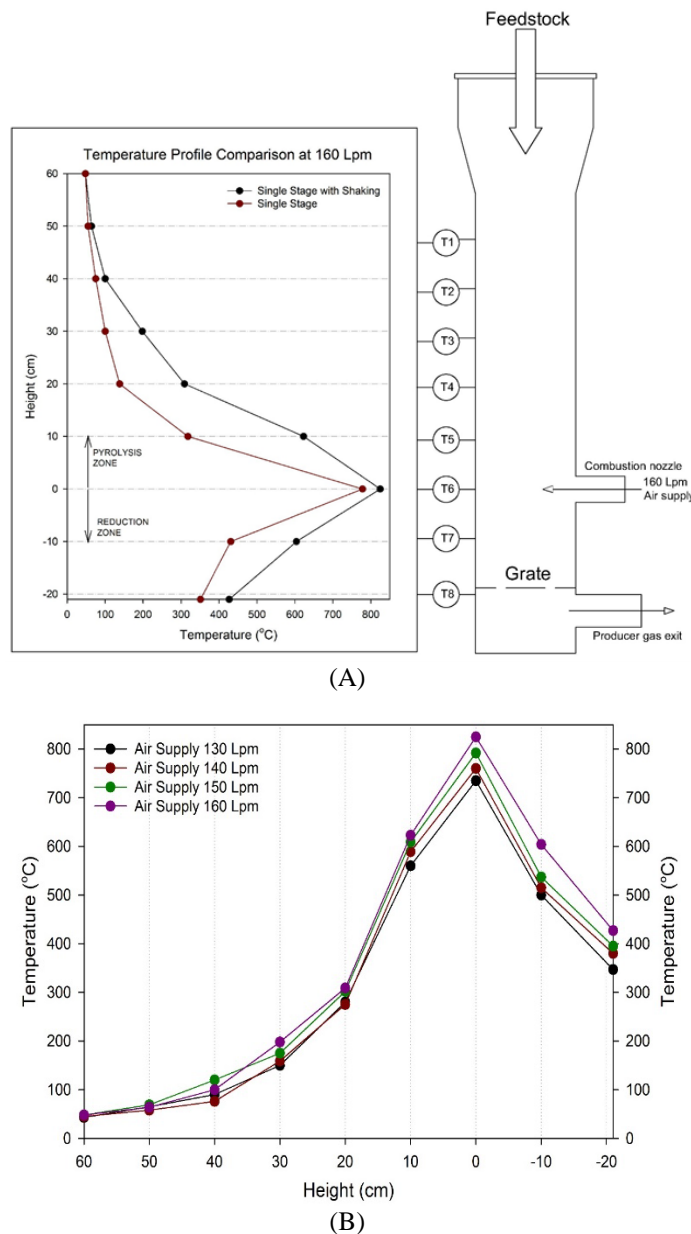


Fig. 2. A) Temperature profile comparison of SS and SG gasification at 160 Lpm air flow rate and B) temperature profile of SG gasification at different air flow rates.

Figure 2B shows the temperature profile at each nozzle for SG condition at different air flow rates. It can be noted that temperature increases as the air flow rate was increased. By supplying more air to the combustion zone, oxygen is increased therefore combustion reactions are hastened resulting to high combustion temperature, high devolatilization, and as an effect is higher feedstock consumption rate. When combustion temperature increases due to high feedstock consumption rate, there will be higher flow of generated volatile gas produced at the pyrolysis zone across the heat flow from the combustion zone. In effect, heat is quenched resulting to temperature profile moving closer to the combustion zone. This is also the reason for the temperature difference at the pyrolysis zone (T5) between SS and SG conditions in Figure 2A. The high temperature at T5 for SG will result to higher amount of volatile gases flowing through a wider temperature zone thereby producing more combustible gases in the process. SG condition further improves the reactions occurring inside the reactor since it can provide longer residence time for volatile gases to be exposed at high temperatures.

3.2 Effect on the Tar Content of the Producer Gas at Varying Air Flow Rates

Also seen from the temperature profile in Figure 2B for SG condition, the temperature starts to elevate 10 cm (T5) above the combustion nozzle ranging from 560 to 623°C and then reaching its peak range from 735 to 825°C at the combustion nozzle (T6) at different air flow rates. This wider temperature zone at longer time provides an effective condition for thermal tar cracking. This is evident based on Figure 3. The tar content significantly decreased to 395, 286, 259, and 245 mg/Nm³ for air supply rates 130, 140, 150, and 160 Lpm, respectively. Compared to the reduction in the tar content of the SS gasification which ranged from 950 to 1250 mg/Nm³. In a downdraft gasifier, the generated tar is allowed to pass through a zone of high temperature thus, it produces gas with relatively lower amount of tar as compared with another gasifier. But the tar can further be reduced as supported by the studies of Cummer and Brown [16] if it passes through a high temperature zone for longer duration. In line to this, the experiment has proven to adhere to the previous studies as the tar content was significantly reduced. The vertical motion during the SG gasification gave favorable conditions for thermal tar cracking by increasing the area of combustion zone thereby providing more time for volatile gases to travel to a zone of high temperature.

3.3 Comparison of the Gas Composition in the Producer Gas for SS and SG Conditions at Varying Air Flow Rates

The effect of varying air flow rate supply on the composition of the producer gas and the combustion temperature for the two conditions are presented in Figures 4A and 4B. There is noticeable improvement on the amount of CO, CO₂, CH₄, and H₂ in the producer gas of SG gasification compared to SS. The wider or higher

temperature zone which occurred during the gasification process due to the shaking grate greatly affected the composition of the gas. Comparing the amount of hydrogen and carbon monoxide for SS (Figure 4A) to SG (Figure 4B), SG was seen to have increased significantly of up to 37% and 20% respectively at higher combustion temperatures for 160 Lpm air flow rate. Whereas carbon dioxide and methane declined with increasing temperature. There was a noticeable 44% increase in the production of methane in SG condition when the two methods of gasification at 160 Lpm air flow rate were compared. Water gas shift reaction takes place at high temperatures which according to Jarungthammachote [15] occurs well at temperature range of 750-900°C. Hence, as seen in Figure 4B, the H₂ content increased significantly at these temperature range. Moreover, since the feedstock used have a high moisture content (approximately 20%), it favored the production of steam which can react with carbon to produce CO and H₂. High temperature is also favorable since it prevents the formation of CO₂ which occurs at a range of 500-600°C. The figure showed a drop in the production of CO₂ as temperature continuously increased. Moreover, since more heat was generated to induce endothermic reactions and produce more volatile gases, more methane was produced compared to the conventional gasifier but not to a very high extent as it gradually lowers with an increase in temperature.

3.4 The Effect on the High Heating Value (HHV), Combustible Gases, and CGE of the SS and SG Conditions at Varying Airflow Rates

The thermodynamic analysis of the gasifier process gives the heating value of the producer gas and process efficiency on the basis of varying equivalent ratio. Results (see Figure 5) showed that HHV decreased as it moves from 0.48 to 0.52 equivalence ratio (ER) for SS. Similar trend was noticed for SG gasification as the ER moves from 0.34 to 0.28. Optimum conventional gasification occurs at ~0.25 equivalence ratio [17]. In a study conducted by Wang [18] in a two-stage downdraft gasifier, an increase in ER from 0.16 to 0.27 has shown an increase in producer gas yield and its CO and H₂ composition, HHV, and cold gas efficiency. Another study for producer gas production, this time using fuel briquette from oil palm and tung tree showed optimum gasification at ER=0.385 and ER=0.372 with LHV of 3.20 and 3.23 MJ/Nm³, respectively [19]. In this study, the maximum HHV in SS setup (Figure 5A) is 4.0 MJ/Nm³ at ER=0.48 whereas SG setup (Figure 5B) achieved 5.70 MJ/Nm³ at ER=0.28. Note that the HHV increase denotes that more combustible gases are being produced by the gasification process but at lower ER. On the other hand, ER is the ratio of the actual air/fuel ratio to the stoichiometric. Hence, based from the results air supply can be reduced to almost 40% at good conditions in SG compared to SS. Similar to previous studies, the SG condition presents higher combustible gases percentage compared to SS since its ER is around the optimum conventional gasification range.

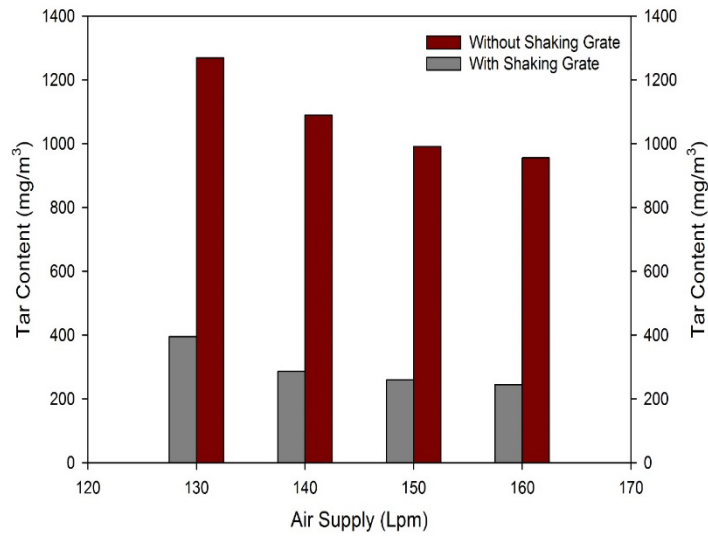


Fig. 3. Comparison of the tar content of the two conditions at different air supply rates (130, 140, 150, 160 Lpm).

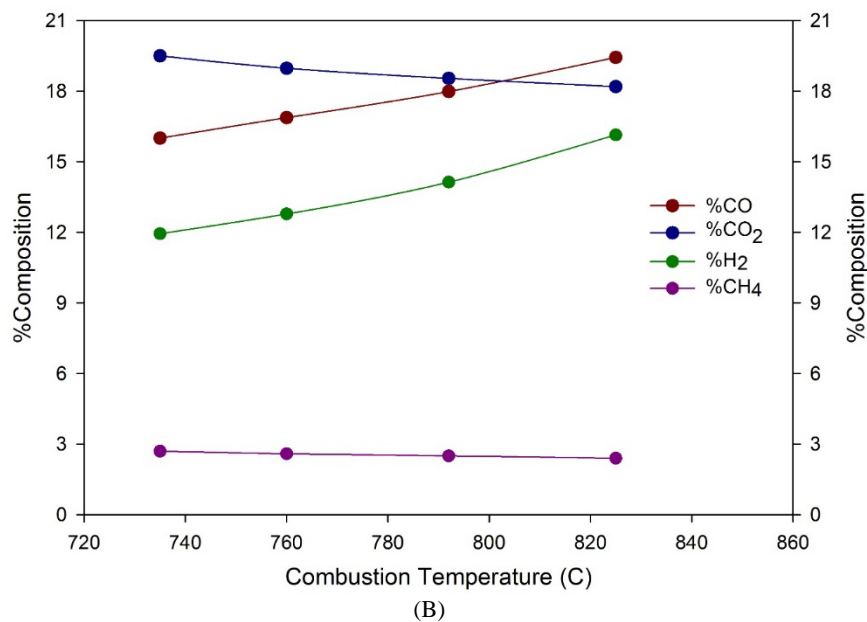
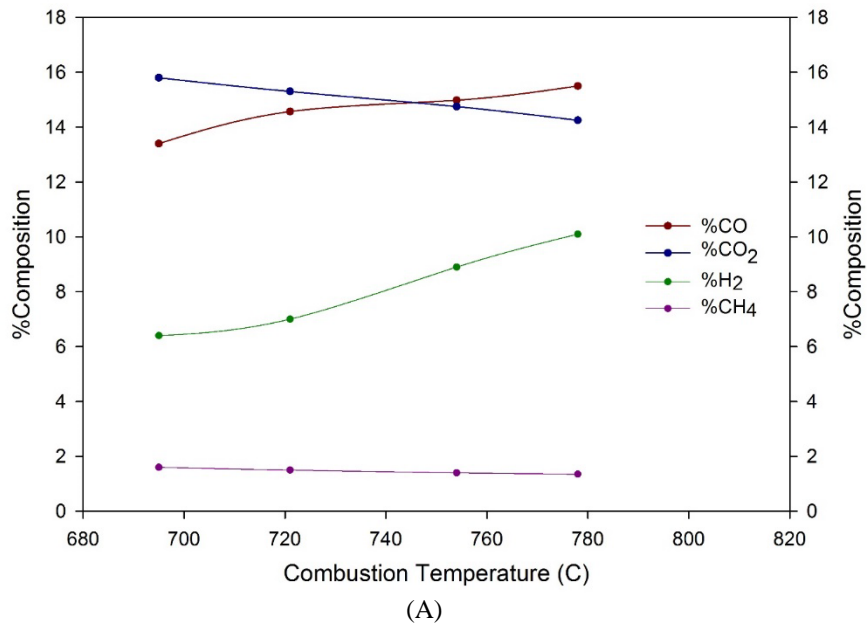


Fig. 4. Gas composition of the A) SS and B) SG conditions at combustion temperatures of 130, 140, 150, and 160 Lpm air flow rates.

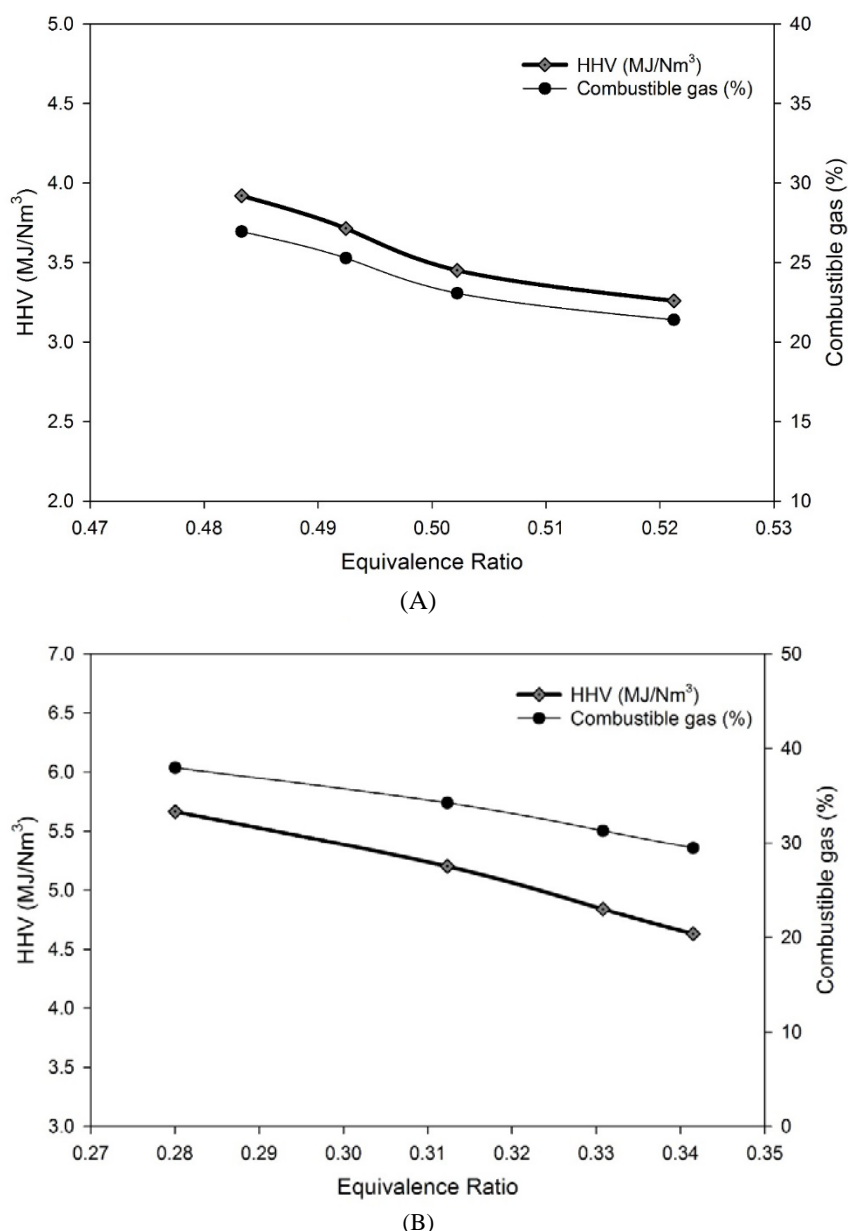


Fig. 5. HHV and total combustible gas comparison for A) SS and B) SG conditions at 130, 140, 150, and 160 Lpm air flow rates.

In comparison, the total combustible gases increased to about 29% when the gasifier with shaking grate was used. The single stage downdraft gasifier with shaking grate (SG) significantly improved the high heating value and total combustible gases compared to the conventional gasifier design.

As for the cold gas efficiency which refers to the potential energy of the fuel, it decreases with an increase in ER. Based on Figure 6, it essentially improved the potential energy of the fuel from 45% at ER=0.48 for SS condition to 62% at ER=0.28 for SG condition.

4. CONCLUSION

A single stage downdraft with shaking grate gasifier was developed to improve the gasification process and reduce the amount of tar in the producer gas. Results obtained reduction in tar content to about 0.245 g/Nm³, 27% combustible gas percentage increase and achieved

5.7 MJ/Nm³ HHV as compared to the conventional downdraft gasifier without the shaking grate at the highest air flow rate (160 Lpm) used in the experiment. Based from the results, the shaking grate mechanism indeed allowed more combustible gases to form when biomass feedstock exposure to higher temperatures was widen. The considerable amount of tar reduction between the two gasifiers has also shown the effectiveness of the developed gasifier to sufficiently lower the amount of tar for ICE applications. As shown from the parameters evaluated, the SG gasifier setup is successful in producing combustible gases with reduced tar content which can be used for application in remote rural gasification plant instead of multistage gasifier. This paves way to more researches concerning the installation of shaking grate mechanism to the gasification reactors for further improving the combustible gas yields.

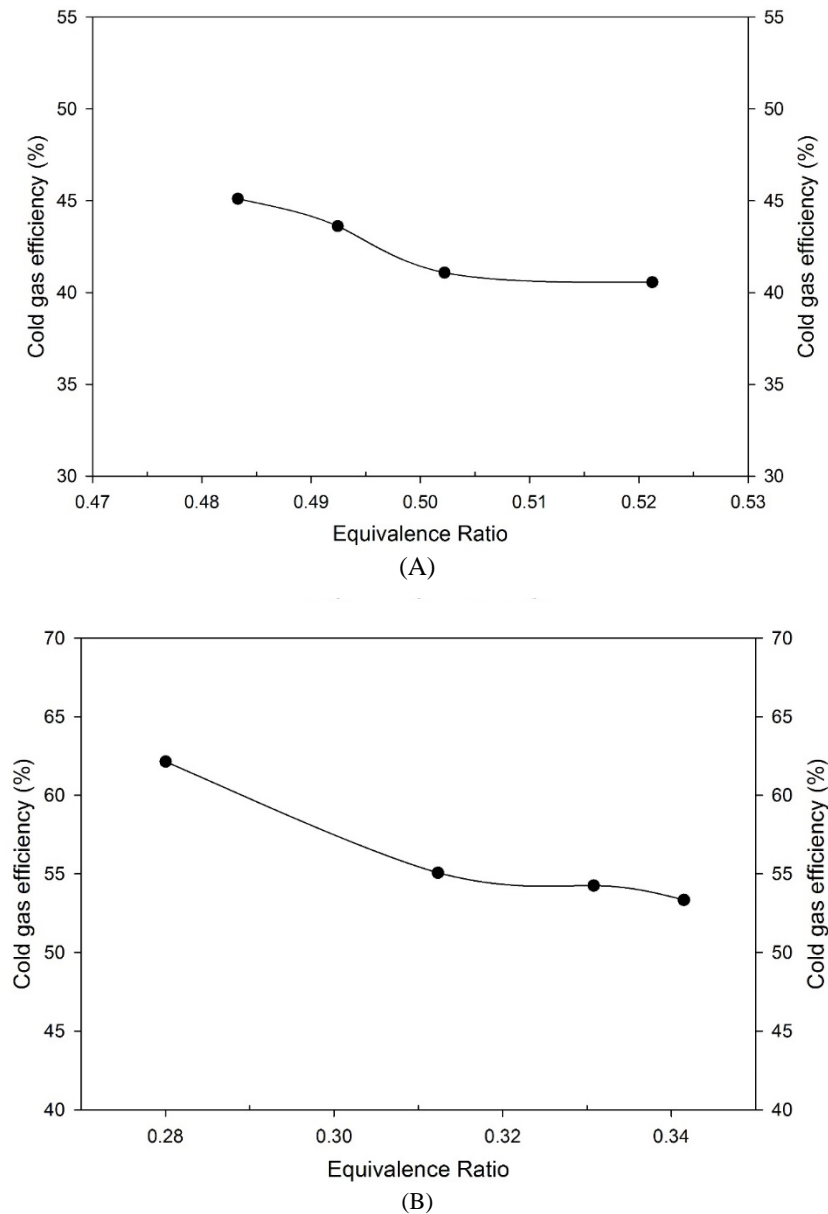


Fig. 6. Cold gas efficiency of A) SS and B) SG conditions at 130, 140, 150, and 160 Lpm air flow rates.

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NOMENCLATURE

CGE % = cold gas efficiency percentage
 db % = dry basis percentage
 ER = equivalent ratio
 FS = full scale
 C = carbon
 H = hydrogen
 O = oxygen
 N = nitrogen

S = sulfur
 LHV = lower heating value, MJ/Nm³
 HHV = higher heating value, MJ/Nm³; MJ/kg
 HHV_{CO} = carbon monoxide higher heating value, MJ/Nm³; MJ/kg
 HHV_{CO2} = carbon dioxide higher heating value, MJ/Nm³; MJ/kg
 HHV_f = fuel feedstock higher heating value, MJ/kg
 HHV_{H2} = hydrogen higher heating value, MJ/Nm³; MJ/kg
 HHV_{pg} = producer gas higher heating value, MJ/Nm³; MJ/kg
 m_f = input mass flow rate of the biomass fuel, kg/h
 m_{tar} = mass of tar, mg

SG	=	single stage downdraft gasifier with shaking grate
SS	=	single stage downdraft gasifier without shaking grate
$v_{\text{sampling gas}}$	=	volume of sampled gas, m ³
Y_{CO}	=	carbon monoxide percentage, % by vol
Y_{CO_2}	=	carbon dioxide percentage, % by vol
Y_{CH_4}	=	methane percentage, % by vol
Y_{H_2}	=	hydrogen percentage, % by vol

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