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A study on thermal efficiency of downdraft gasifier (swirl air type)

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Abstract

This paper presents the analysis of properties of bamboo node, as a potential fuel for gasifiers. Both Proximate and Ultimate Analysis are used. The physical properties of bamboo node contain 5.89% moisture, 70.48% volatile matter, 20.73% fixed carbon and 2.9% ash, while its chemical properties consist of H, C, N, O and S of 5.98, 44.76, 0.11, 46.21, and 0.04%, respectively. The higher and lower heating value of 17,417.09 kJ/kg and 16,161 kJ/kg are evaluated. The properties found indicate that the bamboo node has good potential for biomass fuel application. Besides the property analyses, the bamboo node, as a fuel for gasifiers, is tested in the proposed downdraft gasifier (swirl type), which was developed from the conventional downdraft gasifier. The proposed downdraft gasifier (swirl air type) has a cylindrical furnace, 1.35 m. in length. The combustion zone has two walls – the inner wall in a fireproof mortar and the outer layer consists of a steel sheet. It has a thermal capacity of 4.74 kW. The resulted producer gas from the proposed gasifier consists of CO, CH_4, H_2, CO_2, N_2 and O_2 of 30.0837, 0.2933, 25.1701, 17.0366, 23.955, and 3.4613% by volume, respectively, with thermal efficiency of 70.44%, which is 2.99% higher than that of the conventional downdraft gasifier, because the combustion zone of this downdraft gasifier (swirl air type) is designed by using air inlet circular flow as a nozzle-like injection.

Keywords: *biomass, biomass fuel, bamboo node, downdraft gasifier (swirl air type), producer gas, thermal efficiency*

1. Introduction

This past century, countries around the world have been dependent on energy produced from fossil fuels, e.g. oil, and natural gas, etc. A thorough global fossil fuel consumption and reserve was reported recently (Ritchie & Roser, 2020). Fossil fuel resources are depleting and the reserve estimation is complicated, since the forecast of energy consumption of each country is still a challenge (Sun, Zhang, Teng, Chen, & Fang, 2019). However, there is a trend that energy from fossil fuels will be substituted by renewable energy sources, which will be the major source of energy in the future (Black, 2018). Renewable energy resources, such as solar, biomass, bio-energy, wind, and hydro, etc., with appropriate technology development that can achieve higher efficiency will have potential for substituting fossil fuels in the future. Thailand is a country with abundant biomass resources. Technology for biomass energy production that is suitable with the type of biomass fuel should be developed, so that the efficiency in energy production from biomass will be improved, the production cost will be decreased, and biomass will have high potential for fossil fuel substitution for Thailand in the near future.

Thailand is an agricultural country with abundant and variety biomass resources, for example, rice mill, rice husk, woodchip, bagasse, agricultural waste and fast growing plants. The fast growing plant can be used as biomass fuel and can be planted and grow up in a few years. In other words, it can serve as a replenishing resource. Bamboo is very well-known as one of the fastest growing plants, of which all parts can be used for many purposes. “Better yet, bamboo continuously grows after harvest without having to replant it” (Bamboo Imports Europe, 2019). Different species of bamboo can be found all over the regions in Thailand. The importance of bamboo as biomass resources had been overlooked until 2000 (Scurlock, Dayton, & Hames, 2000). However there has been insufficient research done in this field since then. Therefore, the bamboo’s properties and its potential for biomass fuel application should be studied, including the analysis and development of appropriate technology to achieve higher efficiency in energy harnessing from such fuel.

2. Objectives

The paper aims to analyze the physical and chemical properties of the bamboo node of *Dendrocalamus sericeus* (Sang mon bamboo) bamboo for biomass fuel application. The downdraft gasifier (swirl air type), which was designed and developed from the conventional downdraft gasifier, is proposed to achieve higher thermal efficiency. The gas components of producer gas from the experiment using bamboo solid-node as a biomass fuel for the proposed gasifier are analyzed and thermal efficiency is evaluated.

3. Literature review

3.1 Biomass fuels

Bamboo is a fast growing plant, with a tall and slender trunk, but exceptional strength. Although it has the ratio of height to trunk diameter of 150-250 to 1, bamboo can be used in the construction and served as the support element for heavy loads. This characteristic is quite unique from the other fast growing plants. There are about 75 genera of bamboo, with approximately 1300 species and varieties covering 25 million hectares worldwide (Benton, 2015). Bamboo is a versatile plant that has multiple uses, including food, furniture, medicine and fuel. It is also one of the world's oldest construction materials and has been used for shelter for thousands of years (Cabanas, 2018). *Dendrocalamus sericeus* (Sang mon bamboo), one of the 80-100 species of bamboo found in Thailand (Thongpool, 2009), is commonly found in the northern part of Thailand. *Dendrocalamus sericeus* has tall straight trunks with the height of 15-20 m, 6-10 cm diameter and 30-40 cm intermodal spacing. As shown in Figure 1, the trunk is pensive green – the young one has white flour on the joint, while the mature one has a darker pensive green color. The wood is thick, strong and durable. Its leaves are similar to those of the *Dendrocalamus asper* (Rough giant bamboo). The 4-year-old mature bamboo wood is durable to snout beetles and insects, and therefore is widely used in construction, furniture-making and making chopsticks. Its bamboo shoot has a good taste and has been a famous ingredient in many Thai dishes (Talabgaew & Laemlaksakul, 2007).

Figure 1 *Dendrocalamus sericeus* (Sang-mon bamboo) (Klangjai, 2020)

The configuration of the bamboo grown above the ground from the bamboo shoot is shown in Figure 2. It consists of 2 major parts – node and internode. In most bamboo, the internode is hollow. The internode is longer when observed from the root-end up to the mid-length of the bamboo and shorter up to the top. The so-called "bamboo" in the following content of this paper will stand for the *Dendrocalamus sericeus species*. The part of the bamboo in this study will be limited to the node which is consists of the waste from manufacturing chopsticks.

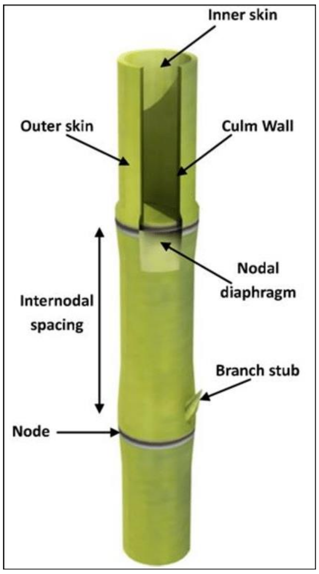

Figure 2 Bamboo culm anatomy (Cabanas,2018)

The amount of biomass resources available in Thailand is abundant. Each type is different in physical and chemical properties. These properties affect the composition and heat value of producer gas that is produced from each type of fuel (Wattana, Janpong, & Supichayanggoon, 2018). In general, biomass fuel contains 3 compositions - moisture, volatile matter and fixed carbon, and ash, as illustrated in Figure 3. The proportions of these 3 compositions are different for different types of biomass fuel as listed in Table 1.

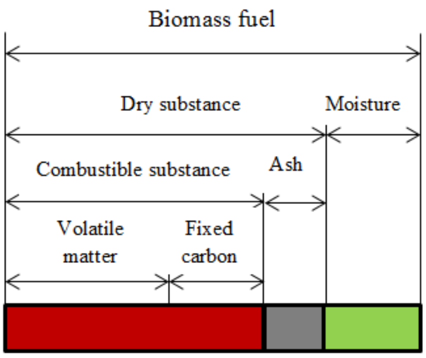

Figure 3 The composition of biomass fuel

Good biomass fuel should have low moisture, since moisture content will have direct impact to thermal efficiency. Higher moisture in biomass fuel will cause more heat loss in evaporation during the combustion process, resulting in lower calorific value of the fuel. Typically, the moisture in biomass fuel should not exceed 15 percent. The higher component of combustible substances, which includes volatile matter and fixed carbon, and the lower proportion of ash will result in higher calorific value of the fuel (Wattana, 1998). From Table 1, comparing the characteristics of bamboo and other biomass fuels, it can be observed that bamboo has high volatile matter and fixed carbon component of 77.86% and 22.03%, respectively. Together with its moisture of 5.89% and 3.08% ash, with moderate calorific value of 17,166 kJ/kg, this indicates that bamboo has good potential to serve as biomass fuel for gasifiers.

Table 1 Proximate analysis and calorific valve data of some biomass fuels*

Biomass fuel	Moisture, %	Fixed Carbon, %	Volatile Matter, %	Ash, %	Calorific value, kJ/kg
Coconut shell	4.23	18.22	76.00	1.43	20,188
Palm shell	13.00	21.05	64.55	1.30	21,235
Eucalyptus	1.14	17.90	79.70	2.64	18,392
Leucaena	0.63	16.59	81.00	1.78	18,778
Para rubber	2.36	14.78	81.00	1.83	18,736
Corncob	10.60	5.54	80.80	3.09	22,472
Bagasse	13.38	19.26	64.73	2.61	16,630
Bamboo	5.89	22.03	74.86	3.08	17,166
Wood chip	8.28	12.82	73.12	5.81	22,386

*(Jareansuk & Patarakeadvit, 2015; Homduang, Dudsade, & Sasujit, 2015;Jitjak & Jaidee, 2012; Saegsook, 2016)

3.2 Gasifier types (Kathi, 2016)

In a gasifier, fuel interacts with air or oxygen. So the gasifiers are classified as per the way air or oxygen is introduced in it. On a bigger scale there are the following four gasifier types which are updraft gasifier, downdraft gasifier, cross-draft gasifier and fluidized bed gasifier that are shown in Figure 4.

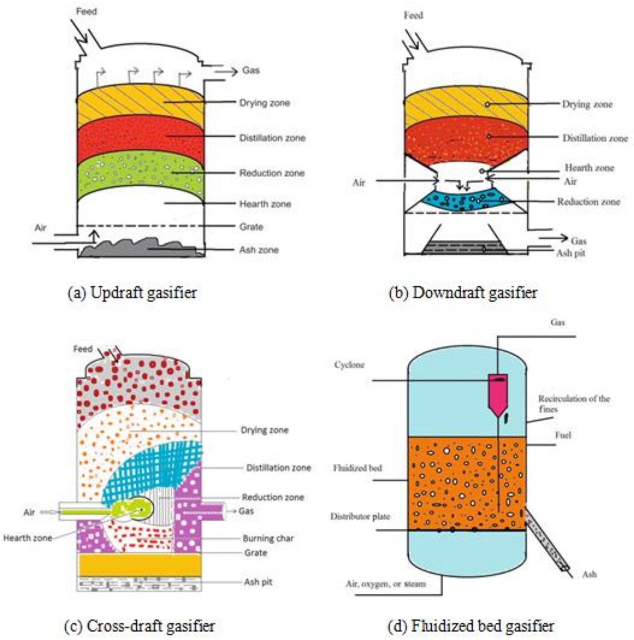

Figure 4 Gasifier furnaces types (Kathi, 2016)

3.3 Biomass gasification process

Biomass gasification involves burning of biomass in a limited supply of air to give a combustible gas (called Producer gas) consisting of carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen, along with contaminants like small char particles, ash and tars. The gas is cleaned to make it suitable for use in boilers, engines and turbines to produce heat and power. Gasification is quite a complex thermochemical process. Splitting of the gasifiers into strictly separate zones is not realistic, but nevertheless conceptually essential. Gasification stages occurs at the same time in different parts of gasifier, as shown in the Figure 5.

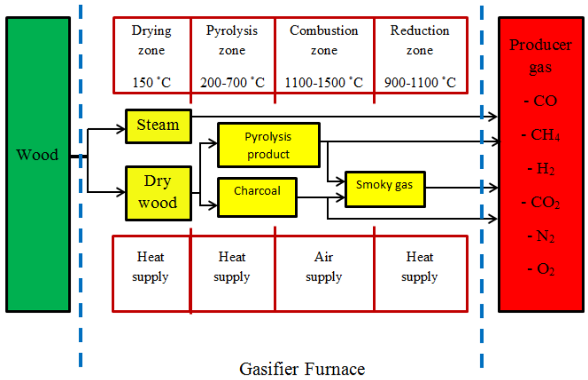

Figure 5 Conversion of biomass into producer gas (Kathi, 2016)

A downdraft gasifier is a co-current reactor where air enters the gasifier at a certain height below the top. The product gas flows downward and leaves through a bed of hot ash. Since it passes through the high-temperature zone of hot ash, the tar in the product gas finds favorable conditions for cracking. For this reason, a downdraft gasifier, of all types, has the lowest tar production rate (Basu, 2010). The operating principle of this gasifier, as shown in Figures 5 and 6, found that the biomass is fed from the top, and are first introduced into the drying zone, followed by the pyrolysis, oxidation, and reduction zones, and finally the product gas is drawn out from the bottom, through the reduction zone. In this system, the gas is quite clean from the downdraft gasifier, and it is suitable for internal combustion engines and turbines for electricity generation (Quader & Ahmed, 2017)

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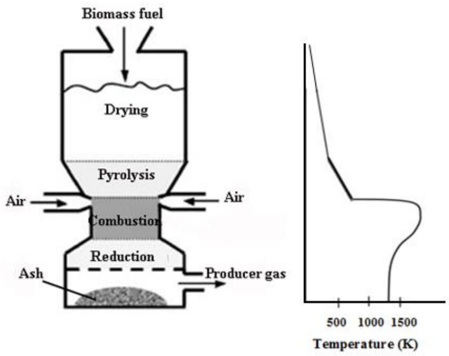

Figure 6 Schematic of the operation of a downdraft gasifier and temperature gradient along the height shown at the right (Basu, 2010).

3.3.1 Combustion zone (Ingle & Lakade, 2015)

In the combustion zone, the oxygen in the air-stream reacts with the carbon and hydrogen in the fuel to reduce carbon and hydrogen to form carbon dioxide and water. Carbon dioxide is obtained from carbon and water is obtained from the hydrogen in the biomass fuel. Also, exothermic reaction takes place here and the temperatures are normally 1100-1500˚C. The main reactions are:

$$C + O_2 \rightarrow CO_2 + \text{Heat} \qquad (1)$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat} \qquad (2)$$

3.3.2 Reduction zone (Ingle & Lakade, 2015)

The partial combustion products, carbon dioxide (CO_2) and water (H_2O) that are obtained from the combustion zone are now passed through the reduction zone. Here, CO_2 and H_2O are reduced to form carbon monoxide (CO) and hydrogen (H_2) by absorbing heat from the combustion zone. The combustion zone raises the temperature of the reduction zone to promote the carbon/steam gasification reaction which has higher activation energy. This reaction requires temperature of 900 ˚C or above. Over 90% of CO_2 is reduced to CO at temperatures above 900 ˚C. The main reactions are:

Boudouard Reaction:

$$C + CO_2 \rightarrow 2CO - \text{Heat} \quad (3)$$

Water Gas Reaction:

$$C + H_2O \rightarrow CO + H_2 - \text{Heat} \quad (4)$$

Water Gas Reaction:

$$C + 2H_2O \rightarrow CO_2 + 2H_2 - \text{Heat} \quad (5)$$

Water Shift Reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 + \text{Heat} \quad (6)$$

Methanation Reaction:

$$C + 2H_2 \rightarrow CH_4 + \text{Heat} \quad (7)$$

3.3.3 Pyrolysis zone (Wattana et al., 2018)

Biomass pyrolysis is an intricate process. Products depend on temperature, pressure and heat losses. Up to 200˚C, only water is driven off. In range 200-280 ˚C, CO_2, acetic acid, and water are given off. In the range 280-500 ˚C, real pyrolysis occurs and produces large quantities of tar and gases containing CO_2. In the range of 500-700 ˚C, gas production is small and contains hydrogen. The main reactions are:

Dry biomass + Heat → Charcoal + CO + Co_2 + CO_2 + H_2O + CH_4 + C_2H_6 + Pyroligneo Acid + Tar (8)

3.3.4 Drying zone (Wattana et al., 2018)

Biomass is being dried in the drying zone. Usually the moisture content of biomass is 10-30% Some organic acids come out during drying process which may cause corrosion of gasifiers and the temperature is normally 150˚C. The main reactions are:

Biomass + Heat → Dry biomass + steam (9)

3.4 Heat energy of producer gas

For higher heating value (HHV) and lower heating value (LHV) of producer gas can be found in equations (10) and (11), which are in kJ/m^3 units (Kowkasikum, 1994).

$$LHV = HHV - 2016(H_2) + 2(CH_4) + \cdots + (n/2)(C_mH_n) \quad (10)$$

$$HHV = 12684(CO) + 12810(H_2) + 39984(CH_4) + 70770(C_2H_6) + 64218(C_2H_4) + 101472(C_2H_8) + 133518(C_2H_{10}) \quad (11)$$

3.5 Gasifier efficiency (Jafari, Wingren, Hellström, & Gebart, 2020)

Gasification efficiency is calculated using formula, that is,

$$\eta_F = \left[\frac{\dot{v}_g(LHV_g)}{\dot{m}_s(LHV_s)+\dot{W}_e}\right] x100 \quad (12)$$

where

η_F = gasification efficiency, (%)

$\dot{v}_g$ = volume flow rate of producer gas, (m³/s)

$\dot{m}_s$ = gasifier solid fuel consumption, (kg/s)

LHV_g = lower heating value of the producer gas, (kJ/m³)

LHV_s = lower heating value of gasifier solid fuel, (kJ/kg)

$\dot{W}_e$ = electrical energy consumption, (kJ/s)

3.6 Gasifier capacity

The capacity of the gasifier furnace or the energy produced can be obtained from (Suntivarakorn & Khosasaeng, 2016):

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$$Q_c = \frac{\dot{m}_S LHV_S \eta_F}{3600} \quad (13)$$

where

Q_c = gasifier capacity, (kW)

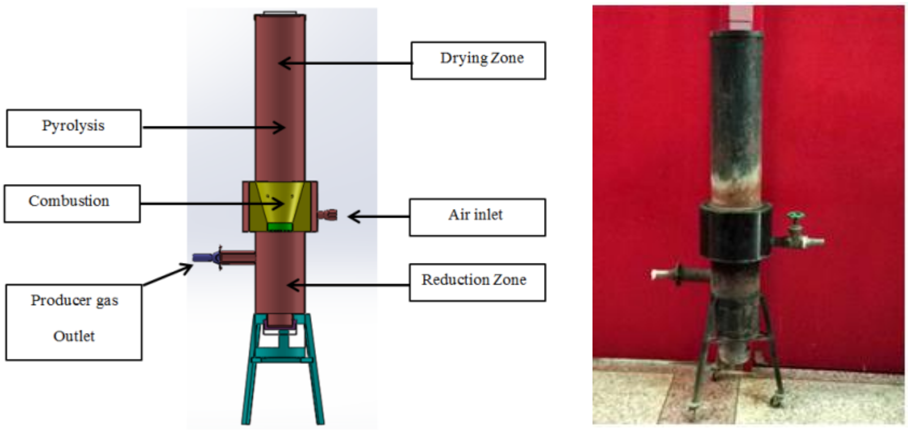
4. Methodology

In order to study the bamboo node as a biomass fuel for gasifiers, the downdraft gasifier (swirl air type) is designed and built aiming for improving the thermal efficiency of the conventional downdraft gasifier (Narongthong & Sottigulanun, 2013). Bamboo solid-node is used as fuel for the gasifier in this experiment. The producer gas is analyzed and thermal efficiency is evaluated.

4.1 Design and build a downdraft gasifier (swirl air type)

The design of the downdraft gasifier (swirl air type) was developed from the conventional downdraft gasifier (Narongthong & Sottigulanun, 2013), in which the air is compressed and injected directly to its furnace. The proposed swirl air type allows the compressed air to circulate in the furnace, in the outer part of the combustion zone before entering into the combustion zone through a nozzle-like injection holes. The furnace is cylindrical, 1.35 m in length, at the combustion zone, there are two walls, the inner wall is fireproof mortar, and the outer layer is sheet steel.

A schematic view from cross section of the main furnace along with the different zones during the gasification is shown in Figure 7 (a) and the complete set of the downdraft gasifier (swirl air type) furnace for producing gas, are shown in Figure 7 (b). The dimension of the downdraft gasifier (swirl air type) furnace is shown in Figure 8. The furnace has a cylindrical shape of 1.255 m in length, the external diameter of 0.304 m., the internal diameter of 0.204 m. and air inlet diameter is 0.0421 m. The outlet diameter of producer gas is about 0.0548 m.



(a) (b)

Figure 7 The downdraft gasifier (swirl air type) furnace: (a) A schematic view; (b) The complete set

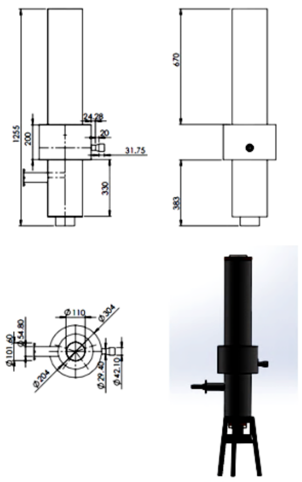


Figure 8 Dimensional drawing of downdraft gasifier (swirl air type), units in mm., designed by Arpakorn Wattana & Pipatpong Watanawanyoo for the current study.

4.2 Bamboo node fuel analysis

The bamboo fuel used in the experiment has a scientific name of "Dendrocalamus sericeus". The size of biomass fuel for gasifiers should be small, and all pieces should be about the same size, but should not be too small and too dense when placed together in the gasifier, which may lead to internal pressure loss inside the furnace. The appropriate woodchip fuel size should range between 10-100 mm, (Wattana, 1998). The average size of bamboo solid-node in this study is 10x20x40 mm. The bamboo solid-node was randomly tested, to analyze both physical and chemical properties, in accordance to ASTM standards - ASTM E 870, D 4239, D 5373 and D 5865.

4.3 Downdraft gasifier (swirl air type) furnace testing

The downdraft gasifier (swirl air type) furnace using bamboo solid-node as fuel is tested. During the test, the following values rates and values are measured:

- electricity consumption rate of the blower used for air compression into the furnace;
- bamboo node fuel consumption rate;
- temperature in drying, pyrolysis, combustion, and reduction zone; and
- mass flow rate of producer gas.

In addition, the sample of producer gas produced are collected and analyzed to evaluate the gas components and the heating value.

5. Results and discussion

5.1 Properties of bamboo node

The property test and analysis results of bamboo node fuel complied with ASTM standards: ASTM E 870, D 4239, D 5373 and D 5865 is shown in Table 2.

Table 2 The properties of bamboo node

Properties	%
Moisture	5.89
Volatile Matter	70.48
Fixed Carbon	20.73
Ash	2.90
H	5.98
C	44.76
N	0.11
O	46.21
S	0.04
HHV, kJ/kg	17,417.09
LHV, kJ/kg	16,161.05

The properties of the bamboo node found from the test showed that it has 5.89% of moisture, considerably a good figure, less than the recommended maximum value of 25% (Basu, 2010). The component of Fixed Carbon and Volatile matter are 20.73% and 70.48%, which are quite high figures compared to the figures of other biomass fuel types in Table 1. The higher the amount of Carbon (C) in the bamboo node will yield more heat per the fuel weight during the combustion process. The 44.76% of Carbon content in the bamboo node indicates its good potential for being efficient fuel for gasifiers.

5.2 Simulation of the air flow characteristics within the furnace

The air flow within the furnace was simulated by Computational Fluid Dynamics (CFD) package using Numerical Method Algorithm. The pattern of the airflow is presented in Figure 9. It can be observed that the injected air in the furnace is circulating in the outer chamber of the combustion zone before entering into the combustion zone of the furnace through the five injecting holes. Within the combustion zone, it is shaped like a cone (throat area design).

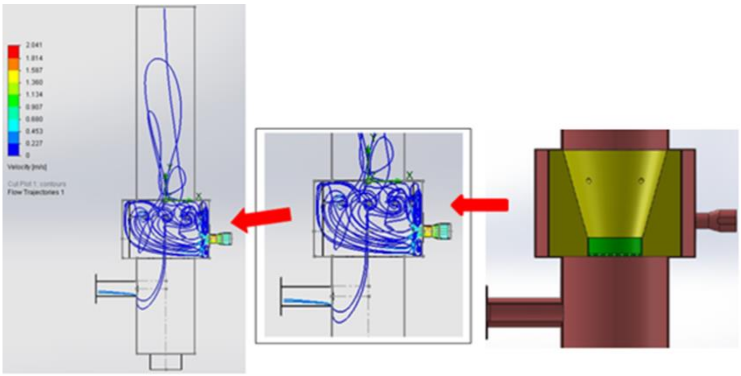


Figure 9 Air flow pattern in the furnace (Designed by Arpakorn Wattana & Pipatpong Watanawanyoo for the current study)

5.3 Experimental results

The downdraft gasifier (swirl air type) was built and bamboo node was used as fuel. The combustion in the furnace was tested. The combination of yellow and blue flames from the combustion of producer gas was observed, as illustrated in Figure 10. The combustion had no smoke, implying the complete combustion. Sample of producer gas was then taken for laboratory analysis. The results are presented in Table 4 and Figure 12. The measured temperatures in different zones in the furnace are shown in Table 3 and Figure 11.

Figure 10 Flame caused by producer gas combustion

Table 3 Temperature of the furnace areas

Gasifier furnace types	Drying zone (˚C)	Pyrolysis zone (˚C)	Combustion zone (˚C)	Reduction zone (˚C)
Downdraft gasifier (mean temperature of theory)	150	450	1300	900
Downdraft gasifier (swirl air type)	135.2	464.1	1150.5	753.9
Downdraft gasifier*	190	570	1011	645

*conventional downdraft gasifier (Narongthong & Sottigulanun, 2013)

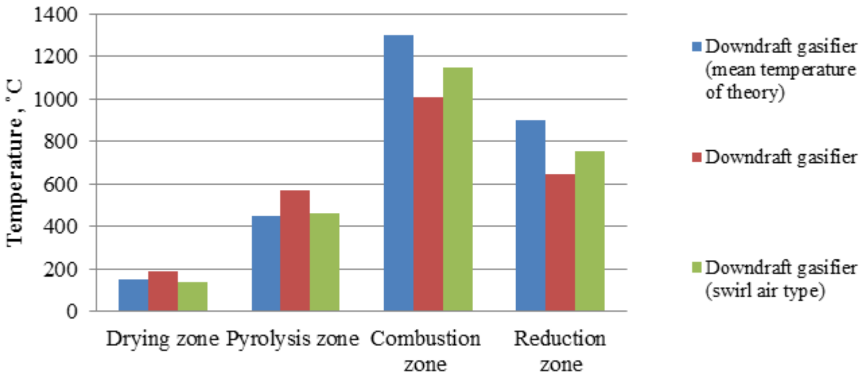


Figure 11 Temperature of the furnace areas

Comparing the temperatures among the three gasifiers - downdraft gasifier (theory), downdraft gasifier (swirl air type) and conventional downdraft gasifier, measured in 4 zones of the furnace, it was found that the values were not significantly different - 150, 135.2, and 190 ˚C, respectively, in the drying zone; 450, 464.1, and 570 ˚C, respectively, in pyrolysis zone; 1300, 1150.5, and 1011 ˚C, respectively, in combustion zone; and 900, 753.9, and 645 ˚C, respectively, at reduction zone. The temperatures measured of the proposed swirl air type mostly lie in between the theoretical value and the conventional design, except in the drying zone, with lowest temperature. The temperatures recorded have direct effect on the components of producer gas from the gasifier (average of 6 samples), which is presented in Table 4 and Figure 12.

Table 4 The producer gas from gasifier furnaces

Gasifier furnace types	**Average producer gas (% by volume)**					
	CO	**CH_4**	**H_2**	**CO_2**	**N_2**	**O_2**
Downdraft gasifier (swirl air type)	30.0837	0.2933	25.1701	17.0366	23.955	3.4613
Downdraft gasifier*	19.8356	6.6320	10.5273	25.4870	35.1951	2.3230

*conventional downdraft gasifier (Narongthong & Sottigulanun, 2013)

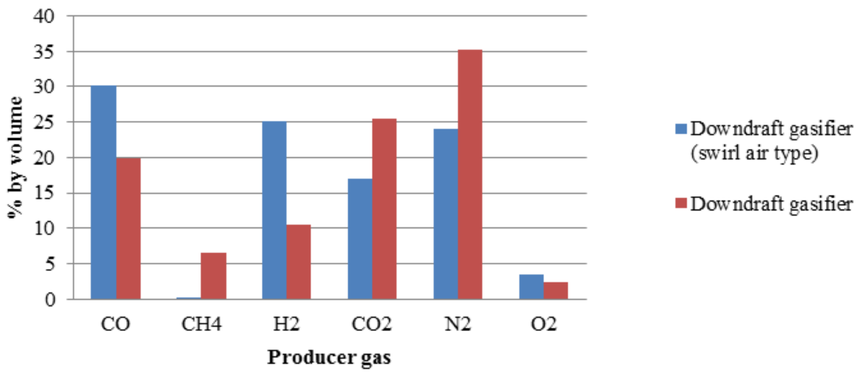


Figure 12 The producer gas from gasifier furnaces

The producer gas from the two gasifiers, presented in Table 4, has the component of carbon monoxide (CO), methane (CH_4), hydrogen (H_2), carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2). Considering only the combustible gas components, CO, CH_4 and H_2, 19.8356% CO, 6.6320% CH_4 and 10.5273% H_2 by volume was obtained from the conventional downdraft gasifier, while 30.0837% CO, 0.2933% CH_4 and 25.1701% H_2 by volume was acquired from the swirl air type downdraft gasifier. The higher producer gas gained from the swirl air type is resulted from its better gasification process. The air entering the furnace was circulated inside the furnace before it was injected into the combustion zone, resulting in better air distribution to biomass fuel during the combustion process. In other words, the contact of air and the fuel was distributed more uniformly in the swirl air type downdraft gasifier. High percentage of carbon monoxide from producer gas was found in the experiment. As temperature in the combustion zone increased until stabilized at 753.9 °C, which is higher than the capability of conventional gasifier, rapid increasing in carbon monoxide and hydrogen was observed. Methane was found to increase slowly as the temperature increased. The thermodynamic changes during the gasification process are due to the chemical reaction obtained within the gasifier. It is clearly compared in Figure 12 that the volume of such three combustible components of producer gas obtained from the swirl air type are more than those produced by the conventional downdraft gasifier, leading to higher heating value gained from the proposed gasifier technology as shown in Table5.

Table 5 Heating value of biomass fuels and producer gas

Gasifier furnace type	Electric power for blower (kW)	Mass flow rate of bamboo solid-node (kg/h)	Volume flow rate of producer gas (m^3/s)	Bamboo solid node		Producer gas	
				LHV (kJ/kg)	HHV (kJ/kg)	LHV (kJ/m^3)	HHV (kJ/m^3)
Downdraft gasifier (swirl air type)	0.25	1.5	0.00074	16161.05	17417.09	6648.16	7155.58
Downdraft gasifier*	0.25	2.5	0.00118	16161.05	17417.09	6304.99	6517.14

* conventional downdraft gasifier (Narongthong & Sottigulanun, 2013)

The downdraft gasifier (swirl air type) has the capacity of 4.74 kW. Applying equation (12) to the results in Table 5, the thermal efficiency of gasifier furnaces can be calculated. The estimated thermal efficiency of the downdraft gasifier (swirl air type) is 70.44% and of the conventional downdraft gasifier is 67.45%. The higher thermal efficiency gained from the swirl air type is resulted from its better gasification process. The improved gasification process of the swirl air type downdraft gasifier is capable of producing the combustible component (CO, H_2 and CH_4) of 55.54% by volume, comparing to 36.99% from the conventional downdraft gasifier and also yield higher heating value of producer gas.

6. Conclusion

The bamboo node of *Dendrocalamus sericeus* (Sang mon bamboo) was proven to be a potential good biomass fuel for gasifiers. According to the proximate analysis, the fuel contained 20.73% Fixed carbon and 70.48% Volatile matter. The ultimate analysis also showed that the bamboo node has 44.76% of C and 5.98% of H, which are the relevant elements in the combustion process. C and H composition found in the bamboo node is quite high in quantity when compared with other types of biomass fuel. Tested in this study, the bamboo node also has high heating values – HHV of 17,417.09 kJ/kg and LHV of 16,161.05 kJ/kg. In the experiment, the bamboo node was used as fuel to test the proposed downdraft gasifier (swirl air type), which was developed from the conventional downdraft gasifier. The gas obtained consists of CO, CH_4, H_2, CO_2, N_2, and O_2 of 30.0837, 0.2933, 25.1701, 17.0366, 23.955 and 3.4613% by volume, respectively. The proposed technology can achieve 2.99% higher thermal efficiency, i.e. 70.44% compared with 67.45% of the conventional downdraft gasifier.

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