Experimental Investigation on Rice Straw Gasification in a Cyclone Gasifier

Worapot Ngamchompoo *

A cyclone gasifier is an effective technology for the gasification of low-density biomass containing a high ash content. The ash removal performance was improved in the gasifier due to being similar to a cyclone dust collector. The cyclone reactor is relatively simple, easy to use, and has low construction costs compared with a traditional fluidized bed gasifier. In this study, the air gasification characteristics of rice straw were investigated in a cyclone gasifier. The results showed that by increasing the equivalence ratio (ER), the gasifier temperature also increased. This, in turn, led to a higher gas quality (higher heating value (HHV) and lower tar content) and enhanced the gasification performance (gas yield, carbon conversion efficiency, cold gas efficiency, and hot gas efficiency). A high ER reduced the amount of the combustible gas component (CO and H_2) and caused the HHV of the producer gas to decrease. The optimum value range of ER was observed to be about 0.29 to 0.34. A smaller feedstock size was more favorable for higher producer gas quality and gasification performance. Biomass moisture content parameters played an important role in the cyclone gasification process. Higher moisture content decreased the gasifier temperature, leading to low gas quality (lower HHV and higher tar content), and resulted in lower gasification performance.

Keywords: Rice Straw; Cyclone Gasifier; Producer Gas; Gasification Process

Contact information: Department of Management Engineering, Faculty of Engineering, Rajabhat Mahasarakham University, Mahasarakham, 44000, Thailand;
** Corresponding author: worapot_1@hotmail.com*

INTRODUCTION

Rice straw, a by-product from rice production, is a valuable biomass waste used as a second-generation biofuel in Thailand. The annual production of rice straw in Thailand is 16 to 24.7 million tons (Suramaythangkoor and Gheewala 2010). After harvest, most rice straw is disposed of by open-field burning, which is fast and low-cost, but this practice has a damaging effect on air quality and human health. To avoid pollution and to provide an alternative energy source, rice straw has been converted to bioenergy instead of open burning. In thermochemical conversion technologies, gasification is an attractive route compared with combustion and pyrolysis, due to its a higher efficiency (Sheth and Babu 2010). The series of chemical processes that transforms solid biomass into a combustible gas by partial oxidation is called biomass gasification technology. The resulting gas, called producer gas or syngas, contains hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen. It is burned for thermal applications or used as an alternative fuel in an internal combustion engine or gas turbine to produce electricity.

The cyclone gasifier technology has excellent advantages when used to generate producer gas from low-density biomass residues (Fredriksson and Kallner 1993; Gabra *et al.* 2001). The conventional fixed-bed gasifier is not appropriate for rice straw conversion because of its low bulk density, poor flow characteristics, high ash content, and low ash melting point. In contrast to the traditional fluidized bed reactor, cyclone reactors are relatively simple, low-cost, and easy to use (Guo *et al.* 2009; Sun *et al.* 2009; He *et al.* 2012). The cyclone gasifier is similar to cyclone dust collectors because they can also decrease the requirement for a gas-cleaning apparatus. This advantage makes significant advances in reducing the initial investment (Sun *et al.* 2009).

Initially, cyclone gasifier technology was developed at the Royal Institute of Technology in Sweden by Fredriksson and Kallner (1993). The furnace outlet temperature was increased gradually to about 820 ºC with an increase in the equivalence ratio (ER). This experiment produced a syngas higher heating value (HHV) of approximately 4.4 MJ/m^3. Gabra *et al.* (2001) studied sugarcane trash gasification in a cyclone furnace. As the ER was varied in the range 0.20 to 0.25, the HHV of the producer gas obtained in this investigation was between 4.4 and 4.7 MJ/m^3. An inverted cyclone gasifier reactor consists of a vortex collector pocket (VCP) and a central collector pocket (CCP), which was developed by Syred *et al.* (2004). The cited study improved ash separation from the vortex flow, which enhances the removal of heavy metal traces and alkali in the producer gas. Sun *et al.* (2009) investigated the process of rice husk powder gasification in the cyclone reactor for producing syngas. In contrast with the traditional fluidized bed gasifier, it was reported that the producer gas temperature was higher. Guo *et al.* (2009) investigated gasification of biomass micron fuel in a cyclone reactor by using air as the gasifying agent. The results concluded that a smaller biomass size resulted in higher syngas quality and gasification performance. By studying the effect of the operating condition on air-steam gasification using a cyclone gasifier, He *et al.* (2012) found that the gas quality was favored by the supply of steam, but too much steam reduced the temperature of the reactor and decreased the gas quality. Bartocci *et al.* (2018) studied steam gasification of charcoal pellet in lab-scale. He reported an H_2 content of 58.25% in the product gas, and a process efficiency of about 25%. Wood powder gasification in the fuel staging cyclone gasifier was studied by Zhao *et al.* (2013). The gasification performance was enhanced when the air-fuel ratio was over 14%. Risberg *et al.* (2014) studied the cyclone gasification process by using four different types of biomass as feedstock, which were peat, rice husk, bark, and wood.

Although there has been extensive research on the application of cyclone gasification to process biomass, there has been none specifically on the cyclone gasification of rice straw. In this study, the characteristics and the performance of a cyclone gasifier for straw gasification were assessed. The influence of the ER, biomass moisture content, and feedstock particle size on the syngas quality and the gasification performance were studied. The results obtained may be beneficial in developing a cyclone biomass gasification technology to use rice straw as feedstock.

EXPERIMENTAL

Feedstock Material

Rice straw was used as the biomass feedstock in this experiment. To analyze the biomass heating value, a bomb calorimeter was used. The proximate and ultimate analyses of the feedstock are illustrated in Table 1. To control the different biomass moistures for this experiment, sun drying was applied to reduce moisture content in the feedstock. To characterize the rice straw, a sieve shaker and disk mill were used. The disk mill was used for grinding and the material was then sieved with different mesh sizes. The automatic-sieve shaker was employed to determine the size distribution.

Table 1. Proximate Analysis and Ultimate Analysis of the Rice Straw

Proximate Analysis (wt.%)		Ultimate Analysis (wt.%)	
Ash	8.55	C	45.69
Volatile matter	67.27	H	4.65
Fixed carbon	13.05	N	0
Higher heating value (MJ/kg)	14.21	S	0
		O	50.32

Experimental Setup

The concept of the rice straw cyclone gasifier is shown in Fig. 1. The air/straw mixture entered the reactor in the tangential direction, which created a vortex flow in the furnace. The incoming feedstock particles were forced by the swirl to the cyclone wall, where the main parts of the reaction took place. These reactions included drying, pyrolysis, combustion, and gasification. When the syngas exited through the top outlet duct of the gasifier, the unreacted char particles fell downwards towards the bottom of the reactor.

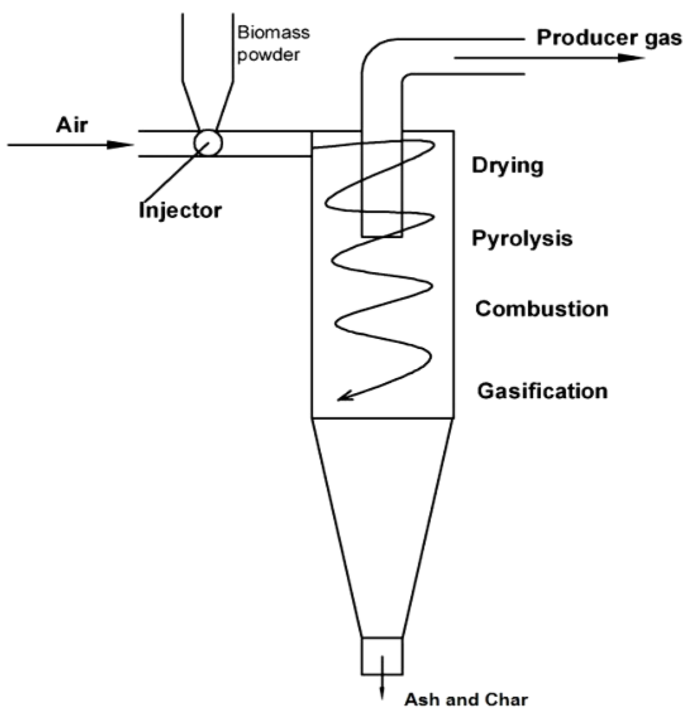

Fig. 1. Concept of the rice straw cyclone gasifier

Figure 2 shows a drawing diagram of the cyclone gasification system, which consisted of four main parts: ring blower, fuel screw feeder, cyclone gasifier, and gas sampling and tar measurement unit.

A photograph of the system is displayed in Fig. 3. Air, the gasifying agent, was injected into the gasifier by an air blower. To control the air flow rate entering the reactor, a valve and rotameter were used. The fuel screw feeder included a fuel hopper, a screw feeder, and a downcomer. The feedstock fuel (rice straw powder) was contained in the hopper, and the screw feeder was used to transfer fuel from the hopper to the downcomer, which was injected tangentially into the cyclone furnace using an air-driven injector. The fuel feed rates were controlled with an electrical inverter varying the rotation of the screw feeder motor.

The cyclone reactor body consisted of a conical and cylindrical chamber. The reactor body was constructed by using a mild steel plate (5 mm wall thickness). The cyclone gasifier was 90 cm high with a diameter of 21 cm and was wrapped with the ceramic fiber insulation materials of 15 cm.

The cylindrical chamber was enveloped with an electrical heater of 20 kW, which is used to preheat the gasifier. The water-venturi educator was installed at the bottom of the furnace for ash removal. The syngas departed the reactor through the exhaust upper port where the gas sampling and tar measurement unit was installed. Thermocouple probes were installed to monitor the temperature variation along the vertical direction of the furnace.

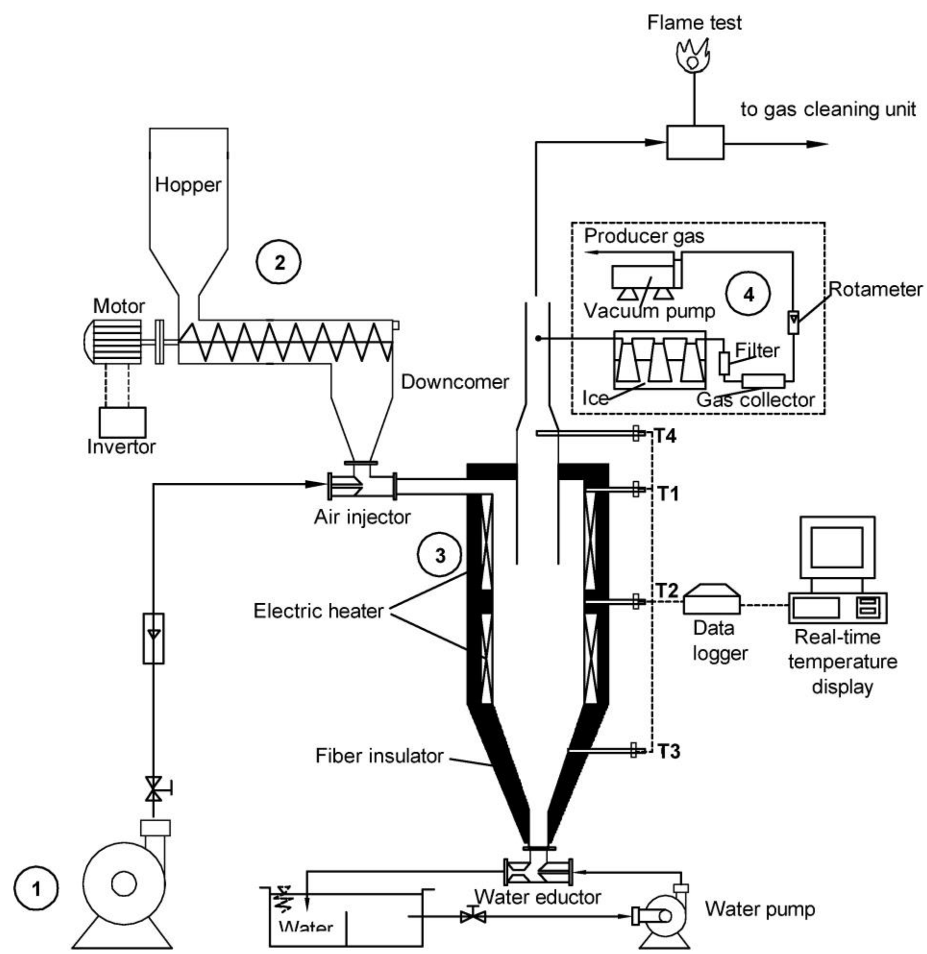

Fig. 2. Schematic of biomass cyclone gasifier systems: (1) air ring blower; (2) fuel screw feeder; (3) cyclone gasifier; (4) gas sampling and tar measurement unit

Fig. 3. Photograph of biomass cyclone gasifier system

Measurements System

When the gasification system was at a stable state, producer gas was sampled and the tar concentration was analyzed (by the gas sampling and tar measurement unit). A gas chromatograph (Shimadzu GC-2014, Shimadzu Corporation, Kyoto, Japan) equipped with a thermal conductivity detector, fitted with unibeads C column was used to analyze the main gas composition (CO_2, H_2, CO, and CH_4). For all experiments, high-purity argon gas was used as the carrier gas. The use of cold trapping was used, which included six 250 mL impingers immersed in an ice bath (-15 ºC) as a tar measuring unit. Sampling gas that was collected by the gas collector flowed into the impinge, and then the tar from the syngas was condensed. Finally, the tar concentration was estimated and contrasted with the syngas flow rate in mg/m^3. Tar content in the producer gas caused critical problems by blocking the pipeline and polluting the environment. Tar elimination by thermal cracking (Bui *et al.* 1994) or by using a catalyst (Hu *et al.* 2018) are widely used methods.

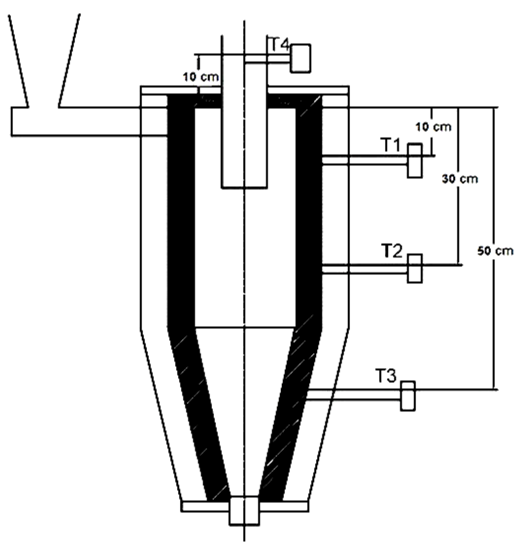

Fig. 4. Schematic of thermocouple locations

The tar removal by physical process is attractive by a technical and economical point of view; moreover it is uncomplicated and adaptable. An oil scrubber combined with char adsorption for tar removal was investigated by Paethanom *et al.* (2013). The demonstrating test was successful and a gravimetric tar removal efficiency was 98.7%. The thermocouple (Chromel-Alumel, K-type, IES-Electric Corporation, Bangkok, Thailand) as displayed in Fig. 4, was used to monitor the temperature profiles along the vertical plane of the gasifier. There was temperature measurement of the upper-reactor zone (T1) at 10 cm, the middle-reactor zone (T2) at 30 cm, the bottom-reactor zone (T3) at 50 cm below the top reactor, and the exit gas (T4) at 10 cm above the top gasifier. To measure and record the temperature, all thermocouples were equipped with a data logger.

Experimental Procedure

The first step of the cyclone gasification experiment was executed by heating the gasifier with an electrical heater to a temperature of 700 ºC (monitored at T2). The fuel screw feeder was switched on at the desired rotation speed keeping a 12 kg/h biomass feed rate, and the air blower was also switched on to supply an excess quantity of air corresponding to the desired ER. When the gasifier temperature was stable and running smoothly (after 20 to 30 min), the testing began and the gas sampling and tar measurement were recorded. All experimental data were recorded by using the average value (three measurements spaced 5 min apart).

To assess the process technology, the following variables were defined and determined.

The equivalence ratio (ER) is defined by Eq. 1 (Zainal *et al.* 2002).

$$ER = \frac{[Flow\ rate\ of\ \ air / Rate\ of\ \ biomass\ consumption]}{[Stoichiometric\ air / biomass\ ratio]} \tag{1}$$

The higher heating value (HHV) of producer gas was calculated using Eq. 2 (Jarungthammachote and Dutta 2010).

$$HHV = 13.1CO + 13.2H_2 + 41.2CH_4 \tag{2}$$

where CO, H_2, and CH_4 are the gas contents of the syngas.

The gas yield is defined by Eq. 3.

$$Gas\,Yield = \frac{Total\ dry\ gas\ \ flow\,rate}{Biomass\ feed\ \ rate\,(wb.)} \tag{3}$$

The carbon conversion efficiency (η_c) was calculated by Eq. 4 (Lv *et al.* 2004).

$$\eta_c = \frac{\begin{bmatrix} m_g \times 1000 \times (CH_4 + CO + CO_2) \\ \times (12/22.4) \end{bmatrix}}{[m_{feed,dry}(1\text{-}X_{ash}) \times C]} \times 100\% \tag{4}$$

where CO, CO_2, and CH_4 were the gas contents of the syngas (vol.%), m_g was the producer gas flow rate (N m^3/h), $m_{feed,dry}$ was the biomass feed rate (g/h), C was the carbon content in the feedstock component (wt.%), and X_{ash} was the ash content in the biomass (wt.%).

The cold gas efficiency (CGE) was estimated by Eq. 5 while the hot gas efficiency (HGE) was calculated by Eq. 6 (Sheth and Babu 2010).

$$CGE = \frac{HHV_{gas} \times m_g}{HHV_{feed} \times m_{feed,dry}} \quad (5)$$

$$HGE = \frac{HHV_{gas} \times m_g + E_{pg}}{HHV_{feed} \times m_{feed,dry}} \quad (6)$$

where HHV_{gas} was the HHV of the syngas (MJ/Nm^3), E_{pg} was the syngas sensible heat (MJ/h), m_g was the syngas flow rate (N m^3/h), HHV_{feed} was the biomass HHV (MJ/kg), and $m_{feed,dry}$ was the biomass feed rate (kg/h).

RESULTS AND DISCUSSION

Cyclone Gasifier Temperature

The gasifier temperature was examined under different operating conditions. The measurements of the temperature along the height of the gasifier (upper gasifier zone (T1), middle gasifier zone (T2), bottom gasifier zone (T3), and exit producer gas (T4)) were analyzed in Figs. 5, 6, and 7.

The influence of ER on gasifier temperature is illustrated in Fig. 5. The temperature profile in the cyclone reactor was very influential based on the ER, and it rapidly increased with the increment of ER. At a higher ER, more oxygen promoted the combustion reaction, which led to more heat being released and resulted in the increase in furnace temperature. Similar results were observed with the research performed by He *et al.* (2012). It has been reported that the cyclone gasifier temperature increased with increasing ER. The temperature of the upper gasifier zone, middle gasifier zone, bottom gasifier zone, and exit producer gas reached 763 to 832 °C, 640 to 756 °C, 418 to 578 °C, and 363 to 511°C, respectively. The highest temperature was shown in the gasifier upper part, which indicated that this position was the main oxidation zone.

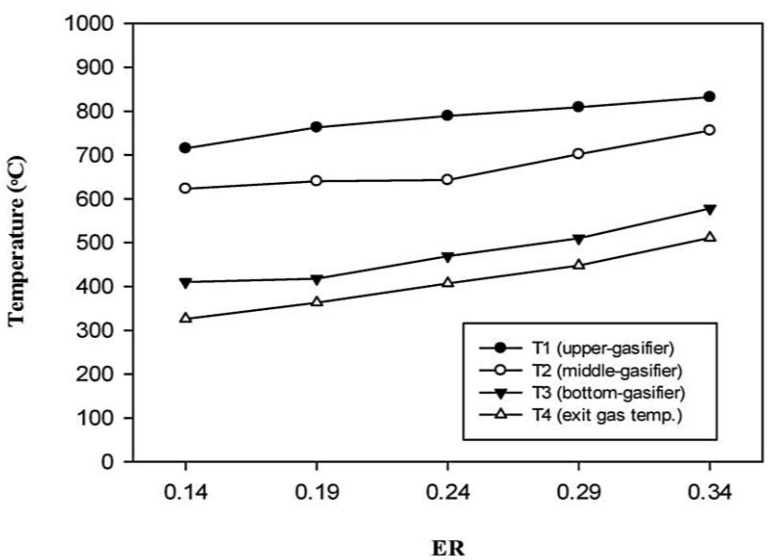

Fig. 5. Effect of ER on gasifier temperature (biomass size 0.25-0.5 mm; moisture content = 9.5%)

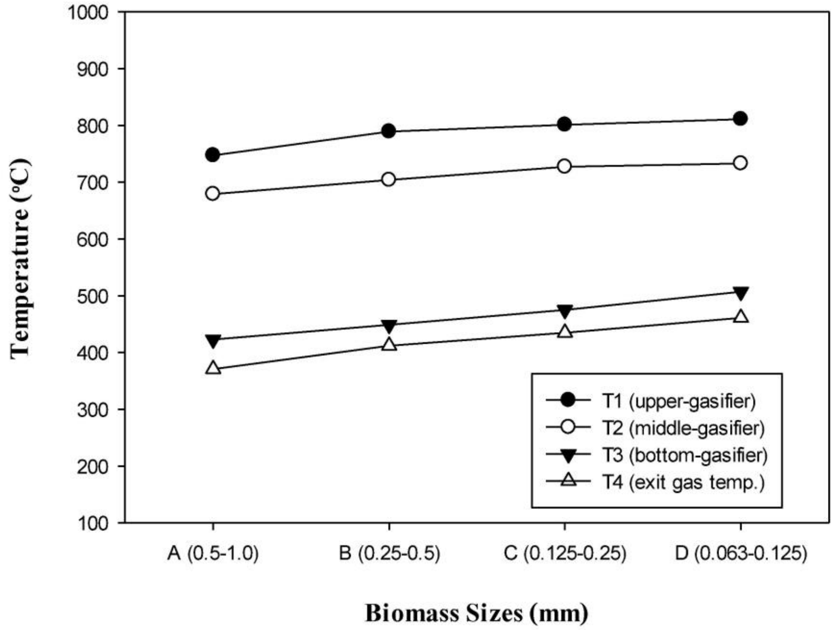

Fig. 6. Effect of biomass size on gasifier temperature (ER = 0.29; moisture content = 9.5%)

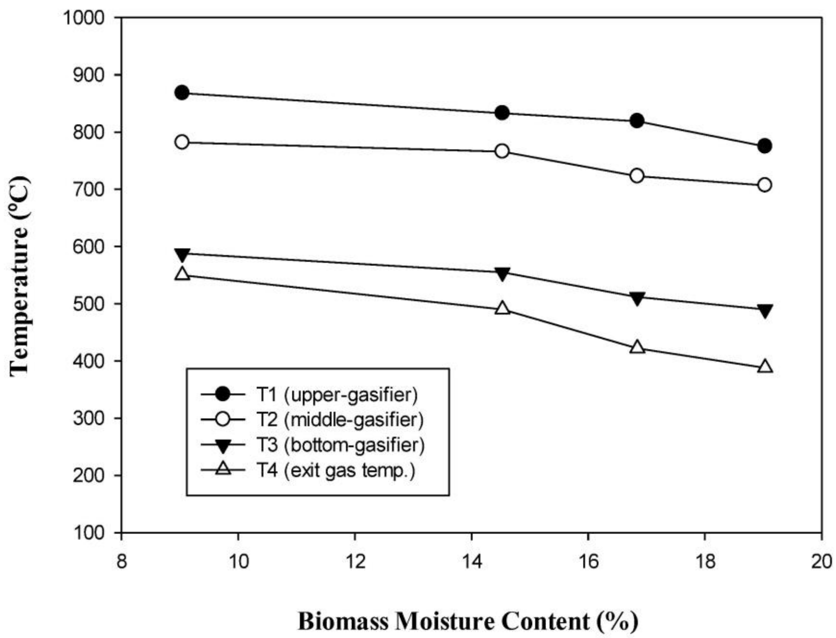

Fig. 7. Effect of moisture content on gasifier temperature (ER = 0.29; biomass size = 0.25–0.5 mm)

Figure 6 shows the effect of biomass size on gasifier temperature, while keeping all other operating conditions constant (ER = 0.29, biomass moisture content = 9.5%). There was a significant increase in the temperature at different positions of the gasifier due to the reducing influence of the feedstock particle size. Due to the heat generation rate of biomass-feedstock, combustion in the reactor has a direct effect on the gasification reaction (Blasi 1996; Lv *et al.* 2004). Since the smaller feedstock had a larger contact area and a rapid heating rate, the size of feedstock will have an influence on gasifier temperature.

Figure 7 shows that the gasifier temperature at difference parts was reduced significantly when the moisture content of the biomass feedstock was increased. The decrease in temperature was due to the large quantity of heat required for moisture evaporation, which would be used essentially by the endothermic gasification reaction. Kaewluan and Pipatmanomai (2011) showed a similar finding that when the moisture content increased from 9.5% to 25.5%, it caused the gasifier temperature to be reduced from 761 ºC to 699 ºC.

Effect of ER on Rice Straw Gasification in the Cyclone Gasifier

In this experiment, ER was changed from 0.19 to 0.34, keeping biomass size in a range of 0.25 to 0.50 mm and moisture content at 9.5%. The air flow rate into the gasifier was changed to study the influence of ER at a constant biomass feed rate at 12 kg/h. Figure 8 illustrates the effect of ER on the main gas component of the syngas. The main oxidizable compositions in the syngas were CO and H_2, and the content of those gases have a direct influence on the quality of the syngas. As a result, the content of CO and H_2 increased from 13.57% to 15.71% (as ER varied from 0.19 to 0.24) and from 8.17% to 9.13% (as ER varied from 0.19 to 0.29), respectively, then decreased from 15.71% to 14.76% and from 9.13% to 8.33%, respectively. At higher ERs, the combustion reaction became more important than other reactions because of the oxygen amount increment, which led to more oxidizable gases (H_2, CO, and CH_4) being used to generate more CO_2, thus causing the gas quality to degrade (Guo *et al.* 2009). When ER varied from 0.19 to 0.34, the content of CO_2 always increased, while the CH_4 concentration showed a very small variation with the changing of the ER.

The combustible composition of product gas was used to estimate the HHV in MJ/Nm^3 (calculated by Eq. 2). The tar content in the product gas caused serious problems by blocking the pipeline and polluting the environment. Tar elimination by thermal cracking or using a catalyst has been widely used. The influence of ER on the syngas HHV and the tar content are shown in Fig. 9. It is indicated that in the ranges of the ER from 0.19 to 0.24, the HHV of syngas increased from 3.96 to 4.34 MJ/Nm^3. As the ER ranged from 0.24 to 0.34, the HHV exhibited decreasing trends, which was possibly due to the strengthened combustion reaction of the oxidizable product gases. In this study, it was found that the contaminated tar in the gasified gas decreased from 136.2 to 98.7 mg/Nm^3 over the range of ERs. Due to tar cracking at higher temperatures (Devi *et al.* 2003; Li *et al.* 2009), a higher ER promotes the oxidization reactions, which leads to more heat release and the temperature increases in the gasifier.

The influence of ER on gasification performance is presented in Table 2. As expected, the gas yields increased from 1.31 to 2.42 Nm^3/kg feed, while the carbon conversion efficiency ranged from 35.9 to 73.4% over the various ER ranges. On the other hand, it was observed that the CGE and HGE reached their highest values at an ER of 0.34. The results suggested that an ER of about 0.29 to 0.34 should be selected for further study, because the most optimal results were obtained for the gas yield and the carbon conversion efficiency, as well as for HGE and CGE, in this range of ERs.

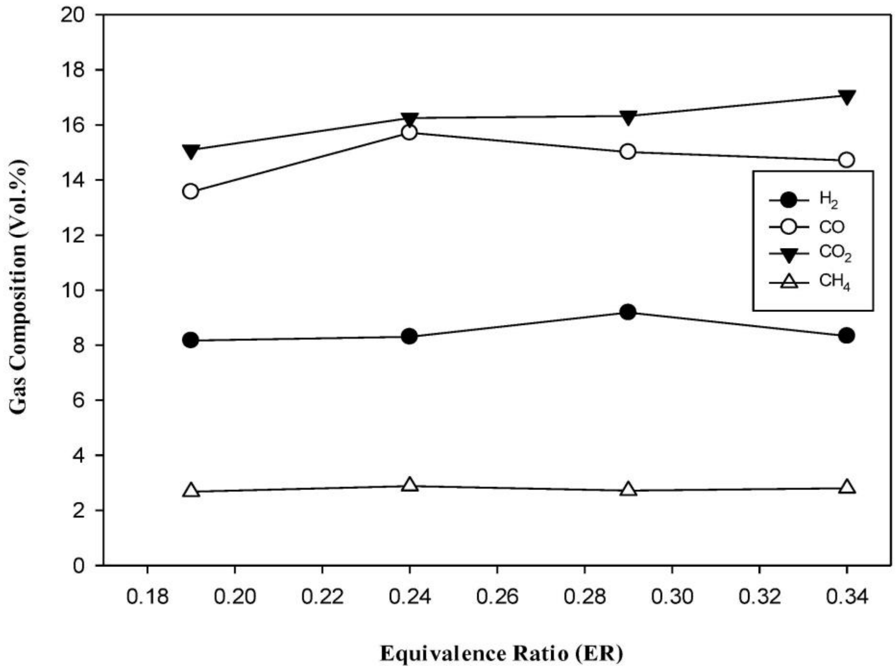

Fig. 8. Effect of ER on the main gas composition (biomass size = 0.25 to 0.5 mm; moisture content = 9.5%)

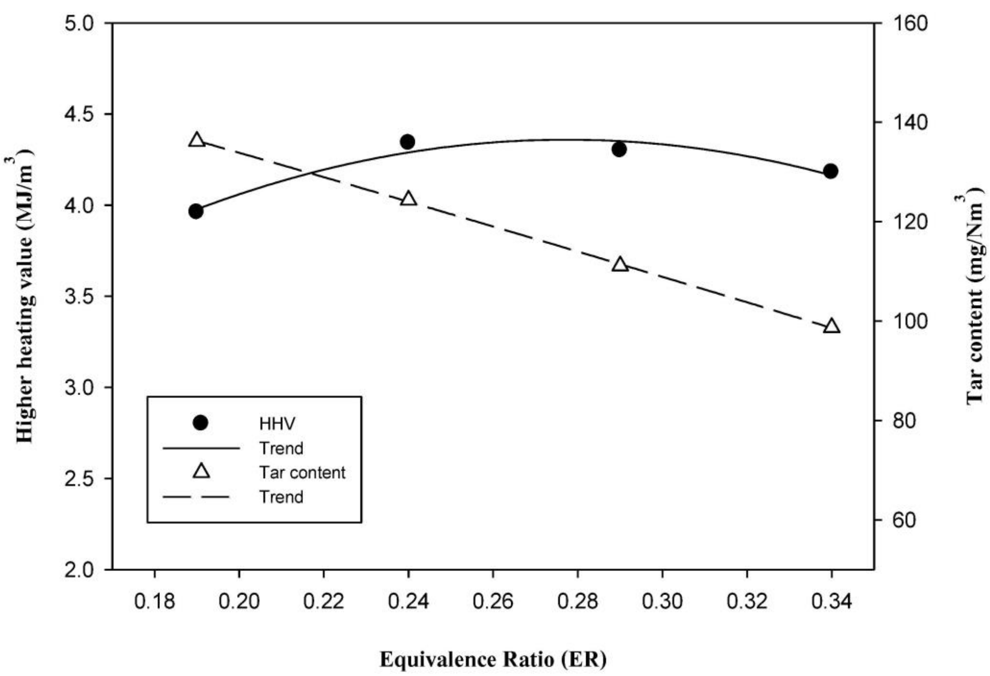

Fig. 9. Effect of ER on HHV and tar content (biomass size = 0.25–0.5 mm; moisture content = 9.5%)

Table 2. Effect of ER on the Gasification Performance

Air flow rate (lpm)	200	250	300	350
ER	0.19	0.24	0.29	0.34
Gas yield (Nm^3/kg,feed)	1.31	1.74	2.09	2.42
Carbon conv. Eff. (%)	35.86	53.01	62.28	73.36
CGE (%)	36.39	53.04	63.18	71.23
HGE (%)	40.99	59.95	72.37	83.49

At biomass size = 0.25 to 0.5 mm; moisture content = 9.5%

Effect of Biomass Size on Rice Straw Gasification in the Cyclone Gasifier

Because the biomass feedstock size directly influences the heating rate in the reactor, it also will have an influence on the biomass gasification process (Lv *et al.* 2004). In this experiment, four size ranges of rice straw powders (0.5 to 1.0 mm, 0.25 to 0.5 mm, 0.125 to 0.25 mm, and 0.063 to 0.125 mm) were selected, holding the ER at 0.29 and moisture content at 9.5%.

Figure 10 shows the influence of biomass size on the main gas component. CO and H_2 concentrations increased from 15.6% to 17.1% and 6.8% to 8.4%, respectively, as the biomass particle size decreased. Similar results were also monitored with the investigation performed by Guo *et al.* (2009). This can also explain the results that the smaller biomass feedstock size may have a higher content of inorganic matter and moisture concentration than large biomass particles to accelerate the gasification process. When the biomass particle size is reduced, the product gas resultant inside the biomass was rather easy to diffuse out. In this experiment, it was found that when the size of the feedstock was reduced, the content of CO_2 increased, while CH_4 concentrations also slightly change with the decreasing size of the biomass particle.

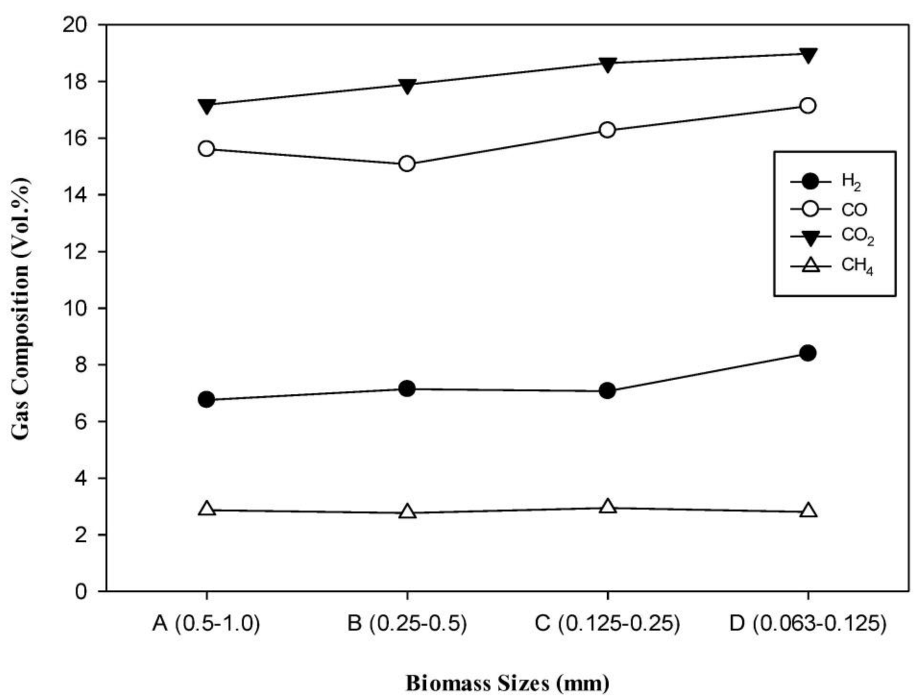

Fig. 10. Effect of biomass size on the main gas composition (ER = 0.29; moisture content = 9.5%)

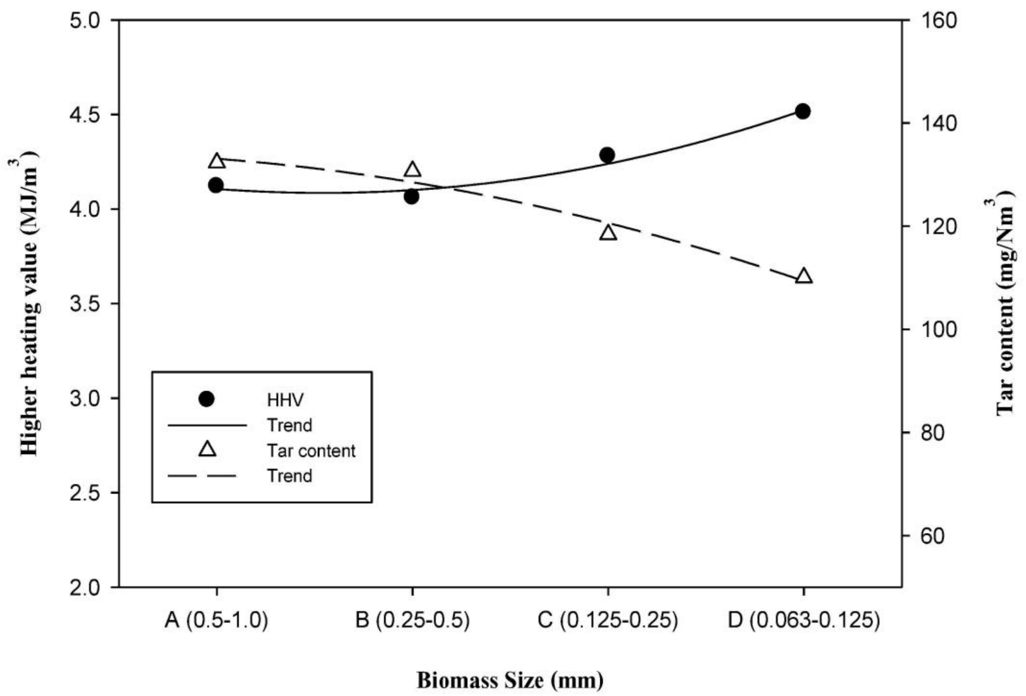

Fig. 11. Effect of biomass size on HHV and tar content (ER = 0.29; moisture content = 9.5%)

The effects of the size of the rice straw powders on the producer gas HHV and the tar content are illustrated in Fig. 11. When the biomass particle size decreased from the A size (0.5 to 1.0 mm) to the D size (0.063 to 0.125 mm), the syngas HHV increased from 4.12 to 4.51 MJ/Nm^3. This indicated that a decrease of feedstock size was more favorable for cyclone gasification, which in turn influenced the increase of combustible gases (CO and H_2), causing an increase in the HHV of the producer gas. Tar content in the producer gas significantly decreased from 132.3 to 110.1 mg/Nm^3. According to Mohammed *et al.* (2011), it has been reported that the smaller the feedstock size, the greater the contact area of biomass and gasifying agent, leads to a higher heating rate, which favors tar elimination by thermal cracking.

Table 3 illustrates the influence of the size of the biomass particles on the gasification performance. It was evident that decreasing feedstock size enhanced gasification performance. The gas yield, the carbon conversion efficiency, CGE, and HGE reached maximum values when the feedstock particle size was in the D size range (0.063 to 0.125 mm). In this way, it is suggested that the feedstock size parameters played a important role in the effects of the cyclone gasifier performance.

Table 3. Effect of Biomass Size on the Gasification Performance

Biomass size	A (0.5-1.0 mm)	B (0.25-0.5 mm)	C (0.125-0.25 mm)	D (0.063-0.125 mm)
Gas yield (Nm^3/kg,feed)	2.02	2.04	2.16	2.22
Carbon conv. Eff. (%)	54.92	56.84	65.57	70.66
CGE (%)	48.34	52.12	57.59	60.03
HGE (%)	54.44	59.01	65.99	69.07

At ER = 0.29; moisture content = 9.5%

Effect of Moisture Content in Biomass on Rice Straw Gasification in the Cyclone Gasifier

The biomass moisture content is a main parameter that influences the gasification process. To study the effect of moisture content, the moisture content in rice straw was varied at 9.50, 14.53, 16.84, and 19.03% (wet basis). All experiments were performed at an ER of 0.29 and biomass size at range of 0.25 to 0.50 mm.

The effect of the moisture content on the main syngas component (H_2, CO_2, CO, and CH_4) is shown in Fig. 12. The negative effect of the moisture content in biomass played a more important role; thus, the concentration of CO and H_2 decreased from 15.73% to 9.67% and from 7.29% to 5.22%, respectively, while the content of CO_2 increased from 16.9% to 18.4%. The CH_4 varied little in the range of the moisture content tested. As a result, it could be explained that the increased moisture content, which decreased the gasifier temperature, was not favorable relative to either the endothermic water-gas reaction ($C + H_2O \leftrightarrow CO + H_2$) or the Boudouard ($C + CO_2 \leftrightarrow 2CO$) reaction. This resulted in a marked decrease of H_2 and CO content and a clear increase in CO_2 content. This behavior agrees with the studies performed by Kaewluan and Pipatmanomai (2011). It was reported that the increase of moisture content in biomass causes a drop in the reactor temperature, which causes a decrease in the production of H_2 and CO content.

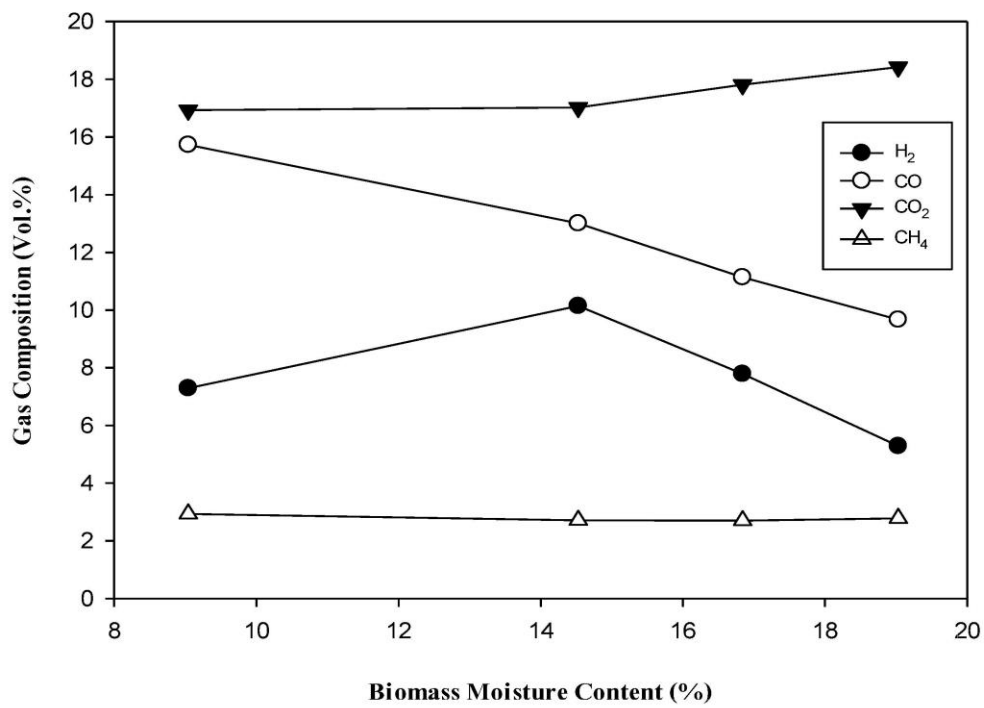

Fig. 12. Effect of biomass moisture content on the main gas composition (ER = 0.29; biomass size = 0.25–0.5 mm)

Figure 13 shows that the HHV of the syngas was reduced significantly with the increased moisture content. The product gas HHV decreased from 4.23 to 3.09 MJ/Nm^3 as the moisture content increased from 9.50 to 19.03%.

This apparent result is also in agreement with the research conducted by Zainal *et al.* (2001) and Morita *et al.* (2004), who created a mathematic model of the biomass gasifier to predict the main component and tar content of the syngas under a steady state operation. As the biomass moisture content varied from 9.50 to 19.03%, the tar concentration in the product gas increased from 101.1 to 150.1 mg/Nm^3. Due to the significant amount of heat from the combustion reaction being utilized for the moisture evaporation process, it led to a decrease in reactor temperature and caused the tar content to increase (Kaewluan and Pipatmanomai 2011).

The effects of the moisture content on the gasification performance are shown in Table 4. It was evident that the higher feedstock moisture was detrimental to the gasification performance. The gas yield, the carbon conversion efficiency, CGE, and HGE exhibited decreasing trends.

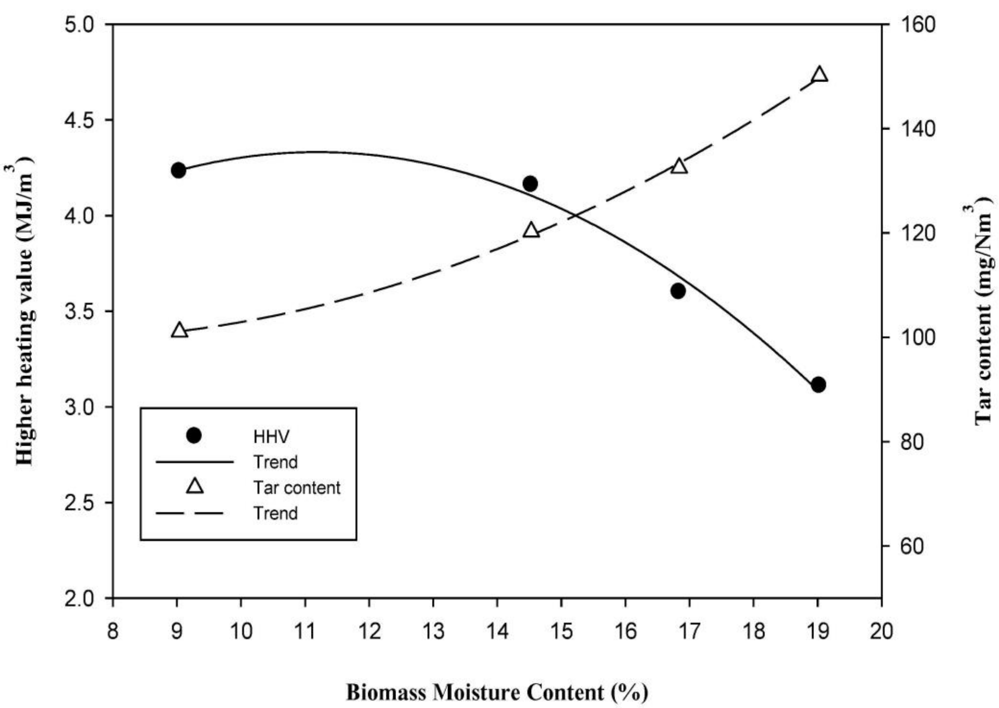

Fig. 13. Effect of biomass moisture on HHV and tar content (ER = 0.29; biomass size = 0.25–0.5 mm)

Table 4. Effect of Biomass Moisture on the Gasification Performance

Moisture content (%)	9.50	14.53	16.84	19.03
Gas yield (Nm^3/kg,feed)	2.07	2.01	1.96	1.86
Carbon conv. Eff. (%)	64.65	62.98	59.01	56.08
CGE (%)	46.65	45.89	37.45	30.69
HGE (%)	55.22	53.48	43.56	35.99

At ER = 0.29; biomass size = 0.25 to 0.5 mm

CONCLUSIONS

1. The equivalence ratio (ER), feedstock size, and feedstock moisture content were examined as the main variables affecting the rice straw gasification in the cyclone gasifier. The increasing ER resulted in the increment of furnace temperature and an increase in gas quality and gasification performance. When the ER was too high, it reduced the combustible gas composition (CO and H_2), which led to lower HHV of the syngas.
2. The optimal ER obtained was 0.29 to 0.34. Under this optimum condition, HHV of the producer gas, tar content, gas yield, carbon conversion efficiency, cold gas efficiency, and hot gas efficiency varied in the range of 4.18 to 4.30 MJ/Nm^3, 98.7 to 111.2 mg/Nm^3, 2.09 to 2.42 Nm^3/kg feed, 62.3 to 73.4%, 63.2 to 71.2%, and 72.4 to 83.5%.
3. A smaller feedstock size was more favorable for higher gasifier temperatures, producer gas quality, and gasification performance.
4. An increase in moisture content persistently decreased both the syngas quality and the gasification performance.

ACKNOWLEDGMENTS

The author kindly acknowledges the financial support by the Energy Conservation Fund (ENCON Fund), Ministry of Energy, Thailand. This work is furthermore supported by the Faculty of Engineering, Rajabhat Maha Sarakham University.

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Article submitted: May 14, 2018; Peer review completed: August 10, 2018; Revised version received: August 17, 2018; Accepted: August 18, 2018; Published: August 22, 2018.
DOI: 10.15376/biores.13.4.7654-7670