A study on designing, manufacturing and testing a household rice husk gasifier

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Abstract

The study was conducted to design, manufacture and test a household rice husk gasifier for families in Mekong Delta, Vietnam. The downdraft gasifier can supply 5,500 kcal/h with a reaction chamber diameter of 0.254 m and height 0.6 m. The rice husk feed stock rate was 6.1 kg/h; synthesis gas was generated at 29.2 m^3/h. The treatments were: five levels of the equivalence ratio (ER) of 0.2, 0.25, 0.3, 0.35 and 0.4. ER is defined as the ratio of the actual air flow rate with the stoichiometric air flow rate, according to the formula ER = Q_{ac}/Q_{st} (the stoichiometric air flow rate is the air required to burn completely); each ER was studied at three removal rates of biochar (10, 12 and 14 rpm of the motor driving the screw that removes the biochar.

The syngas low heating value (LHV) was highest when the equivalence ratio (ER) was 0.3 at all three rotation levels of the biochar removal system. The specific gasification rate (SGR) was increased when ER increased. The highest thermal efficiency was 54% at ER = 0.3 and the rotation of biochar removal was 14 rpm. The corresponding syngas components were CO 24.0%, C_nH_m 0.76%, H_2 7.69%, O_2 0.82% with LHV of 1,627 kcal/m^3 and SGR 122 kg/h/m^2.

Key words: *biochar, equivalence ratio, low heating value, synthesis gas*

Introduction

The conversion technologies for utilizing biomass can be separated into four basic categories: direct combustion processes, thermochemical processes, biochemical processes and agro-chemical processes (Alexis 2005). The thermochemical conversion of biomass (pyrolysis, gasification, combustion) is one of the promising routes among the renewable energy options. Gasification as a method of conversion of energy has several advantages over traditional power generation methods with efficiency from 14 to 25% (Prabir 2010). In the thermochemical conversion technologies, biomass gasification has attracted the highest interest as it offers higher efficiencies compared to combustion and pyrolysis. Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion (Luque and Speight 2015).

Gasification of biomass for energy production has the potential to be a cost effective and environmentally sustainable technology. Biomass energy is derived from the plant sources, such as waste from agricultural and forestry processes, wood from natural forests and industrial, human or animal wastes (Prabir 2010). So the energy obtained from biomass is a form of renewable energy and it does not add carbon dioxide to the environment in contrast to the fossil fuels (Zhang and Zhu 2010; Mofijur et al 2014). Every year more than 15 billion tonnes of CO_2 are added to the environment. The increase in the level of CO_2 in the atmosphere is directly associated with global warming (KoÃ§ar and Civa? 2013; Mofijur et al 2015). Many households in Asian continue to depend on expensive fossil fuel–based sources which are energy inefficient and pollute the environment (Pode 2015).

Vietnam's paddy rice production is around 50 million of tones per year and the Mekong Delta produces more than half of the country's total production. In terms of rice husk production, 20% of the weight of rice is rice husk. Thus around 10 million tonnes of rice husks are generated every year in Vietnam (Hao and Bich 2015).

Downdraft gasifiers have flexible adaptation of gas production to biomass load, low sensitivity to charcoal dust and tar content of fuel. They have good carbon conversion, ease of management, high thermal efficiency and low capital cost (Reed and Das 1988; Gai and Dong et al 2012; Sheth and Babu 2009; Susastriawan et al 2015).

Materials and methods

Materials

The rice husk from the variety IR50404 was used in this study, sourced from a rice mill located in Dong Thap province in the Mekong Delta. The moisture content was 10 %and the bulk density 106 kg/m^3.

The average air temperature at the time of the experiment ranged from 30 to 32^oC. The air humidity was 68 to 71%.

The composition of the gaseous products from the biomass gasification process was measured with the Gas board 3100P device from Wuhan Cubic Optoelectronics Co, Ltd (Figure 1).

Figure 1. The gasboard 3100P syngas analyzer

Methods

The air flow rates were tested based on the orifice plate. This is a device used for measuring air flow rate based on the difference in pressure. This method can be recommended due to its simple manufacture, handy assembly and low cost. The actual air flow rate is calculated as follows:

Where: Q_{ac}: the actual air flow rate, kg/s; ?: flow coefficient; A_2: plate hole area, m^2; $?_{kk}$: density of air, kg/m^3; $?P = P_1 - P_2$: differential pressure before and after the disk, Pa; and $m = A_2/A_1$ the ratio between the area of the orifice plate hole and the area of the tube.

The gasification efficiency is an important factor determining the actual technical operation, as well as the economic feasibility of using a gasifier system. A useful definition of the gasification efficiency if the gas is used for engine applications is: (Cuong et al 2014).

Where: $?_1$, $?_2$: time start and end, h; G_{gt}: volume flow of gas, $m^{3/}h$ LHV_{gt}: heating value of the gas, MJm^{-3}; M_{nl}: rice husk consumption, kg/h; LHV_{nl}: low heating value of rice husk, MJ/kg.

The specific gasification rate (SGR) is defined as the amount of biomass fuel used per unit time per unit reactor area, usually about 110 – 210 [$kg/h^{/}m^2$] (Alexis 2005).

It was calculated as:

$SGR=G_t/S$

Where: G_t : fuel mass flow rate [kg/h] and S = reactor cross-sectional area [m^2].

Location and duration

The fabrication of the downdraft gasifier and the experiments were conducted in the Renewable Energy Laboratory, Nong Lam University, Ho Chi Minh, Vietnam, from March 2016 to April 2017.

Statistical analysis

Linear equatons were fitted to the data using the Excel program in the Microsoft Excel software. The fixed "X" variable was the equivalence ratio; the dependent variables were concentrations of synthesis gas, low heating value, specific gasification rate and efficiency.

Results and discussion

Design and manufacture of the gasifier

Table 1. The technology parameters of the downdraft gasifier

Parameters	Equations
Energy needed	Q_{na}
Low heating value of rice husk	LHV_{tr}
Gasifier efficiency	?
Rice husk consumption (Hasler	$G_{tr} = Q_{na}/ (LHV_{tr}. ?)$

1999)

Specific gasification rate	SGR
Height of the reactor	$H = (SGR . ?) / ?_{bt}$
Operating time	?
Rice husk density	$?_{bt}$
Air needed for gasification	$Q_q = (? . G_{tr} . A) / ?_{kk}$
Equivalence ratio	ER
Stoichiometric air of rice husk	A
Air density	$?_{kk}$
Superficial air velocity	$Vs=Q_q/(?.D^2/4).3600$
Air flow rate	Q_q
Low heating value of gas	$LHV_g = 127CO + 108H_2 + 359CH_4$
Low heating value of rice husk	$LHV_{tr} = 339C^d + 1256H^d – 108.8 (O^d – S^d) – 25.1 (W^d + 9H^d)$
Power input	$N = LHV_{tr} .G_{tr}$
Synthesis gas (Prabir 2010)	$Q_{ga} = N/LHV_g$

The household downdraft gasifier was composed of the reaction unit, cyclone, syngas cooler, dust filter and swirl burner Figures 2a and 2b.

Figure 2a. Schematic diagram of the downdraft gasifier

Figure 2b. The gasifier

The reaction chamber was made by using inox SUS 304 with diameter 0.254 m and height 0.6 m, rice husk hopper 6.1 kg, the biochar removal system connected with the reaction chamber at the bottom. The cyclone gasifier is a type of entrained-flow bed and acted as a preliminary syngas cleaner with diameter D = 0.15 m and height H = 0.4 m. The cooling system transferred the heat from the syngas to the water and from the water to the air, by indirect transfer.

Figure 3. The dust filter of syngas

Rice husk biochar was used to remove impurities, to improve gas quality. We could observed and evaluated the sensation of syngas combustion by swirl burner.

Influence of ER on syngas composition

To completely burn rice husks, 4.7 kg of air are needed per kg of rice husk. Burning it with an using 30 to 40% or an equivalence ratio (ER) of 0.3 to 0.4 only of the air needed for combustion will gasify rice husks, which produces a producer gas. The experiments were conducted to determine the effect of ER and char removal to syngas composition, specific gasification rate (SGR) and system efficiency (?).

The ER is defined as the ratio of the actual air flow rate with the stoichiometric air flow rate, according to the formula.

$ER = Q_{ac}/Q_{st}$

Where: ER: Equivalence Ratio; Q_{ac}: the actual air flow rate (m^3/h); Q_{st}: the stoichiometric air flow rate is the air required to burn completely (m^3/h).

According to (Alexis 2005):

0 ? ER ? 0.2 The process of pyrolysis, the reaction with oxygen begins to occur.

0.2 ? ER ? 0.4 Gasification process.

0.4 ? ER ? 1.0 The process of burning completely.

In this study we selected the ER within the range of 0.2 to 0.4.

The bulk density of both compacted and non-compacted rice husks ranges from 100 to 120 kg/m^3; the specific gasification rate was from 100 to 200 $kg/h/m^2$. In this research, the rice husk density of 100 kg/m^3 was selected. The specific gasification rate depends on the rotation speed of the biochar removal equipment.

This was selected as 10, 12 and 14 rpm. The biochar normally has an energy content of about 3000 kcal/kg kg and, when burned completely, produces about 15 to 21% ash which is almost 90% silica. The gas produced from the gasifier has an energy content of about 3.4 to 4.8 MJ/m^3. After gasification, the percentage biochar leaving the reactor was about 32% of the total volume of rice husks previously loaded.

The content of CO and H_2 in the syngas and the low heating value increased as the equivalence ratio was increased from 0.2 to 0.3 (Table 2), and then decreased as the equivalence ratio was raised from 0.3 to 0.4. These changes probably reflect insufficient air to heat the reaction zone at the low equivalence ratio, and the presence of non-combustible gases such as CO_2 at higher equivalence ratio (Lanh et al 2016; Bich et al 2017).

Table 2. Effect of equivalence ratio on syngas composition, LHV, SGR and ? with rotation of biochar removal of 10 rpm.

ER	**CO** %	**CO_2** %	**CH_4** %	**C_nH_m** %	**H_2** %	**O_2** %	**LHV** kcal/m^3	**SGR** kg/h/m^2	**?** %
0.2	18.12	1.42	5.45	0.57	5.4	0.70	1,190	98	40
0.25	19.16	1.54	6.5	0.63	6.1	0.75	1,334	106	44
0.3	21.17	1.59	7.1	0.72	6.5	0.8	1,460	110	49
0.35	20.74	1.62	5.9	0.58	6.2	0.88	1,333	116	44
0.4	19.18	1.74	4.32	0.49	5.8	0.92	1,134	124	38

The specific gasification rate increased linearly (Figure 5) as the equivalence ratio increased. The gasifier efficiency, defined as the ratio of energy of the producer gas per kg of biomass to the low heating value of the biomass material, varied from 38 to 49% and had a maximum value for an equivalence ratio of 0.3. The low efficiency observed in other ER was perhaps due to the insufficiency of heat for endothermic reactions, at the low level, or the excess combustion of rice husk at the high ER.

Figure 4. Effect of equivalence ratio on syngas composition with biochar removal rate of 10rpm

Figure 5. Ef
v

The composition of the syngas and the 'low heating values' of the producer gas predicted from experimental observations with biochar removal rate set at 12 and 14 rpm are shown in Tables 3 and 4 and Figures 6 and 7 and 8 and 9. The trends with increasing ER were similar to when the biochar removal rate was 10rpm.

Table 3. Effect of equivalence ratio on syngas composition, LHV, SGR and ? with rotation of biochar removal of 12 rpm.

ER	**CO** %	**CO_2** %	**CH_4** %	**C_nH_m** %	**H_2** %	**O_2** %	**LHV** kcal/m^3	**SGR** kg/h/m^2	**?** %
0.2	19.12	1.44	5.45	0.55	5.6	0.72	1,227	98	41
0.25	19.16	1.47	6.5	0.6	6.3	0.75	1,339	110	45
0.3	21.11	1.59	7.3	0.68	7.1	0.81	1,492	116	50
0.35	20.74	1.67	5.9	0.59	6.2	0.84	1,333	124	44
0.4	18.87	1.75	4.32	0.52	5.5	0.87	1,116	129	37

Figure 6. Effect of equivalence ratio on syngas composition with biochar removal rate of 12rpm

Figure efficie

Figure 7 shows the effect of equivalence ratio on the specific gasification rate. It clearly shows that with an increase in the equivalence ratio, specific gasification rate continuously increases. Higher equivalence ratio signifies higher air flow rate for a specific rice husk consumption rate. The specific gasification rate was lower at the rotation of char removal 10 rpm about 124 kg/h/m^2 and higher at the rotation of char removal 12 rpm about 129 kg/h$^/$m^2.

Table 4. Effect of equivalence ratio on syngas composition, LHV, SGR and ? with rotation of biochar removal of 14 rpm

ER	**CO** %	**CO_2** %	**CH_4** %	**C_nH_m** %	**H_2** %	**O_2** %	**LHV** kcal/m^3	**SGR** g/h.m^2	**?** %
0.2	20.2	1.63	6.53	0.88	6.92	0.74	1,389	106	46

0.25	21.2	1.69	7.02	0.74	7.1	0.8	1,469	112	49
0.3	24.0	1.7	7.62	0.76	7.69	0.82	1,627	122	54
0.35	22.5	1.88	6.08	0.66	6.74	0.88	1,416	131	47
0.4	21.2	1.98	4.66	0.48	6.3	0.95	1,240	143	41

A higher equivalence ratio represents a higher air flow rate for a specific rice husk consumption rate which leads to more amount of CO_2 production in combustion zone. Figure 8 shown that the conversion of CO_2 to CO depends upon the rate of reactions occurring in the reduction zone and length of the reduction zone. With an increase equivalence ratio from 0.2 to 0.3, increased CO_2 amount in combustion zone is converted into CO and H_2, and thereby the fraction of CO and H_2 increases from 20.2 to 24.0 and from 6.92 to 7.69, respectively. The increase in CO_2 and decrease in CO and H_2 fractions for the equivalence ratio higher than 0.3 represents that CO_2 produced in combustion zone is in excess to that of the conversion capacity of reduction bed.

Figure 8. Effect of equivalence ratio on syngas composition with biochar removal rate of 14rpm

Figure 9. Ef

The effect of equivalence ratio on rice husk consumption rate is shown in Figure 9. It is found that with an increase in the equivalence ratio, rice husk consumption rate increases. Specific gasification rate is found to vary from 106 to 143 kg/h.m^2 for an equivalence ratio varying from 0.2 to 0.4, respectively. The increase an equivalence ratio provides more oxygen to oxidize and higher amount of rice husk would get combusted. The energy released will increase the rate of drying and pyrolysis. Rice husk consumption rate increases not only due to a higher combustion rate, but also due to the enhanced pyrolysis and drying rate.

In summary (Figure 10) it can be seen that: (i) the lower heat value increases with ER to reach a maximum at a ER value of 0.3, afterwards declining as ER was raised to 0.4; and (ii) the lower heat value increased linearly as the biochar removal rate was increased from 10 to 14 rpm.

Figure 10. Effect of equivalence ratio and biochar removal rate on the ‘lower heat value’ of syngas produced in a downdraft gasifier with rice husks as fuel

Conclusions

- The downdraft gasifier is suitable for small-scale rice husk gasification due to its easy fabrication and operation. The quality of producer gas and the gasification efficiency are output parameters in the downdraft gasifiers that are affected by some important parameters.

- With an increase in equivalence ratio from 0.2 to 0.3 the low heating value increase but with an increase in equivalence ratio from 0.3 to 0.4 the low heating value decrease.

- With an increase in equivalence ratio or rotation of char removal, the specific gasification rate continuously increases.

- The optimum gasification efficiency was 54% for equivalence ratio 0.3 and rotation of char removal 14 rpm.

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