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Enhanced H_2 gas production from wood chip air/steam gasification by using heat recovery in a downdraft gasifier

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Abstract

The purpose of this study is to increase the concentration of hydrogen gas in the process of biomass gasification with self-produced steam by using waste sensible heat of producer gas from a fixed bed downdraft gasifier. The system produces the thermal power of 50 kW_{th}. The temperature of reactor is fixed at 920°C, and biomass consumption is at 14 kg/h. The flow rate of producer gas flowing through the heat exchanger is 32 m^3/h. The sensible heat of the producer gas is 2.04 kW_{th}. The producer gas temperatures at both inlet and outlet of heat exchanger are 350°C and 170°C, respectively. The small shell and tube heat exchanger having a heating surface area of 0.068 m^2 (approximately) produces 2.6 kg/h of steam at 120°C and 1.2 bar. The effectiveness of the heat exchanger is 0.92. In this study, the air/steam mixture is used as the gasifying agents flowing into the oxidation zone of the downdraft gasifier. To conclude, it has been found that the producer gas resulting from the air-steam gasification contains 19% hydrogen, which is 8% higher in hydrogen concentration than the gas product resulting from the air gasification. Furthermore, the heating value of the producer gas resulting from the air-steam gasification is 4.70-5.30 MJ/Nm^3, which is 26% higher heating value than the producer gas resulting from the air gasification. The equivalent ratio, ER, is 0.45.

Keywords: *Wood chip; downdraft gasifier; hydrogen; steam gasification; waste heat*

1. Introduction

Biomass is a renewable energy that is readily available and cheap [1]. It does not cause global warming. Gasification technology changes biomass into low calorific value gas; especially, when air is only used as the gasification agent. The composition of the producer gas, consisting of hydrogen at low concentration, makes the combustible gas to have a low calorific value [2].

Air, as the gasification agent, is easy to find and is at no cost. Unfortunately, the air in the atmosphere consists of nitrogen in excessive amounts. The producer gas from the air gasification has a low calorific value (4.1-4.5 MJ/Nm^3), while oxygen gasification produces a high heating value gas (10-18 MJ/Nm^3) [3,4], however, the production costs are high [5]. The use of steam, as the gasifying agent, is an attractive alternative. Steam is cheap and easy to generate. In addition, the heating value of the producer gas is moderate (5-10 MJ/Nm^3) and the amount of hydrogen in the producer gas can be increased [6].

Air/steam gasification processes have been studied by several authors, in theoretical [7,8] as well as in experimental works. In general, all researchers agree for an increase in the gas H_2 content when adding steam to the process, and many of them point at the importance of the water-gas shift (Table 1.) in the final adjustment of the synthesis gas composition [9-12]. Reactions involved in air/steam gasification [13] are shown in Table 1.

Table 1 The main gasification reactions [14,15]

Processes	Reactions	
Combustion	$C + O_2 \longrightarrow CO_2$	(1)
	$C + \frac{1}{2} O_2 \longrightarrow CO$	(2)
	$CO + \frac{1}{2} O_2 \longrightarrow CO_2$	(3)
	$H + \frac{1}{2} O_2 \longrightarrow H_2O$	(4)
Boudouard reaction	$C + CO_2 \longrightarrow 2CO$	(5)
Hydrogasification	$C + 2H_2 \longrightarrow CH_4$	(6)
Char-steam reforming	$C + H_2O \longrightarrow CO + H_2$	(7)
	$C + 2H_2O \longrightarrow CO_2 + 2H_2$	(8)
	$C + H_2O \longrightarrow \frac{1}{2}CH_4 + \frac{1}{2}CO_2$	(9)
Water-gas shift	$CO + H_2O \longrightarrow CO_2 + H_2$	(10)
Methane reforming	$CH_4 + H_2O \longrightarrow CO + 3H_2$	(11)

Due to the water gas shift reaction, char-steam reforming and methane reforming, the concentrations of CO_2 and H_2 increased with an increasing steam feed rate, while the CO concentrations decreased.

As the gasifying agent, steam from the external source has a high cost. Therefore, the sensible heat of the producer gas can be used to produce steam without an external heat source. (a self-produced system in the same reactor). This steam is fed into the gasification process to produce the enhanced hydrogen gas.

In this study, the downdraft gasifier system is 50 kW_{th}, which uses air as a gasifying agent. It has been found that such a system produces hydrogen at a low concentration. Therefore, a small heat exchanger can be used for this downdraft gasifier system.

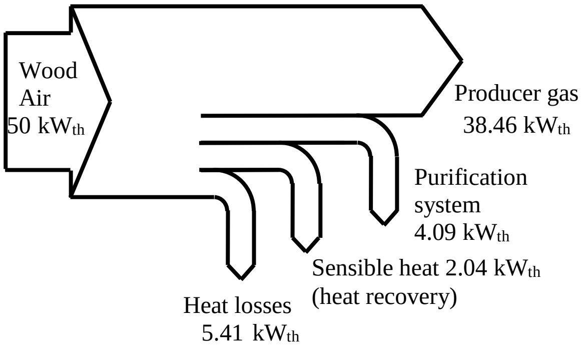


Figure 1 Sankly diagram for energy balance of a 50 kW_{th} downdraft gasifier.

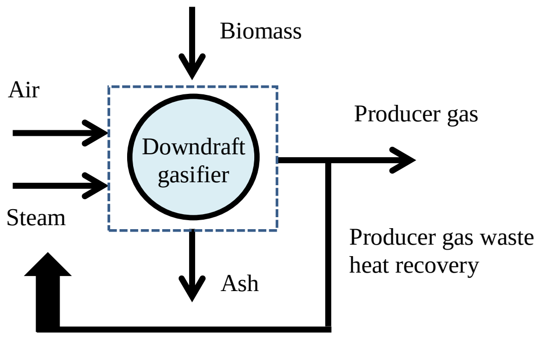


Figure 2 A scheme of the steam generator using waste heat from the same reactor

In Fig. 1 it is indicated that waste heat is 2.04 kW_{th} or 4.1% of total energy input. It can be reused through the heat exchanger.

1.1 Air/steam gasification by using waste heat

The use of air/steam mixture, as gasifying agent, will result in a more efficient production of producer gas, if the process of steam production does not require an external heat source. In this study, steam is generated by the heat taken from the hot producer gas. The 4.1% of total energy (waste heat) is derived from biomass feedstock, and it can produce enough steam for this system. Consequently, a small heat exchanger is designed for steam production, and it can be installed outside the downdraft gasifier where the temperature of the reactor would not be affected as shown in Fig. 3.

The heat exchanger installed close to the throat of the reactor will result in the oxidation of reactor temperature which is not good for the gasification system. The heat exchanger was installed at the outlet of the downdraft gasifier, which is far enough from the oxidation zone.

The subject matter in this article is the evaluation of the effects of steam feed rate to influence the composition of producer gas, including high heating value on the experimental results of the downdraft gasifier. Also, the heat exchanger effectiveness and the cold gasification efficiency will be reported.

2. Methodology

2.1 Downdraft gasifier

To conduct the experimental investigation a downdraft gasifier of 50 kW_{th} capacity unit wass used. A small heat exchanger has been built to be used with the gasification unit. A scheme for using waste heat to produce steam internally is shown in Fig. 2 and the schematic diagram of the gasification system used in performing gasification experiments is shown in Fig. 3. The downdraft gasifier is constructed of cylindrical tube with an inner diameter of 0.40 m and the total height of 0.95 m. The hopper capacity is 20 kg of wood chip. The reactor temperature of the downdraft gasifier is measured by a K-type thermocouple located at the throat of oxidation zone. To measure the flow rate of the air and producer gas, two U-tube manometers are installed in the system. The first u-tube manometer measures the rate of air flow into the gasifier and the other one is used to measure the flow rate of the producer gas. In addition, the temperature of the producer gas at the outlet of the downdraft gasifier and the temperature of the exhaust gases from the heat exchanger are also measured. The heat exchanger is installed between the outlet pipe of the downdraft gasifier and cyclone. Water flowing from the tank to the heat exchanger is boiled into steam with 100-120°C at 1.0-1.2 bar. By a steam control valve, steam, as a gasifying agent, flows into the downdraft gasifier at tdifferent flow rates ranging from 0.7 to 2.6 kg/h. The specifications of the downdraft gasifier system are given in Table 2.

Table 2 Specifications of the downdraft gasifier system.

Parameter	Description
Gasifier type	Downdraft
Capacity (kW_{th})	50
Fuel	Wood chip (Alstonia scholaris)
Fuel size (cm)	2.5 x 2.5 x 2.5 cm^3
Internal diameter (m)	0.40
External diameter (m)	0.45
Height (m)	0.95
Divergence angle (°)	45

Gas cleaning apparatus consists of cyclone, condenser with a cooling tower and carbon filter. Experimental trials have been carried out by using the steam, as gasifying agent. For each flow rate of steam, 4-experimental trails have been done with different settings of steam supply to measure the increase in hydrogen. The air supply was fixed throughout the experiment. Wood chips, of approximate size 2.5 x 2.5 x 2.5 cm^3, are used as the fuel. To measure the properties of the producer gas, a gas analyzer (MRU VARIOplus Gas Analyzer) [16] is installed at the outlet pipe of the downdraft gasifier system.

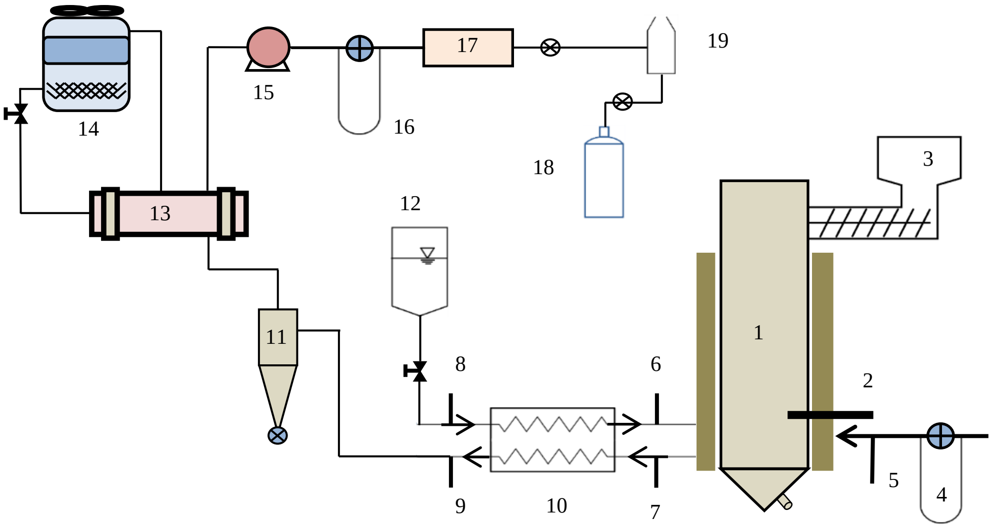


Figure 3 Schematic diagram of steam gasification unit.

(1) Downdraft gasifier; (2) Reactor temp, T_2; (3) Feed Hopper; (4) Air flow meter; (5) Air inlet temp,T_5; (6) Steam temp, T_6; (7) Hot gas temp, T_7; (8) Water inlet temp, T_8 ; (9) Hot gas outlet, T_9 Thermocouple; (10) Heat exchanger; (11) Cyclone; (12) Water tank; (13) Condenser; (14) Cooling tower; (15) Root blower; (16) Gas flow meter; (17) Gas analyzer; (18) LPG tank; (19) Gas burner

2.2 Waste heat from producer gas

It has been found that the producer gas flows out of the downdraft gasifier with temperatures of 350°C at a flow rate of 32 Nm^3/h. The sensible heat of the producer gas is 2.04 kW_{th}. It can be reused by boiling the water into steam; and can be used as an gasification agent in the downdraft gasifier system. In this study, the heat exchanger is used to extract heat from the producer gas for steam production.

The sensible heat (waste heat) of producer gas can be calculated.

$$\dot{Q}_{\text{waste heat}} = \dot{m} C_p \Delta T \qquad (12)$$

where

$\dot{Q}_{\text{waste heat}}$ = Heat rate of producer gas, kW_{th}
$\dot{m}$ = Producer gas mass flow rate, kg/s
C_p = Specific heat capacity at constant pressure, kJ/kg°C
ΔT = Temperature difference of producer gas, °C

2.3 Cold gas efficiency, CGE

Cold gas efficiency is the ratio of energy in the producer gas divided by the energy content in the wood chips [17] :

$$\text{CGE} = \frac{\text{HHV of producer gas } (\text{kJ}/\text{Nm}^3) \times \text{Producer gas production } (\text{Nm}^3/\text{kg})}{\text{HHV of biomass fed into the gasifier } (\text{kJ}/\text{kg})} \tag{13}$$

2.4 Shell and tube heat exchanger

In this study, a heat exchanger with one shell (65 mm ID, 74 mm OD) and seven tubes (12.5 mm ID, 17.0 mm OD, thermal conductivity, k = 20 $\text{W}/\text{m}^2 \cdot \text{K}$) passes has been designed as shown in Fig. 6(a), and it is covered by 10-mm thickness insulation to prevent heat loss as shown in Fig. 6(b). The arrangement and cross section of heat exchanger are shown in Fig. 6(c). Hot producer gas flows in tubes boils water to steam. The inlet and outlet temperatures of hot producer gas are 350°C and 170°C, respectively. At the rate of 2.6 kg/h, water flows through the shell and becomes steam, where its temperature increases from 30°C to 120°C at 1.2 bar.

2.5 Heat Recovery Steam Generation, HRSG (see Fig. 5(b))

Energy balance

$$\dot{Q}_{\text{HE}} = \underbrace{\dot{m}_{\text{water}} C\Delta T}_{\text{Sensible heat}} + \underbrace{\dot{m}_{\text{steam}} h_{fg}}_{\text{Latent heat}} + \underbrace{\dot{m}_{\text{steam}} C\Delta T}_{\text{Sensible heat}} \tag{14}$$

where

$\dot{Q}_{\text{HE}}$ = Rate of heat transfer from hot producer gas to water by heat exchanger
$\dot{m}_{\text{water}} C\Delta T$ = Rate of sensible heat addition of water
$\dot{m}_{\text{steam}} h_{fg}$ = Rate of latent heat addition of vaporization of saturated steam
$\dot{m}_{\text{steam}} C\Delta T$ = Rate of sensible heat addition of vapor

The expression of the maximum heat transfer through a heat exchanger [18] may be written as:

$$\dot{Q}_{\text{max}} = UA\Delta T_{\text{LM}} \tag{15}$$

where

$\dot{Q}_{\text{max}}$ = Heat transfer rate, kW_{th}
U = Overall heat transfer coefficient, $\text{W}/\text{m}^2 \cdot \text{K}$
A = Surface area, m^2
ΔT_{LM} = Logarithmic mean temperature difference as the following equation

$$\Delta T_{\text{LM}} = \frac{[(T_{h_i} - T_{c_o}) - (T_{h_o} - T_{c_i})]}{\ln\,[(T_{h_i} - T_{c_o})/(T_{h_o} - T_{c_i})]} \tag{16}$$

where

T_{h_i}, T_{h_o} = Inlet and outlet temperature of hot fluid
T_{c_i}, T_{c_o} = Inlet and outlet temperature of cold fluid

2.6 The effectiveness

The effectiveness of heat exchanger, ε [19], is defined as

$$\varepsilon = \frac{\dot{Q}_{HE}}{\dot{Q}_{max}} = \frac{\text{Actual heat transfer rate}}{\text{Maximum possible heat transfer rate}} \tag{17}$$

2.7 Assumptions

In the test, there are 10 assumptions as follows:

1. The downdraft gasifier operates at atmospheric pressure and steady-state flow conditions;
2. Potential and kinetic energies are negligible;
3. Gases except H_2, CO, N_2, CO_2, and CH_4 are considered as the diluted gases;
4. Ash residue behind gasification process is negligible;
5. Producer gas density and specific heat are 1.3 kg/m^3 and 1.45 kJ/kg.^{o}C respectively;
6. The downdraft gasifier is isothermal and at equilibrium condition;
7. Air is composed of 21% O_2 and 79% N_2;
8. Tar formation and liquid in the process are negligible;
9. The reactions occur isothermally and at equilibrium condition; and
10. The downdraft gasifier system is represented by the schematic diagram as shown in Fig. 3.

Figure 4 Gasification unit

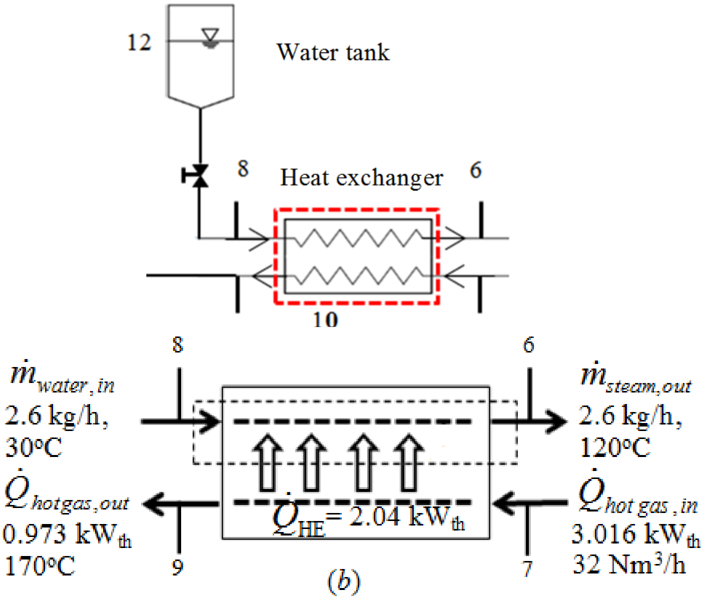
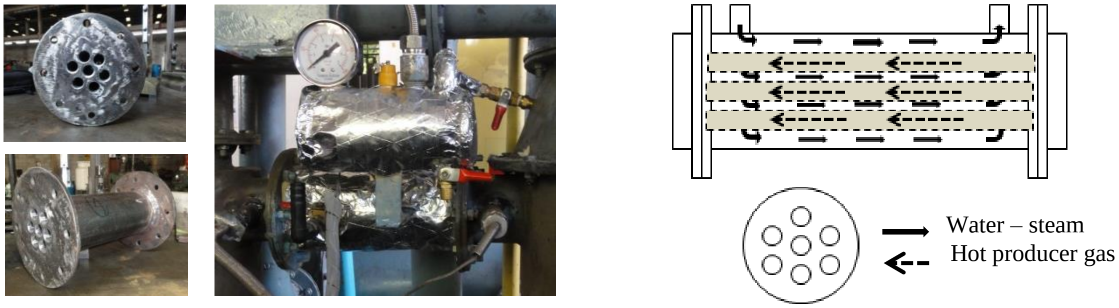


Figure 5 Energy balance of heat exchanger



(*a*) Heat exchanger prototype (*b*) Heat exchanger used in the system (*c*) Cross section of heat exchanger

Figure 6 Shell and tube heat exchanger and cross-section configuration

3. Experimental procedure

Wood chips are fed into the downdraft gasifier by a screw feeder at a rate of 14 kg/h controlled by a limit switch as shown in Figure 4. The ambient air is fed into the downdraft gasifier by root blower at 14.13 m^3/h at 30°C. Then, wood chips are converted into producer gas at the temperature of 920°C. Most producer gases are mainly comprised of CO, H_2, CO_2, CH_4, and N_2.

The hot producer gas from the reactor flows through the heat exchanger, cyclone, and cooling units, respectively. Heat exchanger (or steam boiler) receives waste heat from the hot producer gas and changes water into steam at the rate of 0.7-2.6 kg/h at temperature of 120°C as shown in Figure 5. Air/steam mixture are supplied to the oxidation zone of the downdraft gasifier. During experimental investigations, the downdraft gasifier has been filled with the wood chips. The producer gas is continuously analyzed on-line by a gas analyzer (MRU-Varioplus industrial) that is being installed at the end of a sampling line.

Experimental trials have been done by using the steam as a gasifying agent. For each flow rate of the steam, 4-experimental trails have also been done with different settings of the steam supply to measure the increase in hydrogen. The air is kept supplied at a constant flow rate throughout the experiment. Both proximate and ultimate analyses of a wood chip are given in the Table 3.

Table 3 The proximate and ultimate analysis results of a wood chip (Alstonia scholaris).

Wood chip					
Proximate analysis (% dry basis)			Ultimate analysis (% dry basis)		
Volatile matter	78.35	%	C	46.54	%
Ash content	3.37	%	H	5.84	%
Fixed carbon	17.30	%	N	0.10	%
HHV	15.63	MJ/kg	O	44.23	%
Moisture	1.15	%			

4. Results and discussion

The results of the experiments are shown in Figs.7-11. The cold and hot fluid temperatures of shell and tube heat exchanger are shown in Fig. 7. It is outstanding that the producer gas composition over time seems to be constant over the experimental time as shown in Fig. 8. Also, it can be seen that the steam catalyst can continuously be activated over the testing period for gas production. The bar graph in Fig. 9 shows a comparison of the producer gas composition resulting from two-different gasifying agents which are air and air-steam. It is clearly seen that the hydrogen content is 19% higher than that without steam (11%). It can be summarized that the use of waste heat from the producer gas increases hydrogen content without an external heat source.

4.1 Counter flow heat exchanger: Temperature distribution

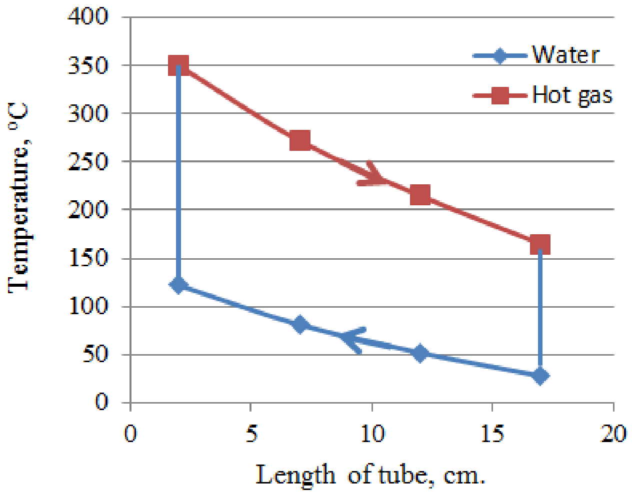
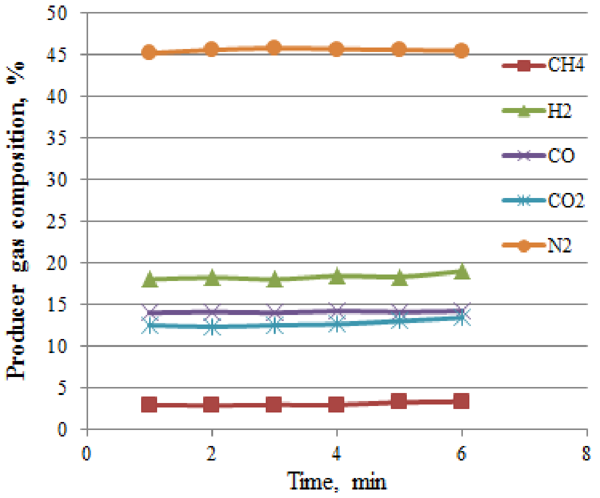


Fig. 7. Counter flow temperature distribution.

The variation of temperatures for both the hot producer gas and water in a shell and tube heat exchanger is shown in Fig. 7. It is noted that the hot producer gas and cold water enter the heat exchanger from opposite ends. The temperature difference at each end is very satisfactory.

Fig. 8 shows the composition of the producer gas resulting from the air-steam gasification. Each value of the gas concentration is quite constant throughout the experiments. Fig. 9 shows a comparison of the producer gas composition~~s~~ between air and air-steam gasifications. It is noted that H_2 and CH_4 have been increased by 8% and 2%, respectively, while CO is slightly decreased. Because H_2 from the reaction (6) reacts with the carbon to CH_4 and steam is fed into the reaction (8) reacts with the CO into CO_2.

4.2 Composition of producer gas



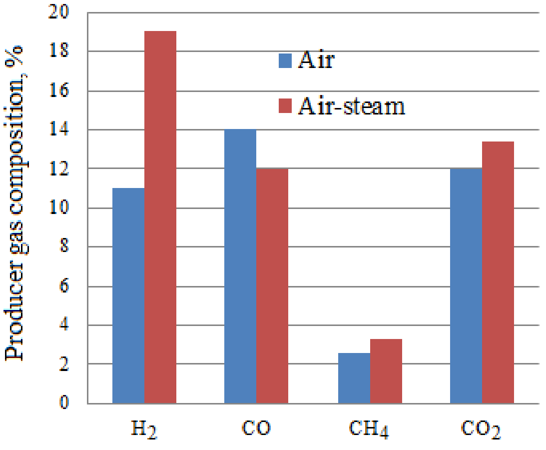


Figure 8 The gas composition versus time at 920°C and steam feed rate of 2.6 kg/h (ER = 0.45)

Figure 9 Effect of steam on gas composition. Comparison between the use of air and air-steam as the gasifying agents. (ER = 0.45) at steam feed rate of 2.6 kg/h

4.3 Composition of producer gas and high heating value (HHV)

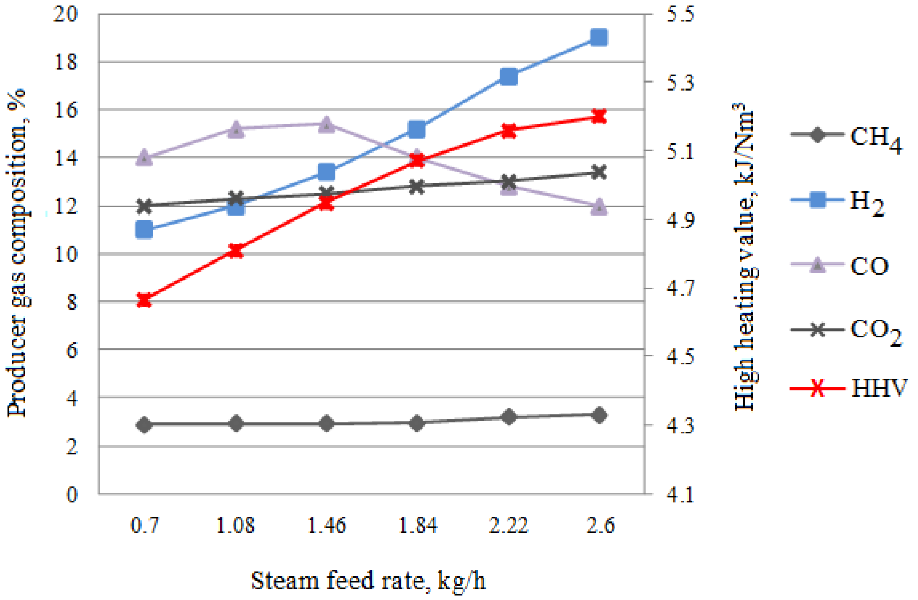


Figure 10 Effect of the steam on high heating value (HHV) (ER = 0.45)

Fig. 10 shows the influence of the steam on the dry gas yielded and the variation of the producer gas composition at the outlet of the downdraft gasifier as a function of the steam flow rate. An increase in the steam flow rate results in a change in the producer gas composition. At the steam flow rate greater than 1.46 kg/h, the molar fraction of CO starts decreasing, but H_2 and CH_4 are increased while steam flow rate is increased. In addition, the HHV is also increased by the steam feed rate. The experiments cannot increase the steam feed rate beyond 2.6 kg/h because waste heat is limited. It can be summarized that H_2 production of the air-steam gasification has been increased by 8% compared to that of the air gasification.

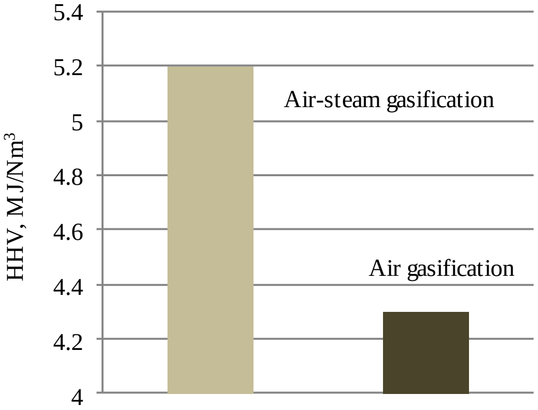


Figure 11 Effect of the steam on high heating value (HHV) of the producer gas (ER =

Fig. 11 shows the high heating value (HHV) of the producer gas as a function of the steam feed rate. The HHV of the producer gas resulting from the air-steam gasification is 4.7-5.2 MJ/Nm^3, which is 16% higher than that resulting from the air gasification. While the steam feed rate is changed from 0.7 to 2.6 kg/h, the HHV seems to be steadily increased. Table 4 presents the performance of air-steam gasification system.

Table 4 A summary of the performance of using the steam as a gasifying agent~~.~~

Gasifying agent	Air	Air-steam
Maximum steam feed rate [kg/h]	0	2.6
Volume flow rate of air [Nm^3/h]	14.13	14.13
Reactor temperature [^{o}C]	920	920
Fuel consumption [kg/h]	14	14
Producer gas flow rate [Nm^3/h]	31	32
H_2 [%]	11	19
CO [%]	14	12
CO_2 [%]	12	13.5
CH_4 [%]	2.6	3.3
HHV [kJ/Nm^3]	4,300	5,200
Cold gas efficiency, CGE [%]	69.4	82.8
Equivalent ratio, ER	0.45	0.45
The effectiveness of heat exchanger, ε = 0.92		

5. Conclusions

This article presents the experimental study on self-produced steam by the waste heat recovery from hot producer gas. The experimental result shows that the use of waste heat to produce steam, a gasifying agent, increases the hydrogen concentration. The hydrogen-rich output resulting from the air-steam gasification is 8% higher than that resulting from the air gasification. Without using an external heat source, HHV has slightly been increased by the use of steam derived from use of waste heat. The waste heat from the producer gas can produce the steam at a maximum rate of 2.6 kg/h by using a small heat exchanger installed in the system. To conclude, the performance of the producer gas resulting from the air-steam gasification system is better than that the result from the air gasification system.

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Nomenclatures

A	area (m^2)
C_p	specific heat capacity at constant pressure (kJ/kg ^oC)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
t	time (s)
T	temperature (K)
U	heat transfer coefficient (W/m^2 ^oC)
k	thermal conductivity (W/m^oC)
HHV	high heating value (MJ/Nm^3)
CGE	cold gas efficiency

Greek Symbols

ε	heat exchanger effectiveness

Subscripts

th	thermal power
fg	difference in property between saturated liquid and saturated vapor
HE	heat exchanger
c	cold
h	hot
i	inlet
o	outlet