

Simulation and Testing of the Calorific Value and Cost Analysis of Biomass Pyrolysis for Heating, Cooling, and Power Production

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Ni-based catalysts supported on olivine were synthesized for cracking the biomass and producing the syngas. Syngas is used directly as fuel source for the cooling, heating, and power (CCHP) system, which can be produced through biomass pyrolysis process. Integrating combined CCHP systems with biomass pyrolysis results in a sustainable distributed energy system that effectively utilizes biomass resources and improves energy efficiency. To achieve a higher energy efficiency and more cost-effective operation, a simplified cost analysis method based on the Advanced System for Process Engineering (Aspen Plus) was applied to the CCHP system based on biomass pyrolysis. First, syngas was used as a fuel source for the CCHP system, which can be produced through a biomass pyrolysis experiment. In the experiment, the yields of the gas before and after the addition of a catalyst were compared. Second, syngas was passed to the reactor in Aspen Plus, which simulated the calorific values of the syngas produced by biomass pyrolysis under different conditions. Moreover, the simulated syngas heat values were applied to a TFRJ3K straw gas engine. Finally, the cost of the syngas for power generation, cooling, and heating was calculated. The power generation cost was 1.2 RMB/kW, the air conditioning refrigeration cost was 22.752 RMB/d, and the household heating cost was 20 RMB/d.

Keywords: Biomass; Pyrolysis; Syngas; CCHP; Cost analysis

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INTRODUCTION

Combined cooling, heating, and power (CCHP) systems that use natural gas as fuel are efficient and act as environmental energy distribution systems in buildings (Wang *et al.* 2014). The problem of energy shortages and environmental pollution has made the energy sector focus increasingly on issues concerning saving fossil fuels and renewable energy development (Wang *et al.* 2015b). Among energy resources, biomass is considered the fourth largest energy source, after oil, coal, and natural gas (Maraver *et al.* 2013; Wang *et al.* 2015b). Therefore, the development and utilization of biomass energy has become an important task (Mertzis *et al.* 2014).

Wang *et al.* (2016) studied the key parameters of the biomass gasification process, proposed suitable temperatures and oxygen equivalent ratios, and simulated the process with Aspen Plus. Wang *et al.* (2015a) studied the effective energy efficiency and effective

energy destruction of the cooling, heating, and power system, product cost and cost allocation, and proposed a sensitivity analysis to determine the factors that affect the unit energy consumption cost of the product, such as the biomass and investment costs, interest rate, service life, and operating hours.

In this study, the effect of Ce and La promoter on the reaction activity were investigated, and the prepared catalysts were calcined at different temperatures. The experimental results showed that different catalysts and calcination temperatures will have a greater impact on the composition and content of biomass syngas. A simplified Aspen Plus model was proposed to introduce biomass syngas into this model and more intuitively observe the cost of biomass for refrigeration, heating, and power generation.

EXPERIMENTAL

Materials

The biomass used in the experiment was wheat straw collected from a farm in Hubei Province. The straw was dried in the natural conditions for a week to remove natural moisture. The materials used included natural olivine (Xixia Hongtai Olivine Co. Ltd., Xixia Henan, China), nickel nitrate (AR, Tianjin Damao Chemical Reagent Factory, Tianjin, China), sodium metavanadate (AR, Tianjin Beilian Fien Chemicals Development Co. Ltd., Tianjin, China), cerium nitrate hexahydrate (AR, Shanghai Macklin Biochemical Co. Ltd., Shanghai, China), lanthanum nitrate (AR, Shanghai Shanpu Chemical Co. Ltd., Shanghai, China), and urea (AR, Tianjin Kaitong Chemical Reagent Co. Ltd., Tianjin, China). The software used was Aspen Plus (AspenTech, Bedford, MA, USA).

Methods

Biomass preparation

The wheat straw was crushed, ground, and sieved to a particle size between 0.15 and 0.3 mm. This particle size made it possible to provide the heat transfer required for the pyrolysis step. The treated wheat straw was placed in a sealed bag and stored under natural conditions for the further use.

Preparation of the catalysts

First, the olivine was crushed to a 20-mesh to 30-mesh size in a crusher (Atong *et al.* 2011). Second, a certain percentage of the olivine and nickel nitrate was placed in a 500-mL three-necked flask. Next, 60 g of urea and 250 mL of deionized water were added to the 500-mL three-necked flask. The three-necked flask was placed in an oil bath and reacted at 115 °C for 2 h, and then stood for 2 h. After evaporation of the excess water, the samples were dried overnight at 110 °C and calcined at 900 °C to 1100 °C for 2 h with a heating rate of 10 °C/min (Shi *et al.* 2018). Finally, six catalysts were synthesized, a) 900-Ni-V, (b) 900-Ni-V-Ce, (c) 900-Ni-V-La, (d) 1100-Ni-V, (e) 1100-Ni-V-Ce, and (f) 1100-Ni-V-La (Named according to the elemental composition of the catalyst using the symbol of the element in the period table).

Evaluation of the Catalytic Activity

The activity of the Ni/olivine catalyst was evaluated in a BTF-1200 fixed pyrolysis furnace (Anhui Beyik Equipment Technology Co. Ltd., Hefei Anhui, China) (Fig. 1).

The wheat straw and catalytic bed with a catalyst, which was in a porcelain boat, was sent to the pyrolysis furnace through the flange mouth before the trial. The purpose of introducing nitrogen was to discharge the air that was in the fixed pyrolysis furnace. The bricks were insulated to maintain the temperature of the reactor. The reactor was pushed to where the biomass particles stayed and the cracking temperature was set (Shi *et al.* 2018). A Gasboard-3100 infrared gas analyzer (Hubei, Ruiyi Automatic Control System Co. Ltd., Wuhan Hebei, China) was used to analyze the gas composition and content. The exhaust gas was processed or burned.

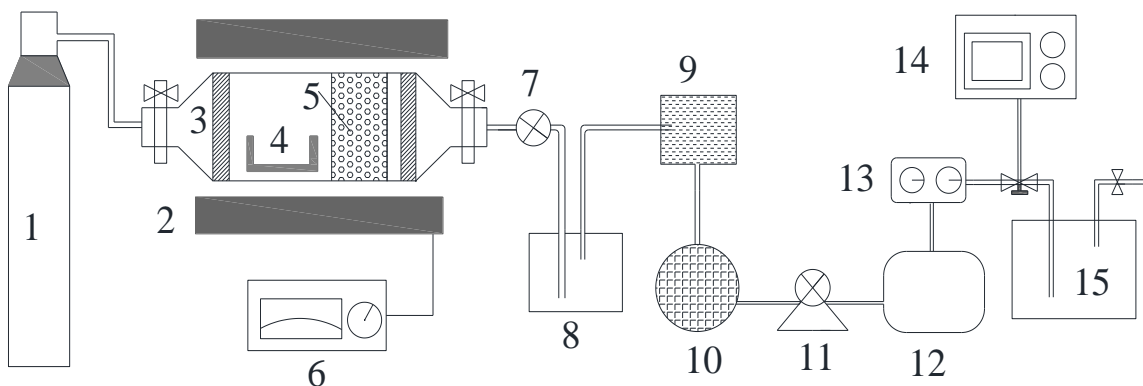


Fig. 1. Flow scheme of the bench scale reactor for catalytic pyrolysis of the straw biomass: (1) nitrogen; (2) pyrolysis gasifier and thermocouples; (3) insulation brick; (4) porcelain boat; (5) catalytic bed and catalyst; (6) temperature controller; (7) waterproof valve; (8) water channel; (9) particle filter; (10) gas dryer (silica gel); (11) pump; (12) gas buffer package; (13) flowmeter; (14) gas analyzer; and (15) fire prevention

RESULTS AND DISCUSSION

Characterization of the Catalysts

XRD analysis

X-ray diffraction was conducted to obtain structural information about the freshly synthesized olivine samples. Figure 2 shows the XRD patterns for the catalysts.

The XRD patterns of the Ni/V, Ni/V-Ce, and Ni/V-La catalysts are shown in Fig. 2. In the case of the 900-Ni/V catalyst, the peaks at 43.419° and 62.919° were identified as NiO (PDF#71-1179) (Quan *et al.* 2018).

In the case of the 900-Ni/V-Ce catalyst, the peaks at 28.063° , 32.379° , and 54.980° were identified as Ce_2O_3 with the pattern PDF#71-0567 (Mokhnachuk *et al.* 2007).

In the case of the 900-Ni/V-La catalyst, the peaks at 29.899° , 39.897° , and 52.420° were identified as La_2O_3 with the pattern PDF#73-2141 (Remiro *et al.* 2013; Valle *et al.* 2013). In the case of the 1100-Ni/V catalyst, the peaks at 36.560° , 43.318° , 62.860° , and 79.120° were identified as NiO (PDF#71-1179) (James *et al.* 2014; Quan *et al.* 2018).

In the case of the 1100-Ni/V-Ce catalyst, the peaks at 27.840° , 35.659° , and 67.121° were identified as Ce_2O_3 with the pattern PDF#74-1145 (Mokhnachuk *et al.* 2007).

In the case of the 1100-Ni/V-La catalyst, the peaks at 26.177° , 29.920° , and 62.039° were identified as La_2O_3 with the pattern PDF#73-2171 (Mazumder and de Lasa 2015).

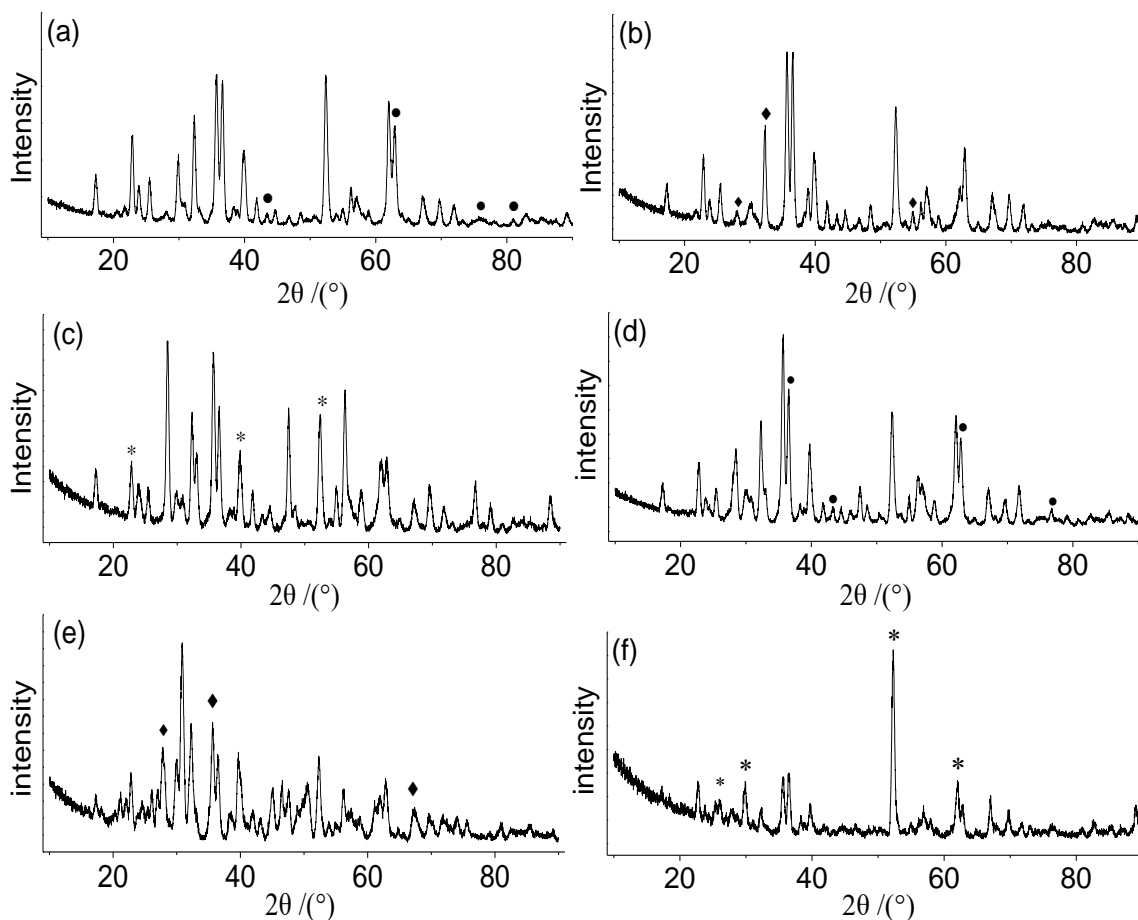


Fig. 2. XRD patterns of the catalysts: (a) 900-Ni-V, (b) 900-Ni-V-Ce, (c) 900-Ni-V-La, (d) 1100-Ni-V, (e) 1100-Ni-V-Ce, and (f) 1100-Ni-V-La

Influences of the Process Conditions

Syngas yield of biomass

The influence of pyrolysis temperature of 600 °C on syngas component by the catalysts is shown in Fig. 3.

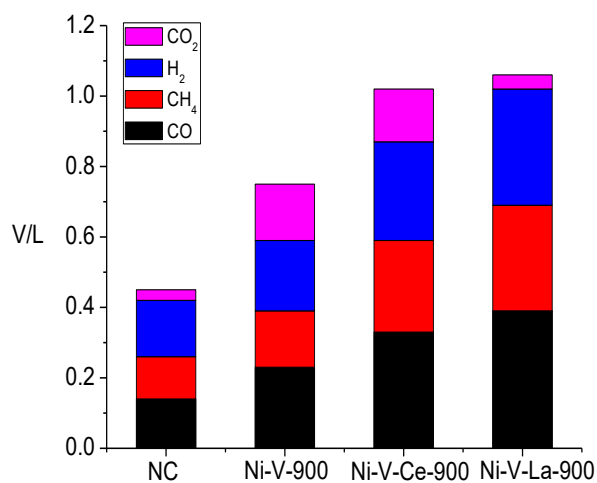


Fig. 3. Influence of calcination at 900 °C with a pyrolysis temperature of 600 °C

The effects of pyrolysis temperature of 800 °C on syngas components by the catalysts are shown in Fig. 4.

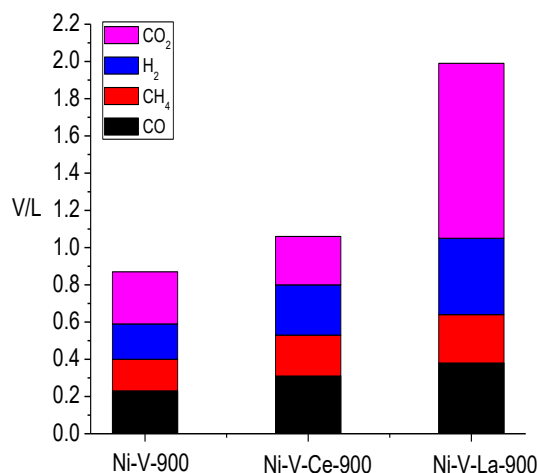


Fig. 4. Influence of calcination at 900 °C with a pyrolysis temperature of 800 °C

The effects of calcination at 900 °C on syngas components by the catalysts are shown in Fig. 5.

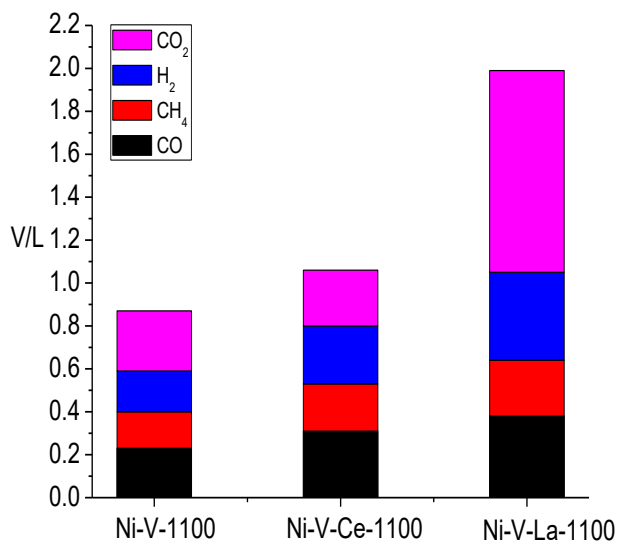


Fig. 5. Influence of calcination at 1100 °C with a pyrolysis temperature of 600 °C

The influence of calcination at 1100 °C on syngas component by the catalysts is shown in Fig. 6.

Effect of the calcination temperature

Figures 3 through 6 compare the gas production of the experimentally determined syngas catalyzed at different calcination temperatures. The syngas yield after adding the catalyst was higher than that with no catalyst (Cheah *et al.* 2013). The carbon monoxide (CO), methane (CH₄), and hydrogen (H₂) yields obtained by calcining the catalyst at two different temperatures were not very different. However, the carbon dioxide (CO₂) yield

produced by the catalyst calcined at 1100 °C was higher than that of the catalyst calcined at 900 °C (Zhang *et al.* 2014). This was because in the catalytic pyrolysis of straw, a lot of tar was produced (Yu *et al.* 2009). Tar causes corrosion and blockage of the equipment pipeline, and the produced CO₂ has a good effect on the catalytic cracking of the catalyst tar (Rezaei *et al.* 2014).

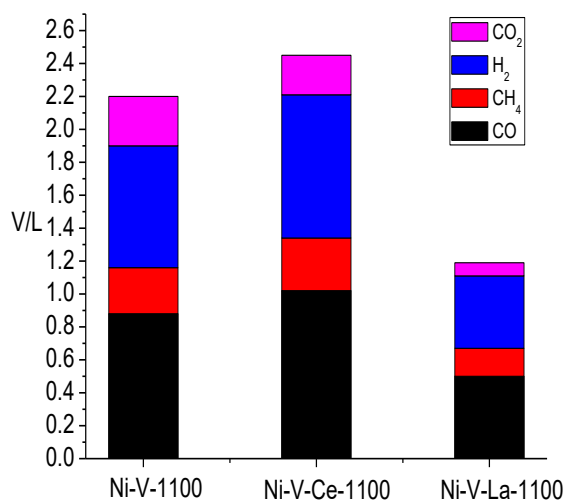


Fig. 6. Influence of calcination at 1100 °C with a pyrolysis temperature of 800 °C

Effect of the pyrolysis temperature

With an increase in the pyrolysis temperature, the CO, CH₄, H₂, and CO₂ contents increased (Horne and Williams 1996). The pyrolysis temperature greatly affected the catalytic performance of the catalyst, which could promote the syngas yield with an increase in the temperature. Higher pyrolysis temperatures are more likely to promote the cracking of tar (Pütün 2010). The cracking of tar promoted the production of H₂, CH₄, and CO (Yu *et al.* 1997). From the above results, the production of syngas at 800 °C was higher than that at 600 °C. This was because at the high pyrolysis temperature, the catalytic activity of the catalyst was promoted, which made the C-H bonds easier to break and caused an increase in the syngas content (Yang *et al.* 2010). Meanwhile, the deposited carbon reacted with CO₂, which caused a relatively high CO content and low CO₂ content (Yang *et al.* 2010).

CCHP System

The CCHP system was conceptualized as two modules. One module was biomass pyrolysis gas production, and the other module was the use of syngas (Wang *et al.* 2015a). In the first module, the gas data obtained from the pyrolysis experiments was used, and the resulting gas data was used in the Aspen Plus software for simulation. In the simulation process, the calorific value produced by the combustion of syngas and oxygen was obtained. The simulated calorific values are shown in Table 1.

Calorific Value Analysis

From Table 1, the highest calorific value was 251.4 J/s. Because the Ni/V-Ce catalyst was added during this pyrolysis process, it was calcined at 1100 °C. Ion-exchange metallic-nickel and cerium nanoparticles were oxidized after calcination, which has been

found to be an effective catalyst composition for the catalytic cracking of biomass. The pyrolysis process was performed at 800 °C, which is a high pyrolysis temperature. The catalytic activity of the catalyst was promoted, which made the C-H bonds easier to break and caused an increase in the H₂ content. Meanwhile, the deposited carbon reacted with CO₂, which caused a relatively high CO content and low CO₂ content.

Table 1. Calorific Value of the Syngas

Catalysts	Calorific Value	
	Cal/s	J/s
NC-600	17.85	74.73
900-NI-V-600	39.41	164.95
900-NI-V-Ce-600	42.98	179.90
900-V-La-600	44.89	187.91
NC-800	39.66	166.02
900-NI-V-800	39.88	166.94
900-NI-V-Ce-800	47.95	200.72
900-NI-V-La-800	53.56	224.21
1100-NI-V-600	39.41	164.95
1100-NI-V-Ce-600	42.08	176.16
1100—NI-V-La-600	45.27	189.51
1100-NI-V-800	56.13	234.96
1100-NI-V-Ce-800	60.07	251.43
1100-NI-V-La-800	46.04	192.71

Equipment Parameter Analysis

Process parameters of the TFRJ3K straw gas engine

The process parameters of the TFRJ3K straw gas engine purchased from Taifa Company (Zhejiang Taifa Mechanical & Electrical Industry Co. Ltd., Taizhou, Zhejiang, China) are given in Table 2.

Table 2. Process Parameters of the TFRJ3K Straw Gas Engine

Model	T420	Maximum Output Power	
Type	Forced Air Cooling	Size L × W × H mm	700 × 525 × 580
Spinning Speed	800 rpm	Weight (kg)	95
Fuel	Straw Gas	Ignition System	Transistor Ignition
Gas Consumption	3.76 Nm ³ /kWh	Start System	Electric Start
H ₂ Minimum Score	14%	Exhaust Gas Temperature	450 °C
Minimum Calorific Value of Gas	4 MJ/Nm ³	Thermal Efficiency	26.5%

TFRJ3K straw gas power generation process parameters

The parameters for power generation in the TFRJ3K straw gas engine are given in Table 3.

Table 3. TFRJ3K Straw Gas Power Generation Process Parameters

Model	TFBG3GF	Piston Movement Volume	3.2 L
Type	Brushed 3 phase	Compression Ratio	9.0
Rated Power	3 kW	Test Maximum Power	3.1 kW
Maximum Output Power	3.3 kW	Voltage Regulation	Automatic Voltage Regulation

From Tables 2 and 3, the H₂ content in the syngas in the pyrolysis experiment was greater than 14%. Therefore, the experimental results can meet the requirements of the power generation equipment. The output of 220V (in China) reaches the standard of household appliances, and the rated power of power generation is 3 kW, which also can meet the requirements of general household appliances. So the equipment can be applied to CCHP mode under the condition that the experimental results are met. The heat value generated by inputting 2 g of straw was 251.43 J/s; when 31.82 kg of straw were added, the calorific value generated was greater than 4 MJ/Nm³. Therefore, the gas output conditions met the parameters required by the generator equipment.

Cost Analysis of the Cooling, Heating, and Power System

Schematic diagram of the cost analysis of the cooling, heating, and power system

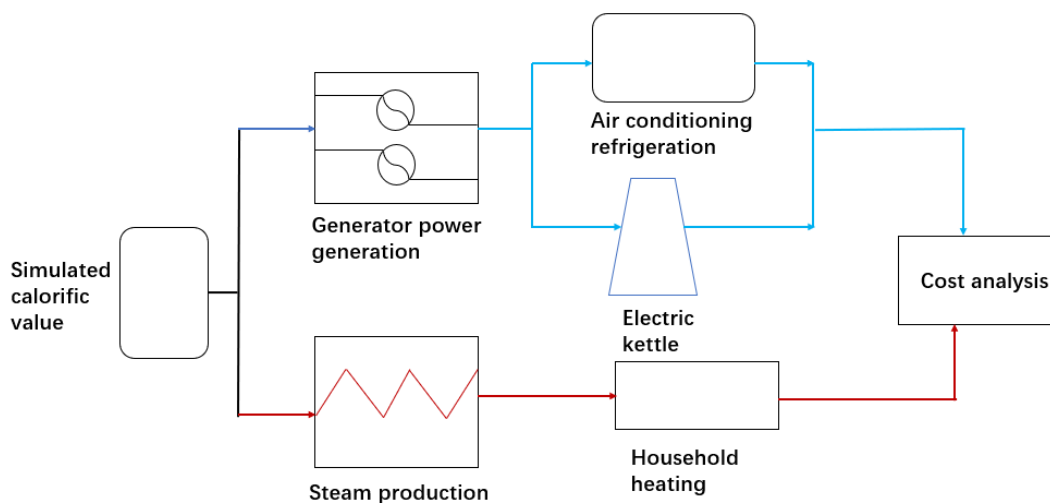


Fig. 7. Schematic diagram for the cost analysis of the cooling, heating, and power

From Fig. 7, the simulated calorific value was used to generate electricity and generate hot steam, the electricity generated was used for air conditioner cooling, and the electric kettle was used to boil hot water. The calorific value generated by straw, which was dried in the natural conditions for a week to remove natural moisture, was used to heat the boiler. The hot steam generated by the boiler was passed to the heating device in the home to perform heating in the winter. Based on the above analysis, the cost of coal-fired power generation can be compared.

For straw syngas power generation (Table 2), 1 g of straw has a calorific value of 125.7 J under the condition of satisfying the minimum calorific value of the TFRJ3K straw syngas generator. Because $3.6 \times 10^6 \text{ J} = 1\text{kW}\cdot\text{h}$, $3.6 \times 10^6 \text{ J} \times 26.5\% / 125.715 \text{ J} = 7588 \text{ g}$. It

follows that approximately 32 kg of straw were needed, which can generate 3 kW of electricity. The market price of the straw was approximately 120 RMB/ton. Calculated in this way, the cost of producing the straw needed for 1.0 kW·h of electricity was 0.12 kg/RMB. In other words, the economic electricity cost was 1.2 RMB. For example, an electric kettle has a power of approximately 1500 W and a pot of water can be boiled in approximately 10 min, which means it takes approximately 0.3 kW to boil a pot of water. Therefore, the economic cost of boiling a pot of water was 0.36 RMB. Another example was a 790 W air conditioner with a cooling temperature of 26 °C; if the air conditioner was used continuously for 24 h, it used 18.96 kW of electricity. Its economic cost was therefore 22.752 RMB.

For household heating, radiator heat can be simplified into a heat exchanger model for calculation. It was assumed in this study that the inlet temperature of the hot steam was 120 °C, the room temperature in the winter house was 10 °C, which was heated to 26 °C, and the heat exchange area was 3.14 m². The flow rate of the hot steam was 1.2 m/s. The equation for heating is as follows:

$$Q = W_h C_{p,h} (T_1 - T_2) = W_c C_{p,c} (t_2 - t_1) \quad (1)$$

where Q is the heat load of the heat exchanger (kW), W_h is the condensation rate of the saturated steam (kg/h), $C_{p,h}$ is the average constant pressure specific heat capacity of the fluid (kJ/(kg·°C)), T_1 is the hot steam inlet temperature (°C), T_2 is the hot steam outlet temperature (°C), t_2 is the room temperature after heating (°C), and t_1 is the room temperature before heating (°C).

From the above equation and using a T_2 of 107 °C, 60 kg of hot steam met the above conditions, provided that 60 kg of steam heat value requires 16.7 kg of biomass. Its economic value was 20 RMB.

CONCLUSIONS

1. After adding the catalyst, the content of syngas was significantly increased.
2. A simplified model of the simulated calorific value of biomass derived syngas was constructed. The biomass syngas yield produced from the experiments was close to the actual situation.
3. The calorific value simulated by the syngas was then used to calculate the cost of cooling, heating, and power by a household user.
4. In addition, the cost for different electricity usage methods was obtained. This provided a new way of thinking for the establishment of a future cooling, heating, and power model.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Technological Innovation Major Project of Hubei Province (Grant No. 2017ABA155) and the Public Welfare Industry (agriculture) Research special project (Grant No. 2015030135).

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Article submitted: December 22, 2018; Peer review completed: April 20, 2019; Revised version received: May 3, 2019; Accepted; May 6, 2019; Published: May 13, 2019.
DOI: 10.15376/biores.14.3.5224-5234