Korean J. Chem. Eng., **26**(2), 528-533 (2009)

Gasification of rice husk in a cyclone gasifier

Shaozeng Sun*, Yijun Zhao*,†, Fengming Su, and Feng Ling***

*Combustion Engineering Research Institute, School of Energy Science and Engineering,
Harbin Institute of Technology, Harbin 150001, P. R. China
**China Power Complete Equipment Co., Ltd., Beijing, 100011, P. R. China
(*Received 15 July 2008 • accepted 15 October 2008*)

Abstract−The experimental results of air gasification of rice husk in the cyclone gasifier were presented at the fuel rate of 20.1 kg/h. With the equivalence ratios varied in the range of 0.21-0.32, the heating value of the producer gas decreases from 6.98 MJ/Nm^3 to 3.11 MJ/Nm^3 and the cold gas efficiency decreases from 64% to 31%. However, the tar content in the prouder gas decreases with the increase of the equivalence ratio. The rice husk and ash were examined under a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) elemental analysis. The outer surface of the fuel particle which is of scale structure does not change basically during the gasification. The pyrolyzed gas is mainly released from the inner surface of the fuel particle.

Key words: Biomass, Gasification, Equivalence Ratio, Cyclone, SEM

INTRODUCTION

The use of renewable energy sources has become increasingly necessary because of the lack of fossil fuels and the serious environmental problems [1,2]. The structure of energy can be improved gradually by developing renewable energy sources. Biomass is the most common form of renewable energy and the use of biomass for energy generation is specially of interest. At present, gasification of biomass is taken as a popular technical route to produce fuel gas for application in boilers, engines, gas turbines or fuel cells.

China has studied most kinds of gasifying technologies, which include up-draft, down-draft, stratified down-draft and circulating fluidized bed (CFB) gasifiers, many of which have found practical applications [3]. But among all the existing technologies for biomass gasification, neither fixed bed nor fluidized bed can satisfy the requirements of industrial application completely because of their structural characteristics and operational conditions. These operational conditions are heavily influenced by the type and structure of the biomass source. A cyclone gasifier is a type of entrained-flow bed used as both a gas cleaner and a gasifier. This approach was put forward first by Fredriksson and Kallner who made experiments at the Royal Institute of Technology in Stockholm in a single inlet separation cyclone where the wood powder was injected by pressurized air and gasified at atmosphere pressure [4]. At the beginning of 1993, the research was continued at the Luleå University of Technology where tests were carried out with cyclones equipped with two or four inlets and where the fuel powder was injected with pressurized steam [5]. An inverted cyclone gasifier was designed by Syred et al. [6]. The gasifier was designed with a vortex collector pocket (VCP) and a central collector pocket (CCP) to maximize particle and ash separation from the flow, and remove alkali and other heavy metal traces that agglomerate with the ash particles.

China is the largest rice producer in the world, and rice husk is a kind of fine energy fuel. However, this resource has been poorly utilized, which is wasted and pollutes the environment. As a kind of abundant and competitive renewable energy resource, promoted by the large power requirements in China, rice husk power generation shows great promise [7]. Cyclone gasification of rice husk has rarely been studied. Literature shows that it will offer significant benefits over the more traditional technologies. The mass and heat transfer in the cyclone gasifier are intense, which results in smaller volume than the fixed bed. It can also reduce the demand for cleaning equipment after the gasifier. These combine together make signifi-

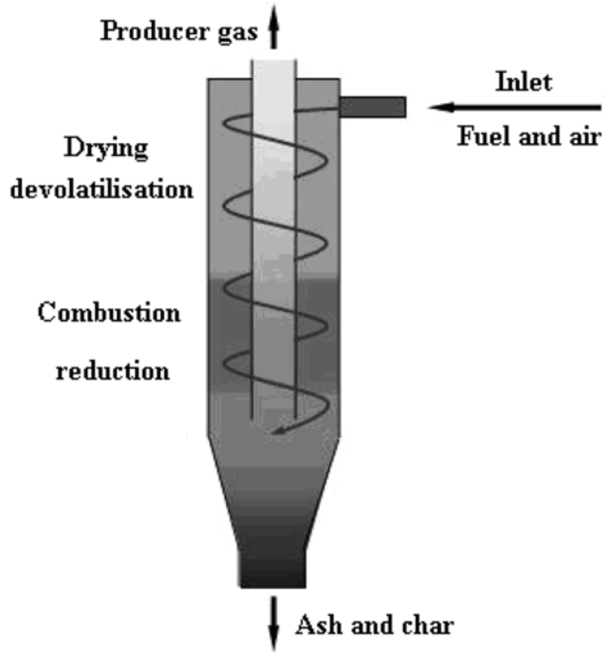


Fig. 1. Principle of biomass cyclone gasifier.

†To whom correspondence should be addressed.
E-mail: zhaoyijun@hit.edu.cn
‡This work was presented at the 7th China-Korea Workshop on Clean Energy Technology held at Taiyuan, Shanxi, China, June 26-28, 2008.

cant advances in reducing initial investment.

The features of cyclone flow mainly include an outer downward vortex and an inner upward vortex at the center. The rotating flow is maintained by the tangentially directed inlet flow. The stream is spiraling downward near the wall from the inlet to the bottom where the stream changes direction and spirals upwards, in the center of the cyclone towards the outlet. The principle of the biomass cyclone gasifier is shown in Fig. 1. As soon as biomass particles enter the cyclone gasifier with air gasification reactions take place. These reactions include drying, release of combustible volatiles, mixing of the volatiles and the oxidant, combustion of the volatiles and gasifying non-volatile combustibles. Ash and char are separated at the cyclone bottom [4,5].

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the cyclone gasifier pilot system is shown in Fig. 2. The experimental apparatus is made up of five parts: main body of cyclone gasifier, air supply system, fuel feeding system, electric heating and temperature control system and sampling system. The fuel feeding system consists of a governor motor, a fuel bin with screw feeder in the bottom and a downcomer. The downcomer is connected to the cyclone gasifier via the fuel injector. The chamber of the cyclone gasifier is made of temperature-resistant stainless steel that is 1,300 mm in height and 200 mm in diameter. A schematic of the electric heater and temperature measurement system is shown in Fig. 3. Temperature is monitored by eight thermocouples, T1 to T8 located along the axial direction of the gasifier. The first temperature point is mounted at the same elevation as that of the entrance of the fuel feeder in the gasifier, and the span between each two adjacent points is 150 mm. The producer gas leaves the gasifier through the top exhaust port of the cyclone where a sample system is installed, which consists of a fiber filter, an ice water condenser, gas washing bottles (acetone), vacuum pump and an on line gas analyzer. The system is proposed in [8], as shown in Fig. 4. Tar

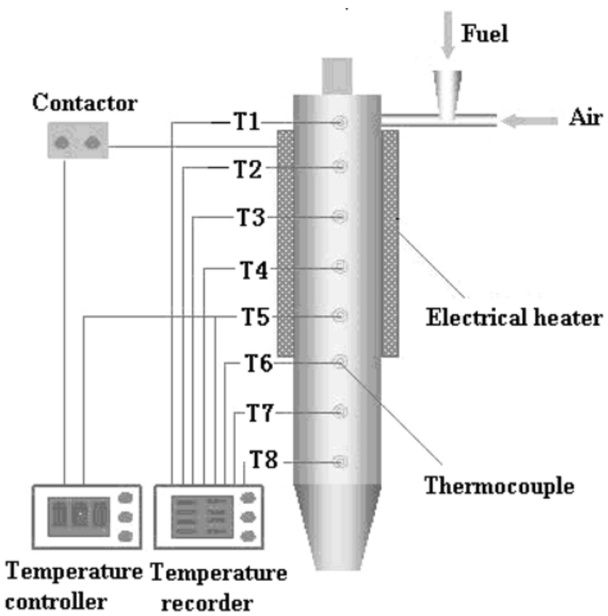


Fig. 3. Schematic of electric heater and temperature measuring system.

content is obtained by the weighing method. A gas analyzer (Gasboard 3020) is used to measure the concentrations of the gas species of interest, CO, CO_2, CH_4 and H_2. The concentrations of CO, CO_2 and CH_4 in the producer gas are measured continuously with the principle of non-dispersive infrared spectroscopy (NDIR). Hydrogen is measured with a thermal conductivity detector. The flowrate of the sampling gas ranged from 0.7 L/min to 1.2 L/min.

The experiments were made at a fuel rate of 20.1 kg/h, and the equivalence ratios were in the range of 0.21-0.32. Equivalence ratio is defined as the ratio of the actual air supplied to the stoichiometric air required for complete combustion. Air was used as gasifying agent, with a flowrate of 14-22 m^3/h which was sucked into the

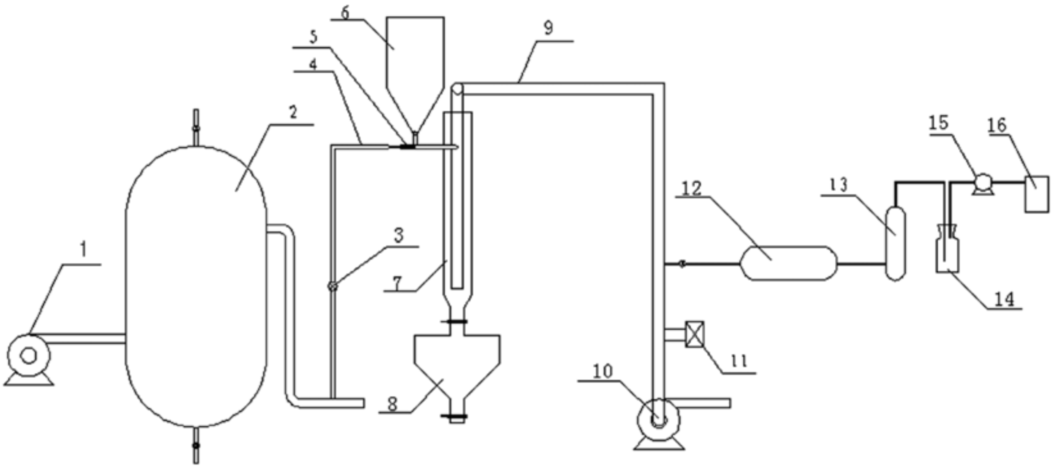


Fig. 2. Schematic of cyclone gasifier pilot system.

1. Air compressor	5. Fuel injector	9. Smoke flue	13. Condenser
2. Buffer tank	6. Feeder	10. Induced draft fan	14. Gas washing bottle
3. Flowmeter	7. Cyclone gasifier	11. Air cooling valve	15. Vacuum pump
4. Air tube	8. Dust bunker	12. Fiber filter	16. Gas analyzer

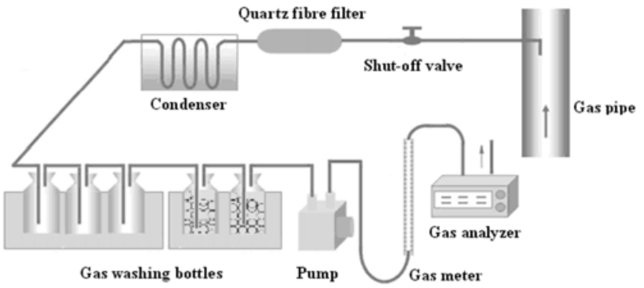


Fig. 4. Schematic of the sample system.

injector together with fuel. The gasifier was heated by the electric heaters, of 15 kw, which are controlled by the fifth thermocouple. The first step of the gasification experiments was heating the gasifier to approximately 650 °C at which point the electric heater stopped working automatically. The heat necessary for the reactions to proceed would then be generated from the reactions themselves. The stream rate in all cases was controlled by flowmeter. Tests were performed at atmospheric pressure. The fuel was transported into the gasifier through the injector and it entered the gasifier in a tangential direction. A governor motor was used to control the speed of the motor which drove the screw feeder. When the operating temperature variations were kept within ±5 °C, the system reached stable conditions.

EXPERIMENTAL MATERIAL

Rice husk contains more than 70% of combustible components. Its heating value is 12.5-14.6 MJ/kg , which is about half of that of standard coal [7]. Ash content in the rice husk is about 16-23% and the ash contains more than 95% silica. When the temperature is less than 700 °C, part of carbon in the fuel remains unburned and accumulates in the gasifier, resulting in lower efficiencies [9]. When the temperature is more than 850 °C, silica and potassium oxide in the ash transform to liquid phase. And they fuse onto the surface of the rice husk char particles, forming a glass-like barrier, which not only prevents the remaining char from further reaction but also jams the exit of the ash [10]. Table 1 shows the composition and the size distribution of the rice husk tested. Rice husk tested here is dried naturally by being exposed thoroughly to air and broken up roughly for the ease of feeding in a small scale screw feeder; the size of rice husk tested is lower than 4 mm.

Table 1. The characteristics of rice husk

Description	Data
Ultimate analysis (air dry basis)	
Carbon C (wt%)	37.99
Hydrogen H (wt%)	4.64
Oxygen O (wt%)	34.66
Nitrogen N (wt%)	0.49
Sulfur S (wt%)	0.07
Proximate analysis (air dry basis)	
Volatiles (wt%)	63.64
Fixed carbon (wt%)	14.21
Moisture (wt%)	4.64
Ash (wt%)	17.48
Heating value (received basis)	
LHV (MJ/kg)	13.78
Particle size (mm)	
>4.0	0
>2.0	23.5
1.0-2.0	15
0.6-1.0	31.2
<0.6	30.3

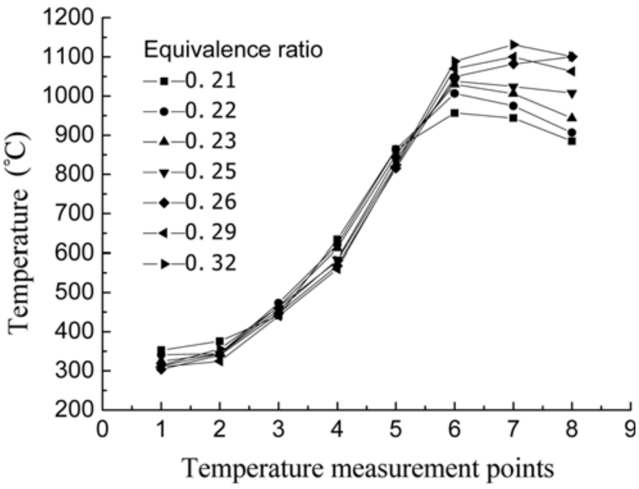


Fig. 5. Effects of the equivalence ratio on the temperature of the gasifier.

RESULTS AND DISCUSSION

1. Gas Temperature of the Cyclone Gasifier

The effect of the equivalence ratio on the gas temperature of the cyclone gasifier is shown in Fig. 5. As soon as the fuel enters the gasifier with air, it is dried and pyrolyzed immediately and the temperature of particles increases from room temperature to 300-350 °C. The temperature increase is attributed to the thermal radiation of the oxidation zone. Similar to the fluidized bed gasifier, no obvious boundary existed between the drying and devolatilization zone. As shown in Fig. 5, the temperature between T1 and T2 increases slowly, but it increases more rapidly after T2. The reason may be that combustible volatiles released in the early stage of gasification accumulate and intensive homogeneous reactions take place. When temperature increases to 600 °C, heterogeneous reactions between carbon and oxygen take place and the temperature here increases quickly. The peak gas temperature usually occurs between T6 and T7, and then temperature begins to decrease, which indicates that the reduction reactions play a dominant role after the turning point of temperature.

With the increase of the equivalence ratio, the gas temperature at the entrance of the gasifier decreases from 353 °C to 304 °C, due to the cooling effect of the incoming air. Gasification is the thermochemical conversion of biomass under deficient-oxygen conditions. The peak temperature T6 of the gasifier increases from 957 °C to 1,038 °C when the equivalence ratio increases from 0.21 to 0.25, which could be explained by the fact that at higher equivalence ratios

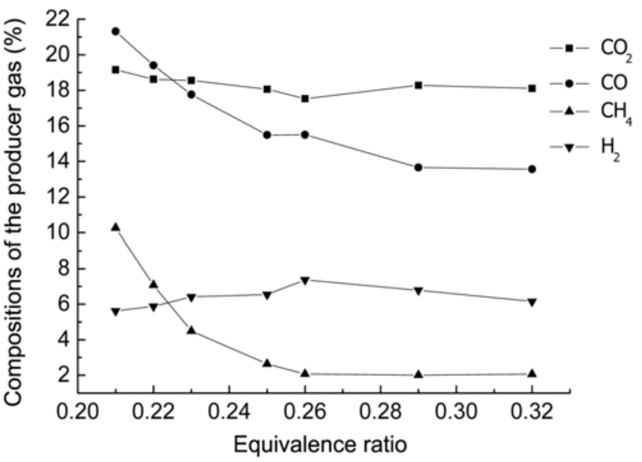


Fig. 6. Effects of the equivalence ratio on composition of the producer gas.

more air is available for the exothermic carbon combustion. The gas temperature at the bottom of the gasifier decreases slowly from T7 to T8, and it increases at T8 with the increase of the equivalence ratio. Gas temperature in the reduction zone will be increased when the temperature of the combustion zone increases. When the equivalence ratio is larger than 0.25, the flow velocity increases and the peak gas temperature moves down.

Fig. 5 also shows the gas temperature in the end of the oxidation zone is about 900-1,100 °C, which is higher than that in fluidized bed gasifiers [11]. However, in a cyclone gasifier, every fuel particle is separated by gas flow, and is pyrolysed and gasified individually. Therefore, there is no fusion in the cyclone gasifier, which is serious in an FB gasifier when the temperature is high.

2. Composition of the Producer Gas

As for gas composition, the volume fraction of CO, CO_2, CH_4 and H_2 is measured at the exhaust port of the gasifier. The N element in the rice husk is 0.49%; it is considered that nitrogen in the producer gas mainly comes from the gasifying agent. The measured concentrations of CO, CO_2, CH_4 and H_2 are shown in Fig. 6. It is seen that there is a decrease in CO from 21.31 vol% to 13.57 vol%, and a decrease of CH_4 concentration from 10.26 vol% to 2.02 vol% respectively, when the equivalence ratio increases from 0.21 to 0.32. At the same time, the concentration of H_2 increases from 5.63 vol% to 7.37 vol% when the equivalence ratio is smaller than 0.26, and it decreases with the increase of the equivalence ratio when the equivalence ratio is larger than 0.26. The concentration of CO_2 varies slightly in the latter range.

Gasification process includes devolatilization, oxidation and reduction. The natural structure of the biomass particle breakdown and devolatilization start when the temperature reaches 160 °C, and it becomes active with the increase of the temperature [12,13]. The products of gasification are solid residue (char) and a gas mixture composed primarily of carbon dioxide, carbon monoxide, hydrogen, water vapour and other pyrolysis products including tar and hydrocarbons. The combustibles react with surrounding air and heat is released due to the oxidation of the combustibles. After the oxygen is exhausted, components of the hot mixture can undergo further reactions (1)-(7) during the gasification.

$$C+CO_2 \leftrightarrow 2CO-160.1\ kJ/mol \quad (1)$$

$$C+H_2O(g) \leftrightarrow CO+H_2-118.8\ kJ/mol \quad (2)$$

$$CO+H_2O(g) \leftrightarrow CO_2+H_2+43.5\ kJ/mol \quad (3)$$

$$C+2H_2O(g) \leftrightarrow CO_2+2H_2-77.5\ kJ/mol \quad (4)$$

$$C+2H_2 \leftrightarrow CH_4+75.6\ kJ/mol \quad (5)$$

$$CO+3H_2 \leftrightarrow CH_4+H_2O(g)+206.1\ kJ/mol \quad (6)$$

$$CO_2+4H_2 \leftrightarrow CH_4+2H_2O(g)+164\ kJ/mol \quad (7)$$

CO_2 in the producer gas mainly comes from two origins: first, from the rice husk pyrolysis below 650 °C, and second, from the oxidation reaction. In the reduction zone a part of CO_2 reacts with char by reaction (1). The absolute content of CO_2 increases because the total content of the producer gas increases with the increase of the supplied air.

CO-generating processes are very complex. A part of CO is produced from the rice husk pyrolysis when the temperature is at 500-700 °C. In the water shift reaction (3) the carbon monoxide reacts with water to produce carbon dioxide and hydrogen, which takes place toward the positive direction when the temperature is over 850 °C. Furthermore, CO is oxidized while oxygen is present in the pyrolysis zone. Therefore, the concentration of CO in the producer gas decreases with the increase of the equivalence ratio.

CH_4 is mainly the result of the breaking-up of volatiles. Some CH_4 may also be formed by reactions (5)-(7) which take place toward the reverse reaction with the increase of the temperature; this could explain why CH_4 tends to decrease with the increase of the equivalence ratio.

H_2 is produced from the rice husk pyrolysis at high temperature. Reactions (5)-(7) show the reactions that produce hydrogen are endothermic; therefore, the temperature increase is favorable to producing hydrogen. On the other hand, when the temperature increases, reforming and cracking of heavier hydrocarbons and tars would make the concentration of hydrogen increase. When the equivalence rate is 0.26, H_2 concentration decreases with the increase of the equivalence ratio. It is probable that H_2 reacts with surrounding air during combustion.

The low heating value of the producer gas at the standard state of 101.3 kPa and 273 k can be estimated from the gas composition by $HV=\sum HV_n \times C_n\%$.

Cn denotes concentration of the combustible components in vol%, HVn denotes the heating value of combustible in MJ/Nm^3.

Cold gas efficiency, E, is used to evaluate the gasification performance, which is defined as the percentage of the fuel heating value converted into the heating value of the producer gas. $[LHV]_g$ (in MJ/Nm^3) denotes the lower heating value of the producer gas, while $[LHV]_f$ (in MJ/Nm^3) denotes the lower heating value of the fuel; V_g denotes the specific dry gas volume, in Nm^3/kg fuel, which may be estimated by nitrogen equilibrium.

$$E=\frac{[LHV]_g \times V_g}{[LHV]_f} \times 100\%$$

Effects of the equivalence ratio on the low heating value of the producer gas and the cold gas efficiency are shown in Fig. 7. The heating value of the producer gas decreased from 6.98 MJ/Nm^3 to

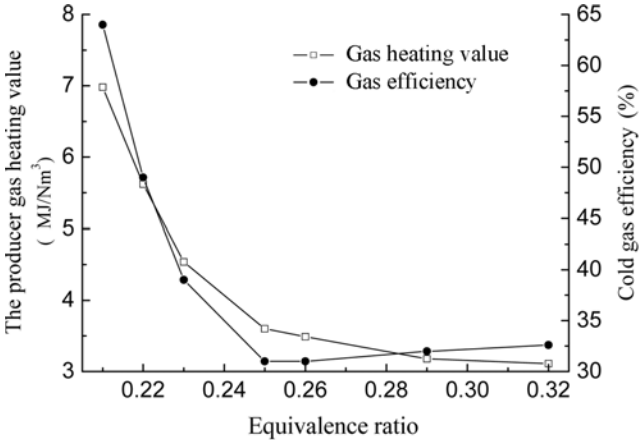


Fig. 7. Effects of the equivalence ratio on the heating value of the producer gas and cold gas efficiency.

3.11 MJ/Nm^3 and the cold gas efficiency decreased from 64% to 31%, respectively, when the equivalence ratio increased from 0.21 to 0.32. It is considered that the increase in supplied air led to the further combustion of the producer gas and dilution of the producer gas by the addition of nitrogen in the air, both of which resulted in the low heating value of the producer gas and the cold gas efficiency of the gasifier decreased.

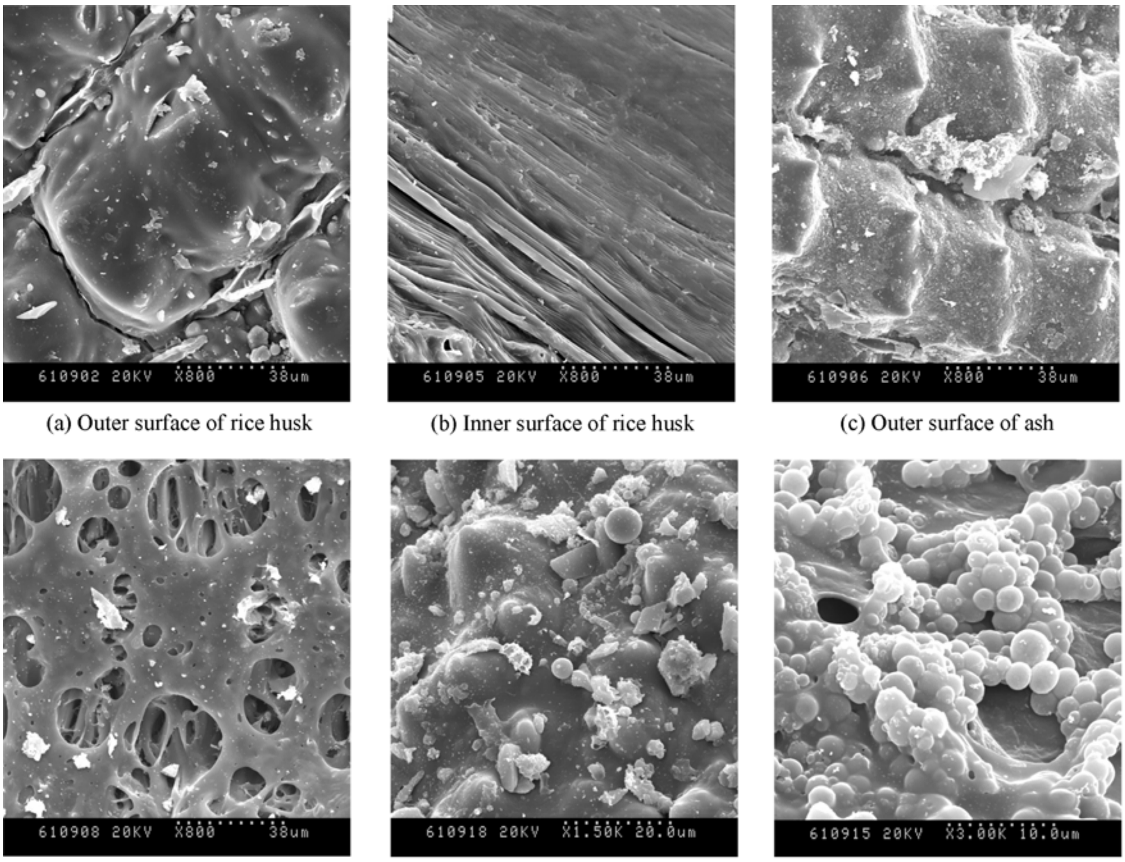
3. Tar Content in the Producer Gas

The type of biomass is the main factor that determines the nature of the tar produced, which is also influenced by the gasification process and the operating conditions [14]. It is generally agreed that primary tar is formed from pyrolysis of solid fuel in air gasification [15]. Increasing temperature promotes the pyrolysis of tar. The tar content significantly decreases from 22.5 g/Nm^3 to 5 g/Nm^3 with the increase of the equivalence ratio from 0.21 to 0.25. The decrease of tar content is mainly because a part of tar is burnt and the other is further thermally cracked into the secondary tar in the high temperature zone when the supplied air increases. As shown in Fig. 5, the temperature in the oxidation zone is above 1,000 ºC. Tar could be cracked into lower molecular weight compounds by catalyst char above 900 ºC [16]. When the reduction reactions take place between the hot gas coming from the oxidation zone and tar and hot char, the tar in the gas could be cracked. Increasing the reduction temperature is favorable to these reactions.

4. Microstructure of Rice Husk and Ash

To study the behavior of microcosmic structure and inorganic components during gasification, the initial rice husk and the ash obtained from the gasification were examined under a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) for elemental analysis.

The SEM micrograph of rice husk and ash is shown in Fig. 8. Fig. 8(a) and (b) show the SEM micrograph of the outer surface



(a) Outer surface of rice husk (b) Inner surface of rice husk (c) Outer surface of ash

(d) Inner surface of ash (e) Meltable spherule on the outer surface of ash (f) Meltable spherule on the inner surface of ash

Fig. 8. The SEM micrograph of the rice husk and ash.

Table 2. Comparison of the elemental components on the particle surface (atom percent, %)

Element	Inner surface of rice husk	Inner surface of ash	Meltable spherule on the ash particle surface
Na	0	0	0.13
Mg	0	0	33.71
Al	0	0.29	7.47
Si	93	86.63	0
S	0.28	0.75	3.93
Cl	0.3	1.5	1.31
K	2.85	5.77	21
Ca	0.39	4.63	18.9
Mn	1.58	0	12.43

and the inner surface of rice husk, respectively. These images show that the outer surface of the rice husk is even, and the inner surface is of fibrous structure. Fig. 8(c) shows the SEM micrograph of the outer surface of ash. It keeps scale structure, which is similar to the outer surface of rice husk. Fig. 8(d) shows the SEM micrograph of the inner surface of ash. The fibrous structure on the inner surface of rice husk disappears, and many nonuniform pores appear. It is considered that the pyrolysis gas is mainly released from the inner surface of the fuel particle. The inner surface of the char particle comes into being as a meltable viscous membrane at high temperature, and the pyrolysis gas penetrates this viscous membrane. There are many meltable spherules on the inner surface of ash particles but only a few on the outer surface, as shown in Fig. 8(e) and (f).

Table 2 shows the elemental analysis of the rice husk inner surface, the ash particle inner surface and meltable spherule on the ash particle surface. It is found that atomic percentage of the elements (K, Ca, Cl, S, Al) in the inner surface of the ash particle is higher than that of the raw rice husk. Inner surfaces of rice husk and ash have much Si. The melting point of SiO_2 is 1,723 °C, but it easily decreases when SiO_2 is mixed with the alkali compounds. As Table 2 shows, such element content as Na, Mg, Al, S, K, Mn, Cl, Ca in the meltable spherule on the ash particle surface is much higher than that on the ash particle surface, but no Si is found in the meltable spherule. It indicates that the meltable spherule is mainly made up of the alkali compounds. It may be the condensation of liquid metal compounds. One possible explanation is that the melting point and boiling point of alkali compounds like potassium or calcium would debase when they are compounded with chlorine or sulfur.

CONCLUSIONS

(1) There exists intensive heat and mass transfer in the cyclone gasifier. The average gas temperature of the oxidation zone is about 900-1,100 °C, which is obviously higher than that in a fluidized bed gasifier. Even though, there is not slagging in the gasifier.

(2) The low heating value of the producer gas decreases from 6.98 MJ/Nm^3 to 3.11 MJ/Nm^3 and the cold gas efficiency decreases from 64% to 31% when the equivalence ratio increase from 0.21 to 0.32.

(3) The tar content in the prouder gas decreases with the increase of the equivalence ratio. The tar content is 5 g/Nm^3 at the equivalence ratio of 0.25.

(4) Scale structure of the fuel particle outer surface does not change basically during the process of gasification. The pyrolysis gas is mainly released from the inner surface of fuel particles.

ACKNOWLEDGMENTS

Financial support from the Heilongjiang Provincial Natural Science Foundation of China (contract no.: 1307396) is gratefully acknowledged.

NOMENCLATURE

Cn : concentration of the combustible component in volume [%]
HVn : the heating value of combustion [MJ/Nm^3]
$[LHV]_g$: the lower heating value of the producer gas [MJ/Nm^3]
$[LHV]_f$: the lower heating value of the fuel [MJ/Nm^3]
V_g : the specific dry gas volume [Nm^3/kg fuel]

REFERENCES

1. H. Sun, B. H. Song, Y. W. Jang, S. D. Kim, H. B. Li and J. Chang, *Korean J. Chem. Eng.*, **24**, 341 (2007).
2. S. Zhou and X. L. Zhang, *Korean J. Chem. Eng.*, **24**, 170 (2007).
3. C. Z. Wu, H. Huang, S. P. Zheng and X. L. Yin, *Bioresour. Technol.*, **83**, 65 (2002).
4. M. Gabra, E. Pettersson, R. Backman and B. Kjellström, *Biomass Bioenergy*, **21**, 351 (2001).
5. M. Gabra E. Pettersson R. Backman and B. Kjellström, *Biomass Bioenergy*, **21**, 371 (2001).
6. C. Syred, W. Fick, A. J. Griffiths and N. Syred, *Fuel*, **83**, 2381 (2004).
7. Z. Q. Zhou, L. L. Ma, H. B. Li and C. Z. Wu, *Resource Energy*, **118**, 7 (2004).
8. P. Simell, P. Stahlber, E. Kurkela, J. Albrecht, S. Deutsch and K. Sjostrom, *Bioenergy*, **18**, 19 (2000).
9. E. Natarajan, A. Nordin and A. N. Rao, *Biomass Bioenergy*, **14**, 533 (1998).
10. X. L. Yin, C. Z. Wu, S. P. Zheng and Y. Chen, *Biomass Bioenergy*, **23**, 181 (2002).
11. X. T. Li, J. R. Grace, C. J. Lim, A. P. Watkinson, H. P. Chen and J. R. Kim, *Biomass Bioenergy*, **26**, 171 (2004).
12. Z. Q. Li, W. Zhao, B. H. Meng, C. L. Liu, Q. Y. Zhu and G. B. Zhao, *Bioresour. Technol.*, **99**, 7616 (2008).
13. S. R. Wang, Q. Liu, Y. F. Liao, Z. Y. Luo and K. F. Cen, *Korean J. Chem. Eng.*, **24**, 336 (2007).
14. M. K. Peter, *Bioresour. Technol.*, **83**, 55 (2002).
15. Y. G. Pan, X. Roca, E. Velo and L. Puigjaner, *Fuel*, **78**, 1703 (1999).
16. Y. H. Lai, M. X. Lu, C. Y. Ma and M. H. Sh, *Acta Energiae Solaris Sinica*, **25**, 547 (2004).