CHARACTERISTICS OF RICE HUSK GASIFICATION IN CYCLONE PYROLYSIS-SUSPENDED COMBUSTION SYSTEM

by

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The cyclonic gasification technology could realize self-separation of syngas and residual carbon, simplifying the purification system. In cyclone pyrolysis-suspension combustion system, bottom air was fed into carbon-rich area of gasifier. Due to the high height/diameter ratio and uneven temperature distribution in cyclone gasifier, the primary/secondary/bottom air rates were 30%, 20%, and 50%, respectively. Effects of gasification intensity and air equivalent ratio on rice husk gasification performance were explored. The results show that for cyclone pyrolysis-suspension combustion, the optimum gasification intensity is 885.24 kg/m^{2}h. Strengthening the subregion of air supplement could cause a gradual increasing of temperature along the axis of gasifier. The syngas yield was independent of gasification intensity, but increased from 0.98 Nm^3/kg at ER = 0.23 to 1.38 Nm^3/kg at ER = 0.32. At ER = 0.26~0.29, the gasification performance is best, with gas heat value of 4.99~5.37 MJ/Nm^3, cold gasification efficiency of 48.25~49.67% and tar content of 5.38~5.75 g/Nm^3.

Key words: *biomass, cyclone pyrolysis, suspended combustion, gasification intensity, air equivalent ratio*

Introduction

Biomass resources are usually diverse, with low energy density and decentralized distribution. The local collection and utilization of biomass, to avoid the long-distance transport, can effectively reduce the transportation costs and improve its market competitiveness [1, 2]. Distributed biomass energy technology is highly adaptable to the type of raw materials, flexible scale, with good economy, and in line with the characteristics of biomass resources [3]. Therefore, the distributed biomass energy technology is the inevitable requirement of the development of biomass energy industry. Biomass gasification is to realize the conversion of low-grade biomass fuels into syngas [4, 5], to achieve the clean and efficient utilization of biomass, which is one of the effective distributed biomass energy technologies. In addition to the traditional power generation technology of biomass gasification, the coupling utilization technologies of biomass gasification and coal-fired power generation, industrial boilers/kilns are widely used

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[6, 7]. However, the current syngas purification system during biomass gasification is too complex and how to simplify the purification system is an urgent problem to be resolved.

The biomass cyclone gasification technology is namely that the gasifier agents (air) would carry the raw biomass particles tangentially into the gasifier, forming the cyclone flow field in the gasifier. Under the action of centrifugal force, the syngas and residual carbon from biomass gasification could be separated during the reaction. At the same time, the gasification syngas may exhausted from the central exhausting pipe, and the residual carbon and ashes would fall into the hopper [8-10]. The advantage of cyclonic gasification technology is that the gasification syngas and residual carbon could realize the self-separation during the reaction, simplifying the subsequent gas purification system. Scholars have made a series of experimental and theoretical researches on the cyclone combustion/gasification of coal or biomass [11-16]. However, the insufficient gas-solid reaction and the high carbon residue content result in a lower gasification efficiency. Further improvement of the current cyclone technology is needed. [17]. Thus, an improved gasification technology with integration of cyclone pyrolysis-suspension combustion was proposed in the present work, with the bottom air jointed into the carbon-rich area of gasifier, to promote the burning of carbon residue and provide heat to the endothermic reactions during gasification, as shown in fig. 1. Gasification intensity and air equivalent ratio (ER) are the two key parameters during the design and operation of gasifier, while there is no relevant data in the current scientific reports.

Therefore, the purpose of this paper is to explore the influences of gasification intensity and air ER on the gasification performance of cyclone pyrolysis-suspension combustion gasifier, and to provide the basic information for the amplification design of biomass cyclone gasifier.

Material and methods

The cyclone pyrolysis-suspension combustion system is based on the biomass cyclone gasification system, with the air ring installed at the bottom part of the cyclone gasifier, as shown in fig. 2. The bottom air ratio is adjusted by controlling the cross-sectional area of the bottom air ring nozzle. The bottom of the air ring is mainly made up of the air inlet, air chamber, guide plate and ash shield. The air chamber is evenly arranged with four air inlets. The bottom air is fed into the air chamber through the air intake, and the bottom wind speed is controlled by the distance of the air-gap in the air chamber, and is finally fed into the gasifier under the action of the guide plate. The role of ash shield is to prevent the clogging caused by biomass gasification ash falling into the bottom of air ring. The angle of inclination of the ash shield is greater than the natural accumulation angle of the biomass ash, and the gasification ash can fall smoothly into the hopper along the ash shield. The

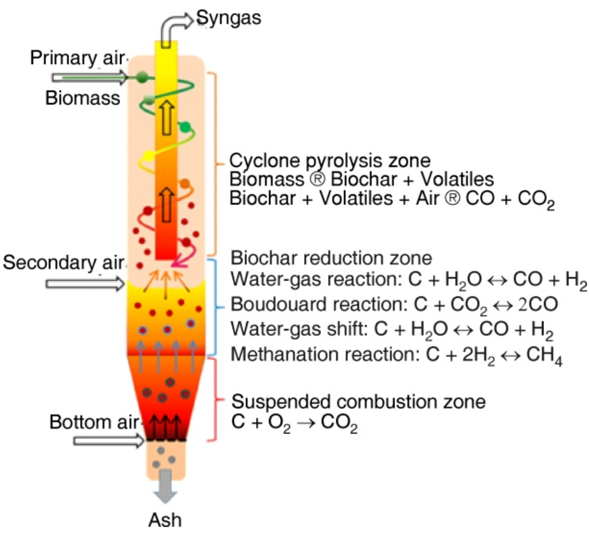

Figure 1. Cyclone pyrolysis-suspended combustion system

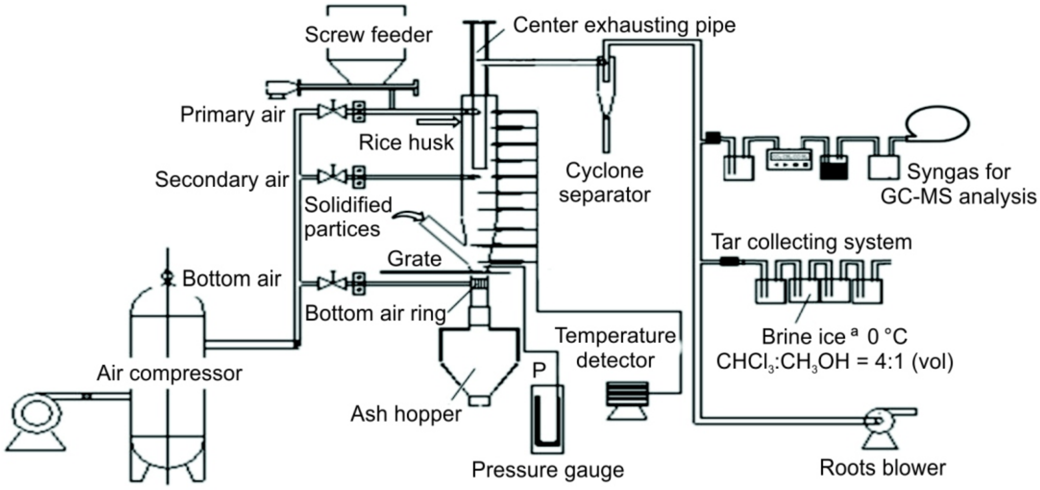

Figure 2. Cyclone pyrolysis-suspended combustion gasifier

gasifier is made of mullite which can withstand the high temperature. Air was used as the gasifier agent, provided by an air compressor. The air was fed into the gasifier through three paths: the primary air vents are located in the upper part of the gasifier for carrying the raw biomass particles into the gasifier and forming a swirl flow field. As the high height/diameter ratio of gasifier, in order to make the furnace temperature distribution as uniform as possible, the secondary air nozzle in the middle of the gasifier was used. The bottom air is located in the bottom part of the gasifier to provide air for the combustion of gasified biochar. Biomass material is conveyed using a screw feeder. The gasifier is arranged in the axial direction with 10 temperature measuring points. The first and fifth temperature measuring points (T_1 and T_5) are at the same level as the primary and secondary air vents, respectively.

The rice husk was selected as the gasification raw material and taken from a rice processing plant in Harbin, Heilongjiang. Its proximate and ultimate analyses are shown in tab. 1.

In this experiment, two materials were used successively to preheat the cyclone gasification system. The lower part of gasifier is equipped with a movable grate. The wood solidification particles (diameter of 5 mm, length of 20 mm) are stacked on the grate. The high temperature syngas formed during the combustion of solidification particle would be used to preheat gasifier from bottom to top, and after combustion the ash may fall down from the voids of the grate into the hopper. When the temperature in the upper part of gasifier reached the ignition temperature of rice husk as 280 °C, the rice husk was fed into the gasifier by the screw feeder

Table 1. Proximate and ultimate analyses of rice husk

Sample	Proximate analysis [wt.%]				Ultimate analysis [wt.%]					Low calorific value [MJkg^{-1}]
	$M_{ad.}$	$A_{ad.}$	$V_{ad.}$	$FC_{ad.}$	$C_{ad.}$	$H_{ad.}$	$O_{ad.(diff)}$	$N_{ad.}$	$S_{t,ad.}$	
Rice husk	6.86	17.00	60.92	15.22	37.35	4.40	34.05	0.20	0.14	13.11

ad. = air dry basis, diff. = by difference, M – moisture, A – ash, V – volatiles, FC – fixed carbon, C – carbon, H – hydrogen, O – oxigen, N – nitrogen, S – sulphur with the sufficient air, to further preheat the gasifier. When the gasifier inlet temperature reached 650 °C, the experimental was started with the adjustment of the air supplement and feeding amount to the specified gasification conditions. After the gasifier is stable, the syngas is sampled and analyzed at the outlet of gasifier. The syngas composition was measured by Gas Chromatograph – Mass Spectrometer (GC-MS) off-line, and the tar content was analyzed by weighing method [18, 19].

Results and discussion

Effect of gasification intensity

Gasification intensity is a necessary parameter for the gasifier design, which refers to the total amount of biomass consumed in the unit cross-section of gasifier per unit time. With the fixed air ER and secondary/bottom air rate, this paper studied the influence of gasification intensity on the gasifier temperature distribution, the syngas components and the gasification performance parameters by adjusting the feeding amount, to obtain the best gasification intensity for the cyclone pyrolysis-suspended combustion system. The air ER was set as 0.26, with the secondary air rate of 20% and the bottom wind rate of 50%. The biomass feeding amounts were 18.16, 29.07, 37.04, and 43.96 kg/h, and the respective gasification intensities were 434.14, 694.78, 885.24 m, and 1050.68 kg/m^{2}h.

Gasifier temperature distribution

The effect of gasification intensity on axial temperature distribution of gasifier can be seen in fig. 3. It can be seen that along the axis direction of the gasifier, the temperature gradually increased from top (T_1) to bottom (T_{10}). Due to feeding of air-flow with different rates from top to bottom, the strengthened partition and cyclone gasification of rice husk was achieved, with a good flow field and reaction partition in the gasifier. As shown in fig. 1, the pyrolysis, reduction, and combustion zones were formed from top to bottom of the gasifier. The biomass feedstock enters the gasifier with the less primary air. Firstly, the dehydration and pyrolysis reactions absorb a lot of heat, which is mainly from the heat radiation of the high temperature zone and partial combustion of pyrolysis syngas in the upper part of gasifier, forming the pyrolysis zone at low temperature (500-700 °C). According to the characteristics of swirl flow field, the generated pyrolysis syngas flow rotated down and reversed from the bottom up at the conical section in the lower part of gasifier, and finally exhausted from the center pipe. The reduction reaction between the self-separated pyrolysis biochar and the CO_2 produced from the suspended combustion of carbon residence and bottom air would take place, with the absorption of heat. This part of reaction heat is mainly generated by the heat radiation from the bottom high temperature zone and the heat from the oxidation reaction near the secondary air vent (namely the T_5 point), forming biochar reduction zone at a moderate temperature (700-800 °C). The downstream gasification biochar and the bottom air are mixed and reacting, forming the suspended combustion zone at a high tempera-

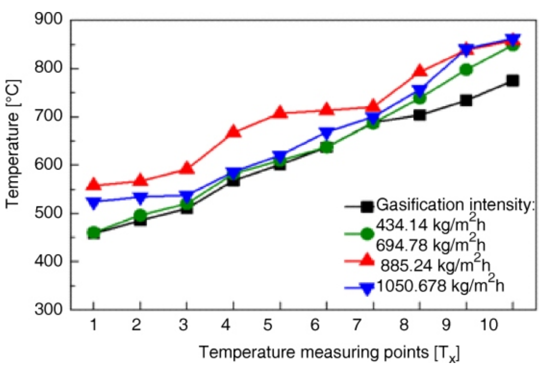

Figure 3. Effect of gasification intensity on temperature

ture (> 800 °C), releasing a large amount of heat to supply the heat required by the upper pyrolysis and reduction reaction.

With the increase of gasification intensity, the overall temperature trend of gasifier increased first and then decreased, for the highest temperature field at the gasification intensity of 885.24 kg/m^{2}h. When the gasification intensity is too large, too much endothermic reaction leads to a decrease in the temperature of the gasifier. It is shown that the optimum gasification intensity of the cyclone pyrolysis-suspension combustion system is 885.24 kg/m^{2}h), which is slightly smaller than that realized by the circulating fluidized bed gasifier [20].

Syngas components

It can be seen from tab. 2 that the contents of CO, CH_4, and H_2 in the gasification syngas increased first and then decreased with the increasing of gasification intensity, and reached the maximum at the gasification intensity of 885.24 kg/m^{2}h. This is because the yield of each component in the syngas is mainly affected by the reaction temperature and the reaction time. On the one hand, as the feed amount increases, the corresponding bottom air rate increases. With the increasing of the bottom air speed in a certain range, the disturbance of gasification biochar from the upper part of gasifier is strengthen, improving the gas-solid mixing effect. While, with the bottom air rate further increasing, the biochar would be blown out of the gasifier, shortening the residence (reaction) time of gasification biochar. On the other hand, from the influence of gasification intensity on the temperature distribution of gasifier as shown in fig. 3, with the gasification intensity of 885.24 kg/m^{2}h and the highest temperature field, the gasification reaction and the yield of each syngas component is promoted.

Table 2. Effect of gasification intensity on the syngas components

Gasification intensity [kgm^{-2}h^{-1}]	Syngas components (×10^{-3} [Nm^{3}kg^{-1}])						
	CO_2	CH_4	C_2H_4	CO	H_2	C_2H_2	C_2H_6
434.14	158.10	32.78	12.77	216.91	16.81	1.32	1.86
694.78	142.78	35.39	14.30	235.52	25.97	1.73	1.75
885.24	146.20	42.19	15.66	255.13	31.15	1.32	2.06
1050.68	142.93	37.48	14.94	234.90	31.02	1.86	1.88

Gasification performance parameters

Table 3 shows the changing rules of gasification performance parameters (such as syngas heating value, syngas yield, cold gasification efficiency, and carbon conversion) under different gasification intensities. The syngas yield can be calculated from the nitrogen conservation [21]. It can be seen that the syngas yield is independent of the gasification intensity. It is difficult to obtain the better gasification results under the smaller and larger gasification intensity, thus its optimum gasification strength is 885.24 kg/m^{2}h.

Effect of equivalence ratio

The ER is an important parameter for the operation of the gasifier, which is the ratio of the amount of air actually consumed by the biomass feedstock to the amount of theoretical air required for the complete combustion of the biomass. With the fixed air ER and secondary/bottom

Table 3. Effect of gasification intensity on the gasification performance parameters

Gasification intensity [kg/m^{-2}h^{-1}]	Syngas heating value [MJNm^{-3}]	Syngas yield [Nm^{3}kg^{-1}]	Cold gasification efficiency [%]	Carbon conversion [%]
434.14	4.56	1.12	39.12	60.31
694.78	4.98	1.14	43.37	61.62
885.24	5.37	1.18	48.25	66.06
1050.68	5.11	1.15	44.80	62.09

air rate, the effects of equivalence ratio on the gasifier temperature distribution, syngas yield, tar content, carbon conversion, and cold gasification efficiency were studied. The feeding amount and gasification intensity were set as 37.04 kg/h and 885.24 kg/m^{2}h, respectively, with the secondary air rate of 20% and the bottom wind rate of 50%. The air ER were 0.23, 0.26, 0.29, and 0.32.

Gasifier temperature distribution

With the air ER increased from 0.23 to 0.26, the temperature of pyrolysis zone in the upper part of gasifier increased obviously, for the T_1 from 464 °C to 558 °C, as shown in fig. 4. While the air ER increased from 0.26 to 0.32, the T_1 changed not so large. This is because the heat in the pyrolysis zone is mainly provided by the heat radiation from the bottom zone and the partial oxidation of pyrolysis syngas. On the one hand, with the air ER increasing, the temperature increased and the radiation heat became larger. The oxidation reaction of the pyrolysis gas would be promoted, increasing the heat release, which makes a significant improvement of the temperature with the equivalence ratio from 0.23 to 0.26. On the other hand, with the fixed feeding amount and increasing air ER, the total amount of air is increased and the amount of heat absorbed by the cold air in the pyrolysis zone increased. So the temperature of gasifier at ER = 0.32 increased only a little from that at ER = 0.29. With the air equivalent increase from 0.23 to 0.29, the temperature of the oxidation zone at the bottom part of gasifier increased significantly, due to the increase of bottom air amount and the strengthened oxidation reaction of biochar.

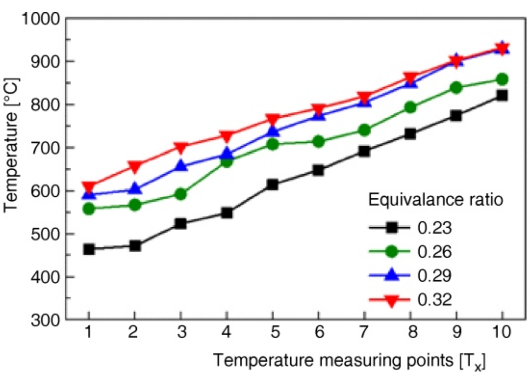

Figure 4. Effect of equivalence ration on temperature

Syngas yield

The CH_4, C_2H_4, and C_2H_6 and other small molecules of hydrocarbons came mainly from the biomass devolatilization reaction and thermal cracking of the macromolecular hydrocarbons, as shown in tab. 4. During the cyclone pyrolysis-suspended combustion gasification, the main air-flow (secondary air) is fed from the lower part of the gasifier and has a certain distance from the end of the central exhausting pipe. Oxygen (air) is mainly consumed by the combustion of gasified biochar, thereby reducing the consumption of oxygen on the upper pyrolysis

Table 4. Effect of equivalence ratio on syngas compositions

Equivalence ratio	Syngas compositions [%]							Syngas yield [Nm^3kg^{-1}]
	CO_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	H_2	
0.23	12.38	3.36	1.31	0.11	0.17	19.51	1.28	0.98
0.26	12.42	3.58	1.33	0.12	0.17	21.67	2.65	1.18
0.29	12.85	2.91	1.16	0.10	0.11	20.54	3.88	1.30
0.32	14.43	2.91	1.23	0.15	0.12	17.72	2.36	1.38

gas-phase product. It can be seen from fig. 4 that before exhausting from the center pipe, the pyrolysis syngas would pass through a low temperature zone with a low cracking level of the macromolecule hydrocarbons. Thus the production of small molecules of hydrocarbons is mainly controlled by the pyrolysis reaction in the cyclone pyrolysis zone.

As shown in tab. 4, with the increase of air ER, the combustion reaction in the gasifier is strengthened, while the pyrolysis and reduction reactions are promoted, increasing the syngas yield from 0.98 Nm^3/kg at ER = 0.23 to 1.38 Nm^3/kg at ER = 0.32. When the air equivalent ratio was 0.23 and 0.26, the volume percentages of small molecule hydrocarbons such as CH_4, C_2H_4, and C_2H_6 in the syngas are significantly increased with respect to the air ER of 0.29 and 0.32. It can be seen that the less the amount of air added into the pyrolysis zone, the less the fraction of the pyrolysis syngas combustion reaction, the more conducive to improve the pyrolysis gas production. On the contrary, the greater the amount of air, the greater the speed of air-flow and the reaction residence time of biomass in the pyrolysis zone is short, which may be not conducive to the pyrolysis reaction. The CO was mainly from the biomass devolatilization reaction and char-CO_2 reduction reaction. As shown in tab. 4, it can be seen that with the air ER of 0.26 and 0.29, the volume fraction of CO in the syngas is larger, with the maximum of 21.67% at ER = 0.26. As it previously mentioned that the temperature of gasifier at ER = 0.26 is higher than that of ER = 0.23. With the ER of 0.26, the biomass devolatilization reaction and reduction reaction is stronger to generate more CO. Although at ER = 0.29, the combustion fraction of CO generated in the pyrolysis zone is larger, resulting in a decrease in the amount of CO produced in the pyrolysis zone, but the total amount of CO in the syngas is large. This is because at ER = 0.29, the reduction zone temperature is higher, to promote the reduction reaction between the biochar and CO_2, leading to an increasing production of CO. While the air ER of 0.32, the content of CO is the lowest. There are two main reasons for this: the amount of air in the pyrolysis zone is large with a larger combustion consumption of CO generated by the pyrolysis, reducing the final yield of CO in the pyrolysis zone. In addition, the larger bottom air volume leads to the high air speed from the bottom of the gasifier, the residence time of biochar decreases in the reduction zone along with the reduced production yield of CO. When the air ER is less than 0.29, the percentage of H_2 in the syngas increases gradually with the increasing of air ER, from 1.28% at ER = 0.23 to 3.88% at ER = 0.29. This is because the pyrolysis zone temperature increases, making the amount of H_2 generated by biomass pyrolysis increases. When the air ER is 0.32, the fraction of H_2 in the syngas is smaller, mainly because the air ER increases, and the combustion fraction of pyrolysis gas production in the pyrolysis zone becomes larger.

It can be seen that in order to increase the volume fraction of CO and H_2 in the syngas, it is necessary that the gasification reactions in the pyrolysis and reduction zones should be taken into account: to ensure the proper biomass devolatilization reaction with the appropriate pyrolysis temperature at the pyrolysis zone and to strengthen the reduction reaction with a higher temperature at the reduction zone of gasifier; to organize the flow field rationally and reduce the oxygen content in pyrolysis zone limiting the combustion fraction of pyrolysis gas production, and to improve the residence time of pyrolysis biochar in the reduction zone.

Syngas heating value and tar content

It can be seen from fig. 5 that with the increase of air ER, the syngas heating value from the rice husk gasification increases first and then decreases, with the maximum of 5.37 MJ/Nm^3 at ER = 26 and the minimum of 4.51 MJ/Nm^3 at ER = 0.32. The tar content in the syngas decreases continuously with the increasing air ER, from 7.24 g/Nm^3 at ER = 0.23 to 5.04 g/Nm^3 at ER = 0.32. With the increase of the air ER, the temperature inside the gasifier increases, promoting the secondary cracking reaction of tar [19]. The amount of air is increased increasing the oxidation reaction of tar. With the comprehensive results of the syngas heating value and tar content, the best gasification effect is obtained at the air ER of 0.26.

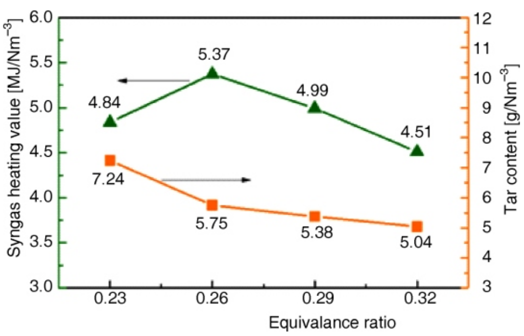

Figure 5. Effect of ER on syngas heating value and tar content

Carbon conversion and cold gasification efficiency

As shown in fig. 6, with the increase of air ER, the carbon conversion rate increased from 51.60% at ER = 0.23 to 71.90% at ER = 0.32. As the air ER increased, the amount of air increased and the oxidation reaction was enhanced. The increased gasifier temperature promoted the pyrolysis and reduction reactions, further improving the conversion of solid-carbon to the gas-carbon, as well as the combustion and secondary cracking reactions of tar. The cold gasification efficiency is mainly related to syngas yield and syngas heating value. The syngas heating value increased first and then decreased, and the maximum was at ER = = 0.26. Under the combined actions of both, with the increase of air ER, the cold gasification efficiency increased first and then decreased, reaching a maximum of 49.7% at ER = 0.29.

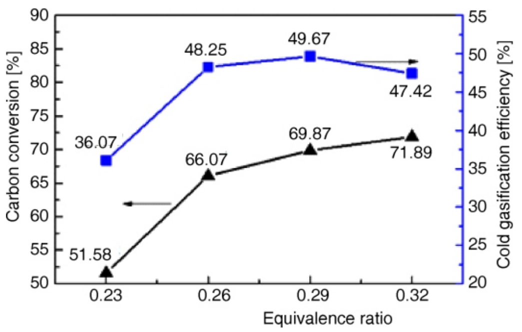

Figure 6. Effect of ER on carbon conversion and gasification efficiency

Conclusion

Effects of gasification intensity and air ER on rice husk gasification performance were explored. For the cyclone pyrolysis-suspension combustion, the optimum gasification intensity is 885.24 kg/m^{2}h. Strengthening the sub-region of air supplement could cause a gradual increasing of temperature along the axis of gasifier. The syngas yield was independent of gasification intensity, but increased from 0.98 Nm^3/kg at ER = 0.23 to 1.38 Nm^3/kg at ER = 0.32. At ER =

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