Experimental Study of the Influences of Temperature on the Properties of Particles in a Gasifier during Coal–Water Slurry Gasification

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1. INTRODUCTION
Coal–water slurry gasification belongs to an entrained flow gasification technology, which is the leading and key technology for obtaining clean coal. In the gasification process of coal–water slurry, a coarse coal gas is produced, as well as byproducts such as particles and slag. Coal particles accumulate large amounts of toxic heavy metal elements (such as lead, cadmium, etc.) because of their large specific surface area, which seriously endanger human health and cause environmental pollution. In addition, because of the different trajectories of the particles in the gasifier, a part of the particles leave the gasifier along with the syngas, and the other part enters the molten slag and becomes a part thereof. Therefore, it is worth studying because the composition of particles has a certain influence on the properties of slag and also directly determines the impact of slag on the environment. At present, scholars, both at home and abroad, have made many studies of the characteristics and formation mechanism of particles formed by gasification and combustion of pulverized coal in fluidized beds and boilers, and some studies have been made of the particle characteristics of coal–water slurry combustion, but few studies have been made of the properties of particles in different stages of coal–water slurry gasification. Therefore, it is necessary to study the characteristics of particles and gasification conditions in the new-type coal–water slurry gasifier, whether it is for the improvement of the basic research of the gasification technology or optimizing the industrial technology. In this paper, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and a Malvern laser particle size analyzer were used to test the effects of gasification temperature and the O/C ratio on particle characteristics in a new-type coal–water slurry gasifier.

2. GASIFICATION EXPERIMENT
2.1. Experimental Procedures. The thermal test procedure of the new-type coal–water slurry gasification is shown in Figure 1. In the experiment, oxygen is used as an oxidant and coal–water slurry is used as the gasification material. The coal–water slurry is transported by the screw pump and enters the air-entrained flow gasifier through the inner channel of the nozzle. Oxygen is supplied by an oxygen cylinder and is measured by a gas mass flow meter and then enters the furnace through the central and the lateral channels of the coal–water slurry nozzle. The oxygen and coal–water slurry burn in the furnace and generate syngas through further
The syngas is discharged from the cooling chamber after cooling. The nozzle is a new-type, three-channel, internal mixing coal−water slurry gasification nozzle. The central and the lateral channel are oxygen channels, and the middle ring channel is the coal−water slurry channel. The furnace chamber of the gasifier measures about 2500 mm, the inner diameter is 600 mm, and the inner diameter of the outlet of the gasification chamber is 150 mm.

2.2. Experimental Materials and Conditions. The coal−water slurry used in the experiment is self-made coal−water slurry. The pulverized coal for the pulping is Ordos coal. The proximate and ultimate analyses of Ordos coal are shown in Table 1. The size distribution of the Ordos coal is shown in Figure 2, and the experimental conditions are listed in Table 2.

2.3. Sampling Method. The sampling system consists of a high-temperature water-cooling sampling tube, a filter, a flow meter, and a suction pump, as shown in Figure 3. During the experiment, the flow rate of the argon is controlled by the mass flow meter first, and the gas velocity in the gasifier is calculated according to the content of argon measured by a mass spectrometer. A constant speed sampling is then guaranteed by adjusting the flow meter of the sampling system. The sampling port is located below the plane of the lower nozzle, and it is 400 mm from the plane of the nozzle.

2.4. Analysis Method. The particle size analysis of the particles obtained by sampling is carried out on the Malvern laser particle size analyzer. The samples are collected in the sampling bottle by water washing during the test. Before
particle size analysis is carried out, pretreatment is carried out in an ultrasonic cleaning machine to ensure an even distribution of particles in the sampling bottle and to ensure the formation of a well-distributed suspension. The testing of some of the suspension samples on the Malvern laser particle size analyzer follows. The morphology of the particles and the distribution of the surface elements are carried out using SEM and EDS, respectively. In the experiment, the dried sample is obtained through sanction filtration of the sample suspension first and then is baked for 2 h in a constant-temperature drying box. The analysis of the carbon content of the particles is done in a high-temperature muffle furnace. After calcination, the difference in mass of particles before and after the burning process is calculated, and thus the carbon content in the particles is calculated.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Influence of Temperature on Particle Properties. 

3.1.1. Influence of Temperature on Particle Morphology. As can be seen from Figure 4, the effect of temperature on the morphology of particles is very obvious. Because the ash melting point of Ordos coal is 1285 °C, when the operating temperatures are 1350 and 1300 °C, which is higher than the ash fusion point, it leads to more melting of particles, and a larger proportion of spherical particles is generated. In addition, the high temperature also leads to the increased volatilization of those volatile elements, and the particles are more easily broken; so the number of condensed spherical particles increases. When the operating temperature is 1200 °C, which is lower than the ash fusion point, fewer spherical particles are generated.

3.1.2. Influence of Temperature on Particle Surface Element Distribution. The surface element distribution of particles at different temperatures is shown in Figure 5. As can be seen from Figure 5, the content of S, Fe, and Na at a temperature of 1300 °C is greater than that at 1200 °C. This is due to the reducing atmosphere in the gasifier. The volatilization of S and Na increases with increasing temperature, while the Fe is restored to a low valence state in the reducing atmosphere, and the volatility is enhanced. The proportion of these elements increased on the surface of the particles.

3.1.3. Influence of Temperature on Particle Size Distribution. As can be seen from Figure 6, the influence of temperature on particle size distribution is obvious. When the temperature rises, the corresponding position of the peak value of particle size distribution decreases in response and the proportion of small particles rises. It shows that the temperature not only affects the proportions of large and small particles, but also affects the distribution of particles.
small particles but also affects the peak position of the particle size distribution.

The studies of Bart Buhre and others\textsuperscript{20} show that the influence of temperature on the formation of small particles is increasingly obvious with the increase of the oxygen content: the oxidizing agent used for coal–water slurry gasification is pure oxygen; therefore, the influence of temperature on the formation of gasification particles will be strong, and the number of small particles generated at high temperatures is much greater than that generated at low temperatures. The experimental results are in agreement with the conclusions of Bart Buhre.

3.2. Influence of the O/C Ratio on the Particle Properties. In the gasification process of coal–water slurry, the O/C ratio which is often called the oxygen/coal ratio in the field is one of the most important factors affecting coal–water slurry gasification. The oxygen/coal ratio refers to the ratio of oxygen to carbon in the gasification material into the gasifier vaporizer, and the commonly used unit in the field is N m$^3$/kg, which is the standard amount of oxygen needed for each carbon element of 1 kg. However, in order to obtain and control the data more directly, the O/C ratio is usually used instead of the oxygen/coal ratio in practical design and online control of field application software. The O/C ratio, which refers to the molar ratio of oxygen atom to carbon atom in the gasification material into the gasifier vaporizer, is a dimensionless quantity and close to the value of the oxygen/coal ratio. For the actual operation of the gasifier vaporizer, generally, when the gasifier load is constant, the main way for the gasifier vaporizer to adjust the temperature is adjusting the amount of oxygen into the gasifier vaporizer, that is, to adjust the value of the O/C ratio. Therefore, the influence of the change of the O/C ratio on the gasification process of coal–water slurry, the ingredient of the coal gas of the outlet, and the temperature of the gasifier vaporizer are the most important concerns. The O/C ratio mainly affects the average temperature in the gasifier vaporizer, the outlet temperature, the concentration distribution of various substances, and the ingredient of the coal gas of the outlet but has little effect on the flow field distribution in the gasifier vaporizer.

3.2.1. Influence of the O/C Ratio on the Morphology of Particles. The SEM output showing particles under different O/C ratios is shown in Figure 7: when the O/C ratio is 1.1, spherical particles predominate; when the O/C ratio is 1.0, the number of spherical particles is greater, and small spherical particles are mostly in the form of single particles; when the O/C ratio is 0.9, the large particles formed are mainly in the form of irregular particles, and the spherical particles are less common. This is because carbon conversion of coal particles increases along with the increase in the volume of oxygen, while the particle size decreases and the amount of mineral volatilization increases; so more spherical particles are produced; however, when the O/C ratio is 1.1, the shrinkage
of coal particles is greater, the mineral fusion probability increases and the small particle aggregates are more common.

3.2.2. Influence of the O/C Ratio on Particle Element Distribution. The element content on particle surfaces and the carbon content of particles under different O/C ratio conditions are shown in Figures 8 and 9: the O/C ratio has a significant influence on the carbon content of particles but has little influence on elements such as S, Fe, Na, Al, Si, and so forth. The carbon content of the particles decreases with an increasing O/C ratio.

3.2.3. Influence of the O/C Ratio on Particle Size Distribution. As can be seen from Figure 10, the O/C ratio exerts a significant influence on the particle size distribution. When the O/C ratio is 1.0, more fine particles are generated (particles of 10–100 um are more common, and particles bigger than 100 um become rarer). When the O/C ratio is 1.1, the amount of coarse particles is maximized, and the amount of fine particles is minimized. When the O/C ratio is 0.9, the particle size distribution is intermediate to the aforementioned two cases. This is because the carbon conversion rate is the lowest when the O/C ratio is 0.9, and the unburned carbon content in the particles is high. When the O/C ratio is 1.1, the carbon conversion rate is the largest, the mineral fusion probability is maximized, and more small particle aggregates are also formed. On the other hand, the probability of fusion of mineral particles in coal increases, and the number of coarse particles formed by the fusion of coal particles is increased and the number of fine particles is reduced, which leads to the fact that the content of coarse particles under these two conditions is higher than the content of coarse particles when the O/C ratio is 1. The trend in the number of fine particles is the opposite to that described above for larger particles.

4. CONCLUSIONS

Based on the experiment on a small thermal coal–water slurry gasification experimental unit, the influences of gasification temperature and the O/C ratio on the particle properties in the gasifier are studied. The following conclusions are drawn from the experiments:

(1) Temperature exerts an obvious influence on the morphology, surface content distribution, and size distribution of particles. The higher the temperature, the more spherical particles are produced, the higher the content of Na, Fe, and S in particles, and the larger the proportion of small particles.

(2) When the O/C ratio is 0.9, the amount of large size particle produced is the greatest and the number of spherical particles is the least. When the O/C ratio is 1.1, the fine particle aggregate content is maximized.

(3) The O/C ratio has the greatest influence on the carbon content of particles but has little influence on elements such as Na, Al, Si, Fe, S, and so forth. The carbon content of the particles decreases with an increasing O/C ratio.

(4) The O/C ratio exerts an obvious influence on the particle size distribution. When the O/C ratio is 1.0, more fine particles are produced (particles of 10–100 um are more common, and particles bigger than 100 um are rarer). When the O/C ratio is 1.1, the number of coarse particles is maximized and the amount of fine particle aggregates also increases.

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Figure 8. Element content on the particle surface at different O/C ratios.

Figure 9. Carbon content of particles under different conditions.

Figure 10. Particle size distribution at different O/C ratios.
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Notes
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