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The role of electrical heating on tribocharging and triboelectrostatic beneficiation of fly ash

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Abstract: Triboelectrostatic beneficiation is an effective technique to remove unburned carbon from fly ash. The purpose of this study is to enhance the particles tribocharging, and improve the efficiency of removal unburned carbon from fly ash using electrical heating. An experimental system with electrical heating was established to realize the tribocharging measurement and fly ash triboelectrostatic beneficiation. The experimental material collected from a thermal power station was fly ash with an average loss on ignition of 20.76%. The operating conditions were electric field voltage of 40KV and air flow rate ranging from 1.7 to 4.25 m/s. The influence of heating temperature and heating position on tribocharging and triboelectrostatic beneficiation was discussed. The feasibility of electrical heating was evaluated by the charge-to-mass ratio (CMR), loss on ignition (LOI) and removal unburnt carbon rate (RCR). The results indicate that the increasing of collision probability for heated particles can improve the charging efficiency. The heating temperature related to gas moisture content and particles dielectric constant is inversely proportional to the LOI of ash, whereas it is opposite for the RCR. The heating position has an effect on the CMR and RCR because of changed contact time between charged particles and compressed air. The optimum conditions are the air flow rate of 4.25 m/s, heating temperature of 90°C. Heating tube III is suitable to install electrical heating system. The electrical heating is proved to be effective to improve the efficiency of fly ash triboelectrostatic beneficiation.

Keywords: fly ash, tribocharging, triboelectrostatic beneficiation, electrical heating

1. Introduction

A development of modern society depends on the sources of power. As a primary energy resource in China, more than 55% of energy consumption is supplied by coal. With the increasing seriousness of the oil crisis, the coal becomes increasingly important for the national economy (Cao et al., 2001). About 56% of coal produced is used for the generation of electrical power. Fly ash is a kind of solid waste produced by coal fired power plants. It is one of the most complex and largest amount of industrial solid wastes generated in China. It also has a harmful effect on the environment. People pay more attention to research the resource utilization of fly ash (Huang et al., 2003; McMahan et al., 2002). As a waste of recoverable resources, it can be used in the soil amelioration, construction industry, etc (Yao et al., 2015). The fly ash is one kind of potential substitute for bauxite because of rich in alumina. So the researchers pay more attention on the recovery of alumina from fly ash (Yao et al., 2014). The fly ash is also considered as a useful and potential mineral resource. The various alumina recovery technologies and the latest industrial applications had been introduced (Ding et al., 2017). Some researches show that the recycling and utilization of mullite in coal fly ash is necessary because of environmental and economic benefits. The unburned carbon can be removed from the coal fly ash by effective humic acid surfactant (Han et al., 2018).

The unburned carbon content is a harmful component for the fly ash utilization (Hwang et al., 2002). For example, several foregone researches had proved that unburned carbon content of fly ash could

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exert an obviously adverse influence on structural intensity of construction industry (Ban et al., 1997; Soong et al., 2001). Accordingly, unburned carbon contents of fly ash should be reduced in order to meet technical requirements for industrial application (Zhang et al., 2018; Ling et al., 2018).

Triboelectrostatic beneficiation is effective to separate unburned carbon from fly ash. A lot of factors have an impact on the separating efficiency (Kim et al., 2001; Li et al., 2013). Especially for ambient temperature and water content of fly ash have a great influence on the fly ash triboelectrostatic beneficiation. A lot of engineering practices have shown that it is difficult to efficiently remove carbon from fly ash in summer or winter because of high humidity or low temperature. The production for some companies is intermittent owing to fly ash particles agglomeration.

Recent researches had been focused on above problems. As for the fly ash triboelectrostatic beneficiation, charge density and separation efficiency were closely related to the relative humidity and temperature. The maximum charge density was obtained at the air temperature of 74℃ and lower than 30% relative humidity(Kim et al., 2000). The moisture and high humidity can dramatically diminish the unburned carbon separation efficiency on account of long-term exposure to moisture. An experimental methodology was introduced to measure the charging distribution for fly ash particles exposed to weather conditions for 6 months (Federico et al., 2009). In addition, particles charging is also influenced by the operation temperature. The collision between particles was related to a tribo-charger temperature field. An appropriate configuration of tribo-charger obtained by particles collision experiments using infrared thermography was verified by the fly ash triboelectrostatic beneficiation (Li et al., 2013; H.S. et al., 2015).

There are also some studies focused on the effect of humidity on the particles charging. The humidity and particle surface moisture had more important effects on the tribocharging than particle size (Cangialosi et al., 2006). If the fly ash is exposed to weather conditions, the charging efficiency will be reduced by moisture or humidity (Federico et al., 2009). The humidity has an important impact on triboelectric charging of polyethylene particles in a vertically vibrated granular bed (Kolehmainen et al., 2017). The specific charge of pharmaceutical granules in a fluidized bed dryer decreased with an increase of moisture content (Taghavivand et al., 2017). The difference of discharge was obvious under different humidity condition. It was shown that the faster charge decay was caused by higher humidity (BIEGAJ et al., 2017). It has been shown that the average charge on the polyethylene particles was influenced by changing the relative humidity of the gas inside a small-scale fluidized bed (Sippola et al., 2018).

Based on the above, it can be found that the higher temperature and lower humidity are favorable conditions for the fly ash beneficiation. The higher temperature can not only enhance the specific resistance but also improve the surface moisture content of the fly ash particles. And the air humidity inside the pipeline would be reduced for heated fly ash. These can be realized by heating. Therefore, the heating may be used to improve the particles tribocharging and fly ash beneficiation efficiency. In a previous study, it is feasible to improve charging efficiency of fly ash triboelectrostatic beneficiation using microwave heating. The microwave intensity and irradiation time should adapt to moisture contents of wet fly ash (Li et al., 2016).

Microwave heating can effectively improve the efficiency of fly ash triboelectrostatic beneficiation, but it is difficult for industrial application. The microwave can only heat particles, not air. The air also has significant influence on the particles charging. The process will be influenced by the particles agglomeration or deposition caused by feeding mass fluctuation. And the microwave system is also costly. The purpose of this study is to improve the efficiency of tribocharging and separation using electrical heating. The feasibility will be evaluated according to the comparison of experimental results between the unheated and heating. Suitable operating parameters are obtained to realize the fly ash triboelectrostatic beneficiation efficiently.

2. Materials and methods

2.1. Materials

The fly ash used in this study was obtained from a thermal power station in the Liaoning province of China. A 30kg portion of a representative sample was divided into 60 portions uniformly. It was put into a sealed container in order to keep them from absorbing moisture of circumstance. The size distribution was achieved by sieve analysis. The content of unburned carbon was obtained by LOI analysis. The samples of fly ash were stored by a desiccator before experiments. The measurements were repeated two times for every sample. The final results were shown in Table 1. The proportion of particles with size -74+45 μm is the most and its LOI is also maximal than others. The fly ash has an average LOI of 20.76%.

Table 1. Size analysis of the fly ash sample

Size range (μm)	Mass (%)			LOI (%)		
	Group1	Group2	Average	Group1	Group2	Average
+74	10.24	10.18	10.21	5.48	5.54	5.51
-74+45	42.54	43.10	42.82	23.35	22.95	23.15
-45+38	14.28	14.32	14.30	20.55	20.67	20.61
-38	32.94	32.40	32.67	18.74	18.52	18.63
Total			100%			20.76

2.2. Experimental system

The experimental system is showed in Fig. 1. The experiments in this study considered the influence of heating temperature (50℃, 70℃ and 90℃) and heating position on fly ash tribocharging and triboelectrostatic beneficiation. The environmental temperature is 18℃ and the air humidity is 36.5%. The feeding mass of fly ash is 20g for every experiment. A frequency changer can control the fan airflow rate ranging from 1.7 to 4.25 m/s. The diameter of charging tube is 0.05m.

Three electrical heating tubes made by copper are installed on the different position of the pipeline. The first heating tube named I lies in the initial section of pipeline. The remaining two positions named II and III is situated on the middle and terminal of the pipeline, respectively. The three electrical heating tubes are not used at the same time. The diameter and length of pipe is 100mm and 300mm, respectively. The thermocouple is inserted into the heating tube in order to detect the temperature inside the pipeline. The temperature controller ranges from 0℃ to 120℃. The working voltage of 220V is input from a plug. The diameter and length of thermocouple is 5mm and 105mm, respectively. A maximal temperature will be set before the experimental study. The controller can adjust the temperature automatically. When the temperature is greater than the maximum value, the power supply is automatically cut off by the temperature controller. Thus, the heating will stop working. It will restore once the temperature is lower than the preset values.

Fly ash fed in by a vibrating feeder is fallen into the pipeline from the container. When the particles flow through the heating tube, they will be charged with different polarity because of collision and friction. The changes caused by heating for particles temperature and air humidity will make a positive impact on the tribocharging and triboelectrostatic beneficiation. The valve can control the flow direction of charged particles. The CMR of particles will be measured by a Faraday cup and electrometer. The gas can escape from two filters installed on the lid. The removal of unburned carbon from fly ash will be realized as the particles flow into the high voltage static field of 40KV. The charge of unburned carbon is negative while the ash is positive. The motion of unburned carbon and ash particles is in the opposite direction due to the electric field force. The separated particles will be gathered by several different collectors.

2.3. Experimental evaluation index

The CMR can be used to evaluate the particles tribocharging. It was defined by Equation (1):

$$\mathrm{CMR} = \frac{Q}{M} \times 100\% \tag{1}$$

where Q is the charge of fly ash particles indicated by electrometer, μC; M is the mass of particles inside the Faraday cup, g.

The separating efficiency of unburned carbon under different operating conditions is evaluated by the LOI and RCR. The LOI was calculated by Equation (2):

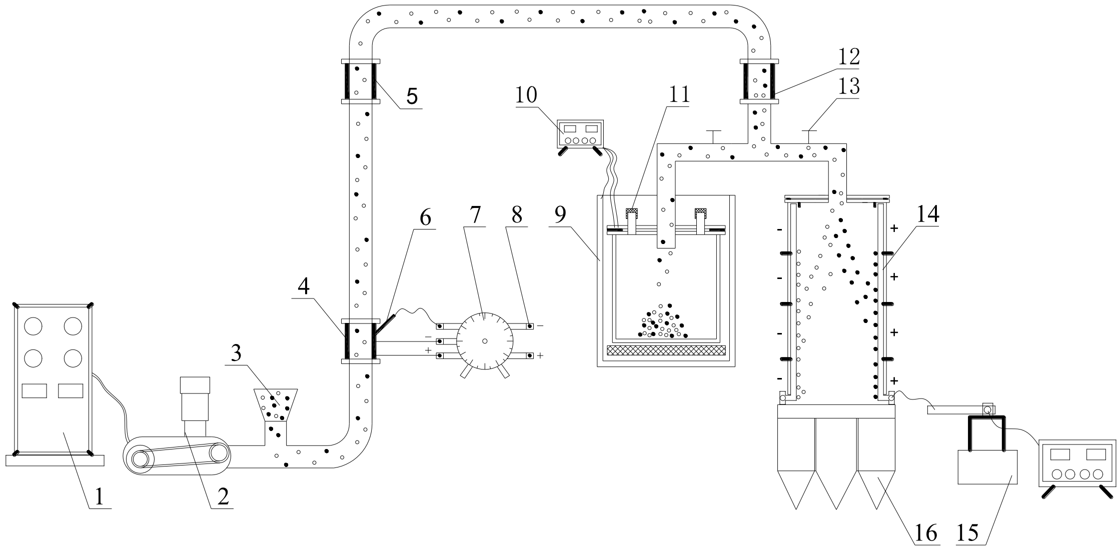
$$LOI(\%) = \frac{M_0 - M_1}{M_0} \times 100\% \tag{2}$$

where M_0 is the mass of unbaked fly ash and crucible, g; M_1 is the mass of baked ash and crucible, g.

The RCR is described by Equation (3):

$$RCR = \frac{LOI_S - LOI_R}{LOI_S} \times 100\% \tag{3}$$

Where LOI_S is defined as the LOI of fly ash sample before experiment. LOI_R describes the LOI of fly ash after removing unburned carbon and it can be obtained from the negative plate product.



1. Power regulator 2. Fan 3. Vibrating feeder 4. Electric heating tube I 5. Electric heating tube II 6. Thermocouple 7. Temperature controller 8. Plug 9.Faraday cup 10.Electrometer 11. Filter 12. Electric heating tube III 13.Valve 14. Electric field 15. High voltage 16. Collector

Fig. 1. Experimental system of fly ash triboelectrostatic beneficiation

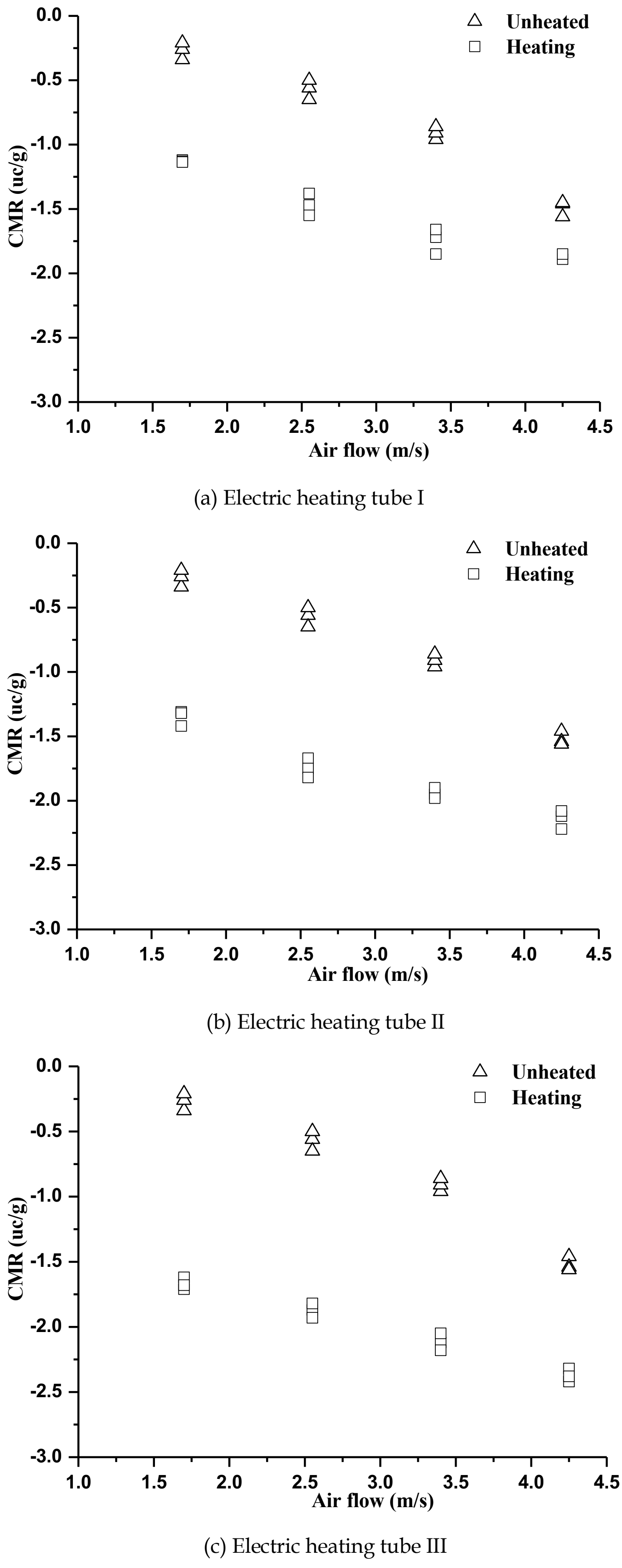
3. Results and discussion

3.1. Analysis of tribocharging experimental results

The purpose of tribocharging experimental was to prove whether the electrical heating is feasible or not for improving the fly ash tribocharging. The CMR for heated fly ash was obtained with the heating temperature of 70℃.The results of each experiment were measured for three times. Comparisons of CMR for different heating position were illustrated in Fig. 2.

The results showed that the CMR was direct proportional to air flow rate whether the fly ash was heated or not. The RCM had the same trend for three heating positions. The CMR of unheated was obviously smaller than that of heating under the same condition. As for the electrical heating tube I, the CMR of heating increased from -1.12μC/g to -1.89μC/g with the air flow rate ranging from 1.7 to 4.25 m/s. While that of unheated only increased from -0.34μC/g to -1.46μC/g. In addition, if the electrical heating tube changed from I to III, the CMR difference between the unheated and heating gradually increased under the same air flow rate. The CMR of electrical heating tube III was larger than that of other positions.

An obvious difference of CMR was attributed to the dispersion and collisions of particles caused by electrical heating. The charging of fly ash was enhanced by heating process. As shown in Fig. 3, the particle's movement inside the heating pipe is divided into four processes: heating, dispersing, collision and charging. The small particles of fly ash were gathered into groups by the action of liquid bridge force. The electrical heating can reduce the adhesive attraction between particles because of removing some moisture on the particles surface. The particles were slowly dispersed and the number of charged particles obviously increased.

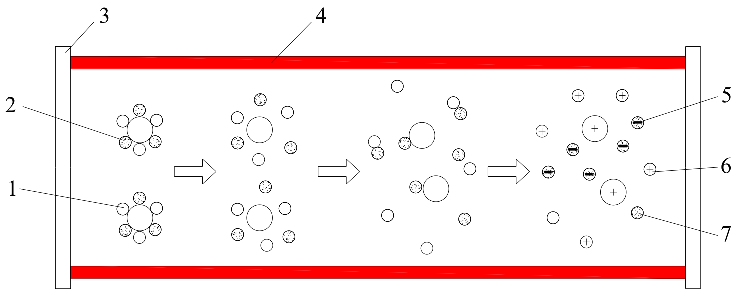


(a) Electric heating tube I

(b) Electric heating tube II

(c) Electric heating tube III

Fig. 2. The influence of the electrical heating on the fly ash tribocharging



(a) Heating (b) Dispersion (c) Collision (d) Charging

1.ash 2.carbon 3.flange 4.heating pipe 5.negative particle 6.positive particle 7.uncharged particle

Fig. 3. Fly ash tribocharging with electrical heating

According to the particles collision model of Sommerfeld (Sommerfeld and G Zivkovic, 1992), the collision probability of two particles can be calculated by Equation (4):

$$\mathrm{p}=\frac{\pi(R_1+R_2)^2\overrightarrow{v_r}N\Delta t}{V} \tag{4}$$

where p is the collision probability. R_1 and R_2 are the particle radius, m. $\overrightarrow{v_r}$ is the relative velocity of particles, m/s. N is the particles number. Δt is the time, s. V is the volume of particles movement, m^3.

The relation between charge and collision number for particles is described by Equation (5):

$$q=q_\infty\left(1-\exp\left(-\frac{n}{n_0}\right)\right) \tag{5}$$

where q is the charge of particles, μc . q_∞ is the saturated charge, μC, n is the collision times, n_0 is the relaxation number.

According to the above equations, the particles number is proportional to the probability of collision. The increase of particles number can improve the probability of particles collision. While collision is the main way of particles charging. With the increase of particles number, the charging efficiency will be improved. Therefore, it is feasible to enhance the CMR of fly ash by electrical heating. This also helps to improve the efficiency of fly ash triboelectrostatic beneficiation.

3.2. Analysis of fly ash triboelectrostatic beneficiation

3.2.1 Influence of heating temperature

The influence of heating temperature on fly ash triboelectrostatic beneficiation was obtained with the heating tube I. Comparisons of LOI and RCR for different heating temperature was illustrated in Fig. 4 and 5. The LOI was inversely proportional to air flow rate whether the fly ash was heated or not. By comparison with the LOI of unheated, that of heating was obviously reduced. At air flow rate of 1.7 m/s, the LOI of the unheated and heating temperature 50 ℃ was 17.86% and 16.42%, respectively. As the air flow rate increased to 4.25 m/s, it was decreased to 15.86% and 14.14%, separately. The higher the heating temperature was, the lesser the LOI would be. At air flow rate of 4.25 m/s the LOI with heating temperature 70℃ and 90℃ was 13.51% and 12.73%, respectively. It indicated the LOI with different heating temperature had noticeable differences as the increasing of air flow.

It can be seen that electrical heating has an impact on the moisture content of gas and the dielectric constant of particles. The temperature of gas rises under heated, while the moisture content will be decreased. Under the condition of high temperature and dry air, the surface moisture of particles gradually decreases because of water evaporation. The resistivity of unburnt carbon and ash increases gradually, and the dielectric constant of them decreases. It will reduce the electrical conductivity of fly ash particles, and influences on the charge transfer between particles. The possibility of charge neutralization will be reduced. Therefore, the heated dry air will contribute to particles tribocharging and improve the separation efficiency of fly ash.

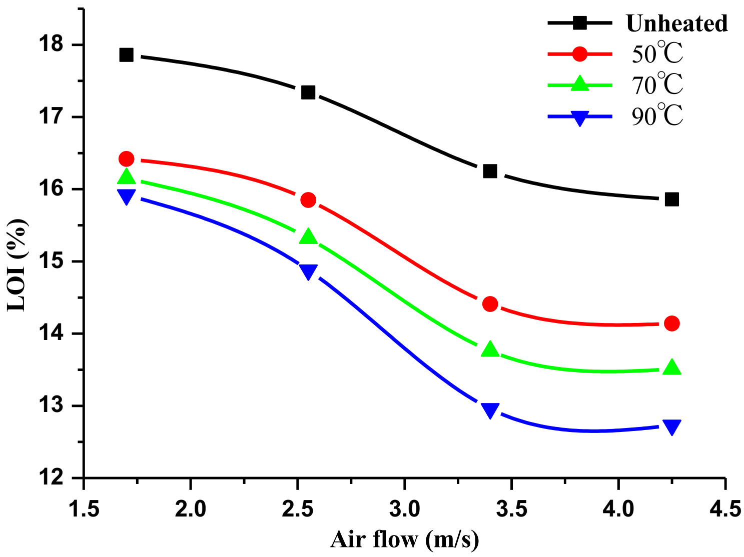


Fig. 4. The influence of heating temperature on the LOI

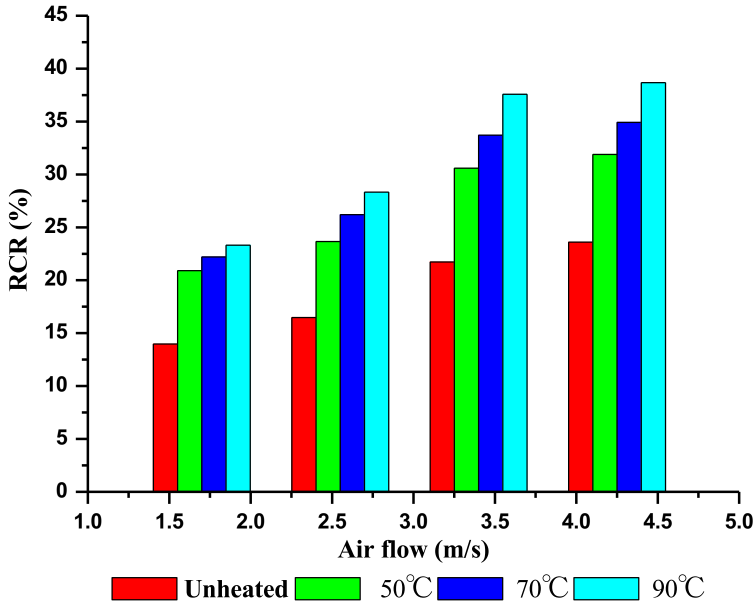


Fig. 5. The influence of heating temperature on the RCR

The electrical heating helps to remove carbon from fly ash. The heating temperature was in direct proportion to RCR. At the air flow rate of 3.4 m/s, the RCR rose from 30.59% to 37.57% when the heating temperature was increased from 50°C to 90°C. With the air flow rate ranging from 1.7 to 4.25 m/s, the RCR increased from 23.31% to 38.68% under the heating temperature of 90°C. The RCR with heating temperature of 90°C was the maximum.

The heating temperature had an effect on the LOI and RCR of negative products. The increase of air flow rate and heating temperature could not only reduce the unburned carbon content, but also improve the efficiency of removal unburnt carbon. The minimum LOI and the maximum RCR were obtained under the heating temperature of 90°C and the air flow rate of 4.25 m/s.

3.2.2 Influence of heating position

The electrical heating improves the charging efficiency of fly ash. But the surface moisture of particles is reduced because of being heated. So this will decrease the resistivity and increase the dielectric constant. The charging efficiency of particles is declined because of the enhancement of conductive capability. The moisture is vaporized into the air inside the delivery pipe. Then the increasing of humidity and conductivity for air promotes the charge transfer and neutralization between the particles. It is the reason for the decrease of CMR. Therefore, the heating position has an important impact on the particles charging and separation efficiency.

The influence of heating position on fly ash triboelectrostatic beneficiation was discussed under the conditions of heating temperature 90℃. Fig. 6 and 7 showed the comparison of LOI and RCR with different heating position. The influence of air flow rate on the LOI and RCR was the same as that of the previous studies. Under the same air flow rate, the LOI of unheated was obviously higher than that of heating, while the results were reversed for the RCR. As the air flow rate increased from 1.7 to 4.25 m/s, the LOI of heating tube III decreased from 15.03% to 11.95%, while the RCR increased from 27.60% to 42.44%.

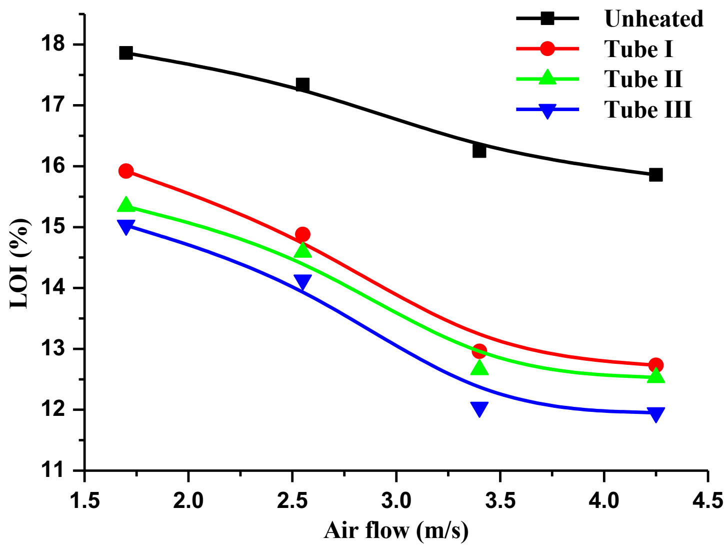


Fig. 6. The influence of heating position on the LOI

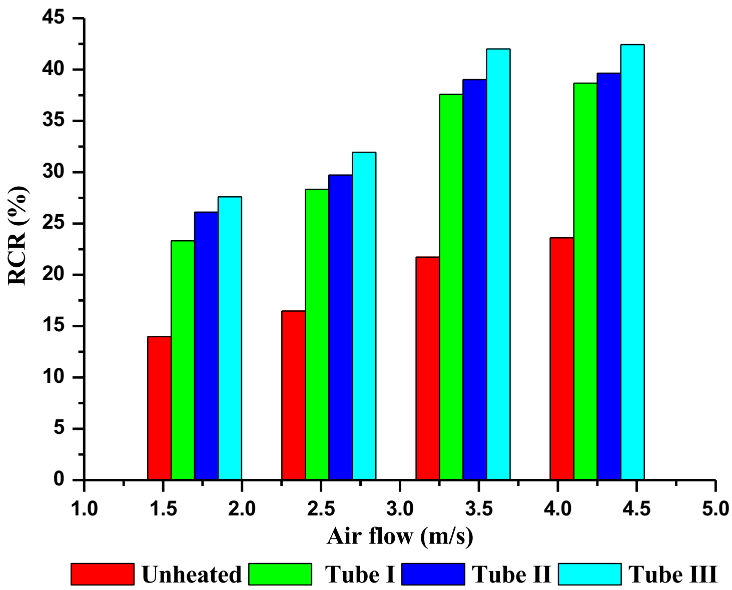


Fig. 7. The influence of heating position on the RCR

The influence of three heating positions on the LOI and RCR was different from each other. The heating tube III has an obvious effect on the fly ash triboelectrostatic beneficiation than others. The influence of heating tube I was almost identical to that of heating tube II according to the difference of LOI and RCR. At the air flow rate of 4.25 m/s, the LOI of heating tube I and III was 12.57% and

11.95%,respectively. The RCR of those was 39.45% and 42.44%. For the heating tube I, the moisture of particles sufficiently released because of the longest motion path from the heating position to the injection of electric field. Thus, the air humidity gradually increased. The CMR and RCR were reduced because of the maximum contact time between particles and moist air. The heating tube III was close to the inlet of high-voltage electric field. The charging enhancement of fly ash with electrical heating was rapidly completed. The motion path of charged particles was shortened, and the charge transfer possibility is reduced due to short contacts time. Thus, the heating tube III was proper to improve the efficiency of removal unburned carbon.

4. Conclusions

An experimental study was conducted to discuss whether the electrical heating was effective to improve the efficiency of removal unburned carbon from fly ash or not. The experimental results were summarized as follows.

(1) The electrical heating can not only improve the temperature of gas-solid inside the pipe, but also reduce the water content of particles surface. The particles number is obviously increased after being heated and dispersed. It will improve the particles collision probability and CMR. The results have been verified by experimental study.

(2) The air flow rate and heating temperature have an important effect on the separation efficiency. The increasing of these parameters can improve the tribocharging efficiency due to reducing the gas moisture content and particles dielectric constant. This will be conducive to particles charging and remove unburned carbon from fly ash. Meanwhile, it is necessary for the suitable heating position to reduce the contact time between charged particles and moist air.

(3) As the experimental conditions of air flow rate 4.25 m/s, heating temperature 90℃ and heating tube III, the electrical heating can reduce the LOI from 15.86% to 11.95% and increase the RCR from 23.60% to 42.44%. Obviously, the electrical heating can improve the efficiency of fly ash triboelectrostatic beneficiation.

Acknowledgments

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