

Ignition of dispersed coal in local conductive heating conditions

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Abstract. Present work studies the ignition of a brown coal by a hot metal particle. The experiments establish the limits of the gas-phase ignition and ignition delay times in conditions when the metal particle is situated on the surface of dispersed coal layer. The coal particle size was different in different series of experiments, and it was ranged from 0.1 to 1 mm; the shapes of the metal particles were sphere, disk, and cube; their initial temperature varied between 1000 and 1400 K. Three modes of gas-phase ignition of coal were established with the ignition zone of volatiles located in the vicinity of the hot particle. The practical application of obtained results is the development of fire prevention guidelines for tightening fire safety management at productions dealing with coal mining, transportation, storage, processing, and combustion.

1. Introduction

Coal is widely used in thermal power engineering as solid fuel or a component of coal water slurry to produce electricity and heat. In chemical industry, coals serve as raw materials to produce synthetic liquid fuel, gas, porous carbons, and sorbents.

All the stages of the technological process are explosion and fire hazardous, starting from coal mining and ending with fuel preparation for combustion at thermal power plants or processing raw materials at chemical plants. Fine dust deposits are the most fire hazardous. A fire may result from a layer of coal dust interacting with heated walls of process equipment [1, 2] or hot metal particles [3]. Local heat sources may emerge due to welding of metalworks, their mechanical treatment, friction of unlubricated moving metal parts, and power line short circuits. Over the recent years, coal dust catching fire (including due to hot metal particles) has become the reason for several major technological disasters at thermal power plants [4]. Therefore, research into the ignition patterns and properties of finely divided solid fuel heated by limited-capacity heat sources is a relevant task with a view to prevent fire outbreaks in mines, at thermal power plants, and chemical plants. The new knowledge may help engage technical experts in tackling this urgent problem, develop fire prevention guidelines, and make fire safety management more rigorous during maintenance and repair at process facilities.

When hot metal particles interact with a layer of coal dust, this induces a number of interrelated physical and chemical processes. Solid fuel heats up, the local source cools down, coal starts decomposing, volatiles are released, a gas mixture is produced, and then it heats and starts burning. As a rule, the ignition of highly reactive brown coals containing about 50% of volatiles leads to the fire spreading over the surface of solid fuel. The energy released during the oxidation of the gas mixture



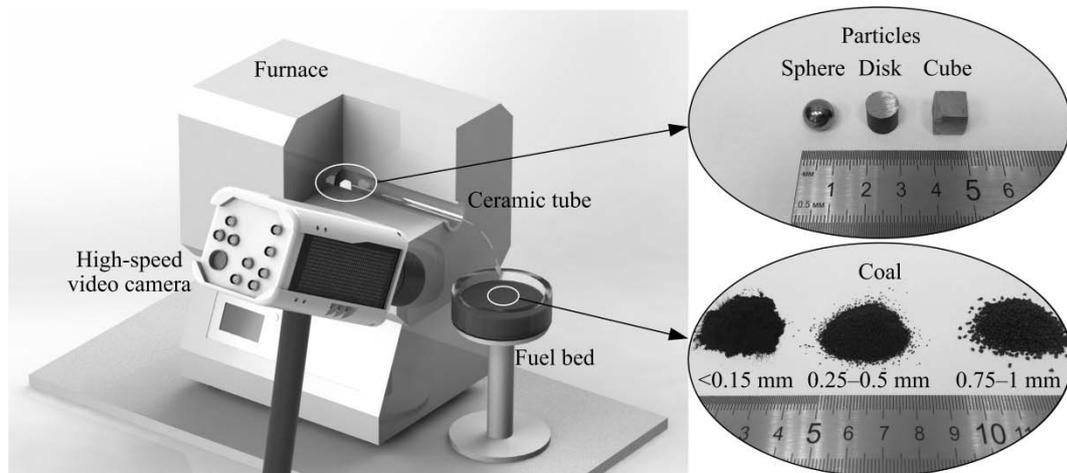


Figure 1. The schematic diagram of the experimental setup.

heats up the near-surface layer of coal. Its thermal decomposition accelerates. More fire gases are released. Thus, the combustion of brown coal is a self-maintained process induced by the ignition of the decomposed gases.

Research [3] aimed at confirming the hypothesis of sustainable ignition induced by the interaction between a hot metal particle and a layer of coal dust. The authors [3] established the dependencies of coal ignition delay time on the initial temperature of a disk-shaped steel particle. The development of fire prevention guidelines requires more information on the patterns and attributes of the process under study. In this work we investigated experimentally the patterns and characteristics of brown coal dust ignition by metal particles of various shapes. Sizes of coal particles and initial temperatures of local heat source varied within a wide range.

2. Experimental investigation

2.1. Experimental setup

Figure 1 shows the schematics of the experimental setup based on a rotary muffle furnace. The inside diameter of the ceramic tube is 40 mm and its length is 450 mm; the temperature ranges from 300 to 1500 K; the temperature was measured using an in-built type S thermocouple. In each series of experiments, a ceramic tube was heated up to the needed temperature. After it stabilized, a metal particle was placed in the center of the ceramic tube (figure 1) and heated for 5–10 minutes. During this time, the particle temperature leveled off. The particle was released to fall perpendicularly to the surface of the fuel in the metal vessel. The free fall of the hot particle in the air until it reached the surface of a fuel sample took approximately 50 ms. Within a short time interval, the temperature of the particle changed by less than 0.5% vs. the temperature set in the muffle furnace. It could be neglected during the experiment analysis because the particle temperature was more than 1100 K.

The processes taking place during the induction period, when a hot metal particle interacted with fuel, were recorded by a Phantom v411 high-speed camera (4200 frames per second at maximum resolution 1280×800 pixels; pixel size 20 μm; 12 bit depth; 16 Gb memory; image-based auto-trigger). The high-speed camera automatically recorded the exact moment of contact between the hot particle and the surface of the fuel bed. The trigger detected two points in time: the contact between the particle and coal, and the flame appearance. The ignition delay time t_d is the parameter of interest and is defined by the elapsed time between these two signals. The TEMA Automotive software was used to analyze the video recording. The random error of t_d determination was calculated according to the results of a set of 7–10 experiments for each configuration of the igniter at a fixed value of T_p . The

average values of t_d and mean-square deviations were calculated for each T_p . The dispersion of values ranged from 4.5 to 8%.

2.2. Materials

Brown coal (rank 2B) of Kansk-Achinsk basin was used in this work. It came from Borodinsky coal strip mine in Krasnoyarsk Krai (Western Siberia, Russia). Such coal is widely used as fuel at thermal power plants. About a half of federal subjects of the Russian Federation use brown coal as the main fuel to produce electricity and heat. The main properties of this coal are as follows: $W^a = 28\%$, $A^d = 12.3\%$, $V^{daf} = 51.54\%$, $Q_s^r = 14.82$ MJ/kg, $C^{daf} = 73.27\%$, $H^{daf} = 4.63\%$, $N^{daf} = 0.88\%$, $S^{daf} = 0.93\%$, $O^{daf} = 20.3\%$.

To prepare the experimental samples, coal was pulverized by using a rotor mill Pulverisette 14. Its specifications are as follows: rotor speed $(6-20) \times 10^3$ rpm; maximum feed size 10 mm; final fineness $d_{50} < 40$ μ m. The resulting coal dust was sieved through a laboratory plansifter (200 cycles per minute; swing 50 mm). A set of sieves were also used according to ISO 3310-1:2000 to classify the coal into groups of samples of different particle size (figure 1): under 0.15 mm; 0.25–0.5 mm; 0.75–1 mm. The maximum coal particle size did not exceed 1 mm. Preliminary experimental studies showed that the ignition of a fuel bed with this particle size is unstable and probabilistic in nature due to the small contact area of a small hot particle with a highly porous fuel bed.

Three different igniters were used in the experiments (figure 1): a steel sphere ($r_p = 5$ mm), a steel disk ($r_p = 5$ mm, $z_p = 10$ mm), and a steel cube ($a_p = b_p = c_p = 10$ mm). The particle temperatures ranged from 1100 to 1400 K. Particles with different configurations had the same characteristic size (10 mm). This parameter describes the heat content of the local heat source at the reference time and may have a significant effect on the characteristics of the ignition process.

According to experimental conditions, at least 7–10 runs were repeated to calculate the ignition delay time under the same conditions to provide valid results. The fuel bed was formed in a metal vessel 40 mm in diameter and 10 mm in height. With this size, the local heat source interacts with the fuel bed under similar conditions as a hot particle does with a layer of coal dust. A heat wave spreads from the heat source into the depth of the fuel. When the fuel ignites, the wave does not reach any interfaces that would change the heat transfer conditions, e.g. the surface where coal dust accumulates. A fresh fuel sample was used in each experiment so that changes in coal characteristics due to volatiles and carbon burnout could not interfere with the research findings.

3. Results and discussion

Figure 2 shows the experimental curves of the fuel bed ignition delay times at the different initial temperatures of a cube-shaped hot particle under the conditions of different dispersion of coal particles. The curves look similar for disk and sphere-shaped particles. The hot particles of different shapes show different ignition delay times. A more detailed analysis of how the shape of the local heat source affects the coal ignition properties will follow. In figure 2, the left boundaries of the curves Nos. 1, 2 show boundary conditions ($T_p = 1150$ K) for the stable gas-phase ignition of coal with a particle size of 0.25–1 mm when interacting with a 10-mm cube-shaped hot steel particle. For the coal with a particle size under 0.15 mm (curve No. 3 in figure 2), the boundary condition of gas-phase ignition was $T_p = 900$ K. At lower T_p , the ignition was unstable. This means that flaming ignition did not occur in each experiment of the series, at that the T_p and the shape of the local heat source held constant.

It was established (figure 2) that the exponential dependence of ignition delay time on the initial temperature of a hot steel particle is typical of a larger particle size (0.25 – 1 mm) of coal. The duration of the induction period increases with the increasing coal particle size. The values of t_d at $T_p = 1150$ K differ from those at $T_p = 1400$ K by about 90%. The shape of the $t_d = f(T_p)$ curve for fine coal (< 0.15 mm) is close to linear within the range of initial particle temperature of 1150–1400 K, and the difference in the ignition delay time amounts to about 40%. This result is likely to stem from the differences in how coal of different particle sizes interacts with a hot particle.

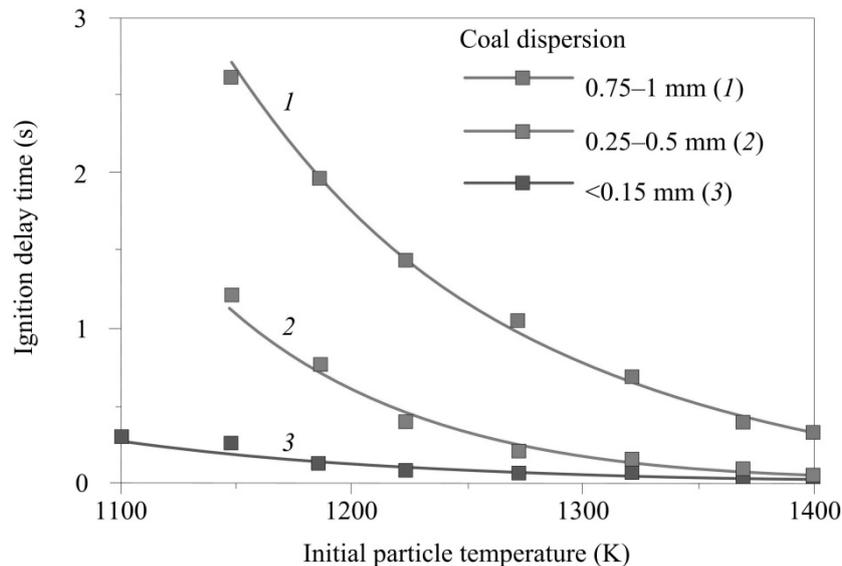


Figure 2. Ignition delay time versus the initial temperature of the steel particle in cube shape (size 10 mm) with different coal dispersion.

Figure 3 shows videograms of the experiments with the ignition of coal by a disk-shaped steel particle with $d_p = 10$ mm, $z_p = 10$ mm, and $T_p = 1230$ K. The conditions of mechanical interaction under external loads are essentially different for coal particles sized over 0.2 mm and under 0.2 mm (for example, from the metal particle falling on the fuel bed surface). In the first case, after the free fall of the metal particle, it is located on the surface of the fuel bed at the reference point of time. The structure of its near-surface layer does not change significantly (figure 3a). As a result of the conductive heat transfer, the near-surface layer of the fuel heats up (figure 3a, frame A). With an increase in temperature, the coal starts to decompose rapidly and volatiles are released (figure 3a, frame B). The thermal decomposition proceeds at its maximum rate near the boundary of coal contact with the hot particle, where the temperature reaches 500–600 K. The gaseous products of thermal decomposition are released from this zone into the ambient medium in a small neighborhood of the base of the local heat source. The coal decomposition reduces the concentration of the organic matter with the fuel volume remaining constant. In a gaseous medium, the flammable mixture is formed through the diffusion of volatile substances and oxygen from the air. The fuel and oxidizer mixture is additionally heated when it moves along the side faces of the hot particle until it ignites (figure 3a, frame C). The coal decomposition then becomes more rapid, the flammable gas emission increases, and the flame enlarges in the vicinity of the local heat source (figure 3a, frame D–F).

In the second case, the metal particle contacts the coal dust surface at the initial moment and embeds in the near-surface layer (figure 3b, frame A). A vortex is formed at the surface of the fuel sample (figure 3b, frame B). Scattering fine particles of coal are rapidly heated in the vicinity of the hot particle and ignite in the oxidizer medium (figure 3b, frame C). Here, the ignition delay times are an order of magnitude smaller than t_d for the coal with a particle size of 0.25–1 mm (figures 2, 3). As a result of the rapid process development, a local convective heat flux is formed in the vicinity of the local heat source. Hot gases ascend with fine coal particles from the sample surface, which are heated and take fire (figure 3b, frame D–F). The research findings show quite a significant difference between the ignition mechanisms of coal with a particle size ranging from 0.25 to 1 mm and that with a particle size <0.15 mm.

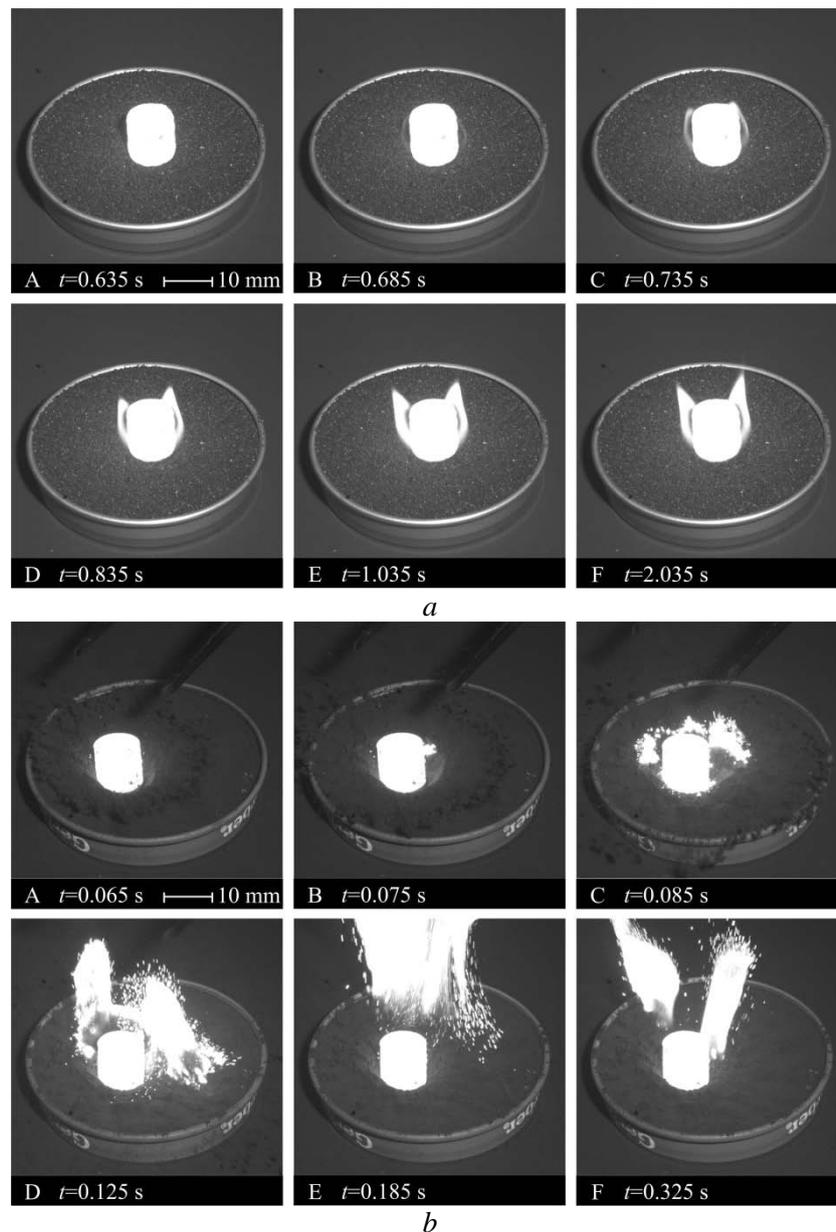


Figure 3. Videogram of the experiment with ignition of coal (*a* – dispersion 0.25–0.5 mm; *b* – dispersion < 0.15 mm) by the steel particle in disk shape with $d_p = 10$ mm, $z_p = 10$ mm, and $T_p = 1230$ K.

Figure 4 illustrates the effect of the local heat source shape on coal dust ignition characteristics with the same typical size of steel particles. The shape of the local heat source most significantly reduces the ignition delay time of coal dust (1.5–2 times) in the range of relatively low initial temperatures of the heat source ($T_p < 1250$ K) close to the boundary conditions of ignition. In this case, due to the heat removal to the coal and gas, metal particles with a higher heat content cool down less rapidly. When coal ignites, their temperature is 20–40 K higher than that of the particles with lower heat content and equal T_p . The shape of the local heat source has less effect on the duration of the induction period at higher initial temperatures $T_p > 1350$ K. Thus, with a relatively high heat content of hot steel particles (at $T_p > 1350$ K), a change in the shape and size of the heat sources has a less significant effect on the intensity of high-rate ($t_d < 0.2$ s) physical and chemical processes, all other conditions being equal.

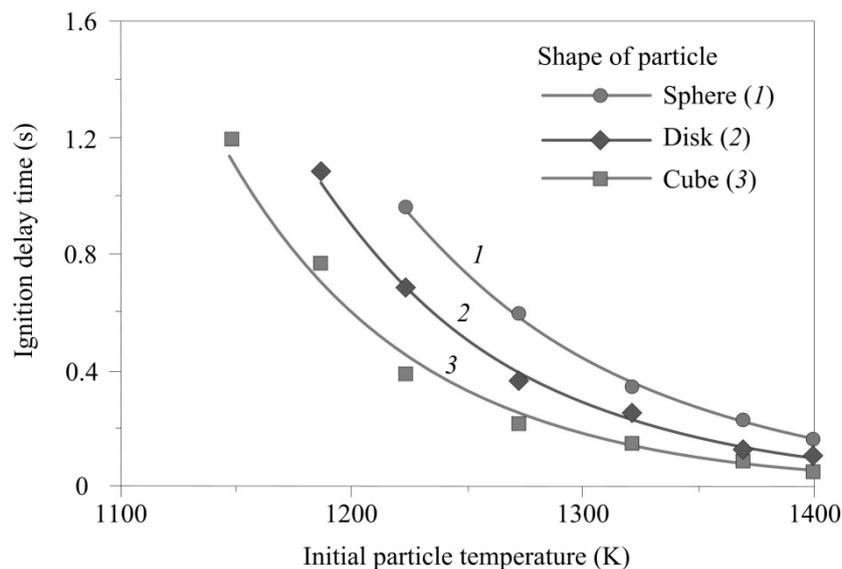


Figure 4. Ignition delay time versus the initial temperature and shape of the steel particle (size 10 mm) for coal dispersion 0.25–0.5 mm.

The heat content of a metal particle changes as a result of the T_p variation. This fact does not only affect the duration of the induction period but it also influences the location of the flaming ignition zone of the coal in the vicinity of the local heat source. Three ignition modes have been identified that can be described by the interrelated parameters of the local heat source (initial temperature) and ignition process (ignition delay time, location of the oxidation zone in the vicinity of a hot particle). In the first mode, $T_p > 1300$ K, $t_d < 0.2$ s, the ignition zone is located near the base of the hot particle. In the second mode, $T_p = 1200$ – 1300 K, $t_d = 0.3$ – 0.6 s, the ignition zone is near the side face of the local heat source. In the third mode, $T_p < 1200$ K, $t_d > 1$ s, the ignition zone is above the hot particle.

4. Conclusions

The results of the experimental study make it possible to conclude that the boundary condition of 0.2–1 mm coal dust ignition by a metal particle with a typical size of 10 mm is its initial temperature equal to 1150 K; high probability of flaming ignition due to the interaction between a hot particle and brown coal dust exists even in a short time period of about 1 s. The configuration of the local heat source has a significant effect on the ignition characteristics. The ignition delay times are in the descending order for sphere, disk and cube-shaped particles, all the other conditions being equal. The obtained results can make fire safety management in thermal power engineering and chemical industry more rigorous during maintenance and repair of process facilities.

Acknowledgments

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