Experimental study on the effects of coal particle size and fissure size on underground coal fires

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Abstract. Underground coal fire (UCF) widely spreads in many countries, which is a serious threat to the environment and the safety of coal mining industries. The cause of UCF is complex and affected by many factors such as fissures and coal seam porosity. For the first time, a novel experimental framework is proposed to simulate UCF. Two variables i.e., the coal particle size (6mm, 9mm and 15mm) and fissure size (1cm, 2cm, 4cm and 6cm) are considered in experiments. The peak temperature, air velocity and the propagation rates of dry front, pyrolysis front and oxidation front are analyzed. The results show that peak temperature and spread rate of UCF increase if the particle size or fissure size increase. In the smoldering stage, the ventilation is driven by buoyancy force produced by hot smoke. And this driving action increases with the particle size or fissure size, which further promotes smoldering by inhaling more air. The smoldering may turn to flaming combustion when the particle size is 9mm with fissure size ≥ 4cm or the particle size is 15mm.

1. Introduction

Underground coal fire (UCF) refer to in-situ uncontrolled burning of coal deposited underground. It can be ignited by spontaneous combustion, forest fire, lightning and so on. The rock formations provide thermal maintenance conditions for the coal fire. Fresh air could enter underground space through fissures[1]. The underground insulation properties and the presence of cracks are favorable conditions for smoldering combustion[2-3]. The coal particle influences the heat conduction and material transfer in the UCF by changing the coal voidage.

As one of the three major fossil fuels, coal resources play an irreplaceable role in economy and society development[4]. UCF not only directly destroys non-renewable coal resources, but also threatens the safe production of coal mines[5]. It can result in soil desertification, vegetation death, subsidence of ground, and release a large number of toxic and harmful gases such as carbon monoxide, carbon dioxide, sulfur dioxide and et al.[6] UCF occurs in many countries such as China[7], India[8], the USA[9], Australia[10], and south Africa[11]. It is the most persistent fire which can burn for hundreds or even thousands of years. Some fire-fighting measures are improved and developed with the advancement of science and technology[12], but so far the UCF has not been able to effectively control.

UCF is a disaster involving multidisciplinary knowledge such as physical, chemistry and so on. Numerical simulations have strong flexibility and arbitrariness, which are not limited by time and space conditions. It is a powerful tool to solve complicated practical problems. J Huang and et al. developed an UCF model to simulate the flow and temperature fields[13]. S Wessling and et al. simulated the dynamic UCF, and researched the relationship between the UCF and the permeability of adjacent...
rock[14]. Z Song and et al. established a numerical model of hill-side coal fires to research the effect of air leakages[15] and atmospheric pressure fluctuations[16]. At present, the verification of UCF numerical model is based on field investigation, and this approach is costly and time-consuming. However, the reliability of numerical simulations has not been verified by small-scale UCF experiments due to the less experimental research.

Experimental research on smoldering of materials such as polyurethane foam[17], peat[18], and coal tar[19] etc. has been conducted. There are many similarities between coal and peat, so the study of peat smoldering can provide reference for the UCF. X Huang and et al. studied the oxygen and moisture influencing mechanisms about upward and downward smoldering fire[18], and they explained the 5-step smoldering kinetics of peat fire[20]. J Yang and et al. [21] studied the influence of inorganic content and piled bed height on peat downward smoldering.

Experimental investigations about UCF have been rarely undertaken. In this work, we propose a novel experimental framework to simulate upward underground coal smoldering combustion in different underground environments by varying experiment variables (fissure size (φ) and coal particle size (d)). The influences of the two variables on propagation rate of evaporation front, pyrolysis front and oxidation front and peak temperature of UCF are analyzed. By researching the relationship between air velocity and smoke temperature, the mechanism of ventilation driven by thermal buoyancy is studied. At last, the phenomenon of smoldering translating into flaming is analyzed. This work provides experimental reference for the development of UCF prevention technology and the verification of numerical model.

2. Experimental

Smoldering experiments of underground coal seam were carried out in a heating furnace, and the schematic diagram is shown in figure 1. It includes an air intake pipe to guide air into the furnace, a reaction furnace and a smoke escape pipe. The intake pipe was made of 1-mm-thick stainless steel (diameter=6cm) and the height could be adjusted to simulate underground cracks at different depths (z). Aperture size of intake pipe (diameter=1cm, 2cm, 4cm and 6cm) could be adjusted in order to simulate the fissures of different sizes. Air velocity was measured by a thermo-anemometer (DT-8880, CEM, China). The insulation cotton was attached to inside wall of the furnace to improve the insulation performance. A metal mesh was put at the bottom of the furnace to support the igniter and fuel, and to ensure the fresh air smoothly enters the furnace at the same time. A flat spiral (diameter=12 cm) inconel cable igniter (220 V, 100 W) was employed. The 30cm coal bed was placed above the igniter to research upward smoldering combustion. 14 K-type thermocouples (TC1-14) were inserted into the centerline of the coal seam to measure the temperature of coal seam, and the highest one (TC14) was located at the top of the coal seam to monitor the temperature of the smoke. The vertical interval of TCs was 2 cm. Six groups of smoldering experiments were carried out as shown in table 1. Each experiment was performed at least by two times.

| Depth (m) | Aperture size (cm) | Coal particle size (cm) |
|-----------|--------------------|-------------------------|
| 2.15      | 1                  | 9                       |
| 1         | 15                 | 1                      |
| 1         | 9                  | 6                       |
| 2         | 4                  | 9                       |
| 4         | 6                  | 6                       |

Table 1. The UCF experiment scheme.
3. Results and discussion

3.1. Base cases

The temperature history of UCF experiments is shown in figure 2. The preheating lasted for about 2.6 hours. Under the action of igniter, the temperature increases steady until TC1 reaches 91℃. Then it keeps a constant value because of the evaporation of the water in the coal. When the evaporation is over, temperatures of the thermocouples near to the igniter rapidly increase up to approximately 760℃. The coal begins to smolder which is characterized by slowly increasing temperature. The heat generated by smoldering is transferred upward and it leads to the upward propagation of smoldering fire. The temperature began to drop after the coal sample was used up.

After the smoldering, a thin black char layer is remained above the ash layer. It is the product of incomplete combustion due to the large heat loss at the top surface of sample. It is worth to mention that coal-bed experiences sinking in the experimental process which is characterized by temperature curve (TC7 to TC14) without successive peaks. This result is attributed to the high density of coal and shrinking of char during smoldering. This is different from the smoldering of polyurethane foam[22], peat [20] and organic waste[23].

3.2. Smoldering propagation velocity

The propagation velocity of smoldering is usually estimated by the ratio of the distance between adjacent thermocouples to the time deltas reaching a certain temperature. The start times of peat smoldering evaporation front and pyrolysis front could be defined according to the temperature gradient curve[21].

Figure 3 shows the temperature history and temperature derivative curve at the TC3 (ρ=0.06m; d=9mm; z=2.39m). At the first peak A (t=0.32h; T=55℃), the heating rate of coal begins to slow down due to the evaporation of water. Within a period of time after this moment, the temperature decreases slightly until the water has evaporated and the temperature rises soon after. Peak B (t=1.12h and T=236℃) indicates the beginning of the coal pyrolysis. The temperature reaches maximum at the critical point C (t=6.83h; T=1028.5℃) which means the end of char oxidation, and the temperature gradient is below 0℃/s after that until the temperature reverts to ambient temperature.
3.3. Effect of particle size

To investigate the effect of particle size on UCF, three coal particle sizes, i.e., 6mm, 9mm, and 15mm were utilized in these experiments with \( \phi = 0.01 \)m and \( z = 2.15 \)m. Figure 4 shows the relationship between peak temperature and particle size. From the peak temperature curves of \( d = 6 \)mm and \( d = 9 \)mm, we found that the peak temperature decreases as the fire spreads upward. This is because the smoldering front is closer to the top surface as the fire spreads, more heat is lost. When \( d = 15 \)mm, the smoldering transforms into flaming, so the peak temperature rises at the end of the experiment. Comparing curves under different particle sizes, it is clearly that the peak temperature increases with the particle size. The peak temperature of UCF with \( d = 15 \)mm at different depth is 1000 ~ 1050°C which is much higher than \( d = 6 \)mm and 9mm.

A similar experimental result is observed from figure 5. The spread rates of evaporation front, pyrolysis front and oxidation front increase if particle size increases from 6 mm to 15 mm. These differences are attributed to the fact that the sample permeability is enhanced with the increase of particle size. The smoke generated from UCF gets through the upper unburned area more easily, and it results in stronger thermal buoyancy, which promotes oxygen supply by driving air convection. Referencing wind speed data can better explain this phenomenon. The air velocities at different particle sizes are shown at figure 6. It indicates that the ventilation \( (d=9\text{mm}) \) is stronger than another one \( (d=6\text{mm}) \). That is to say, increased permeability of coal bed can promote the air circulation.
3.4. Effect of fissure size

The influence of fissure size (1cm, 2cm, 4cm and 6cm) on the UCF peak temperature and propagation velocity is investigated. The fissure size can be adjusted by changing the apertures of intake pipe. The smoldering peak temperatures for the smoldering of four aperture sizes samples are presented in figure 7. They are recorded by thermocouples located at the lower half of sample (TC1 to TC5). The peak temperature data at the upper part is not analyzed due to the subsidence of the coal in the smoldering. The peak temperatures when $\varphi=0.06m$ are between 1000 and 1100°C which are greater than the result when $\varphi=0.04m$. And the trends of peak temperature are gentle first and then rise in both of the two experiments since the transforming from smoldering into flaming. The peak temperatures when $\varphi=0.01m$ are less than the one when $\varphi=0.02m$, and they both decline as the smoldering spreading upward.

The average propagation rates of evaporation, pyrolysis, and char oxidation for different apertures (1cm; 2cm; 4cm and 6cm) are presented in figure 8. We can find that propagation rates increase with apertures. Rock fissures are the oxygen route for UCF. The increase of fissures width will reduce the resistance of air entering combustion zone, and coal oxidation reaction will intensify with increasing oxygen concentration which leads to the higher peak temperatures and spread rates of UCF. This proves that plugging the fissure is an effective method to prevent UCF.
The air velocity of different particle sizes (6mm and 9mm) UCF ($\phi=0.01m; z=2.15m$).

The temperature peak of different apertures (1cm; 2cm; 4cm and 6cm) UCF ($d=9mm; z=2.15m$).

The average propagation rate of the coal (a) evaporation front, (b) pyrolysis front and (c) oxidation front of different apertures (1cm; 2cm; 4cm and 6cm) UCF ($d=9mm; z=2.15m$).

3.5. Air circulation driven by buoyancy force
The velocity of fresh air flow in intake pipe and temperature history ($\phi=0.04m; d=9mm; z=2.15m$) is shown in figure 9. The igniter is turned off at 0.8 h and it marks the beginning of smoldering. The air
velocity shows the steady growth in the smoldering stage and rises up to 0.28m/s. At 6.4 h, the smoldering turns to the flaming. Consistently, the air velocity increases suddenly at the flaming stage and the peak data is 0.35m/s. Then the smoldering went out and the air velocity gradually drops to 0m/s. There is no time difference of $t_{flame}$ between the air velocity and temperature history. It indicates that the air circulation is driven by buoyancy force originating from hot smoke. TC$_{14}$ was placed on the surface of sample, and $T_{TC14}$ could basically monitor the temperature of hot smoke. In order to further study the driven mechanism of buoyancy in the smoldering stage, the air velocity curve with $T_{TC14}$ is plotted in figure 10. A formula to express the air velocity driven by buoyancy with smoke temperature is modified:

$$V = V_0 + A \frac{TC14 - 53}{TC14 - 30} \sqrt{g z} \quad (T_{TC14} \geq 53^\circ C)$$  \hspace{1cm} (1)

where $V_0$ is an initial air velocity because the velocity is not equal to 0 m/s when $T_{TC14} = 53^\circ C$. The gravitational acceleration $g=9.8$ m/s$^2$ and the depth $z=2.15m$ in experiments. The coefficient $A$ can be obtained by fitting the formula as shown in figure 10. The fitting results show that the coefficient $A$ increases from 0.065 to 0.072 if aperture size increases from 4 cm to 6 cm. It indicates that aperture size promotes the UCF, as analyzed previously.

![Figure 9. The temperature history and air velocity of an UCF experiment ($\phi=0.04m$; $d=9mm$; $z=2.15m$).](image)

![Figure 10. The air velocity with $T_{TC14}$ and fitting curve at smoldering stage ($\phi=0.04m$ and $0.06m$; $d=9mm$; $z=2.15m$).](image)

3.6. The transforming from smoldering into flaming

The phenomena of smoldering transforms into flaming are observed in some experiments. As shown in figure 9, before 6.4h, combustion propagates in the form of smoldering which is same with figure 2. However, at 6.4h we can see that the temperatures of TC$_{4}$ and TC$_{6}$ experience a sharp increase and then reach a peak $>1050^\circ C$ with TC$_{5}$ to TC$_{12}$ presenting a sustained high temperature. After this moment, the coal flames until the fuel is exhausted. The experimental parameter differs from self-sustaining smoldering (figure 2) is that the aperture is 4cm, and the same phenomenon is observed when the aperture is 6cm. The transition from smoldering to flaming is the combustion of the gas phase generated from smoldering. More fresh air enters into the reactor due to the large diameter of aperture which favors the flow of oxidizer to the coal bed, results in the transition to flaming. In addition, the high temperature of flame combustion can further promote the fresh air into the underground space, which results in a more intense combustion.

4. Conclusions

UCF novel experimental framework is proposed in this work to experimentally study the effects of coal particle size and fissure size on upward fire spread of UCF. And the peak temperature and spread rates of evaporation front, pyrolysis front and oxidation front of coal smoldering are obviously promoted by them. The voidage of coal sample increases with particle size, and the resistance that hot smoke goes up though the coal bed decreases. This leads to the stronger thermal buoyancy which will promote UCF.
The fissures are necessary to sustain the smoldering, because it can convey oxygen to combustion space by natural convection, and this ability enhances with fissure size. In UCF experiments, the air ventilation is driven by thermal buoyancy and a formula is fitted to express the relationship between the smoke temperature and air velocity. The fitting result indicates that the UCF with wide fissure has a greater thermal buoyancy. In addition, the smoldering will transform into the flame combustion if the particle size and fissure size are large enough.

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