Safety Science 50 (2012) 787–791

Contents lists available at SciVerse ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Special Issue Article: The First International Symposium on Mine Safety Science and Engineering

# Experimental study on oxygen consumption rate of residual coal in goaf ☆

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ARTICLE INFO

*Article history:*
Available online 9 September 2011

*Keywords:*
Goaf
Coal
Spontaneous combustion
Heating and oxidizing
Oxygen consumption
Granularity

ABSTRACT

In order to research the actual oxygen consumption rate of residual coal in goaf, the heating and oxidizing experiment was conducted respectively on five types of single particle size of coal samples and one hybrid particle size of coal samples by using self-developed CSC-B2 test system. This study measured inlet and outlet oxygen concentration of the oxidation tank, and calculated the oxygen consumption rate of each coal sample at different temperatures. For the residual coal in the same goaf, which is regarded as a hybrid particle size of coal consisting of a variety of single granularity of coal, its oxygen consumption rate is the mass weighted average of the rate of each particle size of coal. Accordingly, this paper established the equation of oxygen consumption rate of hybrid particle size of coal samples, taking into account temperature, granularity and oxygen concentration. Then comparison between the calculated value and the actually measured value of oxygen consumption rate of hybrid particle size of coal samples at different temperatures was conducted. And the results reveal that the calculated value basically coincide with the actually measured one. Moreover, the results prove that the established calculation formula for oxygen consumption rate can be used to accurately calculate the actual oxygen consumption rate of residual coal samples. The achievement of this research is of theoretical and practical significance for learning about the characteristics of coal spontaneous combustion and forecasting the self-ignition of residual coal in goaf.

## 1. Introduction

Fire is one of the major disasters that threaten the coal mine production safety (Colaizzi, 2004; Schmal and Duyzer, 1985), among them the spontaneous combustion of the residual coal in goaf is the most serious. According to statistics, more than 60% of mine fires in China resulted from spontaneous combustion in goaf (Zhang and Dai, 2002). The spontaneous combustion in goaf is influenced by various factors. Researchers now commonly believe that the advancing speed of working face, the thickness and granularity of residual coal, the air leakage in goaf as well as the spontaneous combustion characteristics of residual coal jointly affect the severity of spontaneous combustion in goaf (Xu and Deng, 1999; Qin et al., 2009, 2010; Xu et al., 2001).

According to the coal–oxygen theory (Zhang and Dai, 2002), coal spontaneous combustion is the result of a range of complex physical and chemical changes, including adsorption, oxidation, heat release. The main influencing factors include granularity, temperature and oxygen concentration (Wen et al., 2002; Wang et al., 2002; Jiang et al., 1999). In order to analyze the influence of various factors on the coal oxidation rate, it is necessary to study the oxygen consumption rate of coal samples by heating and oxidizing experiment (Dai, 2005; Li and Wang, 2009; Wang and Jiang, 2010; Wang, 2009).

## 2. Experimental apparatus and process

In experiment, the CSC-B2 “Coal spontaneous combustion under low temperature test system” independently developed by China University of Mining and Technology (Beijing) was put into use. The experimental system consists of four parts: (1) coal heating oxidation device, which is made up of experiment tank, heating furnace and insulation shell; (2) coal temperature detection and

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☆ The First International Symposium on Mine Safety Science and Engineering (ISMSSE2011) will be held in Beijing on October 26–29, 2011. The symposium is authorized by the State Administration of Work Safety and is sponsored by China Academy of Safety Science & Technology (CASST), China University of Mining & Technology (Beijing) (CUMTB), Datong Coal Mine Group, McGill University (Canada) and University of Wollongong (Australia) with participation from several other universities from round the world, research institutes, professional associations and large enterprises. The topics will focus on mines safety field: theory on mine safety science and engineering technology, coal mine safety science & engineering technology, metal and nonmetal mines safety science & engineering technology, petroleum and natural gas exploitation safety science & engineering technology, mine safety management and safety standardization science & technology, occupational health and safety in mine, emergent rescue engineering technology in mine, etc.

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doi:10.1016/j.ssci.2011.08.033

control device; (3) gas chromatograph; (4) air supply system. The schematic diagram of apparatuses is shown in Fig. 1.

In this study, the coal samples were collected from the newly exposed coal wall of the 10# coal seam in Hedong Coal Mine, sealed on the site and transported to the laboratory. First, the coal samples were crushed to screen out five types of single particle size of coal samples, which were 7–10 mm, 5–7 mm, 2.5–5 mm, 0.9–2.5 mm and 0–0.9 mm, and then a mixture sample in which each kind of coal was 150 g was prepared. The experimental parameters are shown in Table 1.

Before the experiment, the inlet oxygen concentration of the oxidation tank was measured by gas chromatography. The result is listed in the last column of Table 1. At the beginning of the experiment, one kind of coal samples was put into the oxidation tank. The experiment temperature ranged from room temperature to 190 °C. The inlet air flow was 60 ml/min. In the experiment, the temperature was raised gradually. When heating began, the coal temperature was increased 15 °C at the rate of 1.3 °C/min firstly, and then the temperature was kept constant in 20 min. At this time, the gas chromatograph began to take air samples for analysis of gas composition and concentration. After that the temperature continued to be raised. These procedures were repeated until the temperature was increased 190 °C.

## 3. Experimental results and analysis

### 3.1. Experimental results

The outlet oxygen concentration of the oxidation tank at different temperatures is shown in Table 2.

### 3.2. The analysis of experimental results

Because the process of temperature-rising is stable and slow, and the oxidation tank is of little volume, the inside temperature of the oxidation tank can be considered as uniform (Gouws et al., 1991). The average oxygen consumption rate per unit volume of coal in the oxidation tank can be deduced as

$$v(T) = -\frac{Q\,\mathrm{d}C}{S(1-n)\mathrm{d}x \times 22.4} \qquad (1)$$

where $v(T)$ is the oxygen consumption rate per unit volume of coal at temperature $T$, mol/(cm$^3$ s); $Q$ is the inlet flow rate of the oxidation tank, cm$^3$/s; $C$ is the oxygen concentration of the air flow in the oxidation tank, %; $T$ is the temperature; $S$ is the cross-section area of the oxidation tank, cm$^2$; $n$ is the porosity of the coal sample, %; $x$ is the unit length of the coal sample filled in the oxidation tank, cm.

According to the chemical kinetics and the chemical equilibrium theory, the oxygen consumption rate at any point of the oxidation tank is a functional relation with temperature and oxygen concentration. The oxygen concentration gradually reduces as air flow through the oxidation tank, so the oxygen consumption rate at different point in the oxidation tank are different at a same temperature. In order to analyze the relationship between oxygen consumption rate (Liang and Luo, 2003; Wang and Wu, 2006) and temperature, the experimentally obtained oxygen consumption rate was converted to that of fresh air per unit volume at the same temperature:

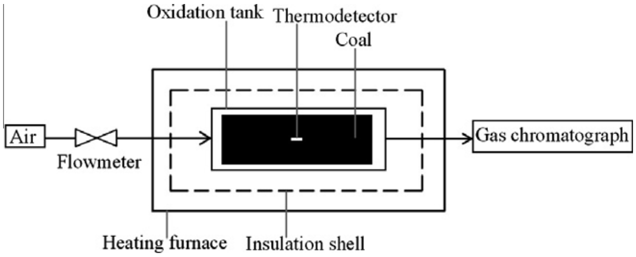

**Fig. 1.** Schematic diagram of equipment heating and oxidizing coal.

$$v_o(T) = C_o v(T)/C \qquad (2)$$

where $v_o(T)$ is the standard oxygen consumption rate at temperature $T$, namely the oxygen consumption rate per unit volume of coal in fresh air at temperature $T$, mol/(cm$^3$ s); $C_o$ is the oxygen concentration in fresh air, $C_o = 21\%$.

Irrelevant to oxygen concentration, the standard oxygen consumption rate $v_o(T)$ is related to the spontaneous combustion characteristics of coal, granularity of coal and temperature instead. According to the formula (1) and (2), the oxygen consumption rate per unit volume of coal in fresh air flow can be expressed as

$$v_o(T) = -\frac{C_o Q}{SL(1-n) \times 22.4} \ln\frac{C}{C_o} \qquad (3)$$

where $L$ is the height of the coal sample filled in the oxidation tank, cm.

According to the oxygen concentration in Table 2, the standard oxygen consumption rate of different coal samples at different temperatures can be calculated by formula (3). The results are shown in Table 3, and then the curve of the oxygen consumption rate of different coal samples changing with temperature can be depicted, which are shown in Fig. 2.

Table 3 and Fig. 2 indicate that:

(i) At a same temperature, the oxygen consumption rate decreases while the granularity increases. The reason for this is that in the same mass of the coal sample, the smaller the granularity, the bigger the surface area, the bigger the contact area with oxygen as well.
(ii) The oxygen consumption rate of the hybrid particle size of coal samples lies between the rate of the largest granularity and that of the smallest granularity.
(iii) Oxygen consumption rate increases with temperature rising. For each kind of coal sample, its oxygen consumption rate curve can be divided into two parts by the demarcation point of 130 °C (Wen, 2003; Liang, 2002), and the curves pre and post 130 °C respectively show approximate linear relationship. Below 130 °C, the linear equation of oxygen consumption rate changing with temperature can be expressed as

$$v_o(T) = AT + B \qquad (4)$$

Above 130 °C, the slope of those lines increases significantly, and the equation can be expressed as

$$v_o(T) = CT + D \qquad (5)$$

In the two formulas above, $A$–$D$ are constants which are related to the types of coal, but irrelevant to granularity of coal, temperature and oxygen concentration. For the coal samples in this experiment, the regression coefficients are listed in Table 4.

By fitting the relation between each coefficient and the average granularity of different coal samples, the following formulas can be derived:

$$\begin{cases} A = 0.0452 - 0.0182\ \ln(d) \\ B = 0.121d - 1.252 \\ C = 0.1842 - 0.0654\ \ln(d) \\ D = 2.2791d - 21.931 \end{cases} \qquad (6)$$

where $d$ is the average granularity of different coal samples, mm.

Substitute Eq. (6) into Eqs. (4) and (5):

**Table 1**
Experimental parameters of coal samples.

| Sample | Granularity (mm) | Average granularity (mm) | Height (cm) | Weight (g) | Volume ($cm^3$) | Porosity (%) | Inlet oxygen concentration (%) |
|---|---|---|---|---|---|---|---|
| Sample 1 | 7–10 | 8.5 | 23.5 | 750.1 | 1665.7 | 0.550 | 21.751 |
| Sample 2 | 5–7 | 6.0 | 21.5 | 750.2 | 1524.0 | 0.508 | 21.323 |
| Sample 3 | 2.5–5 | 3.75 | 20.3 | 749.8 | 1438.9 | 0.479 | 20.854 |
| Sample 4 | 0.9–2.5 | 1.7 | 18.7 | 749.9 | 1325.5 | 0.434 | 20.587 |
| Sample 5 | 0–0.9 | 0.45 | 17.4 | 750.0 | 1223.6 | 0.406 | 20.151 |
| Sample 6 | 0–10 | 4.08 | 19.2 | 750.2 | 1360.9 | 0.449 | 21.728 |

**Table 2**
Outlet oxygen concentration at different temperature.

| Temperature (°C) | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| 40 | 20.721 | 21.237 | 20.720 | 20.097 | 19.163 | 20.728 |
| 55 | 20.675 | 21.144 | 20.682 | 19.828 | 18.547 | 20.674 |
| 70 | 20.652 | 21.109 | 20.380 | 19.720 | 18.730 | 20.503 |
| 85 | 20.459 | 20.968 | 20.293 | 18.882 | 16.766 | 19.927 |
| 100 | 20.140 | 20.615 | 19.818 | 18.482 | 16.478 | 19.495 |
| 115 | 19.931 | 20.356 | 19.543 | 18.196 | 16.176 | 19.180 |
| 130 | 19.650 | 20.040 | 19.166 | 17.881 | 15.954 | 18.797 |
| 145 | 18.765 | 19.066 | 17.981 | 15.973 | 12.961 | 17.074 |
| 160 | 17.931 | 18.175 | 16.873 | 15.016 | 12.231 | 15.962 |
| 175 | 17.334 | 17.232 | 15.316 | 13.416 | 10.566 | 14.743 |
| 190 | 16.863 | 16.338 | 13.816 | 12.313 | 10.059 | 13.290 |

**Table 3**
Standard oxygen consumption rate at different temperature.

| Temperature (°C) | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| 40 | 0.253 | 0.074 | 0.132 | 0.589 | 1.303 | 0.380 |
| 55 | 0.287 | 0.154 | 0.170 | 0.919 | 2.050 | 0.440 |
| 70 | 0.305 | 0.184 | 0.469 | 1.052 | 2.069 | 0.631 |
| 85 | 0.449 | 0.306 | 0.557 | 2.113 | 4.573 | 1.288 |
| 100 | 0.690 | 0.614 | 1.041 | 2.637 | 5.245 | 1.793 |
| 115 | 0.851 | 0.844 | 1.326 | 3.018 | 5.798 | 2.168 |
| 130 | 1.069 | 1.128 | 1.724 | 3.446 | 6.326 | 2.633 |
| 145 | 1.777 | 2.035 | 3.027 | 6.204 | 11.465 | 4.847 |
| 160 | 2.475 | 2.905 | 4.326 | 7.713 | 13.505 | 6.398 |
| 175 | 2.996 | 3.874 | 6.302 | 10.468 | 17.931 | 8.229 |
| 190 | 3.419 | 4.843 | 8.407 | 12.565 | 20.583 | 10.620 |

Measuring unit: $10^{-9}$ mol $s^{-1}$ $cm^{-3}$.

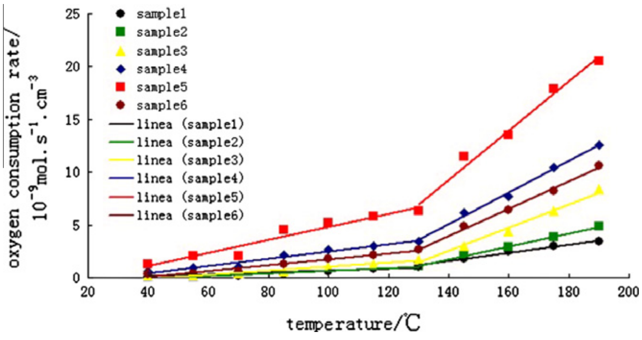

**Fig. 2.** Curve of oxygen consumption rate of each coal sample changing with temperature.

$$T \leq 130\,^{\circ}\mathrm{C},\ v_o = [0.0452 - 0.0182\ \ln(d)]T + 0.121d - 1.252 \quad (7)$$

$$T > 130\,^{\circ}\mathrm{C},\ v_o = [0.1842 - 0.0654\ \ln(d)]T + 2.2791d - 21.931 \quad (8)$$

## 4. Calculation of oxygen consumption rate of residual coal

The residual coal in the same goaf can be regarded as a hybrid particle size of coal consisting of many kinds of single granularity of coal, the oxygen consumption of the residual coal is the sum of that of each granularity of coal. In this study, sample 6 is constituted by the first five types of single granularity of coal samples, so the oxygen consumption of sample 6 inside the oxidation tank is the sum of the oxygen consumption of each coal sample. Therefore, theoretically the oxygen consumption rate of sample 6 is the volume weighted average of the rate of each particle size of coal sample. Because of the same true relative density of all coal samples, the oxygen consumption rate of sample 6 is the mass weighted average of the rate of each particle size of coal sample.

$$v_{0c} = \frac{m_1 v_{01} + m_2 v_{02} + m_3 v_{03} + m_4 v_{04} + m_5 v_{05}}{m_1 + m_2 + m_3 + m_4 + m_5} \quad (9)$$

where $v_{oc}$ is the theoretically calculated oxygen consumption rate of the hybrid particle, mol $s^{-1}$ $cm^{-3}$; $m_1$, $m_2, \ldots, m_5$ are the mass of sample 1, sample 2,...,sample 5, respectively, g; $v_{o1}$, $v_{o2}, \ldots, v_{o5}$

**Table 4**
Regression coefficients of oxygen consumption rate of each coal sample.

| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| Average granularity (mm) | 8.5 | 6 | 3.75 | 1.7 | 0.45 | 4.08 |
| A | 0.0094 | 0.0118 | 0.0182 | 0.0342 | 0.0613 | 0.0271 |
| B | −0.2438 | −0.5349 | −0.7761 | −0.9374 | −1.3000 | −0.9690 |
| C | 0.0395 | 0.0618 | 0.1109 | 0.1500 | 0.2332 | 0.1290 |
| D | −3.9667 | −6.9290 | −12.9930 | −15.9240 | −23.3510 | −14.1010 |

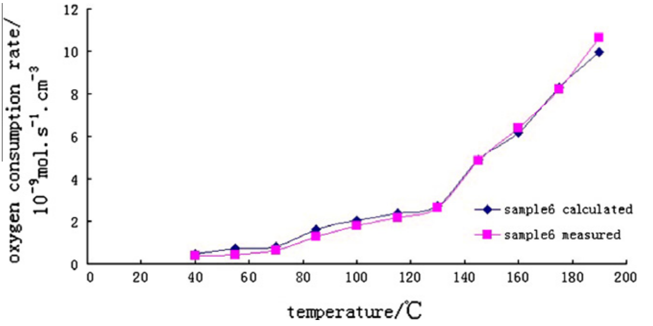

**Fig. 3.** Contrastive curve of calculated and practically measured oxygen consumption rate.

are the oxygen consumption rate of sample 1, sample 2,…,sample 5, respectively, mol $s^{-1}$ $cm^{-3}$.

In order to testify the correctness of the theoretical formula (9), the oxygen consumption rate of sample 6 is calculated according to the data in Table 3. Then the calculated and the practically measured oxygen consumption rate curves of sample 6 with temperature changing are shown in Fig. 3.

It can be seen from Fig. 3 that the calculated and practically measured oxygen consumption rate curves of sample 6 are basically in coincidence. The result proves the correctness of formula (9), which can be used to accurately calculate the actual oxygen consumption rate of residual coal samples.

For the residual coal in goaf on site, its granularity distribution is correlated with the coal types, the physical features of coal and the mining methods (Zhao and Zhang, 2008). Therefore, the coal samples should be collected at the interval between hydraulic supports. In order to obtain the oxygen consumption rate of the residual coal, the particle size distribution of the residual coal sample was analyzed firstly, and then the heating and oxidizing experiment were conducted on each different particle size respectively. After that, similar to equations of (7) and (8), the regression equation between the oxygen consumption rate and the granularity was obtained. Finally, according to the oxygen consumption rate calculation formula (Eq. (10)), the oxygen consumption rate of the residual coal sample was derived:

$$v_o(T) = \begin{cases} \frac{1}{m}\sum\limits_{i=1}^{n}(m_iAT + B) & (T \le T_c) \\ \frac{1}{m}\sum\limits_{i=1}^{n}(m_iCT + D) & (T > T_c) \end{cases} \tag{10}$$

where $m$ is the mass of the hybrid particle size of coal samples, g; $m_i$ is the mass of the single granularity of coal sample $i$, g; $T_c$ is the critical point temperature; $A$–$D$ is the same in formula (4) and (5), which can be got by regression of the experimental data.

In goaf, the residual coal is oxidized constantly to consume oxygen of air flow. Therefore, the oxygen concentration gradually decreases along the air flow route. According to formulas (2) and (10), the oxygen consumption rate at any point of goaf can be obtained:

$$v(T) = \begin{cases} \frac{C}{mC_o}\sum\limits_{i=1}^{n}(m_iAT + B) & (T \le T_c) \\ \frac{C}{mC_o}\sum\limits_{i=1}^{n}(m_iCT + D) & (T > T_c) \end{cases} \tag{11}$$

where the constants $A$–$D$ in formula (10) and (11) vary with different coal walls.

## 5. Conclusions

(i) The oxygen consumption rate of coal samples increases with temperature rise. In this study, the critical point of the curve of oxygen consumption rate changing with temperature is at 130 °C; the curve change is nearly linear pre and post 130 °C, but the linear slope rapidly increases above 130 °C.
(ii) This paper deduces the oxygen consumption rate calculation formula of the mixed particle size of coal samples. The test data prove that in the same true relative density, the oxygen consumption rate of mixed particle size of coal samples is the mass weighted average of the rate of each single particle size of coal sample.
(iii) For the actual residual coal in goaf, this paper establishes the equation of the oxygen consumption rate, taking into account temperature, particle size and actual oxygen concentration. For the coal samples collected at the interval between hydraulic supports, the oxygen consumption rate can be calculated by analysis of the particle distribution and measured the rate of each particle size in the coal sample.
(iv) The achievements of this research are of theoretical and practical significance for learning about the characteristics of coal spontaneous combustion and forecasting the self-ignition of residual coal in goaf.

## Acknowledgements

The financial support for this work, provided by the Undergraduate Scientific and Technical Innovation Plan of State Key Laboratory of Coal Resources and Safety Mining in China University of Mining and Technology (Beijing) (CRSM2009B010) and the National Natural Science Foundation of China (Grant No. 51174211), is greatly acknowledged.

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