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*Published in:* Results in engineering

**DOI:**
10.1016/j.rineng.2021.100272

Published: 01/09/2021

**Document Version**
Publisher's PDF, also known as Version of record

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*Please cite the original version:*
Experimental study on combustion parameters and temperature distribution of linear fire under different oxygen concentration in tunnel

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ARTICLE INFO

Keywords:
Combustion parameters
Oxygen concentration
Linear fire source
Transverse temperature distribution
Maximum ceiling temperature rise

ABSTRACT

Many cables are placed in the underground utility tunnel, which are with greater fire hazards. Once fire occurs in an enclosed tunnel, thermal radiation may ignite the adjacent cables, which will cause cable fire and further expanding of fire scale, and oxygen will be consumed over time. Thus, it’s important to investigate cable fire under low oxygen concentration. In this paper, a fire experiment has carried out in a reduced-scale enclosed tunnel with different heights of linear fire near the side wall. The combustion parameters, as well as transverse temperature distribution and maximum ceiling temperature rise under different oxygen concentration are investigated. Based on oxygen consumption calorimetry, the combustion efficiency and heat release rate of each fire source can be obtained. And two formulas to predict transverse temperature distribution and temperature rise under ceiling are proposed based on dimensionless analysis. Results show that different combustion parameters changing under varies oxygen concentrations, two temperature peaks exist in the cross section and the highest temperature is directly above the fire source. Conclusions are given to provide references in fire protection work in utility tunnel.

1. Introduction

Many pipes and lines such as heat pipes and cables are placed in the underground utility tunnel, and cables are the ones with greater fire hazards. Cables are mainly arranged on cable racks at both sides of tunnel. When fire occurs in a fire partition in tunnel, fire doors at both ends of the interval will be quickly closed to prevent fire and smoke from spreading to the adjacent fire partition. When fire consumes oxygen in the enclosed space to a lower concentration, combustion will be suppressed until it is completely extinguished. However, thermal radiation of fire may ignite the adjacent cables in enclosed tunnel, causing cable fire under low oxygen concentration and further expanding of fire scale. Therefore, it is necessary to study the cable combustion under low oxygen concentration (see Table 1).

Predecessors have carried out a series of experiments in closed tunnel. Chen et al. [1,2] set up a 1:9 reduced-scale tunnel and studied fire development and temperature distribution under the influence of different sealing ratios. It was found that temperature rise reached the highest under a critical sealing ratio, which was negatively correlated with combustion area. Huang et al. [3] built a tunnel model with CFD, and studied the maximum temperature rise and longitudinal temperature distribution under ceiling by changing opening ratio of portals. In addition, an empirical formula for predicting the temperature field of fire plume under ceiling in enclosed tunnel was proposed. Yao et al. [4] studied the influence of different longitudinal positions of fire on the maximum temperature rise under ceiling based on dimensional analysis and reduced-scale model experiment in an enclosed tunnel. It was found that the maximum temperature rise under ceiling decreased exponentially as fire source approached to the tunnel portal.

The side wall and ceiling structure will affect flame shape and combustion parameters when fire appears near side wall. Ji et al. [5] studied the influence of side wall effect on flame characteristics and combustion rate of n-heptane pool fire in tunnel. Results showed that flame will incline to the side wall, which enhanced thermal radiation from surrounding structure and increased burning rate. The shape of the fuel pool had less effect. Fan et al. [6] conducted reduced-scale tunnel model experiment, and influence of side wall on flame characteristics of n-heptane pool fire was studied. Results showed that heat release rate of fire source increased with aspect ratio at the same position, and a flame length model considering side-wall effect and fuel shape was established. Gao et al. [7] studied flame length and transverse temperature
distribution under ceiling in a reduced-scale tunnel model. Results showed that with the increase of heat release rate and fire source height, the flame hit ceiling and diffuses radially. Besides, horizontal flame length was a function of fuel unburned part at impact point. And the relationship between dimensionless effective flame height ratio and flame length of horizontal ceiling was obtained. The relationship of temperature distribution in continuous flame zone, intermittent flame zone and rising plume zone is also obtained. Zhang et al. [8] measured the upward and downward temperature distribution of fire source under the inclined ceiling with different angles and heights. By comparing the experimental data with the correlation coefficient predicted by predecessors, Zhang studied the influence of buoyancy component force parallel to inclined ceiling. New prediction formula of temperature distribution under inclined ceiling was proposed based on the influence of heat release rate, inclined angle and ceiling height.

Previous studies mainly focused on the influence of tunnel structure and different ventilation conditions on fire sources, and there was lack of research on linear fire sources development under low oxygen concentration. When fire occurs under low oxygen concentration, it will cause different hazard compared with fire under full oxygen supply situation. Thus, based on previous research results, adopted the method of combining theoretical analysis and model test to carry out the research. In this paper, a series of model experiments under low oxygen concentration is conducted in a reduced-scale tunnel model. Combustion parameters and temperature distribution of linear fire are investigated by analyzing the experimental data and dimension analysis. Which provides reference for cable arrangement and fire fighting work in circular underground utility tunnel.

2. Experimental setup

At present, experimental model research methods can be divided into two categories: full-size experimental research and reduce-scale model experimental research. The full-size model experiment can simulate the fire development and temperature distribution under real conditions, and the data obtained from the experiment are credible and convincing. However, the full-size fire experiment still has some disadvantages, such as high risk, high cost. Reduce-scale model experiment has the advantages of strong repeatability, economical convenience and low cost, so it is widely used in the field of tunnel fire experiment research. Fig. 1 shows the experimental setup. Based on the actual tunnel situation, a reduced-scale tunnel model with length 20 m and diameter 1.5 m with two rotatable fire doors is built, and the rotatable doors at both ends will be closed during the experiment. Fire source is 30 cm away from vertical centerline of the tunnel, and it is placed at the height of 30 cm downwards, 0 cm and 30 cm upwards from the horizontal centerline respectively. The size of the linear fire source is with length 60 cm, width 15 cm and height 4 cm. Use cable as fire source and the ambient temperature is 20 °C.

A sheet laser source is arranged below the fire source to observe the flow path of smoke, and a high-definition camera is used to record the flow of smoke under laser irradiation. The weighing equipment is SIWAREX weighing sensor with measuring range of 0–10 kg, which can record the quality change of fire source during the experiment. A liquid nitrogen injection port is set 60 cm longitudinal distance from fire to record the quality change of fire source. A liquid nitrogen injection port is set 60 cm longitudinal distance from fire to control the oxygen concentration. Due to the critical oxygen concentration of cable fire in tunnel is 15%–16% [9], so three oxygen concentrations of 21%, 18% and 17% are selected.

3. Results and discussion

3.1. Influence of oxygen concentration on combustion

Under different oxygen concentration, the burning intensity of fire source is different. Three gas measuring points are set in the vertical direction with 0.6 m distance to collect gas after combustion, see in Fig. 1. The influence of oxygen concentration on combustion can be studied by analyzing the gas composition.

Fig. 2(a) shows the oxygen distribution of fire sources at different heights for 30s after combustion. Oxygen concentration shows an obvious gradient distribution phenomenon, with lower oxygen concentration near the ceiling and higher oxygen concentration below the fire source. With the decrease of fire source height, stratification phenomenon is weakened, and oxygen at bottom is gradually thinned. When fire source approaches to the bottom of tunnel, the intensity of oxygen entrainment in upper layer and bottom is consistent, which causes the oxygen concentration in tunnel tends to be the same. Moreover, demand for oxygen of fire source at 17% oxygen concentration increases, and the entrainment intensity is greater than 18% oxygen concentration.

It can be seen from Fig. 2(b) that cables burn more fully under higher

<table>
<thead>
<tr>
<th>List of symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
</tr>
<tr>
<td>$Q^*$</td>
</tr>
<tr>
<td>$Q_m$</td>
</tr>
<tr>
<td>$Q_o$</td>
</tr>
<tr>
<td>$Q_l$</td>
</tr>
<tr>
<td>$q$</td>
</tr>
<tr>
<td>$\Delta H$</td>
</tr>
<tr>
<td>$T_0$</td>
</tr>
<tr>
<td>$\Delta T_t$</td>
</tr>
<tr>
<td>$\Delta T_{\text{max}}$</td>
</tr>
<tr>
<td>$m$</td>
</tr>
<tr>
<td>$h$</td>
</tr>
<tr>
<td>$H$</td>
</tr>
<tr>
<td>$H_{ef}$</td>
</tr>
<tr>
<td>$r$</td>
</tr>
<tr>
<td>$B$</td>
</tr>
<tr>
<td>$L$</td>
</tr>
<tr>
<td>$D$</td>
</tr>
<tr>
<td>$z$</td>
</tr>
<tr>
<td>$V$</td>
</tr>
<tr>
<td>$t$</td>
</tr>
<tr>
<td>$\theta$</td>
</tr>
<tr>
<td>$c_p$</td>
</tr>
<tr>
<td>$g$</td>
</tr>
<tr>
<td>$\rho_0$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
</tr>
<tr>
<td>$\eta$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$\phi_{o,b}$</td>
</tr>
<tr>
<td>$\phi_{o,a}$</td>
</tr>
</tbody>
</table>
oxygen concentration, the chapping degree of cable and carbon black generated after combustion are more serious. Although flame height of fire source at 17% oxygen concentration is higher than that at 18% oxygen concentration, the flame does not ignite along the longitudinal edge of the cable.

At present, methods to obtain flame height include visual measurement and image observation. Visual method is to observe flame height directly and take the average value. Image observation method is to obtain the flame height indirectly by using image, and calculate the average flame height by marking flame position, which is simple but has great error so that it is difficult to get accurate results. In this paper, an image analysis software based on Matlab is used to calculate the average flame height, the software by counting the probability of bright spots in each position of an image during time series to obtain results, as Fig. 3(a) shows. And the average flame height is defined as the flame height above the combustible surface when the intermittent function drops to 0.5.

Fig. 3 shows that with the decrease of oxygen concentration, the average flame height of fire sources decreases first then increases, flame of 30 cm height fire source hits ceiling continuously, while flame of 0 cm height fire hits ceiling intermittently, and flame of 30 cm height fire cannot reach to the ceiling. Additionally, flame height under 17% oxygen concentration is higher than under 18% oxygen concentration. This is because when the oxygen concentration in the environment is lower, the fire needs to contact oxygen in a larger area for full reaction in order to reach full combustion. Fire plume entrain the oxygen under the ceiling firstly, then the remaining oxygen is reduced, and the flame extends in the radial direction to contact more oxygen to participate in combustion, which causes flame height increases.

Hence, when oxygen concentration decreases, fire will entrain more oxygen from surroundings and upper layer to reach fully combustion. As a result, flame height of fire sources at the same height increases when oxygen concentration is low. Also, oxygen concentration of fire source surroundings and lower layer decreases obviously when it at a low level, and the stratification phenomenon of oxygen is weakened with fire source height decreases.

### 3.2. Heat release rate and combustion efficiency under different oxygen concentration

When fire appears in underground utility tunnel, a large amount of hot smoke will gather under the ceiling and the flame will hit the ceiling directly. High temperature and hot smoke generated by the fire will cause great harm to structural stability of tunnel. Moreover, heat release rate is an important parameter to quantify the fire scale, which has great significance.

Heat release rate can’t be measured directly at low oxygen concentration because of unknown combustion efficiency. Predecessor [10] proposed oxygen consumption calorimetry to measure heat release rate.

### Table 1: Experimental conditions.

<table>
<thead>
<tr>
<th>Condition number</th>
<th>Fire source height</th>
<th>Oxygen density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 cm</td>
<td>21%</td>
</tr>
<tr>
<td>2</td>
<td>30 cm</td>
<td>18%</td>
</tr>
<tr>
<td>3</td>
<td>30 cm</td>
<td>17%</td>
</tr>
<tr>
<td>4</td>
<td>0 cm</td>
<td>21%</td>
</tr>
<tr>
<td>5</td>
<td>0 cm</td>
<td>18%</td>
</tr>
<tr>
<td>6</td>
<td>0 cm</td>
<td>17%</td>
</tr>
<tr>
<td>7</td>
<td>30 cm</td>
<td>21%</td>
</tr>
<tr>
<td>8</td>
<td>30 cm</td>
<td>18%</td>
</tr>
<tr>
<td>9</td>
<td>30 cm</td>
<td>17%</td>
</tr>
</tbody>
</table>
For most gases, liquids, and solids, a more or less constant amount of energy is released per unit mass of oxygen consumed. This constant energy is 13,100 kJ of heat for each kilogram of oxygen burned. For many hydrocarbon materials, this constant is considered to be accurate with few exceptions to about \( \pm 5\% \).

Using oxygen concentration measuring device, by calculating the difference of oxygen concentration above fire source before and after combustion. Thus, the consumption of oxygen is obtained and heat release rate can be calculated based on oxygen consumption calorimetry (see Table 2).

According to Section 3.1, oxygen concentration after combustion shows obvious stratified differences. We can assume that combustion only consumes oxygen at upper space above fire source. Therefore, space above fire source is selected as control body, and the volume \( V \) of control body of fire sources at different heights can be obtained. Oxygen concentration after combustion tend to be invariant in a short time, which can be obtained from all extraction points above fire source is taken as the average value, which represents the final oxygen concentration of the control body, as shown in Table 3. And heat release rate can be calculated by using Equation (1) based on oxygen consumption calorimetric method.

\[
\dot{Q}_o = V \rho_o (\phi_{o,b} - \phi_{o,a}) q \frac{t}{t} (1)
\]

Where, \( t \) is combustion time, \( s; \rho_o \) is the density of oxygen at 20 \( ^\circ \)C and standard atmospheric pressure, kg/m\(^3\); \( \phi_{o,b} \) and \( \phi_{o,a} \) are the oxygen concentration before combustion and after combustion respectively; \( q \) is the amount of heat released by burning oxygen of per kilogram, 13100 kJ; \( Q_o \) is the heat release rate calculated by the oxygen consumption calorimetry, kJ/s.

Combustion efficiency of each condition can be calculated by using Equation (2) and data in Table 3, where \( \Delta H \) is the average combustion heat of cables, 22.28 MJ/kg [11,12].

\[
\dot{Q} = \chi \cdot m \cdot \Delta H (2)
\]

As shown in Table 4, when both portals of tunnel are closed, the combustion efficiency under 21% oxygen concentration is 0.74, 18% oxygen concentration is 0.61, and under 17% oxygen concentration is 0.56.

Using combustion efficiency and mass loss rate given in Table 3, the heat release rate \( Q_m \) can be calculated based on the natural weight-loss method and Fig. 4 shows comparison of \( \dot{Q}_m \) and \( \dot{Q}_o \).

It can be seen from Fig. 4 that the error of heat release rate calculated by the weight-loss method and oxygen consumption calorimetry is less than 10%, which proves oxygen consumption calorimetry can predict heat release rate correctly.

Predecessors [13–16] conducted series of studies on flame height of axisymmetric fire sources through theoretical analysis and model experiments. Results showed that the ratio of average flame height \( L \) and equivalent diameter \( D \) have a proportional relationship with heat release rate.
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rate $\dot{Q}$ as follows:

$$\frac{L}{D} \propto Q^{2/3}$$  \hspace{1cm} (3)

However, Equation (3) is only applicable to axisymmetric fire sources. Which is not applicable to the special form of linear fire sources such as cables.

Hasemi and Nishihata [17] studied the relationship between average flame height and heat release rate, and proposed a prediction formula for the flame height of a linear fire with long side three times larger than the short side:

$$L = 0.035 \left( \frac{\dot{Q}}{B} \right)^{1/3}$$  \hspace{1cm} (4)

In Equation (4), when the long side length of the linear fire source is fixed, the average flame height $L$ is mainly determined by heat release

### Table 2

<table>
<thead>
<tr>
<th>Fire source height</th>
<th>Oxygen density</th>
<th>Flame Height</th>
<th>Flame Height</th>
<th>Flame Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21%</td>
<td>15%</td>
<td>17%</td>
<td>18%</td>
</tr>
<tr>
<td>30 cm</td>
<td>26.19 cm</td>
<td>20.22 cm</td>
<td>23.91 cm</td>
<td>20.22 cm</td>
</tr>
<tr>
<td>0 cm</td>
<td>42.42 cm</td>
<td>39.30 cm</td>
<td>44.27 cm</td>
<td>31.10 cm</td>
</tr>
<tr>
<td>−30 cm</td>
<td>29.64 cm</td>
<td>25.10 cm</td>
<td>32.13 cm</td>
<td>27.25 cm</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Condition number</th>
<th>Oxygen concentration after combustion(%)</th>
<th>Burning time(s)</th>
<th>$Q_b$(kJ/s)</th>
<th>Mass loss rate(g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.8872</td>
<td>315</td>
<td>14.73</td>
<td>0.8263</td>
</tr>
<tr>
<td>2</td>
<td>16.8232</td>
<td>308</td>
<td>8.78</td>
<td>0.6149</td>
</tr>
<tr>
<td>3</td>
<td>15.9018</td>
<td>284</td>
<td>8.90</td>
<td>0.7258</td>
</tr>
<tr>
<td>4</td>
<td>18.2831</td>
<td>364</td>
<td>11.62</td>
<td>0.6954</td>
</tr>
<tr>
<td>5</td>
<td>16.7325</td>
<td>332</td>
<td>5.88</td>
<td>0.4124</td>
</tr>
<tr>
<td>6</td>
<td>15.6078</td>
<td>321</td>
<td>6.68</td>
<td>0.5263</td>
</tr>
<tr>
<td>7</td>
<td>17.3839</td>
<td>425</td>
<td>8.9</td>
<td>0.5831</td>
</tr>
<tr>
<td>8</td>
<td>16.2296</td>
<td>386</td>
<td>3.44</td>
<td>0.2622</td>
</tr>
<tr>
<td>9</td>
<td>14.7031</td>
<td>358</td>
<td>4.96</td>
<td>0.3924</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Condition number</th>
<th>$\chi$</th>
<th>Condition number</th>
<th>$\chi$</th>
<th>Condition number</th>
<th>$\chi$</th>
<th>$\chi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>4</td>
<td>0.75</td>
<td>7</td>
<td>0.68</td>
<td>0.74</td>
</tr>
<tr>
<td>2</td>
<td>0.64</td>
<td>5</td>
<td>0.59</td>
<td>8</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>6</td>
<td>0.57</td>
<td>9</td>
<td>0.56</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Fig. 3. Flame height of linear fire sources, (a) Flame height measuring software, (b) Average flame height under different oxygen concentration.
3.3. Transverse temperature distribution

In reality, when fire occurs, hot smoke will spread along longitudinal and transverse directions after hitting the ceiling. Former researchers mainly studied longitudinal spread of hot smoke along the tunnel ceiling, lack of investigations on the flow and fire characteristics of hot smoke in the transverse section. Actually, hot smoke flows along arced ceiling and accumulates downward in the transverse section, which is more complicated than that under horizontal ceiling. Therefore, it is of great significance to study transverse temperature distribution under arced ceiling. The transverse temperature distribution is shown in Fig. 5(a).

It can be seen from Fig. 5(a) that transverse temperature reaches peak in two locations, one is directly above the fire source and the other is located far away from the fire source side. Moreover, transverse temperature far from fire decreases significantly at a critical angle $\theta_c$. When the angle of thermocouple $\theta$ is greater than $\theta_c$, temperature decreases rapidly to ambient temperature. Meanwhile, critical angle $\theta_c$ decreases gradually with fire source height increasing, and the temperature boundary layer position at the critical angle will rise.

In Fig. 5(b), fire plume flows along the arced ceiling. When it reaches to the center of ceiling and continues to expand to the far fire end, it will be hindered by arc-shaped structure and then spread downward slowly, accumulation of hot smoke will cause the temperature rise. With the height of fire source increased, flame will approach to the ceiling and maximum value of transverse temperature will increase. Under different

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**Fig. 4.** Comparison of heat release rates calculated by different methods.

**Fig. 5.** Transverse temperature distribution and plume trajectory under ceiling, (a) Transverse temperature distribution under ceiling, (b) Plume trajectory under ceiling.
oxygen concentration, the maximum temperature under 21% oxygen concentration is the highest, followed by 17% oxygen concentration and the lowest one is under 18% oxygen concentration.

Fig. 6 shows the thickness of hot smoke layer of fire sources at three heights respectively. It can be seen that the lower boundary of hot smoke layer is almost at the same height, and thickness of smoke layer increases with the decrease of fire source height, which is consistent with the change trend of temperature boundary layer at critical angle.

In practice, hot plume hits the ceiling vertically then accumulate along the arced structure under ceiling, so it is inaccurate to express effective ceiling height by the vertical distance between fire source and ceiling according to previous studies. Yuan [18] obtained the distribution of temperature rise along the vertical height in plume centerline of linear fire source by the means of theoretical analysis and experimental study. Yuan divided fire plume into three parts, as shown in Table 5. Based on the principle of three partitions, a semi-empirical prediction model is established:

$$\Delta T(z) = A(z/Q^2)^{2n-1} \quad (5)$$

Where, $\Delta T(z)$ is the plume temperature of reference point at $z$ above the centerline of linear fire source.

In the continuous plume zone, the smoke temperature is constant. When $z$ at intermittent plume zone, the airflow velocity is constant, and temperature rise decreases with the decrease of vertical height from fire source. When reference point in the plume zone, temperature mainly affected by the heating of hot smoke. However, Yuan’s formula is based on experiments of free combustion fire source, which is not applicable to the situation of ceiling restricted combustion.

Compared with square tunnel, circular tunnel has an arced ceiling. Therefore, effective ceiling height can be expressed by vertical height $H$ from fire source to impact point of plume and arc length $r$ from impact

<table>
<thead>
<tr>
<th>Continuous plume zone</th>
<th>Intermittent plume zone</th>
<th>Plume zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \leq z_L$</td>
<td>$1 &lt; z \leq 1$</td>
<td>$1 &lt; z \leq 6$</td>
</tr>
<tr>
<td>$A$</td>
<td>$A$</td>
<td>$A$</td>
</tr>
<tr>
<td>$n$</td>
<td>$n$</td>
<td>$n$</td>
</tr>
<tr>
<td>0.98</td>
<td>1/2</td>
<td>11.8</td>
</tr>
<tr>
<td>7.2</td>
<td>0</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 5: Value table of plume temperature correlation coefficient.
point to the center of ceiling as modified effective ceiling height $H_{ef}$ [19].

$$H_{ef} = h + r$$

Among them, $H_{ef}$ of fire sources at 30 cm, 0 cm and –30 cm heights are 0.387 m, 0.687 m and 0.987 m respectively, and $r$ is 0.61 m.

Thus, dimensionless distance $H_{ef}/l$ can be expressed by ratio of arc length from 0° and modified effective ceiling height, which can represent fire source location. And dimensionless temperature rise can be expressed by $\Delta T/\Delta T_{max}$ by ratio of temperature rise measured by each thermocouple and highest temperature rise. The relationship between dimensionless distance and dimensionless temperature rise can be obtained, as shown in Fig. 7(b).

Fig. 7(b) shows that temperature curves of different plume zones are significantly different. For instance, temperature rise rate of fire sources gradually increases away from fire, while at the near fire region, decrease of fire source height will lower temperature rise rate. Heat transfer mode from thermal radiation of fire to heat convection causes the change.

This is because the main factor affecting the temperature of the smoke layer changes from thermal radiation of the fire source to convective heat transfer of the plume with the decrease of the height of the fire source.

Therefore, temperature prediction formula at near region and far region from fire of different plume regions are obtained.

At near fire region:

$$\frac{\Delta T}{\Delta T_{max}} = \begin{cases} 
0.312 + 1.32e^{-0.590H_{ef}/l} & \text{non - cotact} \\
0.168 + 2.33e^{-1.105H_{ef}/l} & \text{intermittent impact} \\
0.141 + 11.25e^{-3.570H_{ef}/l} & \text{continuous impact}
\end{cases}$$

At far fire region:

$$\frac{\Delta T}{\Delta T_{max}} = \begin{cases} 
0.998 + -14.67e^{-5.36H_{ef}/l} & \text{non - cotact} \\
1.121 + -4.506e^{-3.437H_{ef}/l} & \text{intermittent impact} \\
1.345 + -3.256e^{-2.13H_{ef}/l} & \text{continuous impact}
\end{cases}$$

It should be noted that the above formula is only applicable to the fire source close to side wall, which may not applicable when fire source is located in the center of tunnel.

3.4. Maximum temperature rise under ceiling

The underground utility tunnel is the building with long and narrow structure built by concrete. Fire in tunnel will cause smoke and high temperature and threaten the stability of tunnel structure. Researches find the higher the temperature, the weaker the structural strength of concrete [20]. When temperature reaches 250 °C–420 °C, layer of the concrete surface will burst and fall [21]. As a result, the highest temperature usually appears at the area above fire source when fire occurs. Thus, vertical distance $h$ between fire source and ceiling can be used to express height of fire source. According to previous studies [22–24], variables affecting the maximum temperature rise under ceiling include heat release rate of linear fire source $Q$, ambient temperature $T_0$, air density $\rho_b$, specific heat capacity of air at constant pressure $c_p$, gravitational acceleration $g$, ceiling height $H$ and distance between fire source and ceiling $h$, variables are shown is Table 6. Based on dimensional analysis, the relationship between the maximum temperature rise under arced ceiling and related variables can be expressed as Equation (9):

$$\Delta T_{max} = f(Q, T_0, \rho_b, c_p, g, h, H)$$

(9)

Mass, length, time and temperature are selected as the basic variables, and the symbols are [M], [L], [T] and [θ], respectively. According to the dimensional theory, selecting four independent variables which are not related to each other, which are the ambient air temperature $T_0$, the ambient air density $\rho_b$, the gravitational acceleration $g$ and the height of fire source from ceiling $h$. The eight variables in Equation (9) can be converted into four dimensionless quantities based on Table 6.

$$\Pi_1 = T_0^\theta \rho_b^3 \cdot g^3 \cdot H^4 \cdot \Delta T_{max}$$

(10)

$$\Pi_2 = T_0^\theta \rho_b^3 \cdot g^3 \cdot \dot{Q}$$

(11)

Table 6

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Unit</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature rise</td>
<td>$\Delta T_{max}$</td>
<td>K</td>
<td>$\theta$</td>
</tr>
<tr>
<td>Heat release rate</td>
<td>$Q$</td>
<td>kJ/s</td>
<td>$L^2MT^{-2}$</td>
</tr>
<tr>
<td>Central temperature</td>
<td>$T_0$</td>
<td>K</td>
<td>$\theta$</td>
</tr>
<tr>
<td>Air density</td>
<td>$\rho_b$</td>
<td>kg/m$^3$</td>
<td>$\theta$</td>
</tr>
<tr>
<td>Acceleration of gravity</td>
<td>$g$</td>
<td>m/s$^2$</td>
<td>$LT^{-2}$</td>
</tr>
</tbody>
</table>
\[ \Pi_3 = T_0 \rho_0 \phi g - h^2 \frac{\Delta T_{\text{max}}}{T_0} \]  
(12)

\[ \Pi_4 = T_0 \rho_0 \phi g - h^2 H \]  
(13)

By solving Equation (10)–(13), we can get:

\[ \Pi_1 = \frac{\Delta T_{\text{max}}}{T_0} \]
\[ \Pi_2 = \frac{\dot{Q}}{\rho_0 \phi g h^3} \]
\[ \Pi_3 = \frac{T_0 \phi g h}{gh} \]
\[ \Pi_4 = \frac{H}{h} \]  
(14)

Substitute the four dimensionless variables into Equation (9), we can get:

\[ \Delta T_{\text{max}} = f\left(\frac{\dot{Q}}{\rho_0 \phi g h^3}, \frac{T_0 \phi g h}{gh}, \frac{H}{h}\right) \]  
(15)

For \( Q^* = \frac{\dot{Q}}{\rho_0 \phi g h^3} \), by simplifying the first and second items in Equation (15), results are as follows:

\[ \frac{\Delta T_{\text{max}}}{T_0} = f\left(\frac{\dot{Q}^*}{H/h}\right) \]  
(16)

In this case, Equation (16) can be changed into Equation (17) [25]:

\[ \frac{\Delta T_{\text{max}}}{T_0 Q} = f\left(\frac{H}{h}\right) \]  
(17)

Fig. 8(a) is the schematic diagram of Equation (17) by substituting experimental data into it. It shows that the variation trend of dimensionless temperature rise at three oxygen concentrations gradually decreases with the increase of \( h \), and there is a certain proportion of dimensionless temperature rise at different oxygen concentration. Relationship between the dimensionless temperature rise of normal oxygen concentration and the dimensionless height is as Equation (18):

\[ \frac{\Delta T_{\text{max}}}{T_0 Q} = -27.33 + 230.2e^{-0.394\phi} \]  
(18)

\( R^2 \) of the fitting formula reached 0.999, indicating a high degree of fitting.

Since the combustion of fire source in enclosed tunnel is affected by oxygen concentration, so we use oxygen concentration \( \phi \) to characterize the relationship between \( h \) and the maximum temperature rise \( \Delta T_{\text{max}} \) under ceiling, as Equation (19).

\[ \frac{\Delta T_{\text{max}}}{T_0 Q} = \psi(\phi) f\left(\frac{H}{h}\right) \]  
(19)

Comparing the dimensionless temperature rise under different oxygen concentration with that under 21% oxygen concentration, the function between oxygen concentration and dimensionless temperature rise can be obtained, as shown in Fig. 8(b):

\[ \psi(\phi) = \frac{\Delta T_{\text{max}}}{T_0 Q_{21\%}} \frac{\dot{Q}_{21\%}}{\dot{Q}_{\phi_{\text{max}}}} = 0.42 + 40.68e^{-20.27\phi} \]  
(20)

\( R^2 \) of the fitting formula reached 0.99, indicating a high degree of fitting.

By substituting Equation (18) and Equation (20) into Equation (19), we can propose a prediction formula of the dimensionless temperature rise of fire sources at different heights near sidewall under different oxygen concentration as Equation (21):

\[ \frac{\Delta T_{\text{max}}}{T_0 Q} = (0.42 + 40.68 \cdot e^{-20.27\phi}) \frac{\Delta T_{\text{max}}}{T_0 Q_{\phi_{\text{max}}}} \]  
(21)

Compared maximum temperature rise between predicted value by Equation (21) and experimental value, as shown in Fig. 9. The error is less than 10%, so Equation (21) can predict maximum temperature rise with high precision.
4. Conclusion

In this paper, a series of experiments have been conducted to investigate the effect of oxygen concentration on combustion of linear fire in the enclosed tunnel, combustion parameters and distribution of temperature field are also studied. Main conclusions are as follows:

(1) When oxygen concentration decreases, flame height of fire source at the same height increases at lower oxygen concentration. After combustion process of fire source, the stratification phenomenon of oxygen will occur from top to bottom in tunnel. The lower the fire source height, the weaker the stratification of oxygen.

(2) Based on the oxygen concentration difference above the fire source before and after combustion, heat release rate can be calculated based on the oxygen consumption calorimetry, and combustion efficiency of fire source under different oxygen concentration can be obtained. Therefore, heat release rate based on the weight-loss method can be calculated. The error of two heat release rates calculated by different methods is less than 10%.

(3) Two temperature peaks exist under arced ceiling of each working condition, one is located directly above the fire source, and the other is located at the impact point of plume away from fire. There exists a critical angle at the far fire region, and temperature below the horizontal layer of critical angle drops sharply to ambient temperature. The critical angle increases with the decrease of fire source height, and the temperature boundary layer above the critical angle also becomes thicker. The area directly above fire source can be expressed as continuous impact area, intermittent impact area and plume impact area based on the flame height, and prediction formulas of transverse temperature at near fire region and far fire region are proposed.

(4) Based on the dimensionless analysis, relationship between dimensionless temperature rise and dimensionless fire source height is obtained. Considering the influence of oxygen concentration on temperature rise, a prediction formula of the maximum temperature rise under ceiling of linear fire source at different oxygen concentration is developed.

Credit author statement

Gang Xu: Conceptualization, Data curation, Investigation, Methodology, Writing-original draft, Writing-revised draft. Guo-qing Zhu: Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing. Rong-liang Pan: Conceptualization, Data curation, Investigation, Methodology, Writing-original draft. Xin Liu: Formal analysis, Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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