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Analysis of influencing factors on flashover in the long-narrow confined space

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Abstract

The traditional theory of flashover is not available for the application of flashover in a long-narrow confined space, especially about the critical condition of flashover occurrence. In this paper, according to the measurement of reduced-scale fire tests, the smoke layer's temperature, thickness, gas concentration and heat release rate of fire source were studied. Furthermore, the effects of fire source, opening and ventilation to the occurrence of flashover were further discussed. It is shown that the critical line of flashover for the different fuels is between 600 °C and 700 °C, and critical condition is different for different fuels and different openings; for the different transverse ventilation, the smoke evacuation has the best effect only when the exhaust port neat the fire is opened.

Keywords: Fire source; Opening; Ventilation; Flashover; Long-narrow space

Nomenclature	
A	area of wall surface (m^2)
A_0	opening area (m^2)
A_f	area of fire source (m^2)
c_p	specific heat at constant pressure (J/kg K)
c_v	specific heat at constant volume (J/kg K)
g	gravity acceleration (m/s^2)
h_k	thermal conductivity (W/m^2K)
h_c	convective heat transfer coefficient (W/m^2 K)
Δh_c	combustion heat (J/kg)
h_u	distance between neutral plane and ceiling (m)
H	height of the space (m)
H_0	height of the opening (m)
$\dot{m}_a$	inflow rate of cold air (kg/s)
$\dot{m}_f$	mass loss rate of fire source (kg/s)
$\dot{m}_f^*$	dimensionless mass loss rate of fire source
P	gas pressure (Pa)
t	time (s)

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T	temperature of the control (K)
T_{max}	maximum temperature (K)
Greek symbols	
v	velocity of smoke flow (m/s)
Γ	ratio
Subscripts	
i	inner of confined space
o	exterior of confined space

1. Introduction

In China, hundreds of tunnels and other underground spaces have been constructed. In tunnels or other underground corridors, the combustion products of fire are forced to transfer in one or two directions, resulting in a very fast smoke movement. Besides, it is difficult to exhaust the smoke and heat. These may lead to a rapid threat to life. For this, it is necessary to have a deep understanding of the behaviour of fire and smoke movement in a tunnel.

As the mutation process and the final stage processes of fire development in the confined space, flashover has the enormous destructive power. Over the years, the phenomenon of flashover, mutation patterns and dynamics characteristics have been researched. Through a large number of previous experimental and theoretical researches, a number of practical values of the flashover law and flashover models have been discovered and developed, such as the induction factor of flashover, the occurrence time of flashover, the critical conditions of flashover and thermal expansion model, non-linear model. Kawagoe and Sekine [1, 2] carried out the first research and built the empirical formula to predict the gas temperature in post-flashover. Based on Kawagoe's model, Magnusson and Thelandersson [3] have found a new empirical formula which could predict the temperature in the whole progress of flashover. Thomas and Bennetts [4, 5] have simulated flashover progress using $1.5\ m \times 0.6\ m \times 0.6\ m$ and $8\ m \times 2\ m \times 0.6\ m$ small scale experiment sets and have studied the effect of different opening position on the temperature of flame rushing out.

Although flashover phenomenon has been studied in details by the predecessors, most research has been aimed at chamber fire while laws of flashover on the long-narrow space are rarely found. There are some great differences upon the actual fire development process between the long-narrow confined space and the chamber. Hence, it is difficult to explain flashover reasonably in such a special space with the results of previous studies, especially in the conditions of different areas of fire source and different transverse ventilation.

In order to discuss the effects of fire source and ventilation on the critical condition of flashover in the special space, different fire sources and different ventilation conditions were designed in a small-scale fire test bed of long-narrow space. In addition, based on the previous theory, different boundary conditions for the induction of flashover were studied.

2. Experimental

The experimental tests were conducted in a reduced-scale corridor model, which was 5 m long with square cross section 0.5 m wide, at University of Science and Technology of China, Hefei. The schematic view of the experimental layout and the corridor is shown in Fig. 1. Fig. 1(a) is a longitudinal section from rear side view, Fig. 1(b) is a top view, and Fig. 1(c) is a cross-section from right end view. There was a retractable opening of size 0.5 m × 0.5 m at each end. One was fully opened during each experiment, and the other, which was near the fire source, was closed immediately after the ignition. The material forming the outside of the whole corridor was steel of 4 mm thickness. The sidewalls, ceiling and floor were made of aluminum silicate board of 30 mm thick, which can withstand high temperature up to 1100 °C and insulate heat leakage from outside. Three types of fires, including n-heptane polypro-pylene (PP) cribs and wood cribs, were placed at the closed end of the corridor.

Three types of data were measured in all tests, including gas temperature, mass of fire source and gas concentrations for CO, O_2 and CO_2. An electronic balance (Sartorius, LA64001S) was fixed below the corridor model to measure the mass loss rates of the fire source through a support plate. Forty-four thermocouples (K-Type, $\varphi = 1$ mm) were set to measure the temperatures at different sections and different heights in the corridor, where there were five sections in the longitudinal direction (0.5 m, 1.5 m, 2.5 m, 3.5 m, 4.5 m away from one end) and five points in the vertical direction of each section (4 cm, 8 cm, 12.5 cm, 25 cm, 37.5 cm below the ceiling). The output data of thermocouples was collected through a data transmission module, along with the balance signal. The number of each thermocouple is illustrated in Fig. 1(a). A KANE KM9106 smoke composition analyzer was utilized to measure gas concentration in the smoke layer of the corridor, where the probe was inserted through one hole out of points 6, 9, 12, and 15 in different tests.

The detailed set-up of each test is shown in Table 1. The fuel thickness was set to make sure that fire could burn long enough for the occurrence of fully developed fire. All data were measured every second right after the trays were ignited until the extinguishment of the fire.

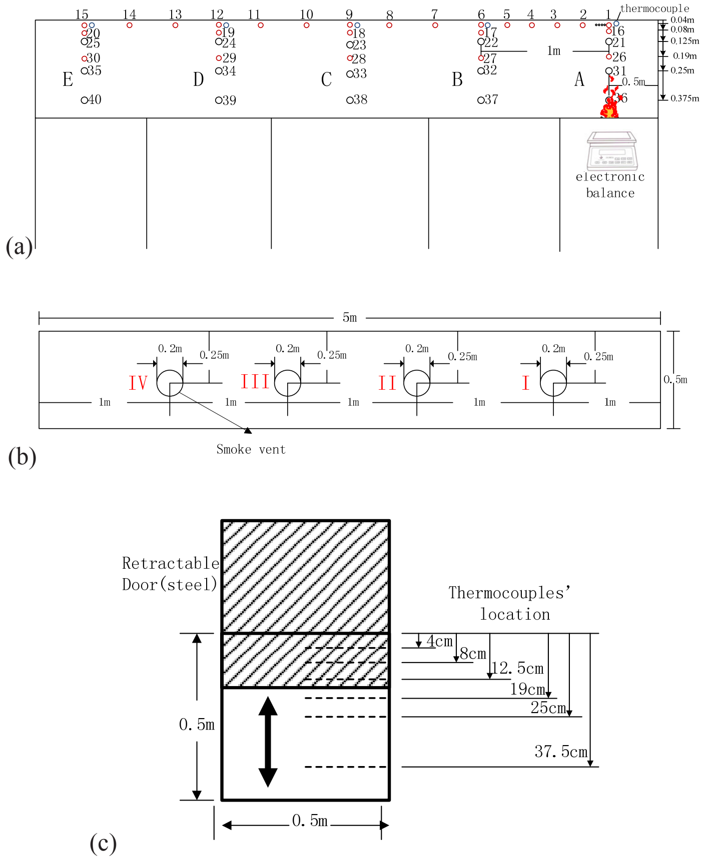

Fig. 1. Geometry of the experimental set-up. (a) longitudinal section view; (b) top view; (c) cross-section view.

In addition, two sets of parallel experiments were designed for Test 8: the measure point of smoke was set in section B for Test 8.a while that was in section E for Test 8.b.

3. Results and discussions

3.1. Analysis of typical experimental results

The typical curve of temperature versus time in the long-narrow confined space fire is shown in Fig. 2(a). About 80 seconds after ignition, the fire reached the quasi steady state of pre-flashover. High temperature was observed over the fire source at the location of TC1, TC21, TC31 and TC35. However, the temperature was lower than 200 °C at other locations. About 300 seconds after ignition, the temperature began to rise by leaps and bounds and rapidly increased to almost 1000 °C above the fire source. The gas temperature also exceeded 600 °C at the position near the fire source while the gas temperature at the position far from the fire source also presented a longitudinal attenuation distribution as same as that in the pre-flashover period, because the space was long and narrow, the energy transmission in the smoke layer had a time difference. Consequently, the time of flashover occurrence also had time-delay in different horizontal positions. In the flashover period, the gas temperature became relatively stable, so the rest of the fuels would be consumed soon and the temperature would fall back again.

Table 1. Experiment conditions for flashover in long-narrow space

Test no.	Fuel type	Fuel dimension (cm × cm)	Open height (m)	Smoke vent and volume (m^3/h)
1	n-heptane	6 × 6	0.5	/
2	n-heptane	7 × 7	0.5	/
3	n-heptane	8 × 8	0.5	/
4	n-heptane	11 × 11	0.5	/
5	n-heptane	12 × 12	0.5	/
6	n-heptane	13 × 13	0.5	/
7	n-heptane	15 × 15	0.5	/
8.a	n-heptane	17 × 17	0.5	/
8.b	n-heptane	17 × 17	0.5	/
9	n-heptane	20 × 20	0.5	/
10	PP cribs	11 × 11	0.5	/
11	PP cribs	13 × 13	0.5	/
12	PP cribs	15 × 15	0.5	/
13	PP cribs	25 × 25	0.5	/
14	PP cribs	30 × 30	0.5	/
15	wood cribs	15 × 15 × 20	0.5	/
16	wood cribs	20 × 20 × 20	0.5	/
17	wood cribs	25 × 25 × 20	0.5	/
18	wood cribs	30 × 30 × 20	0.5	/
19	n-heptane	17 × 17	0.375	/
20	n-heptane	17 × 17	0.25	/
21	n-heptane	12 × 12	0.375	
22	n-heptane	12 × 12	0.25	/
23	wood cribs	30 × 30 × 20	0.375	/
24	wood cribs	30 × 30 × 20	0.25	/
25	n-heptane	17 × 17	0.5	I 250
26	n-heptane	17 × 17	0.5	II 250
27	n-heptane	17 × 17	0.5	I and II 500
28	n-heptane	17 × 17	0.5	I to IV 500

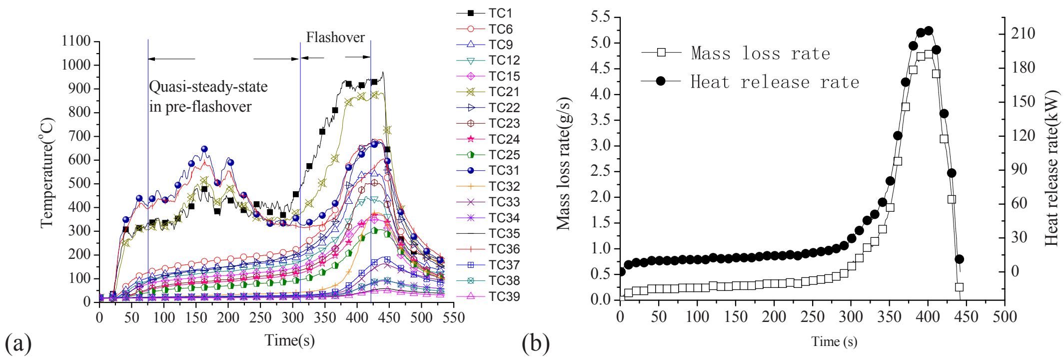

Fig. 2. Results of test 7. (a) variation of temperature *vs.* time; (b) variation of mass loss rate and heat release rate *vs.* time.

The mass loss rate of Test 7 is shown in Fig. 2(b), which is the derivative of mass data obtained through the electronic balance. It can be seen that the mass loss rate in the pre-flashover period was relatively stable. When the flashover occurred, the mass loss rate rose sharply. After the fully developed period, the mass rate stabilized again at a maximum value until the fuel burned out. According to the fuel mass loss rate, heat release rate could be indirectly obtained

$$\dot{Q} = \chi \dot{m}_f \, \Delta h_c \tag{1}$$

where χ is combustion efficiency. Here suppose χ =1, the curve of heat release rate is shown in Fig. 2(b). The heat release rate of pre-flashover is 13 kW or so; in the post-flashover period, it is more than 200 kW.

Gas concentrations of oxygen, carbon dioxide and carbon monoxide are changed with the time in the section B, as shown in Fig. 3. In the pre-flashover period, oxygen consumption was low; carbon dioxide concentrations remained at about 1% and no carbon monoxide ware produced. When the flashover occurred, the oxygen concentration decreased to 1%, the concentration of carbon dioxide had rapidly increased to 16%. As a result of insufficient combustion, carbon monoxide concentration jumped above 10000 ppm. As the fire came into the extinction stage, the values returned to normal level.

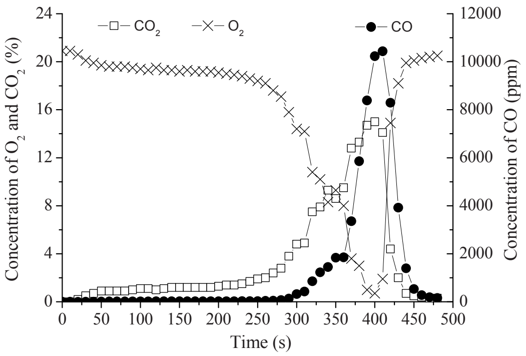

Fig. 3. Variation of smoke density *vs*. time (test 8, section B).

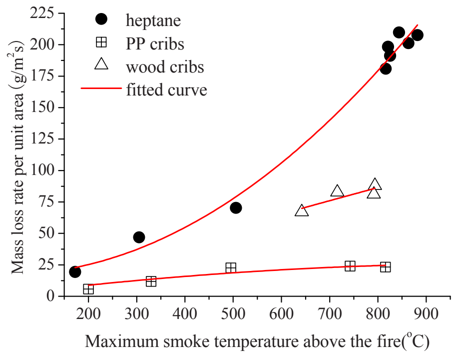

Fig. 4. The influence of smoke layer temperature *vs*. different fuel combustion rates.

3.2. Effect of fire source

It could be seen from the above analysis that the fire intensity was closely related to the heat release rate in the long-narrow confined space. In order to analyze the influence of source parameters on fire development, the temperature data measured from Test 1 to Test 18 were selected, and the effects of different fire source radius and different fuel properties on fire development and flashover were discussed in the paper. The temperature value here is the average temperature of different sections (section A, B, C, D and E) of the smoke layer in the "quasi-steady" period. The state space averaging method [6] on the experimental measurements of the original data is used to get this average value.

$$T_{ave} = (H_T - H_B) / \int_{H_B}^{H_T} \frac{1}{T} dy \tag{2}$$

where H_B and H_T are the height of thermocouples at the bottom and the top of smoke layer, respectively. The denominator of Eq. (3) is defined as:

$$\int_{H_B}^{H_T} \frac{1}{T} dy = \sum_{k=1}^{m} \frac{h_{k+1} - h_k}{T_{k+1} - T_k} \ln\left(\frac{T_{k+1}}{T_k}\right) \tag{3}$$

where h_k and T_k are represented as the height of the thermocouples in the smoke layer from bottom to top and the corresponding temperature, respectively. The space average can be obtained with Eq. (2) and Eq. (3), and then this value is time-averaged in the "quasi-steady-state" period. The average temperature of smoke layer in different sections can be determined with this method.

The heat feedback that the fire source receives mainly comes from the smoke layer right above the fire source, so it is the most representative of analyzing the maximum average temperature of section A to study the reaction of fire source.

The mass loss rate changed with smoke layer temperature for different fuels and different fire radius is shown in Fig. 4. The points in the figure are experimental values, and the red line is the fitting curve of quadratic polynomial. From the comparison results it can be found that the pool fire of n-heptane is very sensitive to the thermal feedback of smoke layer, the mass loss rate per unit area increases rapidly with the increasing temperature. However, the wood fire is insensitive to the thermal feedback of smoke layer. The reason is that wood cribs fire was mainly affected by the heat transfer among the wood interwoven and its internal combustion. Polypropylene is relatively sensitive to the smoke layer thermal feedback, but it needs to consume large amounts of energy for melt and volatilization; thus, the scale of mass loss rate is low and the growth trend of temperature is not clearly shown in Fig. 4. In addition, it can be found that the critical line of flashover is between 600 °C and 700 °C. The fire is the fuel-controlled below the critical temperature. In this period, smoke layer temperature is influenced by the fire area and the mass loss rate per unit area increases with the smoke layer temperature. When it is higher than the critical temperature, the fire is ventilation-controlled; the smoke layer temperature is substantially constant and the mass loss rate per unit area does not increase with the area of fire source any more.

3.3. Effect of ventilation

In addition to the heat release rate, ventilation condition is important for flashover induction. When the outlet area decreases, the oxygen supply to the fire will decrease. Correspondingly, the burning rate will also decrease. At the same time, the critical condition of flashover, to some extent, is affected by the size of the opening. Therefore, the size of the opening and the forced ventilation will be discussed on the fire development in long-narrow space. Among the Tests, Test 5, 8, 18 to 24 are experiments sets with different openings while Test 25 to 28 involves the forced ventilation.

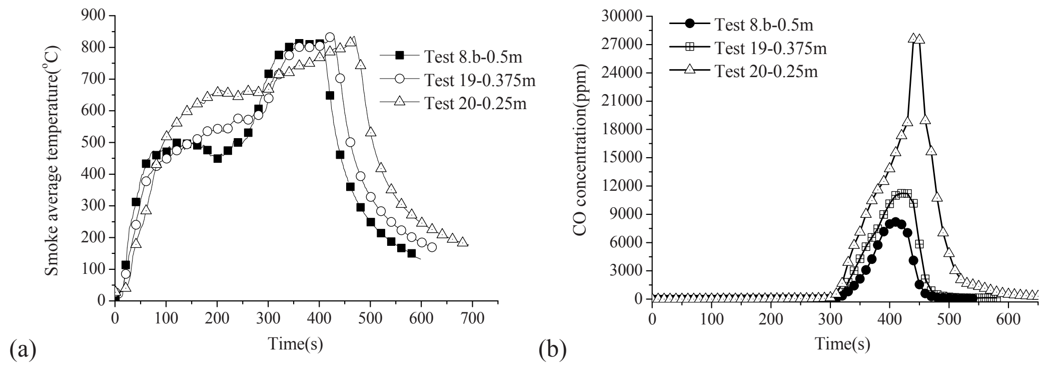

Fig. 5. Influence of opening size on fire development. (a) average gas temperature in comparison (section A); (b) CO concentration in comparison (section E).

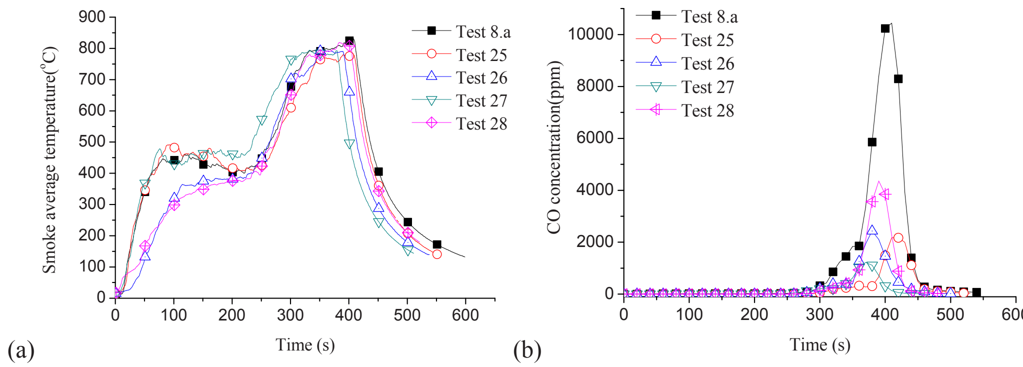

Fig. 6. Influence of transverse ventilation on fire development (a) average gas temperature in comparison (section A); (b) CO concentration in comparison (section B).

The average gas temperature and the concentration of carbon monoxide of different texts are shown in Fig. 5, where the fuel for the n-heptane, area of 17 cm × 17 cm fire experiments, under the condition of different open heights (respectively 0.5 m, 0.375 m and 0.25 m). It can be seen from the temperature comparison (see Fig. 5(a)) that the fire falls into the ventilation-controlled phase ahead of schedule as the opening is contractible. At the same time, due to the inadequate ventilation, the maximum average temperature relatively is reduced and combustion rate will also decrease. It can be seen from the carbon monoxide concentration results (see Fig. 5(b)) that when the opening height decreases from 0.5 m to 0.375 m, the carbon monoxide concentration rises slightly. However, when the opening height decreases from 0.375 m to 0.25 m, carbon monoxide concentration rises very rapidly from 12000 ppm to 27000 ppm.

The average gas temperature and the concentration of carbon monoxide in comparison are shown in Fig. 6, where the fuel for the n-heptane, area of 17 cm × 17 cm fire experiments, under the condition of different transverse ventilation. It can be seen from the temperature comparison results (see Fig. 6(a)) that the influence of transverse ventilation on the smoke layer temperature is not very large. From the carbon monoxide concentration results (see Fig. 6(b)), carbon monoxide concentration decreases from 60% to 80%, and the effect of smoke evacuation is obvious. It can be concluded from the comparison results that when the smoke evacuation has the best effect only when the exhaust port opening is near the fire. Furthermore, if the four exhaust ports are opened at the same time, the smoke exhaust volume near fire source region will decreases, which is adverse to smoke evacuation.

When the flashover occurs, mass loss is related to the area of opening, the opening height and the area of fire source. Quintiere [7] has derived the relation between the dimensionless mass loss rate and opening conditions:

$$m_f^* = \frac{\dot{m}_f}{\rho_\infty g^{1/2} A_0 H_0^{\,1/2}} \propto \frac{A_f}{A_0 H_0^{\,1/2}} \tag{4}$$

While comparing the long-narrow space with the common chamber, the ventilation effect is reduced to a certain extent. The space is much longer and much narrower, the ventilation effect becomes poorer. Therefore, a ratio of equivalent diameter and space length is set, $\gamma = D/L$.

According to Eq. (4), assuming that the fire is in completely developed stage, the fire mass loss rate $\dot{m}_f$ is related to ventilation parameter $\rho_\infty \sqrt{g}\gamma A_o \sqrt{H_o}$ and the area of fire source is A_f.

Fitting the data of Test 5, 8, 19 to 22, the relation between mass loss rate and opening conditions for pool fire of n-heptane can be obtained as below:

$$\dot{m}_f = \begin{cases} 0.21 A_f & \dfrac{\rho_\infty g^{1/2}\gamma A_0 H_0^{\,1/2}}{A_f} \geq 1.75 kg/m^2 \cdot s \\ 0.0135 \rho_\infty g^{1/2} \gamma A_0 H_0^{\,1/2} & \dfrac{\rho_\infty g^{1/2}\gamma A_0 H_0^{\,1/2}}{A_f} < 1.75 kg/m^2 \cdot s \end{cases} \tag{5}$$

Similarly, the relationship for wood crib fire can be determined by fitting the data of Test 18, 23 and 24:

$$\dot{m}_f = \begin{cases} 0.0813 A_f & \dfrac{\rho_\infty g^{1/2}\gamma A_0 H_0^{\,1/2}}{A_f} \geq 0.678 kg/m^2 \cdot s \\ 0.0135 \rho_\infty g^{1/2} \gamma A_0 H_0^{\,1/2} & \dfrac{\rho_\infty g^{1/2}\gamma A_0 H_0^{\,1/2}}{A_f} < 0.678 kg/m^2 \cdot s \end{cases} \tag{6}$$

The comparison between fitting curves of Eq. (5), Eq. (6) and experimental data is given in Fig. 7. It can be seen that when the opening size is greater than a certain value, the mass loss rate per unit area will not increase with the increase of the opening size; when the opening size reduces to a certain value, mass loss rate per unit area will decrease with the decrease of the opening size. However, different fuels have different critical opening conditions.

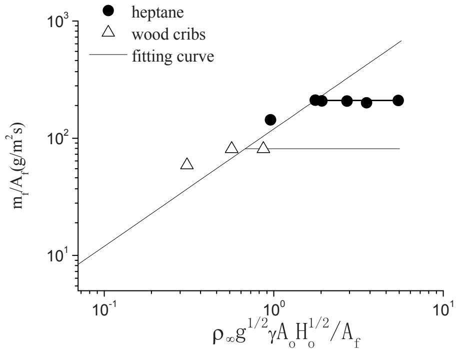

Fig. 7. Influence of opening conditions on burning rate.

4. Conclusions

Scale model experiments were carried out to the flashover phenomenon happened in ordinary compartments. Due to the discrepancy in building structures, the classical flashover model cannot be used to explain the phenomenon occurred in a long-narrow confined space. In the paper, based on the theory of fire dynamics, some physical aspects of fire in long-narrow confined spaces, including the components of smoke and gas temperature, have been discussed. From above discussion and analysis, the conclusions are summarized as following:

(1) In the pre-flashover period, the smoke layer temperature, concentrations and heat release rate will reach a quasi-steady stage during the early fire development. When the condition is enough, flashover will happen and fire will be ventilation-controlled. The thermal parameters change greatly, especially the carbon monoxide concentration, which rises by several orders of magnitude. In the post-flashover period, all thermal parameters will reach its maximum value and the fire will be again in a completely developed quasi-steady-state phase, up to fuels burning out.

(2) The occurrence of flashover is discussed with the change of fuel type, the size of fire source, opening size and transverse ventilation rate etc. For the fire source, it can be found that the critical line of flashover is between 600 °C and 700 °C. The fire is the fuel-controlled below the critical temperature. When it is higher than the critical temperature, the fire is ventilation-controlled.

(3) For the opening size and transverse, different fuels have different critical opening conditions; and when the smoke evacuation has the best effect only when the exhaust port opening is near the fire.

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