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A New Calculation Model of Detection Time for Heat Detector in Long and Narrow Space

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Abstract

Fire detector plays an important role in ship fire safety system. Usually, there are two types of fire detectors including fire smoke detector and heat detector, which are widely used in exit passageway, corridor, ladderway, and other long and narrow spaces in ship. Due to the smoke plume characteristics in these limited spaces are different to that of free plume in open place, the detection time calculating model of heat detector for these two different conditions are consequently different. This work is to develop a new detection time calculating model based on the fire plume rules including characteristics of temperature and velocity of fire smoke distributing in long and narrow spaces. Numeric method for calculating detection time is also presented. Finally, some calculations and analysis for a given fire scenario are performed. The numeric results are compared with that of the existing detection time calculating model based on free plume theory, which demonstrate the applicability of the model proposed in this article.

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Keywords: Ship fire; Heat detector; Detection time; Long and Narrow Space

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Nomenclature

r	radial distance from axis fire plume (m)
$u_{\max}$	maximum velocity at radial distance of r from axis of fire plume (m/s)
$T_{\max}$	maximum temperature at radial distance of r from axis of fire plume (K)
ΔT	excess gas temperature, $T_{\max} - T_{\infty}$ (K) or (℃)
ΔT_p	peak gas temperature rise in plume at the intersection with ceiling elevation(K)
H	ceiling height above fire source (m)
g	gravitational acceleration, 9.8m/s2
c_p	heat capacity of air at constant pressure (kJ/kg·K)
T_{∞}	initial temperature or ambient air temperature(K)
ρ_{∞}	gas density (kg/m3)
$\dot{Q}$	heat release rate (kW)
c_v	fraction of convection
l^b	half-width for corridor or primary beam channel(m)

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a constant, equal to 0.24 to 0.29
β constant, equal to 0.15
u_p rising velocity along the centreline of the plume(m/s)
S_t Stanton number, about 0.03
u smoke velocity (m/s)
T temperature of the heat detector(K)
RTI response time index((m.s)$^{0.5}$)
T_g maximum temperature at a distance of r from the centreline of the plume(K)
z distance above top surface of fire resource (m)
t_a arrival time for smoke transporting from fire origin to heat detector(s)
t_s rising time for smoke from fire to ceiling jet(s)
t_r spread time for smoke from ceiling jet position to radial distance of r(s)
Greek symbols
α fire growth coefficient(kW/s^2)

1. Introduction

Fire detector plays an important role in ship fire safety system. Usually, there are two types of fire detectors including fire smoke detector and heat detector, which are widely used in exit passageway, corridor, ladderway, and other long and narrow spaces in ship[1]. To detect fire without delay in case of fire, the detection time of the heat detector should be calculated in the fire safety design of the ships which has practical application value in disposing and installing of heat detector more reasonable and earlier alarm and control of the fire.

Compared with the land-based buildings, the structure of the ships are more complicated. The zone for the installing of the detector in confined space can be classified as free zone and long-narrow confined zone by considering the influence of fire on the smoke spread. Free zone refers to the spaces in which the smoke flow with no barrier, while long-narrow confined zone is the spaces in which the flow of the smoke is influenced by the barrier like crossbeam and all kinds of crossing pipelines. In ships, the heat detectors are always located in long-narrow spaces and it has been reported that the crossbeam and pipelines would have a great influence on the spread process of the smoke, especially on the velocity of the plume and temperature distribution characteristics after the ceiling jet which differ greatly with that of fire in open spaces[2]. The present detection time model of the heat detector is based on the ceiling jet theory without considering the barrier beneath the ceiling, so it is not suitable for the long-narrow spaces in ships [3][4]. As there is no report on the detection time of the heat detector, it is necessary to build a detection time model of the heat detector used in long-narrow spaces.

In this article, a new detection time calculation model is built and the numerical calculating method is also put forward based on the fire dynamics and the relevant research results on the smoke jet in long-narrow spaces. The research results can provide references and technical supports for the arrangement of the heat detector.

2. The Detection Time Calculation Model of Heat Detector in Long-Narrow Space

2.1. The process of smoke ceiling jet in long-narrow spaces

The smoke plume of the fire located in corridor or the spaces where there are crossbeam below the ceiling, will go up straight and when it come across the ceiling the smoke will spread around which is called ceiling jet. When it reaches the walls, the smoke will spread along the corridor and the process is shown in Figure 1. It can be found that from the beginning of the ceiling jet to the moment when the smoke reaches the walls, the spread of the smoke is not affected by any barrier and the spread process of the smoke will be affected by the walls on the both sides after the smoke reaching the walls. Therefore, the spread of the smoke can be classified as free spread process and confined spread process.

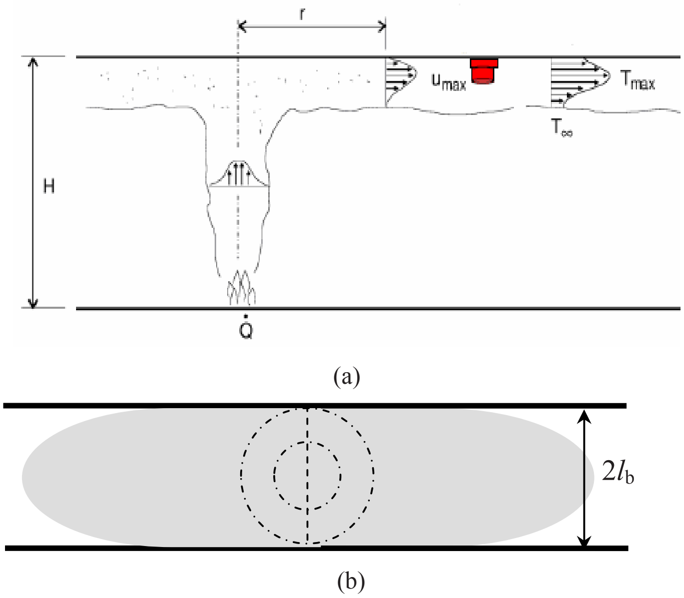


Fig.1. Ceiling jet flows beneath a confined space (a) Front view (b) Top view

Before calculating the detection time of the heat detector, the time needed for the smoke reaching the heat detector t_a and the operating time of the heat detector t_f from the beginning of smoke heating the detector to its operating, should be calculated. It should be noted that the heat detector must detect the fire in the initial stage which is the growing phase of the fire. Consequently, the quasi-steady fire is employed here to depict a short period of time, in which the heat release rate of fire is regarded as a constant, and the temperature and velocity of smoke at a certain location are also constants. In order to get the t_f, the time is divided into many short periods of time, and then the temperature rise of heat detector is calculated with time steps. The t_f will be equal to the time when the operating temperature is achieved.

2.2. The arrival time for smoke reaching the heat detector

The time needed for the smoke reaching the heat detector include two parts, one is the time for the smoke reaching the ceiling, called the rising time (t_s), and the other one is the time for the smoke below the ceiling spreading to the heat detector, called the spread time (t_r). The time needed for the smoke reaching the heat detector:

$$t_a = t_s + t_r \tag{1}$$

For the convenience of calculation, some dimensionless quantity including the heat release rate $\dot{Q}_0^*$, temperature rising ΔT_0^*, and velocity u_0^* are defined as below[2]:

$$\dot{Q}_0^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty g^{1/2} H^{5/2}} \tag{2}$$

$$\Delta T_0^* = \frac{\Delta T / T_\infty}{(Q_0^*)^{2/3}} \tag{3}$$

$$u_0^* = \frac{u_{\max} / \sqrt{gH}}{(Q_0^*)^{1/3}} \tag{4}$$

i the rising time

Hypothesis of the point source in weak plume theory is suitably used here because the fire size is small in the initial stage of the fire[5]. The velocity of the smoke in the centreline of the plume is

$$u_p = \frac{5}{6}\left(\frac{9}{10\pi\beta^2}\right)^{1/3}\left(\frac{g}{c_p\rho_\infty T_\infty}\right)^{1/3}\dot{Q}_c^{1/3} z^{-1/3} \tag{5}$$

The parameters in equation (4) are the same with those in equations (2) to (4). As a result, the rising time of the plume can be calculated as following

$$t_s = \int_0^H \frac{1}{u} dh \tag{6}$$

ii spreading time

(1) unconfined smoke spread

By combining equation (4) with the dimensionless correlations proposed by Heskestad and Alpert shown as below[2], the maximum velocity $u_{\max}$ at the point of the ceiling with a distance of r from the centerline of the plume can be calculated.

$$u_0^* = 1.06(\frac{r}{H})^{-0.69}, \qquad 0.17 \le r/H \le 4.0 \tag{7}$$

$$u_0^* = 3.61, \qquad r/H \le 0.17 \tag{8}$$

(2) confined smoke spread

An equation was proposed by Delichatsio to calculate the maximum temperature rise and velocity at the point with the distance of r apart from the centerline of the plume [2].

$$\frac{\Delta T}{\Delta T_p} = a(\frac{H}{l_b})^{1/3} \exp[-6.67 S_t \frac{r}{H}(\frac{l_b}{H})^{1/3}], \quad r > l_b \tag{9}$$

$$u_{\max} = 0.102\sqrt{H \Delta T}(\frac{H}{l_b})^{1/6}, \quad r > l_b \tag{10}$$

ΔT_p can be calculated through equation (3) and (11),

$$\Delta T_0^* = 6.3, \qquad r/H \le 0.2 \tag{11}$$

It should be noticed that, the equation (9)- (11) can be applied to the ceiling with beam when $h_b/H > 0.1(l_b/H)^{-1/3}$ is satisfied, and it can be used for corridor when $l_b/H > 0.2$ is satisfied.

(3) spread time

The spread time from the beginning of ceiling jet to the smoke spread to the point with its distance of r apart from the centerline of the plume can be calculated as below

$$t_r = \int_0^{l_b} \frac{1}{u_{\max}} dR + \int_{l_b}^{r} \frac{1}{u_{\max}} dR \tag{12}$$

2.3. The procedure of the detection time calculation for the heat detector in long-narrow space

Generally, the temperature rising process of the heat detector can be described as below

$$\frac{dT}{dt} = \frac{\sqrt{u}(T_g - T)}{RTI} \tag{13}$$

The heat detector should be operated at growing stage of fire where the fire size is transient. T-squared fire model can be used to describe its heat release rate.

It can be found that the detection time of the heat detector cannot be calculated by directly integrating equation (13), therefore numerical solution method was developed in this work and the calculation steps are shown as follows.

Step 1: Some parameters should be set firstly, in which there are fire growth coefficient α, time step Δt, time span M Δt (M is a big enough integer), the distance of r from the heat detection to the centreline of the plume, the initial temperature and the circumstance temperature T_0, the trigger temperature of the heat detector T_d. The flag number of iterative calculations i is set as 1.

Step2: Calculate the heat release rate by the equation of $\dot{Q}(i) = C_v \alpha t(i)^2$. Loop calculate $t_a(i)$, $T_{\max}(i)$ and $u_{\max}(i)$ until i=M

Step3: Find the minimum of $t_a(i), i = 1,...,M$, and marked as $t_a(K_1)$, which is the time of the first heat front arriving at the location of heat detector. Its mean that the heat front generated by fire at time of $K_1 \Delta t$, and it is arriving at the location of heat detector with maximum temperature of $T_{\max}(K_1)$ and maximum velocity of $u_{\max}(K_1)$. Meanwhile, to find the minimum one in time range of $i\Delta t, i = K_1,...,M$, and marked as $t_a(K_2)$ which is the time of the second heat front arriving at the location of heat detector with its maximum temperature of $T_{\max}(K_2)$ and maximum velocity of $u_{\max}(K_2)$, and so on. Subsequently, let T_g equal to $T_{\max}(K_1)$, u take a value of $u_{\max}(K_1)$ during the time range from $t_a(K_1)$ to $t_a(K_2)$. The initial T takes a value of the ambient temperature T_0. The temperature of heat detector is calculated numerically according to equation 13 and recorded as T_1 before the second heat front arriving at the detector. At the same time, the initial temperature of detector is updated by T_1 until the third heat front arriving at detector. To implement the loop computing, and update the temperature of smoke and heat detector with a similar mode described above, the detection time is taken as t_d when the temperature of heat detector T is equal to its operating temperature T_d.

3. Calculation and Analysis

In order t o demonstrate the application of the proposed model to fire safety design and assessment for a long-narrow space, three different situations are considered to calculate the detection times.

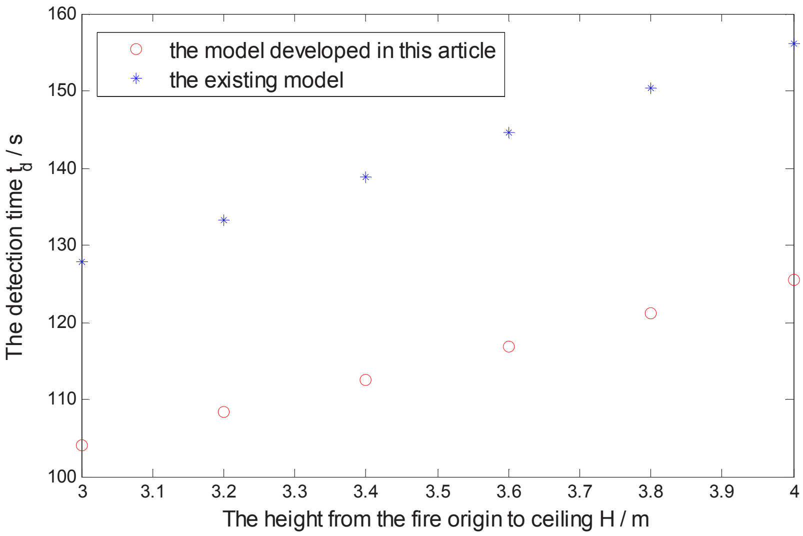
Firstly, the fire is set as t^2-squared fire, α take a value of 0.0117kW/s^2.The heat detector is located on the ceiling at a distance of 1m to the centreline of fire plume, other parameters are shown in Table 1. By varying the ceiling height H from 3m to 4m, the detection time of heat detector are calculated respectively by the proposed model and the existing model without considering the confined situations. The results are shown in Fig.2(a). It can be seen that the detection time of the proposed model is more than that of the existing model for anyone of given scenarios. Furthermore, the detection times of these two models show a good linear relationship with *H*.

Table 1 the given parameters for calculation

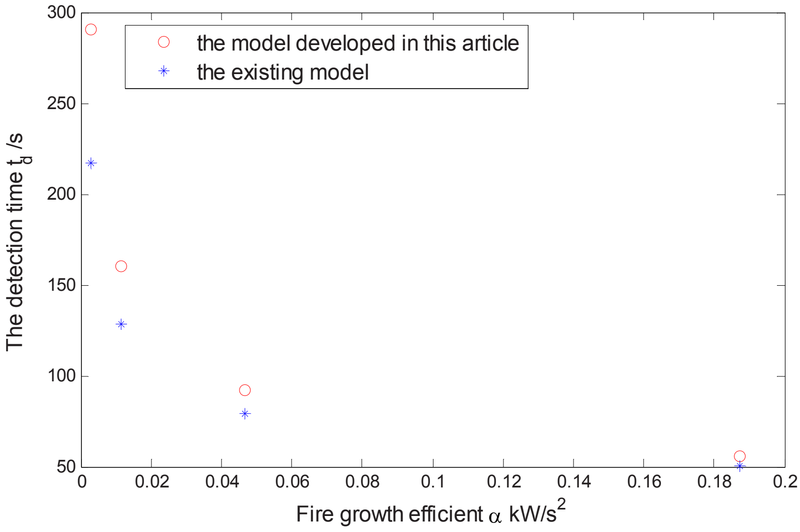
Paramter	symbol	Value
Half-width of beam, m	l_b	0.81
Depth of beam, m	h_b	0.5
Response Time Index,(m.s)$^{0.5}$	*RTI*	60
Initial temperature of heat detector and ambient air,℃	T_0	20
The operating temperature ,℃	T_d	57

Secondly, the ceiling height is set as 4 m, let α taking a different value of 0.0029 kW/s^2, 0.0117 kW /s^2, 0.0469 kW /s^2 and 0.1876 kW /s^2, which responses respectively to slow, medium, fast and ultra-fast fire. The other parameters are shown in Table 1. The detection time of the proposed model is compared to that of the existing model in Fig.2(b). It can be found that the detection time of the proposed model is more than that of the existing model for a given condition. Moreover, with the increase of α, the gap of detection time between the two models become smaller. When the fire is ultra-fast fire, there is nearly no gap between the two models.

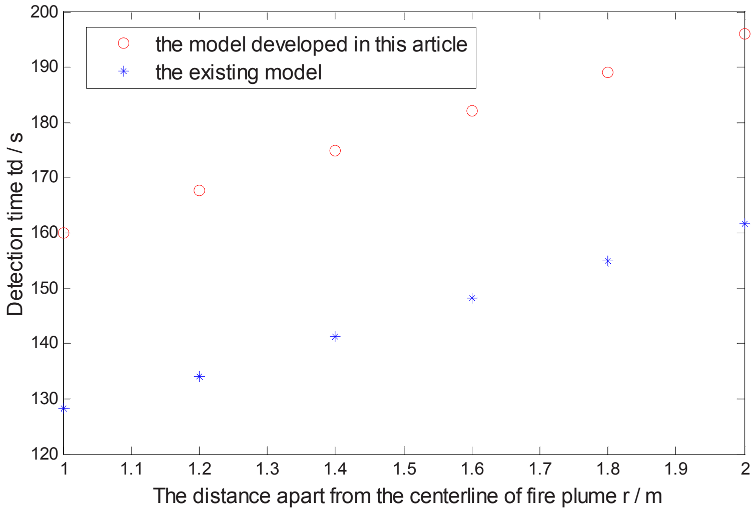
Lastly, by varying the parameter r, letting α take a value of 0.0117 kW/s^2, *H* is set as 4m, other parameters are shown in Table1, and the detection times based on two models are shown in Fig.2 (c). The detection time is increased with the increase of r, and show a good linear relationship with r. At certain r, the detection time of the proposed model is more than that of the existing model.


○ the model developed in this article
✳ the existing model
The detection time t_d / s
160
150
140
130
120
110
100
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4
The height from the fire origin to ceiling H / m

(a)


○ the model developed in this article
✳ the existing model
The detection time t_d /s
300
250
200
150
100
50
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Fire growth efficient α kW/s^2

(b)



(c)

Fig.2. The comparison of detection times calculated respectively by the existing model and the proposed model. (a)detection time versus different ceiling heights,(b) detection time versus different fire growth efficient, (c) detection time versus the distance of the detector apart from the centreline of fire plume

4. Conclusions and Prospect

In this paper, on the base of fire dynamics and the current research achievements concerning with ceiling Jet flows beneath confined ceilings in long-narrow space, the detection time calculation model of heat detector located in long-narrow space is established in theory. Furthermore, the calculating detection time of this proposed model are compared to that of the existing model. Some conclusions are obtained as follows.

Firstly, the detection time of the proposed model for long-narrow space is longer than that of the existing model for a given fire scenario, where the geometric parameter and other parameters such as RTI , T_d and T_0 are given in advance. That is to say, as the increase of α , the gap of calculation results between the two models become smaller. When the fire is ultra-fast fire，there is nearly no gap between the two models. Moreover, the detection time increased linearly with the increase of H and r respectively.

Secondly, it should be pointed that the detection time calculation model of heat detector in long-narrow space is only established in theory. For validate its applicability, more specific experiments should be carried out in the future. Moreover, some modifications to the proposed model should be performed. Due to the limitation of knowledge on fire plume characteristics, the proposed model is only valid for the condition of l_b/H>0.2. The investigations with regard to the velocity and temperature of smoke plume under the condition of $l_b/H \leq 0.2$ should be developed.

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