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On the self-extinction time of pool fire in closed compartments

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Abstract

The self-extinction time of pool fires in closed compartments was studied. Experiments were conducted in two bench-scale compartments with volumes of 0.75 m^3 and 17.55 m^3. It was found that the fire self-extinction time was proportional to the compartment volume but inversed to the pool area for *n*-heptane. The fuel mass loss rate in closed compartments was lower than that in the open space. The fire self-extinction occurred when the local oxygen mole fraction in the flame vicinity descended to a level of 10.7-15.3%. The mean remaining oxygen mole fraction at the self-extinction moment was about 14.1%. Based on the mass conservation of the oxygen, a model for predicting the self-extinction time of pool fires in closed compartments was developed. By defining a concept of the dimensionless fire volume, the dimensionless self-extinction time was proposed. The dimensionless self-extinction time is proportional to the difference between the initial and remaining oxygen mass fraction, fuel properties, such as heat of combustion and stoichiometric ratio etc., but inverses to the dimensionless fire volume and the integrated combustion coefficient. The predicted results showed a good agreement with the experimental results. The model also provides a good prediction for the results of NRL's tests.

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Keywords: Compartment fire; Pool fire; Self-extinction time; Prediction model; Dimensionless analysis

Nomenclature

A	floor area of compartment (m^2)
c_p	specific heat (kJ/(kg K))
D	diameter of pool(m)
g	acceleration of gravity (9.81 m/s^2)
H	height of compartment (m)
$\dot{m}$	mass loss rate (kg/s)
$\dot{m}_b$	burning rate (kg/s)
$\bar{\dot{m}}_D$	average mass loss rate (kg/s)
$\dot{m}_{D0}$	the mass loss rate of fire with the diameter of D in free atmosphere (kg/s)
$\dot{Q}$	heat release rate of fire (kW)
r_0	stoichiometric ratio of fuel to oxygen
T	temperature (K)
t	time (s)
V	compartment volume (m^3)
X_{O_2}	mole fraction of oxygen (%)

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$\bar{X}_{O_2,E}$	remaining oxygen mole fraction (%)
$X_{O_2,U}$	oxygen mole fraction from upper probe (%)
$X_{O_2,L}$	oxygen mole fraction from lower probe (%)
$\bar{Y}_E$	ratio of remaining oxygen to initial (%)
Y_{O_2}	mass fraction of oxygen (%)
$\bar{Y}_{O_2,E}$	remaining oxygen mass fraction (%)
Z_c	characteristic length scale of fire (m)
Greek symbols	
χ	global combustion efficiency
χ_0	integrated combustion coefficient
χ_b	proportion of mass burnt compared to that vaporized from the pool
χ_c	combustion efficiency
Δh_c	heat of combustion (MJ/kg)
Θ	dimensionless fire volume
τ	dimensionless time
ρ	density (kg/m^3)
$\bar{\rho}$	average density (kg/m^3)

1. Introduction

In ship fire accidents, to close the burning cabin is an efficient way to prevent the fire from spreading to other rooms and even to extinguish the fire, especially when the ships are at sea without supports. Under these circumstances, the compartment is completely closed, and the fire will extinguish due to the lack of oxygen. It is dangerous to open the ship cabin prematurely before the fire died out, so a dependable estimation of the extinction time is of great significance [1].

Several studies have been devoted to the fire behaviors in closed compartments. Tatem et al. [2] developed a time-incrementing zone model to estimate the influence of a gas-tight compartment on the burning rate of a pool fire. Bailey et al [3] conducted a series of fire tests in a large scale pressurizable compartment to figure out the impacts of pressure and oxygen concentration on methanol pan fires. The fuel mass loss rate decreased linearly with oxygen depletion from the volume fraction of 21% to 13.5%, and the fire self-extinguished when the oxygen concentration level approached 12%. Nikitin [1] applied the thermal theory to explain the self-extinction phenomenon of pool fire in a sealed compartment. He pointed out that the sharp drop of gas temperature when the fire quenched broke the thermal balance between the flame and the surrounding, and this was the reason caused the self-extinction of the fire. Beyler [4]stated an analytical expression from a well-stirred compartment model to predict when flame extinction would occur for closed compartments. He made the assumption that the burning was steady. However, it is difficult to obtain the heat release rate for unsteady burning in closed compartments. Larsson et al [5] conducted model scale tests to investigate the fire development on a Ro-Ro ferry vehicle deck. The fire self-extinguished when oxygen concentration in the compartment was decreased to a level of 13-15%. Chow et al [6-8] conducted a considerable number of studies on closed compartment fire. He pointed out that the input heat release rate was a key point for CFD modeling on closed compartment fire. Fire self-extinction can be observed not only in closed compartments, but also in poorly ventilated compartments. Ultiskul et al. [9-11] and Hu et al. [12]varied the sizes of fuel beds and wall-vents, in order to control the ventilation condition of the compartment, and found that the flame self-extinction occurred when the oxygen mole fraction decreased below 16%. The existing studies mainly concerned about the limiting oxygen index of burning in closed compartments. However, no prediction model for the self-extinction time was proposed, except the work conducted by Beyler [4]. Nevertheless, Beyler's model made an assumption that the burning was steady and the oxygen concentration at the self-extinction moment was homogeneous.

Although the mechanism of the flame extinction is complicated, it's now widely recognized that flame extinction depends on the heat loss from the flame and its energy release rate [13]. Impact factors, such as the oxygen concentration, lead to the flame extinction by affecting the two competing procedures. Morehart et al. [14] demonstrated that a diffusion flame couldn't sustain when the oxygen in the environment fell below a threshold varying in the range of 10-15% depending on the fuel type. In Bailey's experiments [3], self-extinction occurred when the average oxygen concentration decreased to about 12%, a little higher than 11.1%, the limiting oxygen index (LOI) of methanol in the SFPE handbook [15]. To sum up, doubtlessly, the self-extinction of flame is closely related to the oxygen concentration in the compartment. For pool fires, it has been shown by Quintiere et al. [13] that the point of extinction is not only restricted by the limiting oxygen concentration, but also depends on the local temperature and heat flux to the fuel surface. Quintiere found that the heptane pool fires could sustain with the oxygen concentration of 2% at the pool base level provided that the smoke layer temperature was high enough. Utiskul's experiments [9-11] also supported this viewpoint. So, as a direct consequence of heat flux received by fuel surface, burning rate of the pool fire may be also regarded as an influencing factor of the fire extinction behavior [16].

From the review above, we can see that for pool fires in closed compartments, the criterion for self-extinction time is still unclear. The objective of the present study is to analyze the fire self-extinction time, the oxygen concentration at the extinction moment and the burning rate in closed compartments, then to establish a simple prediction model for the self-extinction time and conduct dimensionless analyses.

2. Experimental setup

Experiments were conducted in two completely closed compartments with interior dimensions of 3.00 m (L) × 3.00 m (W) × 1.95 m (H) (Compartment A) and 1.00 m (L) × 1.00 m (W)× 0.75 m (H)(Compartment B), as shown in Fig. 1. The front side of Compartment A was made of toughened glass and worked as observation window. The other five sides were built with 5 mm thick steel. Compartment B was constructed with 10mm thick rock wool sandwich construction according to A60 class in IMO/SOLAS. The ceiling and the floor were built with 5 mm thick steel. *N*-heptane was burned in fuel pans with diameters of 0.100, 0.141, 0.200 and 0.300 m in Compartment A, while 0.200 m and 0.300 m diameters were performed in Compartment B. The fuel pans were built with 5 mm thick steel and were 4 cm deep. The initial fuel thickness of pool fires in Compartment A and B were 12.8 mm and 25.6 mm respectively, and were located in the center of the compartment floor. An electronic balance with an accuracy of 0.01 g was used to record the fuel mass loss. Oxygen concentration at bottom and top portion of the compartment were measured by a gas analyzer (KANE 9106) with an accuracy of±0.2%. The two sampling points in Compartment A had the same horizontal coordinates, with the distances of 0.25 m and 0.50 m from the two nearest walls, one was set 0.15 m from the bottom and the other 0.15 m from the ceiling. While in Compartment B, the sampling points were 0.75 m to the nearest walls, 0.75 and 1.2 m for the upper and lower sampling points, as shown in Fig. 1. A video camera was used to record the burning process, so as to obtain the self-extinction time more accurately.

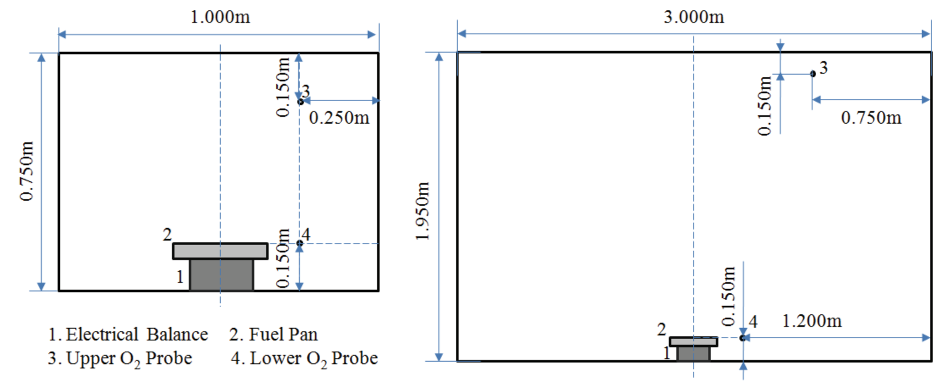

Fig. 1. Experimental arrangements. (a) compartment A, (b) compartment B.

3. Experimental results and discussions

3.1. Self-extinction time

Figure 2 illustrates the average self-extinction time obtained from the experiments. A horizontal ordinate of $V/D^2$was employed to distinguish the difference of conditions including the compartment volume and fire size.

It can be seen that the self-extinction time was proportional to the compartment volume but inversed to the pool area which represents the heat release rate of the pool fire in some degree. This may be due to that a larger compartment volume with more initial oxygen could support a longer burning time for the same oxygen depletion rate. While a larger fire size resulted in a faster oxygen depletion rate and a shorter burning time. A simple empirical formula of $t_E = 4.418\, V/D^2$was found to correlate t_E with V/D^2 by linear fitting for the experimental results.

However, it should be noted that this empirical formula $t_E = 4.418V/D^2$ was fitted based on the present experimental data and may not be a universal expression to all conditions when fuel properties and compartment shape etc. changed. The relationship between t_E with V/D^2 was in accordance with Beyler's expression [4], in which the extinction time was proportional to $V/\dot{Q}$, and $\dot{Q}$ was a constant heat release rate. However, $\dot{Q}$ may not be a constant here because a fire inside the closed compartment is unstable. In addition, Beyler assumed the surrounding was well-stirred, while an obvious stratification occurred in our experiments, shown as Fig. 2.

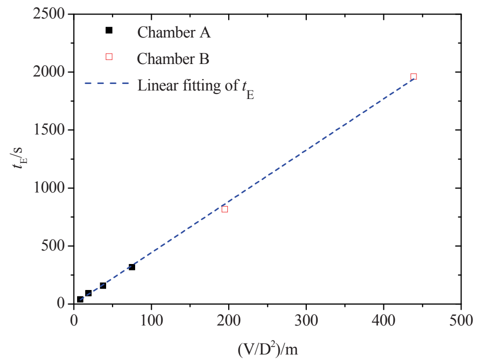

Fig. 2. Experimental results of the average self-extinction time.

3.2. Mass loss rates

Figure 3 shows the mass loss rate versus time in each case. Since there was some fuel left in the pan after the extinction, it was verified that the fire extinguished due to oxygen starvation. The mass loss rate experienced an increasing period followed by a quasi-steady burning period, and then dropped until extinction. This tendency was clear especially in relative small fuel pan cases. While the pool diameter increased to 0.200 m and 0.300 m, as the fire durations were short, the steady stages were not as apparent as the other situations in Compartment A. In Fig. 3(b), an obvious increase of mass loss rate was found just before the extinction in Compartment B, and this was due to the boiling over of the fuel as observed.

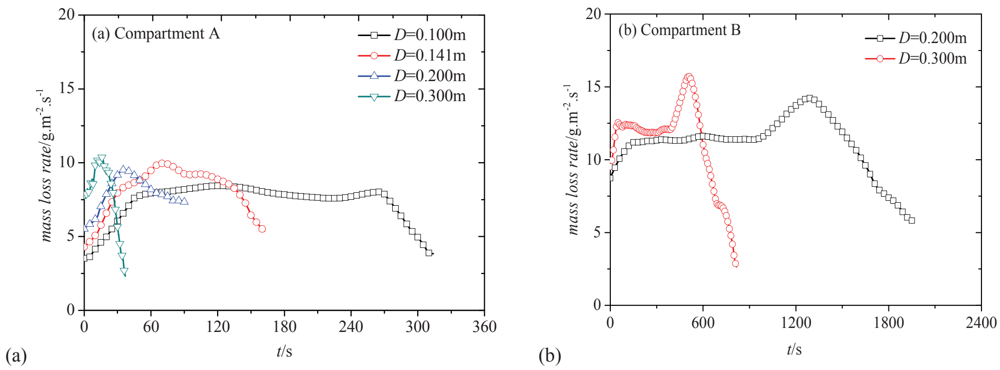

Fig. 3. Experimental results of the fuel mass loss rate versus time in (a) compartment A and (b) compartment B.

The average mass loss rate of heptane $\bar{\dot{m}}_D$ and the self-extinction time t_E in each case were obtained, as listed in Table 1. The average mass loss rate can be determined by $\bar{\dot{m}}_D = \frac{1}{t_E}\int_0^{t_E} \dot{m}_{D0}$. In Compartment A, $\bar{\dot{m}}_D/\dot{m}_{D0}$ from the pool fires with diameters of 0.100 m, 0.141 m and 0.200 m showed that the increase of pool size expanded their difference. The fuel mass loss rate in Compartment B was larger than that in Compartment A. For D=0.200 m case, $\bar{\dot{m}}_D/\dot{m}_{D0}$ was 53.2% in Compartment A and 71.8% in Compartment B. Results were similar for the D=0.300 m case, the ratio became 55.4% and 73.1%, respectively. This can be explained by the competition of the impact factors as discussed above. For the same compartment volume, the increase of fire size would lead to a larger mass loss rate as well as a shorter burning time. For a given pool diameter D, $\bar{\dot{m}}_D$ was about 17.3-46.8% lower than $\dot{m}_{D0}$. This was the results of the coupling effect by many factors, including the decreasing oxygen concentration, increasing pressure and temperature etc. [3, 13, 16]. Repeated experiments of each case showed quite similar results.

Table 1. Self-extinction parameters of pool fires in closed compartments

No.	V/m^3	D/m	t_E/s	$\dot{m}_{D0}$/10^{-4}kg.s^{-1}	$\bar{\dot{m}}_D$/10^{-4}kg.s^{-1}	$\bar{\dot{m}}_D/\dot{m}_{D0}$	$X_{O_2,U}$/%	$X_{O_2,L}$/%	$\bar{X}_{O_2,E}$/%	$\bar{Y}_{O_2,E}$/%	$\bar{Y}_E$/%
1	0.75	0.100	317	0.75	0.62	82.7%	13.2	14.3	14.5	16.0	69.4
2	0.75	0.141	157	2.03	1.27	62.6%	11.3	12.7	13.8	15.2	65.9
3	0.75	0.200	93	4.83	2.57	53.2%	10.0	10.7	13.3	14.7	63.7
4	0.75	0.300	39	10.93	6.06	55.4%	10.0	13.2	14.8	16.3	70.7
5	17.55	0.200	1961	4.83	3.47	71.8%	12.7	15.2	14.5	16.0	69.3
6	17.55	0.300	817	10.93	7.99	73.1%	11.8	15.3	13.8	15.2	65.9

$\bar{Y}_{O_2,E}$ is a changing value under the experimental conditions. It is hard to obtain because it is difficult to measure the oxygen concentration field. In the present work, the mean of $\bar{X}_{O_2,E}$=14.1%, and the mean of $\bar{Y}_{O_2,E}$=15.6% equivalently.

3.3. Oxygen concentration

Figure 4 shows the oxygen concentration versus time, as measured from the lower and upper probe in the compartment. For the convenience of comparison, time was normalized by the self-extinction time, then $t/t_E = 0.00$ represented the ignition moment, while 1.00 represented the self-extinction moment. From Fig. 4, the oxygen concentration in the ceiling level was always lower than that in the bottom level in each case. The oxygen concentrations of the upper layer dropped immediately from the ignition, while the values of the lower layer hold for a while before descending. In Compartment A, the normalized time delay was about 0.25, while in Compartment B, the normalized time delay was about 0.12.

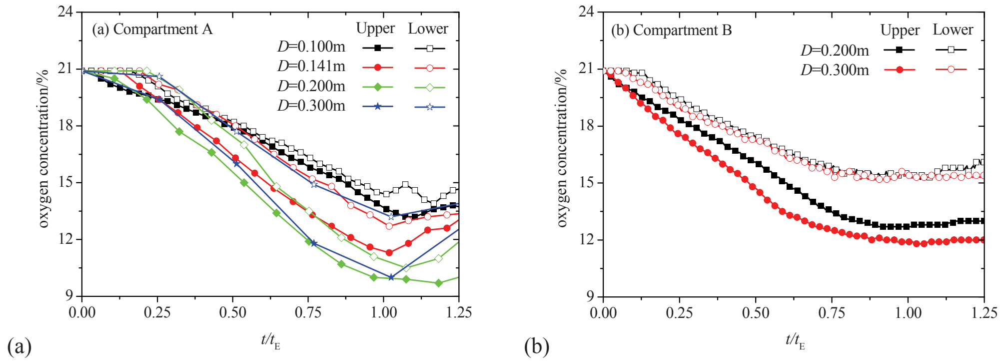

Fig. 4. Experimental results of oxygen concentration in (a) compartment A and (b) compartment B.

As the driving of fire, hot smoke quickly impinged the ceiling. After a short spreading period, the smoke layer began to form and accumulate. Combustion products and entrained air of the fire plume were the main compositions of the smoke layer, so the oxygen concentration in it was much lower. Therefore, the oxygen concentration at some position would drop sharply once the smoke layer reaches there. When the oxygen concentration decreased below the limiting value, or the heat release from the flame couldn't sustain the combustion, the self-extinction occurred. The oxygen concentrations of each case are listed in Table 1. Obviously, the local oxygen concentration $X_{O_2,U}$ is much lower than $X_{O_2,L}$ in each case. From all experiments, $X_{O_2,U}$ ranged from 10.0% to 13.2%, while $X_{O_2,L}$ ranged from 10.7% to 15.3%. The concept of remaining oxygen fraction at extinction, volume fraction $\bar{X}_{O_2,E}$ or mass fraction $\bar{Y}_{O_2,E}$, was proposed to present the average oxygen concentration in the compartment at extinction. $\bar{X}_{O_2,E}$ was in a range of 13.3-14.8%. Previous studies also showed an uncertainty of the fire self-extinction oxygen concentration [3]. Larsson's tests revealed that a wood crib fire in unventilated compartment would self-extinguish when oxygen concentration decreased to a level of 13-15% [5]. In Table 1, $\bar{X}_{O_2,E}$ or $\bar{Y}_{O_2,E}$ decreased with pool diameter in each compartment except for the D=0.300 m case in Compartment A. For this case, the fire size was relatively large compared to the compartment volume, which seriously restricted the flame pulsation and air entrainment, an extremely low local oxygen fraction near flame occurred. Consequently, the fire self-extinguished suddenly although the average oxygen concentration of compartment was higher than the limiting oxygen concentration.

4. Theoretical analyses on the self-extinction time

Beyler et al. [15] proposed a model for predicting the self-extinction time in closed compartments based on the homogeneous assumption. He considered that the self-extinction time had a linear relationship with $V/\dot{Q}$ for a constant heat release rate fire. However, the heat release rate in closed compartments is difficult to obtain due to the incomplete combustion and the combustion efficiency is an undefined variable. We attempted to solve this problem by involving with the fuel mass loss rate. Consider a fire with a burning rate of $\dot{m}_b$in a closed compartment of the volume V. The total fuel reacted $m_b = \int_0^t \dot{m}_b \, dt = \int_0^t \chi_b \, \dot{m} dt$ with the consumption of oxygen $m_{o_2} = \chi_c m_b / r_0$, where $r_0$is the stoichiometric ratio of fuel to oxygen. Usually, the combustion efficiency is ratio of the heat released in a combustion reaction to the theoretical heat of complete combustion. Two efficiencies are defined here, χ_b is the proportion of mass burnt compared to that vaporized from the pool and $\chi_c$is the combustion efficiency. The mass conservation of the oxygen in the compartment could be described as

$$m_{O_2} = V(\rho_{O_2,0} - \bar{\rho}_{O_2}) \tag{1}$$

$$\text{or} \frac{\chi_c}{r_0} \int_0^t \chi_b \dot{m} dt = V(\rho_0 Y_{O_2,0} - \bar{\rho} \bar{Y}_{O_2}) \tag{2}$$

where ρ_0 and $\rho_{o_2,0}$ are the initial average gas density and oxygen density respectively, $\bar{\rho}$ and $\bar{\rho}_{o_2}$are the average values at the moment of t, $Y_{O_{2,},0}$ and$\bar{Y}_{O_2}$are the average oxygen mass fractions of the initial state and the moment of t respectively. Neglecting the gas mass increase due to the combustion and supposing χ_b is constant, Eq. (2) could be rewritten as

$$\chi_b \chi_c \int_0^t \dot{m} dt = r_0 \rho_0 V (Y_{O_2,0} - \bar{Y}_{O_2}) \tag{3}$$

Here we define global combustion efficiency $\chi = \chi_b \chi_c$, and the fuel mass loss rate could be expressed by an average $\bar{\dot{m}}_D$, according to Eq. (3), the oxygen mass fraction could be described as

$$\bar{Y}_{O_2} = Y_{O_2,0} - \frac{\chi \bar{\dot{m}}_D}{r_0 \rho_0 V} t \tag{4}$$

In other words, if the mass loss rate is constant the average oxygen mass fraction $\bar{Y}_{O_2}$drops linearly with time, and the extinction would occurs when the average oxygen mass fraction decreases to the limiting value of$\bar{Y}_{O_2,E}$. The extinction time could be described as

$$t_E = \frac{r_0 \rho_0 V}{\chi \bar{\dot{m}}_D} (Y_{O_2,0} - \bar{Y}_{O_2,E}) \tag{5}$$

Figure 5 presents the self-extinction time from the experiments and the predictions by Eq. (5). To compare the difference of combustion efficiency in closed compartment with that in the open space, $\bar{\dot{m}}_D$and $\dot{m}_{D0}$ listed in Table 1 were used respectively in the prediction. At same time, $r_0 = 1/3.52$ and $\chi = 1$. It shows that the predicted results were lower than the experimental results. The predicted self-extinction time with $\bar{\dot{m}}_D$was closer to the experimental results than that with $\dot{m}_{D0}$. It indicated that the completeness of the burning of vaporized fuel was much less than that in the free atmosphere. As discussed above, the self-extinction had almost linear relationship with V/D^2 from experimental results, but the prediction did not agree with the experimental results. So proper integrated combustion efficiency is necessary in a precise prediction.

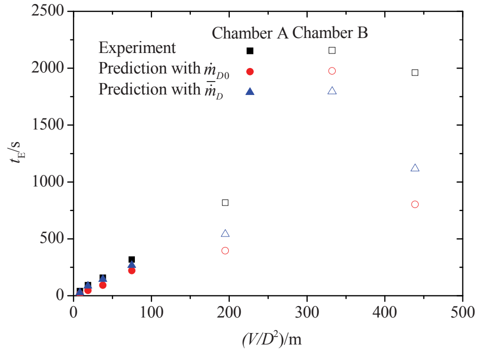

Fig. 5. Comparisons between experiment results and predictions by Eq. (5).

5. Analyses of the dimensionless self-extinction time

To find the dominant factor influencing the self-extinction time in closed compartments with different sizes, the dimensionless fire volume is defined as Eq. (6) to reflect the relative size of the fire.

$$\Theta = z_c^3 / V \tag{6}$$

where, Z_c presents the characteristic length scale of fire [16]:

$$z_c = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \tag{7}$$

where $\dot{Q} = \Delta h_c \dot{m}_{D0}$ is employed to estimate the heat release rates of the reference fire, Δh_c =44.6 MJ/kg for heptane, ρ_∞ = 1.1 kg/m^3, c_p = 1.0 kJ/(kg K), T_∞ = 293 K and g = 9.81 m/s^2.

Define dimensionless self-extinction time as $\tau_E = t_E (g/z_c)^{1/2}$,since $\bar{Y} = Y_{O_2}/Y_{O_2,0}$, from Eqs. (5), (6) and (7), we obtain

$$\tau_E = \frac{r_0 \Delta h_c}{c_p T_\infty} \frac{\rho_0}{\rho_\infty} \frac{\dot{m}_{D0}}{\chi \bar{\dot{m}}_D \Theta} Y_{O_2,0} (1 - \bar{Y}_E) \tag{8}$$

Suppose $\rho_0 \approx \rho_\infty$ and let the integrated combustion coefficient $\chi_0 = \chi \bar{\dot{m}}_D / \dot{m}_{D0}$

$$\tau_E = \frac{r_0 \Delta h_c}{c_p T_\infty} \frac{Y_{O_2,0}}{\chi_0 \Theta} (1 - \bar{Y}_E) \tag{9}$$

In Eq. (9), it is obvious that $r_0 \Delta H_c Y_{O_2,0}/(c_p T_\infty)$ is constant for a given fuel and ambient condition. In this case, dimensionless compartment volume, the integrated combustion coefficient and the remaining oxygen concentration determine the self-extinction time. In other words, the dimensionless self-extinction time of fire is proportional to the difference between initial and remaining oxygen mass fraction and fuel properties such as heat of combustion and stoichiometric ratio etc., but inverses to the dimensionless fire volume and the integrated combustion coefficient.

The mean value of $\bar{Y}_E$, signed as $\bar{Y}_{E,avg}$, is found to be 67.5% with standard error of 2.45% from Table 1. $\bar{Y}_{E,avg}$ is expected to be a parameter concerned with self-extinction behaviors. χ_0 can be expressed by $\chi_0 = r_0 \Delta H_c Y_{O_2,0}(1 - \bar{Y}_E)/(c_p T_\infty \tau_E \Theta)$ according to Eq. (9). χ_0 can also be treated as the ratio of dimensionless self-extinction time by Eq. (9) to a nominal $\chi_0 = 1$ to the dimensionless time directly from the experiments. The comparisons between the experimental results and the predicted results of Eq. (9) with $\bar{Y}_{E,avg}$ are shown in Fig. 6, where $\tau_{E,e}$ represents the dimensionless self-extinction time of experimental results while $\tau_{E,m}$represents that of prediction of Eq. (9) with $\bar{Y}_{E,avg}$. Fig. 6 shows the dimensionless self-extinction time $\tau_E$varies inversely as dimensionless fire volumeΘboth in Compartment A or Compartment B. $\tau_{E,m}/\tau_{E,e}$is about 0.44, this value could embody the integrated combustion coefficient.

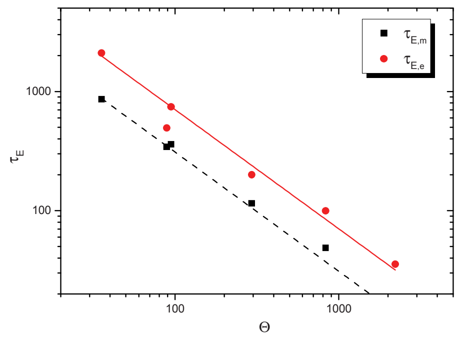

Fig. 6. Comparisons between experiment results and predictions by Eq.(9).

An extensive comparison was performed by involving the experimental results by NRL [3]. A $\bar{Y}_{O_2,E}$ of 15.6% for heptane in our experiments and 13.3% for methanol in NRL tests are employed. τ_E depends on$r_0\Delta H_c\, Y_{O_2,0}(1-\bar{Y}_E)/(c_pT_\infty\Theta)$ is plotted in Fig. 7. The dimensionless time of experimental results is well power fitted. By comparing the power fitting of experimental results and predictions, the integrated combustion coefficient could be described as

$$\chi_0 = 0.089(r_0\Delta h_c Y_{O_2,0}(1-\bar{Y}_E)/c_pT_\infty\Theta)^{0.239} \quad (10)$$

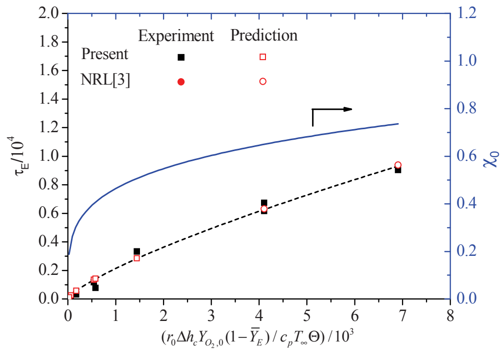

Fig. 7. Analysis of dimensionless self-extinction time and integrated combustion coefficient.

6. Conclusions

The self-extinction time of n-heptane pool fire in closed compartments in laboratory scale was studied in order to understanding the phenomena of fire self-extinction under these conditions. The results show following remarkable conclusions.

(1) The fire self-extinction time was linear to V/D^2 for a pool fire in closed compartment and $t_E = 4.418V/D^2$ under present experimental conditions. The fire self-extinction occurred when local oxygen mole fraction in the vicinity of the flame decreased to a level of 10.7-15.3%. The remaining oxygen concentration when fire self-extinguished $\bar{X}_{O_{2,E}}$ was in a range of 13.3-14.8%. The mean of $\bar{X}_{O_{2,E}}$was about 14.1 %. The fuel mass loss rate in closed compartments was lower than that in the open space.

(2) Based on the mass conservation of the oxygen in closed compartments, a prediction model of self-extinction time of the pool fire in closed compartment was developed and the dimensionless self-extinction time was obtained by defining and the dimensionless fire volume. It revealed that the dimensionless fire self-extinction time was proportional to the difference between initial and remaining oxygen mass fraction, as well as fuel properties, such as the heat of combustion, stoichiometric ratio etc., but inverse to the dimensionless fire volume and the integrated combustion coefficient. Comparing

the predictions with the experimental results, we obtained a proper estimation $\chi_0 = 0.089(r_0 \Delta H_c\, Y_{O_2,0}(1-\bar{Y}_E)/c_p T_\infty \Theta)^{0.239}$. The results of tests conducted by NRL were in good agreement with our model. Further research should be conducted on the combustion efficiency of pool fire in closed compartments in the future.

Note that we tried to focus on improving improve existing theories by taking into account the unsteady burning of the pool fire and this paper was the first step, *i.e.*, to establish a model that accounts for the combustion efficiency and the dimensionless fire size, and use the average values to deal with the unsteady burning. Then we will use time-dependent values in the next step. The experiential values and correlations of unsteady burning could be achieved in the future. So some work on the combustion efficiency variations during the burning process should be conducted and more experiential correlations should be obtained.

Acknowledgements

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