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Analysis of the combustion efficiencies and heat release rates of pool fires in ceiling vented compartments

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Abstract

This study focuses on the combustion efficiencies and further the heat release rates for pool fires in ceiling vented compartments. The concept of plume equivalence ratio (PER) is introduced to express the ventilation conditions for the flames in such compartments. The transient PER is estimated using the fire plume theories because the complex bi-directional vent flow makes it impossible to measure or calculate directly. The combustion efficiencies can thus be predicted utilizing the empirical correlation proposed by Tewarson, and subsequently the heat release rates can be decided in combination with the fuel mass loss rates. Heptane pool fires in a small-scale ceiling vented compartment were experimentally investigated. The increment of the opening size had limited impacts on the fuel mass loss rates, but significantly raised the oxygen concentrations in the compartment; however, the oxygen concentrations at the bottom began to decrease earlier. The PERs inclined with the burning procedure until extinction in general indicating the ventilation conditions for the flame grew worse; the combustion efficiencies declined correspondingly. Increasing the opening size may improve the ventilation conditions for the flame in general and consequently increase the combustion efficiencies but it seemed to have little impacts on the heat release rates.

Keywords: Ceiling vent; Compartment fire; Combustion efficiency; Heat release rate; Plume equivalence ratio

Nomenclature

- \( c_p \): specific heat of air (kJ/(kg K))
- \( D \): pool diameter (m)
- \( L \): size of the ceiling opening (m)
- \( \dot{m}_f \): mass loss rate of the fuel (g/s)
- \( \dot{m}_{f,\infty} \): steady mass loss rate of the fuel under free burning condition (g/s)
- \( \dot{m}_{O_2,\text{act}} \): real oxygen consumption rate that reacts in the flame (g/s)
- \( \dot{m}_{O_2,\text{stoich}} \): stoichiometric oxygen consumption rate (g/s)
- \( \dot{m}_{\text{ent},H_\text{f}} \): air entrainment rate below the mean flame height (g/s)
- \( \Delta H_f \): real combustion heat (kJ/g)
- \( \Delta H_{th} \): theoretical heat of complete combustion (kJ/g)
- \( \dot{Q} \): heat release rate (kW)

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\( \dot{Q}_c \) convective heat release rate (kW)
\( t_e \) fire duration (s)
\( T_{\infty} \) ambient temperature (K)
\( T_0 \) initial temperature (K)
\( \Delta T_{H_f} \) excess temperature at the flame tip (K)
\( V \) volume of the compartment (m\(^3\))

**Greek symbols**
\( \chi \) combustion efficiency
\( \phi \) equivalence ratio
\( \phi_p \) plume equivalence ratio
\( \Psi_o \) stoichiometric oxygen demand (g/g)
\( \lambda \) heat loss fraction

1. Introduction

The heat release rate is widely adopted to quantify the fire hazard. In compartment fires, it is largely dependent on the conditions of the openings. In typical building fires with vertical opening, the heat release rates can be predicted using the opening factors [1]. However, in compartments in which the only opening locates at the ceiling, like ships and basements, there are no similar factors capable of describing the ventilation conditions for such circumstances. Fire heat release rates are thus difficult to estimate. In addition, complex interactions between the bi-directional vent flows and the inside environment make the burning unsteady. In this way, it is important to find an effective method to predict the heat release rates in the ceiling vented compartment fires for the purpose of better understanding the fire characteristics.

In fire research, the heat release rates are calculated using the fuel mass loss rates combined with the combustion efficiencies. Thus, combustion efficiency defined as the degree of combustion completeness turns to be the key sources of inaccuracies. The dominant factors for the combustion efficiencies are the fuel type [2] and pool size [3, 4] for free-burning condition whereas the ventilation conditions for enclosure fires. Oxygen concentration was thought to be another major factor in enclosure fires. However, Morehart [5] varied the oxygen concentrations in his experiments with the ventilation condition carefully controlled, and found that combustion efficiency rarely changed until the fire extinguished indicating that they were independent. Similar conclusions were observed by Santo and Delichatsios [6].

The concept of Equivalence Ratio (ER) has been utilized to express the overall ventilation conditions for a control volume. The ER is also an indicator of two distinct burning regimes, ER < 1 for the over-ventilated condition and ER > 1 for under-ventilated condition [5, 7]. Combustion efficiency, the production rates of CO, CO\(_2\) and soot and the consumption rate of O\(_2\) were found to have relations with the ER. Tewarson [8, 9] summarized the measurements for various types of fuels, and proposed empirical correlations for these parameters. Pitts [10] reviewed the application of ER in both hood experiments and compartment fires and confirmed that this is a promising way.

Because of the complex interaction between the fire plume and the environment, a unique definition does not exist. When the control volume is referred to a fire compartment, the Global Equivalence Ratio (GER) is calculated using the instantaneous fuel mass loss rate and air flow rate into the compartment [10]. When applying to the fire plume, the Plume Equivalence Ratio (PER), means the ratio of fuel mass loss rate to the mass of oxygen entrained into the plume normalized by the stoichiometric fuel-to-oxygen ratio [10]. Gottuk [7] preferred to use the PER because it focuses on the flame rather than the compartment. If all of the air drawn into the compartment is entrained into the fire plume, the GER has the same value as the PER during steady burning conditions. However, for ceiling-vented compartment fires, vent flow is complicated and there may be no inflow air for relatively small opening, additionally, the inflow air would not necessarily enter the fire due to the buoyancy of hot smoke. Moreover, the GER is only valid in steady or quasi-steady state, while the PER can be used in transient conditions.

Although the concept of PER is very valuable in describing the ventilation conditions for the fire plumes, the determination of its value is quite complex. In hood experiments, it can be determined by controlling the air flow rates that supplied to the fire. In compartment fires with vertical ventilation, the PER can take the same value as the GER under steady or quasi-steady condition with the GER be estimated or measured using the air inflow rates at the openings. But, for transient burning, there is still no practical method to estimate its value.

To conclude, in ceiling vented compartments, fires inside are usually unsteady, so the transient combustion efficiencies and the resultant heat release rates are not easy to estimate. The present study focuses on the determination of plume...
equivalence ratio for compartment fires only with ceiling vent, and combustion efficiency is then derived from the plume equivalence ratio following existing theories and correlations. This would improve the accuracies in estimating the heat release rate from fuel mass loss rate.

2. Combustion efficiency based on the concept of plume equivalence ratio

2.1. Plume equivalence ratio

The equivalence ratio, \( \phi \), is defined as the actual fuel-to-oxygen mass ratio divided by the stoichiometric fuel-to-oxygen ratio according to ISO 17903:2010. When applying to the flame, a concept of PER can be written as Eq. (1) shows.

\[
\phi = \frac{\dot{m}_f / \dot{m}_{O_{2, act}}}{\dot{m}_f / \dot{m}_{O_{2, stoich}}} = \frac{\dot{m}_f}{\dot{m}_{O_{2, act}}} \times \Psi_o
\]

where \( \Psi_o \) is the oxygen-to-fuel ratio for stoichiometric combustion, for heptane, it equals 3.52. Because of the transient nature of ceiling vented compartment fires, a real-time formation should be used. \( \dot{m}_{O_{2, act}} \) is the oxygen consumption rate that reacts in the flame. With \( \dot{m}_f \) directly taken from experimental measurements, \( \dot{m}_{O_{2, act}} \) is the only parameter that required when calculating \( \phi \) in Eq. (1). It should be noted that the present study focuses on the flame instead of the whole fire plume, so only entrainment beneath the mean flame height is considered. The correlation for the entrainment rates were given in Eq. (2) according to Heskestad [11].

\[
\dot{m}_{ent,t_{H_f}} = 0.878 \left( \frac{T_{H_f}}{T_a} \right)^{0.56} \left( \frac{T_a}{\Delta T_{H_f}} \right) + 0.647 \frac{\dot{Q}}{c_p T_a}
\]

where \( \dot{Q} \) is the convective heat release rate, taking as 0.7\( \dot{Q} \) for the near-field fire plume [12], \( \Delta T_{H_f} \) is about 500 K according to Heskestad [13]. The coefficients in Eq. (2) were drawn from numerous experiments carried out in uniform and quiescent atmosphere. In enclosure fires, the entrainment rates may be different due to the complex interaction between the plume and the stratified environment, as well as the potential vent flows and wall flows. Researches by Çetegen [14] and Zukoski [15] showed that any kind of disturbances would increase the entrainment rate by 20~50%. However, Quintrie [16] found the disturbances had limited influence on the entrainment rate unless obvious flame tilt occurred.

In Eq. (2), \( T_a \) is the ambient temperature in the compartment taking as the average temperature of smoke because one-zone state was proved to be quickly reached in under-ventilated and ceiling vented compartments [1, 17, 18]. The gas properties throughout the compartment trend to be uniformly distributed. So gas temperature in the compartment can be derived from energy conservation [19, 20].

\[
T_a = T_0 + \frac{\int_{0}^{\tau} \dot{Q}(1 - \lambda) d\tau}{\rho_{atm} V_c c_p}
\]

The heat loss fraction \( \lambda \) ranging from 0.6 to 0.9, has great impacts on the prediction. Cooper [19] suggested 0.8 should be reasonable for compartment fires. Changing \( \lambda \) from 0.8 to 0.9 would decrease the temperature rise by one time and subsequently increase the plume buoyancy by large.

For relatively complete combustion, extra air is required other than the stoichiometric amount. A parameter, \( n \), referring to the ratio of entrained air up to the flame tip and the stoichiometric air requirement, was introduced. Ma and Quintiere [21] examined numerous measurements by former researches and found \( n \) varied between 5 and 15. Quintiere and Grove [12] also got \( n = 9.6 \) in their analysis.

\[
\dot{m}_{O_{2, act}} = \frac{\dot{m}_{ent,t_{H_f}}}{n} \cdot Y_{O_2}
\]
In this way, the reacted oxygen $\dot{m}_{\text{o}_2,\text{act}}$ in Eq. (1) can be calculated using Eq. (2) - (4).

2.2. Combustion efficiency and heat release rate

Combustion efficiency $\chi_c$ is defined as the ratio of real heat released in the combustion to the theoretical heat of complete combustion, as Eq. (5) shows.

$$\chi_c = \frac{\Delta H_c}{\Delta H_{th}}$$

where $\Delta H_{th}$ is the theoretical heat of complete combustion and $\Delta H_c$ is the real combustion heat. The combustion efficiency $\chi_c$ correlates the equivalence ratios $\phi$ well. Eq. (6) represents this correlation in terms of the plume equivalence ratio $\phi_p$ for non-halogenated polymers based on a large series of fire experiments in ASTM and reduced scale compartments [8, 22] whereas $\chi_w$ is the combustion efficiency for this pool fire in well-ventilated condition.

$$\chi_c = \chi_w \left[ 1 - \frac{0.97}{\exp \left( \phi_p / 2.15 \right)} \right]^{1.2}$$

With the transient $\dot{m}_f$ and $\chi_c$, the instantaneous heat release rate can be calculated using Eq. (7).

$$\dot{Q} = \chi_c \dot{m}_f \Delta H_{th}$$

3. Experimental

3.1. Description

Experiments were carried out in a cabin with dimensions of 1.00 m (Length) × 1.00 m (Width) × 0.75 m (Height). Heptane pools with diameter ($D$) of 0.10 m and 0.20 m were placed on an electronic balance in the centre of the floor. The initial depth of the fuel was 0.04 m in each test. The cabin was constructed mainly with 0.005 m thick steel boards, and one sidewall was built of glass for the purpose of observing the fire behaviour inside. In each test, a square vent was set on the corner of the ceiling and the opening size ($L$) varied from 0.05 m to 0.30 m.

The time evolutions of heptane mass were recorded by the electronic balance. There was a gas sampling point right next to the fuel pan rim in order to measure the oxygen concentration near the fire base. The arrangement of the experiments was demonstrated in Fig. 1. Detailed descriptions of the experimental setups can be found in Ref [23].

![Experimental apparatus](image-url)
3.2. Experimental results

Changing the sizes of the pool and vent, diverse burning behaviours were observed in the experiments. Two regimes were observed in the experiments according to the cause for flame extinction as Utiskul [17, 24] suggested. In test with $D = 0.10$ m and $L = 0.30$ m, the fire burned steadily until the fuel was exhausted. For other tests, the flames extinguished because of the oxygen depletion. The fire behaviours were ascribed to the complex horizontal vent flows. According to Chen [23], when $L = 0.05$ m, the vent flows were unidirectional and outwards. When $L = 0.10$ m, bi-directional flows occurred, but the air inflows were very weak. Increasing the opening size to 0.20 m and 0.30 m, the inflows were further reinforced.

The mass loss rate of the heptane, is a significant variable, and is indicative of the coupling between thermal and oxygen depletion effects. Fig. 2 presented the transient $\dot{m}_f$ in each test. The mass loss rate profiles were very similar for different opening sizes except for the case with $D = 0.10$ m and $L = 0.30$ m. In tests with $D = 0.10$ m, $\dot{m}_f$ was reduced about 25% from its free value $\dot{m}_{f,\infty}$ for the most part; in tests with $D = 0.20$ m, $\dot{m}_f$ was almost half of its free value. The larger gap between $\dot{m}_f$ and $\dot{m}_{f,\infty}$ indicated a worse ventilation condition with a larger pool size. While for the test with $D = 0.10$ m and $L = 0.30$ m, a second growth was observed and $\dot{m}_f$ exceeded $\dot{m}_{f,\infty}$ showing in Fig. 2(a). Chen [25] explained this phenomenon as the results of fuel boiling.

![Fig. 2. Histories of fuel mass loss rates for (a) $D = 0.10$ m and (b) $D = 0.20$ m.](image)

![Fig. 3. Histories of oxygen concentrations for (a) $D = 0.10$ m and (b) $D = 0.20$ m.](image)

Figure 3 gave the time evolutions of oxygen concentration taken from the sampling point shown in Fig. 1. Oxygen is decided by both the fire entrainment and vent flow. The oxygen concentrations near the fuel pan, measured just before extinction, varied in the range of 13-17% in most cases, apparently lower than the results with vertical openings in the bottom [17]. For $D = 0.10$ m and 0.20 m, increasing the opening size from 0.05 m to 0.10 m would rarely increase the
oxygen concentrations because there were no incoming airflows when \( L = 0.05 \) m and for \( L = 0.10 \) m, the inflows were too weak to affect the burning environments. Further expanding the ceiling vent would raise the oxygen concentrations obviously because the inflows grew stronger as reported by Chen [23]. However, it should also be noted that increasing the opening size would introduce apparent disturbances in the burning environments. With \( L = 0.30 \) m, the oxygen concentrations taken at the sampling point began to decrease earlier than those with small opening sizes because of the entrainment by the significant air inflow.

4. Results and Discussion

4.1. Plume equivalence ratio

The calculation of the PER was going with the assumption of uniform distributions in the vertical direction. Thus, the oxygen concentrations measured at the sampling point were used as the average oxygen concentration below the mean flame height and the average temperatures were taken as the ambient temperatures. Initially, burning was not affected by the compartment, indicating well ventilation for the flame. So, \( \chi_e \) equalled to 0.92 as the value of heptane pool fires in free-burning condition [26]. The calculation process is described as below. At a particular moment, heat release rate \( \dot{Q} \) is determined using \( \dot{m}_f \) and \( \chi_e \) from the former time step. \( T_{\infty} \) and \( m_{O_2,act} \) are then calculated using Eq. (2) ~ (4) together with \( Y_{O_2} \) at this time step. In this way, the time evolution of PER can be obtained as plotted in Fig. 4.

Fig. 4. Transient plume equivalence ratios for (a) \( D = 0.10 \) m and (b) \( D = 0.20 \) m.

The PER in each test was below 1.0 in the beginning which meant that the flame was over-ventilated. Along with the burning, the PER inclined gradually and accelerated rapidly for tests with \( L = 0.05 \) m and 0.10 m in the later stage. This meant that the ventilation condition of the flame grew worse. Not long after ignition, the PER exceeded 1.0 and the flames turned to under-ventilated. For fires with opening sizes of 0.05 m and 0.10 m, the PER grew to relatively high values and little differences were observed between each profile with the same pool diameter. This phenomenon can be expected because the fuel mass loss rates and oxygen concentrations appeared to be very similar as shown in Figs. 2 and 3, and the calculation of the PER depended largely upon \( \dot{m}_f \) and \( X_{O_2} \). Till the extinction, the PER reached nearly 4.8 and 8.0 for \( D = 0.10 \) m and 0.20 m respectively. The PERs for \( D = 0.20 \) m were much higher than that for \( D = 0.10 \) m because the large fire was more restricted by the compartment. When \( L = 0.20 \) m and 0.30 m, the PER dropped to almost half of the values with \( L = 0.05 \) m and 0.10 m, suggesting the ventilation conditions were greatly enhanced. Comparing Fig. 4 (a) and (b), with the same opening size, the PER for \( D = 0.20 \) m was much higher than that for \( D = 0.10 \) m indicating a worse ventilation condition for the flame. In test with \( D = 0.20 \) m and \( L = 0.20 \) m, the PER rose to 4.0 and it seemed to reach a quasi-steady state when approaching the extinction. This trend was much clearer in case of \( L = 0.30 \) m. After about 70 s, the PER kept almost unchanged, or even slightly declined.

In the test with \( D = 0.10 \) m and \( L = 0.30 \) m, fire extinguished due to burning out of the fuel. The PER inclined almost linearly until the extinguishment. For \( X_{O_2} \) rarely increased since \( t = 400 \) s, the further growing of the PER was resulted from the increasing \( \dot{m}_f \) due to fuel boiling.
4.2. Combustion efficiency and heat release rate

With the predicted PER in Fig. 4, the combustion efficiencies $\chi_c$ and the resultant heat release rates $\dot{Q}$ can be then solved using Eq. (6) and (7), as given in Fig. 5. The time was normalized using the extinction time in each test. In the present study, $\chi_c$ equalled to 0.92 for $\phi_p < 1$, and began to decline since $\phi_p > 1$. It is obvious that $\chi_c$ changed in correspondence with the increasing PER as Eq. (7) demonstrated. Its decreasing rate also accelerated owing to the exponential dependence upon $\phi_p$. For the tests with $D = 0.10$ m and $L = 0.05$ m and 0.10 m, the combustion efficiencies decreased to as low as 0.30 when approaching the extinction, suggesting the burning became quite incomplete. Increasing $L$ to 0.20 m, the combustion efficiencies were evidently raised with value of 0.56 at the extinction. However, when $L$ grew to 0.30 m, the flame extinguished due to fuel burning out and the combustion efficiencies changed differently. $\chi_c$ kept lower than that with $L = 0.05$ m, 0.10 m and 0.20 m except for a short period before extinction and the combustion efficiency was about 0.45 at the extinction, lower than that with $L = 0.20$ m. Also, the flame turned to under-ventilated much earlier because of the fierce disturbances introduced by the air inflows.

For tests with $D = 0.20$ m, the combustion efficiencies were lower than those with $D = 0.10$ m for the same opening size. With the increase of the opening size, the combustion efficiencies increased. For $L = 0.05$ m, the combustion efficiency was only 0.20 at the extinction, while increased to 0.65 for $L = 0.30$ m. Like the condition with $D = 0.10$ m, the combustion efficiencies began to decrease earlier when $L = 0.30$ m. Such phenomena were probably because for tests with $L = 0.30$ m, the air inflows were relatively strong as reported by Chen [23] and produced disturbances in the bottom part of the compartment which can be supported by the time evolutions of oxygen concentrations in Fig. 3.

![Fig. 5. Combustion efficiencies and heat release rates versus dimensionless time for (a) $D = 0.10$ m and (b) $D = 0.20$ m.](image-url)

The heat release rates $\dot{Q}$ were also presented in Fig. 5. It can be seen that for each pool size, $\dot{Q}$ rarely grew with the increment of the opening size although $\chi_c$ varied a lot, especially approaching to the extinction. The heat release rates in test with $D = 0.10$ m and $L = 0.30$ m were slightly higher in the late stage because that fuel was boiled and the resultant fuel mass loss rates continued to grow since $t = 400$ s. In other tests with $D = 0.10$ m, the burnings were steady although the heat release rates declined slowly with the burning processes. Similar tendency was found in tests with $D = 0.20$ m, the heat release rates appeared to be unaffected by the opening sizes although strong fluctuations can be found. Along with the burning, the heat release rates increased initially with the peak values of about 15 kW for each test and then decreased almost linearly till the extinction.

5. Conclusions

This paper has discussed the issue of combustion efficiencies and heat release rates for pool fires in compartment with only ceiling vent. With the fuel mass loss rates and oxygen concentrations near the fire base taken from experimental data, the combustion efficiencies and subsequently heat release rates were predicted using the correlation between equivalence ratios and combustion efficiencies. Typical fire plume theories were used to estimate the plume equivalence ratios for the flame. The major conclusions are summarized as below:

The impacts of ceiling vent sizes on the fuel mass loss rate and oxygen concentration at the fire base were studied. The
fuel mass loss rates were not affected and the oxygen concentration at the bottom didn’t necessarily increase with the increasing opening size. However, the oxygen concentration at the bottom began to decrease earlier with larger opening size.

Plume Equivalence Ratios for the flame in the ceiling vented compartment were calculated using the semi-empirical fire plume theories. For each test, its value exceeded 1.0 indicating the flame became under-ventilated not long after the ignition and it kept growing suggesting the ventilation condition grew more and more serious with the burning procedure.

The impacts of the opening sizes on the plume equivalence ratios were investigated. The PER mainly declined with the increasing opening sizes. While for conditions with very small opening, the PER rarely changed because of the air inflows couldn’t affect the bottom part of the compartment.

The impacts of opening size on the combustion efficiencies and consequently the heat release rates were studied. The combustion efficiencies are in accordance with the PER. In general, the combustion efficiencies decreased with the burning procedures since the PER exceeded 1.0. With the increment of opening size, their values were evidently raised except for conditions with very small openings; however, the heat release rates appeared to be unaffected.

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