Experimental study of the influence of varying ceiling height on the heat release rate of a pool fire

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Abstract. To investigate the influence of ceiling height on the combustion process of a pool fire whose flame impinges the ceiling, a sequence of pool fires with varying ceiling heights was performed using a scaled-down cone calorimeter. N-heptane and jet-A were employed as fuels to conducted the tests. Experimental findings reveal that with the decreasing ceiling height, the maximum and average heat release rates will initially increase due to the enhanced heat feedback, and then decrease as a result of the restriction of air entrainment caused by the extremely small ceiling height. In addition, the dimensionless ceiling height is found to have a linear relationship with the logarithm value of the dimensionless averaged heat release rate for the two given fuels with the similar slope of -2/3.

1. Introduction
When a flame impinges on an unconfined ceiling, the unburnt gas fuels will spread out radically and entrain air for combustion, and a circular flame will be established beneath the ceiling. This phenomenon has received comprehensive scientific attentions because the fire development under the ceiling is often the trigger for the occurrence of the flashover for a compartment fire [1-2]. The parameters concerned in previous studies mainly include the flame extension length and maximum excess temperature distribution beneath the ceiling, which are essential aspects in characterizing the danger of the flame impingement. You and Faeth [3] initially proposed the correlation for the flame extension length along the ceiling based on the experimental data in the range of \((H_f-H)/D=0-5.8\), expressed as

\[ r_f/D = 0.502 \left[ (H_f-H)/D \right]^{0.877} \]  

(1)

where \(r_f\) is the flame extension length, \(D\) is the fuel dimension, \(H_f\) and \(H\) are the flame height and ceiling height, respectively. This empirical equation has been validated by Zhang et al. [4], and extend its application to a wider range of 0-14.5. With respect to the maximum excess temperature distribution beneath an unconfined ceiling, Heskestad and Delichatsios [5] indicated that the non-dimensional excess temperature \(\Delta T^* = (\Delta T/T_{\infty})/Q^{2/3}\) can be applied to partition the temperature profile of the turbulent impinging flame into two parts. For \(r/H \leq 0.2\), \(\Delta T^*\) is independent of the horizontal distance \(r\) with constant value of 6.3, while for \(0.2 < r/H < 4.0\), \(\Delta T^*\) can be correlated with \(r/H\) as

\[ \Delta T^* = (0.188 + 0.313r/H)^{4/3} \]  

(2)

where \(Q^*\) is the non-dimensional heat release rate expressed as,
Here, $Q$ is the heat release rate (HRR) of fire source, $T_a$ and $\rho_a$ are the ambient temperature and density of air, $c_p$ is the specific heat of air, $g$ is the gravitational acceleration.

These classical correlations have been verified by many previous researchers [4,6-7]. However, these equations were mostly summarized from the experiments with constant HRR, where relatively steady flames were presented. Scarce research focused on the influence of presence of a ceiling on the combustion process of a fire with buoyancy-controlled turbulent jet diffusion flame, such as a pool fire. Karlsson and Quintiere [1] indicated that the boundaries including ceilings and walls could significantly enhance the burning intensity as they were close enough to a fire. Other studies concerning the effect of presence of ceilings or sidewalls on the combustion behaviors of pool fires also demonstrated the enhancement effects [8-9].

To quantitatively understand the effect of varying ceiling height on the HRRs of pool fires, a sequence of pool fires under a ceiling with adjustable ceiling heights was performed in a cone calorimeter in current study. The HRRs for all the tests were measured and analyzed carefully. The results may be helpful for evaluating the risks of fire scenarios where the flame impingement occurs.

### 2. Experiments

#### 2.1. Test platform

To cater for the current need, a scaled-down calorimeter with dimensions of 40% of that in ISO 9705 was built, as shown in Figure 1. The dimensions of the combustion chamber were $1.2 \times 1.2 \times 1.2$ m, and a gap of 0.15 m was reserved to guarantee the supplement of fresh air. A volumetric air flow rate of 0.18 m$^3$/s was sustained to remove the combustion products by the fan, which ensured the over-ventilation environment for all the tests. The exhaust gases including oxygen, carbon monoxide and carbon dioxide were continuously recorded by the Servomex 4100 analyzer, which was eventually calculated in the PC to give the real-time HRR. The specified introduction to this platform can be found in [10]. Before conducting all the experiments, a standard gas fire originating from the propane fuel with purity above 99.9% was employed to calibrate the test platform.

#### 2.2. Experimental setup and configurations

A $60 \times 60$ cm square mica smooth plate with excellent heat resistance performance was supported by the four iron stands at a distance of 70 cm away from the floor to serve as the ceiling. The circular steel pan with diameter of 14 cm and depth of 2 cm was placed on the lifting table with a $20 \times 20$ cm square insulation board between them to shield from the elevated temperature. These devices were positioned on an electronic scale with resolution of 0.1 g to measure the mass loss of the fuel during the test. The ceiling height, defined as the vertical distance between pan bottom and ceiling, was designed as 5, 15, 25, 35 cm for each fuel. Two kinds of fuels, i.e. n-heptane and jet-A, were employed to conduct the tests. The tests without the ceiling were also involved in current study to investigate the effect of the ceiling. A summary of experimental configurations is shown in Table 1. The ambient temperature and relative humidity were recorded for the tests, which were $25 \pm 3$ °C and $45 \pm 5\%$, respectively. The typical cases were repeated for three times and the results exhibited good repeatability with discrepancy less than 5%.

| Fuel     | Ceiling height (cm)                      |
|----------|------------------------------------------|
| N-heptane| 35,25,15,5, case without the ceiling     |
| Jet-A    | 35,25,15,5, case without the ceiling     |
3. Results and discussion

3.1. General results

The HRRs for all the configurations are averaged among the repeated tests, and the ultimate results together with the cases without the ceiling are plotted in Figure 2. It can be seen that the HRRs for cases with varying ceiling height exhibit quite different combustion process. The ceiling board significantly affects the buoyancy-driven surrounding flow and then the burning behaviours. For the cases without the ceiling, the combustion process shows the typical characteristics of the thin-layer pool fire, where four stages can be clearly identified, i.e. pre-burning stage, quasi-steady burning stage, boiling stage and decay stage [11-12]. The cases with the ceiling height of 35 cm also experience the similar burning process because the flame height is comparable to or slightly higher than the ceiling height, and thus the burning process will not be influenced by the ceiling markedly. Meanwhile, the presence of the ceiling definitely imposes restriction on the entrainment in the test, leading to a prolonged burning duration.

With the decreasing ceiling height, the quasi-steady burning stage for the thin-layer pool fire gradually disappears, and the HRRs sharply increase from the beginning of the combustion, as observed for the curves of cases with ceiling height of 25 and 15 cm. As a result of the flame extension beneath the
ceiling, the heated ceiling will become hotter and thus generate a stronger radiation to the fuel [9]. Consequently, the boiling phenomenon occurs soon after the ignition. Previous researchers [13] indicated that a lower value of latent heat of gasification should be expected when the fuel boiled. Thus, the continuously increasing HRRs can be observed. It is worthwhile to note that the maximum HRR for the cases with ceiling height of 15 cm appear earlier than that of 25 cm, implying a higher fire risk. However, as the ceiling height decreases to 5 cm, the burning intensity seems to be weakened, and no sharp increase can be seen for the two fuels. This may be attributed to the effect of ceiling on the air entrainment when the fire source is extremely close to it.

3.2. Analysis on the results
The averaged HRR for a fixed configuration is defined as the average value over its whole combustion duration, expressed as

$$\bar{\phi} = \left( \int_{t}^{\phi} dt \right) / t$$  \hspace{1cm} (4)

The mass losses for all the configurations can be obtained by the electronic scale, and similarly, the averaged mass loss rate (MLR) can be calculated. The maximum and averaged HRRs of each test together with their corresponding MLRs are listed in Table 2, where AVE and MAX represent the average and maximum values, respectively. The combustion efficiencies $\eta$ are also calculated by the following equation and listed in the table.

$$\eta = Q / (m \cdot \Delta H_c)$$  \hspace{1cm} (5)

where $\Delta H_c$ is the combustion heat of the fuel. Here, $\Delta H_c$=48 kJ/g for n-heptane [14], and $\Delta H_c$=43.5 kJ/g for Jet-A [15]. From the Table 2, the quantitative results can well coincide with the discussion in Section 3.1. In addition, the combustion efficiencies for maximum and average results of different configurations vary slightly, which also testifies the well-ventilation experimental condition in current study. The combustion efficiencies of n-heptane are always higher than that of jet-A, which may be explained by the different sooting levels of the two fuel. N-heptane is assigned to be moderately-sooting fuel, while jet-A is a highly-sooting fuel with lower combustion efficiency [16]. Based on the experimental findings, the ceiling height will undoubtedly impact the average HRR of a pool fire. To well understand the relationship between them, two dimensionless parameters are employed, i.e. dimensionless ceiling height $H/D$ and a different dimensionless average HRR $\bar{Q}_{\text{AVG}}$ concerning the effect of ceiling height and pool dimension [17].

| Fuel  | Ceiling height (cm) | MAX-HRR (kW) | MAX-MLR (g/s) | $\eta$ | AVE-HRR (kW) | AVE-MLR (g/s) | $\eta$ |
|-------|---------------------|-------------|-------------|-------|-------------|-------------|-------|
| N-heptane | No ceiling | 16.88 | 0.45 | 0.78 | 9.83 | 0.24 | 0.83 |
|       | 35 | 19.16 | 0.47 | 0.84 | 9.14 | 0.24 | 0.81 |
|       | 25 | 37.58 | 0.86 | 0.91 | 14.01 | 0.33 | 0.88 |
|       | 15 | 35.23 | 0.82 | 0.89 | 20.37 | 0.45 | 0.92 |
|       | 5 | 20.87 | 0.53 | 0.82 | 12.9 | 0.32 | 0.85 |
| Jet-A | No ceiling | 15.44 | 0.47 | 0.76 | 8.16 | 0.26 | 0.72 |
|       | 35 | 15.79 | 0.44 | 0.82 | 6.84 | 0.21 | 0.75 |
|       | 25 | 24.39 | 0.70 | 0.80 | 8.73 | 0.28 | 0.72 |
|       | 15 | 31.84 | 0.86 | 0.85 | 12.88 | 0.46 | 0.66 |
|       | 5 | 14.26 | 0.47 | 0.70 | 8.02 | 0.27 | 0.68 |
Figure 3. The relationship between H/D and $Q_{DH}^*$. 

Figure 4. The relationship between H/D and ln($Q_{DH}^*$).

\[ Q_{DH}^* = \frac{\bar{Q}}{(\rho_c T_c C_p \sqrt{g})} \left( \frac{g}{\rho_c T_c C_p} \right)^{1/2} \]  

(6)

Figure 3 plots H/D versus $Q_{DH}^*$, where an exponential relationship can be observed. Furthermore, considering the correlation of H/D vs ln($Q_{DH}^*$), the relevance of them is presented in Figure 4. The linear fittings for the two fuels are successfully achieved with $R^2 = 0.995$ and $R^2 = 0.985$ for n-heptane and jet-A, respectively.

Moreover, as observed in Figure 4, the slopes for the two fuels are quite similar, i.e. -0.65 for n-heptane and -0.68 for jet-A, which are approximate to -2/3. Therefore, the relationship between H/D and $Q_{DH}^*$ can be summarized as

\[ H / D = \frac{2}{3} \ln(Q_{DH}^*) + C_1 \]  

(7)

This expression can be further rearranged as

\[ Q_{DH}^{\frac{2}{3}} \cdot \exp(H / D) = C_2 \]  

(8)

where $C_1$ and $C_2$ are the constants depending on the fuel, and $C_2$ equals to 6.0 and 4.6 for n-heptane and jet-A in current study, respectively. The data in this research are a little limited, and more experiments in such scale or larger scale with different pool dimensions and fuels are necessary to validate the equation (8) in future research.

4. Conclusions

The effect of ceiling height on the combustion behavior of a pool fire whose flame height is comparable or larger than the ceiling height was experimentally examined in current study by means of a scaled-down cone calorimeter. The HRR and corresponding MLR were quantitatively analyzed. The major results are summarized as follows:

1) The quasi-steady burning stage disappears with the reduced ceiling height, and instead, the HRR sharply increases from the beginning of the combustion, which may be attributed to the
enhanced heat feedback from the ceiling. As the ceiling height decreases to 5 cm, the HRR is mitigated due to the restriction of air entrainment.

2) The dimensionless ceiling height has a linear relationship with the logarithm value of the dimensionless averaged HRR for the two given fuels with the similar slope of \(-2/3\). The expression of 
$$Q_{\text{HRR}}^{2/3} \cdot \exp(H/D)$$
is found to equal to a constant for a given fuel.

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