

## BURNING RATE OF CONDUCTION-CONTROLLED ETHANOL POOL FIRES UNDER A CEILING

by

**Jin ZHOU, Jinfeng MAO\*, Zheli XING, Zhongkai DENG, and Yuliang HUANG**

College of Defense Engineering, PLA University of Science and Technology, Nanjing, China

Original scientific paper

<https://doi.org/10.2298/TSCI170310156Z>

*The burning characteristics of conduction-controlled pool fires under a ceiling have not been revealed in the past. In this paper, experiments on square ethanol pool fires with dimensions of 4, 6, and 8 cm under the ceiling of various heights were conducted to investigate the ceiling effect on the burning rate of conduction-controlled pool fires. Results show that when the ceiling close to the pool, the burning process exhibited an extra initial steady-stage before its development stage in the burning process. Moreover, a flame-wrapping phenomenon was observed in the later period of this burning process. The pool rim wall temperature and mass burning rate exhibited an increase with the decreasing ceiling height. The rim wall temperature increase was pronounced in relative larger pool fires. However, the burning rate enhancement was prominent in relative smaller ones. The burning rate enhancement was found to be mainly attributed to the increase in pool rim wall temperature. A global factor was developed to correlate the mass burning increment with rim wall temperature increase and pool size, which was confirmed by experimental data.*

Key words: conduction-controlled, hydrocarbon pool fire, ceiling, burning rate, heat transfer

### Introduction

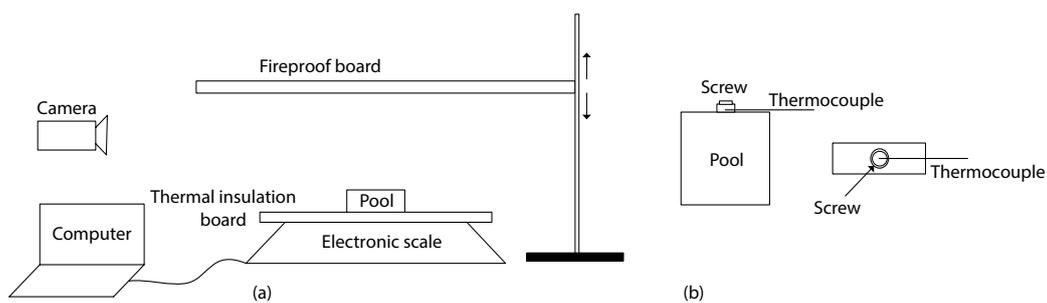
When fire impinges on the ceiling, the flame and burning rate will be dramatically changed. Numerous studies have been conducted on the flame extension length under the ceiling, and several theoretical models and empirical correlations were proposed [1-8]. You and Faeth [1] presented a correlation for flame length under a ceiling in terms of free flame height without the ceiling. Ding and Quintiere [5] provided an analytic study using an integral model for turbulent flame radial lengths under a ceiling, which in good agreement with the experimental data from previous studies. Gao *et al.* [7] studied the flame flush with the sidewall under a ceiling, and obtained correlations for the flame length under the ceiling in both longitudinal and transverse direction.

However, the flames in the aforementioned research are produced by a fixed heat release rate (HRR) fire, which is different from real fire. In a real fire, the mass burning rate (and HRR) will be affected by the ceiling. Ji *et al.* [9, 10] performed experimental study on burning rate of sidewall fires with varying ceiling height in a corridor-like structure, using methanol pool fires with side length ranging from 0.1-0.3 m and ceiling height ranging from 0.1-0.45 m. It is found that the burning rate increase with the effective ceiling height decrease. Liu *et al.* [11]

\* Corresponding author, e-mail: maojinfeng\_lgdx@sina.com

investigate the combustion behaviors of n-heptane pool fires with pan diameters of 0.12 m and 0.14 m beneath a ceiling in the range of 0.06-0.3 m. The results showed that with the ceiling height decreases, the burning rate initially increased and then decreased, exhibiting a parabolic variation tendency.

Nevertheless, the works for the burning rate of pool fires under a ceiling were limited in convective-controlled (pool size is between 10 cm and 20 cm) and radiation pool fires (pool size is beyond 20 cm). Previous studies [12-14] proposed that the burning behavior of a pool fire can be divided into three different regimes according to the predominant heat feedback to the fuel: conduction-controlled which heat supply from pool rim dominated when pool size less than 10 cm, convection-controlled which convective heat from flame is predominated when pool size between 10 cm and 20 cm, when pool size is beyond 20 cm, and radiation-controlled which thermal radiation feedback from the flame dominated. The burning behavior of a conduction-controlled pool fire under a ceiling has not been revealed. Thus the main objective of this study was to investigate the effect of the ceiling above the pool on the burning rate of conduction-controlled pool fires. The controlled parameters in this study are the pool size and ceiling height. The measured parameters include the mass burning rate and the pool rim wall temperature.



**Figure 1. Schematic illustration of the experimental set-up; (a) experimental facility, (b) temperature measurement of pool wall**

## Experiments

Figure 1(a) shows the schematic illustration of the experimental apparatus. Since this study focus the conduction-controlled pool fires, three square pools with dimensions of 4 cm, 6 cm, and 8 cm were used. The pools were made by 1 mm thick steel plate with inner depth of 1.5 cm. Ethanol was used as fuel and the initial thickness of the fuel for each case was 1 cm. The pool was placed on an electronic balance, with a range of 0-2100 g, sampling intervals of 1 second, and resolution of 0.01 g, to measure the mass loss rate. The uncertain of the measured mass burning rate is estimated to be less than 5%. A thermal insulation board was placed between pool and the electronic scale to prevent the damage from pool fire. Prior to the test, the thermal insulation board was placed in the desiccator for a minimum of 6 hours to prevent the error due to the evaporation of humidity in the insulation board. A 50 cm × 50 cm fireproof board as a ceiling was installed above the pool, and its height could be adjusted. The ceiling heights,  $H_c$ , were set as 2, 4, 6, 8, and 12 cm, respectively. The range of the ceiling height in this study was based on the flame characteristics under the ceiling. The 2 cm ceiling height was chosen for it is low enough to examine the burning behavior when the flame beneath the ceiling covers the partly rim wall of pool fires which is observed in the experiment. The maximum ceiling height was set at 12 cm when flame tip can just touch the ceiling to make a ceiling jet. A camera with 20 frames

per second was placed in front of the pool fire to record the flame image. The K-type thermocouple with bead diameter of 1 mm, accuracy less than 1.5 °C and respond time less than 1 second was used to measure the temperature of the pool rim wall. The thermocouple was screwed to the outer surface of pool rim wall, as shown in fig. 1(b). A summary of cases tested is shown in tab. 1. The experiment was conducted under the ambience temperature of  $30 \pm 2$  °C and humidity of  $30 \pm 10\%$ . The typical cases were repeated for three times and exhibited good repeatability.

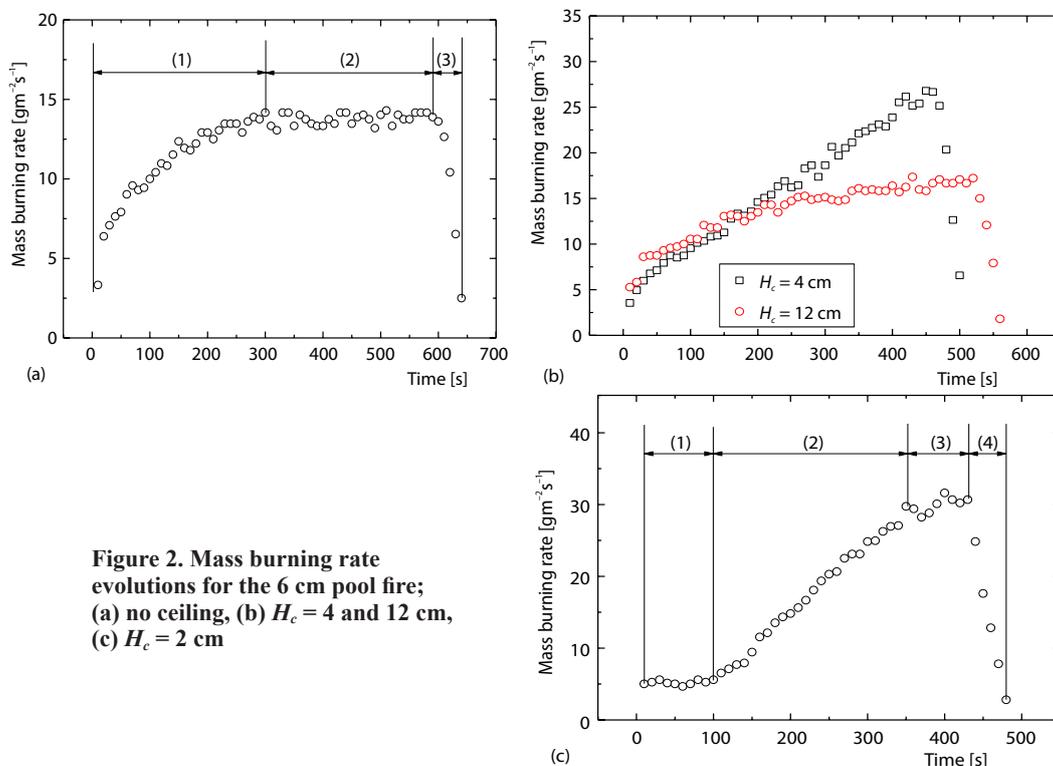
**Table 1. Summary of the cases tested**

Side length [cm]	Ceiling height, $H_c$ [cm]
4	2, 4, 6, 8, 12
6	2, 4, 6, 8, 12
8	2, 4, 6, 8, 12

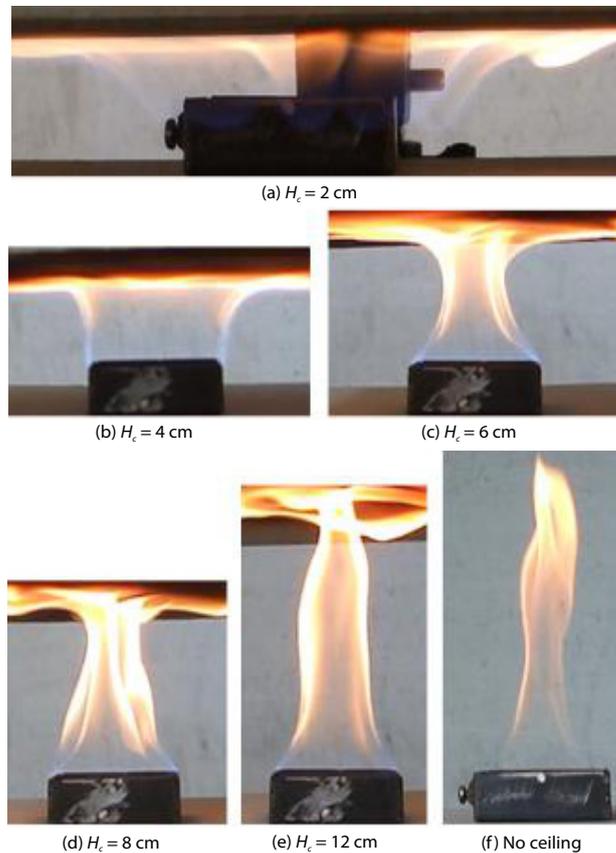
**Results and discussion**

*General observation*

Figure 2 presents the mass burning rate histories derived from the measured data by the electronic balance for the 6 cm square pool fire. Clearly, for the pool fire without ceiling the burning process can be divided three stages, *i. e.*, an initial development stage, a steady burning stage, and a decay stage, fig. 2(a), as reported by Quintiere [15]. For the pool fires under the ceiling when the ceiling height is more than 4 cm, fig. 2(b), the burning processes experience the three stages as well. Moreover, compared to the pool fire without ceiling, the pool fires under the ceiling reach their steady burning stage later, which is pronounced as the ceiling height decreases. However, when ceiling height decreases to 2 cm, fig. 2(c), the burning process can be divided into four stages: (1) an initial steady-stage, (2) a development stage, (3) a developed steady



**Figure 2. Mass burning rate evolutions for the 6 cm pool fire; (a) no ceiling, (b)  $H_c = 4$  and 12 cm, (c)  $H_c = 2$  cm**



**Figure 3. Flame images with different ceiling heights for 6 cm square fire**

Figure 3 shows the detailed flame structures for the 6 cm pool fires at their developed steady burning stages. It is observed that the outer boundary of the flame along the rim are pulled outward for the pool fires under the ceiling compared to that without ceiling. This phenomenon is more obvious when the ceiling is nearer to the pool. This outward pulling of flame results in more efficient heating the rim wall, which will be illustrated explicitly in next section. Moreover, for the case when ceiling is close to the pool (ceiling height of 2 cm), the flame covers upper part of the rim walls, fig. 3(a) which pronounced the flame heating the pool rim wall.

#### *Burning rate and pool wall temperature*

Figure 4 presents the variation of the pool rim wall temperature with the ceiling height for the pools with three sizes. It is noted that the pool rim wall temperature and the mass burning rate presented in this section and the remaining part of this paper are the values at the developed steady-stage. As can be seen from fig. 4, the pool rim wall temperature increases with the decreasing ceiling height and the trend is more pronounced in the larger size pool fire. This is attributed to the fact that larger pool fire produced larger flame, which resulted in more efficient heating of the pool rim wall.

burning stage, and (4) a decay stage. An extra initial steady-stage immediately after ignition was observed before the burning rate start to grow. This is caused by the change in the heat transfer to the fuel. The burning rate of liquid fuel is controlled by the heat transfer to the fuel, which is composed of the heat transfer from the flame to the exposed fuel surface and the conduction from the rim walls of the pool to the fuel. In its early period of burning process, the heat transfer to the fuel is dominated by the heat transfer from the flame to the exposed fuel, which is the sum of the convective transfer and radiation heat transfer, for the temperature of rim wall was low. When the ceiling was close to the pool (referring to the ceiling height of 2 cm in this study), the radiation heat transfer become significantly less because of the lower flame height which determined the mean beam length of the flame. The less heat transfer cannot warm the fuel below the vaporizing layer. Therefore, the mass burning rate maintained a constant low value.

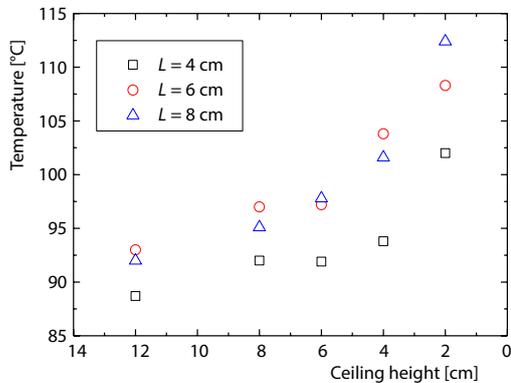


Figure 4. Variation of rim wall temperature with ceiling height

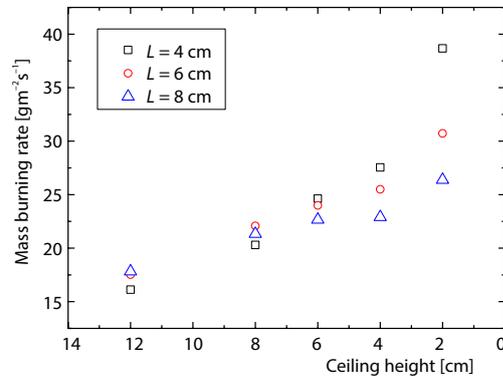


Figure 5. Variation of mass burning rate with ceiling height

Figure 5 presents the variation of mass burning rates with the ceiling height. The variation of mass burning rate with the ceiling height shows a similar trend to the pool rim wall temperature, which exhibits an increase with the decrease of ceiling height. The mass burning rate is affected by the ceiling in three ways. Firstly, when the pool fire burning occurred under the ceiling, the radiation heat transfer reduced due to the reduced mean beam length of the flame. Secondly, an extreme radiation heat transfer from the ceiling heated by the flame to the fuel was introduced. Thirdly, the conduction heat transfer from the rim wall to the fuel increased due to the increase in the rim wall temperature. The convective heat transfer from the flame to the exposed fuel surface is supposed to remain unchanged for it is still natural horizontal convection. The mass burning rate was enhanced. Therefore, the sum of the heat transfer to the fuel should be enhanced. Figure 5 also demonstrates that the mass burning rate enhancement is pronounced in smaller size pool, which is different from the temperature enhancement. The variation of mass burning rate with the ceiling height for conduction-controlled pool fires beneath a ceiling in this study is different from larger pool fires with dimensions of 12 cm and 14 cm in [11] which exhibits an initial increase to peak at  $H_c/D = 1.38$  and then decrease with decreasing ceiling height (ranged from 30-6 cm). The different variation trend was ascribed to the different predominated heat transfer to the fuel for the pool fires, which will be discussed in the subsequent section.

### Discussion

The mass burning rate can be expressed:

$$\dot{m}^* = \frac{\dot{Q} - \dot{Q}_1}{L^2 [L_v + c_p (T_{\text{boil}} - T_0)]} \quad (1)$$

where  $L$  is the length of the pool,  $L_v$  – the vaporizing latent heat of the fuel,  $c_p$  – the specific heat of the fuel,  $T_{\text{boil}}$  – the boiling temperature of the fuel,  $T_0$  – the original temperature of the fuel,  $\dot{Q}$  – the heat transfer to the fuel, and  $\dot{Q}_1$  – the radiation heat loss from the fuel to the surroundings. For the liquid fuel, the radiation loss from the fuel can be negligible because of its low temperature and emissivity, *i. e.*,  $\dot{Q}_1 = 0$ .

For the pool fire burning without ceiling, the heat transfer to the liquid fuel can be expressed:

$$\dot{Q}_0 = \dot{q}_{f,\text{conv},0} + \dot{q}_{f,\text{rad},0} + \dot{q}_{w,\text{cond},0} \quad (2)$$

where  $\dot{q}_{f,conv,0}$ ,  $\dot{q}_{f,rad,0}$ , and  $\dot{q}_{f,cond,0}$  are the convective heat transfer from the flame, the radiation heat transfer from the flame, and the conduction heat from the rim wall to the fuel, respectively, when pool fire is burning without ceiling. The conduction heat transfer from the pool rim wall can be evaluated as a convection term [16], for the liquid fuel and the rim steel wall are different phase. Therefore, the conduction heat feedback from the pool rim walls can be expressed:

$$\dot{q}_{w,cond,0} = 4Ldh_0(T_{w,0} - T_l) \quad (3)$$

where  $d$  is the depth of the fuel,  $h_0$  – the convective heat coefficient,  $T_{w,0}$  – the temperature of the pool rim wall, and  $T_l$  – the temperature of the fuel.

When the pool fire was under the ceiling, the heat transfer to the liquid fuel changes:

$$\dot{Q}_c = \dot{q}_{f,conv,c} + \dot{q}_{f,rad,c} + \dot{q}_{f,cond,c} + \dot{q}_{c,rad} \quad (4)$$

where  $\dot{q}_{f,conv,c}$ ,  $\dot{q}_{f,rad,c}$ , and  $\dot{q}_{f,cond,c}$  are the corresponding heat transfers to the fuel, same terms with eq. (2), when pool fire is under a ceiling, and  $\dot{q}_{c,rad}$  – the radiation heat transfer from the ceiling which heated by the flame to the fuel. An assumption was made that the enhanced conduction heat transfer from the pool rim walls is the major factor of the increase of the heat transfer to the fuel, which attributed to the mass burning rate enhancement. Then, from eqs. (2) and (4):

$$\Delta\dot{Q} = \dot{q}_{w,cond,c} - \dot{q}_{w,cond,0} \quad (5)$$

Combining eqs. (1), (3), and (5) yields:

$$\Delta\dot{m}'' = \dot{m}_c'' - \dot{m}_0'' = \frac{4Ldh_c(T_{w,c} - T_l) - 4Ldh_0(T_{w,0} - T_l)}{L^2 [L_v + c_p(T_{boil} - T_0)]} \quad (6)$$

where  $\Delta\dot{m}''$  is the mass burning rate increment,  $\dot{m}_c''$  – the mass burning rate for the pool fire under the ceiling, and  $\dot{m}_0''$  – the mass burning rate for the pool fire without ceiling. In eq. (6),  $h_c$  can be taken as equal approximately to  $h_0$ , for both can be referred to horizontal convection. Then eq. (6) can be written:

$$\begin{aligned} \Delta\dot{m}'' = \dot{m}_c'' - \dot{m}_0'' &= \frac{4Ldh_0(T_{w,c} - T_{w,0})}{L^2 [L_v + c_p(T_{boil} - T_0)]} \\ &= \frac{4dh_0}{[L_v + c_p(T_{boil} - T_0)]L} (T_{w,c} - T_{w,0}) \\ &= \alpha \frac{T_{w,c} - T_{w,0}}{L} \end{aligned} \quad (7)$$

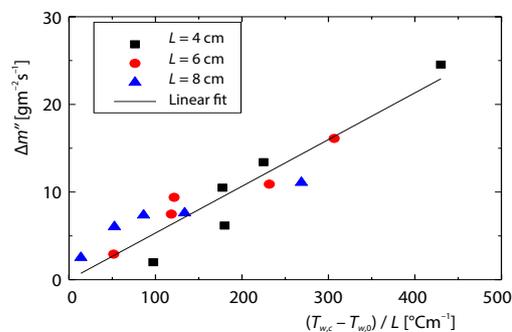


Figure 6. Correlation of burning rate increments with the value of  $(T_{w,c} - T_{w,0})/L$

where  $\alpha = 4dh_0/[L_v + c_p(T_{boil} - T_0)]$ . The mass burning rate increments are plotted against the value of  $(T_{w,c} - T_{w,0})/L$  in fig. 6. It is shown that the relationship can be successfully fit linearly with slope of 0.053 and Pearson correlation coefficient of 0.98, which validate the assumption and the theoretical formula of eq. (7). The burning rate enhancement for the conduction-controlled pool fire under a ceiling is attributed to the increase in pool rim wall temperature, which increases with the decreasing ceiling height. However, the burning rate

enhancement for larger pool fires (12 cm and 14 cm) in [11] is attributed to the ceiling radiation, which initially increases and then decreases with decreasing ceiling height [11]. That explains why the variation trend of mass burning rate with ceiling height for pool fires under a ceiling in this study is different from reference [11]. Equation (7) also shows that the mass burning rate increment is inversely proportional to the pool size, which illustrates that the burning rate enhancement is more pronounced in the smaller size pool mentioned in the section *Burning rate and pool wall temperature*.

## Conclusions

Experiments were performed with conduction-controlled pool fires, using ethanol as representative fuel, at various heights below a ceiling to study the burning characteristics of conduction-controlled pool fires under a ceiling. The major conclusions are summarized as follows.

- When the ceiling was close to the pool, the burning process could be divided into four stages: initial steady, development, developed steady, and decay. A flame-wrapping phenomenon was observed in the later period of this burning history. The pool rim wall was heated more efficiently when pool fires under the ceiling compared to no ceiling condition.
- The pool rim wall temperature and mass burning rate exhibited an increase with the decrease of ceiling height. The temperature enhancement of relative larger pool fires is higher than that of relative smaller pool fires. However, the mass burning rate enhancement is higher for the relative smaller pool fires.
- The burning rate enhancement for the conduction-controlled pool fire under a ceiling was found to be mainly attributed to the increase in pool rim wall temperature. A global factor was developed and validated by experimental data to account for the pool length effect on the mass burning increment.

## Acknowledgment

The authors greatly acknowledge the PLA University of Science and Technology, Nanjing, for its support.

## Reference

- [1] You, H. Z., Faeth, G. M., Ceiling Heat Transfer during Fire Plume and Fire Impingement, *Fire and Materials*, 3 (1979), 3, pp. 140-147
- [2] Babrauskas, V., Flame Lengths under Ceilings, *Fire and Materials*, 4 (1980), 3, pp. 119-126
- [3] Hou, S. S., Ko, Y. C., Effects of Heating Height on Flame Appearance, Temperature Field and Efficiency of an Impinging Laminar Jet Flame Used in Domestic Gas Stoves, *Energy Conversion and Management*, 45 (2004), 9-10, pp. 1583-1595
- [4] Weng, W. G., Hasemi, Y., Theoretical Analysis on Flame Dimension in Turbulent Ceiling Fires, *International Journal of Heat and Mass Transfer*, 49 (2006), 1-2, pp. 154-158
- [5] Ding, H., Quintiere, J. G., An Integral Model for Turbulent Flame Radial Lengths under a Ceiling, *Fire Safety Journal*, 52 (2012), 8, pp. 25-33
- [6] Zhang, X., et al., Flame Extension Length and Temperature Profile in Thermal Impinging Flow of Buoyant Round Jet Upon a Horizontal Plate, *Applied Thermal Engineering*, 73 (2014), 1, pp. 13-20
- [7] Gao, Z., et al., An Investigation of the Detailed Flame Shape and Flame Length under the Ceiling of a Channel, *Proceedings, Combustion Institute*, 35 (2015), 3, pp. 2657-2664
- [8] Zhang, X., et al., Flame Extension Lengths Beneath an Inclined Ceiling Induced by Rectangular-Source Fires, *Combustion and Flame*, 176 (2017), Feb., pp. 349-357
- [9] Ji, J., et al., Experimental Study of Non-Monotonous Sidewall Effect on Flame Characteristics and Burning Rate of n-Heptane Pool Fires, *Fuel*, 145 (2015), 8, pp. 228-233
- [10] Ji, J., et al., Experimental Study on Behavior of Sidewall Fires at Varying Height in a Corridor-Like Structure, *Proceedings of the Combustion Institute*, 35 (2015), 3, pp. 2639-2646

- [11] Liu, J., *et al.*, Impacts of Ceiling Height on the Combustion Behaviors of Pool Fires Beneath a Ceiling, *Journal of Thermal Analysis and Calorimetry*, 126 (2016), 2, pp. 881-889
- [12] Hottel, H. C., Certain Laws Governing the Diffusive Burning of Liquids, *Fire Research Abstracts and Reviews*, 1 (1958), pp. 41-44
- [13] Hu, L., *et al.*, Flame Radiation Feedback to Fuel Surface in Medium Ethanol and Heptane Pool Fires with Cross Air Flow, *Combustion and Flame*, 160 (2013), 2, pp. 295-306
- [14] Hu, L., *et al.*, Burning Characteristics of Conduction-Controlled Rectangular Hydrocarbon Pool Fires in a Reduced Pressure Atmosphere at High Altitude in Tibet, *Fuel*, 111 (2013), 9, pp. 298-304
- [15] Quintiere, J. G., *Fundamentals of Fire Phenomena*, John Wiley and Sons, New York, USA, 2006
- [16] Hu, L., *et al.*, A Wind Tunnel Experimental Study on Burning Rate Enhancement Behavior of Gasoline Pool Fires by Cross Air Flow, *Combustion and Flame*, 158 (2011), 3, pp. 586-591