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Evolution of heat feedback in medium pool fires with cross air flow and scaling of mass burning flux by a stagnant layer theory solution

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Abstract

This paper quantifies experimentally the evolution of heat feedbacks through conduction, convection and radiation in medium square pool fires (10–25 cm) with horizontal cross air flows ranged in 0–3.0 m/s. Ethanol and heptane are used as representative fuels producing typically less-sooty and sooty flames. Results show that the overall conduction heat feedback flux through the four sides increases with cross air flow speed, being more prominent for smaller pools than for larger ones. And the rate of overall conduction heat feedback increment is more prominent for heptane, of which the rate of increase with flow speed nearly 2 times that of ethanol. Meanwhile, the radiation heat feedback declines with cross air flow speed, with its contribution fraction nearly negligible at larger flow speeds for both fuels. The convection feedback fraction increases with cross air flow speed. Its increment is more prominent (a) for heptane (increasing fast with flow speed to be even the dominate one among the three heat feedbacks) than ethanol (increasing slowly with flow speed; being nearly constant and maintaining to be the dominant one); and (b) for larger pools than for smaller ones. The changing of dominant heat feedback mechanism with cross air flows, results in the change of the scaling behavior of the mass burning flux with pool size. A stagnant layer solution theory is then proposed, by including fuel mass transfer Spalding number B, to describe the change of mass burning flux of different size pool fires with cross air flow speed for different fuels in relative strong cross air flows [as indicated by Froude number ($\mathrm{Fr} = u/[gd]^{1/2}$) larger than about unity]. Experimental data are shown to be well correlated by the proposed theory.

Keywords: Heat feedback (conduction, convection, radiation); Pool fire; Cross air flow speed; Mass burning flux; Spalding number B

1. Introduction

Pool fire burning rate (per unit surface area, or namely mass burning flux) is controlled by the overall heat feedbacks through conduction (through rim wall), convection and radiation [1–9],

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$$\dot{m}'' \sim \dot{Q}''_F = \frac{4\sum \dot{q}}{\pi D^2} = 4\frac{k_1(T_F - T_l)}{D} + k_2(T_F - T_l) + k_3(T_F^4 - T_l^4)(1 - \exp(-k_4 D)) \quad (1)$$

where D is pool size (diameter). Different dominant heat feedback mechanism gives different scaling behaviors of burning rates. Conductive (1st term, $[4\frac{k_1(T_F - T_l)}{D}]$) dominating small pool fires (<0.1 m) gives their mass burning flux decreases with pool size. The potion from convection (the 2nd term, $[k_2(T_F - T_l)]$) and radiation (the 3rd term, $[k_3(T_F^4 - T_l^4)(1 - \exp(-k_4 D))]$) increases with pool size, which results in increment of mass burning flux with pool size and finally approaching asymptotic values independent of pool size.

The above theory has successfully explained the scaling behaviors of pool fires in no wind [1–9]. However, direct measurement data of above different feedbacks are still few as it is hard to distinguish them from their overall contribution to burning rate. Ditch and de ris [7] have measured the radiation feedback as to propose an empirical correlation for mass burning flux. Hamins [8,9] has measured the radiation feedback showing it plays an important role for the 0.3 m liquid pool fire. Even so, such limited data on heat (radiation) feedback are collected with no cross air flow.

The presence of cross air flow makes above problem even more complex, due to the shift of the relative position of the deflected flame to the pool (change of radiation view angle), as well as the change of the flow boundary layer condition at the fuel surface (the upward buoyancy "blowing away" convection is suppressed; meanwhile a horizontal forced flow boundary layer is formed). However, in contrast, the studies on pool fire behavior in cross air flows are still much relatively fewer, where only the burning rate is addressed [e.g., [1], [10–13]] as shown to be enhanced by cross air flow. More recently, Hu [12] has found that, at a certain cross air flow speed, the mass burning flux decreases with pool size (5–25 cm), even in a contradictory trend to that in no wind. The change of the scaling trend indicates that the dominant heat feedback mechanism has been changed by cross air flow. It is then revealed [13] that the flame radiation feedback declines remarkably with cross air flow speed. However, by far, there is still no direct measurement of how the relative portions of the three heat feedback mechanisms change due to cross air flow, meanwhile it is indeed the fundamental base to find out scaling law for the mass burning flux.

Then, this paper is to quantify experimentally the heat feedback fractions through the three mechanisms (conduction, convection and radiation) in medium pool fires and their evolutions with cross air flow speeds; and to characterize how this affects the scaling of mass burning flux:

(1) When subjected to a cross air flow, the flame is deflected and the temperature of the four side walls should change to be not symmetrical any more as that in no wind. This has not been quantified in the literatures, which is firstly clarified in this work.
(2) The conduction heat feedback through the wall received by fuel is then calculated based on the measured temperature difference between the wall and adjacent fuel, and its evolution with cross air flow speed is further quantified.
(3) The radiation feedback received by fuel surface in the pool fire is measured directly by radiometers. Then, the evolutions of relative fractions of the three heat feedback mechanisms with cross air flow speed are quantified. Finally, the corresponding scaling behavior of the mass burning fluxes is discussed in relevance to the change of the dominant heat feedback mechanism (their fractions) accordingly, and a stagnant layer theory solution is proposed to characterize the mass burning flux in relative strong cross air flows where convection feedback is found to be predominant.

2. Experimental

2.1. Experimental facility

The wind tunnel experimental setup is shown in Fig. 1(a), where more details have been described in [13]. The steel pool fires are squared with dimensions of 10–25 cm with inner depth of 3.0 cm. Two types of fuels (ethanol and heptane) are used. The fuel surface level is maintained (0.4 cm lip [13]). The fuel mass loss is measured by a balance (resolution of 0.1 g). The experiments are repeated four times showing good repeatability [13].

2.2. Measurement of conduction feedback through wall to fuel

For each pool side wall, there are four thermocouple pairs installed as shown in Fig. 1(b). One is to measure the wall temperature and the other for adjacent fuel temperature. For such pool fires with a small wall height (3.0 cm), the vertical temperature profile along the side wall is near uniform (burning duration is 1800 s to ensure steady state) by preliminary measurements. The characteristic temperatures of the wall and the fuel are then taken as the measured values at the middle height of the fuel depth. The thermocouple for measuring the wall temperature is embedded into a hole