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An experimental investigation and characterization on flame bifurcation and leaning transition behavior of a pool fire in near wake of a square cylinder

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ABSTRACT

This paper is to investigate the fire behaviors in the wake of buildings. Experiments are carried out in a wind tunnel to reveal and to characterize flame behavior of a pool fire in the near wake behind a square cylinder of different cross sectional sizes (12 cm, 18 cm, 24 cm and 30 cm) under horizontal wind flow speeds in the range of 0–1.72 m/s, with corresponding Reynolds number (Re) in the range of 0.5–3.5×10^4. Both square (10 cm) and rectangular (4 cm width and 24 cm long) ethanol pool fires are used as fire source. The flame behavior is recorded by two CCD cameras from two directions (normal to the flow or in the direction of the flow). It is found that the flame in the near wake bifurcates and its leaning direction transits, behaving uniquely different from those in the quiescent air or in just a horizontal wind flow without the square cylinder bluff body. The distance from flame bifurcation point (rectangular pool fire) to the cylinder correlates well linearly with the cylinder width (size). Another interesting behavior revealed is that there is a transition of leaning direction of the flame of the square pool fire, from towards the cylinder transisting to the opposite direction. This happens either when increasing the distance (D) between the pool fire and the cylinder for a given cylinder width (L), or when decreasing L for a given D. A parameter Left Flame Area Ratio (LFAR, 2-D projected flame area at the left side of the vertical axial of pool center divided by the total flame area) is brought forward to quantify the flame leaning extent and direction, as to find out quantitatively the critical scale relation between these valuables at the transition state. The critical value of D corresponding to LFAR = 0.5 (indicating the transitional turning point of the flame leaning direction) is found to vary remarkably with cylinder size but independent of wind speed. However, the normalized value of this critical distance between the pool center and the cylinder by the characteristic length scale taking as the cylinder width is found to converge to be all about 1.0.

1. Introduction

A significant difference between a fire in an open urban and that in a compartment is the effect of the wind flow [1]. The wind flow makes all aspects of the fire behavior incorporating mass and heat transfer process to be much more complex. A special issue is the influence of turbulent boundary layer in the urban underlying surface domain near the ground level. Buildings are fundamental elements of the urban underlying surface structure. The blockage effect of the buildings (acts as a bluff body in the flow dynamics) makes the wind flow to be much more complex when passing through them and so as the fire product transportation behavior in this area, than that in the plain without blockage effect.

Pool fire combustion behavior, which incorporates complex heat and mass transfer process, has attracted great attention and has been subject to extensive amount of research for decades (e.g., [2–13]) on its fundamental aspects including burning mass flux, flame height and pulsation, thermal radiation, soot formation and air mass entrainment mechanism. However, these works were mainly in a quiescent ambient air condition. Relatively, the studies on burning behavior of pool fire under a wind flow are still less (e.g., [8–13]). Even for these limited amounts of works in the literatures on the effect of wind flow on pool fire behaviors, they have been only considering the scenario of just purely a horizontal wind flow passing across the pool fire.

A building in the urban area acts as a cylindrical blockage bluff body in the wind flow field. Flow past square cylinder is characterized by alternate vortex shedding from two side walls of the cylinder, causing a complex transient flow field in the cylinder wake. In recent year, extensive works [14–21] have been reported and provide detailed good knowledge of characteristics of the turbulent flow dynamics past a bluff body. For example, Shanbhogue et al. [16] have reviewed both non-reacting and reacting fluid mechanics of bluff body (triangle shape cross section) wake flows. Saha et al.

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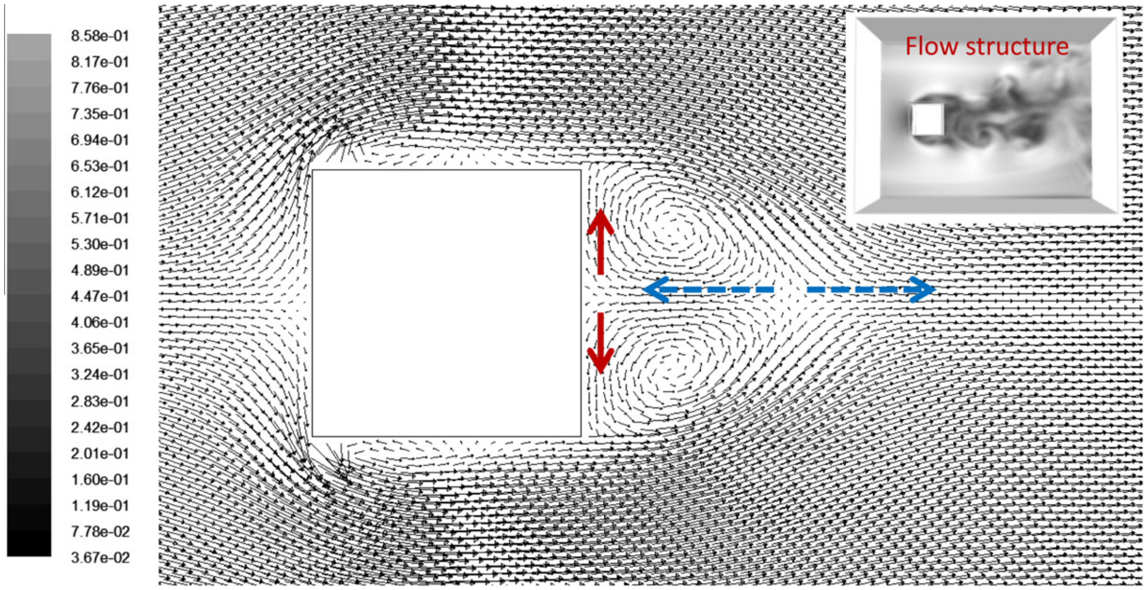

Fig. 1. Schematic of typical near wake flow structure induced by horizontal wind passing around a square cylinder showing a recirculation zone behind the cylinder and possible drag effect to a flame there.

[17], Sohankar et al. [18], Kim et al. [19], Druao et al. [20], and Lyn et al. [21] have revealed the characteristics of flow past a square cylinder based on experiments, Direct Numerical Simulation and Large Eddy Simulation. It is reported [19–21] that as shown in Fig. 1, when the wind flow passes around a square cylinder, a near wake recirculation flow region will be formed behind the blockage cylinder. A pair of counter-rotating vortices is identified downstream of the cylinder in the near wake flow region. As a building is always of finite height/width ratio, flow around it has highly three dimensional effects. Wang and Zhou [14] investigated the near wake of finite-length square cylinder (height/width ratio ranges from 3 to 7) experimentally. The instantaneous flow structure around the cylinder is arch-type, consists of two span wise vertical 'legs' and their connection near the free end. The maximum longitudinal length of the reverse flow zone has a dependency on its aspect ratio. Olvera et al. [22] numerically studied the effects of buoyancy/non-buoyancy plume within the recirculation cavity of a cubic building on the near-wake flow structure. They found the increase of source buoyancy or momentum causes the recirculation cavity to decrease in size.

This paper aims to reveal interdisciplinary knowledge between these two topics, pool fire flame behavior and near wake flow dynamics. That is, how a pool fire flame behaviors in the near wake of a square cylinder, a topic has seldom been investigated before. The near wake flow is much more complex in turbulent and time-variable instantaneously than a pure horizontal wind flow without bluff body cylinder. This will pose significant transient effect on the flame behaviors of a pool fire positioned there. Recently, Chen et al. [23] had reported some phenomenological qualitative observation on the flame interaction of two adjacent pool fires behind a building in a cross-wind. The interaction of the two pool fires, including the possible merging of the two pool fire flames and initiation of fire swirling, had been discussed. However, even for a single pool fire, the knowledge on the flame behavior in the near wake is still lacking.

Numerical simulation of air flow ($V = 0.55$ m/s) past a two-dimensional square cylinder (cylinder width $L = 0.18$ m) has been carried out using FLUENT. Inviscid flow condition is assumed. SIMPLE algorithm is employed for the pressure–velocity coupling. The velocity vector in the near wake of the cylinder is shown in Fig. 1. This simple computational case is not meant for a detailed flow field analysis, but for the illustration of the effects of vortices on the flame, as will be discussed in the later sections. As shown in Fig. 1 the schematic of the near wake structure, two shedding vortices form behind the cylinder. At the position quite adjacent to the cylinder surface, there should be a pulling effect induced by the flow to drag the flame there to possibly trace in the two opposite directions (solid-line red arrow) parallel to the cylinder surface. And if the pool fire is positioned some distance downstream at the interface of the two shedding vortices, the flame also have the possibility to be drag to another kind of two opposite directions (dashed-line blue arrow): facing the cylinder or opposite downstream. There is still no report or knowledge about how such a single pool fire flame behaves in the near wake of a square cylinder.

In this paper, experimental research had been carried out in a wind tunnel to investigate the pool fire flame behavior in the near wake behind a square cylinder. Due to the high level of turbulence in the wake flow, an image averaging technique was used to establish the mean position of the flame for further quantitative characterization. Different square cylinder widths, pool-cylinder distances and wind flow speeds were considered to find out and to characterize the transient aspects of the flame under the above coupling effect for both a square and a rectangular shape pool fire in the near wake.

2. Experimental

Experiments were carried out in a wind tunnel with total length of 72 m and cross sectional dimension of 1.5 m wide and 1.3 m high. Horizontal wind flow is generated by a mechanical fan at one end, screened in a 6 m long section to provide a stable horizontal air flow of 0 – 4.5 m/s with turbulence fluctuation intensity less than 2%. The top and two sides of the test section are made of glass for phenomenon observation and image recording. The other end of the wind tunnel is opened. The test site is at 40 m after the screen section to ensure that the air flow there is full developed. The experimental setup is shown in Fig. 2.

Square cylinders with same height of 0.5 m, but four different cross sectional width L of 0.12, 0.18, 0.24 and 0.3 m were posi-