Experimental study of the velocity and temperature profiles due to wind-blown flames

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ABSTRACT

The study of physical processes associated with the wind-fire interaction is of significant interest due to its importance and has wide applications in scientific and engineering fields. In this paper, the boundary layer profile and thermal structure of a wind-blown diffusion flame were investigated experimentally. Measurements of simultaneous velocity and temperature were made using a high temperature anemometer downstream of a line fire produced by a propane gas pipe burner with a heat release rates (HRR) of approximately 17 kW. In comparison to the well-established isothermal flow, the combustion boundary layer produced prominent local effects on velocity profile downstream of the leading flame edge slightly aloft the tunnel floor. We observed the consequences of the interaction between fire-induced buoyancy and momentum wind flow in terms of altered velocity as well as temperature profiles. This is likely to play an exacerbating role in the behaviour of fire spread and exert impact on building structures. This study can be extended to predict the dynamics behaviour of a local flow enhancement near the ground notably during wildfire or bushfire events.

1. Introduction

Wind is critical to the initiation, development, behaviour, and spread of wildfire. Several review articles, particularly by Pitts (1991), Beer (1991), Hu (2017), show that many uncertainties remain today, including those concerning the interactions of wind and fire, thus limits the understanding of the influence of fire on wind and the aerodynamic impacts on building structures. The study of the impact of atmospheric boundary layer (ABL) flow on bluff bodies have been an active field for many years. When a heat source such as wildfire is involved, another degree of difficulty is added to the problem. Understanding the role of cross wind in affecting the heat feedback mechanisms (conductive, convective, and radiative) is critical in unveiling the interaction of a fire and ambient ABL flow.

The characteristics of flame containing boundary layer produced by a relatively strong wind and the potential wind load on structures during bushfire events have been preliminarily investigated numerically by He et al. (2011) and Kwok et al. (2012). Some detailed mechanisms through which wind is enhanced by fire were also analysed recently using numerical simulations (Eftekharian et al., 2019a). However, confidence is still lacking on the outcomes of numerical analysis because of the scarcity of experimental evidence. Hence, additional information on the physical processes in boundary layer diffusion combustion will present essential improvement to existing prediction schemes.

This paper reports the results of a fire-wind tunnel investigation of combustion in the aerodynamics and thermal structure of the combusting boundary layer in the vicinity of a stationary flame in the fire-wind tunnel. Although these methods are not free from errors, they are useful to discuss the relation between fire-induced wind and the temperature field.

2. Experimental setup

The experiment was performed in the Western Sydney University's fire-wind tunnel, measured 2.4 × 0.8 × 0.6 m (L × W × H), with a cross sectional area of 0.48 m^2, as shown in Fig. 1(a). The wind tunnel is an open circuit design, with a Flakt Woods reversible-flow fan controlled by an ABB variable speed drive capable of generating wind speeds up to 10 m/s. The structure of the tunnel is made of steel sheet of 2 mm in thickness. One side wall has a glass window to allow visual observation. A contraction section fitted with a grid mesh was installed at the inlet of the test section, as shown in Fig. 1(b), to produce a relatively stable uniform flow.

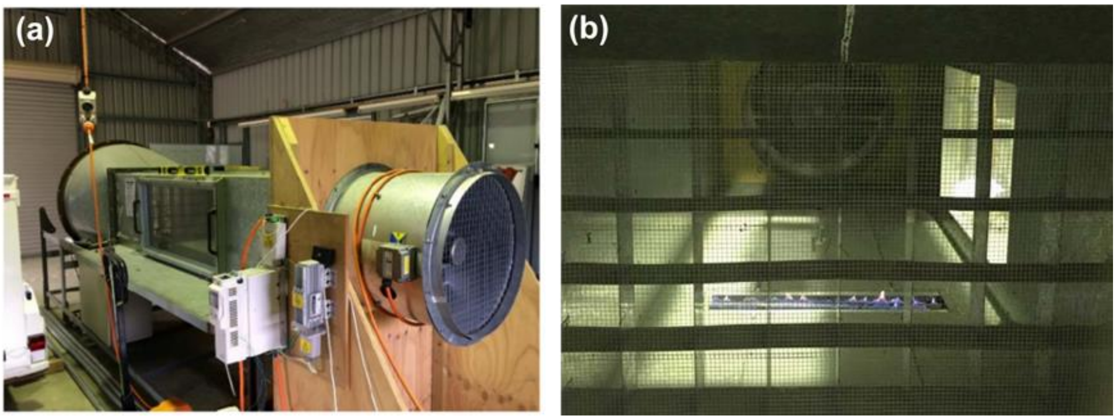

Figure 1: (a) The open circuit fire-wind tunnel; (b) A view into the test section from the inlet.

A propane pipe-burner was used to simulate a line-source fire, and the fuel volumetric flow rate was regulated with a calibrated rotameter. The burner was housed inside a sealed plenum that abuts a slot opening 110 mm in width and 560 mm in length mid-plane of the tunnel floor at 1 m downstream of the section inlet, as shown in Fig. 2(a). The burning intensity across the pipe's length was found to be relatively uniform, as shown in Fig. 2(b) and 2(c). A flush floor cover was applied to the slot opening when conducting the wind-only experiments.

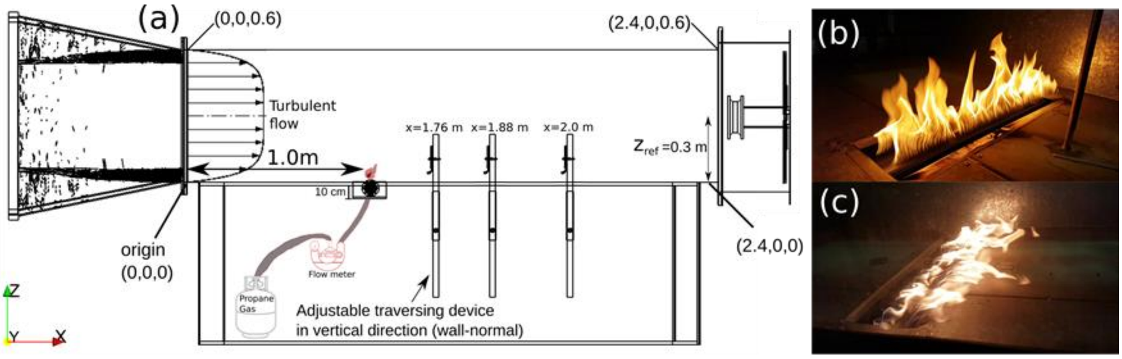

Figure 2: (a) Schematic cross-section of the experiment; (b) Still flame; and (c) Wind-blown flames.

Simultaneous measurements of velocity and temperature were made using a Kanomax high-temperature anemometer and a thermocouple, respectively. The high-temperature probe can withstand robust condition up to 500 ˚C, and its temperature compensation circuitry ensured measurement accuracy. The probe, together with the thermocouple, traversed the boundary layer in the central plane of the tunnel, with the first measurement point being close to the tunnel floor (∼2 mm), and thereafter spaced equidistant within the outer boundary layer up to the tunnel mid-height. The velocity and temperature profile measurements were taken at three longitudinal locations at x=0.76, 0.88 and 1.0 m downstream of the burner producing a line fire with a heat release rate (HRR) of approximately 17 kW, or a fire intensity of approximately 30 kW/m.

3. Results

Figure 3 shows the normalised mean wind velocity profiles, U_R versus normalized height z_R, downstream of the fire-front at three locations, i.e. 0.76 m, 0.88 m, and 1.00 m from the leading flame edge. The normalised mean wind velocity profiles without the fire at these locations are also presented for comparisons. The reference height z_{ref} and the reference velocity $U(z_{ref})$ for the normalisation are the mid-height of the tunnel and the velocity measured at that height. In comparison to the boundary layer velocity profiles without fire, the profiles downstream of the fire-front exhibit significant variations. The variation is prominently noticeable for the boundary layer closer to the fire base (or smaller x). The mean wind velocity is strengthened by the fire at the near-floor region and gradually decreases with height. There is a maximum enhancement $U_{R\text{-}max}$ in each velocity profile at the three x locations, and the height corresponding to the maximum wind velocity progressively increases downstream. It is anticipated that the maximum wind velocities are aligned with the core region of the fire flume. As z_R increases, the velocity asymptotically approaches that of the freestream without the fire. However, further downstream at x = 1.00 m, a reversal phenomenon, i.e., the velocity with fire is reduced below that is observed as z_R increases without the fire. These observations are consistent with the results of numerical predictions of our previous studies (He at al., 2011; Kwok et al., 2012; Eftekharian et al, 2019b).

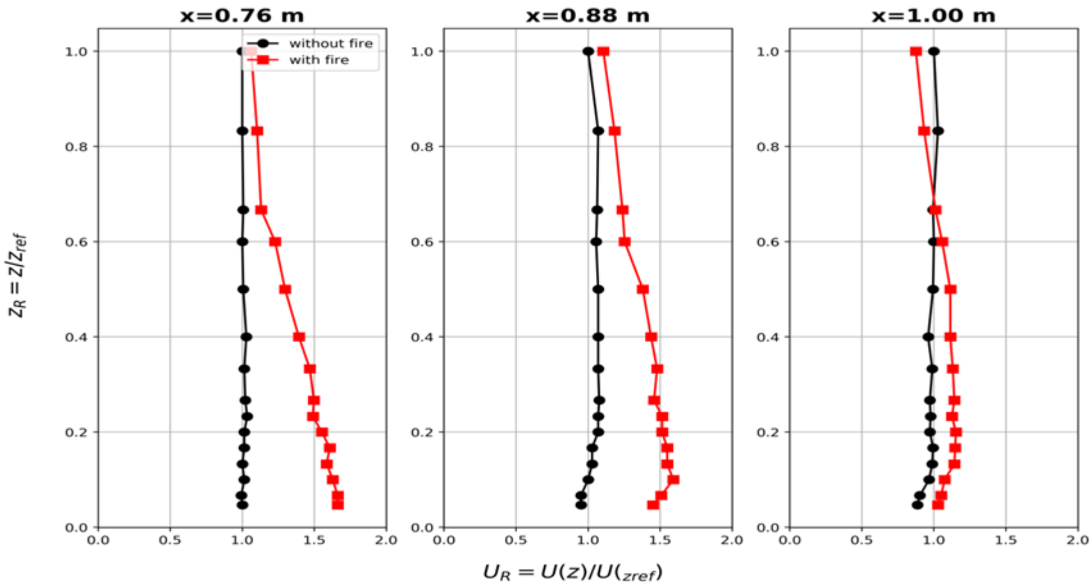

Figure 3: Normalised velocity profiles with and without fire at different downstream locations.

It is noteworthy from Figure 4 that the location of velocity overshoot almost coincides with the position of maximum mean temperature increase, a manifestation of similarity between thermal and viscous effects. A large temperature gradient was present within the boundary layer, as expected, decreasing with respect to height. The boundary layer temperature increases to a maximum at the flame zone and decreases with z to freestream temperature at the outer boundary layer edge. Similar to the velocity profiles, the maximum temperature in the profile decreases with increasing x-direction. The temperature variation is caused by heat losses to freestream air and through the tunnel floor to ambient.

Temperature rise in the fire plume is directly caused by heat release from the combustion. Consequently, air undergoes thermal expansion and buoyancy force is created. Hence the observed wind velocity enhancement is believed to result from the combined effects of thermal expansion and buoyancy interaction with the freestream momentum flow.

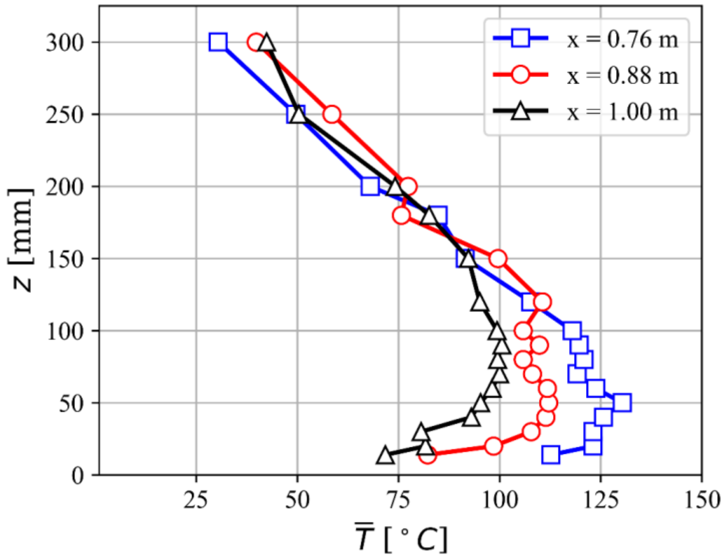

Figure 4: Temperature profiles with and without fire at different downstream locations.

4. Conclusions

The results of an experimental investigation in a fire-wind tunnel show that the interaction of fire and wind causes a significant local acceleration of mean velocity profiles, thereby creating a strong local effect close to the leading flame edge just above the tunnel floor. This study provides the laboratory evidence of the wind velocity enhancement by fire. Moreover, it is revealed that the similarity between thermal and viscous effect is preserved under the condition of momentum-buoyancy interactions. The effect of the coupled interaction between the fire and ambient flow on turbulence characteristics await further analysis. From a practical application point of view, greater attention should be paid to determining the fire-enhanced wind flow and the resultant increase in wind loads to buildings or structures, particularly at close to the fire-front in severe bushfire events.

Acknowledgement

This work was funded by Australian Research Council Discovery Project (ARCDP) grant DP160103248.

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