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Numerical analysis of heat effects on fire wind enhancement

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ABSTRACT

Fire-wind enhancement is a phenomenon referred to the increase of free-stream wind velocity due to fire-wind interaction. The potential adverse effects of enhanced wind on the pressure loads around the buildings highlight the necessity of investigating the phenomenon. The phenomenon has been observed by previous researchers, however, investigation of the factors affecting the phenomenon has not received due attention. One of the factors that affect this phenomenon is the effects of fire intensity. Computational Fluid Dynamic solver called FireFoam was used to evaluate how fire-wind enhancement is related to the fire intensity. The results revealed that the wind velocity enhancement increases with the increase of fire intensity. The results also showed that the enhancement of wind happens within the fire plume where there is a higher temperature than the ambient air.

1. Introduction

Interaction of wind and fire is a two-way problem. That is wind causes a change of fire plume geometrical features and also fire affects flow (wind) aerodynamic properties. Many studies have focused on the effects of wind on fire plume geometrical properties (Hu, 2017). Fire plume tilt angle and flame length were investigated by Hu et al. (2013a) and Hu et al. (2013b).

As for the effects of fire on the wind, it was experimentally shown that interaction of wind and fire can result in the increase of wind velocity downstream of the fire (Hirano and Kinoshita, 1975). Thermal expansion and low-density area within the plume region were found to be the reasons for distortion in the velocity profile (Volchkov et al., 2004). Therefore, the knowledge of thermal and geometrical details of plume region will help better understanding of the phenomenon.

Fire-wind enhancement is one of the consequences of many major bushfire attacks. Lambert (2010) and McRae et al. (2013) reported that wind can be intensified due to the interaction with bushfire. He et al. (2011) and Kwok et al. (2012) numerically investigated bushfire-wind interaction and showed that it can potentially enhance the near ground wind velocity downstream of the bushfire source up to 50%. They showed that accompanied by the increase of wind velocity, bushfire-wind interaction results in an increase of turbulence and wind gust. Coanda effects were postulated to be the reason why the wind is enhanced downstream of the bushfire source. As a result of the increase in wind velocity due to fire-wind-interaction, the pressure coefficient around the buildings downstream of the bush-fire source was shown to be increased.

The presented literature review shows the lack of information concerning the factors and parameters affecting bushfire-wind enhancement phenomenon. The main aim of this study is to employ Computational Fluid Dynamics technique to investigate the effects of fire intensity on the bush-fire wind enhancement phenomenon.

2. Numerical Approach

FireFOAM, a solver of OpenFOAM platform was employed to simulate the interaction of fire and wind. OpenFOAM is an open-source CFD code with different solvers for different thermo-fluid application problems. FireFOAM uses large eddy simulation (LES) to capture turbulent structures of the flow. Continuity, momentum, energy, state and species equations solved by fireFOAM are as below:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_j} = \frac{\partial}{\partial x_j}[\bar{\rho}(\nu + \nu_t)\left(\frac{\partial(\tilde{u}_i)}{\partial x_j} + \frac{\partial(\tilde{u}_j)}{\partial x_i} - \frac{2}{3}\frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij}\right) - \bar{p}\delta_{ij}] + \bar{\rho}g_i \tag{2}$$

$$\frac{\partial(\bar{\rho}\tilde{h})}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j\tilde{h})}{\partial x_j} = \frac{\overline{Dp}}{Dt} + \frac{\partial}{\partial x_j}\left[\bar{\rho}\left(D_c + \frac{\nu_t}{pr_t}\right)\left(\frac{\partial \tilde{h}}{\partial x_j}\right)\right] + \dot{q}''' - \nabla.\dot{q}_r{}'' \tag{3}$$

$$\frac{\partial \bar{\rho}\widetilde{Y_m}}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j\widetilde{Y_m})}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\bar{\rho} + \left(D_c + \frac{\nu_t}{\mathrm{Pr}_t}\right)\frac{\partial(\widetilde{Y_m})}{\partial x_j}\right] + \omega_m \tag{4}$$

$$\bar{p} = \bar{\rho}R\tilde{T} \tag{5}$$

where the superscripts "–" and "~" indicate spatial and Favre filtering. *P* is static pressure, *h* is total enthalpy, Y_m is mass fraction of species *m, g* is gravitational acceleration, ν, ν_t, D_c, *R*, Pr_t, δ and ω_m, are laminar viscosity, turbulent viscosity, laminar diffusion coefficient, gas constant, Prandtl number, Kronecker delta and production/sink rate of species *m* due to gas reaction respectively. $\dot{q}'''$ is heat release rate per unit volume (W/m^3) from a chemical reaction and $\dot{q}_r{}''$ is the total radiation emission intensity (W/m^2) of the gas mixture.

3. Model description and boundary conditions

The computational domain consists of a rectangular box with the dimension of 3×3×18m as shown in Figure 1. A line source of fire with the width of 0.3m is introduced 1.35m downstream of the domain inlet.

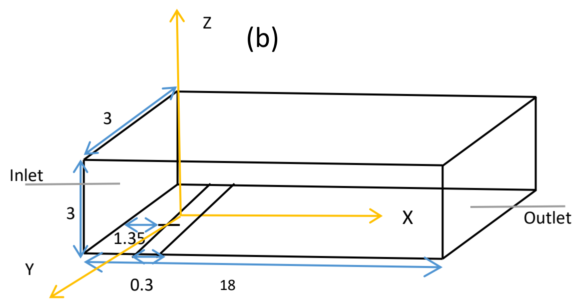

Figure 1. A schematic view of the computational domain.

Atmospheric boundary layer (ABL) condition with power law velocity profile as in Eq.(6) was considered for the domain inlet.

$$U(Z) = U_{ref}\left(\frac{Z}{Z_{ref}}\right)^{\alpha} \tag{6}$$

in which U_{ref} and Z_{ref} are respectively the reference velocity (3 m/s) and reference height (3 m). α is a coefficient determined according to the terrain category. The two dimensional vortex method developed by Mathey et al. (2006) was used to take into account turbulent structures at the domain inlet.

No-slip wall boundary condition was prescribed for the domain base, while slip boundary was suggested for the domain sides. Open boundary condition was used for the domain top. This boundary allows the flow to freely get in or out of the computational domain. Pressure-outlet boundary was applied to the domain outlet.

Methane was used as the fuel in the burner (fire source). Two different fire intensities (580KW and 1.5MW) were considered to investigate the effects of fire intensity on the fire wind enhancement.

4. Validation

Experimental data of buoyant diffusion flame reported by McCaffrey et al. (1979) was used to validate the numerical model of the current study. McCaffrey et al. (1979) used methane to produce buoyant diffusion fire plume in still conditions. The considered fire intensity is Q=58KW. Figure 2 compares the normalized vertical velocity profile at the centerline of the fire plume between the results of the current study, numerical results of Wang et al. (2011) and experimental data produced by McCaffrey et al. (1979). It is shown that there is a reasonably good agreement between the current numerical results and the experimental data of McCaffrey et al. (1979).

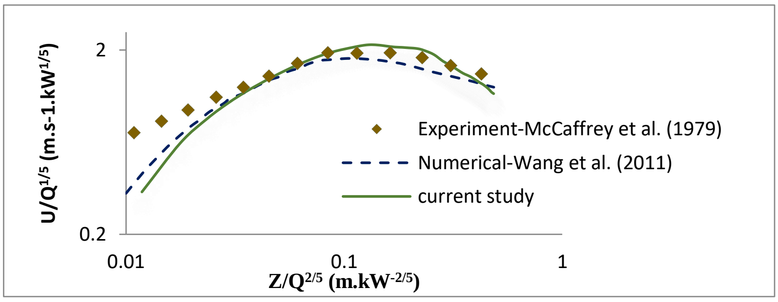

Figure 2. Comparison of numerical results of the current study with the numerical results of Wang et al. (2011) and experimental data produced by McCaffrey et al. (1979)

5. Result and discussion

Simulation time for all simulation cases is 20s. The first 7 second is considered as the transition period for the simulation to reach quasi-steady condition. Therefore, all the presented results are based on the average of the last 13 seconds of the quasi-steady period.

Figure 3 shows the effects of fire on the horizontal wind velocity. Comparison of wind velocity distributions for different fire intensities including the case without fire shows that due to the interaction of fire and wind, wind velocity increases downstream of the fire. Figure 3 also shows that immediately downstream of the fire source, because of Coanda effects, the plume becomes horizontal, attaching to the ground. However, further downstream of the fire source buoyancy force starts to lift the plume up from the ground.

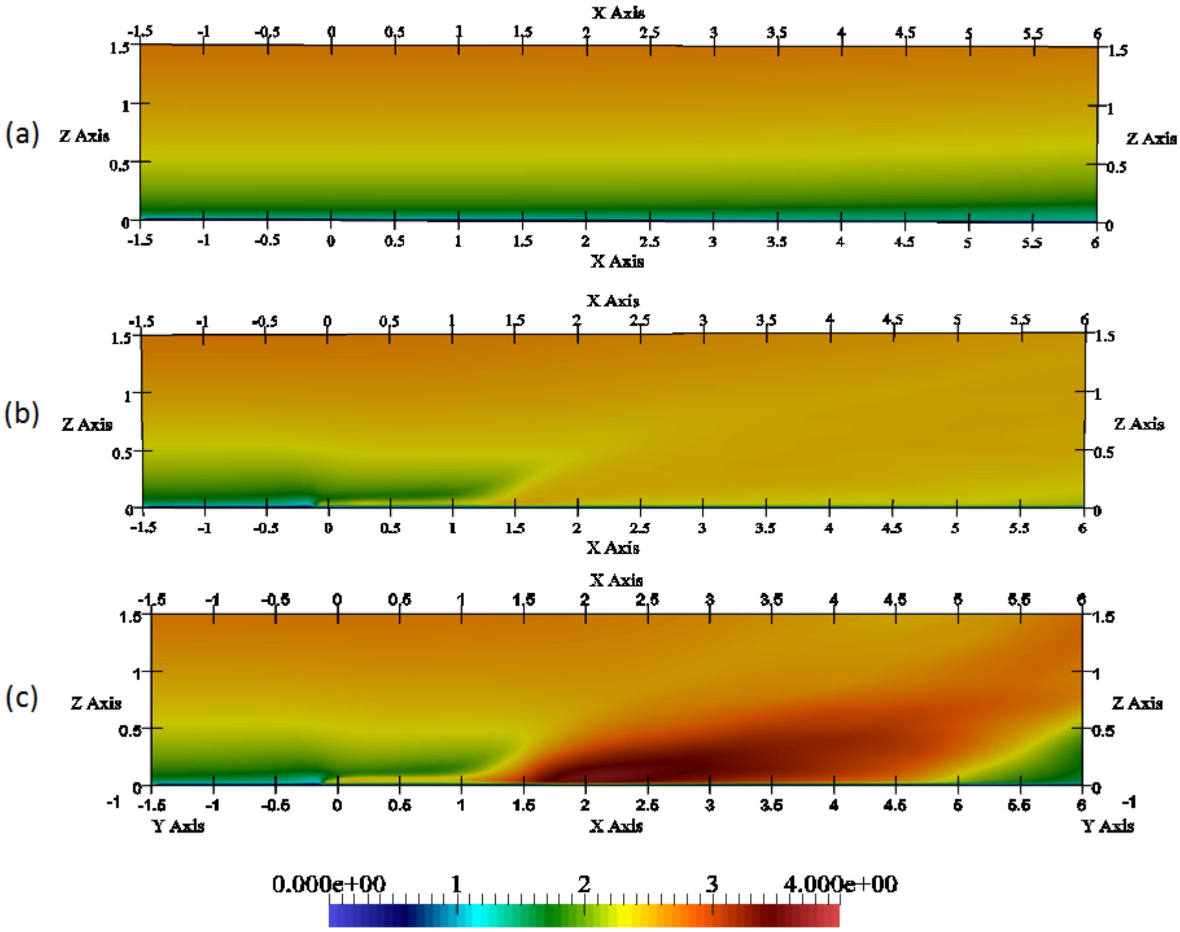

Figure 3. Horizontal velocity distribution over a vertical plane passing the domain centreline for the case (a) with no fire (Q=0) (b) Q=580KW and (c) Q=1.5MW.

Figure 4 indicates that although the maximum temperature is not highly varied between the simulations with different fire intensities, the fire plume area is extended in the case with higher fire intensity. A comparison of Figure 3 and Figure 4 also indicates that enhancement of the horizontal velocity happens in the plume area. Moreover, it can be observed that the level of wind enhancement is higher where there is a higher temperature.

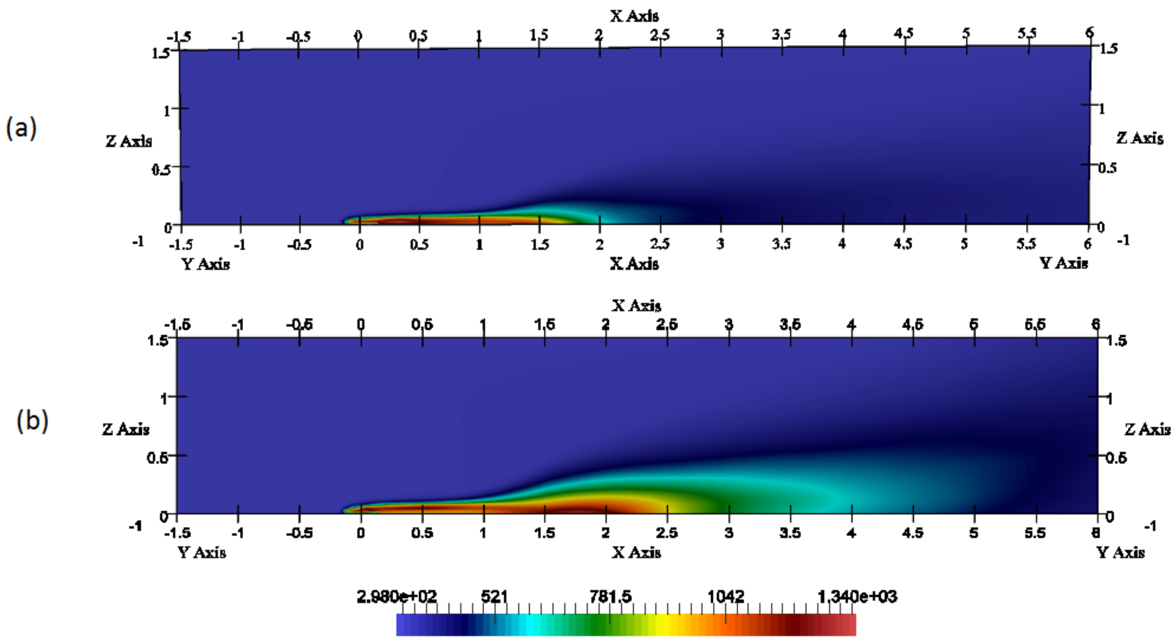

Figure 4 Temperature distributions of the cases with fire intensity of (a) 580KW and (b) 1.5MW

6. Conclusions

This study used Computational Fluid Dynamics to investigate the effects of fire intensity on fire wind enhancement. The results of this study can be concluded as below:

- With the increase of fire intensity, a higher velocity enhancement is generated.
- Enhancement of fire happens in the fire plume region and is more intense where there is a higher temperature difference with the ambient air.
- Fire plume region and correspondingly wind velocity enhancement region is extended when fire intensity increases.

7. Acknowledgement

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