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Effect of wind speed on wildfire interaction with multiple structures in the wildland–urban interface

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Abstract: Structure loss in wildland fires has substantially escalated during the last few decades, affected by expanded development in the countryside region, variation in fuel treatment strategies, and climate change. Wildland-urban interface (WUI) fires are a complex multi-physics problem, especially with wind direction and speed varying along natural environments. Comprehending the influence of wind speed on the behaviour of wildland fires and the resulting thermal effects is vital for accurately predicting the damage that structures may incur when exposed to such fires.

This paper presents a numerical modeling approach to investigate the effect of wind speed variation on the thermal heat flux and temperature profiles of an array of structures in a typical WUI area. To simulate the effects of a wind-driven wildfire on a suburban area, nine cubic structures, each measuring 6 × 6 × 6 m, were arranged in a grid of three rows of three. The size and shape of these structures were modeled after those used in the full-scale Silsoe cube experiment (Richards and Hoxey 2012).

The numerical modelling was performed using FireFOAM, a coupled fire-atmosphere model supported by a large eddy simulation (LES) solver in an open-source CFD tool called OpenFOAM. A set of two wind velocities was modelled to simulate fires burning with an intensity of 10 MW/m. The accuracy of the numerical results was confirmed by comparing them with the aerodynamic measurements of a full-scale building model under normal conditions, without the presence of fire. This analysis revealed the key physical factors that influenced the spread of the fire and its thermal effects on the buildings.

The results show that at a constant fire intensity of 10 MW/m^2, an increase in wind speed from 6 m/s to 12 m/s causes an increase in the surface temperature of all buildings, however, the temperature rise is higher on the first row of buildings compared to the second and the third row. A comparison of the temperature contours at wind speeds of 6 m/s and 12 m/s also revealed that both the average and local temperatures increased with higher wind speeds, reaching a maximum value. However, further increases in wind speed up to 12 m/s resulted in a decrease in the temperature downstream of the fire source due to convective cooling.

Furthermore, the analysis of the surface temperature profile ahead of the fire front revealed that the presence of buildings has a significant impact on the development and formation of buoyant instabilities, which directly influence the behaviour of the advancing fire line. This integrated approach of fire-atmosphere modeling represents a crucial advancement in comprehending the dynamics and potential consequences of large wind-driven wildfires in the WUI region.

Despite the limitations posed by experimental results in studying the effects of wind-driven wildfires on structures, the current research aims to contribute to the understanding of fire behaviour prediction in WUI. This article serves as an initial report on the application of CFD modeling to examine how variations in wind speed affect wind-fire interaction with multiple buildings in the WUI area.

Keywords: *Wildland fires, CFD modeling, multi-buildings, wind speed, simulation*

1. INTRODUCTION

Much of Australia is susceptible to catastrophic wildfires. Climate projections suggest the frequency of these events and the risk to communities and infrastructure in bushfire-prone regions are destined to increase (Sullivan, A. L., 2010). Buildings and other structures in the WUI respond to the exposure conditions created by adjacent wildland fires. These exposure situations are specified as flames associated with radiation, direct flame contact, and ember exposure (Caton et al., 2016).

Subject to the exposure circumstances, buildings and other forms of structures may burn as a wildland fire propagates near a WUI community (Mell et al., 2010, Ghaderi et al., 2020) . Eventually, structures should ignite so that fires spread into the community. Thus, realizing the ignition possibility of structures and improvement tactics to lessen or stop their ignition is one approach to cutting down WUI losses.

The destruction of homes at the interface is largely caused by a lack of connection between building codes and standards and the potential risk of fire and ember exposure. The currently available information and the research are insufficient to cover the complete range of realistic WUI exposures to a wildland fires, and they do not provide adequate guidance for designing landscapes and buildings that are resistant to ignition.

In areas with high-density communities, fires that originate from a fully engulfed single-family residence can spread quickly and become difficult to contain, particularly in windy conditions. The ability of a structure to survive such an event depends on the way it was constructed and the duration and intensity of exposure to flames and embers. Embers that are produced by a structure that is burning intensely can ignite structures that are hundreds of meters away, and intense heat radiating from a burning structure can ignite a structure that is several meters away. Therefore, it is imperative to maintain a sufficient separation distance between structures in order to control the spread of fire between them.

Computational fluid dynamics codes have become increasingly essential in comprehending the physical processes underlying fire behavior and enhancing our capacity to predict it. These computational tools are commonly utilized to supplement laboratory-scale investigations and to overcome the challenge that laboratory-scale study outcomes are often challenging to apply directly to large-scale wildfire conditions. Grishin's pioneering multiphase wildfire model (Grishin et al., 1986), which was the first fully physical model of its kind, laid the groundwork for the development of more advanced and fully physical wildfire models that can handle additional physicochemical phenomena such as WFDS (Mell et al., 2013) and FIRETEC (Pimont et al., 2011).

Although full physical models have been widely used to improve our understanding of wildfire behaviour, including mechanisms for fire spread (Rothermel, R.C., 1972; Frangieh et al., 2020; Morvan et al., 2018; Andrew L. Sullivan 2009), there have been relatively little research on fire spread in WUI fires. Consequently, the mechanisms of fire spread in such fires are not well-understood. However, some recent efforts have been made to investigate fire configurations more relevant to WUI fires such as those of (He et al., 2011; Fryanova and Perminov, 2020) but on single building configuration which is not representative of a realistic WUI scenario.

This study explores the fundamental mechanisms of how the interaction of horizontal cross-wind flow of different velocities with a fire line, alters the heat flux around a set of multi buildings and the surface temperature of the buildings downstream of the fire source. FireFOAM was used as a CFD solver in this study. This solver is a derivative of the OpenFOAM platform (Jasak et al., 2007), specifically designed for fire dynamic simulations.

The key purpose of this article is to present the results of simulations performed to evaluate the effects of variations in wind speed on the interaction between wind and fire, and how it affects a group of nine cubic buildings arranged in a row of three. The simulations were aimed at determining the amount of thermal exposure from a line fire source with a known intensity to each individual structure, as well as from one group of structures to the next.

2. NUMERICAL MODELING

In this paper, nine 6 × 6 × 6 m cubes are used to represent a WUI area, impacted by a wind-driven wildfire. The geometric dimensions of each cubic structure are the same as those used in the full-scale Silsoe cube experiment of Richards and Hoxey (2012). The designed WUI community is surrounded by a 75 × 50 × 25 m computational domain as shown in Figure 1.

A static fire source running across the entire domain was placed 15 m upstream of the first row of buildings to mimic a line fire configuration with a fixed fire line intensity of 10 MW/m, equivalent to a common wildfire setting over a fuel load of 0.4 kg/m[2], which characterizes "average" grassland fuels (Byram, 1959). At the inlet of the domain, a velocity profile for the inflow was implemented using Equation (1), which follows a power-law pattern.

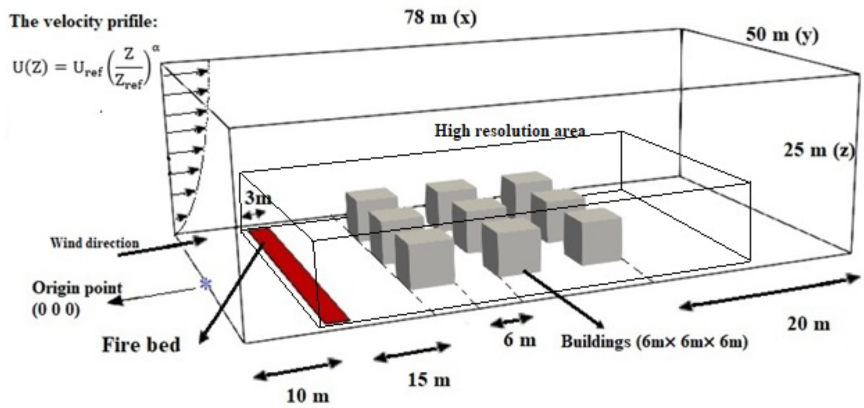

Figure 1. Schematic of computational domain and the location of the buildings

$$u^{*} = \frac{U(Z)}{U_{ref}} = (\frac{Z}{Z_{ref}})^{\alpha} \qquad (1)$$

In the above equation, Zref is the reference height which is equal to the building's height (6m) and Uref is the reference velocity equal to 6 and 12 m/s to investigate the effect of moderate and strong breeze (Beaufort, 1977) on the fire behavior. Alpha is a function of terrain characteristics and is assumed to be 0.16 in the present study. A typical atmospheric pressure condition was applied for the top and outlet boundaries. Also, the side boundaries were treated as free-slip boundaries.

A successive zonal refinement technique was implemented to produce a high quality grid. As part of this approach, a subdomain measuring 58m x 40m x 10m was established to capture the complex vortical flow structures that emerge behind the building with precision. The next refinement level of the grid was dedicated to resolving the near-wall areas surrounding the building. Moreover, a spanwise refinement was adopted across the entire domain to ensure that the mesh close to the floor is of high resolution.

2.1. Model description

FireFOAM (Wang et al., 2011), which is a finite volume solver based on Large Eddy Simulation (LES) and is available as a C++ library in the OpenFOAM CFD package, was used to perform numerical simulations. FireFOAM has a range of efficient CFD sub-models that can describe processes such as pyrolysis, combustion, turbulence, and radiant heating. The prevalent method to simulate fire dynamics, as outlined by Favre, A. (1983), involves solving the Favre-filtered equations for continuity, momentum, energy, species, and state, which pertain to fully compressible flow.

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i} = 0 \qquad (2)$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\bar{\rho}(\upsilon + \upsilon_t)\left(\frac{\partial(\tilde{u}_i)}{\partial x_j} + \frac{\partial(\tilde{u}_j)}{\partial x_i} - \frac{2}{3}\frac{\partial(\tilde{u}_k)}{\partial x_k}\delta_{ij}\right)\right] - \frac{\partial(\bar{P})}{\partial x_i} + \bar{\rho}\, g_i\,, \qquad (3)$$

$$\frac{\partial(\bar{\rho}\tilde{h})}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j\tilde{h})}{\partial x_j} = \frac{D\bar{P}}{Dt} + \frac{\partial}{\partial x_j}\left[\bar{\rho}\left(\alpha_t + \frac{\upsilon_t}{Pr_t}\right)\left(\frac{\partial\tilde{h}}{\partial x_j}\right)\right] + \dot{q}''' - \nabla.\dot{q}_r'', \qquad (4)$$

$$\frac{\partial(\bar{\rho}\widetilde{Y_m})}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j\widetilde{Y_m})}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\bar{\rho}\left(D_c + \frac{\upsilon_t}{Sc_t}\right)\frac{\partial(\widetilde{Y_m})}{\partial x_j}\right] + \omega_m, \qquad (5)$$

$$\bar{P} = \bar{\rho}R\tilde{T}, \qquad (6)$$

where, "‾" and "~" indicates spatial and Favre filtering, correspondingly. p is the static pressure, h signifies the total enthalpy, Y_m is the mass fraction of species m, g is the gravitational acceleration. Pr_t, Sc_t, D_c , υ, υ_t, P, R, α_t, δ and ω_m are the turbulent Prandtl number, turbulent Schmidt number, laminar diffusion coefficient, laminar viscosity, turbulent viscosity, density, gas constant, thermal diffusion coefficient, Kronecker delta and production/sink rate of species m due to gas reaction, respectively. Coupled velocity and pressure is applied in the PIMPLE scheme, which is used by FireFOAM, and the combustion Eddy Dissipation Model (EDM) is also used in this numerical model.

2.2. Model validation

In order to validate the numerical model, two different experimental data sets are utilized. The first set of experiments entails taking measurements of pressure on both the horizontal and vertical centerlines of the Silsoe 6m cube as suggested by Richards and Hoxey (2012). These researchers have generated a comprehensive non-overlapping dataset consisting of tap pressure measurements on the surface of the cube and upstream approach flow measurements at the height of the cube. The second experiment used to authenticate the present simulation is based on the research conducted by Castro and Robin (1977). They studied the flow over surface-mounted cubes in uniform, irrotational, and sheared turbulent flows and reported measurements of body surface pressures, as well as average and oscillating velocities within the wake.

In addition to the two aforementioned empirical analyses, which were carried out in the absence of fire, the current numerical model is also validated through comparison with the numerical study conducted by He et al. (2011). He et al. (2011) utilized the Fire Dynamic Simulation (FDS) package to predict the distribution of pressure coefficients over a building under no-fire conditions. The Eddy Dissipation Concept (EDC) is predominantly influenced by turbulent mixing, and as a result, the dynamic behaviour of fires is closely linked to the aerodynamics of the building. Consequently, the pressure distribution on the structure under no-fire conditions is a logical parameter that indicates the precision and reliability of the numerical results.

Figure 2 shows the graphical representation of the pressure coefficient calculations on the rear, top, and front surfaces of the building, along the centrelines denoted by solid lines 0-1-2-3. The graph includes the results of the current study's numerical calculations, as well as those of previous research, computed from different grids.

Although the simulated data matches well with the experimental investigation of the building's faces, there are still noticeable inconsistencies on the roof face of the cube, indicated by line 1-2. These discrepancies have also been observed in other studies illustrated in Figure 2 and can be attributed to the experimental measurements' high scatter of wind velocity and direction data.

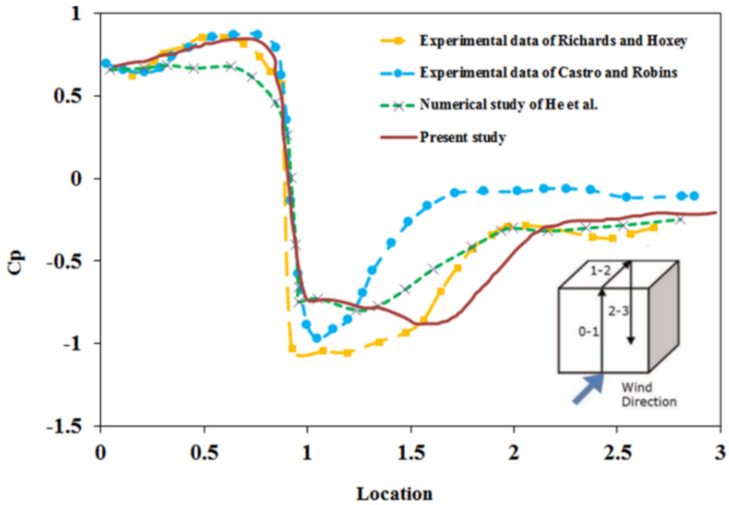

Figure 2. Comparison of the mean pressure coefficient for the experimental studies of Richards and Hoxey (2012) and Castro and Robin (1977) and numerical simulation of He et al. (2011)

2.3. Mesh sensitivity analysis

To minimize numerical uncertainties, a sensitivity analysis of the mesh was conducted on the domain using three different sets of structured mesh sizes: 9.1 million, 12.2 million and 15.8 million. The meshes are uniform in all directions. As mentioned earlier, the resolution of the subdomain mesh was set at five times higher than that of the primary domain. The mesh size in primary domain is 0.5m, 0.165m, 0.5m and in the subdomain is 0.165m, 0.165m, 0.165m. The results of the grid independency study shown in Figure 3, indicate that increasing the number of grid cells initially leads to an increase in the area weighted temperature of the buildings, while a further increase in the number of cells marginally affects this index (integrated temperature).

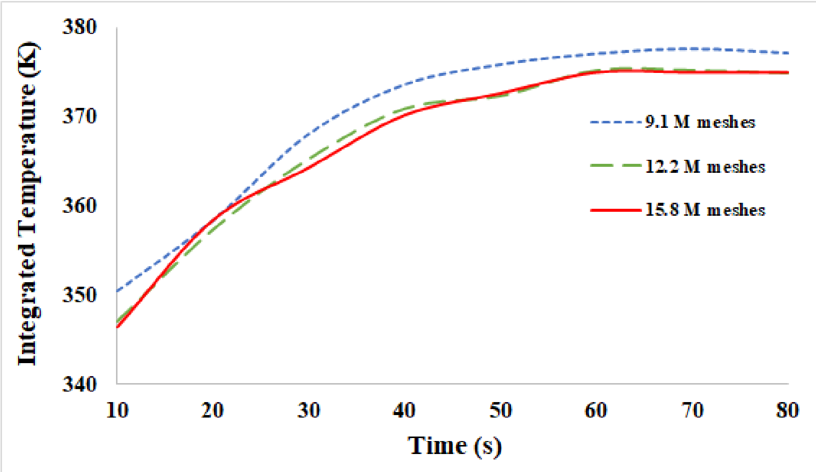

Figure 3. Comparison of the average temperature of the domain versus time for three different grids number

3. RESULTS

The focus of this work is to use a large eddy simulation (LES) fire dynamics transient solver to simulate three-dimensional numerical full-scale model of nine buildings placed in three rows to represent a typical high density WUI area.

In the context of wildfires and their potential impact on structures located in the WUI, wind speed is a crucial factor that distinguishes these types of fires from other types. This study aimed to investigate the behaviour of fires and downstream aerodynamics when multi building structures are present, with a particular focus on the effect of wind velocity on the fire line and the associated hazards posed to multiple structures. By examining the fire characteristics and aerodynamic behaviour at two different wind speed values, this research sheds light on the importance of understanding the impact of wind velocity on the behaviour of wildfires and the hazards they can generate. Ultimately, this information can be used to inform modeling efforts aimed at predicting the behaviour of wildfires in the WUI and improving the safety of structures located in these areas. Figures 4 and 5 compare the effect of wind speed variation on the temperature distribution downstream of the fire source at constant burning intensity of 10 MW/m. As can be seen in Figures 4 and 5, increasing wind speed from 6m/s to 12 m/s causes the flame to tilt further towards the first sets of buildings (three buildings which placed in the first row).

Comparing the temperature contours under wind speed of 6 m/s and 12 m/s highlights that both average and local temperature intensified with raising wind speed and reached to a maximum value (Figure 4a). Further increase in wind speed up to 12 m/s decreases the temperature of domain downstream of the fire source which is due to convective cooling. Also, increasing wind speed results in tilting the flame more toward the ground and changes the view factor and consequently, reduces the radiant energy leaving the fire incident on the surface of the cubes and decrease the temperature.

As wind velocity increases, the concentration of oxygen in the area surrounding the fire also increases, resulting in an initial rise in temperature (Figure 4a). However, as the wind velocity continues to increase, a phenomenon known as "convective cooling" comes into effect and begins to decrease the temperature of the flame as depicted in Figure 5a. Therefore, while wind velocity and temperature initially exhibit a direct relationship, their connection can become inverse as convective cooling becomes more dominant. Figure 5a demonstrates this dynamic relationship between wind velocity and temperature, where the curve representing temperature initially slopes upward but then flattens and begins to slope downward as wind velocity increases further. Ultimately, this illustrates the complex and nuanced interplay between wind velocity and temperature in the context of a fire.

(a)

(b)

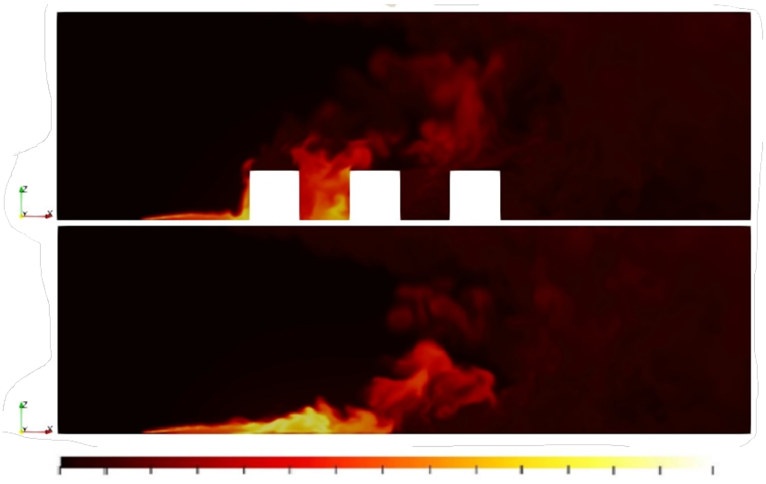

Figure 4. The contour of temperature distribution for the case with U= 6 m/s and I= 10 MW/m: (a) cross section at y=0m (b) cross section at y=6m

(a)

(b)

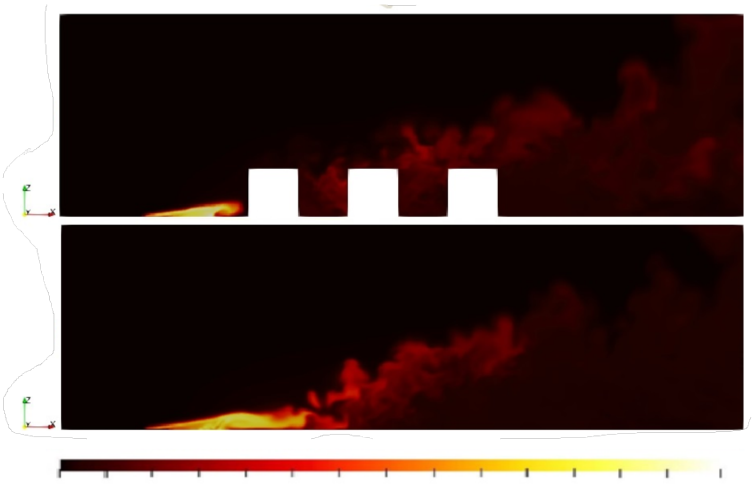

Figure 5. The contour of temperature distribution for the case with U= 12 m/s and I= 10 MW/m: (a) cross section at y=0m (b) cross section at y=6m

4. DISCUSSION AND CONCLUSION

A 3D CFD analysis of the dynamic characteristics of wind-driven line fires and their impacts on an array of buildings consists of nine cubic structures has been presented, with a focus on the impact of wind speed variation on multibuilding scenario in WUI.

The methodology used in this study involved developing a model based on Large Eddy Simulation (LES) of a wind-driven fire. The FireFOAM solver, an open-source Computational Fluid Dynamics (CFD) software designed specifically for fire dynamic modeling and the simulation of turbulent diffusion flames, was utilized to derive this model. The results of the numerical simulations were then compared with empirical data collected under no fire conditions. The comparison revealed a high degree of alignment between the numerical findings and the experimental data, suggesting that the model accurately captures the behaviour of wind-driven fires. Although there are some limitations in this study, including static fire source, and idealized line fire, overall, this methodology helps to investigate the behaviour of fires under different conditions and can be used to inform future research and modeling efforts in this area.

A detailed comparison of the dynamics of the line fire with a known intensity on series of structures located on different distance from source of fire, revealed that change in wind speed, varies the plume geometry and characteristics, also the presence of multi buildings can considerably change the plume attachment pattern.

Raise in wind speed causes a significant increase of the temperature downstream of the source of fire in such a way that even at the back of the building a zone of particularly higher temperature can be seen.

A comparison of the temperature contours at wind speeds of 6 m/s and 12 m/s reveals that, as wind speed increases, both the average and local temperatures become more intense and reach a maximum value (as depicted in Figure 4a). However, at wind speed of 12 m/s and beyond, the temperature of the domain downstream of the fire source begins to decrease, owing to the dominant effect of convective cooling. It should be noted that the notion of a consistent and unchanging correlation between wind velocity and downstream temperature is unfounded, as this relationship is subject to variability.

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