ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Numerical investigation of the effect of wind speed on wildfire interaction with an idealized building

Maryam Ghodrat *[1]; Ali Edalati-nejad [2]; Phillip L. Davies[1]

[1]School of Engineering and Information Technology, University of New South Wales, UNSW Canberra. Campbell, ACT, Australia, {m.ghodrat@unsw.edu.au}
[2]School of Science, UNSW Canberra, Canberra, ACT 2612, Australia, {a.edalatinejad@adfa.edu.au}

**Corresponding author*

Keywords

Wildfire; wind-driven surface fire; wildland-urban interface; LES; FireFOAM

Abstract

This paper presents an investigation into the impact of wind speed on the interaction of wind driven surface fire with an idealized building structure. The open-source large eddy simulation (LES) fire dynamic solver, FireFOAM, was used to simulate fires burning with an intensity of 10 MW/m under different wind speeds. The numerical data was validated using a wind only simulation which compared aerodynamic data to the previous full size experimental and numerical studies. The results show the aerodynamic flow characteristics and their interaction with the idealized structure located downstream of the fire source. Increase in wind speed showed a linear relationship to increase in the coefficient of lift on the building. The local coefficient of pressure on the building was calculated which indicated significant risk of damage due to aerodynamic lift caused by buoyant fire updraft. The results also show that at a constant fire intensity, increasing wind speed leads to an increase in the average temperature of the domain downstream of the fire to a certain value and then decreases.

1. Introduction

Wildfires are a natural disaster which can cause significant damage to the local environment, both natural and man-made. Whilst many plants and animals have adapted to wildfire and require regular fires to maintain biodiversity (Walker et al., 2019), urban structures face high risk of damage and destruction. With large wildfires becoming a more likely occurrence (Theobald & Romme, 2007) and urban sprawl into wildland areas, there is a need for continued study into reducing the risk wildfires pose to urban structures in the wildland-urban interface. Research in this area is useful for improving the design of wildfire resistant buildings, thereby reducing the socioeconomic impact of wildfires in the future.

Wildfire studies using CFD solvers have been used since the 1980s when Grishin and his team developed the first fully physical multiphase wildfire model (Grishin, Zverev, & Shevelev, 1986). From this model more advanced wildfire simulation software has been developed including Wildland Fire Dynamics Simulator (WFDS) (Mell, Charney, Jenkins, Cheney, & Gould, 2013) and FIRETEC code (Frangieh, Accary, Morvan, Méradji, & Bessonov, 2020; Morvan, Accary, Meradji, Frangieh, & Bessonov, 2018; Pimont, Dupuy, Linn, & Dupont, 2011). Several wildfire prediction software programs have been developed to provide fast predictions in an operational environment through simplification of wildfire spread. These are tools based on the Rothermel model (Rothermel, 1972), BehavePlus (Andrews, 2007) and FARSITE (Finney, 1998). These programs perform well during a wildfire but cannot provide accurate data to help improve the understanding of fire spread and damage to buildings on a small scale. This is where accurate fire modelling CFD tools are required, as they provide data that are rather difficult to obtain experimentally. He and his team were the first to carry out a numerical analysis of wind-driven wildfire interaction with an idealized building in 2011 (He, Kwok, Douglas, & Razali, 2011). Since then, studies by Fryanova and Perminov (Fryanova & Perminov, 2017), and Pimont, Dupuy, and Linn (Pimont, Dupuy, & Linn, 2014) investigated the likelihood of structure ignition and the minimum clearing distance to avoid ignition caused by radiation and convective effects. In 2020 Ghaderi and his team used fireFOAM to investigate wind-driven wildfire interaction with an idealized building focusing on the radiative heat flux experienced by the building (Ghaderi, Ghodrat, & Sharples, 2020). Further research is

https://doi.org/10.14195/978-989-26-2298-9_111

required into the interactions between wind-driven wildfires and urban environments to prevent loss of life and property. In the present study, the effect of wind speed, at a constant fire intensity, on the fire-line dynamics, downstream temperature, and local pressure coefficient along the centrelines over the front, top and rear surfaces of an idealised building investigated. The results of this research will help inform decisions in building design in the Wildland Urban Interface.

1.1. Model description

1.1.1.Case design

The modeling case was designed to be a simplified representation of a wildfire interaction with an idealised building. The line fire is a fixed mass flow rate inlet of methane. The mass flow rate is fixed to produce a 10 MW/m line fire intensity, representing a typical grassland fuel fire propagating at a rate of spread of 0.75m/s and a fuel load of 0.4kg/m^2 (Byram, 1959). The idealized building was chosen to be a six-meter cube, as was used in several previous studies on wind-building interactions (Castro & Robins, 1977; Ghodrat, Shakeriaski, Nelson, & Simeoni, 2021; Richards & Hoxey, 2012). This provides reference data for qualitative and quantitative validation of the modeling case. The size of the computational domain was chosen to be 50 ×30 × 25 m to minimize adverse boundary condition effects as per the recommendations by Richards and Norris (Richards & Hoxey, 2012) in their work on LES modelling of unsteady flow around the Silsoe Cube (Figure 1a). The five-meter distance from the inlet to the line fire was chosen to provide proper boundary layer development and reduce the sensitivity to the inlet velocity profile at the price of greater simulation cost.

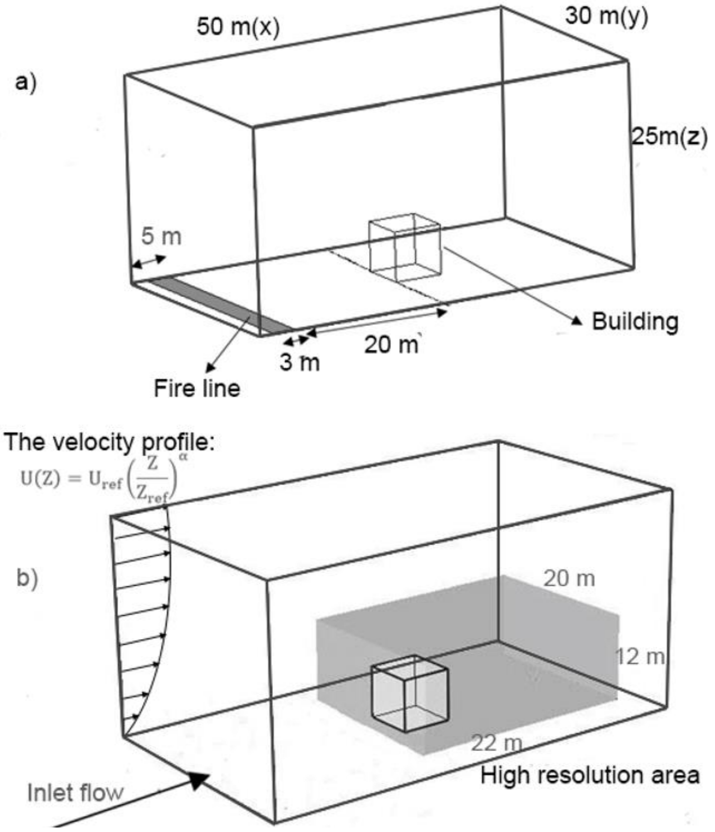


Figure 1- Schematic of the computational domain and the location of fire source and the building. (a) the calculated domain (b) Subdomain configuration

The inlet velocity profile is a power-law inflow velocity profile superimposed with random noise to simulate a realistic turbulent wind (Equation 1). This equation simulates the expected boundary layer formation, allowing for a reduction in the length of the flow development section prior to the fire, thereby reducing simulation cost (Bonnet, Delville, & Lamballais, 2003; Lund, Wu, & Squires, 1998).

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

Where u* is the velocity at each height, U_{ref} is the reference velocity, Z_{ref} is the reference height (6 m). γ is an exponent which corrects for terrain characteristics and assumed to be 0.16 based on the terrain at the experiment site (Lund et al., 1998). The roof and outlet of the simulation were set at atmospheric pressure to allow inflow and outflow as required. The walls are set to be free slip boundaries as suggested by Launder and Spalding (Launder & Spalding, 1983).

The mesh was created using consecutive reginal refinement. First a subdomain of size 22×20×12m was determined all over the building to make sure the complex vortical flow structures generated behind the building were recorded precisely (see Figure 1b). The next level of mesh refinement was arranged to sort out the near-wall regions around the building. In addition a high-resolution mesh near the floor was defined and provided all over the domain.

1.2. Numerical modeling

In the present paper, FireFOAM, as a well-known computational tool in fire research, was employed. FireFOAM is an open-source CFD code based on OpenFOAM, capable of being used for diffusion flames modeling. It has been successfully used for many practical applications such as solid fuel pyrolysis (Liu, Wang, & Zhang, 2020), fire suppression (Myers, Trouvé, & Marshall, 2018), and fire-wall interaction (Ren, Wang, Vilfayeau, & Trouvé, 2016).

The Favre-filtered formulation of the fully compressible Navier-Stokes equations representing the fire dynamics in the most common form is written as a set of conservation equations of mass, momentum, energy, and chemical species mass fraction (Poinsot & Veynante, 2005):

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla.(\bar{\rho}\tilde{u}) = 0 \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{u}}{\partial t} + \nabla.(\bar{\rho}\tilde{u}\tilde{u}) = -\nabla\bar{p} + \nabla.\left[\left(\mu + \mu_{sgs}\right)\left(\nabla\tilde{u} + (\nabla\tilde{u})^{T} - \frac{2}{3}(\nabla.\tilde{u})I\right)\right] + \bar{\rho}g \tag{3}$$

$$\frac{\partial \bar{\rho}\widetilde{Y_k}}{\partial t} + \nabla.(\bar{\rho}(\tilde{u} + \tilde{u}_c)\tilde{Y}_k) = \nabla.\left[\left(\frac{\mu_{sgs}}{Sct} + \bar{j}_k\right)\nabla\widetilde{Y_k}\right] + \overline{\dot{\omega}_k}^{'''} \quad k = 1, \dots, N_s - 1 \tag{4}$$

$$\frac{\partial \bar{\rho}\widetilde{h_s}}{\partial t} + \nabla.(\bar{\rho}\tilde{u}\tilde{h}_s) = \frac{D\bar{p}}{Dt} + \nabla.\left[(\alpha + \alpha_{sgs})\nabla\tilde{h}_s\right] - \nabla.\overline{\dot{q}_r}^{''} + \overline{\dot{q}_c}^{'''} + \nabla.(\alpha\sum_{k=1}^{N_s}(h_{s,k}\nabla\tilde{Y}_k)) + \nabla.(\sum_{k=1}^{N_s}(\bar{j}_k h_{s,k})) \tag{5}$$

In these equations, ρ, P, u, h_s, Y, Sct are the density, pressure, velocity, sensible enthalpy, mass fraction, and turbulent Schmidt number. The symbols "–" and "~" show spatial and Favre filtering. $\overline{\dot{q}_c'''}$ is the heat generated by combustion (assuming complete combustion, i.e., $\chi = 1$) and $\overline{\dot{q}_r''}$ is the total radiation heat transfer emission intensity (W/ m^2) of the gas mixture. The eddy dissipation concept (EDC) (Magnussen & Hjertager, 1977) was used for combustion modeling. The infinitely-fast reaction assumption was applied to determine the reaction mechanism as the EDC in coupled with the infinitely-fast combustion model reveals higher superiority in modeling well-ventilated diffusion flames (Wang, Chatterjee, & de Ris, 2011).

1.3. Validation

Two methods of validating the numerical model were used to ensure both simulation accuracy and grid independency. Validation of simulation accuracy of the aerodynamic component of FireFOAM was achieved through a wind-off test. The coefficients of pressure measured on the building were compared to previous experimental results and numerical results by Castro and Robins (Castro & Robins, 1977) and He et al. (He et al., 2011), respectively. Both tests were run in a similar condition with an identical building (6 m cube) and wind speed (U $_{ref}$= 6m/s), and the measured and calculated coefficients of pressure can therefore be directly compared. Experimental data to validate grid independence was created by running three cases with differing mesh refinement. The grid numbers were set to 6, 8, and 10 million. The result of the validation cases showed good similarity in the area from 0-1 and 2-3 but not between 1-2. The three mesh refinements produced very similar results and therefore the 8 million cell grid was selected for all simulations.

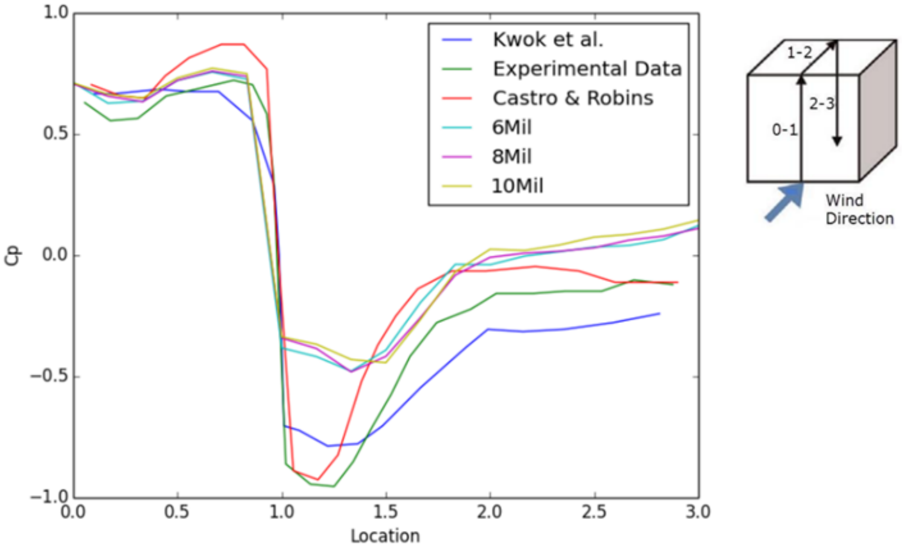
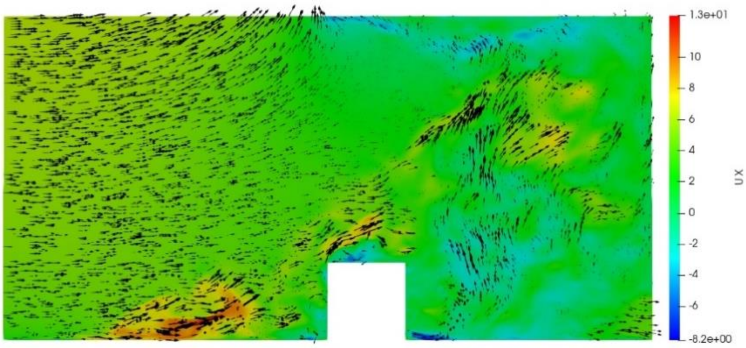


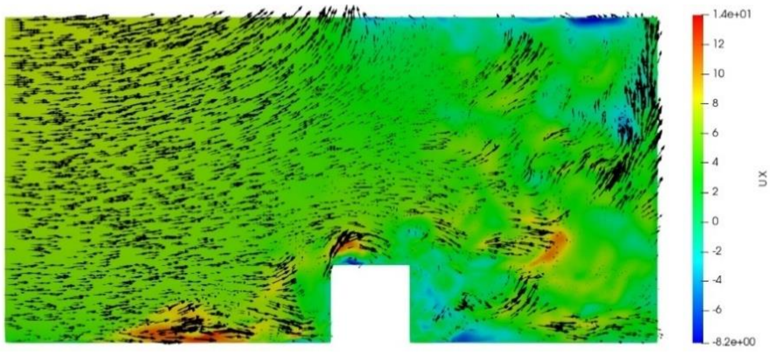
Figure 2- Comparison of the measured mean pressure coefficients on the building centreline, U_{ref}=6 m/s (no-fire case).

2. Results and discussion

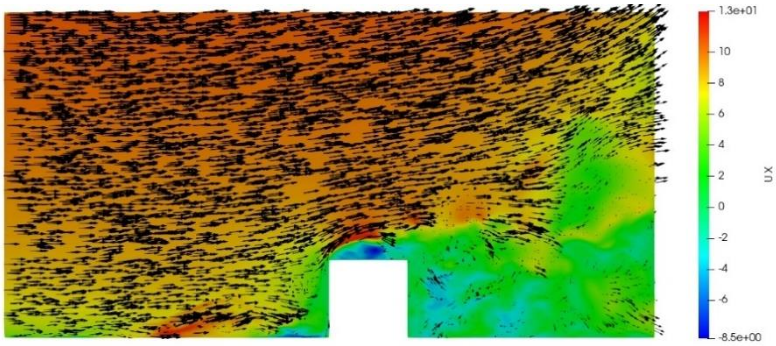
The present study examined the simulated impact of a dynamically varying wind-field on a motionless heat source, correspond to a line fire configuration. The modeling results allowed analysis of the transient fire behaviour under different wind velocities (4.5 m/s, 6m/s and 7.5 m/s) and constant fire intensity of 10 MW/m. Figure 3 shows the time dependent flow pattern of wind speed variation in the fire field. As shown, increasing wind speed leads the fire front to be leaned towards the ground downstream of the line-fire bed. This is largely associated with the inertia forces becoming more dominant in this region with rising wind speed. Furthermore, as can be seen from the wind speed contours, air entrainment hooked on the turbulent surface line fire generates a low-pressure zone in the flame-ground area in front of the fire and due to this the fire plume is accelerated and create an area attached to the ground.



(a)



(b)



(c)

Figure 3- Vertical transects of instantaneous streamwise wind speed component and corresponding velocity vectors at different lateral locations. (a) U_{ref}=4.5 m/s (b)U_{ref}=6 m/s (c) U_{ref}=7.5m/s

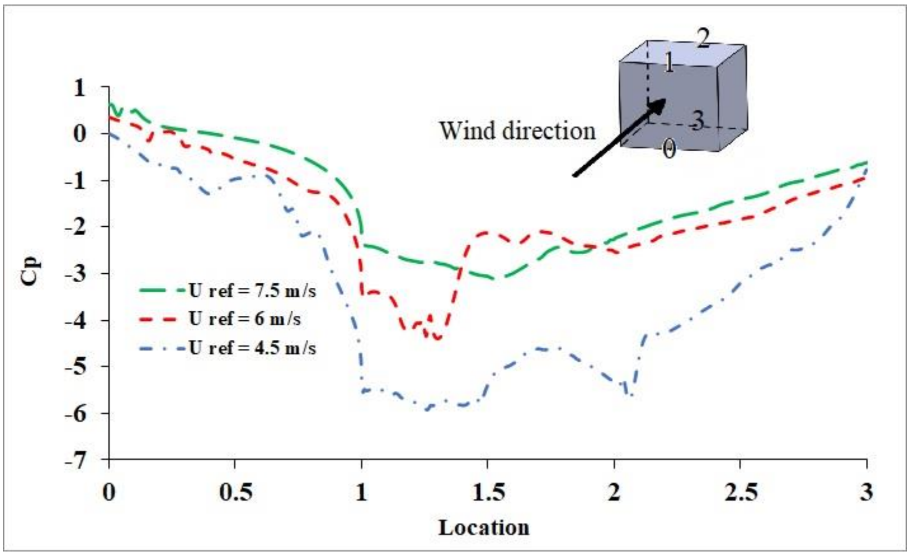
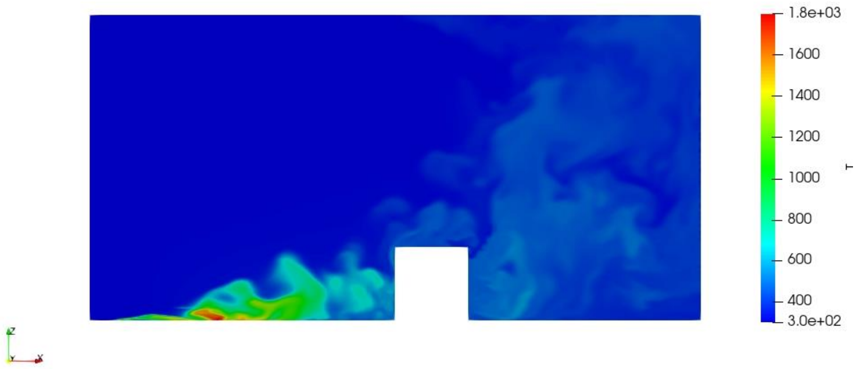
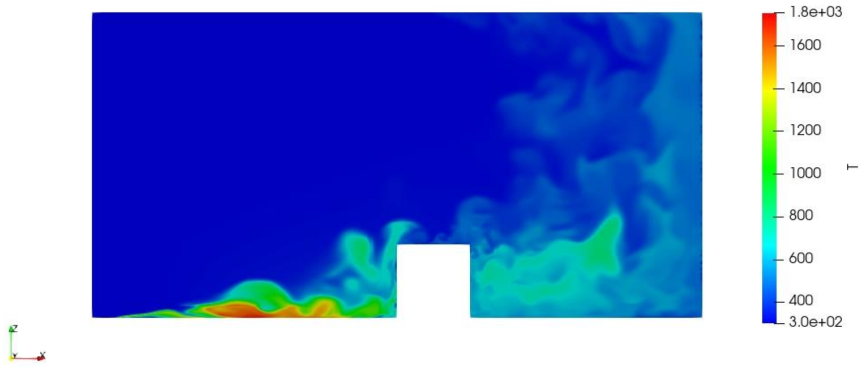


Figure 4- Coefficients of pressure on different location on the building under different wind speed

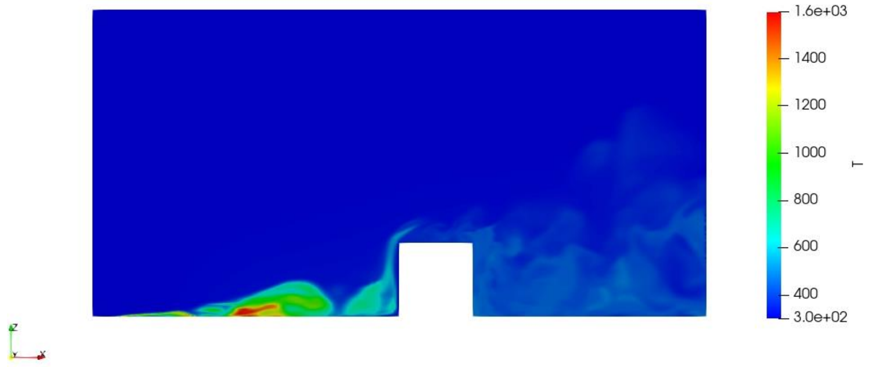
Figure 4 compares the coefficients of pressure on different location of the building with the focus on the front and back surface and the roof of the building during the three test cases for three wind velocities. The result shows strong negative coefficient of pressure primarily on the roof of the building, between locations one and two. The strong updraft created by the buoyant fire combined with the vortex's development on the roof of the building, seen in the visual analysis above, are responsible for creating this. The lowest negative coefficient of pressure decreases with increasing wind velocity, meaning higher wind velocities generate more lift on the roof and may have the potential to cause both window and roof failure (Castro & Robins, 1977).



(a) 4.5 m/s



(b) 6m/s



(c) 7.5 m/s

Figure 5- Temperature profile downstream of the line-fire source under different wind speed

Figure 5 shows 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 this figure increasing wind speed causes the flame to tilt further towards the building. Comparing the temperature contours under wind speed of 4.5 m/s and 6 m/s highlights that both average and local temperature intensified with raising wind speed and reached to a maximum value at wind speed of 6m/s (Fig. 5 a). Further increase in wind speed up to 7.5 m/s decreases the temperature of domain downstream of the fire source as the convective cooling become (Fig 5 c).

3. Conclusion

This paper detailed a numerical investigation into the effect of varying wind velocity in a simulated idealised structure using FireFOAM. The results show the flow characteristics expected in the wildfire structure interactions as well as the associated effects. The coefficient of pressure on the roof decreases dramatically with increased wind speed creating a large lifting force which has the potential to cause failure. The results also show that at a constant fire intensity, increasing wind speed leads to an increase in the average temperature of the domain downstream of the fire to a certain value and then decrease.

4. Reference

Andrews, P. L. (2007). *BehavePlus fire modeling system: past, present, and future.* Paper presented at the In: Proceedings of 7th Symposium on Fire and Forest Meteorology; 23-25 October 2007, Bar Harbor, Maine. Boston, MA: American Meteorological Society. 13 p.

Bonnet, J.-P., Delville, J., & Lamballais, E. (2003). *The Generation of Realistic 3D, Unsteady Inlet Conditions for LES.* Paper presented at the 41st Aerospace Sciences Meeting and Exhibit.

Byram, G. M. (1959). Combustion of forest fuels. *Forest fire: control and use*, 61-89.

Castro, I., & Robins, A. (1977). The flow around a surface-mounted cube in uniform and turbulent streams. *Journal of fluid Mechanics, 79*(2), 307-335.

Finney, M. A. (1998). *FARSITE, Fire Area Simulator--model development and evaluation*: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Frangieh, N., Accary, G., Morvan, D., Méradji, S., & Bessonov, O. (2020). Wildfires front dynamics: 3D structures and intensity at small and large scales. *Combustion and flame, 211*, 54-67.

Fryanova, K., & Perminov, V. (2017). Impact of forest fires on buildings and structures. *Magazine of Civil Engineering*(7 (75)), 15-22.

Ghaderi, M., Ghodrat, M., & Sharples, J. J. (2020). LES Simulation of Wind-Driven Wildfire Interaction with Idealized Structures in the Wildland-Urban Interface. *Atmosphere, 12*(1), 21.

Ghodrat, M., Shakeriaski, F., Nelson, D. J., & Simeoni, A. (2021). Existing improvements in simulation of fire–wind interaction and its effects on structures. *Fire, 4*(2), 27.

Grishin, A., Zverev, V., & Shevelev, S. V. (1986). Steady-state propagation of top crown forest fires. *Combustion, Explosion and Shock Waves, 22*(6), 733-739.

He, Y., Kwok, K. C., Douglas, G., & Razali, I. (2011). Numerical investigation of bushfire-wind interaction and its impact on building structure. *Fire Saf. Sci, 10*, 1449-1462.

Launder, B. E., & Spalding, D. B. (1983). The numerical computation of turbulent flows. In *Numerical prediction of flow, heat transfer, turbulence and combustion* (pp. 96-116): Elsevier.

Liu, H., Wang, C., & Zhang, A. (2020). Numerical simulation of the wood pyrolysis with homogenous/heterogeneous moisture using FireFOAM. *Energy*, 117624.

Lund, T. S., Wu, X., & Squires, K. D. (1998). Generation of turbulent inflow data for spatially-developing boundary layer simulations. *Journal of computational physics, 140*(2), 233-258.

Magnussen, B. F., & Hjertager, B. H. (1977). *On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion.* Paper presented at the Symposium (international) on Combustion.

Mell, W., Charney, J., Jenkins, M. A., Cheney, P., & Gould, J. (2013). Numerical simulations of grassland fire behavior from the LANL-FIRETEC and NIST-WFDS models. In *Remote Sensing and Modeling Applications to Wildland Fires* (pp. 209-225): Springer.

Morvan, D., Accary, G., Meradji, S., Frangieh, N., & Bessonov, O. (2018). A 3D physical model to study the behavior of vegetation fires at laboratory scale. *Fire Safety Journal, 101*, 39-52.

Myers, T., Trouvé, A., & Marshall, A. (2018). Predicting sprinkler spray dispersion in FireFOAM. *Fire safety journal, 100*, 93-102.

Pimont, F., Dupuy, J.-L., & Linn, R. (2014). Fire effects on the physical environment in the WUI using FIRETEC. *Chapter*.

Pimont, F., Dupuy, J.-L., Linn, R. R., & Dupont, S. (2011). Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC. *Annals of Forest Science, 68*(3), 523-530.

Poinsot, T., & Veynante, D. (2005). *Theoretical and numerical combustion*: RT Edwards, Inc.

Ren, N., Wang, Y., Vilfayeau, S., & Trouvé, A. (2016). Large eddy simulation of turbulent vertical wall fires supplied with gaseous fuel through porous burners. *Combustion and Flame, 169*, 194-208.

Richards, P., & Hoxey, R. (2012). Pressures on a cubic building—Part 1: Full-scale results. *Journal of wind engineering and industrial aerodynamics, 102*, 72-86.

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels* (Vol. 115): Intermountain Forest & Range Experiment Station, Forest Service, US ….

Theobald, D. M., & Romme, W. H. (2007). Expansion of the US wildland–urban interface. *Landscape and Urban Planning*, *83*(4), 340-354.

Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Ebert, C., Goetz, S., . . . Schuur, E. A. (2019). Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature, 572*(7770), 520-523.

Wang, Y., Chatterjee, P., & de Ris, J. L. (2011). Large eddy simulation of fire plumes. *Proceedings of the Combustion Institute*, *33*(2), 2473-2480.