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The effect of downslope terrain on wildfire dynamics in the presence of a cubic structure

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Abstract

In the current work, a numerical study is performed to investigate the effect of the downslope field by a wind driven surface fire in the presence of an idealised building structure. Fires burning with different intensity values of 4, and 15 MW/m on inclined terrain with various downslope angles of 0, -10, -20, and -30°, and under two different wind speed of 6, and 12 m/s are simulated using a large eddy simulation (LES) solver, implemented in open-source platform FireFOAM. The results are validated with experimental measurements of a full-scale cubic building model. The presented outcomes highlight the physical effect of sloped terrain on a building in the vicinity of a line-fire. The results show that at high wind velocity values, the buildings at the higher downslope terrains are at higher risk of wildfire damages

1. Introduction

Wildfire is a highly complex phenomenon and while it is an important ecological process, it can also have detrimental effects when it spreads from wildland areas and impacts the wildland-urban interface (Verma, 2019). They are important elements of ecosystem management and functional ecosystems (Menage, Chetehouna, & Mell, 2012).

To mitigate the disastrous impact of wildfire and manage its environmental and economic impacts, people interact with wildfires in different ways. This includes the use of prescribed fires to reduce fire hazard and thereby lessen the associated likelihood of damage to assets, particularly in the Wildland-Urban Interface (WUI) (Canfield, Linn, Sauer, Finney, & Forthofer, 2014). The growing pace of urbanization resulting in increasing encroachment of urban development into forested areas, is considered one of the most significant reasons for landscape transformation in many countries including Australia (Manzello et al., 2018).

Protection of assets (dwellings, associates structures and other infrastructure) in areas likely to be impacted by wildfire requires precise assessment of factors, such as wind and topography, that might affect the many facets of a wildfire and its impact on assets in the WUI (Cruz, Sullivan, & Alexander, 2014; Ghodrat, Shakeriaski, Nelson, & Simeoni, 2021a; Hilton et al., 2017; Mell, Manzello, Maranghides, Butry, & Rehm, 2010).

Terrain slope is generally considered to be a key element impacting the way in which wildfires spread (Abouali, Viegas, & Raposo, 2021; Butler, Anderson, & Catchpole, 2007). It is commonly accepted that fires increase speed up a hill and many deadly incidents have been reported linked with the hilly terrain (Butler et al., 2007; Dupuy, Maréchal, Portier, & Valette, 2011).

Wildfire behaviour reflects a wide range of complex physical and chemical processes (Ghaderi, Ghodrat, & Sharples, 2020; Verma, 2019) that encompasses aerodynamic behaviours, topographic impacts (such as terrain slope) (Edalati-nejad, Ghodrat, & Simeoni, 2021; Verma, 2019), atmospheric conditions (Ghodrat et al., 2021a; Ghodrat, Shakeriaski, Nelson, & Simeoni, 2021b)(wind speed and direction, temperature, and humidity), the rate of fire spread (ROS) (Canfield et al., 2014), and the effects of fuel type and state (Edalati-nejad, Ghodrat, Fanaee, & Simeoni, 2022), including fuel moisture content (FMC) (Morvan, 2013). As such, it is infeasible to

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comprehensively account for the myriad effects driving fire behaviour. Instead, researchers have conducted targeted studies that focus on understanding the effects of a small subset of the most significant driving factors, such as Viegas (Viegas, 2004) who carried out an experimental investigation of the combined effect of terrain slope and wind. In this study a plane fuel bed under uniform wind and slope conditions was studied.

These studies provide valuable information about the effect of terrain slope on fire dynamics when fires are spreading upslope. However, there has been considerably less attention paid to scenarios where fires are burning downslope. Sullivan and his co-authors, (Sullivan, Sharples, Matthews, & Plucinski, 2014) developed a rate of spread correction for fires burning downslope, but there is still much to be understood about the dynamics of line fires burning downslope. For example, questions about how negative slopes interact with pyroconvective flows and how they affect the temperature profile downstream of the line-fire source are still relatively unexplored and require further study. Such studies are critical in informing further development of wildfire risk mitigation measures. The outcome of the present study contributes to alleviate the wildfire damages and helps the risk managements, for example, Australian Standard AS 3959 (Debnam, Chow, & England, 2005), the Australian Standard for Building in Bushfire Prone Areas.

In the present investigation, the effect of downslope terrain, at a constant wind speed and fire intensity, on the fire-line dynamics and downstream temperature has been investigated. Moreover, the pattern of heating on an idealised building structure is investigated to better understand the impacts of downslope fires on built assets.

2. Physical model

In the present work, an idealized (cubic) building structure with a size of 6 × 6 × 6 m is located downstream of a fire line. As can be seen in Fig. 1, the size of the computational domain is 50 ×30 × 25 m. The building structure is located 20 m downstream of the fire line.

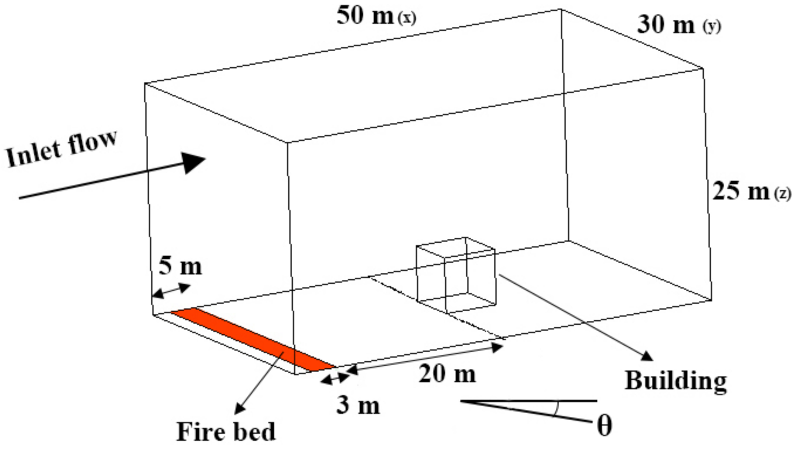


Figure 1- Computational domain and physical model

The fire-line is placed at the edge (near the inlet) of the domain, which is inclined at various downslope angles, with a constant fire intensity and wind velocity to investigate the impact of slope-fire interactions on downstream temperature and air density in the presence of the building structure. In this investigation, a constant fire intensity (Byram, 1959) equal to 15 MW/m is considered, which is equivalent to a forest wildfire (Smith, 2014), and is provided by invoking model parameters in FireFOAM, corresponding to the burning of methane with a heat of combustion equal to 45,435 kJ/kg (Kremer & Schäfer, 1973).

In this model, the boundary layer in the vicinity of the ground has been considered by applying a power-law velocity profile:

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

Where U_{ref} is the reference velocity which in this paper is considered 12 m/s, Z_{ref} is the reference height, which is equal to the building's height (6 m), and α is a constant taken equal to 0.16 based on the terrain category of the experimental study (Tominaga et al., 2008).

The angle of inclination of the terrain, θ, is the angle of gravitational acceleration to the z direction, which is defined via:

$$g_x = -g\sin(\theta) \text{ and } g_z = -g\cos(\theta) \tag{2}$$

3. Numerical modelling

To numerically solve the governing equation of the problem, the FireFOAM solver of OpenFOAM, which is an open-source CFD software, is used. FireFOAM is an efficient tool to simulate wildfire behaviour (El Houssami, Lamorlette, Morvan, Hadden, & Simeoni, 2018; Le et al., 2018). To account for the effects of turbulence, the Large Eddy Simulation (LES) (Wang, Chatterjee, & de Ris, 2011) method is utilized. The governing equations for the problem are as follows:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i}=0 \tag{3}$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\bar{\rho}(\upsilon+\upsilon_t)\left(\frac{\partial(\tilde{u}_i)}{\partial x_j}+\frac{\partial(\tilde{u}_j)}{\partial x_i}-\frac{2}{3}\frac{\partial(\tilde{u}_k)}{\partial x_k}\delta_{ij}\right)\right]-\frac{\partial(\bar{P})}{\partial x_i}+\bar{\rho}\,g_i \tag{4}$$

$$\frac{\partial(\bar{\rho}\tilde{h})}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_j\tilde{h})}{\partial x_j}=\frac{D\bar{P}}{Dt}+\frac{\partial}{\partial x_j}\left[\bar{\rho}\left(\alpha_t+\frac{\upsilon_t}{Pr_t}\right)\left(\frac{\partial\tilde{h}}{\partial x_j}\right)\right]+\dot{q}'''-\nabla.\dot{q}_r'' \tag{5}$$

$$\frac{\partial(\bar{\rho}\widetilde{Y_m})}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_j\widetilde{Y_m})}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\bar{\rho}\left(D_c+\frac{\upsilon_t}{Sc_t}\right)\frac{\partial(\widetilde{Y_m})}{\partial x_j}\right]+\omega_m \tag{6}$$

$$\bar{P}=\bar{\rho}R\tilde{T} \tag{7}$$

where "‾" and "~" show spatial and Favre filtering, respectively, h is the total enthalpy, Y_m represents the mass fraction of species m, P is the static pressure, and g is the gravitational acceleration. $Sc_t, Pr_t, \upsilon, D_c, \upsilon_t, \rho, \alpha_t, R, \delta$ and ω_m are the turbulent Schmidt number, the turbulent Prandtl number, the laminar viscosity, the laminar diffusion coefficient, the turbulent viscosity, density, thermal diffusion coefficient, gas constant, Kronecker delta, and production/sink rate of species m due to gas reaction, respectively. The PIMPLE algorithm (Jasak, 1996)for pressure-velocity coupling, is applied. The differencing scheme of first order upwind is also used.

In order to validate the simulations, the mean pressure coefficients around the idealized building structure for the current work and an experimental measurement of Richards and Hoxey (Richards & Hoxey, 2012) in the absence of fire were compared as shown in Fig. 2. The pressure along the vertical and horizontal centrelines of the Silsoe cube, at the Silsoe Research Institute, UK, has been measured. In this figure, X-axe corresponds the yellow dashed line shown on the cube, starts from point 0, goes to the point 1, passes point 2, and continues to the point 3.

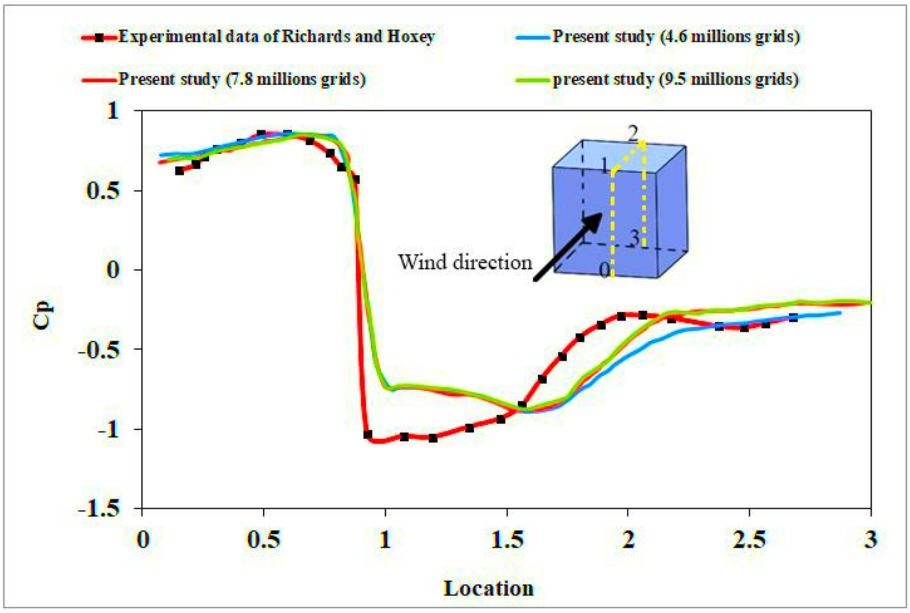
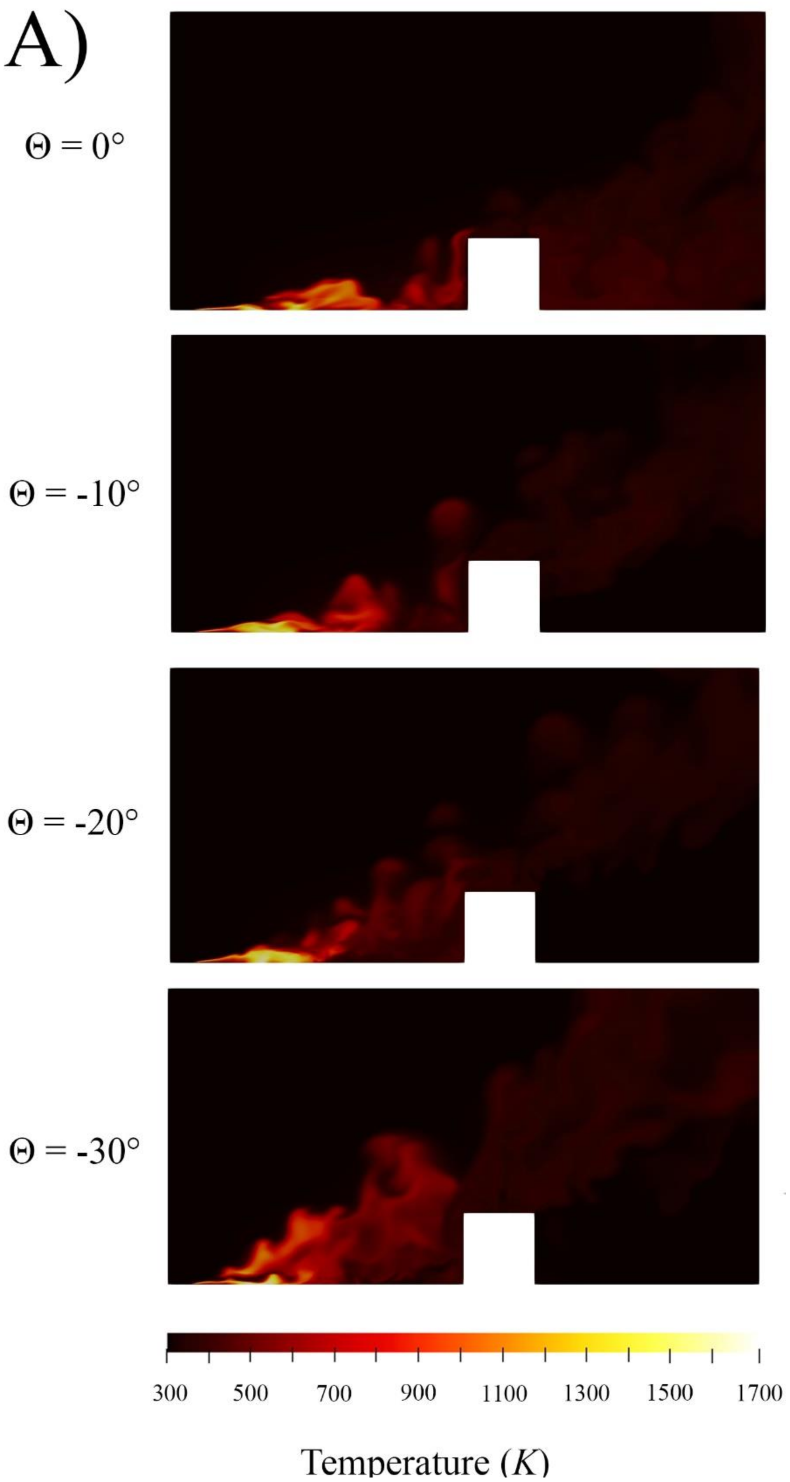


Figure 2- Comparison between the mean pressure coefficient for three different grids number of the current investigation and the experimental measurement (Richards & Hoxey, 2012)

In addition, to study the grid dependency, three different grid numbers of 4,600,000, 7,800,000, and 9,500,000 into the domain have been applied and tested. At the first, increasing the mesh number, changes the mean pressure coefficient, then a further increase will not affect the results. Therefore, the second mesh numbers have been selected for the present study. As can be observed in Fig. 2, there is an acceptable agreement between the present work's results and the experimental measurements.

4. Results

Figure 3 shows the effect of downslope terrain angles on the temperature distribution for the cases at U_{ref} = 6 m/s and fire intensities 4, and 15 MW/m. As can be seen in this figure, at all cases, the wind causes the flames to tilt towards the building. The flame tilt angle is defined as the angle between the centreline of flame and the vertical direction (Li et al., 2021; Li, Wan, Gao, & Ji, 2019). Also, the flame tilt angle decreases as the terrain slope becomes more negative increasing the terrain downslope. This is due to the fact that buoyancy forces cause the flame to rise in the direction opposing gravity, thus reducing the tilt angle. Looking at the figures in more detail, they reflect that in the mentioned cases (U_{ref} = 6 m/s and fire intensities 4, and 15 MW/m), the increasing in the negative downslope, leads to decreasing the risk of being the building in the exposure of high temperature air, caused by the fire.


A)
Θ = 0°
Θ = -10°
Θ = -20°
Θ = -30°
300
500
700
900
1100
1300
1500
1700
Temperature (*K*)

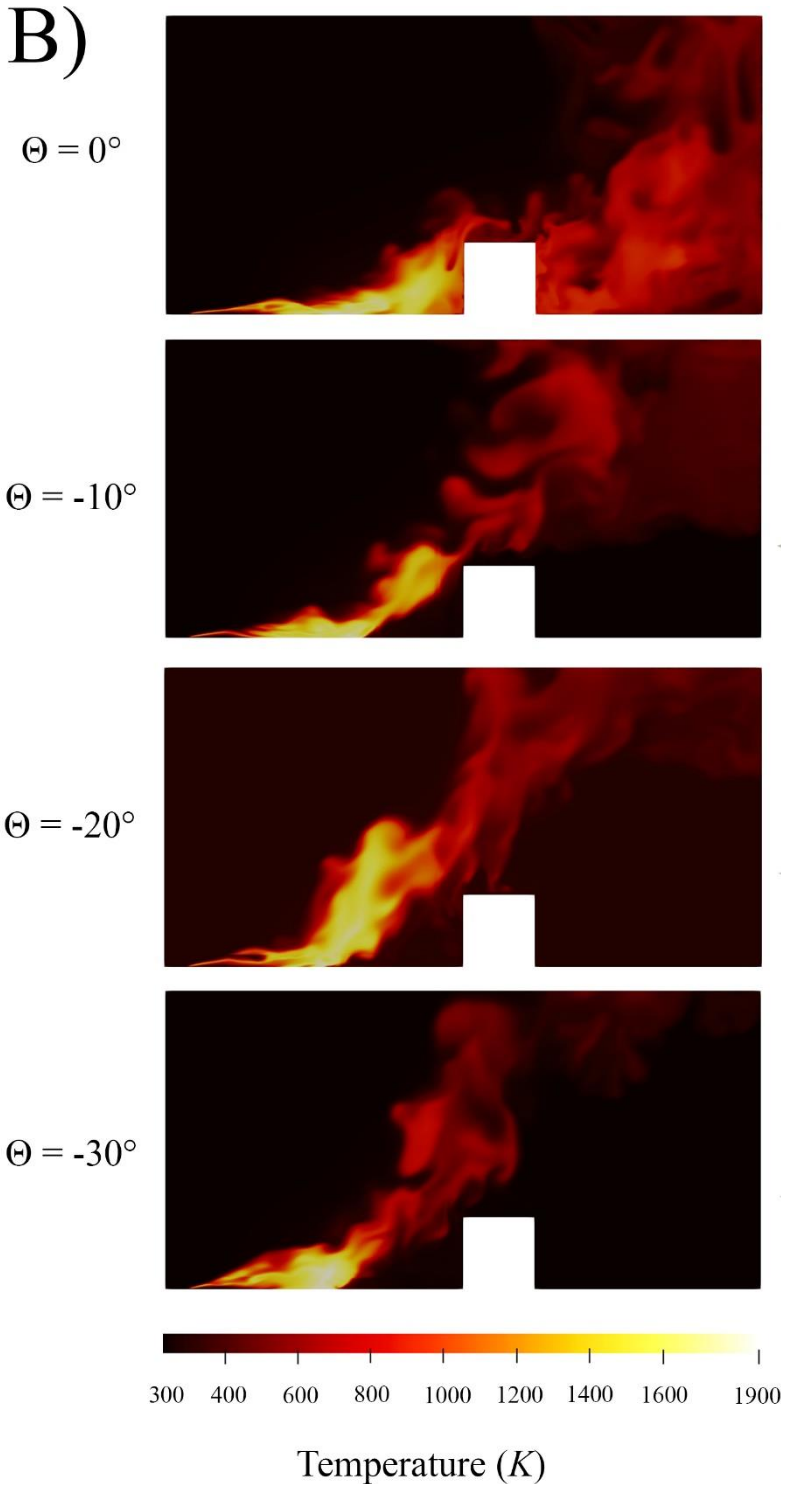


Figure 3- Temperature distribution for the cases at fire intensity (A): 4 MW/m and (B): 15Mw/m and wind velocity 6 m/s for different downslope degrees

Figure 4 shows how the average temperature downstream of the fire-line and the building surface varies with the downslope terrain angle. Considering the effect of wind, the fire plume is directed in the downstream direction so that in the case with no slope, the fire plume is close to the ground. This is due to the effect of wind on enhancing the tilt angle toward to the building. Increasing the downslope angle, decreases the flame tilt angle and the takes the plume closer to the higher altitude surfaces of the building structure. So, for the cases with U_{ref} = 12m/s, an increase in the downslope inclination leads to an increase in the higher temperature region downstream of the fire, which can be seen in Fig. 6. It can also be observed that by increasing the downslope terrain angle, the building temperature increases, for the mentioned cases. This is also due to the combination of the wind speed and the downslope terrain, which have contrary effects on the flame tilt angle in the current cases. For the cases with U_{ref} = 12 m/s (I = 4, and 15 MW/m), increasing the downslope angles from 0˚ to -30˚, increases the average temperature of the building surface by 14%, and 30%, and increases the temperature of the zone downstream of the fire by 3%, and 9%, respectively.

On the other hand, the effect of increasing in the downslope angles, on the temperature of the building surface and downstream, for the cases with U_{ref} = 6m/s, is in the contrast with the cases with U_{ref} = 12 m/s. Because the wind velocity is lower and the fire plume is not that close to the ground, compared to the cases with U_{ref} = 12 m/s. Accordingly, for the cases with U_{ref} = 6 m/s (I = 4, and 15 MW/m), increasing the downslope angles from 0˚ to -30˚, decreases the average temperature of the building surface by 15%, and 30%, and decreases the temperature of the zone downstream of the fire by 3%, and 17%, respectively.

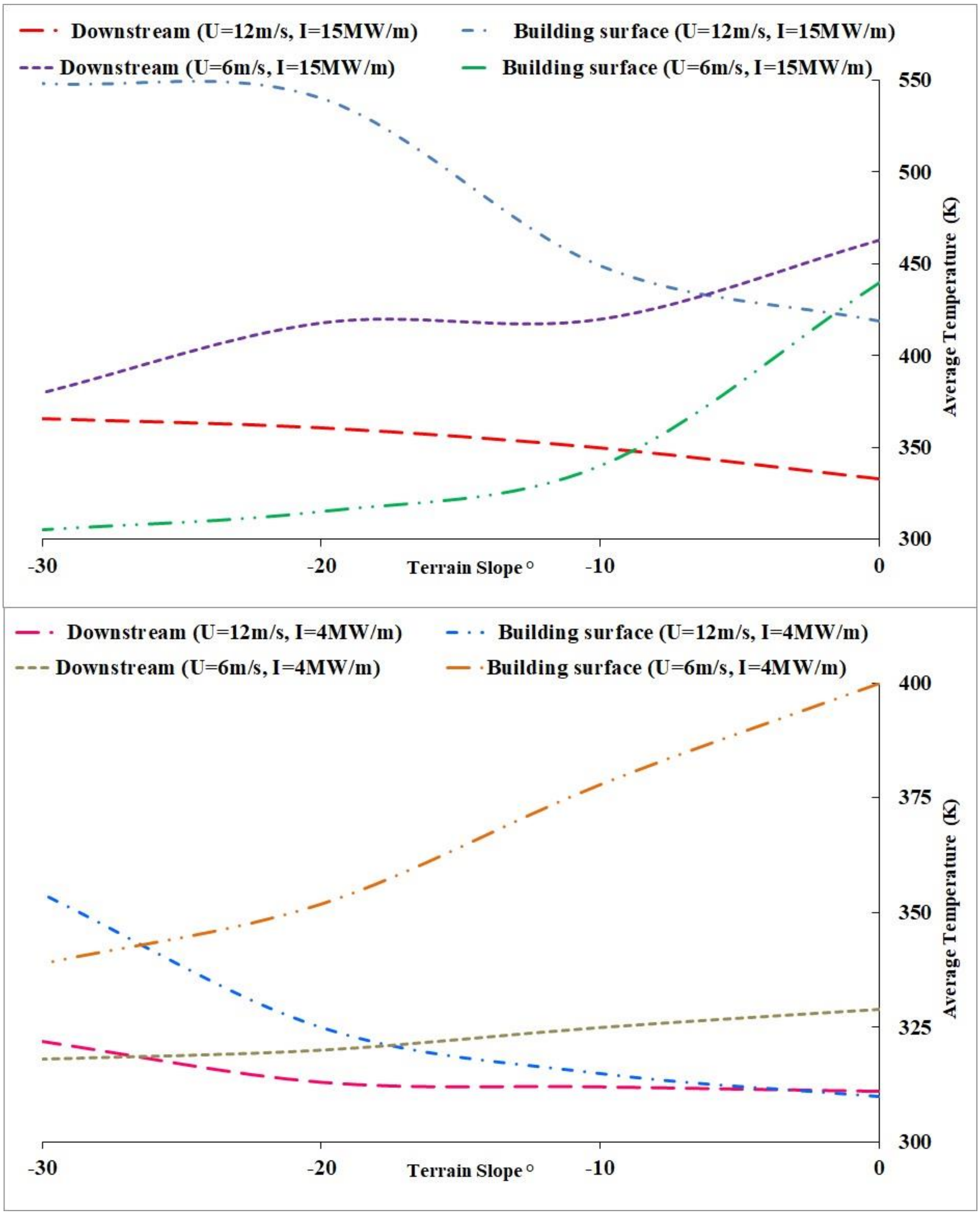


Figure 4- Average temperature of the downstream of the domain and the building surface versus the terrain slope for the cases with U_{ref} = 6, and 12 m/s and fire intensities 4, and 15 MW/m.

5. Conclusion

In the present work, the effect of downslope terrain on fire-line dynamics and downstream temperature, at a constant wind and fire intensity, in the presence of an idealized building structure has been numerically studied. The downslope angles varied from 0˚ to -30° and a wind-field with reference velocity of 6, and 12 m/s and fire intensity 4, and 15 MW/m are considered. The main results of the present investigation are summarized as follows:

- The calculated results show an acceptable agreement with the empirical measurements in the absence of fire.
- At constant wind velocity of 12 m/s, the buildings at the higher downslope terrains are at higher risk of wildfire damages, in contrast, at constant wind velocity of 6 m/s, the buildings at the higher downslope terrains are at lower risk of wildfire damages.
- For the cases with U_{ref} = 12 m/s, increasing the downslope angles from 0˚ to -30˚, increases the average temperature of the building surface by 14%, and 30%, and for the cases with U_{ref} = 6 m/s, increasing the downslope angles, decreases the average building temperature by 15%, and 30%, respectively.

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