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Fuelbreaks design: from CFD modelling to operational tools

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Abstract

Dimensioning a fuelbreak remains always a challenging problem. For a long time, this problem was tackled using an empirical approach from the experience of operational users such as the fire fighters and the foresters. During the last decades, new approaches coming from fire safety engineering have completed the set of tools adapted to study this problem. These tools are all based on physical considerations, more or- less sophisticated. The simplest ones, consist in assimilating the flame as a radiant panel, calculating the distribution of radiant heat flux as a function of the distance separating the flame to a potential target and defining at what distance this heat flux reached a critical threshold level susceptible to produce damages on this target (pain for people or ignition for materials). The most complex ones, consist in solving the conservation equations (mass, momentum, energy ...) governing the behaviour of complex coupled problem formed by the vegetation, the flame front and the surrounding atmosphere. This new generation of engineering tool, based on CFD approach allows to directly predict the behaviour of a fire front propagating toward a fuelbreak, in order to evaluate its efficiency as a function of the amount of surface fuel (grass, shrubs) removed to reduce locally the fuel load and therefore the intensity of an incoming fire. These two approaches are fully complementary, only the first one has the potentiality to be spread operationally on the field, whereas the second one can contribute to improve the first one and to study with more detail some very sensitive situations such as those encountered in the wildland urban interface (WUI). The main part of this study concerns numerical simulations of the propagation of a fire front through a homogeneous vegetation layer (a grassland) in the vicinity of a fuelbreak represented by a band more or less wide inside which all the fuel was removed. The simulations were performed using a fully physical wildfire model (FIRESTAR3D), three variable parameters were considered in this study: the 1m open wind speed (U1 ranged between 3 and 10 m/s), the fuel height (HFuel ranged between 0.25 and 1m) and the fuelbreak width (LFB). With these conditions, the simulations covered a large range of values of the Byram's convective number NC ($0.3 < NC < 60$) in order to explore wind as well driven fires ($NC < 2$) and plume dominated fires ($NC > 10$). The 72 simulations carried out in this study have been classified in three categories: 1/ Propagation (if the fire has crossed the fuelbreak with a propagation after); 2/ Overshooting or Marginal (if the fire has crossed the fuelbreak without a propagation after); 3/ No-propagation (if the fuelbreak has stopped the fire). The main objective of this study was to determine the optimal fuelbreak width LFBx separating between the Propagation and the No-propagation regimes, in order to generalize the conclusion, the results have been presented in dimensionless form (similitude theory) in representing as an example the ratio LFBx/HFuel versus the Byram's convective number NC.

1. Introduction and numerical configuration

Most of criteria used to design the optimal width of a fuelbreak are based on the assumption that the ignition of the fuel located beyond the fuel break will be due to radiation heat transfer. One of the first formula proposed by Emmons (1964) assumed that the ignition of the solid fuel located ahead of the fire front was initiated from the foot of the fire (1D vision), conducting to an expression including the extinction length scale characterizing the solid fuel layer and the depth of the fire front. Whereas other ones included the role played by the flame inside and above the vegetation layer (2D vision), proposed criteria based on the geometry (length or height) of the flame (Rossi & al, 2011; Butler & Cohen, 1998). We propose with this work to explore this problem with more details and without a priori ideas, using numerical simulations based on a fully physical approach, with the objective to study both the influence of heat transfers coming from radiation and convection upon the effectiveness of a fuelbreak built in an homogeneous grassland. The spotting phenomena, which can play also a great role for this problem, was not taken into account in this study.

A set of 72 numerical simulations of the propagation of a quasi-infinite fire front has been carried out in a grassland inside which a x-meter width (L_{FB}) fuelbreak has been positioned. Outside the fuelbreak the vegetation layer was constituted as follows: a dry grass (FMC = 5%) with a fuel load ranged between 0.25 and 1 kg/m^2. In order to reproduce a quasi-infinite fire front (to avoid some effects, such as the curvature of the fire front resulting from finite ignition line), periodic boundary conditions have been imposed on the lateral sides of the domain (see Figure 1) (Frangieh & al, 2021). As indicating in the abstract, a quite large set of conditions (wind, fuel height) has been tested to cover the two regimes of propagation identified in the literature, namely the wind-driven fires and the plume-dominated fires. As suggested in many previous studies, the transition between these two regimes of propagation can be defined from the Byram's convective number N_C representing the power ratio between the buoyancy (plume) and the inertia (wind) forces (see Eq.1): $N_C < 2$ for wind-driven fires and $N_C > 10$ for plume-dominated fires (Morvan, 2014).

$$N_C = \frac{2\,g\,I}{\rho\,C_P T_0 (U_{10} - ROS)^3} \quad (Eq.1)$$

Where g and I represent respectively the acceleration of gravitation and the fireline intensity, ρ, C_P and T_0 the density, the specific heat and the temperature of the ambient air, U_{10} and ROS the 10m open wind velocity and the fire rate of spread.

The numerical simulations have been performed using a multiphase formulation, consisting in solving the balance equations (mass, momentum, energy …) governing the evolution of the coupled system formed by the vegetation and the surrounding atmospheric layer. The main advantage of this approach is its ability in reproducing main physical phenomena, such as the thermal decomposition of the vegetation, the mass and heat transfer between the vegetation and the atmosphere, the combustion process both in the gas phase (the flame) and in the solid phase (embers), the radiation heat transfer, the atmospheric turbulence, and the interactions (drag effect) with the vegetation and so on … To achieve these objectives a relative fine grid must be used for the representation of the computational domain. As shown in previous studies, the size of the grid must respect some criteria in order to represent correctly the radiative heat transfer between the flame and the vegetation (at least the grid size must be smaller than the extinction length scale characterizing the vegetation layer). But this level of details needs also to pay a high price in terms of computational resources and to collect numerous data on the field to describe the structure and the state of the fuel. For these reasons, this kind of formulation is presently limited to describe a fire front at a relatively small scale (< 1 km), however sufficient in many fire safety engineering problems, such as the present one, the evaluation of the effectiveness of fire breaks (Frangieh & al, 2021; Morvan, 2015), or others more fundamental problems associated to wildfires physics (Morvan, 2014, 2013; Frangieh & al, 2020).

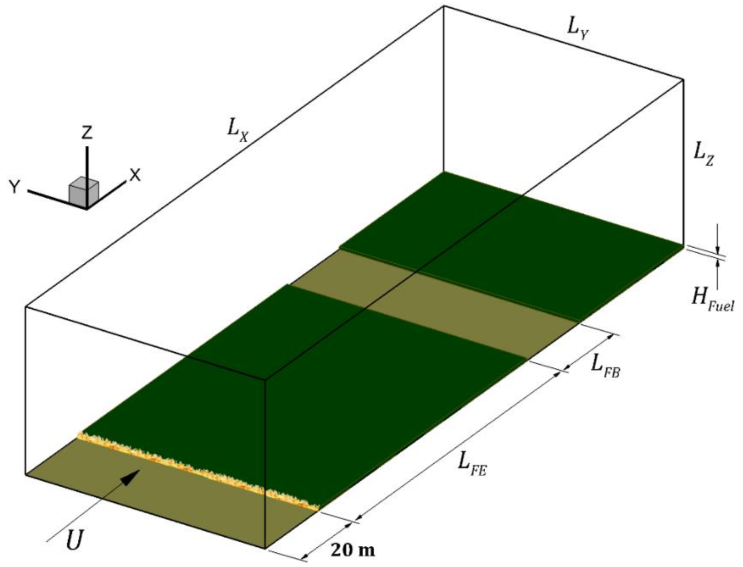

Figure 1- Numerical configuration: L_{FB} fuelbreak width .

2. Some numerical results

After analysis, the set of numerical results was classified in three categories: 1/ Propagation; 2/ Overshooting or Marginal; 3/ No-propagation. The first and the last ones are easily understanding, they correspond respectively to the cases for which the fire front was able to propagate (1) or was stopped (3) beyond the fuelbreak. The middle case (2) includes two sub-cases: Overshooting (2.a) for which some pocket ignition was observed beyond the fuelbreak followed by a propagation along a short distance and an extinction; Marginal (2.b) very similar to Overshooting, the fire behaviour switch to No-propagation if the fuelbreak width increased by 1 m. A 3D view of a fire front crossing a 6.5 m wide fuelbreak is shown in Fig.2. This representation illustrates how a fire front was able to cross such fire prevention device. As the fire front reached the border of the fuelbreak, the fuel located on the opposite side is ignited punctually (see Fig.2), forming a set of burning pockets. Then these punctual fires merged in forming a continuous fire front which can then propagate again through the solid fuel layer. In comparison the Overshooting situation was observed when the ignition points were too distant to be able to merge and to sustain a continuous propagation of the fire (Frangieh & al, 2021).

The yellow surface represents the isovalue surface (T = 1000 K in the gas phase), therefore this zone includes both the flaming zone and the smoldering zone. It is for this reason that it seems so wide.

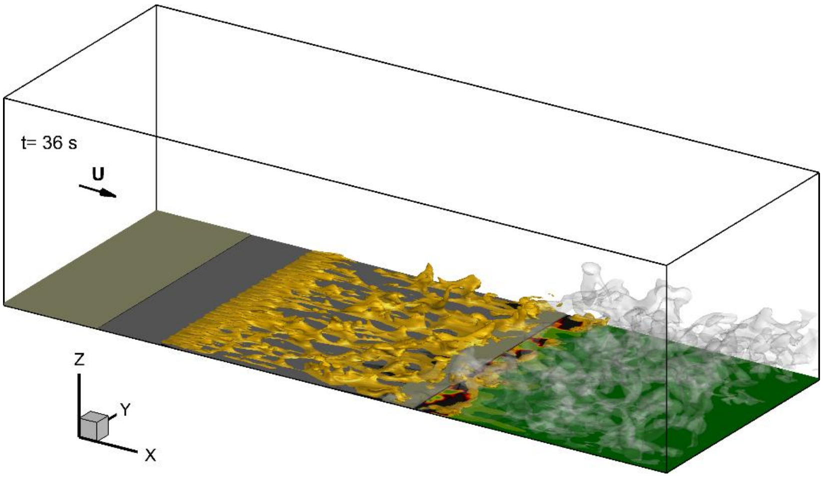

Figure 2- 3D visualization of grassland fire obtained for U_1 =8 m s^{-1} and W = 0.35 kg m^{-2} (Nc = 1.95) as it crosses a 6.5-m wide fuelbreak. The yellow surface is the isovalue surface T = 1000 K of the gas temperature and the semi-transparent grey surface is the isovalue surface Y_{H2O} = 10^{-3} of the mass fraction of water vapor.

The ratio between the critical fuel break width with the fuel height (L_{FBx}/H_{Fuel}) versus the Byram's convective number N_C is reported in Fig.3. This curve shows clearly the role played by the regime of propagation. The range of variation of the ratio L_{FBx}/H_{Fuel} seemed to be particularly important for wind-driven fires ($N_C < 2$), between 30 and 80 (for the present cases), whereas the same parameter varied between 25 and 10 for plume-dominated fires ($N_C > 10$). This effect can be attributed to the mechanisms of heat transfer between the flame and the fuel located beyond the fuel break: for plume-dominated fires the fuel is exclusively heated by radiation whereas for wind-driven fires heat transfer by convection and sometimes by flame contact (the flame can be significantly tilted by the wind flow) plays an increasing role (Emmons, 1964; Butler & Cohen, 1998). These results highlight that the optimal design of a fuel break cannot be only reduced to a constant ratio between the fuel break width and the upwind fuel depth (and therefore the fuel load), this ratio must necessarily depend on the wind flow conditions and also of the slope (not study in this work). However, in looking the worst case (wind driven fire with $N_C << 1$), a ratio LFBx / HFuel nearly equal to 100 (see Fig.3) seems to be quite secure to avoid a crossing of an incident fire front.

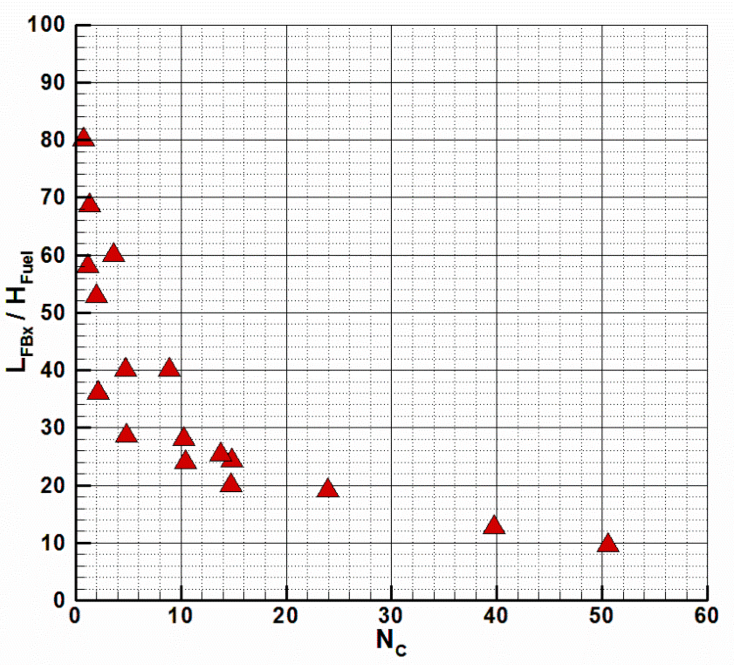

Figure 3- Optimal fuelbreak width L_{FBx} (lower limit of extinction) scaled by the fuel height H_{Fuel} versus Byram's convective number N_C (Frangieh & al, 2021).

The results obtained at various fireline intensity in the present study, have been also confronted to those predicted with a more operational tool (DIMZAL), based on a simplified physical analysis (mainly the radiant panel theory) (Rossi & al, 2011; Bisganbiglia & al, 2017). This comparison has allowed to highlight some agreements but also some differences between the two set of data, allowing to foresee some progress in a new version of this operational tool. Better agreement between these two approaches can be noticed in Fig.4 for relatively less critical configurations, obtained here for weak wind conditions, i.e. plume dominated fires mainly piloted by radiation heat transfer. This result is not surprising in considering the scientific base retained in DIMZAL tool. As suggest in (Frangieh & al, 2021), a adaptative evolution of the critical heat flux implemented in DIMZAL to evaluate the optimal fuel break width could be an interesting way to cover a larger spectra of fire behaviour, from plume dominated fire to wind driven fire. This work is already in progress and could be presented in a future publication.

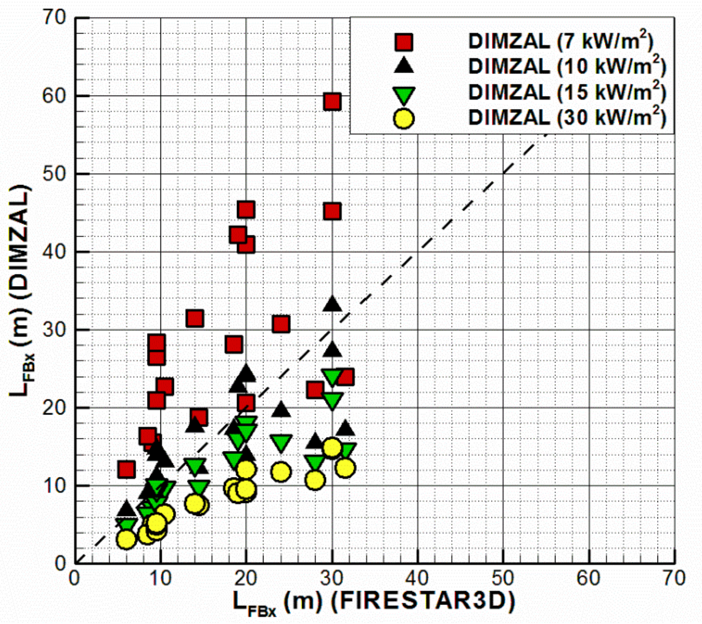

Figure 4- Optimal fuelbreak width obtained by numerical simulations (FIRESTAR3D) and from DIMZAL operational tool for critical heat flux values (Rossi & al, 2011; Frangieh & al, 2021).

3. Acknowledgments

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