Post Doc Proposition: Development of a Lattice Boltzmann Method (LBM)-based wildland fire simulator

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1 Description of the project

1.1 Context

Global warming was found to enhance the frequency and severity of favourable weather conditions for widland fires in southern Europe, contributing to a lengthening of the fire weather season as well as an increased frequency of days with elevated fire danger. In addition, although the term "mega fires" is not well defined and seems to be more appropriate to refer to extreme fires occurring in the US or in Australia, gobal warming effects have modified the wildland fire behaviour in Mediterranean regions, leading to fires of higher intensity, higher spread rate and more difficult to handle, especially at the Wildland Urban Interface (WUI) [1]. WUI defines areas where wildland vegetation intermingles with human settlements. In the current context of climate change, there is an increasing attention on the WUI since these areas are often considered as one of the main drivers of fire risk, as witnessed in the recent tragic fire events (115 deaths in Portugal, 2017 and 102 deaths in Greece, 2018). During these events, most deaths have resulted from suffocation at home or on the road due to the conjugated effects of an exposition to a large amount of smoke particles, extreme thermal radiation emitted by the fire and convection due to hot gases [2].

This change of topology in wildland fires requires the development of specific simulation tools to understand and predict the physics related to the WUI processes. In particular, two mechanisms were identified to be responsible for the transition from a wildland fire to an urban fire [3]. The first, which will be the focus of the present project, is related to the exposure of urban structures to heat flux from flames, mainly by radiation but also by direct flame impingement. Typically, a windblown fire front, fed by the gaseous combustible pyrolysis products released from the vegetation stratum due to the heat feedback from the flames themselves, emits thermal radiation toward urban structures. These latter may ignite if the heat flux is sufficiently high and the exposure time sufficiently long. Heat fluxes and exposure times are mainly related to the front geometry and wildland fire spread rate, respectively, which depend themselves on a significant amount of parameters such as meteorological conditions, fuel type, load and moisture content, and landscape topology. The second mechanism is related to the ignition of urban structure or urban vegetation by flaming or glowing embers, called firebrands, generated by forest fires.

The modelling of a wildland fire is a complex phenomenon involving several scales whose range goes from micrometers to several kilometers. The four scales of interest for wildland fire modeling have been identified by Séro-Guillaume and Margerit [4]:

- The smallest scale, the microscopic scale, is the scale of a vegetation element (needle, twig, branch, leave,...). This scale is relevant to investigate heat and mass transfer within a vegetation element and the associated drying, pyrolysis, and char oxidation processes [5, 6].
- The second scale of interest is the so-called mesoscopic scale. At this scale, all the elements of vegetation and the air around them form a porous medium. The corresponding model contains the thermal decomposition model previously described for the vegetation fuel and the usual balance equations for reactive media for the gaseous phase, together with mass, momentum, and heat transfer between the two phases expressed as "jump" conditions at the gas-solid interface [7].

- The third scale is the macroscopic scale and the corresponding model is derived by upscaling the mesoscopic one to obtain the continuous governing conservation equations of an equivalent homogenized medium [7]. The macroscopic scale is the typical size of the forest structure with length scales of the order of the thickness of the vegetation stratum or the height of the flames. Wildland fire CFD models are developed at this scale [8] and are well designed to deal with WUI problems [9]. Examples of wildland fire CFD models are the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) developed at NIST [10] or the Fire Foam-based simulator [11, 12].

- The last scale is called the gigascopic scale. This scale is typically the scale of observation of the fire front from an airplane. The fire front can be viewed as a one-dimensional line separating the burnt and unburnt forest fuels and moving over a two-dimensional surface. This scale is the most relevant for firefighters and the modelling tools of interest have to provide real-time predictions of the fire front spread. A consequence is that the most appropriate models to deal with this problem seems to be either semi-empirical [13] or stochastic [14, 15]. Stochastic models involve some global parameters that can be estimated from wildland fire CFD simulators.

1.2 Background and objective

As discussed previously, CFD models are the optimal tool to model WUI problems since they are able to predict the details of the heat transfer between the wildland fire and the urban structures. In particular, this heat transfer is mainly governed by thermal radiation which requires to predict accurately the flame structure, the soot production as soot radiation may contribute for an important part of this transfer and the spectral radiative properties of radiatively participating species. The wildland fire CFD simulators solve the conservation equations of mass, momentum, energy, species for both the gas and solid (vegetation) phases along with exchange terms between the two phases due to mass (drying, pyrolysis, char oxidation), momentum (drag force) and energy (convection, radiation, mass transfer) transfers in both Reynolds-Average Navier-Stokes (RANS) [9] or Large Eddy Simulation (LES) frameworks [10, 11]. However, mainly due to limitations in the computational resources, the chemistry/soot production/radiation/turbulence interaction is treated in an oversimplified manner with crude approximations for gas-phase chemical kinetics (mainly based on 1 step irreversible reaction), turbulent combustion (infinitely fast chemistry), radiative heat transfer (grey-approximation for combustion gases, soot and vegetation particles, turbulence/radiation interaction ignored) and soot production (ignored or simply model by conversion factor of fuel into soot) [11]. These approximations are no longer justified today since more sophisticated modellings in the fields of turbulent combustion [16], radiative heat transfer [17] and soot production [18] have been developed and have to be considered to fully understand and predict the interactions between wildland fires and the urban structures.

On the other hand, the PhD thesis of Mostafa Taha supervised by our group has demonstrated the capability of LBM-based solver to reproduce with fidelity the purely buoyant flows, characteristic of unwanted fires, with computational costs significantly lower than those reported with classical Navier-Stokes solvers [19, 20]. These results demonstrated that LBM is a good candidate to serve as a basis to develop a wildland fire simulator. The objective of this project will be then to develop a LBM-based wildland fire simulator involving LES and state-of-the art subgrid-scale models for the degradation of the vegetation fuel, turbulent combustion, thermal radiation and soot production. This model will be constructed and validated step by step starting from the results that buoyant flows can be described accurately. The strategy of development is described in the next section.

1.3 Strategy

The starting point will be the low-Mach lattice-Boltzmann based fire model developed in ProLB [21] by Mostafa Taha [20]. The model involves a hybrid Lattice Boltzmann method where continuity and momentum are solved with the lattice Boltzmann equation and the other conservation equations (e.g. enthalpy, species,..) are solved by classical finite difference methods. The capability of the model to reproduce the dynamics of purely buoyant flows representative of fires was established through LES of 1 meter helium and methane pools [20]. The objective of this research effort was mainly to demonstrate the potentiality of LBM solver for the modelling of fire flows, explaining that rather crude turbulent combustion and radiation models were considered. The extension of this code toward a wildland fire simulator will include the main following steps:

1. **Radiation model:** the radiation problem can be decomposed into three sub problems [17]: i) the radiative property of the participating species. This problem was deeply addressed in our previous studies and, based on our conclusions, variants of the Full-Spectrum k-distribution models will be considered [22]. ii) The subgrid-scale turbulence/radiation interaction contributes for a non-negligible part to the radiative loss and has to be considered. Its modelling will be based on a probability density function (PDF) approach in line with our previous studies [23]. iii) The radiative transfer equation (RTE) solver constitutes the main challenge to save computational resources as the classical methods, such as the Discrete Ordinates Method or Finite Volume Method, are time consuming. Lattice Boltzmann model (LBM) for the RTE have emerged in the literature [24, 25] and will be specifically investigated. This research topic will benefit from the strong knowledge of the M2P2 on Lattice Bolzmann method. The development, validation and the evaluation of the RTE solvers will made in decoupled manner by considering, on the one hand, benchmarks from the literature and, on the other hand, test cases with thermal input (temperature, species mole fraction, soot volume fraction,...) representative of wildland fire problems.

2. **Vegetation fuel and thermal degradation of the forest fuel:** The vegetation elements and the surrounding gas form a multiphase medium. Consistently with previous studies [9, 11], an Eulerian-Eulerian approach will be considered. In addition, our recent studies on thermogravimetric analysis (TGA) showed that the modelling of the thermal degradation of forest fuel requires more sophisticated semi-global reaction mechanisms than the classically-used three-step degradation model (drying, pyrolysis, char oxidation) [5, 6, 11]. Such sophisticated kinetic scheme will be implemented.

3. **Gas-phase turbulent combustion:** Flamelet progress variable/PDF modelling of turbulent combustion is a good candidate for fire applications [26]. In this ap-

proach, gaseous species, temperature, molecular transport properties are tabulated as function of a reduced set of parameters (mixture fraction, mixture fraction variance, progress variable, enthalpy defect,...) and, therefore, it provides a detailed prediction of the non-premixed flame structure at moderate cost even for conditions far from equilibrium. In wildland fires, the generation of water vapour due to the drying process and of CO/CO_2 due to char oxidation, complicates the formulation as the two-stream configuration is no longer appropriate and additional mixture fractions are required to describe the mixing problem. The objective of this topic will be to develop a consistent formulation of the flamelet progress variable model for wildland fire applications. To the authors best'knowledge, this has not been reported in the literature.

4. **Validation of the complete model:** The validation of the model will be performed on both lab-scale and medium-scale experiments from the literature. The lab-scale experiments will consider experiments performed in well-controlled conditions in the Flame Propagation Apparatus (FPA) as in example in Refs. [11, 27]. These experiments will assess the capability of the model to reproduce the piloted ignition and burning processes for different type of the vegetation elements, vegetation humidity, fuel bed porosity,.. Medium-scale experiments will consider flame spread over fields of order of 200 m $\times$ 200 m under well-identified conditions in terms of vegetation properties and wind (or slope) (see Ref. [28] for example).

1.4 Supervisions

This research will be conducted under the supervision of a unique group with complementary skills: 1. Jean-Louis Consalvi has well-recognized skills in the fields of radiative heat transfer, combustion and fire research. 2. Pierre Boivin has a strong expertise in both combustion and Lattice-Boltmann methods. 3. Aymeric Lamorlette has a strong background in the fields of wildland fire and heat transfer.

1.5 Impact

These researches will address two academic issues:

- The first challenge is related to the development of computationally efficient RTE solver. To this end, LBM-based RTE solver will be investigated to deal with conditions representative of fire applications. LBM approaches are relatively new in the field of radiative heat transfer and are not explored for coupling with combustion and fire applications.
- The second challenge is related to the development of a FPV model for wildland fire applications.

In addition, the existing fire simulators do not consider detailed modellings for vegetation degradation, radiation, and turbulent combustion as described in the previous section. The implentation of advanced submodels will constitute a plus value of this work to address the wildland fire/WUI interaction problem. The results of these researches will be disseminated in international journal and international conferences related to combustion, heat transfer and fire safety science. Once validated, the developed LBM-based wildland fire simulator will be a useful tool to assess the fire risk at the WUI and to provide some guidance to mitigate this risk.

2 Post doctoral subject

The objective of this Post Doc will be to develop a wildland fire CFD simulator based on the lattice Boltzmann method (LBM).

The Phd thesis of Mostafa Taha [20] has demonstrated the capability of low-Mach LBM to simulate flows representative of unwanted fires with significantly lower computational resources as compared to classical Navier-Stokes solvers. This low-Mach LBM version, implemented in the software ProLB [21], will be then considered as the starting point to perform the developments.

The development will consist in implementing state-of-the-art submodels for the thermal degradation of the vegetation fuel, turbulent combustion and radiative heat transfer and to properly model the chemistry/radiation/turbulence interactions. These developments will be performed with the constant objectives to find a compromise between accuracy and computational efficiency. A special emphasis will be put, on the one hand, on the radiative transfer equation (RTE) solver and, on the other hand, on the development of a specific turbulent combustion model for wildland fire applications based on the flamelet progress variable model. In particular, the capability of LBM-based RTE solver to be applied in fire applications will be deeply investigated for the first time.

Based on the description of the research topic, the candidate should demonstrate strong knowledge in numerical methods for CDF simulation, turbulent combustion and heat transfer. In addition to the development of this research project, the candidate will have the possibility to participate to the supervision of some PhD candidates of the groups lead by Jean-Louis Consalvi at IUSTI and Pierre Boivin at M2P2.

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