## 1. Background

Figure 1 – *Wall flame bench scale*

The risk of wildfires is particularly high in the Nouvelle-Aquitaine region of France. In recent years, several large-scale fires, such as the Landiras fires of 2022, have underscored the severity of this issue. These fires have significant environmental consequences, including the increasing vulnerability of buildings due to the expansion of forest-residential interface zones. Data indicate that 80% of fires originate within 50 meters of homes, highlighting the critical nature of building vulnerability in wildfire-prone areas. Two key factors contribute to this increasing vulnerability : climate change, which expands fire-prone areas, and urban development, which leads to clustered or scattered housing and urban sprawl. These factors complicate fire suppression efforts.
Despite substantial firefighting resources, it is not possible to protect all buildings. While this phenomenon has become more pronounced in France in recent years, it has already been a long-standing issue in regions such as Catalonia in Spain, California in the United States, and Australia. This research project aims to study building vulnerability to wildfires. Two main strategies can mitigate this vulnerability : reducing fire intensity and preventing its spread to structures (e.g., through biomass reduction, control of fire propagation vectors such as ornamental vegetation, and increasing defensible space), and enhancing construction practices to limit the flammability and combustibility of buildings. Fire intensity and spread mitigation strategies are defined through forestry and urban planning regulations, including legal clearing obligations (OLD), fuel breaks, and access requirements for fire services. However, current OLD regulations apply uniform clearance depths, irrespective of the site's environmental configuration, which can lead to inadequate measures or excessive costs. Furthermore, regulations concerning fire-resistant construction materials and techniques are poorly defined and inconsistently enforced. Improving fire-resistant construction methods remains a major challenge. The increasing use of bio-based materials in new buildings, despite their environmental benefits, raises concerns about their performance in wildfire-prone areas.

## 2. Reasearch focus and methodology

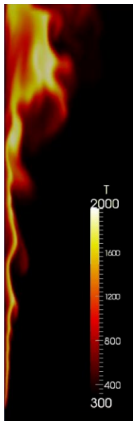


Figure 2 – *Wall flame bench scale*

During a fire, building facades are among the most exposed structural elements. This study will focus on two critical aspects : ignition conditions and flame spread along building facades. A case study will be conducted on wooden cladding using Douglas fir, the most common bio-based facade material in Nouvelle-Aquitaine. In the case of flame spread on a solid surface, a boundary layer forms, within which various physicochemical processes interact (turbulence, radiation, combustion, etc.). The interaction between the solid-phase (condensed phase) and the boundary layer in the gas phase is crucial in determining the flame spread rate. This process can be viewed as a moving ignition front, where the flame's leading edge acts as both a heat source – raising the material to its ignition temperature – and an ignition pilot. Flame propagation depends on physicochemical processes in both the gas and condensed phases, as well as mass and heat transfer at their interface.

The leading edge of the flame remains *"anchored"* to the pyrolysis zone, where combustion is predominantly laminar and heat transfer is mainly convective. Upstream, buoyancy forces dominate, leading to turbulent flow. Mass transfer from pyrolysis reactions significantly affects the boundary layer, as pyrolysis gases are ejected perpendicular to the surface, strongly influencing convective heat transfer. These physicochemical interactions at the interface play a key role in flame development.
This project aims to develop a coupled model integrating the physical effects in the condensed phase, gas phase, and their interface to investigate the key mechanisms governing ignition and flame spread along facades. Identifying these parameters will support the development of fire-resistant and resilient building materials for wildfire-prone areas. The study will combine experimental and numerical approaches. An experimental setup has been developed to analyze flame propagation on a solid fuel under controlled conditions. The setup includes a calcium silicate sample holder, ensuring well-defined boundary conditions for modeling. A porous radiant burner provides ignition and sustains flame propagation. Burner parameters (power, inclination) will be varied to simulate different wildfire scenarios.
Two configurations will be studied :

1. **Baseline Tests** : Using an inert plate to characterize airflow and thermal boundary layers induced by the radiant panel in the absence of combustion.
2. **Wooden Facade Tests** : Studying flame propagation along a combustible surface.

Three key phenomena will be investigated :

— **Char formation** in the condensed phase and its impact on flame structure.
— **Flame structure** evolution in vertical propagation, transitioning from laminar to turbulent flow.
— **Heat and mass transfer** mechanisms at the solid/gas interface.

Various measurement techniques will be employed, including : a balance to monitor mass loss over time, thermocouples embedded at different depths into the solid to capture heat transfer dynamics, gas-phase thermocouples to measure flame temperatures an infrared camera for 2D temperature field visualization, Particle Image Velocimetry (PIV) for gas-phase velocity measurements, convective and radiative heat flux sensors on the solid surface, gas analyzers and high-speed cameras to characterize ignition process.

A numerical model will be developed to simulate the experiments. The research team has developed a detailed thermal degradation model for porous materials, based on the PATO (Porous Analysis Toolbox) code. Originally developed by NASA for spacecraft thermal shield calculations, PATO has been adapted to wildfire conditions by incorporating sub-models for finite-rate pyrolysis reactions and secondary char formation. The numerical model is based on a 3D and homogenized formulation of the conservation equations within the material. A porous medium can be characterized by several spatial scales, distinguishing between macroscopic scales (referred to as Darcy scale) and scales related to the materials morphology, grains, and pores. In a homogenization process, an intermediate scale is defined – small compared to macroscopic scales but large compared to pore-scale – called the Representative Elementary Volume (REV) scale. Volume-averaging homogenization theories are used to establish equations for averaged variables at the REV scale, incorporating the mediums heterogeneities. These equations reveal effective properties dependent on local properties and morphology. Each gas is transported separately within the porous medium through diffusive and convective processes,

originating from pyrolysis and heterogeneous reactions. A general formulation of the reaction mechanism is adopted, accounting for detailed reaction schemes involving *"competitive"* and *"consecutive"* reactions. A pressure equation is solved, and gas velocity is calculated using Darcy's law. Energy is computed as the sensible enthalpy of the gas volume. Currently, the model assumes local thermal equilibrium, with gases passing through the material assumed to be at the same temperature as the condensed phases. Similarly, local compositional equilibrium is assumed, with heterogeneous reactions expressed in terms of averaged gaseous species concentrations rather than interface concentrations. For this study, the PATO code will be coupled with FireFOAM, a computational fluid dynamics (CFD) solver initially developed by FM Global for fire simulations. The coupling at the interface will be addressed with increasing complexity :

1. **Initial coupling** : Considering mass transfer from the solid to the gas phase and heat transfer from the flame to the solid surface.
2. **Advanced coupling** : Incorporating bidirectional mass and heat exchange between the two phases.

FireFOAM employs Large Eddy Simulation (LES) framework for conservation equations, using the WALE model for turbulence, the EDC model for combustion, and the Discrete Ordinates Method (DOM) for radiation, assuming an optically thin medium. Special attention will be given to modeling convective heat transfer. Two strategies will be evaluated : (1) Direct computation of shear stress and convective heat flux using fine near-wall meshing, (2) wall models based on classical boundary layer theories, whose validity will be assessed in the presence of pyrolysis gas injection. The combustion model will also be scrutinized, particularly in transitioning from laminar to turbulent combustion. The impact of molecular diffusion use in improving laminar flame modeling will be explored, as well as its effects on the overall representation of physicochemical phenomena at the interface.

## 3. Conclusion

This research will enhance our understanding of flame spread and ignition mechanisms on combustible facades, providing valuable insights for fire-resistant construction in wildfire-prone regions. By combining experimental and numerical approaches, this study aims to inform the development of resilient building materials and contribute to more effective wildfire risk mitigation strategies.

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