FireFOAM simulation of a localised fire in a gallery

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ABSTRACT

Thermal marks were identified on the walls of the Chauvet-Pont d’Arc cave. In order to reproduce similar thermo-alterations, an experiment was carried out. The interests being archaeological, the chosen location was a natural gallery. Then, the combustion consisted in a localised wood fire within a quarry. The experimental site was instrumented and temperatures, velocities, gases concentrations and soot deposits were measured. A comparison between the experiment and a FireFOAM simulation is performed. Thanks to photogrammetry, the simulation takes place within the exact geometry of the quarry. FireFOAM manages to produce significant results that are largely in good agreement with experimental data. The encountered difficulties are also exposed as well as the corresponding solutions. The appropriate care taken to reach convenient results is detailed. Especially, a boundary condition expressing energy balance at a wall has been added to the software. Moreover, the existing thermocouple model has been modified in order to reach relevant corrected temperatures. In order to calculate the soot deposition, the Beresnev-Chernyak model has been implemented in FireFOAM. Finally, the hazard of toxicity, radiation and heat are also estimated by means of the fractional effective dose approach (FED).

KEYWORDS: localised fire; gallery; FED; CFD; FireFOAM; rock art caves
INTRODUCTION

For several years, numerical simulation has been on the rise in fire engineering. Especially, the computational fluid dynamics simulation (CFD) has been used to simulate fire. The increasing performance of computers enables simulations of sizeable combustions. Nonetheless, the coupling of complex physics is still a difficulty to manage accurate simulation. Many investigations try to simulate fire in different configurations thanks to CFD simulation. Compartment fires take a significant place in such researches. Besides, the LES modelling is used to compare this kind of experiment with simulation [1], [2]. Close to this configuration, this study falls within fires in geometries like galleries. This type of geometry is similar to tunnels and mines for instance. Furthermore, for safety reasons, a lot of investigations about tunnel fires simulation were conducted [3], [4].

The present research is driven by archaeological interests. High temperature caused alterations to the ceilings and walls of the Chauvet-Pont d’Arc cave (Ardèche, France) [5]. Some clues attest it. First, important spallings occurred in different locations within the cave. Secondly, some areas have a red colour, resulting from rubification (high-temperature chemical reaction). Eventually, soot is still on the walls of the cave. Therefore, it confirms that the walls were thermally marked, and more specifically by fires. Currently, the scales of these fires are unknown and the archaeologists would like to characterize their intensity to assume their function.

The first part of the presentation is the description of an experiment conducted with the aim of reproducing similar thermo-alterations to those in the Chauvet-Pont d’Arc cave. Wood was placed in the back of a former quarry. The quarry dimensions resemble to the Megaloceros Gallery ones (part of the Chauvet-Pont d’Arc cave). They are deeper described in the following section. A same fire was reproduced three times within three days to test the variability of the results. The fire consisted in a supplied wood hearth in a gallery. Thereby, the fire was localized during all the experiment. The experimental protocol is described thereafter.

The second part corresponds to the model description. The simulation is performed by the solver FireFOAM-4.0 [6], embedded in the software OpenFOAM [7]. The code structure and the models are outlined in this section. The set of general equations is presented and radiation, turbulence and combustion modellings are detailed. FireFOAM being an open-source software, contributions can be implemented. We add a boundary condition for temperature where the wall temperature is estimated from energy balance. This is similar to the default one in the Fire Dynamics Simulator (FDS [8]). In the same way, the simulation of soot deposit and the evaluation of toxicity, radiation and heat hazards are implemented to FireFOAM. Finally, a thermocouple correction is added as post-processing.

The last part is devoted to discussion about numerical results and comparison with experimental data.

EXPERIMENTAL PROTOCOL

Experiment description

The experiment was carried out within a former quarry in Lugasson (France). It is composed of two perpendicular galleries (Fig. 1). Each gallery is about 240 cm wide. A localized wood fire was placed at 80 cm from the back of the second gallery (250 cm high) and centered between walls. The hearth diameter was 80 cm. This fire was reproduced three times for three days (one per day) in order to evaluate its reproducibility. For archaeological reasons described in the introduction, the hearth was designed to impact the ceiling as much as possible in order to reach 250°C for 10 minutes in the rock ceiling (rubification threshold). According to preliminary tests, a tepee shape was chosen to maximize the flames height (Fig. 1). The fuel was pine sylvestris because this is the burnt one in Chauvet-Pont d’Arc. The 80 cm branches were gathered in 4.5 kg bundles. At the ignition, four bundles were placed at the fireplace and a blowtorch started the fire. Then, at each supply time, two bundles were brought by firefighters with security equipment. The supply times were adopted to avoid any heat release rate (HRR) decrease during the first fire. The same times were kept for the two other fires. Globally, 30 bundles supplied the fire, corresponding to 135 kg.
**Instrumentation of the gallery**

With the aim of comparing this experiment with the tool FireFOAM, the quarry was instrumented (Fig. 2). Sensors were positioned throughout the galleries to measure velocities, temperatures, soot deposits, gases and particles concentrations (oxygen, carbon dioxide and carbon monoxide). The type-K thermocouples trees were homogeneously placed to map the temperature during the fire. On each tree, several sensors allowed to measure the vertical gradient temperature. The gas concentration sensors were situated in the hot layer as well as the pegasor particle sensors (PPS), measuring particles concentrations. Two sensors measured the velocities of the cold and hot layers at the entrance of the quarry. In different locations, several plates were fixed to the wall in the purpose of collecting deposited soot at the end of the combustion. On the ground, a camera filmed the fire from the quarry corner. Eventually, a weighing scale was under the hearth, indirectly providing the HRR against time (considering that the heat of combustion remains constant).
NUMERICAL MODEL

FireFOAM description

FireFOAM solves the Favre averaged aerothermochemistry equations. The LES modelling is chosen to simulate turbulence. The turbulent kinetic energy $k$ (m$^2$.s$^{-2}$) is calculated thanks to the model [9] and the turbulent viscosity is then evaluated $\nu_t = C_k \sqrt{k} \Delta$ with $C_k = 0.094$ and $\Delta$ the filter size (m).

As regards radiation, the radiative transfer equation is solved with the underlying assumption of a grey medium. Moreover, the gases are supposed to be independent on wavelength. Scattering is not taken into account because of the low experimental soot concentrations. 30% of the combustion energy is assumed to be radiatively released [10]. To solve the radiation equation, the finite volume discrete ordinary method (fvDOM) is adopted. The weak particle quantity in smoke justifies the application of this model (optically thin medium).

Concerning combustion, the Magnussen model (Eddy-Dissipation Model) [11] turns out to be sufficient for the chemical reaction rate estimation:

$$\dot{\omega} = -\rho c_p \varepsilon \min \left( Y_{\text{f}}, Y_{\text{o}} \right)$$

where the indices $f$ and $o$ correspond to the fuel and the oxidizer respectively, $s$ is the stoichiometric coefficient of the oxidizer, $\varepsilon$ is the turbulent kinetic energy dissipation (m$^2$.s$^{-3}$), $k$ is the turbulent kinetic energy and $C$ is a model constant.

Advances in FireFOAM simulation

First, the thick walls of the quarry compel the use of an adequate boundary condition corresponding to a heat flux balance:

$$q_r + h(T_g - T_w) = \lambda (T_w - T_0)/dx$$

with $q_r$ the total radiative heat flux, $h$ the convective heat transfer coefficient, $\lambda$ the rock thermal conductivity and $T$ the temperature. The indices $g$, $w$ and $x$ denote the gas outside the boundary layer, the wall surface and the center of the first cell in the wall respectively. The energy received by the wall is diffused through it. In order to estimate the heat conduction in the solid walls, the 1-D heat equation is solved for each surface cell of the geometry mesh. This boundary condition is implemented in FireFOAM that did not include it. The convective heat transfer coefficient is calculated from empirical formulations. This condition is similar to the default one in the Fire Dynamics Simulator [8].

Second, a consistent thermocouple model is implemented to the initial FireFOAM-4.0 in order to compare experimental data with numerical results. Indeed, a gap necessarily exists between the measurements of the sensor and the temperature of the surrounding gases. Then, based on energy balance, a post-processing calculation solving the Eq. 3 is added to the software:

$$\rho c_p d \frac{dT}{dx} = q_r + h_{\text{conv}}(T_g - T)$$

with $\rho$ the thermocouple density (kg.m$^{-3}$), $c_p$ its heat capacity (J.kg$^{-1}$.K$^{-1}$), $d$ its diameter (m) and $h_{\text{conv}}$ the convective heat transfer coefficient (W.m$^{-2}$.K$^{-1}$).

Third, the hazards of toxicity, heat and radiation are evaluated thanks to the fractional effective dose (FED). Some experiments were conducted on animals to estimate death rates in specified conditions. From them, mathematical correlations can value hazard [12], [13]. We add these estimations to FireFOAM. It worth noting that the gases toxicity correlations are implemented in FDS but not the radiation and heat ones. For instance, [14] deals with FED in FDS.

Eventually, by assuming that the main process of particles deposition is thermophoresis, the Beresnev-Chernyak model [15] is added to the global modelling in the purpose of evaluating the mass of the deposited soot. In such a case, particles mainly impact walls because of a temperature gradient. Consequently, this model highly depends on the convective heat transfer coefficient through the temperature gradient.
COMPUTATIONAL SETUP

The CAD file is the quarry morphology constructed from a photogrammetry survey. The mesh of the quarry is managed by the OpenFOAM tool “snappyHexMesh”. The geometry mesh consists of about 250,000 cells (Fig. 3). 3 cm cells mesh the part above the hearth, 6 cm cells mesh the hot layer and other cells measure 12 cm. In addition to the geometry on the figure 3, a big box representing the outside is meshed with 96 cm cells. The mesh convergence has been performed.

At the boundaries, the velocity is fixed at zero. The wall temperature is computed thanks to (2). Outside, the box-wall temperature is fixed at the initial temperature 12°C. Each mass fraction gradient is set at zero at the walls.

The HRR is dictated through a mass flow rate boundary condition. Therefore, the experimental measures of mass losses during the fire are prescribed at the burner. The fuel is then assumed to be a gas in the simulation instead of solid wood in reality. Thus, no pyrolysis model is used.

To solve the radiative transfer equation, a 32 solid angles discretization is adopted. The Courant number is compelled to remain inferior to 0.6 during the overall simulation.

RESULTS AND DISCUSSION

In the following, we expose some results from the achieved simulation. Results are accurate concerning the expected layers separation. The temperature field in the middle of each gallery 40 minutes after the ignition is presented on the Fig. 4. The hot and cold layers are well segregated, even after 40 minutes. The temperature in the hot layer reaches more than 500°C at the end of the combustion. It is in accordance with the simulated temperatures (Fig. 4). The thermocouple measures demonstrate that the cold layer is barely affected by the fire. The numerical results agree with this reality even if the numerical cold layer is less affected than in the experiment at the tree T1. It is not the case for all thermocouples trees.

As regards soot deposit, we have trouble simulating consistent results. The differences between experiment and simulation could be explained by the grid size (as studied in [16]) and by the convective heat transfer model itself. Better results should be given by wall-resolved LES. However, the prohibitive time consumption of this technique prevents its use. Besides, most similar simulations (default FDS simulations for instance), use empirical convective coefficients. Fortunately, because the interests are archaeological, only soot deposit locations are important in the study and the information about the amount of deposited soot is not critical.
CONCLUSION

Archaeological investigations about the Chauvet-Pont d’Arc cave have conducted to the achievement of an experimental localised wood fire in a natural gallery. The geometry of the experimental site makes the results applicable to general simulations in tunnels or mines. The quarry is instrumented in order to compare the experimental fire with a numerical simulation. The modelling is performed by FireFOAM [6]. This open source software can be modified thanks to its adequate framework. Accordingly, four improvements are added to the initial solver. To estimate the wall temperatures, an appropriate boundary condition based on energy balance is added. Then, in order to evaluate soot deposit, the Beresnev-Chernyak model is implemented. Because the experimental measurements correspond to the thermocouples temperatures, a gap exists with the surrounding gases. Therefore, a relevant thermocouple correction is performed after the calculation. Finally, the fractional effective dose is used to evaluate hazard during the experimental fire. The gases toxicity and the heat and radiation hazards are computed by means of existing correlations [12], [13].

It turns out that the simulation gives satisfactory results that are close to the experimental data except for soot deposit. The temperature field remains in accordance with the experiment and the thermocouple measurements validate the modelling of the fire. Other data regarding velocities, gas and particle concentrations demonstrate the same trend. Thereafter, this tool will be applied to archaeological matters. Several scenarios will be carried out in the Chauvet-Pont d’Arc cave, with various input parameters (amount of fuel, duration, fire numbers and supply).

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