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# Large eddy simulation of turbulent vertical wall fires supplied with gaseous fuel through porous burners

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## ABSTRACT

This paper presents a large eddy simulation (LES) study of vertical turbulent wall fires, which aims at bringing fundamental insight into the near-wall flame structure and heat transfer characteristics. The LES simulations are wall-resolved, *i.e.*, the simulations are performed with sufficient grid resolution to capture the wall gradients and do not require a wall heat transfer model. The wall fires considered herein correspond to a simplified configuration in which gaseous fuel is supplied from an array of vertical porous burners, featuring a series of meter-scale wall flames with different fuel mass flow rates and different fuel types. Four fuels (methane, ethane, ethylene and propylene) are studied with prescribed fuel flow rates. Simulations are performed using an LES solver called FireFOAM. The Wall-Adapting Local Eddy-viscosity (WALE) model is used for turbulence modeling. The Eddy Dissipation Concept (EDC) model is used for combustion modeling. The thermal radiation model uses the discrete ordinate method with the simplifying assumption of an optically-thin medium characterized by a fixed radiant fraction. In the fuel blowing region, grid convergence is achieved using a 3 mm computational grid; while in the downstream flame preheating region, a 1.5 mm near-wall grid spacing is required to fully resolve the wall convective heat transfer. The change in grid requirement is due to the presence or absence of fuel blowing which affects the thickness of the wall viscous sub-layer. The simulations are in good qualitative and quantitative agreement with experimental data in the turbulent flame region; in particular: the radiative heat flux increases with elevation and with the fuel mass loss rate, while the convective heat flux remains approximately constant with elevation and decreases with the fuel mass loss rate. The present wall-resolved simulations are considered a first step on the route to developing accurate wall models needed for engineering simulations of wall fires.

## 1. Introduction

Boundary layer flames, *i.e.*, non-premixed flames that develop in the vicinity of solid wall surfaces, correspond to a canonical configuration in fire research [1,2]. These flames are first characterized by the orientation of the solid surface with respect to the direction of the gravity acceleration: one differentiates between configurations in which the surface is vertically-oriented (generally called a wall fire configuration), configurations in which the surface is horizontally-oriented (sometimes called a floor fire or a ceiling fire configuration), and configurations in which the surface orientation is arbitrary. Boundary layer flames are also characterized by the wall material and fuel supply mechanism: one differentiates between configurations in which the flame is developing along a passive wall (*i.e.*, a wall made of a chemically-inert material) and is fueled by external sources, and configurations in which the flame is developing along an active wall (*i.e.*, a wall made of a flammable material) and is fueled by the vapors produced by the in-wall thermal degradation processes (called pyrolysis) that result from the flame-to-wall heat transfer. In the case of a boundary layer flame fueled by a flammable wall, the region in which fuel vapors are produced is called the pyrolysis region and the region in which combustion takes place is called the wall flame region. Boundary layer flames are also characterized by the dynamics of these regions: one differentiates between configurations in which the wall flames are not spreading (the pyrolysis and wall flame regions are time-independent) and configurations in which the wall flames are spreading (the pyrolysis and wall flame regions are time-dependent). Lastly, boundary layer flames are characterized by the flow regime: one differentiates between laminar or turbulent flow configurations; one also differentiates between configurations in which the flow is momentum-driven or buoyancy-driven. In the present study,

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we focus attention on vertical wall fires featuring non-spreading flames and turbulent buoyancy-driven flow dynamics.

Boundary layer flames have been extensively studied in the fire research literature, using experimental, theoretical and, more recently, computational approaches. We focus in the following on the computational approach. Early computational studies of wall fires were performed using Reynolds-Averaged Navier–Stokes (RANS) models and were focused on simulations of buoyancy-driven, turbulent, non-spreading, vertical wall flames burning along non-flammable [3] and flammable walls [4]. The RANS approach has also been more recently applied to the case of flames that burn and spread along flammable walls [5,6]. While these studies demonstrate the potential of the Computational Fluid Dynamics (CFD) approach for wall fire simulations, the reported accuracy of the RANS simulations is variable and depends heavily on the careful selection of suitable models to treat near-wall turbulence, combustion, thermal radiation, soot formation and wall heat transfer. Wall heat transfer models (*i.e*., models that reconstruct the wall convective heat flux) are needed, unless the computational grid resolution is sufficiently fine and wall gradients are accurately resolved.

During the past two decades, several computational studies of wall fires have also been performed using Direct Numerical Simulation (DNS). So far, DNS studies have been primarily focused on simulations of momentum-driven, laminar, wall flames developing along solid (or occasionally liquid) fuel surfaces, both with [7–11] and without [12,13] flame spread (note that while the term DNS was initially introduced in the context of simulations of turbulent flow, we follow here some of the literature and use it more loosely as a generic term that refers to fully-resolved, first-principles, unsteady reactive Navier–Stokes simulations, including detailed simulations of laminar flame-flow phenomena). The DNS approach has also been recently applied to the case of buoyancy-driven, laminar, wall flames spreading along a solid fuel slab [14]. These studies use a finite rate, global chemistry approach in which pyrolysis and combustion processes are described using semi-empirical Arrhenius-like expressions. The computational grid resolution varies appreciably among DNS studies but remains consistent: grid-converged solutions are achieved by using sub-millimeter grid resolution at the fuel surface (from 0.2 to 1 mm in Refs. [7–14]). While DNS studies provide unique insight into wall flame physics and are a natural companion to detailed experimental studies, they are limited to small-scale laminar flames and cannot currently be used for simulations of the large-scale wall fire configurations that are relevant to fire safety engineering applications.

Surprisingly, while Large Eddy Simulation (LES) has now emerged as the dominant CFD approach for fire simulations [15], to the best of our knowledge, there are very few examples of applications of LES to detailed computational studies of wall fires. One example is found in Ref. [16]. Wang et. al. [16] presents LES simulations of buoyancy-driven, turbulent, non-spreading, vertical wall flames and illustrates the potential of LES for wall fire simulations. However, the comparison between measured and simulated gas temperature and vertical flow velocity presented in Ref. [16] is not satisfactory and the exact accuracy of the LES simulations remains unknown. Like RANS (but *a priori* less than RANS), LES is sensitive to the accuracy of the physical models that treat near-wall turbulence, combustion, thermal radiation and soot formation. In addition, like RANS, the LES performance is adversely impacted when the computational grid resolution is not sufficiently fine. The near-wall grid resolution in Ref. [16] is 1 cm; this grid resolution is not sufficiently fine to resolve wall gradients (the simulations correspond to wall-modeled LES, see below) and therefore the LES simulations in Ref. [16] rely on a heat transfer model to reconstruct the wall convective heat flux and are affected by the limited accuracy of this model.

The scarcity of detailed LES-based studies of wall fires is in large part due to the fact that the simulation of turbulent boundary layer combustion remains a challenging task. First, LES simulations of boundary layer flames require high grid resolution in order to suitably resolve the small-scale flame-flow structures and are computationally expensive. In addition, while the classical theory of turbulent boundary layers is concerned with high-Reynolds number (or equivalently high-Rayleigh number) flow conditions, this theory does not apply to the low-to-moderate Reynolds-Rayleigh number flow conditions that are more relevant to buoyant wall fire applications. Finally, boundary layer flames feature multi-physics phenomena, *e.g*., mass transpiration (due to pyrolysis), combustion and thermal radiation, and these phenomena require specific near-wall model descriptions that so far have not been the focus of fundamental studies.

LES simulations of wall flows belong to one of the following two categories reviewed by Piomelli and Balaras [17]: (1) wall-resolved simulations in which the near-wall computational grid spacing is sufficiently small to accurately capture the gradients of flow velocity and temperature at the wall surface, and in which the wall shear stress and wall convective heat flux are obtained directly from the LES solution; or (2) wall-modeled simulations in which the near-wall gradients remain un-resolved, and in which the wall shear stress and wall convective heat flux are obtained through reconstruction by subgrid-scale wall models. Wall-resolved LES features large computational grid requirements and its domain of application is therefore limited to research-level simulations. In comparison, wall-modeled LES features reduced computational grid requirements and is therefore the preferred approach for engineering-level simulations. Note that wall-resolved LES is generally considered a necessary first step to inform the development of the subgrid-scale wall models that are required in wall-modeled LES.

In this paper, we present wall-resolved large eddy simulations of a turbulent vertical boundary layer diffusion flame configuration. The configuration corresponds to a series of meter-scale wall flame experiments previously performed at FM Global [18,19]. The experimental facility features an array of porous burners supplied with gaseous fuel and thereby corresponds to a simplified configuration in which the fuel mass flow rate is prescribed. This simplified configuration, in which the problem of the fuel supply is conveniently decoupled from the problem of the thermal feedback, is viewed as a valuable intermediate step in the development of a wall fire modeling capability.

The series of experiments reported in Refs. [18,19] use different gaseous fuels and, for each fuel, a range of fuel flow rate conditions; accordingly, the present study presents simulations of wall flames fueled with methane, ethane, ethylene and propylene, and with fuel flow rates ranging from 8.8 to 29.3 $g/s/m^2$. The focus of the present study is on characterizing the flame-to-wall heat transfer (due to both convection and radiation) in the fuel source region of the wall flame, *i.e*., in the region where fuel is supplied. In an equivalent configuration featuring a flammable wall instead of porous burners with gaseous fuel, this region would be the pyrolysis region.

The experimental configuration studied in Refs. [18,19] is presented in Section 2.1. Classical expressions for the wall heat transfer are then presented in Section 2.2; these expressions will be used to support the discussion of the results and help interpretation. The LES solver adopted in the present study is FireFOAM [20,21] developed by FM Global; the solver is presented in Section 3.1, including a discussion of the specific models introduced and used for turbulence, combustion and thermal radiation. The numerical configuration is presented in Section 3.2, including a discussion of the choices made in the design of the computational grid. Results are presented in Section 4, including results on grid