Sub Topic: Turbulent Flames

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Validation of a Low Mach Fire Environment Model with Vertical Porous Burner Experiments

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Abstract: Validation of computational models against experiments is crucial to understanding their predictive capabilities. Frequently, computational modeling packages will have a variety of model form options available to represent the physics (e.g. turbulence models). When modeling a given scenario, it is important to understand the biases of model forms on predicting quantities of interest in similar scenarios. This work seeks to evaluate the ability of a low Mach code to model gases transpiring from a solid boundary in to the fluid domain and subsequent combustion of those gases. We examine the performance of the $k-\varepsilon$ Reyonlds-Averaged Navier-Stokes (RANS) turbulence model with and without modeling of buoyant kinetic energy production compared to experimental data. In addition, we examine the effect of the discretization of the domain on the predictive capabilities of the models. An experimental data set of temperatures and heat fluxes for a vertical, water-cooled porous burner in a 38 *cm* wide channel was chosen for this validation exercise.

***Keywords:* Fire, CFD, Validation**

1. Introduction

The heat-release and fire-spread rates in fires are driven by the heat transfer to surfaces involving a combination of boundary-layer and radiation heat transfer. While these processes have often been described through phenomenological models based on experimental observations, [1] computational models are approaching the point where predictions are feasible. However, these computational models models require validation, and the validation needs to be conducted on a limited scope of the physics to separately understand the predictive capabilities of different aspects of the model predictions. When the complexities of these heat transfer processes are combined with the challenges in the condensed-phase decomposition, discussed in our companion work [2], it is difficult to separate the range of uncertainties to understand the degree to which different physical processes are being predicted correctly.

One experimental configuration that reduces the complexities involves replacing a condensed-phase fuel with a porous burner having a known fuel flow rate and well defined thermal properties. Measurements exist in this configuration based on work by de Ris [3], and this data set has recently been used to assess the predictions of different computational models in a workshop setting [4] as well as in an earlier study by Ren et al. [5]. These studies involved large-eddy simulations

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where a substantial fraction of the turbulence is resolved. Because fire modeling often needs to predict greater geometric complexity, good resolution of boundary layers is not always possible and the present study focuses on Reynolds-averaged Navier-Stokes (RANS) results for this work. The configuration involves a vertical porous burner so that the flame exists well within a buoyant boundary layer, providing a challenging evaluation of boundary layer heat transfer that is a known challenge in RANS modeling. In this work we evaluate the dependence of the predictions on the form of the RANS model and on the mesh resolution.

2. Experimental Configuration

An experimental data set for a vertical porous burner conducted by de Ris et al. [3] was chosen for this validation exercise. The goal of this experiment is to characterize the gas phase processes in vertical flame spread when decoupled from solid pyrolysis by measuring the gas temperatures and thermal signature on the wall in the form of net heat flux. The experimental setup consists of a vertical channel that is 0.38 m wide containing a water-cooled, porous sintered bronze burner with an adjustable height. The channel depicted in Figure 1 is 1.452 m tall and the burner occupies the lower 0.792 m of the channel wall while the remaining top portion is solid material. Both sections consist of water-cooled panels that are 0.132 m tall and panels can be added or removed to change the height of the burner. Side walls extending 0.152 m perpendicular to the burner wall were included to constrain the flow in an effort to limit three-dimensional side effects.

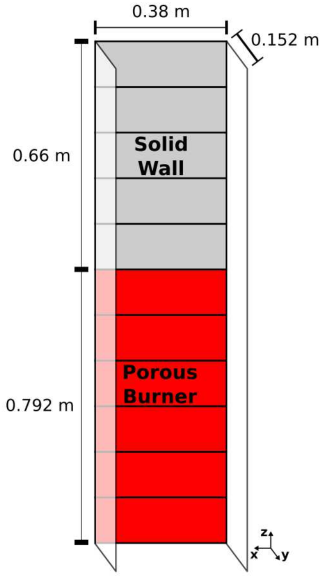

Figure 1: Porous burner experimental geometry.

Experimental data is publicly available in the Measurement and Computation of Fire Phenomena (MaCFP) database [6]. The database contains measurements of gas temperature, wall heat flux, and soot deposition for different fuel flow rates of C_3H_6. In this work, we focus on the 17.05 $g/m^2/s$ flow rate data set. The soot depth and heat flux measurements are reported as a function of elevation while the temperature measurements are given as a function of distance from the wall at an elevation of 0.771 m from the base of the burner. The MaCFP database also contains computational model validation results from FireFOAM [5] and Fire Dynamics Simulator [7] for the porous burner.

3. Numerical Model

The model of interest in this validation exercise is the computational fluid dynamics code, SIERRA Fuego [8, 9], coupled with Nalu [10] for participating media radiation. Fuego uses the control-volume finite-element (CVFEM) method for solving the low-Mach number Navier-Stokes equations and contains models for turbulent incompressible flow, buoyant effects, heat transfer, and combustion while only the discrete ordinates model for radiation transport from Nalu is used. Combustion is modeled using the eddy dissipation concept (EDC) model and turbulent flow is represented by the $k-\varepsilon$ turbulence model.

Additional investigations were conducted on the inclusion of a model for production of turbulent kinetic energy due to buoyant forces from Ris [11]. The form of the source term given as

$$G_B = C_{deris}\Delta k^{0.5}(|\nabla\rho\times\vec{g}| - \nabla\rho\cdot\vec{g}) \tag{1}$$

where Δ is the mesh length scale, k is the turbulent kinetic energy, ρ is the fluid density, and $\vec{g}$ is the gravitational acceleration vector. The model constant (C_{deris}) must be tuned.

The computational domain is displayed in Figure 2 and has dimensions of 0.38 *m* by 0.8 *m* by 1.848 *m* in the x, y, and z directions respectively. At the porous burner boundary, fuel is injected in to the domain while the the wall shear stresses and heat transfer to the wall are modeled. Gases are allowed to enter and exit the domain through the top and side boundaries. The porous burner and channel walls were held at 348 *K* via water-cooling, and all other surfaces are assumed to be solid and at an ambient temperature of 298 *K*.

The mesh resolution was determined by the spacing of the first node off of the wall in the y-direction (Δy). In a similar validation study with FireFOAM, Ren et al. [5] found that an off-wall node spacing of 5 *mm* was sufficient for quantities such as gas temperature and velocity, and ultimately chose to use a spacing of 3 *mm* for comparisons to experimental data. In this study, we examine y spacings (Δy) of 2.5 *mm*, 5 *mm*, and 10 *mm*. Following cues from Ren, the resolution in the x and z directions is set at approximately 2.5 times Δy ($\Delta x \approx \Delta z \approx 2.5\Delta y$).

Proceeding from the burner wall outwards in the y-direction to 0.152 *m*, Δy is held constant. From this point out to 0.304 *m*, the y discretization grows linearly to 2.5 times Δy. At this point, two wedge layers are inserted in the $x-z$ plane to transition the mesh to cells with dimensions of 2 Δx by 5 Δy by 2 Δz. From the wedge layer to the domain boundary at a y location of 0.8 *m* the y spacing grows linearly to $7.5\Delta y$.

4. Results

The performance of Fuego in the wall fire scenario was evaluated through comparisons with several quantities of interest including the gas temperature and velocity at 0.771 *m* from the base of the burner, the heat flux profile along the burner in the vertical direction, and the estimated soot-layer thickness. When available, comparisons will be made to data from experiments. Other

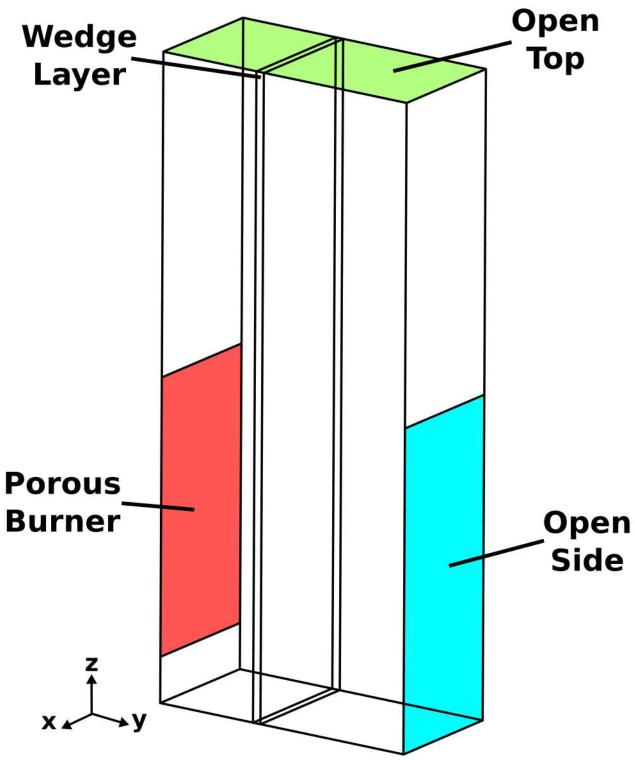

Figure 2: Computational domain and locations of boundaries where flow in and out of the domain is allowed.

comparisons can be made with the large-eddy simulation results presented by Ren [5], but note that the resolution of the two cases is similar.

4.1 Mean Flow Field

As the experimental gas temperature measurements were made with thermocouples, the model gas temperatures must be corrected for radiative and convective heat transfer. The RANS results from Fuego are time-averaged quantities, so we take the steady-state energy balance for a modeled thermocouple

$$0 = \varepsilon_{tc}\left(G - \sigma T_{tc}^4\right) + h_{tc}\left(T_g - T_{tc}\right) \tag{2}$$

where G is the radiant flux from the discrete ordinates prediction, T_{tc} is the thermocouple temperature, and T_g is the gas temperature. The emissivity of the thermocouple bead (ε_{tc}) is assumed to be one as they are generally coated in soot from the flame. The heat transfer coefficient (h_{tc}) from De Ris et al. [3] is approximated as

$$h_{tc} \approx 100\left(\frac{T_{tc}}{T_\infty}\right)^{4/5} \tag{3}$$

where T_∞ is the ambient temperature.

Using Equations 2 and 3, we solve for the modeled thermocouple temperature and report these values. Figure 3 shows the gas temperature profile at 0.771 m for three different off-wall grid spacings compared to predictions from FireFOAM [5]. There is little difference between the Fuego EDC-model predictions using the k-ε model with the 2.5 *mm* and 5 *mm* meshes, while the coarser 10 *mm* mesh predicts slightly higher temperatures. This suggests that the spatial resolution requirements are comparable when using the k-ε model to the requirements using the WALE model in [5], but the temporal resolution requirement for RANS simulations is not as severe.

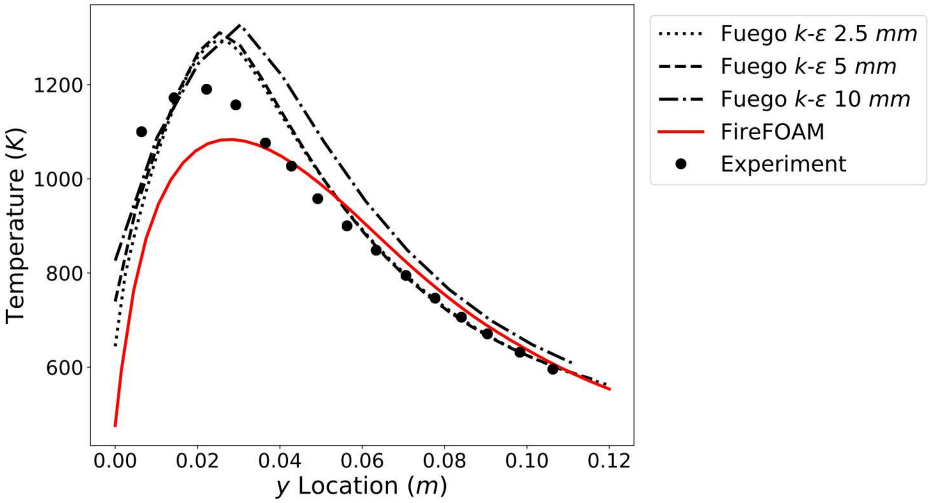

Figure 3: Thermocouple corrected temperature comparison between Fuego EDC-model, experimental measurements, and FireFOAM [5].

There is good agreement between Fuego EDC/k-ε predictions and experimental values beyond about 0.05 *m* from the wall, however the peak temperature predicted by Fuego EDC model is approximately 110 *K* higher than the experimental predictions.

De Ris et al. [3] used the soot deposition depth (δ_{soot}) and fuel to air mass ratio (Ψ) to characterize the thickness of the flaming region for a range of mass flow rates and measurement locations. De Ris found that when the soot depth was normalized by the height from the bottom of the burner (z), the experimental data closely followed the correlation

$$\frac{\delta_{soot}}{z} = 0.32(\Psi - \Psi_0)^{1/2} \tag{4}$$

where Ψ_0 is 0.006 and Ψ is given by

$$\Psi = \frac{s\int_0^z \dot{m}'' dz}{\rho_A z\sqrt{2gz}} \tag{5}$$

and s is the stoichiometric oxidizer to fuel ratio by mass, ρ_A is the density of ambient air, g is acceleration due to gravity, $\dot{m}''$ is the mass flow rate of fuel per unit area. De Ris notes that δ_{soot} is approximately at the off-wall location beyond the flaming region where the gas temperature is 1000 *K* for all values of Ψ. With this, we calculate δ_{soot} based on the location where the average temperature is 1000 *K* and Ψ at a range of vertical locations and compare to Equation 4 as shown in Figure 4. We can see that reasonable agreement is achieved at higher z values (smaller Ψ) with a coarser mesh tending to predict a slightly greater boundary layer thickness.

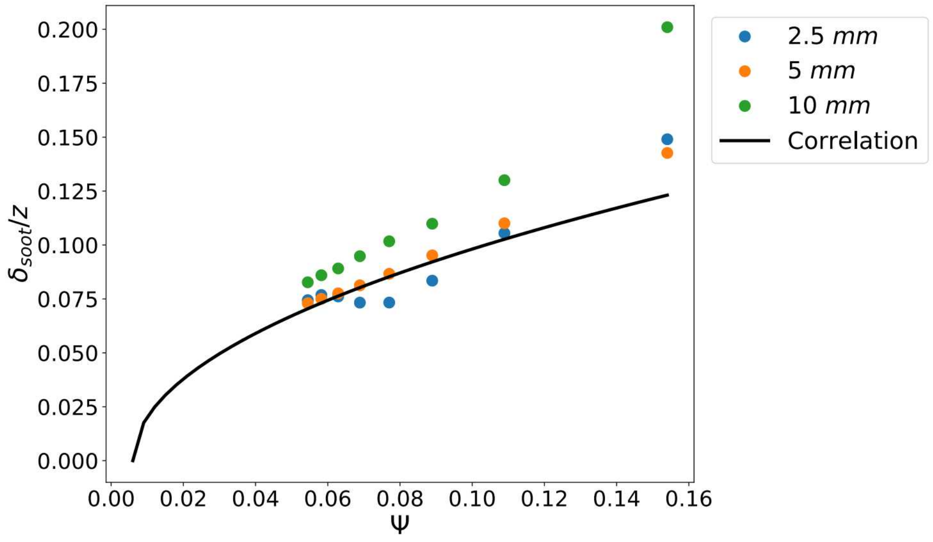

Figure 4: Soot depth verse de Ris correlation.

While no velocity data is available for this specific fuel flow rate, de Ris found that the velocity profiles above 0.6 *m* with a fuel flow rate of 5.4 $g/m^2/s$ collapsed when scaled by the square root of $2gz$ and plotted against the off wall distance as a function of δ_{soot} with the peak velocity being approximately $0.9\sqrt{2gz}$. Ren found a that the predicted peak velocity at 0.771 *m* was insensitive to flow rates between 12.7 and 22.4 $g/m^2/s$ and predicted a value of approximately $0.9\sqrt{2gz}$. For the Fuego simulation with an off wall resolution of 5 *mm* the peak velocity is $1.7\sqrt{2gz}$. This difference could be due to the over-prediction of the gas temperature by Fuego, which results in larger buoyant forces in the wall plume which drives the flow to a higher velocity, or due to poor prediction of the wall shear stress with blowing.

4.2 Wall Heat Flux

The net heat flux to the water-cooled porous burners was measured in the wall fire experiment for each of the six burner sections. Comparisons to Fuego and FireFOAM [5] are shown in Figure 5. The Fuego simulations with 2.5 and 5 *mm* meshes produce similar results while the 10 *mm* mesh simulation predicts a lower heat flux. Fuego over-predicts the heat flux on the lower half of the burner where the flow is transitioning to turbulence while good agreement is shown with the experiments for the upper three burner sections.

Predictions from FireFOAM with a 3 *mm* mesh show good agreement with the experiments, though refined meshes showed behavior similar to that predicted here. As seen in Figure 6, the heat flux is dominated by the convective contribution in the present predictions. Fuego predicts the convective flux to be approximately constant above 0.1 *m* with a higher magnitude than the radiative flux. We note that both FireFOAM and Fuego (5 *mm* and smaller meshes) are wall-resolved and the convective heat transfer is calculated from the temperature gradient times the fluid conductivity, but FireFOAM is an LES model while Fuego is being run in RANS mode.

The radiative flux grows with vertical distance as the flame thickness grows as the radiative interaction between the burner and surroundings in attenuated. Based on this observation, we see

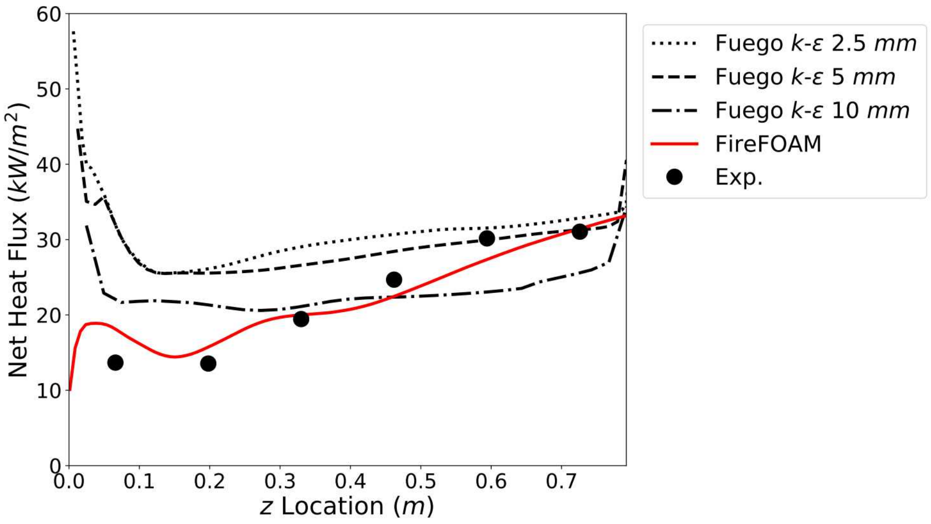

Figure 5: Wall heat flux comparison between Fuego, experimental measurements, and FireFOAM [5].

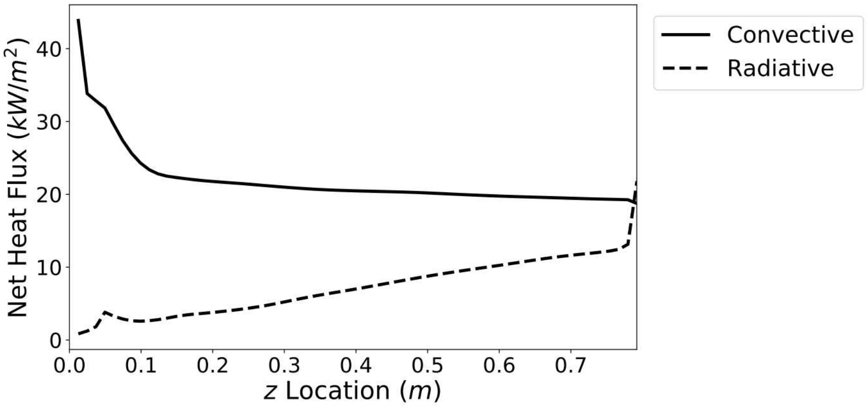

Figure 6: Radiative and convective wall heat flux components from the 5 mm Fuego simulation.

that the radiative flux in the experiments grows by approximately 15 kW/m^2 from the bottom to the top of the burner. When examining the radiative and convective components, Ren found the radiative flux to be the larger of the two components while Figure 6 shows the opposite trend. As the EDC soot model in Fuego is tuned for larger pool fires, this issue could be addressed by adjusting model parameters for smaller fire sizes to better model the radiative flux of soot particles produced by combustion.

4.3 Turbulence quantities

The wall-fire is a developing turbulent flow, with transition happening at the height of roughly 0.3 m, subject to buoyant accelerations that potentially create their own turbulent fluctuations. Here we describe the predictions from the baseline k-ε model and also address the potential role of buoyancy generated turbulence. Turbulence quantities are important in predicting the mixing and transport behavior at the larger scales, once transition has occurred.

Figure 7 shows the turbulent kinetic energy based on the predictions of the k-ε model. The velocity field has a maximum associated with buoyant acceleration at a distance of approximately 0.02 m from the wall. Turbulence is generated by the shear layers on either side of that maxima in accordance with the typical shear-driven production contribution. The magnitude of the turbulence is comparable to the resolved turbulences predicted in the large-eddy simulations in [5].

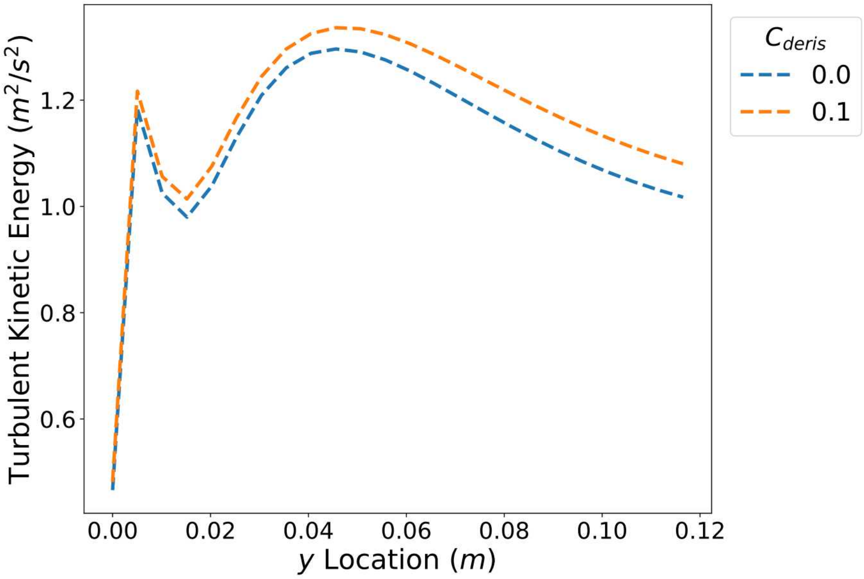

Figure 7: Turbulent kinetic energy for $C_{deris} = 0.0$ and 0.1.

To assess the potential influences of models for buoyant contributions to the turbulence, the model introduced by De Ris is also incorporated. The contribution of that model appears to be modest and most significant far from the wall where dissipation rates are lower. With the constant associated with this model, C_{deris}, set at 0.1 there is a slight improvement in the thickness of the thermal boundary layer, but increasing C_{deris} above 0.1 tends to result in a thicker thermal boundary layer than can be reconciled with the measurements. Uncertainties in the k-ε model itself could also be significant here, so the present results only suggest that the shear-driven turbulence production can account for the majority of the turbulence.

5. Conclusions

The performance of the one of the k-ε turbulence model with EDC combustion in Sierra Fuego was evaluated on a wall fire scenario with measured experimental data. The mesh resolution was found to have little effect on the predictions for off-wall resolutions of 5 *mm* and smaller. Fuego was found to over-predict the peak temperature in the core of the flaming region while good predictions were observed just beyond this region. The thickness of the flaming region was also found to agree with previously published correlations. Good agreement in the heat flux to the wall was observed for the upper half of the porous burner, while over-prediction was observed for the lower half. It was hypothesized that tuning model parameters related to radiative losses from soot could improve predictions. This study served to evaluate predictive capabilities for quantities that will ultimately drive flame spread on a burning vertical surface as it is important to understand the heat transfer in this situation before modeling the pyrolysis of a burning material.

6. Acknowledgements

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