Simulation of Radiative Laminar Coal Dust Flames

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1 Introduction

The influence of radiation on dust flames is surprisingly controversial [1]. Some studies indicate that the effect of radiation is small [2], while others show that it can be dominant [3], depending on the size of the system, particle diameter, concentration, etc. Understanding the influence (or lack thereof) of radiation on dust flames will likely require a combination of experiments and high-fidelity numerical simulations that include thermal radiation by formally solving the radiative transfer equation (RTE).

The high-temperature products of dust flames emit thermal radiation that is absorbed by the cold particles to produce an elongated preheat zone relative to a purely conductive flame. This produces a preheating effect that has been shown to increase the burning velocity of dust flames [3]. Thus, radiation may have a substantial impact on the propagation of coal dust flames [4, 5].

In the present study, we explore the effect of radiation on the ignition and propagation of two-dimensional laminar coal dust flames propagating in channels by solving the RTE. The numerical model solves the multiphase, compressible, reactive Navier-Stokes equations with an Eulerian approach for both the gas and granular phases [6]. Radiation is modeled with third-order filtered spherical harmonics (FP_3). The governing equations are solved using high-order Godunov methods. Adaptive mesh refinement is implemented using the AMReX library [7]. As a result of the inclusion of compressible flow and radiation effects, the present model can simulate dust flame and acoustic wave interactions as well as dust flame and radiation interactions.

2 Numerical Model and Geometrical Setup

The geometrical setup and initial conditions for the simulation are shown in Fig. 1. The geometry considered has a propagating coal dust flame in a closed narrow channel that is 20.48 cm long by 0.64 cm tall. The domain length is discretized with 4096 cells ($\sim$12.5 particle diameters) at the finest level of refinement. The channel is filled with coal dust particles and air at 300 K and 1 atm. The optical boundary conditions are modeled as reflective, so no radiation leaves the domain. The coal dust flame is ignited with a region of high-temperature products and coal at 2300 K for the first 5 cm against the left edge of the channel. A transparent window is placed in the center of the channel using an immersed boundary method. The window separates the dust mixture into two separate clouds by blocking convective and conductive heat transfer, but allowing radiation to pass through freely. Windows

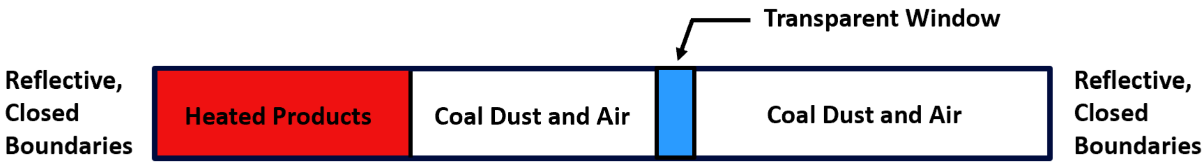

Figure 1: Computational domain and initial conditions.

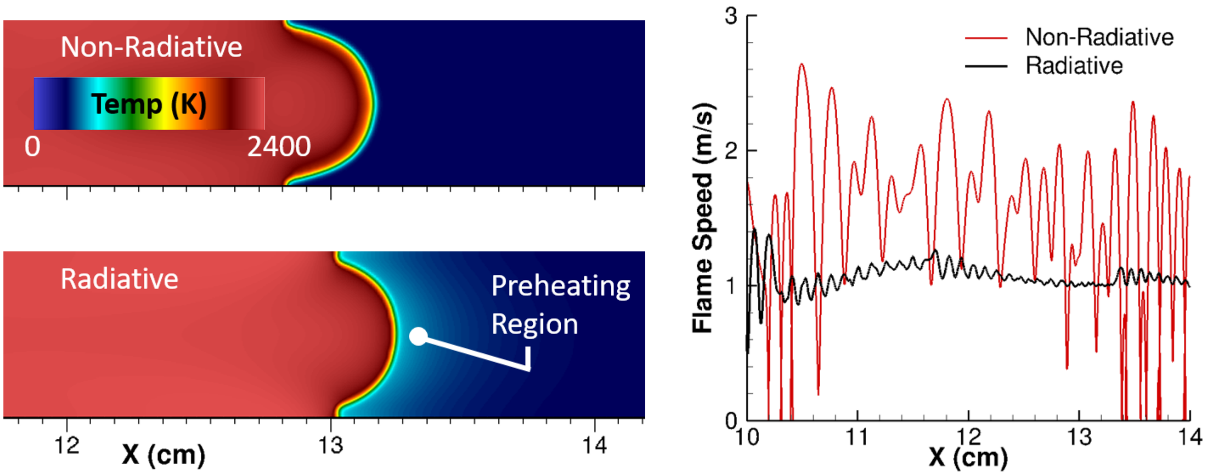

Figure 2: Computational results showing (left) flame structure and (right) flame tip velocity for radiative and non-radiative coal-dust flames.

of varying thicknesses are considered. In addition, separate cases where flames propagate in windowless channels were also simulated to examine the effect of radiation on flame velocity and structure.

The coal dust particles considered are 4 μm in diameter with a concentration of 215 g/m^3, corresponding to an equivalence ratio of ϕ = 1.4. The coal composition used is based on reported values from [8] with 57.9% carbon, 15.2% ash, 26.9% volatile matter, and 1.4% moisture. The volatile composition is approximated as 42.9% CH_4, 42.5% CO and 2.6% H_2 [8]. The gas phase reactions are modeled with a 22-species, 15-step reduced mechanism for C_2H_4 and air from [9]. The moisture evaporation [10], fuel devolatilization [11], and combustion of carbon char [12] are modeled with Arrhenius expressions. The coal dust devolatilizes via two competing reaction rates based on [13]. Details of the solid phase reactions used in the model can be found in [14].

Radiation is accounted for by solving the radiation transfer equation with a third-order filtered spherical harmonics approximation [15]. The radiation is assumed to be gray to reduce computational expense. The resulting spherical harmonic equations are solved using a third-order TVD approach with a Rusanov Riemann solver [16]. The optical properties of the coal dust particles are computed using the Buckius and Hwang correlation [17] with the Planck-mean extinction and scattering coefficients. The Planck-mean coefficients for CO_2, CO, CH_4, and H_2O are taken from [18].

3 Results

The results for a coal dust flame burning through a mixture of 4 μm-diameter coal particles with a concentration of 215 g/m^3 and air through a windowless channel are shown in Fig. 2. The radiative and non-radiative flame both develop qualitatively similar finger-like flame shapes. However, the radiative flame propagates relatively stably near 1 m/s, while the non-radiative flame propagates with a highly oscillatory flame speed. The frequency of these oscillations was determined to be due to acoustic waves

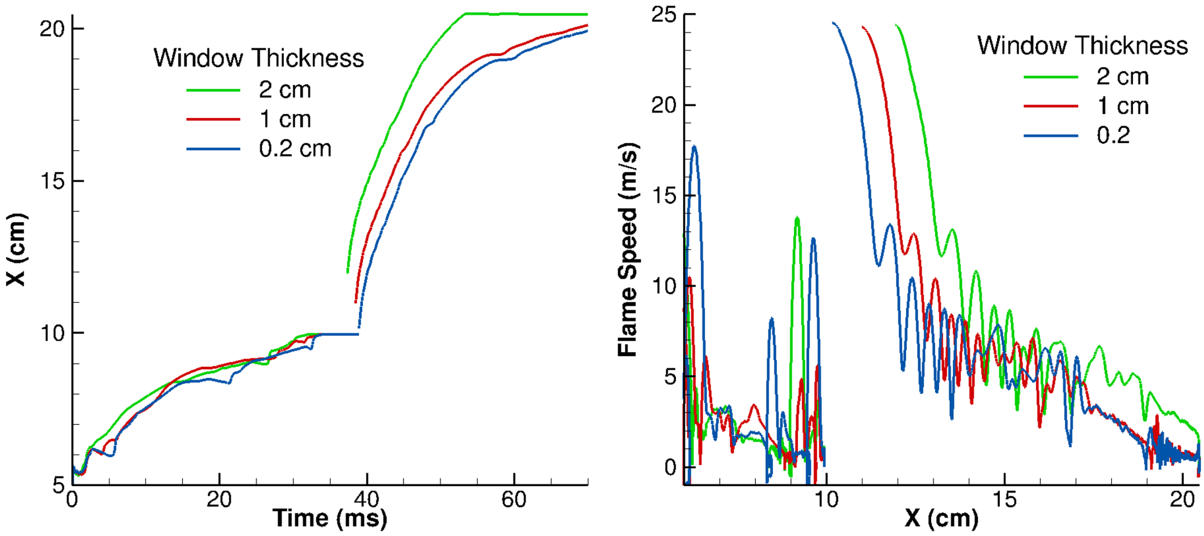

Figure 3: Simulation results showing flame tip position as a function of time (left) and flame speed as a function of flame tip position (right).

reflecting between the flame and end wall. These acoustic interactions produce a large variation in the flame speed due to a sloshing-like effect where combustion products are continually moving back-and-forth relative to the flame surface. (Analyzing the details of these acoustic interactions are part of our ongoing work.) Radiation causes a significant preheat zone in front of the radiative flame, which is completely absent when radiation is neglected. This preheated region stores thermal energy and causes the acoustic waves to have a weaker influence on the flame speed.

The flame position and speed for the three windowed cases considered are shown in Fig. 3. Figures 4 and 5 show a position-time diagram of temperature and profiles of incident radiation at selected times for the 0.2 and 1 cm-thick window cases, respectively.

The high-temperature products from the initial conditions ignite a dust flame that propagates to the right starting from $x = 5$ cm. The flame forms finger-like shapes similar to those shown in Fig. 2. The propagation of the flame is influenced by repeated interactions between acoustic waves and the flame. (See Fig. 4 at ∼10 ms.) The flame continues to propagate through the reactants in the left chamber and eventually reaches the window. This process is almost identical for all three window thicknesses.

At ∼35 ms the flame in the left chamber reaches the window. The intense incident radiation from the high-temperature products in the left channel heat the reactants in the right chamber as shown in Figs. 4 and 5. The reactants are heated in the right chamber for a period of ∼5 ms before ignition. This relatively long period of time prior to ignition produces a relatively large heat-soaked region at ∼ 39 ms in the right chamber. This radiative preheat region produces a reactivity gradient [19] that causes the initial flame velocity to be 25 m/s for all three cases when the flame ignites in the right chamber. The flame then propagates similarly for all three window thicknesses.

4 Discussion and Conclusions

Numerical simulations of radiative and non-radiative coal-dust flames were performed to evaluate the influence of thermal radiation on flame speed and structure. Radiation was modeled with a third-order filtered spherical harmonics approach with a gray radiation approximation. The cases considered are channels with a transparent window placed near the center of the channel.

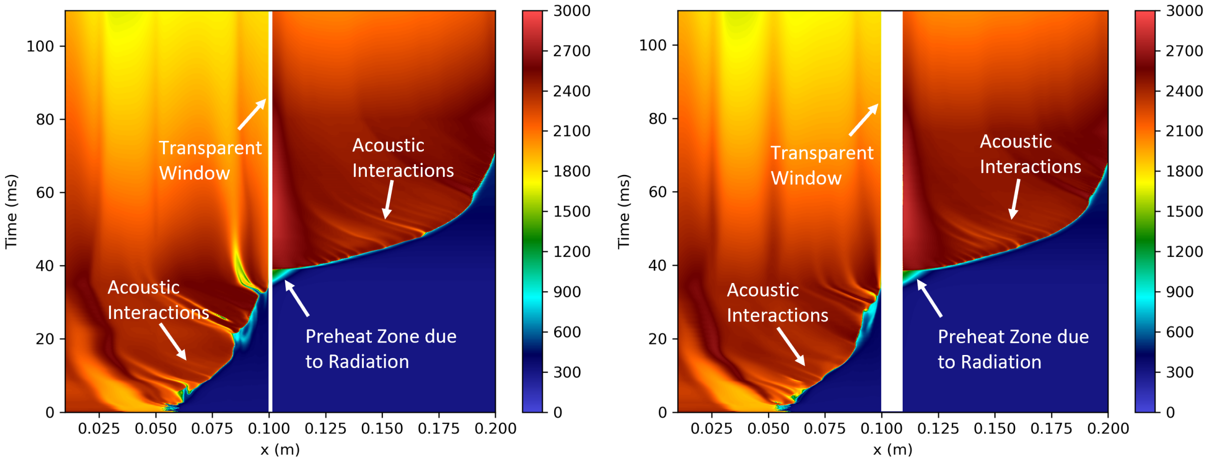

Figure 4: Simulation results showing two position time diagrams with the temperature variation in the channel. The white rectangle indicates the transparent window. Left: 0.2 cm window. Right: 1 cm window.

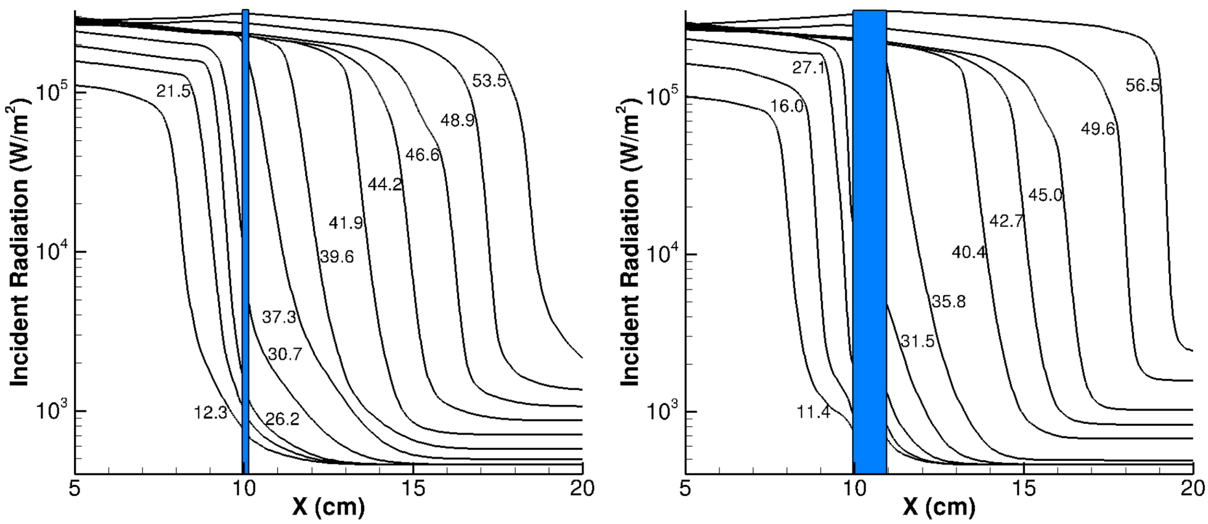

Figure 5: Results showing the incident radiation in the channel as a function of time. The transparent window is indicated by the blue rectangle. Time (ms) is annotated on each curve. Left: 0.2 cm window. Right: 1 cm window.

The computed results show that radiation produces an elongated preheat zone, which is consistent with experimental measurements of Al dust flames [3]. Interestingly, the inclusion of thermal radiation stabilized the propagation of laminar coal dust flames relative to cases where radiation was neglected. This is likely due to the sensible energy stored in the preheat zone, which is not present if the radiation is neglected and the flame is purely conductive. The results also show that radiation can also have a substantial impact on the ignition of nearby dust clouds. Thermal radiation has enough intensity for the cases considered to cause the flame to “jump” across a transparent window. In addition to the radiative effects, the results also show that acoustic waves can affect flame propagation due to multiphase flow effects arising from drag time scales between the gas and particle phases.

Understanding the complex interplay between dust flames, thermal radiation, and acoustic waves is a topic of ongoing work. In addition, the effect of using cold and black radiative boundary conditions will be studied to examine their influence on the propagation of laminar coal dust flames and to determine dust cloud size effects on the ignition of secondary dust flames. Parameters such as dust concentration, particle diameter, volatile composition, and channel size are also being examined to study their effect on the radiative coal dust flame ignition, structure, and propagation.

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