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An investigation of pyrolysis and ignition of moist leaf-like fuel subject to convective heating

Babak Shotorban[*], Banglore L. Yashwanth, Shankar Mahalingam, Dakota J. Haring

Department of Mechanical and Aerospace Engineering, The University of Alabama in Huntsville, Huntsville, AL 35899, USA

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ABSTRACT

The burning of a thin rectangular-shape moist fuel element, representing a living leaf subject to convective heating, was investigated computationally. The setup resembled a previous bench-scale experimental setup (Pickett et al., *Int. J. Wildland Fire* **19**, 2010, 153-162), where a freshly harvested horizontally oriented manzanita (*Arctostaphylos glandulosa*) leaf was held over a flat flame burner and burned by its convective heating. Computations were performed by FDS coupled with an improved version of Gpyro3D. This improvement was concerned with the calculation of the mean porosities in the computational cells to account for the net volume reduction that the condense phase experiences within the computational cells during moisture evaporation and pyrolysis. The dry mass was assumed to consist of cellulose, hemicellulose and lignin undergoing the pyrolysis reactions proposed by Miller and Bellan (*Combust. Sci. Technol.* **126**, 1997, 97-137) for biomass. The reaction scheme was initially validated against published experimental and computational TGA results. Then, the burning of leaf-like fuels with three initial fuel moisture contents (40%, 76%, 120%), selected as per the range of experimentally measured values, was modeled. The time evolutions of the normalized mass were good for the modeled fuels with 76% and 120% FMCs and fair for the one with a 40% FMC, as compared to the experimental burning results of four manzanita leaves with unspecified FMCs. The computed ignition time was also in good agreement with the measurement. The computed burnout time was somewhat shorter than the measurement. Modeling revealed the formation of unsteady flow structures, including vortices and regions with high strain rates, near the fuel that acted as a bluff body against the stream of the burner exit. These structures played a significant role in the spatial distribution of gas phase temperature and species around the fuel, which in turn, had an impact on the ignition location. Fuel moisture content primarily affected the temperature response of the fuel and solid phase decomposition.

1. Introduction

The relative importance of the role of external heat transfer mechanisms in wildland fires has been a subject of discussion for the past few decades [1,2]. Van Wagner [3] suggested three likely mechanisms: (1) flame-fuel contact [4]; (2) radiation from burning fuel particles, i.e., embers [5] in pine needle fires in still air [6], or other fires with low rates of spread; and (3) radiation from flames, as the main mechanism for sloped beds or surface fires driven by moderate winds. Anderson [7] performed experiments and modeling of fire behavior in otherwise still, ambient air, and concluded that between 15% and 40% of the thermal energy required for fire propagation was supplied by radiation heat flux, and the remainder was supplied by convection heat transfer. Frankman et al. [8] concluded that ignition of the fuel element by radiation heating alone is more likely under circumstances where the fire is very intense and even then it may still be dependent on pilot/convective heat sources. Albini [9] developed a simple model for the radiation-dominated heat transfer case, arguing that radiation dominates for backing, no-wind and some heading fires while convection could play a larger role for other heading fires. Rothermel [10] investigated the relative effects of convection and radiation by performing heading, no wind, and backing burns on fine fuel beds. His temperature-time plots of fuel element and gas temperatures suggested that radiation dominantly preheats fuel in no wind and backing burns; however, for a heading fire, the fuel is significantly preheated by convection. Pagni and Peterson [11] formulated a simple model that included radiation, convection, and conduction heat transfer modes and compared the model output with laboratory results in pine needle fuel beds [12]. They reported that under no-wind ambient conditions, radiation was dominant while in wind-aided fire spread, convection was the dominant mode of heating of yet-to-burn fuel ahead of the fire.

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[*] Corresponding author.
E-mail address: babak.shotorban@uah.edu (B. Shotorban).

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Although the impact of heat transfer mechanisms on overall fire behavior continues to be an area of study, relatively little work has been done to examine the relative importance of convective and radiative heat flux on the initial pyrolysis and subsequent ignition of thin solid fuels. These processes precede the development of a spreading fire, and play a significant role in fire spread. Even less is known in situations involving live solid fuels that are characterized by significant fuel moisture content (FMC). In particular, the treatment of fuel moisture in previous studies has been simplified or eliminated by considering dead fuels with little to no moisture content [10,13,14]. Bartoli et al. [15] studied ignition of dead pine needles and reported that forced convection of ambient air delayed ignition due to dilution effect of pyrolysis gases and due to convective cooling. There are several studies focused on the thermal decomposition of the fuel and the nature of resulting pyrolysis gases [16–18]. Yedinak et al. [2] reported that flame contact was essential for fire spreads in their experimental work involving in deep fuel beds. McAllister et al. [19] conducted experiments on ignition of lodgepole pine and Douglas-fir needles where thermal radiation alone was used as the heating mode. They showed that an additional pilot source was required to initiate ignition. Anand et al. [20] conducted physics-based modeling of McAllister et al.'s experiments [19] and found the measured and calculated ignition times in good agreement. On the other hand, Pickett et al. [21] performed experiments on freshly harvested leaves of several species including chamise where only convection heating was applied to the fuel sample. They showed that leaves could ignite without the aid of a pilot flame; however, it is important to note that their experiments involved the introduction of a high temperature gas (products of combustion involving a mixture of methane, hydrogen, nitrogen and oxygen over an FFB with some entrained air) which provides a favorable environment to ignite pyrolysis gases emanating from the leaf. Gallacher et al. [22] used a similar setup, including a radiative panel in the experiments, to investigate the impact of convection and combined convection-radiation heat flux. Their findings indicated that ignition time and solid fuel temperature had a strong dependence on the nature of heating mode adopted in their experiments. Yashwanth et al. [23] studied the effects of thermal radiation on the pyrolysis, ignition, and burning of a moist leaf-like fuel element in a setup similar to [21]. They improved and used the coupled FDS-Gpyro3D computational model [24–26], and showed that it is possible to achieve ignition through imposed radiation heat transfer provided the heat flux is sufficiently large. A shortcoming in Yashwanth et al.'s work was that the solid fuel dry mass was composed of cellulose only. However, in addition to this compound, hemicellulose and lignin constitute the main compounds in biomass [27] and should be included in the pyrolysis modeling [28,29].

The current work is motivated by our desire to seek an improved understanding of the physical processes that lead to pyrolysis and subsequent ignition of live fuel subject to convective heating. Here, the computations are also performed by the coupled FDS-Gpyro3D model with an improvement made on Gpyro3D. In this improvement, the calculation of the mean porosities in the computational cells follow a new formulation (Appendix A) to account for the net volume reduction that the condense phase experiences within the cells during moisture evaporation and pyrolysis. The computational setup resembles a previous bench-scale

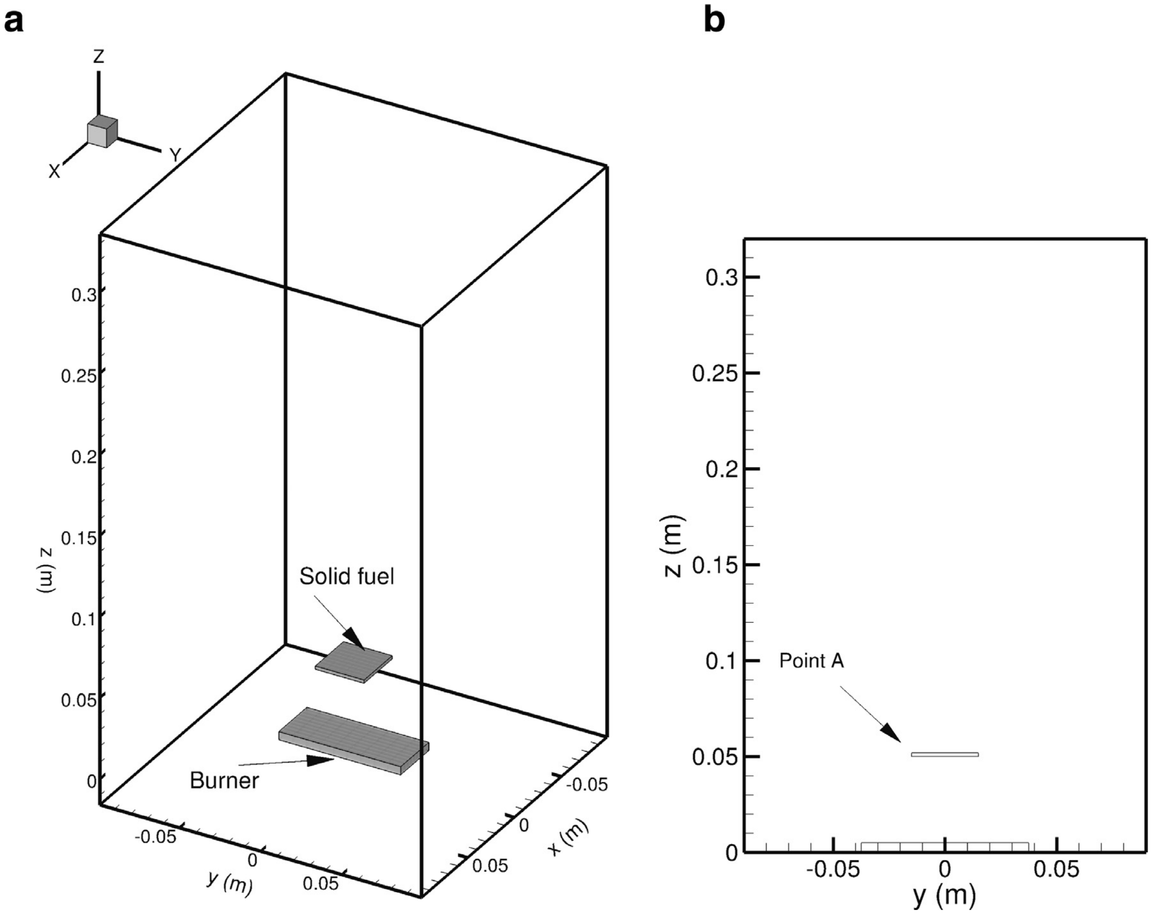

Fig. 1. (a) Isometric view of computational domain showing thin solid fuel subjected to convective heating from the burner, (b) two-dimensional view of computational domain along a *zy*-slice at $x = 0$. Point A considered for a detailed investigation is located at $y = -0.01185$ m, $x = 0$, $z = 0.051$ m.