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Temperature and CO_2 fields of a downward spreading flame over thin cellulose: A comparison of experimental and computational results

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Abstract

The flame structure of a downward flame spreading over thermally thin cellulose in a normal gravity quiescent environment is investigated in this work. A novel experimental set up called the flame stabilizer is used to arrest the motion of the flame by moving the fuel sample. The frozen flame is probed by K-type fine-wire thermocouples and a non-dispersive infrared radiation (NDIR) sensor with force induction to produce the experimental temperature and CO_2 concentration fields. A two dimensional, steady computational model is used to generate the computational fields, which are compared to the experimental measurements. The measured peak value of CO_2 compares quite well with the computational prediction, but the peak temperature measured is significantly lower than the computational peak temperature. The overall measure and computed fields are similar in shape and size. The flame spread rates also agree reasonably well. Although a downward moving flame over thin solid fuel is often considered a laminar flame, the fluctuation data from the probes indicate there is considerable presence of turbulence along the outer edge of the flame.

Keywords: Temperature field; CO_2 field; Downward flame spread; Laminar flame; Turbulence flame

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1. Introduction

Flame spread has been a topic of research interest for quite some time. While flame spread rate is heavily sought after, there appears to be lacking data in flame structure, particularly the temperature, velocity, and species fields. While the driving mechanism of flame spread has already been well established, a better understanding of the flame structure may provide useful information toward predicting spread rate, extinction, and other behaviors. One of the important factors, among many, to account for when flame spread is of concern, is the orientation of flame spread, which may occur horizontally, upside or underside, and vertically, upward or downward. While the spread rate may change drastically from

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one orientation to another, it remains steady nonetheless. The structure of the flame, however, is drastically different from downward to upward. To simplify the problem, we choose to investigate the downward flame spread orientation since spread rate and the flame structure remain quite steady. Attaining the flame structure, along with flame spread rate data experimentally, would be invaluable to model validation.

While flame spread rate can easily be measured with image analysis, determining the structure of a flame is much more difficult. Measurement of the temperature field is common and feasible. Measuring a species field, such as CO_2, becomes more difficult. However, temperature and species are scalar quantities and are more manageable than a velocity field, which is a vector field. Nevertheless, some researchers have been able to measure the flow field. Hirano et al. [1] measured the flow field by the particle tracing method and the temperature field with fine wire thermocouples over thermally thin cellulosic fuels. Hirano et al. [2] also used a particle tracer and fine wire thermocouples and they found instability of downward spreading flames in the pre-heating zone. Juste [3] applied Moiré deflectometry to measure the temperature field of PMMA and found good agreement with thermocouple measurements. Yamamoto et al. [4] measured the flame structure and spread rate of cellulose paper in premixed atmospheres containing various mixtures of gaseous hydrocarbon fuels. They found that spread rate increases with additional pyrolysis and flame shape is enlarged in gaseous fuel-rich premixed environments. Di Blasi [5] developed numerical simulations on thermally thin and thick cellulosic fuels and found that gas phase conduction dominates in the thermally thin limit, while solid phase conduction is more dominant in the thermally thick limit. Fernandez-Pello and Williams [6] measured PMMA flame fields with fine wire thermocouples, interferometry, radiometer, gas phase chromatography, and particle tracking photography. They concluded that conduction through the solid phase is the most dominant mode of heat transfer over thermally thick PMMA fuels. Fernandez-Pello and Santoro [7] later conducted a similar study on PMMA rods measuring the temperature and flow fields. They also concluded that conduction through the solid phase is the dominant mode of heat transfer for flame spread over thick PMMA rods. Ito and Kashiwagi [8], however, also performed experiments on thick PMMA with holographic interferometry and found that conduction in the gas phase, and not in the solid phase, is the more dominant mode of heat transfer. Their conclusion is later supported by numerical models by Bhattacharjee et al. [9] for thermally thick fuels. Bhattacharjee et al. [10] also developed numerical models to investigate the temperature and velocity fields of downward spreading flames; they found reasonable agreement to experimental results.

In this work, we seek out to investigate the temperature and CO_2 fields. The purpose is to provide modelers with field data in addition to the overall flame spread rate that is typically used to validate models. Additionally, flame spread in a microgravity environment has been found to be radiation dominated [11] for low opposed-flow velocities. An accurate prediction of the CO_2 field, the primary radiating species, requires verifiable ground based work. In this work, the gas phase temperature is measured with K-type unsheathed bare-wire exposed-bead thermocouples, and the CO_2 field is measured with a non-dispersive infrared radiation (NDIR) sensor with forced induction. As far as we are aware, this is the first appearance of a CO_2 field measured experimentally on a moving diffusion flame. A numerical model we developed generates the flame spread rate and structure, including the temperature, species, and flow fields. We are seeking model validation with supporting experimental data, with the greater goal of exploring microgravity flame spread with the developed model.

2. Experimental setup

Downward flame spread experiments were conducted using the Flame Stabilizer apparatus in the San Diego State University Combustion Laboratory, under atmospheric conditions in a quiescent environment. The apparatus utilizes a PID control algorithm to keep the flame stationary to a laboratory frame of reference. As a flame propagates downward, it reaches a tracking thermocouple that reads a temperature signal. The signal is relayed to a computer and the computer sends a signal to a motor. The motor rotates to translate the fuel sample holder upward at the same velocity as the flame propagates downward. The thermocouple tracks the leading edge of the flame at a reference temperature. The flame is therefore rendered stationary and the spread rate is calculated from the motor rate of rotation. The spread rate found from the motor matched that of Spotlight [12] analysis, and flame shape from long-exposure photography is similar to a moving flame image to assure the Flame Stabilizer apparatus does not impose a significant effect on the flame. The sample holder on the Flame Stabilizer is composed of 24-gage 302 stainless steel with a fuel width of 3 cm and a length of 100 cm. The fuel investigated in this work is GE Whatman Grade 1 cellulose. It has an area density of 88 g/m^2, a thickness of 180 μm, and is considered to be thermally thin. Ignition is achieved via a butane lighter. More details about the Flame Stabilizer hardware and operation can be found in [13-15]. Besides eliminating the video post-processing time