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Measurement of instantaneous flame spread rate over solid fuels using image analysis

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ABSTRACT

Spread rate is an overall property of flame propagation that characterizes the condition of a flame better than any other property. As a result, prediction and measurement of spread rate is central to flame spread studies over solid fuels. Significant amount of data have been collected over last four decades of research on flame spread over various fuels under different conditions. In most of these studies, however, only average spread rate is reported which is adequate for steady phenomena. Given that a flame may not face the same conditions during the spread, it is possible for the spread rate to change during the duration of the spread continually. In this work a methodology for image analysis is presented with the goal of evaluating instantaneous spread rate to study time-dependent phenomena. The parameters that control the error and time resolution of the flame spread history are identified, and a sensitivity study is carried out to validate the results of a scale analysis. A MATLAB-based Flame Image Analyzer (FIA) package is developed and applied to flame spread videos recorded in several experiments in different regimes of opposed-flow flame spread. An expression for the error in spread rate for a given time resolution is expressed in terms of the imaging parameters. The two parameters that are found most important are the pixel resolution and the frame rate. A non-dimensional imaging parameter is identified that is shown to govern the quality of imaging for spread rate measurement. Theoretical prediction from the error analysis is confirmed by doing various case studies using the Analyzer.

1. Introduction

Flame spread rate plays a fundamental role in multiple areas of research, such as fire safety and combustion, since it is related to the flame growth and the research of flammability limits. It is well known that flames can be very different in shape and behavior on the basis of fuel properties and the surrounding environment. In general, ambient conditions may vary during the propagation of the flame, such as in a boundary layer region where the flow velocity profile depends on the location along the surface, and therefore we would expect a variation in the flame spread rate.

Determining the correct value of flame spread rate in different burning conditions has always been challenging, and many different approaches have been developed in the last fifty years, thanks also to the evolution of technology. In early studies, slow flames (with velocity lower than about 2.5 mm/s) were tracked with stop-watch-measurements of the time needed by the flame itself to spread for few centimeters or regular marks [1,2]. This approach could work only for "steady flames", i.e. flames that do not accelerate or decelerate during the experiment, and it is not very accurate. For faster flames it seemed necessary to calculate the spread rate using other methods, such as video analysis. During video analysis, the user was required to manually measure the distance covered by the flame on a monitor [1,3], or on printed pictures [4]. A good alternative to video analysis for relatively fast flames is the use of thermocouples; in their experiments, Fernandez-Pello et al. used arrays of thermocouples placed at regular intervals normal to the direction of propagation to calculate the flame spread rate [2]. Thermocouples were used also by Bhattacharjee et al., but in a completely different way: flames spreading downward were rendered stationary thanks to a PID control and a thermocouple placed close to the flame leading edge; the sample holder, connected to a motor, moves upward when a reference temperature is reached, and the velocity of the motor can be directly related to the flame spread rate [5]. Even though thermocouples are relatively cheap and reliable, they can make the experimental apparatus very complicated for small scales or particular conditions. An interesting alternative is the use of infrared sensors to obtain temperature profiles, like in the study of Arakawa et al., who measured two-dimensional flame spread rates over vertical solid fuel, showing good agreement with the results obtained with thermocouples [6]. The IR camera can give really accurate temperature

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Nomenclature Listing

V_g	Free stream velocity (cm/s)
V_f	Flame spread rate (mm/s)
Y	Intensity of the pixel luminance
Y_T	Threshold value of Y
n_Y	Number of pixel used to average the luminance
f	Frames per second of the video
p	Pixel per millimeter of the video
n_p	Number of pixel
n_f	Number of frames
t	Time (s)

profiles of the solid fuel [7], and it is beneficial respect to the thermocouples because there is no contact with the sample. However, the flame can interfere with the readings so it is not always applicable. Temperatures profiles were obtained also using holographic interferometry by Ito et al., even though they had to use an additional video camera in order to calculate flame spread rate and pulsation frequency [8]. To overcome the limitations of IR camera and interferometry, Konishi et al. combined the two techniques in the so called infrared-holographic interferometry (IR-HI), and they were able to gather temperature profiles and species concentration at the same time [9]. However, this technique requires a special apparatus and high precision systems, whereas video cameras are more accessible, and researchers usually record their experiments. Furthermore, the rapid growth in the last couple of decades of video quality and coding software made video analysis for flame spread rate much easier and faster. It is not easy to find many details in the literature, but there are examples of researchers developing their own codes in MATLAB, such as Avinash et al., who could track a certain region of the flame for different frames in order to calculate the downward flame spread rate with an accuracy of ± 1 mm/s [10]. The same concept of area tracking is used in Spotlight, a piece of software developed by NASA [11], and used by many authors during the last decade [5,12,13]. One of the disadvantages of Spotlight is that it becomes very time-consuming for processing large amounts of videos of experiments in different conditions and the user has still an important role, increasing the possibility of a human error.

In this paper we present a method to calculate flame spread rate starting from experiment videos and certain parameters chosen on the basis of the experiment; after these input, the software will give us leading edge position and spread rate over time. In this way it is possible to process large amount of data relatively fast, without the need of expensive instruments or complicated set up. Moreover, FIA can reveal time or space dependent variations of the propagating flame, due for example to an opposing flow or lack of oxygen.

2. Image analysis

It is important that we select a simple flame spread experiment as a baseline for this analysis, an experiment which is relatively easy to reproduce and whose behavior is well characterized by developed theory and computational prediction. Opposed flow flame spread over thin fuels offers such a case. There are three well known regimes [14] of flame spread based upon the oxidizer condition. In the radiative regime [15], characterized by very small opposing flow velocity V_g, the residence time at the flame leading edge can be large enough for the radiative effects to be significant. A reduction of V_g(which can be zero in a microgravity environment in the absence of buoyancy) leads to enhanced radiative losses and eventually the radiative quenching of the flame. In the thermal regime [16] of opposed flow flame spread, the spread rate V_f is known to be independent of opposing flow velocity V_g for thermally thin fuels [17], and proportional to V_g for thermally thick fuels. This is because a thermally thin fuel, by definition, is uniformly heated across its thickness irrespective of the strength of V_g while only a thin layer of fuel at the leading edge is heated for a thermally thick fuel,

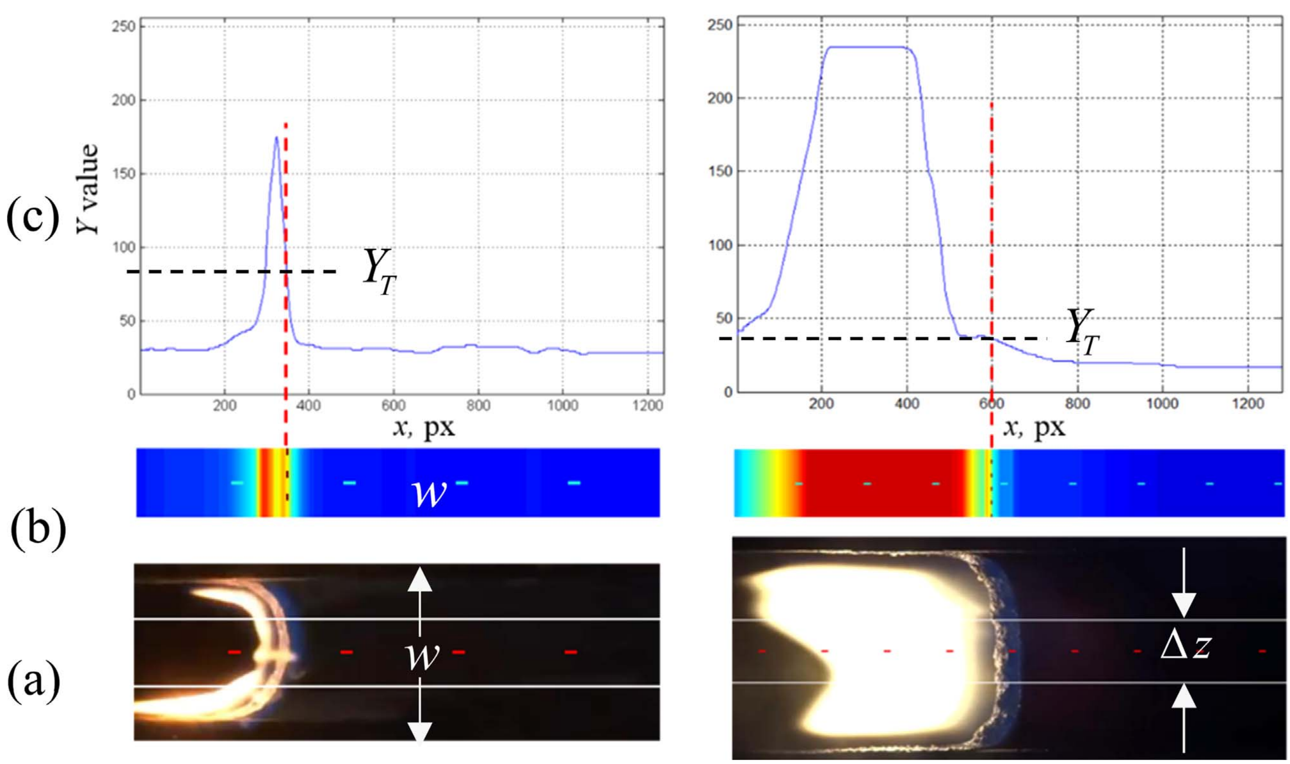

Fig. 1. Flame spread over 75 μm and 3.1 mm thick PMMA: (a) Top view of flame image; (b) two-dimensional averaged image; and (c) Y profile to locate the flame leading edge.