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Experimental analysis of diffusion flame spread along thin parallel solid fuel surfaces in a natural convective environment

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ABSTRACT

An experimental investigation of diffusion flames spreading along thin solid fuels in concurrent and opposed configurations in a gravity induced flow is presented in this study. Flame spreading over one side as well as on both sides of the fuel is studied. MATLAB is used to post process high definition flame videos to obtain flame spread rate as a function of inclination angle of the fuel surface, number of fuel sheets and separation distance. For one side burning, present results are compared with those from literature. For double side burning, the inclination angle is varied from 90° (upward spread) to −90° (downward spread), measured with respect to the horizontal (0°). The spread rates in double side burning are higher and the maximum spread rate is observed for 90° case, as opposed to 120° in single side burning. The upward flame spread displays a non-uniform temporal variation, especially when the orientation angle is greater than 20°. Fuel cracking was noted to be most severe at 90°. However, the downward flame spread rate is almost steady. The multiple fuel sheets (2 and 3 sheets) are kept parallel to each other with the separation distance between them varied from 0.5 to 3 cm. In upward flame spread, for a small separation distance of 0.5 cm, multiple sheets produce spread rates lower than the single fuel case due to insufficient oxygen supply. At 1.5 cm separation, maximum flame spread rate is observed for multiple sheet cases, due to increased availability of oxygen and enhanced heat transfer from neighboring flames. At 3 cm, the spread rate is almost the same in all cases indicating that the interference effects have become weaker. The variation of flame-spread rate in multiple fuel sheets with respect to inclination angle is almost similar to that of single sheet cases.

1. Introduction

Research on flame spread over thin solid fuels has gained importance due to safety concerns. In large-scale room fires, where multiple fuel surfaces are present, a solid surface is always subjected to high heat flux from the fire as well as from hot surfaces surrounding it. The amount of heat received by the fuel, which is normally from all the three modes, further depends on the number of neighboring flaming surfaces and their separation distances. These scenarios can also be encountered in warehouses, libraries and storage areas having tall vertical racks with commodities. The effect of gravity, based on the location of ignition and the inclination of the fuel surface, is also important. Flame spread mechanism under these variable conditions can be highly complex and difficult to understand. The maximum spread rate in any of these situations determines the worst-case scenario that should be accounted for, in the design of fire detection and fire suppression systems. Such situations make the study of multiple flame spread intriguing and prominent. Over the recent years, there has been a significant progress in our understanding of the physics of flame spread, which is essentially a complex phenomenon. Based on the direction of movement with respect to the gravity vector, the flame-spread phenomenon is traditionally categorized as concurrent and opposed flame spread. The spreading behaviors of the two flame types are distinct by nature. However, each of them further results in varying consequences based on the physical conditions they are subjected to. It is important to understand their mechanism in order to prevent a rapid flame spread in an actual fire. For this reason, more careful observation and analysis of flame spread under various combustible scenarios are to be studied.

While flame spread over vertical surfaces has been traditionally studied over the years [1–6], literature related to inclined flame spread was initially presented by Hirano et al. [7]. They

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experimentally examined the heat transfer to the unburnt surface in front of the pyrolysis zone along downward flame spread over thin sheets using Schlieren photography. Another work of Hirano et al. [8] described the gas velocity and temperature profiles of spreading flames over paper oriented at three different angles, using particle tracer techniques and fine wire thermocouples. The spread behavior has been described with respect to entrained air, vortex formation and its interaction with the flame. Kashiwagi and Newman [9] employed α-cellulose sheets to measure downward flame spread velocity from vertical to horizontal configurations under varying external radiant fluxes. Quintiere [10] reported the critical transition angles while burning metalized polyethylene terephthalate and paper on glass fiber insulation at various upward to downward flame spread configurations. Ito et al. [11] experimentally investigated the propagation and extinction mechanisms of opposed flow flame spread along a thick slab of PMMA at four different orientation angles subjected to different air flow rates. Numerical results were presented by Ali et al. [12] on laminar, quasi-steady burning characteristics of a thin film of methanol under atmospheric pressure and normal gravity conditions. The orientation range of $-90^{\circ} \leq \theta \leq +90^{\circ}$ was considered and the mathematical model was accounted for normal as well as cross flow buoyancy components so as to differentiate between upward and downward burning rates. Later, Ali et al. [13] extended the studies of Ahmad [3] by estimating the variation of heat flux parameter along the fuel and downstream wall surface. Honda and Ronney [14] carried out an experimental study on the upward flame spread over thermally thin solids (KIM wipes) to find approximate relations for steady spread rates in the presence of heat and momentum losses for laminar and turbulent flows, buoyant and forced convection, and thick and thin fuels. Recently, Gollner et al. [15] studied upward flame spread over wide samples of corrugated cardboard during early-stage burning. In a later study, Gollner et al. [16] used a thermally thick slab of polymethyl methacrylate to study the effects of inclination angle of fuel surface on upward flame spread. It was shown that maximum spread rate doesn't correspond to maximum fuel mass loss rate. Kleinhenz et al. [17] investigated the flame propagation speed and surface temperature distributions over a composite fabric (50% cotton and 50% fiberglass) and found that the fiberglass acted as a flame arrester. In a following work on composite fabric by Johnston et al. [18], upward flame spread experiments were conducted on long thin composite fabric fuels made of 75% cotton and 25% fiberglass. The fuel specimen width was varied between 2.5 cm and 8 cm and the fuel lengths were greater than 1.5 m. Effect of fuel width on flame blow off was reported. Previous studies pertaining to the effect of sample width on flame spread are reported in Refs. [19–21].

Limited studies on multiple fuel sheets are also reported in the literature. Kurosaki et al. [22] studied the characteristics of steady, two-dimensional, vertical downward spread of flame along single sheet and two parallel sheets of paper kept at different separation distances in air-conditioned environment. Results showed that the flame spread rate for parallel burning was approximately half of that of the single fuel sheet case, when the separation distance was lower than 3 mm. When the separation distance was increased beyond 5 mm, the spread rate was found to be more than that of the single fuel sheet case. The flame spread rate reached a maximum value when the separation distance was around 1.5–2 cm. In the study by Itoh and Kurosaki [23], it was reported that when the separation distance was greater than 5 mm, the spread rate reached a constant asymptotic value irrespective of the number of sheets used. At separation distances lower than 3 mm, the flame did not spread with more than 2 fuel sheets. Comas and Pujol [24] analyzed the flame front speed during the downward propagation in multiple parallel samples of thermally thin fuels under normal gravity. Results from several models based on energy balance were compared against the experimental results. Recently, numerical studies on flame spread over parallel thin fuel samples in reduced gravity environment were reported for concurrent flame spread in Shih [25] and opposed flow flame spread in Malhotra et al. [26]. In both these studies the flame spread rate exhibited a non-monotonic variation with a decrease in separation distance.

Few studies related to vortex-flame interactions in condensed fuels are available. Hirano et al. [8] reported the vortex interaction effects on flame spread over single side of a blank computer card. Baki and Tarek [27] suggested a puffing mechanism involving large scale vortical structures causing periodic oscillations near the source of buoyant diffusion flames. In Yang et al. [28], convective ignition of PMMA in a combustor was investigated and the influence of flame-vortex interactions was reported. A brief note on vortex shedding and puffing of flames from methanol surfaces was elucidated in Ali et al. [12].

Most of the research works presented above have concentrated on the burning characteristics of single fuel surface kept at various inclination angles. A few experimental studies are available on flame spread on multiple parallel fuel surfaces, however, oriented only in the vertical configuration. Therefore, filling up some of the above mentioned knowledge gaps in literature forms the primary motivation to this study. Here, the spread rates of flames established on both sides of thin paper samples have been carefully measured using lab-scale experiments. Cases of single fuel sheet and multiple fuel sheets placed parallel to each other at different separation distances have been studied. Further, the orientation angle of the fuel sheets with respect to the gravity vector has also been varied considering both upward and downward flame spread. The flame spread rate is controlled by the rate of thermal energy feedback from the flame to the unburnt surface. The heat feedback to the unburnt surface depends on the number of flaming surfaces and its proximity to the flame.

2. Experimental setup and procedure

An experimental setup, shown in Fig. 1, has been fabricated to hold thin solid fuel sheets such that they can be inclined at any desired orientation angle while burning. The setup consists of two sections (Fig. 1(a)). The lower section is made of mild steel. This lower section clutches the upper section, made up of aluminum, and enables it to be fixed at a specific orientation angle with respect to the horizontal. The lower base consists of two L-shaped mild steel plates of 0.5 cm thickness, which are firmly fixed 30 cm apart by two arms welded at the bottom of the plates. Two arc shaped slots are provided on both the plates to enable the rotation of the upper casing to a desired angular orientation. A common lift rod passing through these slots are clasped at a desired location by a knob fixed into the rod through a wing nut mechanism. The lift rod is connected to the upper casing by a link arm.

The upper aluminum section holds the fuel sheets while burning. It consists of a base plate of thickness 0.5 cm and has 6 holes drilled through it. The holes are separated by 15 cm in the height wise direction and 20 cm in the width wise direction. A pair of aluminum frames firmly holds a fuel sheet. Owing to their low density, high strength and low emissivity, aluminum plates have been used traditionally in fire experiments [9,14,25] to hold fuel samples. The minimum distance of the first fuel sheet from the base plate is about 5 cm in order to ensure that the flame spread phenomena is not affected by the presence of the plate. There are provisions for holding multiple fuel sheets with double the amount of aluminum frames. Figure 2 shows an isometric view and a side view of multiple fuel sheets for 90° upward flame spread clad with aluminum side plates mounted together on screw rods. Similar multiple aluminum frames with fuel sheets are rigidly mounted