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Investigation of flame propagation over an inclined fuel wetted porous bed

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ABSTRACT

This experimental study was conducted to investigate the rate of flame spread over an inclined porous solid (sand) wetted with finite quantities of fuel (iso-propanol). The study comprised experiments that were conducted over 15° and 30° inclined beds with depths ranging from 13.3 mm to 39.9 mm and consisting of average sand particle diameters ranging from 0.5 mm to 5 mm under quiescent, assisted and opposed airflow conditions.

Analysis of the resulting data indicate that the rate of flame spread is significantly decreased by increasing the bed inclination angle or the airflow velocity and is applicable for both assisted and opposed directions. Furthermore, the rate of flame spread is decreased to the minimum value and actually ceased halfway along the bed with a 30° inclination angle. This behaviour was observed mainly for beds containing coarse sand particles. The rate of flame spread was higher for thinner beds rather coarse beds under any given airflow conditions. Finally, the rate of flame spread in upward direction was relatively quicker in comparison with downward direction counterpart.

1. Introduction

Images of large scale fires in industrial settings or residential areas often demonstrate the destructive power of fire and the rate at which it can spread to nearby areas. Flame spread is a difficult and complex concept to explain given the large numbers of physical, chemical and environmental aspects; and the large number of variables involved in combustion at different stages of the process. Of the many types of fires, those occurring in industrial settings, particularly those in petrochemical industries, are responsible for considerable loss of life and property in many parts of the world every year. Quite often the accidental spillage and subsequent ignition of combustible liquids is the cause of fires in large-scale industrial settings (e.g. petrochemical industry). In many such fires the liquid fuel spills over a porous inert surface (e.g. a concrete slab or gravel) penetrating into its open pores and/or cavities. If the fuel is ignited, a stable flame may form and subsequently spread over the surface of the porous bed. If not treated flames may rapidly spread and envelop nearby buildings and components leading to massive destruction and losses. The characteristics of the flame spread phenomenon over porous beds are significantly different from those over non-porous solids and liquid pools. While there are many papers on pool fires for example [1–4] and flame spread over porous bed flushed-up with liquid fuel [4–19], there has been very little research on the rate of flame spread and flame behaviour over a bed soaked with a finite amount of liquid fuel [4–7,9,12,16,17,19]. Ishida [6–9], Takeno and Hirano [15] performed broad experimental studies of the flame spread over glass, sands and steel beads. These studies exclusively focused on scenarios where an unlimited supply of liquid fuel was available to soak the inert porous bed. They found that the flame spread rate is strongly dependent on the size of the solid particles [7]. It was also found that the rate of flame spread is generally slower than that of pool fires. The porous bed fuel content is a significant parameter in the flame spread phenomenon. The flame spread velocity and flame behaviour is strongly affected by the initial amount of liquid fuel in the porous bed [7]. For a bed with an unlimited fuel supply, the surface of the porous bed is flushed with fuel. In the flushed bed, if a fire occurs, the flame behaves similarly to a flame on a liquid pool. The majority of previous studies have been conducted on this type of fuel-flushed beds, while in practical situations there is typically only a limited fuel supply. As such the porous bed is not soaked, but rather wetted by the liquid fuel which slowly penetrates through the bed. The finite quantity of the liquid fuel in this case has a significant impact on the flame, altering its propagation behaviour and/or other characteristics [7]. To narrow down this knowledge gap we undertook a series of combined experimental and theoretical investigations were undertook at the University of Newcastle (Australia). Results obtained from these investigations [20–29] revealed that the flame

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spread rate under both assisted and opposed airflow configurations noticeably decreased as the air speed was increased although the extent of decay in the flame spread rate was more pronounced in the case of the opposed airflow configuration [20,21]. However, regardless of airflow speed and/or direction the rate of flame spread was found to decrease as either the bed depth or particle size are increased [22]. Moreover, the investigations revealed that the fuel penetration rate into the porous bed was a function of bed permeability and the mass of the liquid fuel. The permeability of the porous bed and consequently the rate of fuel penetration were found to decrease as either the tortuosity or specific surface area were increased [23]. Knowing the flame spread behaviour in fire caused by fuel spillage will help responders to take proper action to control and suppress the fire at the beginning of the combustion process. The present study which builds upon our previous investigations [20–29], aims to examine in detail: (1) the flame spread rate over an inclined porous bed wetted with flammable liquid and (2) the effect of assisting and opposing airflow on the rate of flame spread. Moreover the rate of flame spread for different inclinations and various particle sizes under airflow configuration is examined by applying the concept of the Damköhler number.

2. Experimental set-up and procedure

Experiments were performed using the set-up shown schematically in Figs. 1 and 2. The set-up consisted of: a rectangular channel mounted on a support frame; a hydraulic jack for traverse movement; a heat exchanger unit fitted to the bottom of the channel to maintain its temperature around the ambient temperature; a water bath; a thermocouple grid (type K, Ni/Cr – Ni/Al, -200–1370 °C) for temperature measurements; a ducted fan; a fuel distributor (not shown in Fig. 1); a canopy hood connected to an exhaust fan; a high speed digital camera; and a data acquisition system comprising a data logger and a computer. A scaled channel was designed to mimic the spread of flames over a range of porous media under realistic conditions within a controlled laboratory setting (Fig. 1). The $1500 \times 80 \times 40$ mm^3 channel shown in Fig. 2 was made out of stainless steel. It was fixed to the support frame at one end through the hinge point (displayed by "A" letter in Fig. 1) and was mounted on the hydraulic jack at the opposite end. This arrangement allowed us to vary the inclination angle of the channel if needed. The external surfaces of the channel were covered with a 5 mm thick insulating material (calcium silicate sheet) to prevent heat losses. The channel was filled with 6 different particle sizes of sand (0.5, 1, 2, 3, 4 and 5 mm; density=2680 kg/m^3) in three different depths (13.3, 26.6 and 39.9 mm) as the porous bed. The effect of air flow on the flame

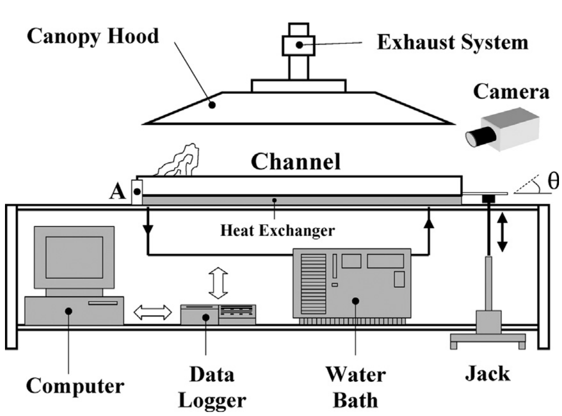

Fig. 1. Experimental set-up to measure flame spread rate over fuel wetted porous bed.

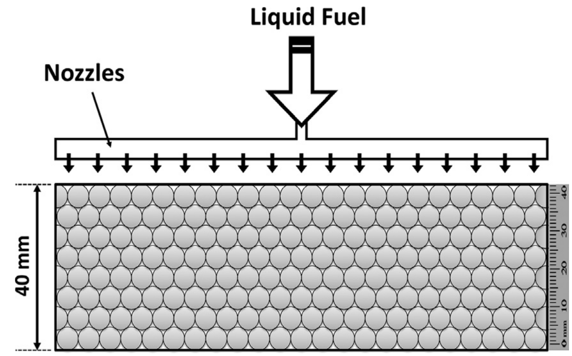

Fig. 2. Porous bed sketch.

spread was simulated using the $1300 \times 200 \times 200$ mm^3 ducted fan. The duct was used to have a uniform airflow at the duct outlet. The airflow was measured at the duct outlet using a grid frame and an accurate anemometer. In this technique the duct outlet cross section is divided into numbers of small imaginary squares. The airflow velocity is then measured and recorded at the centre of each square. The fan air flow velocity is calculated by averaging these recorded air velocities. To avoid any turbulence the duct was kept clear of any deformation, protrusion and indent. The air flow passageway was kept open and all other air sources (open window, air condition, etc.) were eliminated to prevent interference with the airflow coming from the fan.

2-Propenol was used as the liquid fuel and uniformly distributed by a liquid fuel distributor all over the porous bed. The ratio of fuel volume to the weight of the sand bed (i.e. fuel volume/sands weight) in all experiments was kept at about 0.1 L/kg. This ratio was calculated based on the bed volume, fuel and sand particles density and void fraction. The void fraction for this type of particles and bed formation was assumed to be 0.41 [30]. Ignition was achieved using a pilot flame. The flame speed and hence the spread rate were digitally determined from high-speed video cinematography, video image processing techniques and visual observation. In these techniques the recorded video is split to frames, then frames are analysed and studied.

To assure data validity and reliability, three experiments were conducted for each data point. To eliminate any possible error which could come from the operator, instrumentation and environmental conditions, all instruments were calibrated prior conducting experiments. To minimise personnel (operator) errors all samples preparation were carried out by one person only. The support person provided quality assurance in terms of ensuring that all procedures were correctly followed.

The rates of flame spread over porous bed were digitally determined from high-speed video cinematography, video image processing techniques and visual observation. In these techniques the rates of flame spread for each individual experiments was calculated based on the recorded videos, time and distance travelled by flame front.

3. Results and discussion

The channel was initially filled with desired sand particles according to the experimental plan. The surface of the porous sand bed then was smoothed out using a very small trowel with no compaction. The fan airflow was regulated (if required) to planned airflow prior to fuel distribution. The fuel was uniformly distributed over the porous bed with zero inclination ($\theta=0$) by the liquid fuel distributor described earlier in Section 2. The bed then was then tilted up to the desired inclination angle and lit by a gas lighter.