Experimental Investigation of the Fire Spread on Inclined Wooden Rods

Yufeng Lai, Hangxu Zhou, Yang Zhang
University of Sheffield
Sheffield, South Yorkshire, UK

1 Introduction

The flame propagation rate of a burning rod, as one of the most important properties, is dependent on numerous factors including inclined angle, oxygen concentration and moisture content. Among those, the inclined angle of fuel surface could be the dominant factor which affects the flame propagating rate. From Moodie's study in 1992 [1], it is found that the inclined angle of 30° on the wooden escalator strongly enhanced the fire spreading which resulted in the disaster of King's Cross fire. Meanwhile, Drysdale investigated the flame spread rate on inclined surfaces by using the PMMA slabs, and it was found that the flame spread rate could be significantly increased by the side walls [2]. The characteristics of the fire plume on inclined surface was visualised and analysed by using a Schlieren system in Wu's study [3]. From his results, it was observed that there is a critical angle of 24° at which the flame attachment length started to increase sharply in a broad range of inclined angles. Zhang et al. investigated the deceleration of downward flame propagation and determined the critical angle of fire extinguish was -45°, as well the fire spread rate on upslope surface in a combustion chamber was measured, he had established an empirical formula to predict the extinction of fire at critical angles [4][5]. Zhou burned single species fuel bed in a metal platform with the side walls mounted at different angles to study if the fires could propagate successfully in certain angles and had highlighted the angle range above which the fire could spread successfully [6]. By using retroreflective shadowgraph technique, the flame attachments of uphill flames were qualitatively analysed by Grumstrup et al. [7]. In 2017, Yang et al. [8] studied the flame geometry along the inclined surface using the grey scale image and found the flame length increased with the inclination angle at lower angle. From the above literatures, it has been demonstrated that the visualization analysis is an effective method to investigate the flame dynamics around an inclined surface. However, there is few of publications focusing on the study of inclined-surface-burning with visualization analysis. As a new study, the fire propagation rate of a single wood rod without side walls is investigated by using a high-speed Schlieren imaging system. As a great advantage, the Schlieren imaging system can be utilized to visualize the fire induced heated flow which cannot be observed by direct imaging. Furthermore, a wood rod is easily controlled under certain experimental conditions, which could be helpful for the understanding of real circumstances. In this paper, a sequence of oak wood rods with different diameters has been ignited at various angles to investigate the effects of inclined angle on the fire propagation rate and burning lifetime. A high-speed imaging system with a CMOS camera has been used to capture the images of burning rods, as well a Schlieren system has been utilized for visualising the fire induced flow around the wood rods.

2 Experiments and Methods

In this study, the oak wood rods, which covered a broad range of diameters including 6mm, 7mm, 8mm, 9mm, 10mm, 11mm, 12mm, were tested. In order to minimise the effects of cylinder length on flame propagations, all testing samples had been cut into the same length of 400 mm. Before the ignition, the wooden samples had been pre-dried in an electrically controlled furnace for 24 hours at the temperature of 150 ^{o}C. The samples were hold above the burner by an adjustable holder at various inclined angels, which is shown in the left panel of Fig. 1. The angle θ indicates the inclined angle between rod and horizontal direction. The positive θ value was used to indicate the downward fire propagation, whereas the negative value indicates the upward direction. Each case was tested at -30^{o}, 0^{o} and 30^{o} to investigate the effect of different rod diameters and fire spread direction on flame propagations. In order to investigate the effects of inclined angles on flame propagations, the group of 12 mm diameter samples was tested at six different angles, including 30^{o}, 0^{o}, -15^{o}, -30^{o}, -45^{o}, and -60^{o}. All cases had been repeated for at least 3 times, and the results were averaged. A pre-mixed methane and air gas flow was used to ignite the samples. The burner was immediately turned off once the samples was ignited.

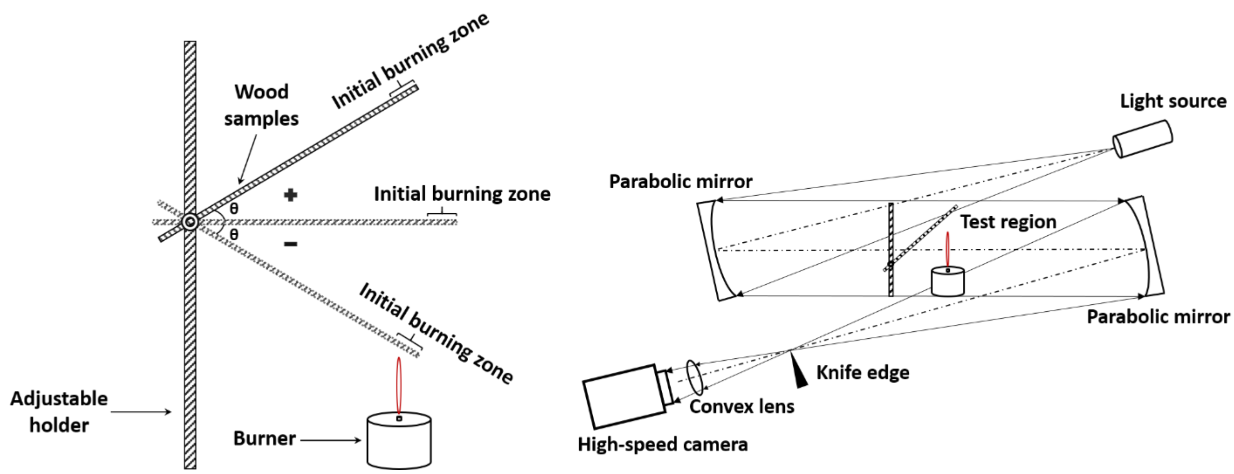


Figure 1. Left: Schematic representation of the experimental set-up, Right: The Setup of Schlieren imaging systems.

A high-speed CMOS camera was set in the front of the testing zone to capture the images of burning rods. The propagation rates of surface charring were calculated to represent the fire propagation rates. Meanwhile, the burning lifetime was determined from time duration since ignition until flame extinguishment. Furthermore, a Schlieren imaging system was used to capture the flow images during the burning, at as shown in the right panel of Fig.1. The schlieren system can be used to observe the ambient flow field around the objects which cannot be seen by actual imaging system. As well the schlieren imaging system has a high sensitivity which could use into analysing the effect of different diameter wooden rods.

3 Results and Discussion

3.1 The properties of flame spread

The comparisons of the burning status of direct imaging are presented in the Fig.2, including the rod diameters of 6mm, 9mm and 12mm, and at the inclined angle ranged from -30° to 30°. Respectively, three images in each frame is shown in the sequence of time, including the beginning of self-sustained burning, the middle-aged flaming and the extinguishment (142.5s in -30° group). Horizontally, the frames indicate the results of increasing diameters from 6 mm to 12 mm, whereas vertically they indicate the results at different inclined angles of 0°, -30° and 30°. It is found that the burning at -30° had the highest intensity and longest lifetime which could keep burning until the fire spread thought the whole wood. Furthermore, the flame attachment phenomenon could be clearly observed in the negative angle groups, that the flame tilted toward to the unburned surface due to the dynamic effect created by the decreased air entrainment into the fire plume [2]. Comparatively, the cases burning at positive angles were weaker and the flame rarely spread along the rods. Also, the spreading distances of flame were shorter than other cases. The fire always extinguishes in short period of time after a slow and short propagation. Compared with different diameter samples in positive -30° case, it had been calculated that the 6mm diameter sample had the longest charring distance (77mm) when it burned for 142.5s followed by 9mm (66mm) while the 12mm sample(47mm) had the shortest charring distance, which means the fire on larger diameter sample would have a lower propagation rate.

a)
b)
c)

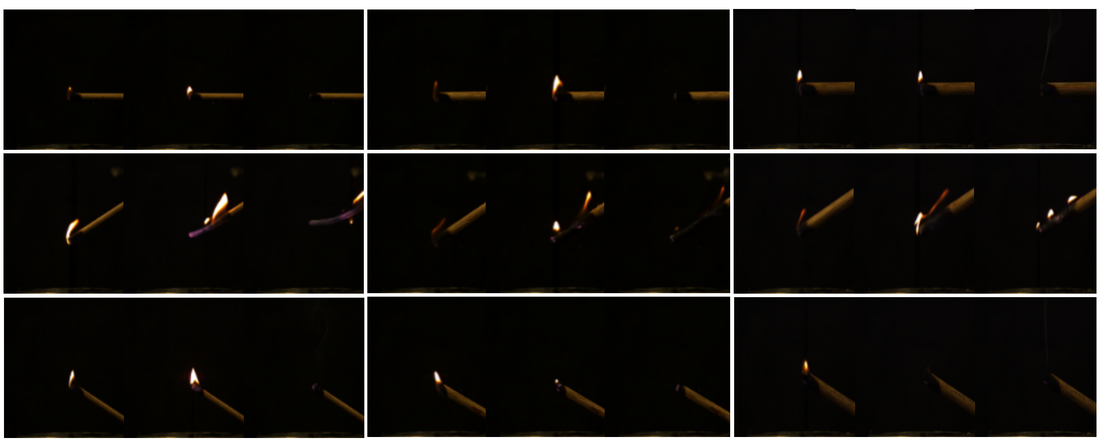
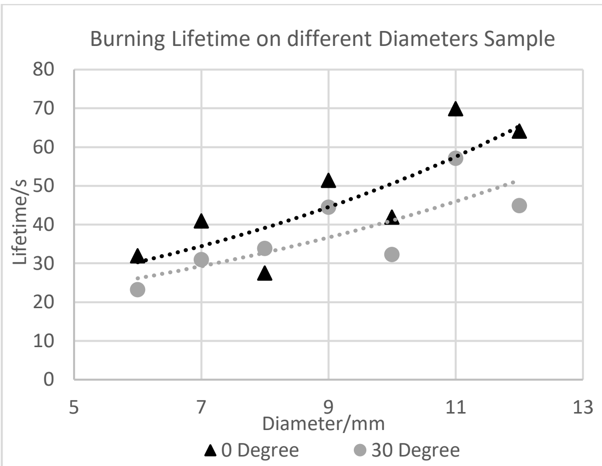


Figure 2. The burning images of different diameter woods (left:6mm, middle:9mm, right:12mm). a) presents 0°, b) presents -30°, c) presents 30°.

The results of the self-sustained burning lifetime of the rods at 0° and 30° are shown in the left panel of Fig. 3. It must be highlighted that the burning time of the rods at −30° were much greater than other cases, which had exceeded 160s as the doubled maximum value of the results of 0° and could keep burning until the fire spread through the whole woods. Comparing the cases of 0° and 30°, it can be seen that the horizontal rods had longer burning time than positive ones, averagely about 23.1% longer. Meanwhile, the burning status of 0° group also was more stable, that the flame could be easily extinguished on the positive inclined rods. For the effect of rod diameters, it is found that the larger-diameter-group generally could be burnt with a longer lifetime. The combustion is stronger, and the flaming is more stable as well.
The surface charring rates in different experimental conditions are presented in the right panel of Fig.3. It is found that the charring rate of -30°-angle-groups reaches the largest value up to 0.7 mm/s, whereas the charring rates of the horizontal and positive angle groups are smaller, as 0.23mm/s and 0.18mm/s

respectively. For the effects of rod diameter on the charring rate, it is found that the charring rate is decreased with the increasing diameter. The charring rate in -30° groups had a significant decrease from 0.67mm/s to 0.30mm/s with the increased diameters from 7mm to 12mm, decreased by 55%. Moreover, the surface to volume ratio can be calculated by setting a unit length of the sample, and the ratio is presented in the figure with black-dotted line showed in Fig.3 (right). As the very similar trending of surface-to-volume-ratio comparing with the experimental results, a possible mechanism of such effect can be found that the smaller diameter rod sample has higher surface to volume ratio which means higher efficiency in burning and fire propagation.



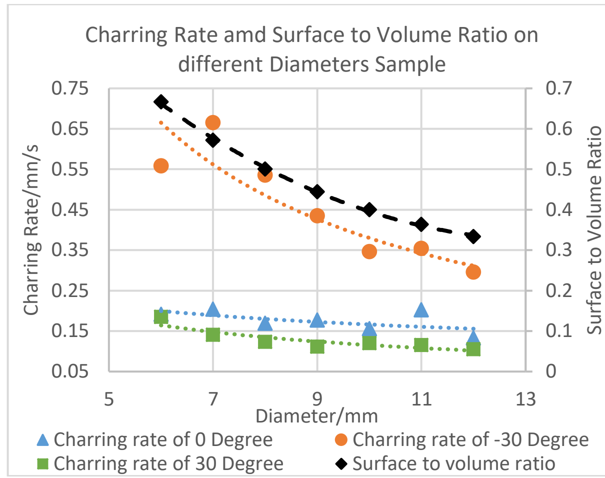


Figure 3. Left: the burning lifetime of woods, Right: averaged propagation rate of char

3.2 The heat flow around surfaces

The ambient flow of burning rods can be visualised by the Schlieren imaging system which is introduced in the Fig. 1. Some of the results, including the rod diameters of 6 mm, 9 mm and 12 mm, are presented as examples in the Fig. 4. For each group of the testing cases with same diameters, the range of the inclined angle was from -30° to 30°. For the group of 12 mm-in-diameter, more details of the results, including six chosen inclined angles of 30°, 0°, -15°, -30°, -45°, and -60°, are presented in Fig.3 c) to show the effects of inclined angle on ambient flow. It can be seen that the combustion of rod trends to be stronger while the decreasing inclined angle from 30° to -30°, meanwhile the attaching flame phenomenon has the similar trending where the strongest occurred at -30°. The heat flow had been bent into the surface due to the decreased pressure created by the confinement on air entrainment into the flame front, this could significantly increase the fire spread rate [2][7]. Meanwhile, it is found that the flow had a slight tilt when the sample burned with -15° inclined angle and the flow tilt angle had significantly increased at the -30° case. Such finding is similar with Wu's conclusion [3] that the critical angle, which the flame attachment length would increase sharply, was found as -24°. It should be highlighted that there is no significant increase of the flame tilt angle when the inclined angle was decreased from -30° to -60°, although the heat flow attachment length had increased. Moreover, it is found that the intensity of heat flux trends to be stronger with the decreasing inclined angle. Comparatively, the heated flows above the rods at positive inclined angle had a deviation from vertical direction and were away from the woods surface which would significantly decrease fire propagation rate because of the decreased contact area between the fuel and heat flow.

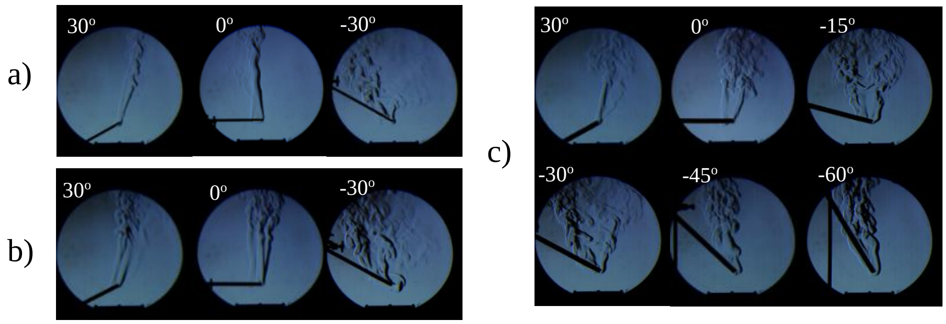


Figure 4. The schlieren images of different diameter woods, a) presents 6mm, b) 9mm, c)12mm

For the effects of rod diameter on the combustion, the cases of different diameters are further compared. It has been observed that the flow around the rods of large-diameter-group became more turbulent and the dimension increased significantly. This is due to the larger amount of fuel were ignited for the larger-diameter-cases, and they had more cross propagation characteristic on its surface. However, no significant difference of the flame attachment was found and the flow tilt angle has been determined at different inclined angles. It is true that the fire spread rate seems not increased with the increasing diameter of cylinder. Furthermore, due to the cross propagation characteristic, the propagation rate of larger-diameter-cases can be smaller than small-diameter-cases.

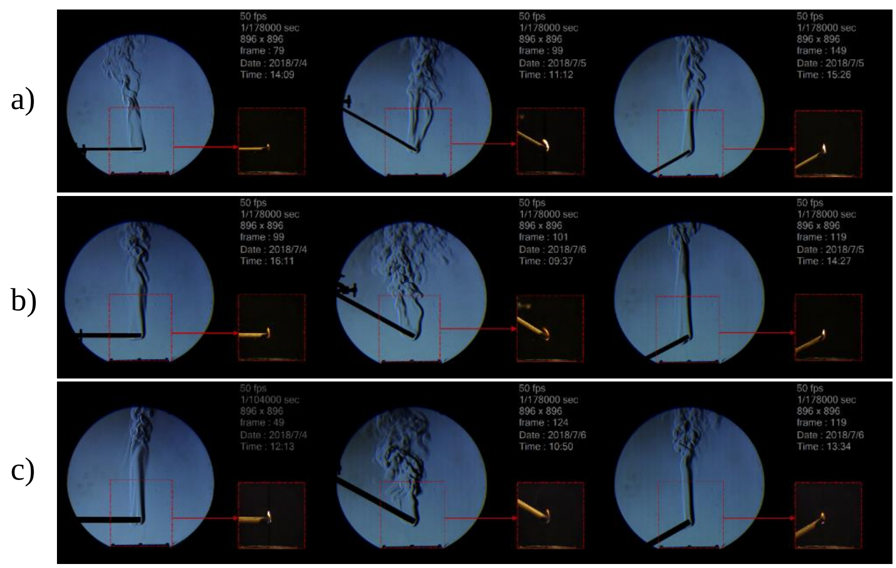


Figure 5. The comparison between direct imaging and schlieren imaging at the same time of the wood just ignited. a) 6mm, b) 9mm, c) 12mm. Left: horizontal, middle: -30º, right: 30º.

The Fig.5 shows the comparison between actual flame images and schlieren images at the same moment of the wood rod just ignited. Both images are of the same optical zoom, which indicates the same rod size presented in pictures. The red-dotted-frame illustrates the testing area of actual flame. The visible images show the burning status which contains the fire spread rate and the intensity of burning. Comparatively, the schlieren images present fire dynamics information which visualize the ambient flow field. It can be seen that there is no sharp distinction between different cases in the actual images, and the flames are weak at the beginning of burning. Comparatively, it can be seen that the Schlieren imaging system is able to efficiently visualize the fire heated flow around rods. From the results, it can be observed that the ambient flows of the rods at negative angles are much wider than those at horizontal direction and positive angles.

One of the possible mechanisms can be found as more radiations and heat transfer in negative-inclined-angle-groups. In addition, it can be seen that the flow of negative-inclined-angle-group trends to be more turbulent. Since the larger amount of smoke observed from negative-inclined-groups, the possible reason can be found that more soot produced in the negative-angle-groups and more radiation had been emitted during the burning. Although no significant difference among the flames can be observed by direct imaging, the visualization by Schlieren system is able to effectively present the effects of the inclined angle and the diameters on the flow around burning rods.

3 Conclusion

The effects of inclined angle and diameter of wooden rods on the flame propagation are investigated in this study, including flaming status, charring rate and burning lifetime. Moreover, the ambient flow of burning rods are visualised by a High-speed Schlieren imaging system, of which the results are further compared with the colour images. From the results, it is found that the negative inclined angle of rods can significantly improve the flame propagation with stronger flaming, higher charring rate and longer burning lifetime, such as the charring rate is increased by 254% when the inclined angle is decreased from 30° to -30°. Meanwhile, it can be observed that the flame propagation is weakened by increasing rod diameter, such as the charring rate has significantly decreased by 55% when the diameter is increased from 7mm to 12mm. The flows tilt angles and attachment lengths changed with decreasing inclination. Moreover, the burning heated flow above burning rods are tilted forward to the surface when the inclined angle is decreased to -30^{o}, and then the heated flow tilt angle would not change much although the inclined angle was continually decreased to -60°. The direct flame imaging was compared with the corresponding schlieren imaging. It is found that images of negative angle groups have broader turbulence flow than those of horizontal and positive.

References

[1] Moodie K. (1992). The King's Cross Fire : Damage Assessment and Overview of the Technical Investigation. Fire Safety Journal, vol. 18, pp. 13–33.

[2] Drysdale D. (2000). Flame Spread on Inclined Surfaces. Fire Safety Journal,vol. 18, pp. 245–254.

[3] Wu Y, Xing H, and Atkinson G. (2000). Interaction of fire plume with inclined surface. Fire Safety Journal, vol. 35, pp. 391–403.

[4] Zhang Y, Chen X, Song Y, Huang X, Niu Y, and Sun J. (2017). The deceleration mechanism and the critical extinction angle of downward flame spread over inclined cellulosic solids. *Appl. Therm. Eng.*, vol. 124, pp. 185–190.

[5] Zhang Y, Ji J, Wang Q, Huang X, Wang Q, and Sun J. (2012). Prediction of the critical condition for flame acceleration over wood surface with different sample orientations. *Combust. Flame*, vol. 159, no. 9, pp. 2999–3002.

[6] Zhou X, Mahalingam S, and Weise D. (2005). Experimental Modeling of the Effect of Terrain Slope on Marginal Burning. Fire Safety Science-Proceedings, pp. 863–874.

[7] Grumstrup T P, Mcallister S S, and Finney M A. (2017). Qualitative Flow Visualization of Flame Attachment on Slopes. 10th U.S. National Combustion Meeting pp. 1–6.

[8] Yang Z, Chen H, and Chen H. (2017). Experimental Study on Flame Geometry along the Inclined Surface with and without Sidewalls by Using a Gas Burner. *Procedia Eng.*, vol. 211, pp. 925–933.