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The Effect of Preheating on Fire Propagation on Inclined Wood by Multi-spectrum and Schlieren Visualisation

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Abstract

A systematic visualisation system that can image the visible flame, invisible hot gas and the wood surface temperature, was applied to study self-sustained fire propagation in a wood rod at different inclination angles. It was found that the burned wood rods at positive inclination angles presented longer burning lifetimes and charring lengths than those at negative and horizontal angles. Three physical phenomena were found to determine the fire sustaining and propagation: 1. Underneath hot gas layer; 2. Flame attachment phenomenon; 3. Impact point of piloted imping heat flux. Longer underneath hot flow was observed at positive inclination angles. The underneath hot gas flow could preheat the adjacent wood making them more readily for fire propagation. The flame attachment length and flame tilt angle had been investigated and quantified with enhanced thermal images. It was found that the flame is more prone to attach to the rod at positive angles. The impact point of piloted impinging heat flux was analysed by multiple imaging systems. Higher positive inclinations mean that a larger part of the rod is contacting with the impinging heat flux. The new insights gained are beneficial for fire safety in construction especially for the fire propagation at early stage.

Keywords: wood combustion; heat convection; underneath hot gas parcel; pyrolysis; gas-phase combustion

1. Introduction

Fire propagation on a fuel surface is a complex process which depends on many factors, such as the angle of inclination, the moisture content, the ambient flow, and so forth [1]. Among those factors, the inclination can play a dominant role in affecting the fire spread due to its effect on fire dynamics and airflow. In 1992, the investigation of the disaster of King's Cross Fire revealed that wooden beams angled at 30 degrees enhance the fire propagation [2]. In order to find out the effect of inclination angle on the fire spread, many researchers studied the effect of geometrical factors on fire spread on planar surfaces. Drysdale investigated the aerodynamic effect on the fire propagation on PMMA slabs at different inclination angles, and stressed on the sharp increase of fire spread rate with the side walls [3]. Yang et al. [4] studied the effect of the inclination angle and trench configuration on the flame geometry using image processing. Gollner et al. [5] studied the upward flame spread with PMMA slabs, in which he measured the burning rate and flame spreading rate at different inclination angles.

There are two key factors which influence the fire spread on an inclined surface: flame attachment from the top of the surface (produced by the imbalanced air pressures); the convective preheating of the underside of the fuel. In the research into the effect of inclination on flame spread by Wu et al. [6], the flame attachment length and tilt angle were introduced, and a critical angle of 24 degrees for strong flame attachment was discovered. Grumstrup et al. [7] studied the aerodynamic effect by qualitatively analysing the flame attachment phenomenon with the retroreflective shadowgraph technique. In addition to aerodynamic effect, research of the convective heat transfer on combustion has been established. Weber et al. [8] had revealed the importance of underneath convective pre-heating. Hirano et al. [9] studied the fire spread mechanism on paper sheets at different inclination angles, they considered that the heat transfer to the unburned fuel take place in the front of pyrolysis zone and mainly occurred from the underneath. In Zhou et al. 's study [10], the effect of convective heat transfer for fire propagation in the case of a metal platform was reported. Moreover, with a set of matchsticks, Hwang et al. [11] investigated the flame propagation on inclined base boards, in which he demonstrated the preheated region increases caused by inclinations.

The investigation of fire spread on individual cellulosic fuels could help in the comprehension of more complex wildfire phenomenon. For example, the fuel bed inside the trench could be seen as comprised by many individual cellulosic fuels. In order to understand the critical condition of fire spreading, Zhang et al. [12], [13] tested different inclination angles and defined four stages of flame propagation, namely acceleration, steady-state, deceleration and extinguishment. Weber et al. [14] used single ponderosa pine needles to investigate the effect of sample orientation on the fire spread rate and modelled the marginal conditions of sustaining flame related to moisture and inclination angles. Hirano et al. [15] used the paper sheets to explore the mechanism of fire spread by using schlieren and fine wire thermocouple. Furthermore, in the research by Lai et al. [16] and Zhou et al. [17], the burning and fire spread on an inclined oak rod surface was studied using visible, schlieren imaging system and modelling, which showed the importance of local aerodynamic effects on fire spread.

Many previous papers focused on the overall geometric features on fire propagation. Others emphasised how the flow field affected the fire spread. The fire propagation mechanism varies greatly from case to case. However, few published papers have analysed the flame propagation with specific focus on convective preheating from underside of the fuel by means of a systematic visualisation of the wood temperature, visible flame and the invisible hot gas simultaneously. Moreover, the importance of convective heat flow from the underside of the fuel has been briefly reported in the aforementioned studies. However, there was no quantitative measurements to explicitly show the difference between preheating length and pyrolysis length. The use of schlieren imaging provides the visualisation of this invisible hot gas layer, from which the layer length can be measured. The length of the fuel under pyrolysis can be measured using the selective enhancement technique in combination with thermal temperature distribution. Then, the pre-heating length ahead of the pyrolysis region, which is the difference in those two measured lengths, can be quantified. The sample of wooden rod could be used to study the mechanism and help improve the understanding of the large-scale circumstances, the wooden structure of the building and unconsolidated fuel bed in trenches for instance. The cylinder shape sample could show the effect of the pre-heating underneath the surface and on the upper surface separately. In addition, the thickness of the wooden rod allows to visualise the longitudinal direction of the pyrolysis process. By synchronising visible, schlieren and thermal imaging systems, a more comprehensive diagnostics of fire propagation on a wood surface has been made in this paper. This paper focuses on the convective preheating of the underside using quantitative measurements, which is proved to be the driving factor for flame propagation.

2. Experiment setup and methodology

In this study, the same batch of oak wood rods, which were 9 mm in diameter and 400 mm in length were used as samples for tests. To minimise the effect of moisture, all the rods were pre-dried in an electrically controlled furnace over 24 hours at 150°C. An adjustable holder was used to fix the rods at the desired orientation. As shown in Fig. 1a, the inclined angle θ is defined as the angle from the horizontal to the rod surface. At negative angles, the fire tends to spread downwards, while it will spread upwards at positive angles. In the experiments, rods at five different inclination angles -30°, 0°, 20°, 25° and 30° were used to investigate the effect of inclination angle on convective heat transfer for fire propagation. The rods were subjected to a piloted ignition by a Bunsen burner with pre-mixed fuel (methane and compressed air). For the purpose of consistency, the distances between the burner nozzle and the impact point on the wood were kept same in all test cases. The piloted ignition flame was controlled at an equivalence ratio (fuel-to-air) of 0.6. All the testing rods were ignited for 20s and the burner was immediately turned off thereafter. The experiment for each case was repeated at least 15 times and all the results were averaged.

The setup of the imaging system is illustrated in the Fig. 1b. A Z-type high-speed schlieren system was employed to visualise the hot flow during the combustion. In addition, an InGaAs thermal camera and a high-speed CMOS camera were placed alongside the parallel optical path of the schlieren system. The InGaAs thermal camera was used with a cut-on filter to restrict its spectral sensitivity to 1550-1670 nm, such that the thermal camera was sensitive to temperatures in the range 250-580 ºC. Therefore, in total, three types of visualisation were utilised: schlieren imaging, visible light imaging and thermal imaging. All three imaging systems were synchronised.

From the visible images, the self-sustained combustion lifetime and charring length were measured. Moreover, the weak blue flame underneath the flame front was selectively enhanced for better visualisation.

The thermal images were used to determine the heated length underneath the rods. Because of its ability to see radiation from objects with a lower temperature, it is very effective to observe the preheating which aids flame propagation. With the measured temperature map under 600 ºC, the thermal pyrolysis can be studied. Also, the flame attachment length and flame tilt angle had been determined at 20 s after turning off the burner for each case with the enhanced thermal images.

The schlieren system helps to visualise the hot flow in combustion zone as well as the preheating zone. Through image processing, it further demonstrates the importance of convective heat transfer for fire propagation.

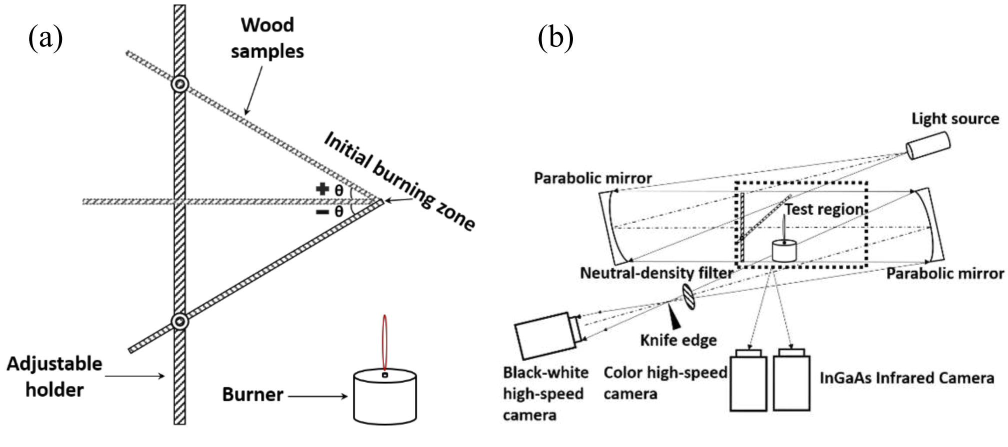

Fig. 1. (a): Schematic representation of the experimental set-up, (b): The Setup of imaging systems.

3. Results and Discussion

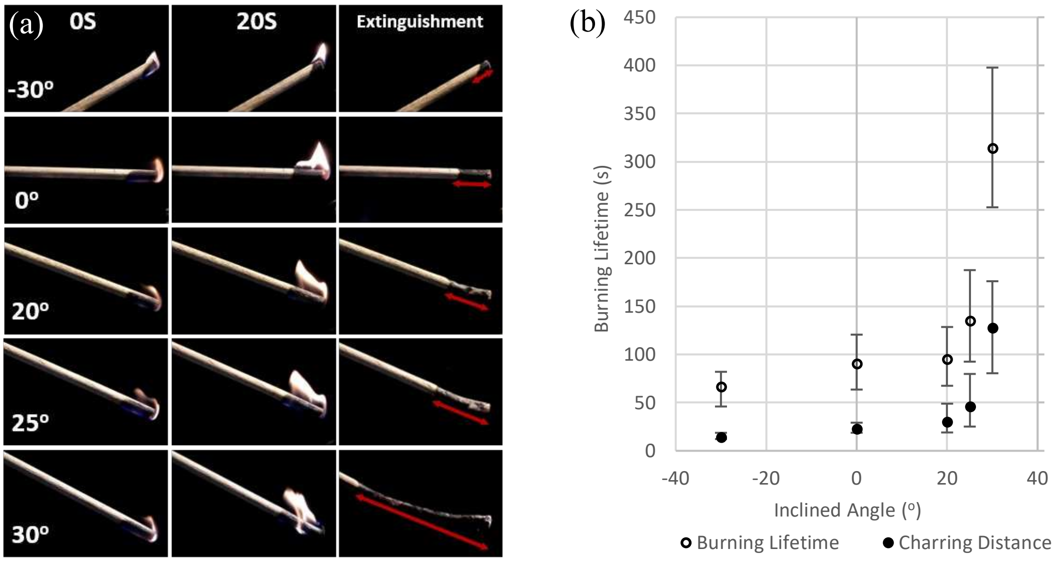

Fig. 2. (a): The typical burning images at different inclination angles, (b): the burning lifetime and charring length against inclination angle.

The visible images captured by the high-speed colour camera are presented in the Fig. 2a. Horizontally, three frames indicated the beginning of self-sustained burning (the time turning off the burner after 20s of ignition); during the self-sustained burning (20s after turning off the burner) and the end of the burning respectively. Vertically, five different inclination angles were compared, which covered -30°, 0°, 20°, 25°, and 30°. The maximum charring lengths for each inclined angle case are highlighted with red lines. In general, the charring length and burning lifetime increases as the orientation angle of the oak rod increases, as plotted in Fig. 2b. The burning lifetime is measured by the duration from pilot ignition turned off to extinguishment of the flame. The charring length is measured as the maximum charring distance on the wood surface. The data points are the average of total repeated test for each case, with maximum and minimum indications. The deviation mainly caused by material nonuniformity, namely density and grain orientation [18].

The most sustainable combustion happened in 30 degrees inclination group, which has the longest combustion lifetime and charring length with an average of 315 s and 128 mm, respectively. It is worth pointing out an abrupt change from 25 degrees to 30 degrees, which covers the critical fire propagation angle [12].

Conclusively, the fire propagation is sensitive to the inclined angle. In the positive angle groups, the flame tends to lean onto the wood surface. The flame attachment phenomenon is due to the pressure difference induced by the surface confinement on the entrainment of air upslope and down-slope of the fire plume [4], [19]. It is also observed that while the flame is burning vigorously, there was a faint blue flame underneath the rod. This blue flame came from gas-phase combustion originating from pyrolysis of the wood, which is an indication of the source of convective preheating length [20]. In the cases with positive inclination angles, due to the stronger flame attachment and larger contact area, heat convection is more significant for the flame to develop [3].

The radiation from the flame consists of two parts: upper diffusion flame and underneath blue flame. The radiation from upper part of the flame, would help on the pyrolysis of the top side of the wood because the diffusion flame emits most of the radiation. However, it does not play a significant rule to help flame propagation. In those short burning-life time cases, notwithstanding the top side of the wood is still burning, the flame vanishes in the absence of underneath pyrolysis. In addition, the radiation from the upper flame to the top side of the wood is assumed to be constant for two reasons: 1. the flame sizes during progression were observed to be similarly small in our test groups; 2. The size of samples is small. Furthermore, the bottom side blue flame emits a very short band of radiation, therefore its effect is negligible. Under these assumptions, the experiments are in a controlled manner to isolate the effect of convective preheating.

Three main effects were observed in order to sustain the fire propagation: 1. The presence of hot gas parcel underneath the rod which is generated by the blue flame but with burnt gas extended to the preheating layer, as observed using schlieren imaging; 2. The long preheating length due to convection, which is directly proportional to the inclination angle. 3. Flame attachment generated by the local imbalance air pressure. Through visualisation and image processing, these phenomena can be quantified and analysed further.

3.1. The effect of underneath hot gas parcel

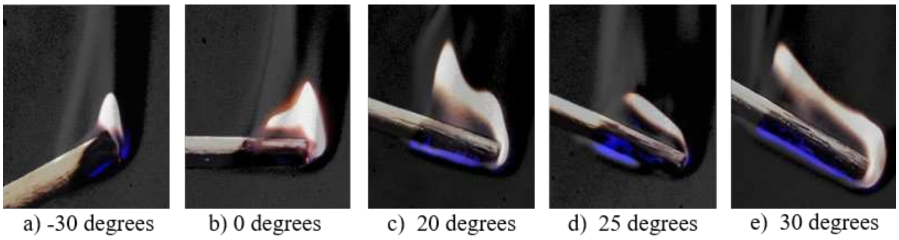

Fig. 3. Selectively enhanced weak blue flame with schlieren imaging at $t = 20 \ s$.

Previous researches [8], [15], [9] had found that the gas phase would help the heat transfer to the unburned fuel and it could extend further than the pyrolysis zone. However, the detailed preheating zone was not systematically investigated by the previous studies. The thick hot flow underneath the rod in the schlieren image is longer than the pyrolysis length which is indicated by the enhanced blue flame. The difference in length is the preheating zone. The preheating of the unburnt rod is significant in sustaining the flame. Pyrolysis involves the decomposition of the three main constituents of the wood, namely, hemicellulose, cellulose, and lignin [18]. The decomposition generates combustible gases that are essential for flaming combustion [8]. In order to visualise the surface under pyrolysis, in Fig. 3, the dim blue flame of gas-phase combustion from pyrolysis was selectively enhanced for visualisation. The length and thickness of the blue flame when the rods were inclined at a positive angle were significantly larger than when the rods were inclined at zero and negative which means there are more fuels taking part in the rapid pyrolysis at positive inclinations. In addition, through schlieren imaging, the hot flow enclosing the visible flames was observed to have a much longer coverage of the rod. As the inclination increase from -30 degrees to 30 degrees, the hot gas layer ahead of the combustion zone became longer, the reason is that the burnt gas flow extended further due to the buoyancy at positive angles. The hot burnt gas preheats the adjacent wood to help pyrolysis, which in turns promotes fire propagation.

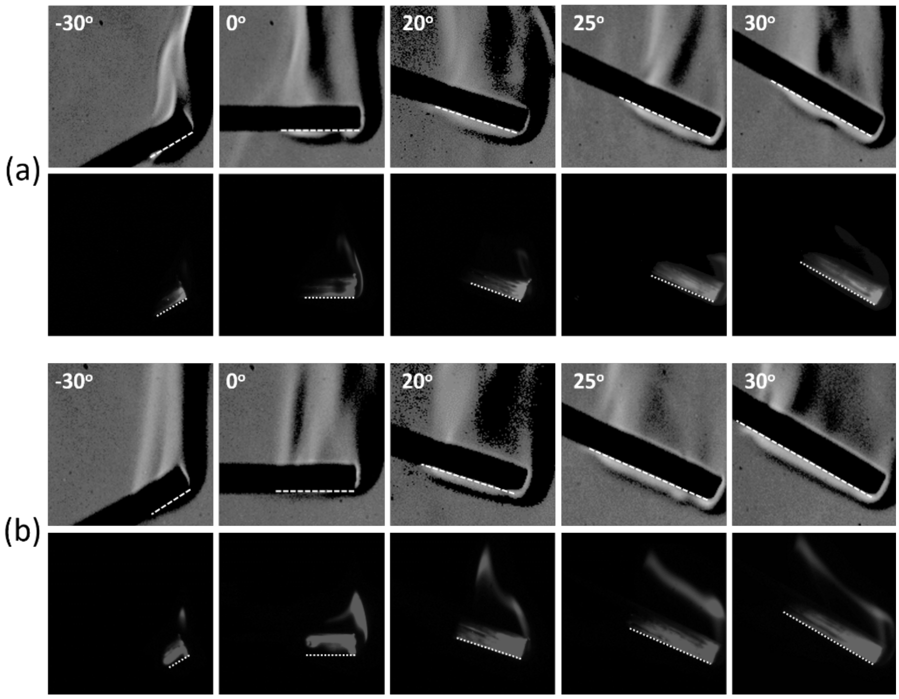

Fig. 4. The visualisation of bottom heated area at (a) the point when the piloted ignition is turned off ($t = 0 \quad s$) and (b) 20s after piloted ignition is turned off ($t = 20 \quad s$). For each time point, top: the schlieren images of different inclination angles; bottom: the corresponding thermal images.

It is worth noting that the hot gas parcel underneath the rod had a significant increase when the inclined angle increased from -30° to 30° which is marked by the white-dotted line at Fig. 4. Longer preheating length helps to remove moisture content and to raise the temperature, which makes it more readily for subsequent pyrolysis to sustain the flame. From the Fig. 4, the comparison of the flow field at the beginning of self-sustained combustion and 20 seconds after shows this effect. It is notable that the underneath hot gas flow at 0 s is thicker than the topside from the schlieren images. Weber et al. [8] found the underneath temperature gradient is larger than which in the topside from the interferometry pattern in their study. Under the hypothesis of constant pressure, it is similar to the density gradient which is obtained by the schlieren image according to the Ideal Gas Law. The thicker hot flow could seem as an isolation layer which could prevent the convection heat loss from the wood surface to the ambient cold flow, results in a higher temperature. In Hirano et al. 's study [15], the blackening of the paper is used to measure the pyrolysis, which is less inaccurate. The blackening does not necessarily indicate pyrolysis. For pyrolysis to happen, certain temperature has to be reached. The choice of using InGaAs camera for temperature distribution is because its measurable range overlaps with the temperature of typical wood pyrolysis. The temperature map produced by infrared camera gives a more precise indication of pyrolysis. As an example, the temperature map of 30° inclined angle case is presented in Fig. 5. It can be seen that the temperature of the surface underneath is higher than the temperature on the upper surface. The thermal gradient through the wood leads to the upper surface becoming heated. The results could verify the theory from Weber et al. [8] and Hirano et al. [9] that the underside pre-heating is crucial to flame spread along the fuel sample, they set thermocouple at top and bottom of the fuel separately and recorded the thermocouple from the bottom reached the high temperature faster than the one from the top. Unfortunately, it is hard to obtain the accurate temperature response from thermocouple especially on the small samples. In order to further verify the importance of underneath pre-heating, the thermal images are utilised to present the heated area of the rods. The measured temperature in Fig. 5 shows the underneath heated area had exceeded the temperature point for rapid pyrolysis started occurring from other research which is around 300 °C [21], [22]. Longer heated length at positive angles means that a larger part of rod was undergoing the rapid pyrolysis. At $t = 0 \ s$, the tips of the rods all had a hot gas parcel, which indicated the onset of self-sustained combustion. However, at $t = 20 \ s$, the hot flow in 0 and -30 degrees angles were almost gone; while the hot flow underneath had extended along the rod for positive angle groups. The subsequent pyrolysis followed the hot flow direction because the underneath hot gas flow drove the convection upward due to the lateral pressure gradient created by the buoyancy [18], [8]; therefore, instead of propagating along the rod, it progressed from bottom to top. This can be seen from the thermal images of 0 and -30 degrees cases: at $t = 20 \ s$, the top fibre was bright and bottom fibre was dark. With no convective preheating longitudinal, the pyrolysis was limited. This is the main reason that these two cases have a short burning lifetime. By contrast, at positives angles, hot convection from the longer pre-heating zone ahead of the pyrolysis area helped to propagate the flame, which in turn generates more heat flux for pyrolysis, not only along the rod but in deeper layers. This can be observed from thermal images of the positive angle groups in Fig. 4, where the bottom fibre was still bright even when there was the presence of char. Another reason that they had shorter combustion lifetime is charring. Because char has lower thermal conductivity than wood [18], it acts as a barrier for the pyrolysis in deeper layers. Therefore, a higher heat flux is required in order to generate combustible gases from deep layers.

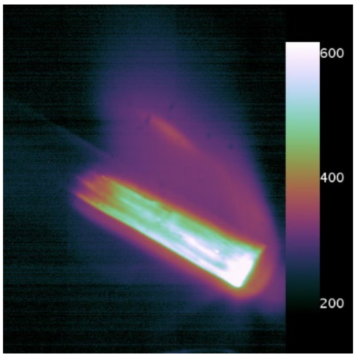

Fig. 5. The measured temperature distribution at 30° inclination angle as example.

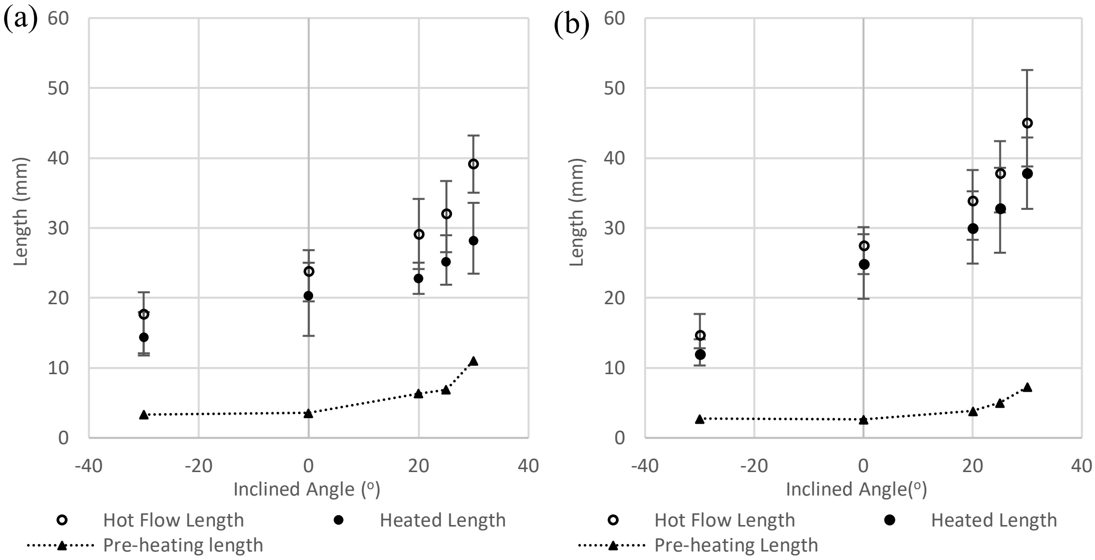

Fig. 6. The underneath hot gas flow length and the heated length against the inclination angle, (a) at the beginning of self-sustained burning, and (b) 20 s after the start of self-sustained burning.

Fig. 6 shows the comparison of measured convective hot flow length and heated length. The pre-heating length is calculated by the differences between the hot flow length and the heated length. It is obvious that both hot flow length and heated length increase as the inclination angle increases. Meanwhile, it can be observed that the pre-heating length increases significantly with the increasing positive inclination angle while it remains constant at horizontal and negative angle. The flame spread process requires an amount of fuel pre-heating ahead of the flame[8]. The longer pre-heating length at positive angles helps the fire spread and results in a longer burning lifetime and charring distance. By contrast, at horizontal and negative angle groups, heat conduction plays the main role of fire spread due to the limited pre-heating length. Under such circumstance, the fire cannot spread effectively and results in a shorter burning lifetime and charring distance. In addition, the pre-heating length at $t = 0\ s$ (Fig. 6a) is larger than that at $t = 20\ s$ (Fig. 6b) which is because just after the piloted impinging heat flux is turned off, the high temperature region is concentrated near the impact point. By comparing Fig. 6a and Fig. 6b, it can be found that heated length of rods at positive angle cases had a larger increment after 20 s of self-sustained burning than those at negative and horizontal inclinations. The larger increase of the heated area suggested there was higher pyrolysis rate when the rod was inclined at a positive angle. A possible mechanism is due to the larger extent of the hot gas parcel underneath the rod drove the convection upward and then increased the thermal pyrolysis [18]. Overall, in positive inclination groups, a longer preheated length ahead of the pyrolysis area means that more virgin wood is readily available for subsequent pyrolysis; more water content is removed, and the temperature raised.

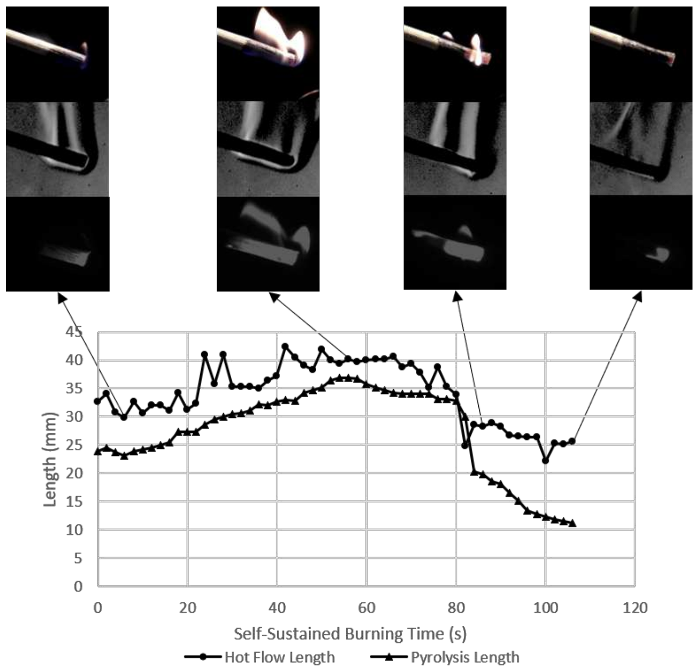

Fig. 7. The combustion process at 20° inclination angle.

As the fire propagation can be considered to be related to the underneath pre-heating. The underneath hot flow length and pyrolysis length can be used to track the combustion process of burning woods. It can be seen from Fig.7 that the wood combustion is divided into three stages: the acceleration, the deceleration and extinguishment. At the first stage, both the hot flow length and pyrolysis length had increased from the start of self-sustained burning to around 60 s, at which point the heat convection is strongest. Although the actual flame is weak, the subsequent combustion would accelerate due to the long pre-heating zone ahead of the pyrolysis area. This greatly promotes pyrolysis because the unburnt wood was preheated. After the peak point, the hot flow length rarely increased, as the consequence, the fire propagation stopped. After 80 s of self-sustained burning, the hot gas length and pyrolysis length both shrinks, indicating a weakening combustion because of the lack of sustainable pyrolysis gases. It can be seen the top fibre was bright while the bottom fibre was dark. As the decreased heat convection was insufficient to sustain the combustion, the longitudinal pyrolysis was limited and finally the wood gradually extinguished.

3.2. The effect of flame attachment phenomenon

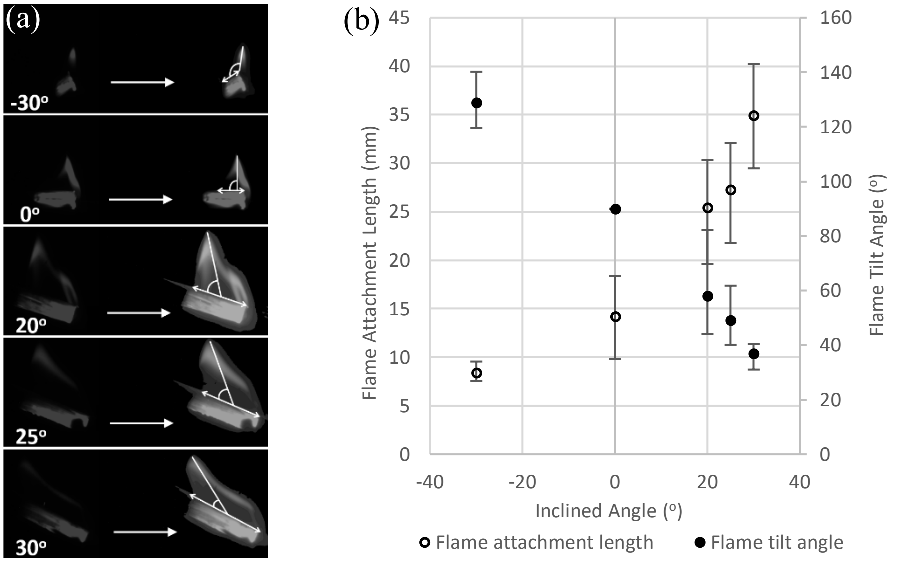

Fig. 8. (a): The thermal images at different inclination angles at 20 s after the turning off the burner, the original images (left column) and the enhanced images (right column), (b): flame attachment length and flame tilt angle against inclination angles.

In contrast the blue flame underneath the rod, which helps the flame propagation longitudinal, the attachment of the flame on top of the rod promotes longitudinal propagation. As the inclination angle increases, the difference in air entrainment caused by the buoyancy on the left and right side of the flame give rise to a local pressure imbalance [16]. As a result, referring to Fig. 8, the flame is more prone to lean onto the rod, which helps with flame propagation. More specifically, the attachment of the flame increased the length of the rod submerged in the hot convective flow.

As indicated in Fig. 8a, the flame attachment length is measured as the contact length of the flame and rod; the flame attachment angle is measured as the angle between the line connecting the frontmost tip to the midpoint of attachment length, to the rod. From Fig. 8b, the attachment length is direct proportional to the inclination angle. There is an abrupt change in this length from 25 degrees to 30 degrees, in details, 1.536mm/° in averaged, which is three times larger than which from other inclination range. This phenomenon coincides with the previously reported critical inclination angle [6]. The longer flame attachment length could significantly increase the convective heat transfer between the flame and the fuel , which in turn enhances the combustion [23]. Moreover, the flame tilt angle sharply decreased with the increasing angle. Smaller attachment angle led to higher radiative heat transfer from the diffusion flame above the rod because of the increased view factor and shorter distance which could enhance the pre-heating on the upper surface. With the aid of longitudinal propagation, it is very probable that the rate of decomposition for combustible gases is higher; therefore, the flame is more likely to be sustained [6].

3.3. Observation on the impact point of piloted impinging heat flux

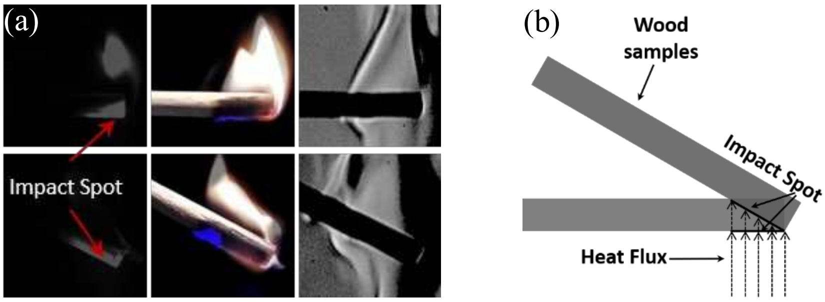

Fig. 9. (a): The comparison between 0 degrees and 30 degrees at 1 second before the piloted impinging heat flux is turned off. Top row: 0 degrees; Bottom row: 30 degrees, (b): demonstration of the effect of inclination on impact spot.

As indicated by the red arrow in Fig. 9a, the impact spot was subjected to intense heat flux during the piloted ignition, where rapid pyrolysis and char formation took place in deep layers, causing a locally fuel rich diffusion flame. The temperature at this spot was much higher than the adjacent regions in the thermal image. Combustible gases produced were quickly ignited by the piloted heat flux. By contrast, in the vicinity of the impact spot, the temperature gradient was less sharp; the deep layers gradually reached pyrolysis temperature, which can be observed from the selectively enhanced blue flame. This phenomenon was observed in most inclination angles. By comparing the images of 0 degrees and 30 degrees, it is found that a longer length of the rod was heated by the impinging heat flux during the ignition at an inclination of 30 degrees, and more combustible gases were produced. For positive inclination angles, more inclination means a longer length submerged in the impinging heat flux which is demonstrated by Fig. 9b. Consequently, the rods inclined at large positive angles have a strong initiation for self-sustained flame propagation.

4. Conclusion

With a systematic visualisation, the influences of the inclination angle on fire propagation were investigated. The schlieren imaging revealed the hot convective flow field both above and underneath the oak rods. Its propagation mechanism was visualised. Meanwhile, thermal imaging gave the temperature distribution of the surface of the rods, which was affected by the preheating of the convective flow field. Despite uncertainties caused by texture variation and discrepancies of wood rod production, the experimental results showed a general trend that fire propagation and flame attachment length increase as the inclination angle increases; the sharp increase from 25 degrees to 30 degrees corresponded to the critical point beyond which the flame propagates more rapidly. The physical mechanisms as to how the flame propagated were studied by means of combined visualisation. The effect of the inclination angle on improving the flame propagations were attributed to three main effects. Firstly, convective preheating is essential for longitudinal pyrolysis, hence aids to the fire propagation longitudinal; for positive inclinations, the larger is the angle, the longer will be the preheating length, which in turn resulted in longer progression of flame along the rod. Secondly, the increased flame attachment length at positive inclinations helps pyrolysis in the perpendicular direction to the rod. Thirdly, in the case with piloted impinging heat flux, the inclination affects the initiation of the self-sustained flame propagation; because a longer length of the rod is submerged in the heat flux at ignition for positive inclination angles, from which more combustible gases are produced at the start of self-sustained flaming.

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