THE EFFECT OF POLYURETHANE SPONGE BLOCKAGE RATIO ON PREMIXED HYDROGREN-AIR FLAME PROPAGATION IN A HORIZONTAL TUBE

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ABSTRACT

The effects of sponge blockage ratio on flame structure evolution and flame acceleration were experimentally investigated in an obstructed cross-section tube filled with stoichiometric hydrogen-air mixture. Experimental results show that the mechanisms responsible for flame acceleration can be in terms of the positive feedback of the unburned gas field generated ahead of the flame, the area change of the gap between the sponge and the tube, and the interaction between the flame and the shear layer appearing at the sponge left top corner. Especially, the last one dominates the flame acceleration and causes its speed to be sonic. Then both the second and third contribute to the violent flame acceleration. In addition, the unburned gas pockets can be found in both upstream and downstream regions of the sponge. With increasing blockage ratio, the unburned gas pockets disappear easier, and the flame acceleration is more pronounced. Moreover, the sponge tilts more evidently and resultantly the maximum tilt angle increases.

Keywords: Hydrogen safety; Sponge; Flame structure; Flame acceleration

1.0 INTRODUCTION

Since the fossil fuels for transportation and power generation brings a large amount of environmental and economic problems, hydrogen as an alternative energy carrier has attracted more attentions in the laboratories and industries because of its clearness and high efficiency [1-3]. Moreover the demand for hydrogen has increased dramatically over the past years and will continuously increase in future. For example, the demand of hydrogen in USA will reach 15 million tons by 2040[4]. However, its safety problem should be considered more, related with production, transportation, storage etc., which is supposed to the main barriers for wide use of hydrogen. Some special properties of hydrogen, such as low density, high diffusivity, low ignition energy and a wide flammability concentration limits (e.g.5-75% by volume in air), make it be prone to accidental fire even explosion [2].

Generally, hydrogen is transported mainly by the pipelines, thus from the point of safety, it is of great importance and fundamental to investigate the propagation mechanism of premixed hydrogen-air flame in a tube. Flame propagation in an obstructed tube has been studied for many years [5], and is significantly influenced by the blockage ratio (BR) of the obstacle. Moen[6] discovered that the maximum flame speed increases with increasing H/D, where H is the obstacle height and D is obstacle spacing. He further pointed out that the flame acceleration mechanism is interpreted in terms of the positive feedback coupling the flame, the turbulence and the flow field distortions, where the intensity of turbulence and flow field distortions are dominated by H/D. Schhelkin[7] showed that turbulence generated downstream of obstacles induces rapid flame acceleration. Abdulmajid[8] suggested the intensity of turbulence increases with BR. Moen and Lee[9] performed experiments in a vented tube with regularly spaced orifice plates providing BR from 0.16 to 0.84, and found the pressure increases with the BR. This can be attributed to the increased burning rate as the flame encountered the severe distortions flow field induced by the bigger BR. Masri et al. [10] studied flame propagation with various solid obstacles and also found the flame speed increases with the BR due to the turbulence. Veser et al.[11] performed experiments with different BR obstacles and found that a choked flame was achieved due to the enhancement over flame surface. In Tedorczyk[12] work, flame propagation regimes are associated with BR. Johansen[13] visualized the unburned gas flow field in a square tube with three different BR obstacles ,and discovered that the initial flame acceleration is most pronounced in the tube with the largest BR obstacles. However the effectiveness of the largest BR on flame acceleration diminishes near the end of the tube. Gu et al.[14] attributed this phenomenon to momentum and heat losses, and discovered that the larger the blockage ratio is, the more significant the velocity deficit is.

According to above reviews, it can be concluded that the flame acceleration in a tube with rigid and inflexible obstacles is mainly affected by BR. So we are curious about the flame phenomena if the obstacle is flexible. Moreover, at this situation, how does the BR influence the unburned gas flow field and flame evolution. Especially, does it still induce flame acceleration? In the present paper, a series of experiments with stoichiometric hydrogen-air mixture in a tube laden with a polyurethane sponge taken as a typical flexible obstacle were conducted to, firstly, investigate the effect of sponge BR on flame fine structure and speed, secondly, clarify the effect of sponge on flow field, and lastly expect the flame acceleration mechanism.

2.0 EXPERIMENTAL

The experiments on premixed hydrogen-air flame interaction with the flexible obstacle were performed in a combustion vessel with the length 1m and cross section 70mm×70mm, as shown in Fig.1. Two 30 mm thick rectangular quartz glass windows are installed on front and back sides to provide a 235mm×70mm optical access for visualization of flame fine structure and sponge deformation. The windows have a distance of 90mm away from the spark on the left end wall. The schlieren system is employed for optical visualization, mainly consisting of a 50 Watt point light source, two focusing lenses, two 300mm diameter concave mirrors with the focal length of 3.5m and a digital high-speed camera. In experiment, the camera is operated with a 50000 frames per second and a 10 μs shutter. The cubic polyurethane sponge with density of 13.18kg/m^3 is installed as the flexible obstacle 160mm away from spark in the vessel. It has a base size of 70mm×70mm and a varying height from 10mm to 60mm. Therefore the BRs are 1/7,2/7, 3/7,4/7,5/7 and 6/7. It should be noted that initially the sponge was stuck on the bottom wall with super glue for avoiding unexpected movement. All experiments are carried out using stoichiometric hydrogen-air mixture with the initial pressure and temperature of 1atm and around 298K respectively. For spark ignition system, a spark plug set at the left end of the tube is triggered by high voltage pulse from a well-designed high-voltage AC power and affords an energy release of around 7 Joules. For well capturing the flame images, both the ignition system and the high-speed camera are controlled by the synchronization system.

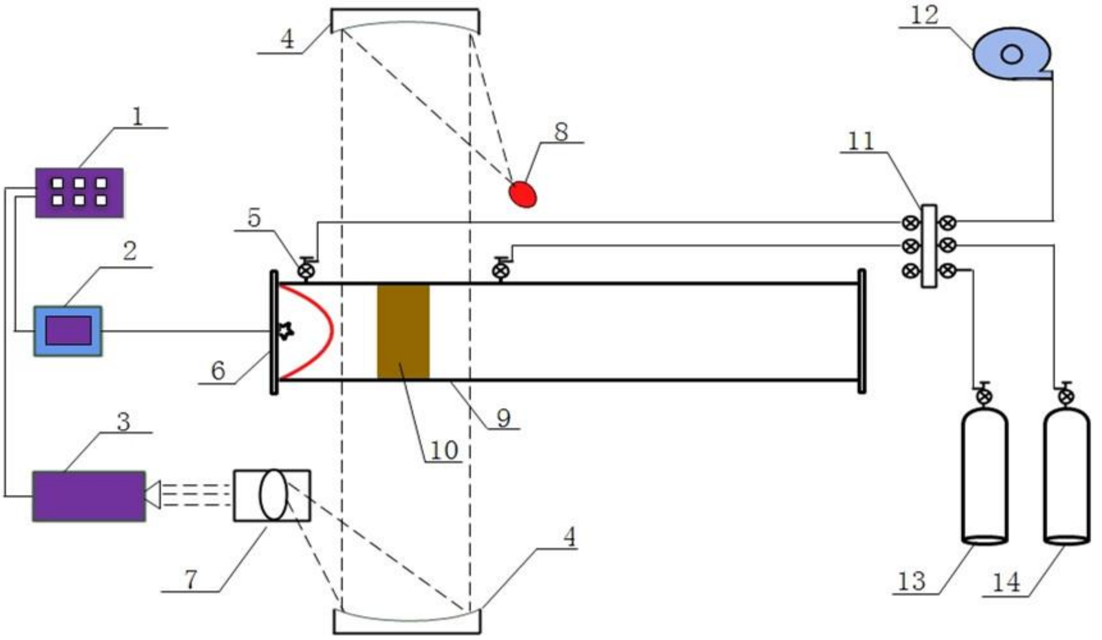

Fig.1 sketch of experimental apparatus

1-synchronization controller 2-high voltage AC power 3-high-speed camera 4-concave mirror 5-valve 6-flange 7-lens 8-light source 9-quartz glass windows 10-sponge 11- 12-vacuum pump 13-hydrogen tank 14-air tank

3.0 RESULTS AND DISCUSSIONS

3.1The evolution of flame front

Fig.1 presents a series of schlieren photographs of premixed flame propagating in tube laden with 50mm-high sponge. Fig.2 presents the corresponding evolutions of flame tip position and speed. Combustion is initiated immediately following ignition and a flame propagates outward in a semi-spherical shape until it approaches the side walls or the sponge before 0.24ms. Since the flame first travels in a laminar mode, its surface area can be supposed to undergo a monotonic increase that is approximately proportional to the square of semi-spherical diameter. The growth of flame surface facilitates a similar increase on flame volumetric burning rate, which in turn gives feedback to flame propagating velocity. Note that, during this period, the sponge has little influence on flame propagation, so the flame shape shows no difference with the first stage of tulip flame reported by Clanet and Searby[15]. In Fig.2, it is clear that the initial flame acceleration is not pronounced in the early period, where a maximum velocity of 125m/s is achieved at 0.22ms. In addition, the flame speed experiences many well defined oscillations superimposed on the speed curve. The oscillations can be reasonably attributed to non-uniformities in the flow field, caused by the interaction of the acoustic waves emitted from the flame with the sponge, wall etc.

The appearance of sponge has significant effects on flame front. At 0.40 ms, influenced by the reflected acoustic waves or compression waves from the sponge, and also affected by sponge blockage, the flame near the lower wall travels slower than that near the upper wave, which leads to a sloping flame shape. The moving unburned gas driven by the expansion of the hot combustion products approaches the sponge and travels in the gap between the top wall and the sponge top surface. In this process, due to abrupt decrease of the flow area, the flow is accelerated and especially forms a shear layer, which can be easily found from 0 ms to 0.56 ms. This shear layer is very important for the following flame instability and its transition from the laminar one to the turbulent one. For the flame traveling from the large tube space into the gap at 0.54 ms, the similar situation is illustrated as the unburned gas. In other word, the flame is also abruptly accelerated. In this gap, due to the tilt sponge, the gap area gradually increase, which is evidently different from the cases with the rigid obstacle. For the latter, the gas area is always kept same. If the flame enters the sponge gap, according to the iso-entropic correlation ($\frac{dV}{V} = \frac{-1}{1-Ma^2}\frac{dA}{A}$,where V A and Ma are the speed, cross area and Mach number, respectively), the increasing area causes the subsonic flame to be decelerated and however the supersonic one to be accelerated. For current cases, typically shown in Fig.2, the flame is subsonic at the gap inlet and its speed is around 160m/s at 0.54 ms. Therefore the subsonic flame should be decelerated in the gap, which is contradictory to that shown in Fig. 2. A probable reason is that the shear layer interacts with the flame, and induces the latter's the Kelvin-Helmholtz(K-H) instability, which causes the latter to be more turbulent. At 0.64 ms and 0.72 ms, the more winkled lateral surface of the flame can afford the strong proof. Resultantly, the flame is accelerated to be supersonic, giving rising to more steep increase of the flame speed. So, in this gap, the interaction between the flame and the shear layer dominates the flame behavior.

Just after passing though the gap or at 0.66 ms, the supersonic flame travels at 750 m/s. From the gap to the tube, the cross area abruptly increases. The flame is over-expanded, giving rising to evident increase of flame surface. This leads to a large burning rate and facilates the flame acceleration. On the other side, the flame surface increase also decreases its turbulence and part of the turbulent and winkled flame surface looks more smooth. Even it transits from the turbulent one to the laminar one. At this situation, the flame is decelerated. In addition, the rarefaction waves, emitted from the sponge top-right corner, also causes the flame to decay. All these results in the flame deceleration. In Fig.2, it is easily found that the flame speed decreases about 30%. Certainly, with the flame further traveling forward, the flame is more turbulent and accelerated with large speed fluctuation.

It is interestingly noted that a unburned gas pocket is cut by the sponge and the flame front. It maintains for a long time in the upstream region of the sponge. With the time elapsing from 0.56 ms to 1.12ms, this unburned gas pocket shape is kept nearly triangular and slowly burnt. More cells or wrinkles appears on the flame surface. Another striking phenomenon is the flame evolution towards the bottom wall in the downstream region of the sponge. The evident flame wrinkles and adjacent gas pocket appear at 1.04 ms. Especially the flame projecting portion propagates in the directions of the bottom, left and right. At 1.12 ms, the left part of gas pocket is completely consumed, while a narrow and unburned gas pocket is left on its right, typically shown In Fig.1. So another special phenomena to be concerned are the unburned gas pockets.

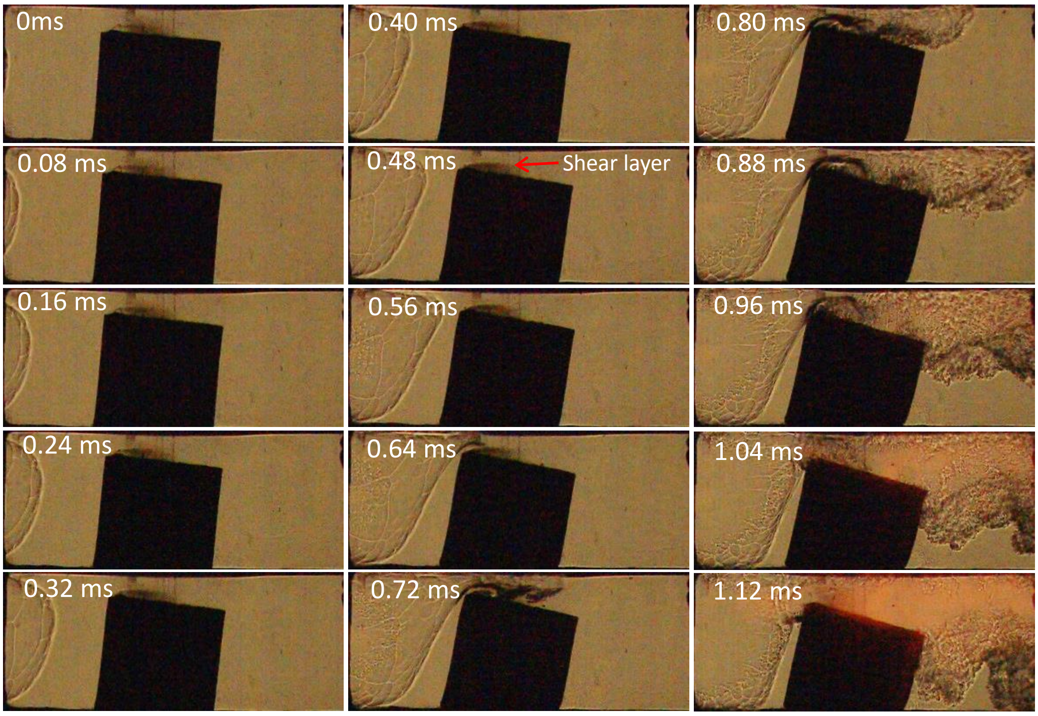

Fig.1. Schlieren photographs of premixed flame evolution for BR=5/7

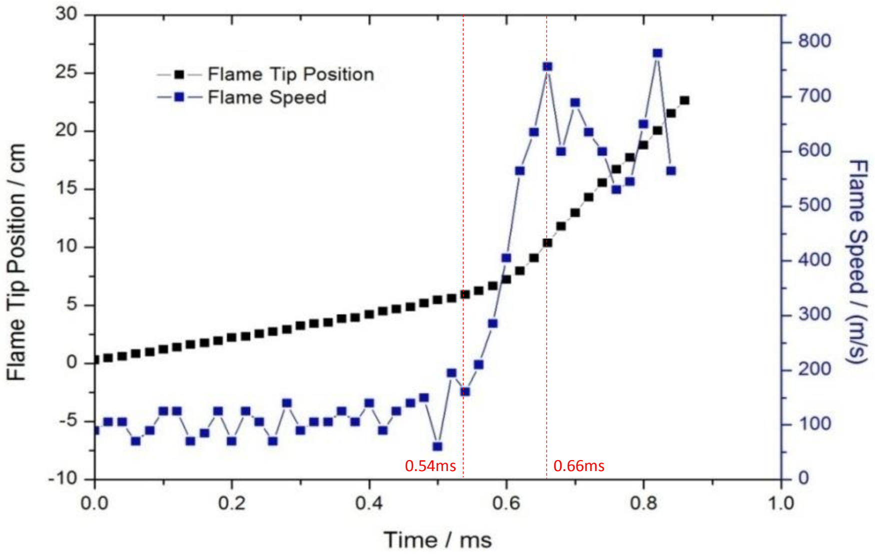

Fig.2 Evolution of flame tip and speed versus time For BR=5/7

3.2 Effect of height on flame acceleration

In present experiments, the BR determined by the sponge height has a strong effect on both the gas flow around it and flame acceleration. Fig.4 shows evolution of flame fine structures in tube laden with six different BRs. As described above, at the initial stage the flame propagates outwards in a semi-spherical shape or an elliptical shape until it approaches the sponge, as shown in column 1.

In column 2, the flame travels in the gap, it is accelerated and stretched in horizontal direction. It is clear that, with the BR increase, the stretched flame becomes thinner. For example, the width of the stretched flame for BR=1/7 is nearly five times as that for BR=6/7, which illustrates that the higher sponge can provide a more effective natural contraction. The sponge not only can induce flow contraction, but also is responsible for the formation of shear layer attached around the sponge left corner. In addition, the stretched flame is separated from the left and top edges of the sponge, which shows that the shear layer and the recirculation zone in the upstream region can effectively prevent the flame from propagating close to the sponge. The flame surface is almost kept smooth, indicating that the flame is laminar, except the lateral sides of the flames for BR=5/7 and BR=6/7. The wrinkled surfaces can be attributed to the interaction of the shear layer and the flame.

In column 3, the flame travels out of the gap and in downstream region of the sponge. For all BRs, the combustion appears to be laminar on the flame leading front except its lateral side where the surface is severely wrinkled and evidently turbulent. Note that the flame leading front propagates in sloping mode For BR=5/7 and BR=6/7 instead of a planar mode in other cases. Dunn-Rankin et al[16] and Gonzalez et al[17] attributed this sloping flame phenomenon to “squish flow”, which means an accelerated flow in the unburned zone which is wedged by flame front and side walls [18]. Since the high diffusivity and high burning rate of hydrogen, the “squish flow” is more pronounced during premixed hydrogen-air flame evolution. In addition, the difference for the six BRs is the unburned gas pocket evolution. It is easier for the shorter sponge to causes the unburned gas pocket to disappear. The probable reason is a combined effect of the recirculation zone size in the upstream region of the sponge and the strength of shear layer.

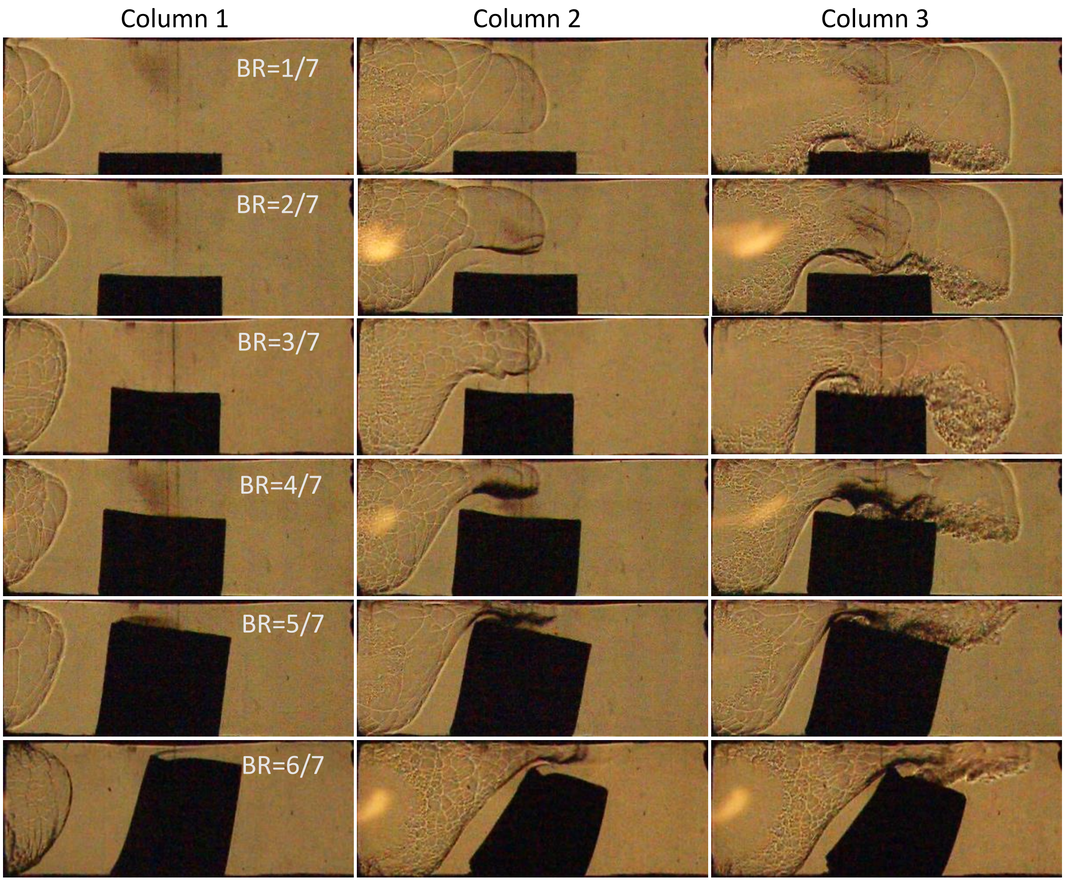

Fig.3 Schlieren photographs of premixed flame evolution for different BR

Fig.4 presents flame tip speed as a function of the time for varying BR. As described in Fig.2, for all BRs, the flame speed experiences a slow increase before it approaches the sponge. Then the flame speed exhibits a fast increase with a different amplitude for varying BR. After the speed reaches the maximum value, it decreases. By comparison, it is found that the flame acceleration is most pronounced for larger BR or higher sponge. For example, the maximum flame speed is roughly 730m/s for BR=6/7, and only 200m/s for BR=1/7. As mentioned above, the dramatic influence of BR on flame acceleration can be understood as follows. The first one is the different structure of flow field corresponding to the different BR. As pointed out by Ciccarelli et al [19], for larger BR, the recirculation zone positioned upstream and downstream of the obstacle are larger and can separate the recirculation zone with outer flow more efficiently to accelerate the flame. The second one is the cross section between the tube and sponge. Smaller cross section for larger BR can more facilitate the flame acceleration. The third one is the interaction between the flame and the shear layer. The larger the BR is, the stronger the shear layer is, which can induce more instability and in turn leads to more evident flame acceleration.

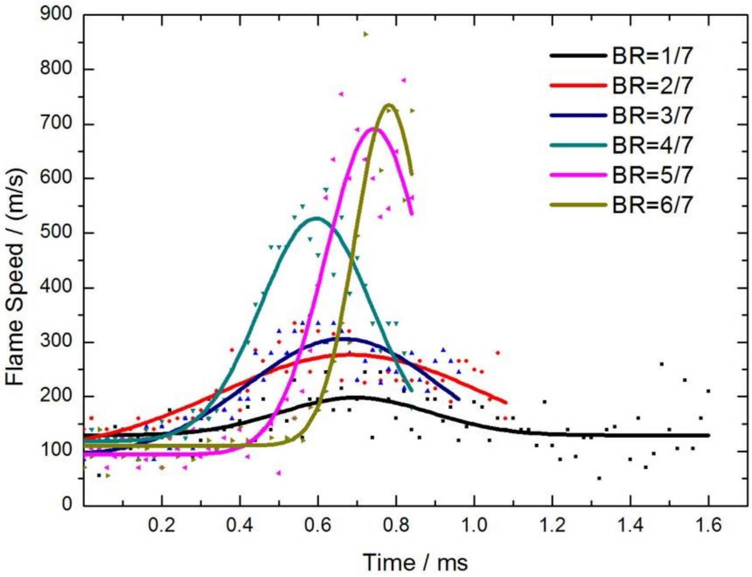

Fig .4 Flame tip speed versus time for varying BR

3.3 The Tilt Angle Change of Sponge

It can be easily observed in Fig.3 that the sponge tilt angle experiences only slight change for BR less than 5/7. So Fig.5 only presents the sponge tilt angle changes for BR=5/7 and BR=6/7. For BR=6/7, due to the expansion of combustion products in the upstream region of the sponge, the sponge is pushed to the right. Its tilt angle increases as a monotonic function with the time and reaches the maximum value of 47.5 degree at 0.96ms. After the flame passes around the sponge, the push force increases in the reversed direction (to the left) and resultantly the angle decreases after a balance with slight fluctuation. For BR=5/7, the similar trend with a different amplitude can be easily observed. The maximum tilt angle is around 18 degree. So an indirect information can be derived that the flame is accelerated more and the push force rises on the sponge, with increasing the sponge BR.

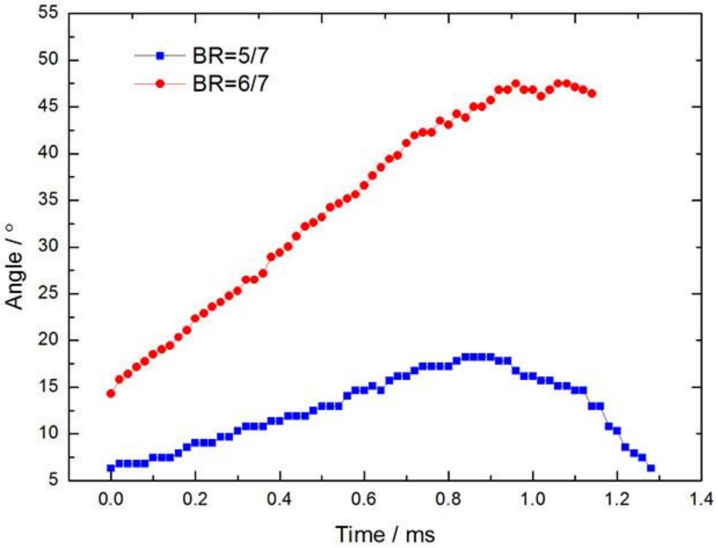

Fig.5 Sponge Tilt Angle versus time for BR=5/7 and BR=6/7

4.0 CONCLUSIONS

The effects of sponge height on flame structure evolution and flame acceleration were experimentally investigated in an obstructed cross-section tube filled with stoichiometric hydrogen-air mixture. Experimental results show that the flame propagates as a semi-spherical shape at the beginning and then is stretched in horizontal orientation. After flame leading tip passes through the polyurethane sponge, the flame lateral side is seriously distorted. The flame is accelerated as it pass through the sponge and then experiences deceleration downstream of the sponge. The mechanism responsible for flame acceleration can be in terms of the positive feedback of the unburned gas field generated ahead of the flame, the area change of the gap between the sponge and tube, and the interaction between the flame and the shear layer appearing at the sponge left top corner. Especially, the last one dominates the flame acceleration and causes its speed to be sonic. Then both the second and third contribute to the violent acceleration of the flame.

The unburned gas pockets can be found in both upstream and downstream regions of the sponge. With increasing BR, the unburned gas pockets disappear easier, and the flame acceleration is more pronounced. Moreover, the sponge tilts more evidently and resultantly the maximum tilt angle increases.

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