Visualization of Deflagration-to-detonation Transition in a Channel with Rough Wall

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1 Introduction

There are two types of combustion wave propagating in a combustible mixture: a deflagration wave propagating at subsonic speed and a detonation wave propagating at supersonic speed. When a combustible mixture is filled in a closed-end tube and the mixture is ignited in the one end, the deflagration wave firstly propagates to the other end. The local explosion occurs in the unburned gas through the successive acceleration of the deflagration wave, and finally the detonation wave starts to propagate. This entire process is called as "defragmentation to detonation transition (DDT)" [1-3]. As a method for promoting flame acceleration and DDT, installation of obstacles and roughening of the wall surface in the tube are effective. For typical example, when fence-type obstacles are placed at constant intervals on the wall surface of the channel, the obstacles induce complicated flow field in the unburned gas ahead of the flame. This increases the burning velocity and promote the flame acceleration. However, it has been indicated that the enhancing effect of DDT was not significant when the blockage ratio (BR) of the obstacle was less than 0.1 [3]. On the other hand, Houim and Oran [4] conducted the three-dimensional numerical simulation of the DDT process in the channel in which small roughness elements were densely distributed on the wall and surface roughness can be large. The roughness element destabilized the boundary layer and promoted turbulence. In addition, the interaction of the preceding shock wave with the roughness element generated a number of reflected shock waves, which induces Richtmyer-Meshkov instability and increased the surface area of the flame, leading to further flame acceleration. Their results showed that the DDT distance was reduced to by a factor of ten in comparison with the smooth wall tube, when such roughness existed in the channel wall.

The authors [5] have investigated experimentally the effect of wall roughness on the flame acceleration and DDT process by controlling the surface roughness of channel wall by installing a sand-cloth on the channel wall. The results showed that the flame acceleration was divided into the initial stage right after the ignition, which was not affected by the surface roughness, and the second stage which was greatly affected by the surface roughness. In the second stage, the time-sequential schlieren images exhibited the characteristic density gradient which greatly deforms the shape of the flame surface near the rough wall. However, the details of this phenomenon have not been clarified. In this study, we conducted the chemiluminescence observation of propagating flame on the rough wall, in addition to pressure measurement and schlieren visualization using ethylene-oxygen mixture.

2 Experimental apparatus and conditions

A schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental equipment was a square channel of 486 mm overall length, 10 mm width, and 10 mm height. The electrical spark plug was installed at the ignition wall, and it ignited the ethylene-oxygen mixture of pressure at 30 kPa filled in the channel. Six pressure transducers (PCB Piezotronics, Inc.) were installed on the upper wall of the channel at intervals of 80 mm at the positions P1 to P6. The wall conditions were as follows: (a) smooth wall condition, (b) rough lower wall condition, and (c) rough side wall condition. In rough wall conditions, a stainless-steel plate with knurling (hereinafter referred to as knurled plate) as shown in Fig. 2 was set on the lower or side wall to obtain the channel wall with the large surface roughness. The surface roughness of the channel wall without the knurled plate was about 1 μm for Rz (maximum height roughness) and about 0.15 μm for Ra (arithmetic average roughness). On the other hand, the surface roughness of the knurled plate was about 700 μm for Rz and about 70 μm for Ra. A pair of acrylic optical windows on the side surfaces of the channel covered the total length, and the whole combustion channel could be observed. In addition to the observation of density field using schlieren optical system and high-speed video camera (UltraCam HS-106 E, nac Image Technology, Inc.) with stroboscopic light source (MECABLIZ, 76MZ-5 digital, Metz), the chemiluminescence observation using high-speed video camera (Phantom V7.3, Vision Research, Inc.) with a bandpass filter was carried out to selectively visualize the self-emission of hydrocarbon combustion. The bandpass filter transmitted the emission of 430 nm center wavelength and 10 nm half bandwidth so as to observe the chemiluminescence of CH* radical generated in the reaction of ethylene-oxygen mixture. In order to capture the emission as clearly as possible, the black vinyl tape as a blackout curtain was attached to the outside of the optical window which was opposite to the optical window on the side where the high-speed camera was installed. The exposure time of the high-speed camera was 0.1 μs for schlieren observation and 14.5 μs for chemiluminescence observation. In the schlieren observation, the experiment was carried out under two wall conditions of the smooth wall condition and the rough lower wall condition of Fig. 1, and in the chemiluminescence observation, the experiment was carried out under three wall conditions of Fig. 1.

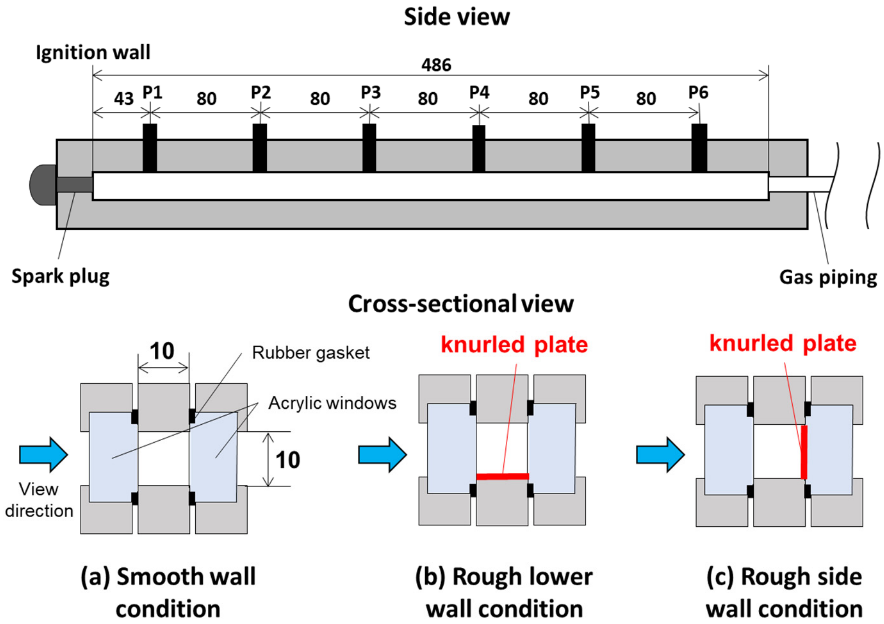

Figure 1: Experimental apparatus (unit of length: mm).

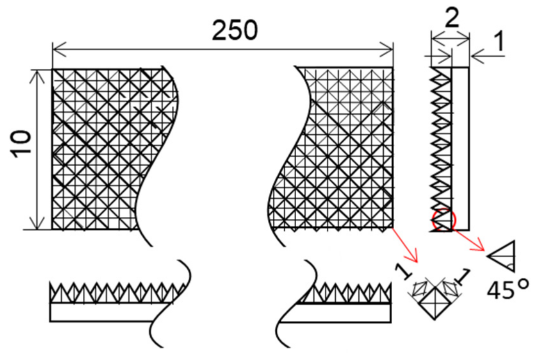

Figure 2: Stainless-steel plate with knurling (unit of length: mm).

3 Results and discussion

Figure 3 shows the evolutions of the flame tip velocity against the propagation distance. The flame tip velocity was measured using the time sequential schlieren and chemiluminescence observations under the three wall conditions of Fig. 1. The two dashed lines in the figure represents the sound speed of combustion products, a_p and the propagation velocity of Chapman-Jouguet detonation, D_{CJ} (hereinafter referred to as CJ velocity), which were calculated using the chemical equilibrium software NASA CEA [6]. The flame accelerated from the ignition wall to around 40 mm in almost the same trend under all wall conditions. In the smooth wall condition, the flame subsequently decelerated until about 110 mm and then accelerated again. On the other hand, in the rough wall conditions, although the flame acceleration slowed around 40 to 100 mm, the flame continuously accelerated and finally reached discontinuously to near the CJ velocity around 200 mm, which meant transition to detonation. These results indicated that the knurled plate used in this study had the effect on shortening the DDT distance by drastically promoting the flame acceleration. In addition, the results of chemiluminescence and schlieren observations under the same wall conditions show approximately the same flame tip velocity evolutions, which can be discussed in correspondence with each other while these results were obtained in the separate experiments.

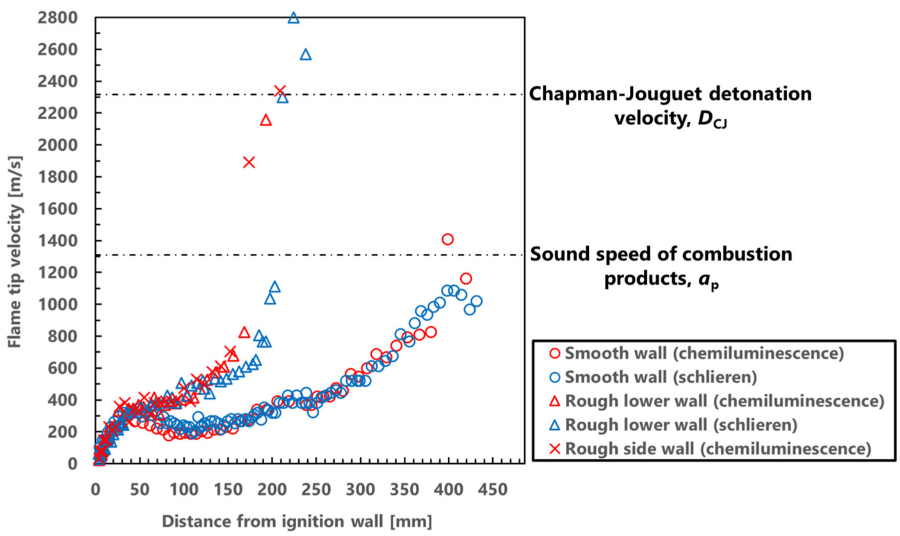

Figure 3: Evolutions of the flame tip velocity in the schlieren and chemiluminescence observations in each wall condition.

Figure 4 shows the schlieren and chemiluminescence images at the period of the transition from the initial stage to the second stage of flame acceleration in the smooth wall condition. The distance from the ignition wall is shown at the top of each image, and the time in the image indicates the elapsed time from the spark ignition. Since the field of view along the channel length in single experiment was about 60 mm, the images on the left side of the figure show the range from the ignition wall to around 60 mm, and the images on the right side show the range from around 60 mm to 120 mm. The range until the flame tip reached about 40 mm was the initial stage of flame acceleration, and the convex flame (so-called finger flame) propagated to the downstream. In the following deceleration stage of the flame, the flame front deformed to the plane shape at around 105 mm, and the flame near the wall surface subsequently deformed to the shape called the tulip flame at around 120 mm. These propagation processes can be understood not only by the density gradient in the schlieren images but also by the chemical reaction surface obtained by the chemiluminescence images. In addition, the chemiluminescence images showed that the reaction front of side surface (so-called flame skirt) extended long to the vicinity of the ignition wall in the initial convex flame (208 μs). The flame skirt became shorter by attaching to the wall surface with the propagation, and it indicated that the flame deceleration occurred in the process of decreasing the flame surface area.

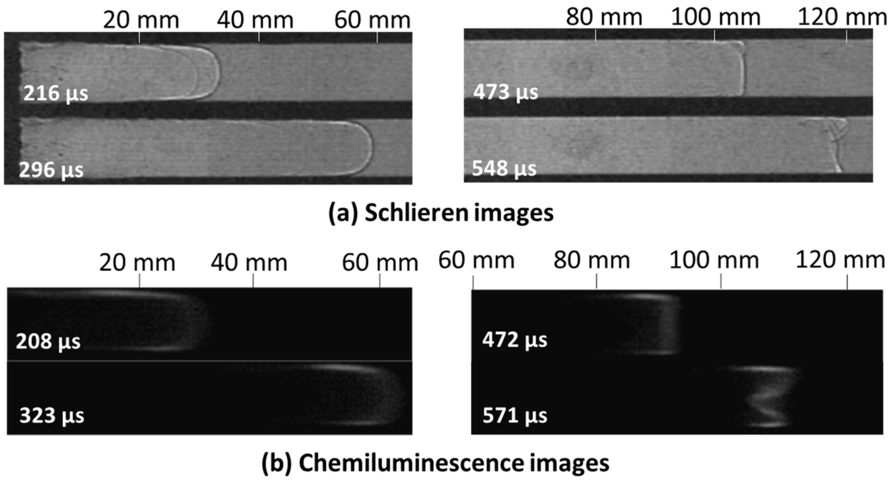

Figure 4: Schlieren and chemiluminescence images in the smooth wall condition

Figure 5 shows the schlieren and chemiluminescence images in the rough wall conditions with the knurled plate on the channel wall taken in the same field of view as Fig. 4. The schlieren and chemiluminescence images of the rough lower wall condition are Fig. 5 (a) and (b), respectively, and the chemiluminescence image of the rough side wall condition is Fig. 5 (c). In the region where the flame tip position was up to 40 mm, the convex flame propagated as in the smooth wall condition in Fig. 4. In this region, there was no significant difference in the chemiluminescence images in Fig. 5 (b) and (c). However, in the second stage of the flame acceleration, the propagation process of the flame greatly differed from the smooth wall condition. Figure 5 (a) showed the development of the characteristic density gradient (pointed by the white arrows in the images) from near the lower wall where the knurled plate was installed at around 100 to 120 mm from the ignition wall. This has also been observed in the previous studies [5] by the authors which installed the sand cloth on the channel wall. Then in Fig. 5 (b), the region of strong luminescence (pointed by the white arrows in the images) was observed near the lower wall where the knurled plate was installed, which was clearly stronger luminescence than that of the reaction front near the upper wall where the knurled plate was not installed. In Fig. 5 (c), the region of stronger luminescence (pointed by the white brackets in the images) was observed in the region of about 15 mm around the flame front, which was hardly seen in the image at 193 μs of the initial stage of flame acceleration. This luminous region roughly corresponded to the region of strong luminescence observed near the lower wall in Fig. 5 (b).

The region of prominent characteristic density gradient seen in Fig. 5 (a) corresponded to the region where the stronger chemiluminescence was observed in Fig. 5 (b) and (c). Therefore, the chemical reaction was especially promoted in this region, which was considered to cause the flame surface to protrude. In the vicinity of the knurled plate, the flow of unburned gas in front of the flame is disturbed, and the compression wave and shock wave which precede the flame are complicatedly reflected on the knurled elements, and they will interact with the flame front. These effects will greatly increase the flame surface area near the knurled plate and cause to enhance the combustion reaction. This effect of the rough wall seems to compensate for the decrease in flame surface area due to the loss of the flame skirt of the convex flame, resulting in the enhancement of flame acceleration without the flame deceleration as shown in Fig. 3.

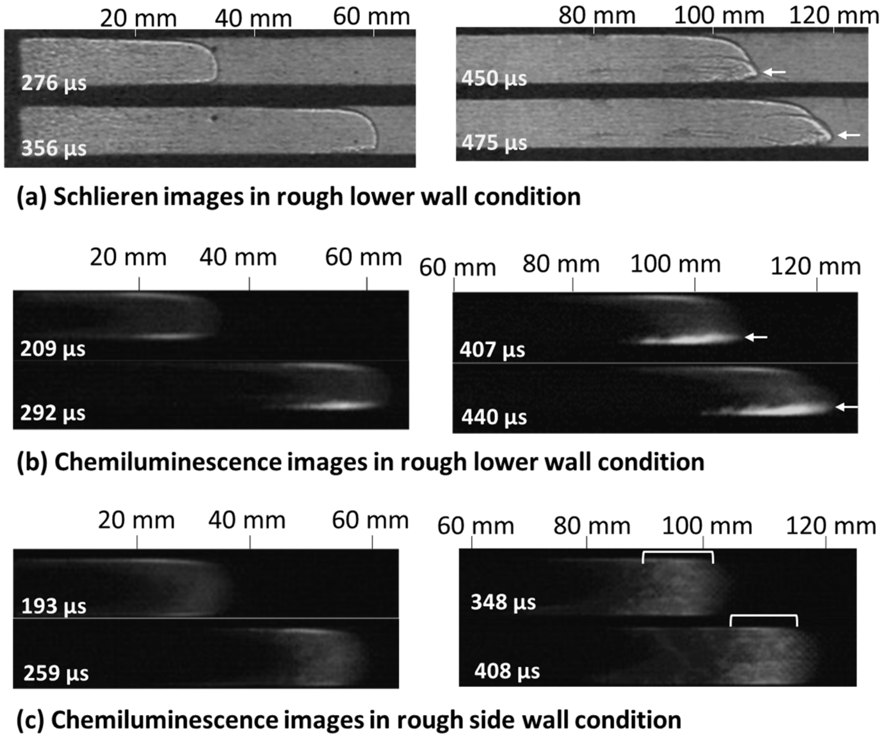

Figure 5: Schlieren and chemiluminescence images in the rough wall conditions.

4 Conclusions

The knurled plate with the maximum height roughness Rz = 700 μm was installed on the lower or side wall of the channel, and the effect of the surface roughness on flame propagation was investigated. The flame acceleration process was observed by schlieren recording and chemiluminescence recording using the high-speed camera. The observations indicated that the flame acceleration was divided into two stages. The initial stage immediately after ignition was not affected by the wall roughness, but in the second stage, the flame acceleration was enhanced, and the DDT distance was greatly shortened in the large surface roughness using the knurled plate. Correlation of the schlieren and chemiluminescence images at the transition period from the initial stage to the second stage of the flame acceleration indicated that the chemical reaction was promoted on the rough wall surface, and it formed the protruded flame front. This effect seems to be due to the increase in the flame surface area caused by the disturbance of the velocity and pressure fields by the rough wall, and this will greatly affect the second stage of the flame acceleration.

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