Suppression of Deflagration-to-Detonation Transition by Sintered Wire Mesh

K. Kashiro and K. Ishii
Yokohama National University
Yokohama, Kanagawa-ken, Japan

1 Introduction

Detonations have occurred in coal mines and cooling pipes of nuclear power plants and, caused severe damages. It is well known that deflagration-to-detonation transition (DDT) occurs in a closed pipe after deflagration, which is generated by a weak ignition source, propagates over a certain distance. In order to prevent damages by detonation, many studies on DDT have been conducted, including a novel visualization experiment by Urtiew and Oppenheim [1] and the SWACER mechanism proposed by Lee et al [2].

It has been found that DDT process has two phases: one is a flame-accelerating phase that prepares an mixture condition for onset of detonation and the other is the onset of detonation phase [3]. Liberman et al. [4] proposed that the flame-accelerating phase could be separated into two stages and found flame speed being constant just before detonation initiation occurs. The shadowgraph images reveal existence of preheated zones made by concentration of numerous compression waves and shock waves ahead of the flame, leading to conclusion that the preheated zone thickness is related to the onset of the detonation. Poludnenko et al. [5] numerically studied turbulent flames formed by the accelerating flame and the flow field ahead of the flame and proposed turbulence–induced DDT (tDDT), involving quantitative index of DDT based on turbulent burning velocity. Hytovick et al. [6] confirmed tDDT experimentally by visualization and pressure measurements in the turbulent flow field ahead of the flame front. However, actual proof of tDDT remains still uncertainty because the flame shape is strongly influenced by development of the boundary layer and the geometry of the experimental apparatus. Ishihara et al. [7] succeeded in causing DDT with good reproducibility by using a shock tube. They made visualization from two perpendicular directions, indicating that the flame accelerates behind the Mach stem formed by the Mach reflection of the leading shock wave and concluded that a local- explosion to induce detonation initiation is due to shock wave interaction near the channel wall.

In this research, effects of shock reflection at the channel walls on the DDT process are experimentally studied using partially porous walls. Because porous materials have a damping effect to detonation waves, many studies have been made on the shock weaking effects of porous wall [8], wire mesh [9], soft fiberglass wool [10], and wire mesh layers [11]. For detonation waves, attenuation of transverse waves consisting of the cellular structure by porous materials induces the detonation wave to decoupled into a shock and reaction wave, leading to failure in propagation. Radulescu et al. [12] quantitatively determined the critical conditions for detonation failure by porous walls with tubes with a circular and

Correspondence to: kashiro-kenji-zk@ynu.jp

a rectangular for various tube diameter, height, and initial conditions. They concluded that the detonation wave begins to decouple when the cell size becomes equal to one-quarter of the diameter of the circular cross-section and the height of the rectangular cross-section. However, it is still insufficient to analyze the detonation attenuation quantitatively by porous materials regarding the relation between the amplification of the triple points and the attenuation of transverse waves.

In the present study, sintered wire mesh (SWM) was selected as porous materials and effects of SWM on the detonation initiation was studied aiming to control the DDT process with attenuation of a local pressure rises on the channel walls.

2 Experimental Apparatus

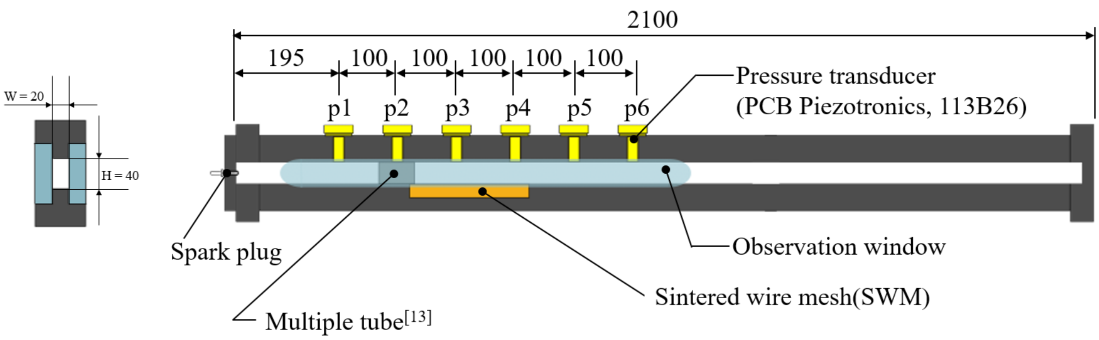


Figure 1 : Schematics of experimental apparatus.

Figure. 1 shows a schematic of the experimental apparatus used in the present research. The detonation tube is approximately 2.1 m long with a rectangular cross-section of 20 mm × 40 mm.

SWM made of SUS304 with 3 mm in thickness is used as porous materials. Three mesh sizes of the SWM were used; #20 (nominal aperture 0.77 mm, wire diameter 0.5 mm), #40 (nominal aperture 0.385 mm, wire diameter 0.25 mm), and #300 (nominal aperture 0.05 mm, wire diameter 0.035 mm) with screening areas of 36.8%, 36.8%, and 34.4%, respectively. Nominal aperture and wire diameter are represented by A [mm] and d [mm], respectively and then mesh sizes M can be calculated from the following equation:

$$M = \frac{25.4}{A + d}$$

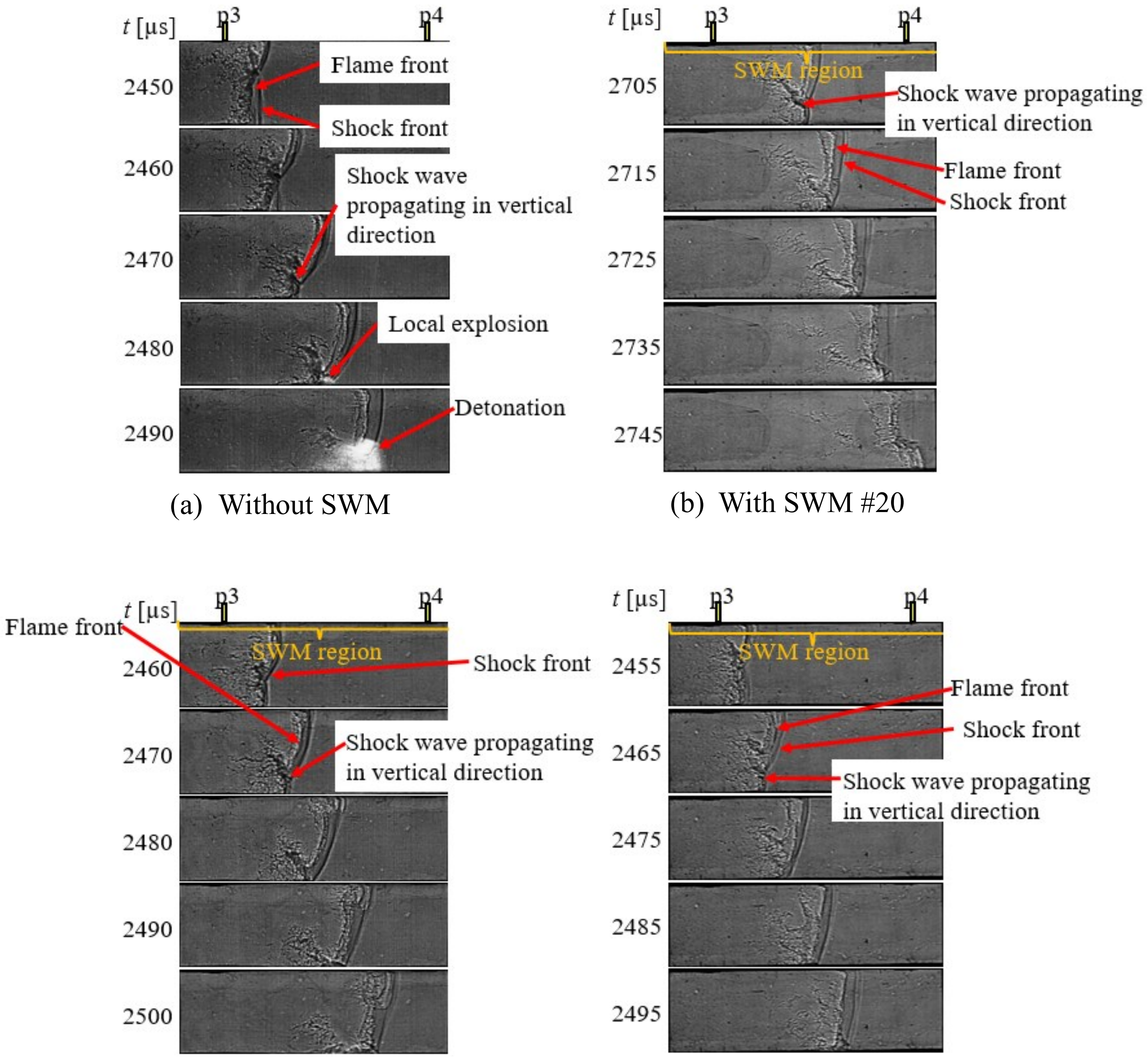
The lower wall within 320 mm to 520 mm from the tube end can be replaced with the SWM of 200 mm in length. A spark plug for automobile use is fixed at the end of the detonation tube. A pair of observation windows of plexiglass are placed on the side walls to permit visualization of the flow field.

The test gas was a stoichiometric ethylene-oxygen mixture, which was charged into the detonation tube at an initial pressure of P_0 = 8 kPa. A specially designed DDT enhancement devise, which was made from a bundle of 1/4” tubes approximately 30 mm long [13], were installed at 70 mm from the tube to shorten the DDT distance so that DDT can occur within the visualization area. Shadowgraph images were taken with a high-speed camera(nac Image Technology, MEMRECAM ACS-1) at 2×10^5 fps. Pressure profiles during the DDT process were measured using six conventional pressure transducers (PCB Piezotronics, 113B26) placed at 100 mm intervals at the upper wall, as shown in Fig. 1. The pressure acquisition mode is single, with a duration of 50 ms, at a sampling rate of 1 MS / s.

3 Experimental Results

Figure 2 shows shadowgraph images of the DDT process for the observation area of 370 mm to 510 mm from the tube end. In Fig. 2 (a), the case without SWM, the flame is found to propagate accompanied by the shock waves at 2450 µs (this kind of flame is called shock-flame complex). The upper portion of the shock-flame complex is accelerated, forming a shock wave propagating in vertical downward direction, just before the local explosion triggering the detonation initiation on the lower wall at 2480 µs. The local explosion on the lower wall occurred 8 times out of 11 tests, and the local explosion on the upper wall 3 times.

Fig. 2 (b) shows the images with a SWM with mesh size of #20 (SWM#20). At 2705 µs, the shock-flame complex is observed and the flame near the upper wall is found to be faster, generating a vertically propagating shock wave. This scenario is essentially the same with the case in Fig. 2 (a). In Fig. 2 (b), no local explosion was observed, indicating that the SWM can successfully suppress DDT. As for SWM#20, DDT suppression was observed 7 times out of 8 tests and the local explosion occurred on the lower wall one time.



(a) Without SWM (b) With SWM #20

(c) With SWM #40 (d) With SWM #300

Figure 2 : Shadowgraph images of DDT process in C_2H_4+$3O_2$ mixture at P_0 = 8 kPa.

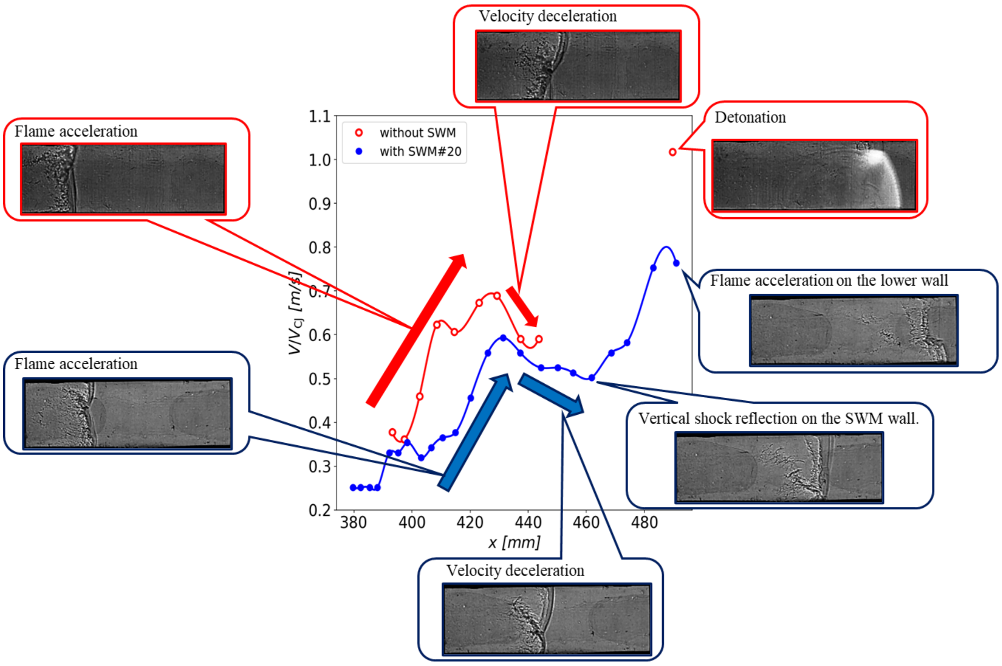


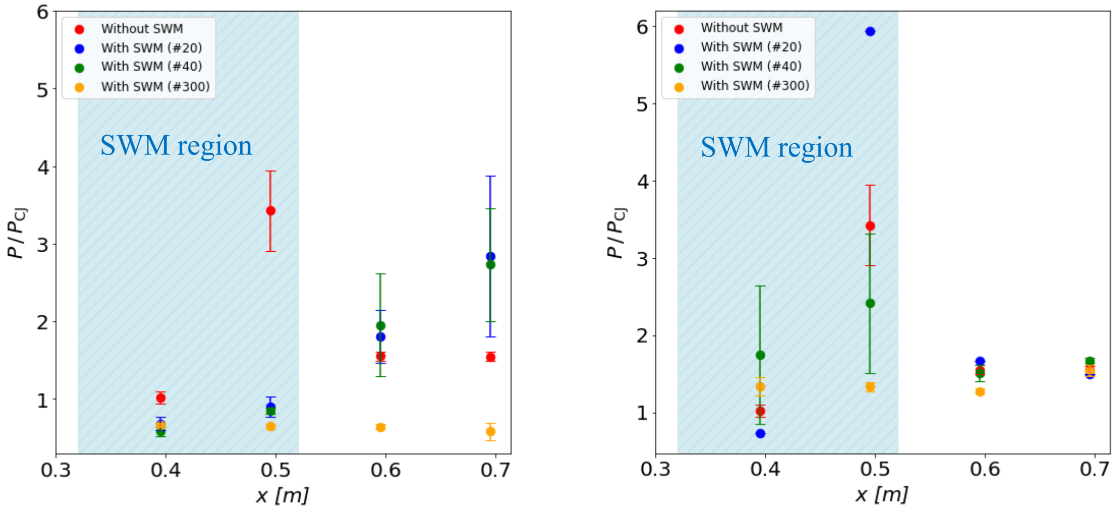
Figure 3 : Verocity profiles of the shock-flame complex corresponding to Fig. 2 (a) and (b) .

Shadowgraph images for SWM#40 are shown in Fig. 2 (c). Although propagation of the shock-flame complex is similar to Fig. 2 (a), the DDT event cannot be observed in this case. In 16 tests with SWM#40, DDT suppression was confirmed 10 times, while the local explosion occurred 2 times on the lower wall and 4 times on the upper wall.

Fig. 2 (d) shows the case with SWM#300. In this case, the vertically propagating shock wave is found to travel toward the upper wall at 2485 µs, after its reflection on the lower wall at between 2475 µs and 2480 µs. SWM#300 can suppress the DDT 3 times out of total 7 tests, and the local explosion causing the DDT is observed once on the lower wall and 3 times on the upper wall.

Velocity profiles of the shock-flame complex measured from shadowgraph images at Fig. 2 (a) and (b) are shown in Figure 3. The flame front accelerates up to approximately 60–70% of the CJ velocity, and then decelerates in both cases. During this acceleration process, the upper portion of the shock-flame complex propagates at higher speed than the lower portion, gradually transforming into a downward convex shape. In the case without SWM, the velocity jumps to CJ velocity near 480 mm from the ignition end due to DDT. In the case with SWM#20, the flame accelerates again after the reflection of the vertically propagating shock wave on the SWM wall. In this re-acceleration phase, the speed of the flame near the SWM wall reaches 70% of the CJ velocity.

SWMs are expected to weaken the shock wave, whether DDT occurs or not. Figure 4 shows the maximum pressure at propagation of the shock-flame complex. As for the case without SWM, the pressure almost reaches the CJ- pressure at 0.4 m from the end of the detonation tube and the onset of detonation can be determined to occur between 0.4 m and 0.5 m. When the SWMs are installed on the lower wall, the pressure is approximately 0.6 - 0.7 times the CJ- pressure at 0.4 m in Fig. 4 (a), demonstrating the pressure attenuation effect of the SWM. This effects is almost the same for SWM #20 and #40 and detonation initiation occurs at 0.6 m to 0.7 m after the shock-flame complex passes the SWM region. SWM#300 exhibits the highest attenuation effect and no detonation initiation is observed in Fig. 4 (a). In contrast, Fig. 4 (b) shows that the maximum pressure at 0.4 m already exceeds the CJ-pressure except for SWM#20. It is also found that in all cases the DDT occurs in the SWM region.



(a) DDT suppression by SWMs

(b) No DDT suppression

Figure 4 : Comparison of maximum pressures of shock-flame complex with and without SWMs.

4 Summary

The effects of installation of SWMs on DDT were experimentally studied with the pressure measurements and shadowgraphy. Table 1 shows summary of the experimental results, namely probability of DDT suppression. The SWM with mesh size of #20, which has the largest aperture, shows the highest probability of DDTsuppression, while the pressure attenuation effect is most significant for SWM#300.

Table 1: Probability of DDT suppression by SWM.

		Without SWM	With SWM		
			#20	#40	#300
No DDT		0 / 11	7 / 8	10 / 16	3 / 7
DDT	Upper wall	3 / 11	0 / 8	4 / 16	3 / 7
	Lower wall	8 / 11	1 / 8	2 / 16	1 / 7

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