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Effects of silicone rubber and aerogel blanket-walled tubes on H_2/Air gaseous detonation

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ABSTRACT

The experimental study of hydrogen-air detonation was performed in a 6.3-m-long circular cross-section tube, the rear section of which was walled by silicone or aerogel material. Mixtures of 25% or 29.6% hydrogen with air by volume with an initial pressure of 0.1 MPa and temperature of 293 K were used in the experiments. A short Shchelkin spiral was fixed at the tube head to accelerate the deflagration-to-detonation transition. The flame and pressure wave propagation velocities were measured by ion probes and pressure transducers, respectively. The detonation regimes and velocities of flame propagation in walled tubes of different materials were compared. It was found that it is difficult for a silicone rubber-walled tube to reduce the intensity of the detonation wave. In this case, for the stoichiometric mixture, a reduction in the propagation velocity by 5% and the pressure peak by 12% was recorded in order to compare those parameters in a stainless smooth tube. An aerogel blanket wall has a strong ability to reduce the intensity of the detonation wave with the peak pressure decreased by 35% for the stoichiometric hydrogen-air mixture. The attenuation of the steady detonation wave can occur in the aerogel blanket-walled tube under the present experimental conditions. This is because of the effective suppression of transverse waves by interaction with the aerogel wall; then, the generation of stable detonation cells is no longer possible, and thus, the shock wave and flame front are decoupled, and detonation is suppressed.

1. Introduction

Instantaneous high temperature and pressure caused by detonation in gaseous explosion accidents cause significant damage to both personnel and equipment. Therefore, people have been investigating how to attenuate the intensity or even extinguish it when a detonation occurs. However, because of the complicated process of the deflagration-to-detonation transition (DDT) and rapid propagation of a detonation flame, it is not easy to propose efficient approaches to suppress the spread of detonation, especially in a closed tunnel.

People found experimentally that a surface made of nonflexible or compressible porous material can depress the detonation propagation. Therefore, examinations of different wall materials have been performed over three decades. Gvozdeva et al. (1986) studied the reflection of a normal shock wave when it impacts porous compressible materials and found that the reflected wave is obviously attenuated in the porous material. Using the flat layers of expanded polymers attached to the tube wall, Dupre and Lee (1988) studied the attenuation of the steady detonation wave. They explained that the main reason for the attenuation of the detonation was that the reflection of the transverse wave is weakened by the porous surface. Teodoreczyk and Lee (1995) analyzed the attenuation phenomena of the intensity of the detonation wave by means of high-speed photography, and by carefully examining the experimental images, they observed that the transverse wave reflection is weakened by soft rock wool fiber glass. Radulescu and Lee (2002) experimentally studied the inefficacy mechanism of the detonation wave through porous media. It was found that the failure mechanism of typical hydrocarbon detonations in porous wall tubes is by attenuation of their transverse wave structure. The experimental results further confirmed that the transverse wave is highly important for stable propagation of the detonation wave.

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Mazaheri et al. (2015) studied the propagation mechanism of steady and unsteady detonation waves inside the pipe with the wall surface in a wire mesh structure. The experimental results showed that the frontal wave curvature increases and the number of transverse waves decreases in the porous section because of the attenuation of the detonation wave. Mehrjoo et al. (2015) studied the failure mechanisms in the critical tube diameter phenomenon for stable and unstable mixtures. It was shown that the failure is caused by the suppression of the generation of local explosion centers or by excessive global front curvature in stable mixtures.

The studies on the multilayer-structure metal mesh, foamed ceramics and some other types of porous materials also verified that porous media are able to perform well in wave absorption and explosion suppression (Radulescu, 2003; Joo et al., 2006; Johansen and Ciccarelli, 2008; Ciccarelli et al., 2011; Nie et al., 2011). However, those studies were performed with compressible or non-flexible porous materials. Some other common materials, e.g., silicone rubber, are compressible but lack porosity. The effects of such compressible materials, if used as a wall liner, on the detonation propagation are yet to be investigated. In addition, we notice that aerogel materials are widely applied in industrial applications for thermal insulation. Compared to the other types of insulation or retardant material, aerogel has even lower thermal conductivity and a stronger property of absorbing acoustics. However, how effectively aerogel materials can suppress detonation propagation remains unknown because they are made for the tube or tunnel liner.

It is easy to generate a gaseous detonation once a well-prepared mixture is ignited in a single-trial detonation tube; a single-trial detonation tube is a good experimental platform to study wall effects on the DDT and detonation propagation. Therefore, in this paper, silicone rubber and an aerogel blanket are used to form the tube liner in a single-trial detonation tube for experimental studies on the suppression performance of the DDT and the detonation wave. The flame and pressure wave propagations are measured and compared for a hydrogen/air mixture detonation with different hydrogen volume concentrations.

2. Experimental details

2.1. Experimental setup and procedures

The experiment system mainly consists of a detonation tube, a gas delivery system, an igniter and a data acquisition system (DAS), as shown in Fig. 1.

The smooth stainless steel pipe is manufactured as a single-trial detonation tube. The detonation tube is 6300 mm long with a 40-mm inner diameter. The rear section of the detonation tube is the testing segment with a length of 1000 mm and an inner diameter of 50 mm. A 300-mm-long Shchelkin spiral is installed in the front of the detonation tube.

The wall lining material can be changed in the experiments, either using stainless steel, silicone rubber or aerogel blanket with thicknesses of 5 mm. Careful treatments are performed to the section connection to guarantee the smooth transmission of the detonation wave from the front smooth tube to the rear testing tube.

The DAS consists of different sensors, including pressure transducers and flame sensors, and a data acquisition device. The detonation tube is equipped with five PCB pressure transducers and three in-house made ion probes. The PCB pressure transducers (Type: 113B24) have a range of 0–68,950 KPa and a rise time of 1 μs. Three of the pressure transducers are fixed at the test section of the detonation tube. Three ion probes are fixed opposite to the pressure transducers at the same position. The other two pressure transducers are fixed in the smooth tube upstream from the test section, as shown in Fig. 1(b–c). An 8-channel data acquisition device (National Instruments USB-6366) collects data at a frequency of 2 M samples per second.

An adjustable igniter system (BWKT-II) has wide ignition energy, ranging from 35 to 3000 mJ. In the present study, fixed ignition energy of 1500 mJ is used for all relevant experiments after several trials.

The mixture of H_2 and air was prepared in a vacuumed vessel respecting Dalton's law of partial pressure and stood for at least 24 h to obtain sufficient mixing. Before the experiment, the detonation tube was vacuumed by a vacuum pump. Then, the mixture is filled until the initial pressure was required. The mixture was then ignited and all of the available data were simultaneously recorded by the DAS.

2.2. Tube wall materials

As mentioned above, three types of wall materials were used in the experiments: silicone rubber, aerogel blanket and stainless steel.

The silicone rubber holds the notable feature of high temperature stability. The strength of silicone rubber at normal temperature is only half of that of natural rubber or some synthetic rubbers. Silicone rubber can maintain a certain degree of flexibility, elasticity and surface hardness in an environment with a high temperature of more than 500 K and minimal changes in mechanical properties. A typical industrial silicone rubber tube used in the experiment is shown in Fig. 2(a) and SEM images are shown in Fig. 3(a).

The aerogel material used in this study is generally made with organic fibers (such as PET or polyester fiber) as the substrate, in which nano-silica aerogel is implanted with special technology. This material has low heat conductivity and density, high flexibility and strong crush resistance, as well as superior performance of acoustical insulation and shock absorption. A typical industrial aerogel blanket as the testing material is as shown in Fig. 2(b) and SEM images are shown in Fig. 3(b).

The stainless steel is commonly used in pipelines in the industry. As the reference case, a stainless steel (304) tube is used in the testing section that is not very thermally conductive. In this experimental study, the used stainless steel tube is polished to obtain a high smooth inner surface. All of these materials are walled in the testing segment, as shown in Fig. 4(a) and (b).

3. Results and discussion

3.1. Silicone rubber walled tube

Fig. 5(a) shows the measured propagation velocity of a pressure wave along the detonation tube in the case of hydrogen volume with 29.6% in air ($\Phi = 1$). In this figure, measurements were repeated four times, and their averaged values are shown compared to the C-J theoretical value. The error bars are only added to the averaged value.

Because of the function of the head Shchelkin spiral, a detonation wave appears at a length of 5 m into the detonation tube, where the averaged measured detonation wave velocity, in the DDT region, is slightly higher than the theoretical value of the C-J detonation. Successively, the detonation wave velocity begins to decrease, and a stable detonation wave is finally formed at 6100 mm, which is slightly lower than the C-J theoretical value.

Fig. 5(b) provides the measuring data when the hydrogen concentration in air is decreased to 25% ($\Phi = 0.8$). As shown by the experimental results, the acceleration and deceleration process of