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Experimental investigation on shock waves generated by pressurized gas release through a tube

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ABSTRACT

An experimental investigation on the flow structures and the strength of shock waves generated by high-pressure gas release through a tube into air was conducted. The results demonstrated that a leading shock wave was generated in front of the compressed gas jet and the shock wave speed increased firstly, then decreased and finally kept constant with an increase of the propagation distance in the tube. The experimentally measured Mach numbers of shock waves were close to those calculated from the theory of ideal shock tube flow. After spouting out of the tube, the normal shock quickly developed into a hemispherical shape. The Mach disk was observed in the under-expanded jet. For high-pressure combustible gas release, the concept of theoretical critical pressure of ignition was introduced and several theoretical critical pressures of common gaseous fuels were obtained.

1. Introduction

In the industrial field, the high pressure gas equipment has a very wide range of applications, such as in the process of gas production, storage, transportation, use, and so on. However, once the pressurized gas is suddenly discharged from the high pressure equipment, a highly under-expanded gas jet will be produced in the open space due to the large pressure ratio between the equipment and the atmosphere. Meanwhile, a leading shock wave will be generated in front of the jet. In general, a shock-effected air region would be formed between jet front and leading shock wave due to the shock wave which travels faster than the gas jet. It is well known that the pressure, density and temperature in the shock passed region undergo a sharp increase due to shock compression. For high-pressure combustible gas release into air, such as compressed hydrogen, methane, ignition might be initiated if the temperature of shock-heated air exceeds the threshold temperature for spontaneous ignition. Potential ignition without clearly identifiable ignition sources can be induced by shock waves. This shock-induced ignition is usually called spontaneous ignition or self-ignition, which was proposed and first referred to as diffusion ignition by Wolanski and Wojcicki (1972). Before the ignition, a combustible mixture layer was produced between expanding combustible gas jet and shock-heated oxidizer by mass and heat diffusion. Then when the temperature of the mixing layer reached the ignition temperature of the mixture and the concentration of combustible gas was in the flammability range, spontaneous ignition occurred. The temperature and fuel concentration of the mixing layer depend on the strength of the shock wave significantly. From this perspective, the shock wave generated by compressed gas release plays an essential role in the diffusion ignition. So it is necessary to investigate the shock wave generation and propagation after pressurized gas sudden discharge from high-pressure equipment.

The generation and development of shock waves due to high-pressure gas release is a very complex flow process. Berger et al. (2010) examined the effects of different obstacles on shock propagation and attenuation in a shock tube. It was revealed that shock wave developed in diverging nozzle-like obstacles was attenuated significantly. The shock waves emerging from different exits of an open-ended shock tube into ambient atmosphere were observed by Yu and Grönig (1996) based on experiment and numerical studies. It was found that the tube exit with ring or the coaxial tube

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exit could be used for reducing the attenuation of the shock wave. In the numerical work of Irie et al. (2003), characteristics and distance decay of a spherical shock wave were reported.

Shock waves are the core of shock-induced ignition. Dryer et al. (2007) experimentally investigated the spontaneous ignition of sudden compressed hydrogen releases. They proposed that multi-dimensional transient flows promoted the rapid formation of combustible mixture and chemical ignition. It was implied that the transient flows included shock formation, reflection and interactions. Xu and Wen (2012) suggested that shock formation, reflection and interaction could increase the temperature of the combustible mixture. Mogi et al. (2008) proposed that the shock wave became stronger with the discharge pressure increases. Consequently, the temperature of air in front of the jet was raised, thereby increasing the tendency of spontaneous ignition. Kim et al. (2013) reported that multi-dimensional shock interaction with the mixture layer front might enhance the mixing of the cold expanding hydrogen jet and shock-heated air, which affected the occurrence of spontaneous ignition. The early ignition occurring near the wall boundary layer was demonstrated by Lee and Jeung (2009). They thought that the ignition was caused by the multi-dimensional shock reflections and shock-boundary layer interaction with the contact surface.

Some characteristics of shock waves generated by high-pressure gas release, such as shock overpressure, speed and attenuation have been clarified in previous work. However, to date there have been few systematic works on shock structures, strength, and propagation at different release conditions, which are essential to fully understand the phenomenon of shock-induced ignition. In this study, an experimental study was conducted on shock waves generated by high-pressure gas release through a tube. And most attention was given to the main characteristics of shock wave generated in different downstream tubes with various release pressures, including shock strength, structure and propagation. Additionally, the concept of theoretical critical pressure of ignition was proposed.

2. Experiment

A schematic diagram of the experimental apparatus is shown in Fig. 1. It mainly consists of a high-pressure gas tank equipped with a pressure transducer for monitoring the pressure in the tank, a diaphragm holder fitting with a burst disk, a downstream tube, a data recording system, and a high-speed schlieren photography system.

The high-pressure gas tank had a volume of 0.44 l. The burst disk was used as a diaphragm, which separated the high-pressure chamber from the downstream tube. The burst pressure of the diaphragm depended on its thickness. Three kinds of burst disk were used with pressure design values of 2, 5, and 10 MPa. The high-pressure gas tank was fed by experimental gas until the burst disk was ruptured; in the meantime, the pressure inside the tank was gradually increased. After the break of the diaphragm, pressurized gas was rapidly discharged into the atmosphere through the downstream tube. The assembly of the diaphragm holder, burst disk, ring gasket and downstream tube is shown in Fig. 2(a). The ring gasket and the extension tube had the same internal diameter. Three tubes with different diameters of 10, 15 and 20 mm were used in the experiments. In addition, two kinds of tubes with lengths of 160 and 360 mm were employed at each diameter size, as shown in Fig. 2(b). Most of the experiments with the same downstream tube and the same disk thickness were repeated three times in order to reduce the uncertainty.

The burst pressure (*Pb*) was measured by the pressure transducer (Nanli, PTS705). To detect the pressure wave propagation inside the tube, three piezoelectric pressure transducers (PCB Piezotronics, 113B22) were installed on the tube wall. Positions of the pressure transducers are shown in Fig. 2(b). A rising signal was detected at the time of the shock wave passing through the first transducer, which was used to trigger the pressure recording system and the high-speed video camera. The schlieren system was composed of a line light source, two focusing lenses, two spherical concave mirrors, a vertical schlieren knife edge, and a high-speed video camera. The high-speed video camera (Phantom, v710) was used to record the configurations and position of the shock wave outside the tube as a function of time. The operating speed of the high-speed video camera in the experiment was about 80,000 frames per second.

Whether it was combustible or non-combustible gas, both of them spouting from high-pressure equipment into the ambient air show a typical under-expanded flow pattern. Moreover, the main purpose of this study was to explore the shock waves produced by high-pressure gas release rather than the mechanism of shock-induced ignition. Therefore, a non-combustible gas used in this experiments was recognized. In addition, for leakage of high-pressure combustible gases, hydrogen demonstrates a stronger tendency to shock-induced ignition (Dryer et al., 2007). Since helium gas (He) has the similar physical properties with hydrogen, it was used as the experimental gas.

3. Results and discussion

3.1. Shock wave strength inside the tube

When compressed helium gas was abruptly discharged through

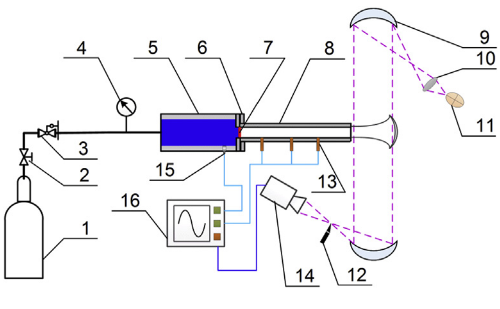

Fig. 1. Schematic of the experimental setup: (1) compressed gas cylinder, (2) cylinder valve, (3) regulator valve, (4) pressure gage, (5) high-pressure tank, (6) diaphragm holder, (7) diaphragm (burst disk), (8) downstream tube, (9) spherical concave mirror, (10) focusing lens, (11) light source, (12) knife edge, (13) piezoelectric pressure transducer, (14) high-speed video camera, (15) strain gauge pressure sensor, (16) data recorder.

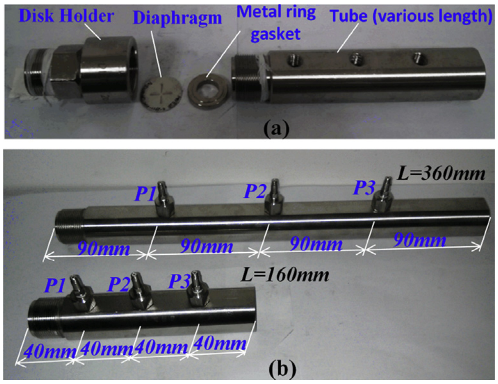

Fig. 2. Pictures of downstream tubes and the tube assembly with a diaphragm: (a) assembly of a downstream tube, a burst disk and a diaphragm holder; (b) two tubes with different lengths, *L*-tube length, *Pn*-pressure transducer.