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14. ABSTRACT

Shock tubes have been widely used since the 1950s to study physical phenomena such as shock waves, combustion chemistry, and the response of materiel to blast loading. Recently, laboratory-scale shock tubes driven by oxy-acetylene were described. It was estimated that these shock tubes would not have a significant "jet effect" of expanding gases following the shock front because the combustion reaction is initiated at ambient pressure, and the molar volume of the products is less than that of the reactants. In this study, the transfer of momentum from a shock wave and expanding gases generated by oxyacetylene laboratory scale shock tubes to a solid object was quantified using high speed video (20,000 frames per second). A golf ball (diameter 42.7 mm, mass 0.0454 kg) was placed at the opening of a 27 mm diameter shock tube. The golf ball reached a peak acceleration of 478 g and a peak momentum of 1.2 kg m/s about 1 ms later. Similarly, a hollow aluminum sphere (diameter 101.6 mm, mass 0.240 kg) was placed at the opening of a 79 mm diameter shock tube. The sphere reached a peak acceleration of 1374 g and a peak momentum of 4.5 kg m/s about 2 ms later. In each case, most of the momentum transfer was due to the shock wave itself. The results support previous estimates that the oxy-acetylene shock tube design does not produce a significant "jet effect" of expanding gases or add significant loading to a test object.

15. SUBJECT TERMS

shock tube, oxy-acetylene, jet effect, jet wind

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Quantifying Momentum Transfer Due to Blast Waves from Oxy-Acetylene Driven Shock Tubes

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Abstract

Shock tubes have been widely used since the 1950s to study physical phenomena such as shock waves, combustion chemistry, and the response of materiel to blast loading. Recently, laboratory-scale shock tubes driven by oxy-acetylene were described. It was estimated that these shock tubes would not have a significant “jet effect” of expanding gases following the shock front because the combustion reaction is initiated at ambient pressure, and the molar volume of the products is less than that of the reactants. In this study, the transfer of momentum from a shock wave and expanding gases generated by oxy-acetylene laboratory scale shock tubes to a solid object was quantified using high speed video (20,000 frames per second). A golf ball (diameter 42.7 mm, mass 0.0454 kg) was placed at the opening of a 27 mm diameter shock tube. The golf ball reached a peak acceleration of 478 g and a peak momentum of 1.2 kg m/s about 1 ms later. Similarly, a hollow aluminum sphere (diameter 101.6 mm, mass 0.240 kg) was placed at the opening of a 79 mm diameter shock tube. The sphere reached a peak acceleration of 1374 g and a peak momentum of 4.5 kg m/s about 2 ms later. In each case, most of the momentum transfer was due to the shock wave itself. The results support previous estimates that the oxy-acetylene shock tube design does not produce a significant “jet effect” of expanding gases or add significant loading to a test object.

Keywords: shock tube, oxy-acetylene, jet effect, jet wind

1 Introduction

Shock tubes have been widely used since the 1950s to study physical phenomena such as shock waves, combustion chemistry, and the response of materiel to blast loading [1]. In recent years, laboratory-scale shock tubes have been developed to study the effects of blast loading on biological tissues, animal models, scale models and armor prototypes [2-8]. This effort has been spurred by summary statistics and studies documenting the large human, military and financial costs of blast injuries in recent conflicts [9-12].

Current shock tube designs include compressed gas driven [e.g. 8] and blast driven [e.g. 2] designs of varying dimensions. Each type has certain strengths and limitations. Blast-driven shock tubes produce realistic pressure-time profiles, but their operation requires facilities, liability, and personnel overhead for storing and using high explosive materials. In addition, equipment and personnel need to be isolated from the large mechanical and electromagnetic waves caused by detonation. Compression-driven shock tubes are more amenable to laboratory use but produce pressure waves with durations longer than typically encountered from real threats, do not usually reproduce the Friedlander waveform of free-field blast waves, and have significant shot-to-shot variations in peak pressure. Moreover, the jet of expanding gases following the shock wave applies additional force and transfers additional momentum to a test object. Chandra et al. [13] recently used a numerical model to study this jet effect for a compressed gas-driven shock tube and acknowledged the need for experimental measurements. They caution that samples outside the opening of the compressed gas-driven shock tube actually experience greater loading from the jet wind than from the initial shock front. This secondary loading may be especially undesirable for studies of the primary effects of blast waves on biological specimens, because it may introduce additional changes or responses that cannot be distinguished from the primary blast effects upon later assessment.

Recently, a modular design for laboratory-scale shock tubes driven by oxy-acetylene was described [14]. It was estimated that these shock tubes would not have a significant “jet effect” of expanding gases following the shock front because the combustion reaction is initiated at ambient pressure, and the molar volume of the products is less than the molar volume of the reactants. In this study, the transfer of momentum from a shock wave and expanding gases generated by oxy-acetylene laboratory scale shock tubes to a round object was quantified using high speed video (20,000 frames per second).

In addition to characterizing the shock tube design, quantifying the transfer of momentum from blast waves to an object may be a useful technique in the development of protective materiel. Experimental results could also provide data for validation of theoretical models used to predict outcomes of interaction of objects with blast waves.

2 Method

Driven and driver sections of the shock tube consist of steel pipe coupled by a steel flange [14]. The driver section is sealed with a steel cap, which has a small hole for ignition access. A piezoelectric, high-speed pressure sensor (PCB 102B18) is mounted near the end of the driven section to measure pressure parallel to the direction of travel of the shock wave. The driver section is filled with a stoichiometric mixture of oxy-acetylene at ambient pressure, which is separated from the driven section of the shock tube by a thin layer of polyethylene film prior to ignition. The fuel is ignited by an electric match, which is connected by wire leads to a remote voltage source. The pressure wave travels down the driven section of the shock tube and a shock front develops. At the opening of the shock tube, the pressure-time curve shows a steep shock front followed by near exponential decay with a duration of about 1 ms for a 27 mm diameter configuration and about 2 ms for the 79 mm diameter configuration (Figure 1).

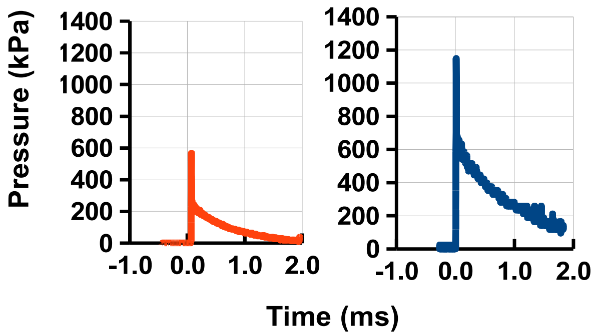

Fig. 1 *Pressure at the opening of each shock tube configuration used in the present study, measured using a high speed piezoelectric sensor facing the direction of propagation of the blast wave (reflected pressure). Left: 27 mm diameter shock tube with 21 mm diameter driving section. Right: 79 mm diameter shock tube with 79 mm diameter driving section.*

In the first set of experiments, a golf ball (diameter 42.7 mm, mass 0.0454 kg) was placed at the opening of a 27 mm diameter shock tube. The golf ball rested on a tee placed so that part of the golf ball just fit onto the opening of the shock tube. In the second set of experiments, a hollow aluminum sphere (outer diameter 101.6 mm, mass 0.240 kg) was placed at the opening of a 79 mm diameter shock tube. The hollow aluminum sphere rested on a plastic cap (approximately 27 mm outer diameter, 22 mm inner diameter, 13 mm deep) placed so that part of the aluminum sphere just fit onto the opening of the shock tube. Five trials were conducted for each experimental setup.

Using an IDT Motion Pro X4 high speed camera (Integrated Design Tools, Pasadena, CA), the position of the golf ball or aluminum sphere was recorded on video at 20,000 frames per second. A frame-by-frame analysis of each video was performed using Motion Studio software (Integrated Design Tools, Pasedena, CA). Position data were determined at 50 microsecond intervals. Time equal to zero was standardized to the beginning of the combustion reaction, which was identified by a flash in the video originating at the driver end of the shock tube. Because light travels much faster than the shock wave, there is a time delay before the object begins to move.

Position data were entered into a spreadsheet program. Velocity of the golf ball or aluminum sphere was computed for each frame using the slope formula. To reduce the effects of random noise and digitization error, an average velocity was computed using the velocity data from frames 0.5 ms before the frame of interest through 0.5 ms after each frame. The momentum of each object was computed as its velocity times its mass for each frrame. The acceleration of the golf ball or aluminum sphere was computed by finding the change in velocity of the object as a function of time using the slope formula. To smooth the data, a moving average acceleration was computed using the acceleration data 0.5 ms before through 0.5 ms after each frame.

3 Results

The golf ball reached its peak acceleration of 478 g (standard error of the mean 30 g) around 1 millisecond after time zero (Figure 2). After 2 ms, the acceleration of the golf ball oscillated between approximately 100 g and -100 g. There was no obvious increase in acceleration due to secondary loading, i.e. from expanding gases.

Figure 3 shows that the momentum of the golf ball increased rapidly for about 2 ms and then leveled off at a mean of 1.28 kg m/s (standard error of the mean 0.01 kg m/s) after 4 ms. The momentum of the golf ball then oscillated between approximately 1.4 kg m/s and 1.2 kg m/s. There was no obvious increase in momentum that would indicate a significant amount of secondary loading.

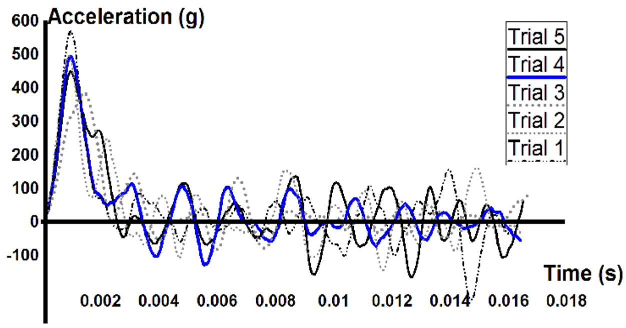

Fig. 2 *Acceleration of a 42.7 mm diameter golf ball due to blast wave exposure from a 27 mm diameter oxy-acetylene driven shock tube for five separate trials. Acceleration was computed as a moving average of the change in velocity with time.*

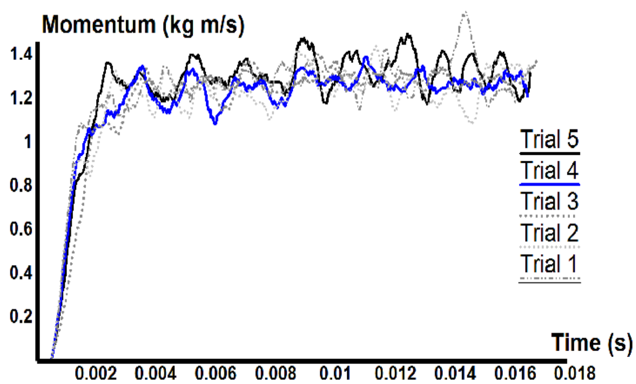

Fig. 3 *Momentum of a 42.7 mm diameter golf ball due to blast wave exposure from a 27 mm diameter oxy-acetylene driven shock tube for five separate trials. Momentum was computed as a moving average of the change in position with time (velocity) times the mass of the golf ball.*

The peak pressure applied to the aluminum sphere and the resulting kinetic energy of the aluminum sphere were about twice that for the golf ball. With regard to anticipated applications of these shock tubes, the peak pressure applied to the aluminum sphere with the 79 mm diameter shock tube was several times higher than that used to produce mild to moderate blast-induced TBI in small animal models. Thus, it represents a generous upper limit of relevant loading for that kind of experiment. Similar to the results for the golf ball and smaller diameter shock tube, the results for the aluminum sphere do not show an obvious secondary peak in acceleration or additional momentum due to secondary loading.

The aluminum sphere reached a peak acceleration of 1374 g (standard error of the mean 36 g) approximately 1 ms after time zero (Figure 4). After 2 ms, the acceleration of the aluminum ball oscillated between approximately -200 g and 400 g. Between 4 and 8 milliseconds, there was some variation (both positive and negative) in acceleration that differed in time from trial to trial and seemed less consistent than the acceleration of the golf ball by the smaller diameter shock tube.

Figure 5 shows that the momentum of the aluminum sphere reached a peak of approximately 4 kg m/s in 3 ms, and leveled off at 4.55 kg m/s (standard error of the mean 0.05 kg m/s) after 4 ms. After 4 ms, the momentum of the aluminum sphere oscillated between about 4.3 kg m/s and 4.8 kg m/s.

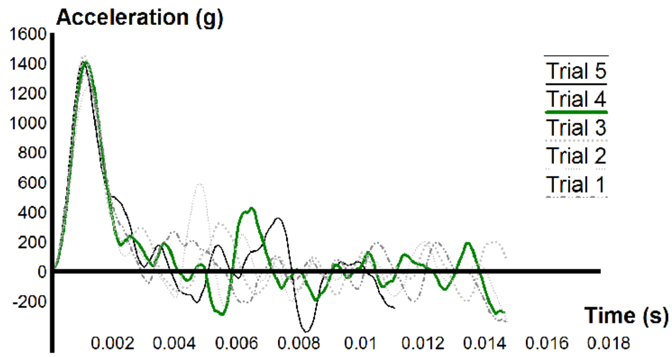

Fig. 4 *Acceleration of a 101.6 mm hollow aluminum sphere due to blast wave exposure from a 79 mm diameter oxy-acetylene driven shock tube for five separate trials. Acceleration was computed as a moving average of the change in velocity with time.*

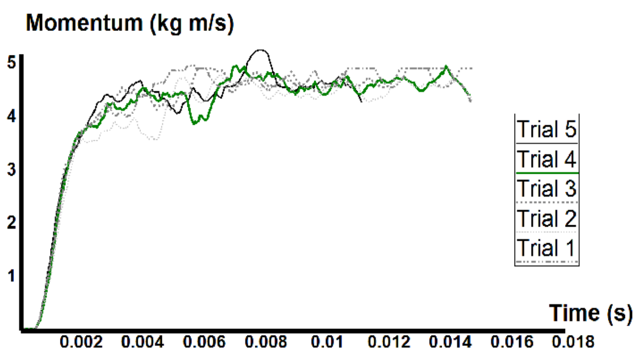

Fig. 5 *Momentum of a 101.6 mm diameter hollow aluminum sphere due to blast wave exposure from a 79 mm diameter oxy-acetylene driven shock tube for five separate trials. Momentum was computed as a moving average of the change in position with time (velocity) times the mass of the sphere.*

4 Discussion

Previously, a simple analysis of the chemistry of oxy-acetylene driven shock tubes suggested that this design would not have a significant jet effect, especially compared to compressed-gas driven shock tubes [14]. In the present study, the momentum transfer to round objects from the blast wave and any jet effect were quantified for 27 mm and 79 mm diameter driven sections. In each case, most of the momentum transfer was due to the shock wave itself. The results support previous estimates that the oxy-acetylene shock tube design does not produce a significant jet effect of expanding gases or add significant loading to a test object.

The modular, oxy-acetylene driven shock tube design offers several additional advantages over blast-driven or compressed gas-driven shock tube designs: a high degree of repeatability, true blast characteristics of the pressure-time curves, and amenability to laboratory use without the overhead and requirements of using high explosive materials. Dimensions can be selected for specific peak pressures, area of exposure, and, to some extent, pulse duration.

Several numerical models have been developed to assess the interaction between blast waves and objects, but published comparisons between model predictions and experimental results are lacking. The present study also provides a laboratory scale, experimental framework for quantifying the transfer of momentum from a blast wave to an object. This experiment employed round objects, and simple geometries such as these can be used to validate or refine numerical models of blast wave interactions with objects. Similar techniques can be used to study the effects of blast waves on objects with non-uniform cross sections or mass distribution.

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