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Facility for Shock and Detonation Wave Interaction with a Reactive Turbulent Field

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A novel shock tube facility is described for studying the interaction of a reactive, turbulent field with a shock or a detonation wave. This shock tube is different from existing approaches due to the need to propagate a shock wave into a quiescent, reactive, turbulent medium. The turbulence is generated by pulling a turbulence-generating grid through the test section. The turbulence is allowed to decay prior to propagating either a shock or a detonation wave. The shock tube can be configured in different ways depending on whether a shock or a detonation wave is to be propagated through the medium. A preliminary test of a weak shock propagation is reported. Recommendations for future work are included.

I. Introduction

WAVE interactions with a turbulent field is a topic of fundamental interest with studies involving various classes of turbulent fields.[1] In practice, these interactions can occur in mixing and boundary layers or in combustion processes, resulting in a variety of phenomena. These interactions continue to be pacing items in the development of fluid mechanics.

Shock/turbulence interaction is a mutual one that can result in substantial distortion of the shock wave and an amplification of the turbulence. Specifically, the interaction with homogeneous, isotropic turbulence (HIT) is highly idealized and removes other effects contributing to turbulence amplification, such as flow separation, longitudinal velocity gradients and the effects of surfaces. In this regard, the development of direct numerical and large eddy simulations has led to substantial inroads in its understanding.[2–12] Shock interaction with HIT has also been studied theoretically.[13–15]

Other than theoretical and computational studies, experimental studies have a long history.[16–26] The propagating shock is usually generated by a shock tube. Moreover, a standard experimental approach for simulating HIT is to use one or more turbulence generating grids or baffles, the turbulence is then also termed "grid-generated turbulence." Diagnostics for studying the flow include those based on density fluctuations,[18,19,27] hot-wire anemometry,[20,21,28] laser Doppler velocimetry[24] and pressure.[29]

The mutual interaction between the shock and the turbulence results in an increase in turbulence, details of which can be found in the above-cited studies. This turbulence amplification has been proposed for increasing mixing as in scramjet combustors[30] and as a mechanism for deflagration-to-detonation transition.[31] The interaction in these situations is complicated by the reactivity of the mixture. DNS[32] and linear analysis[33] have been applied to increase the understanding of the interaction between shock and detonation waves with a turbulent, reactive mixture. Experiments are needed to validate the computations and analysis,

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as well as to explore the phenomenon. Toward this end, a major modification of an existing shock tube[34–36] is described in this paper.

II. Facility Sizing and Construction

Unlike previous arrangements in which a shock propagates past a fixed array of grids, the present approach first creates a homogeneous, isotropic turbulent field by pulling an array of grids through the test section. The grid turbulence is then allowed to decay. Subsequently, a shock wave is propagated through this turbulent field. The facility is designed so that both inert and reactive gases can be used for generating shock and detonation waves.

The modular design of the facility makes it extremely versatile. Various arrangements can be implemented depending on test requirements. A possible arrangement is shown schematically in Fig. 1. The figure shows an existing 7.62 cm (6 in.) driver tube, capped at one end which also houses an igniter. In this arrangement, the driver tube is filled with a reactive mixture. A detonation wave develops upon igniting the mixture. The driver tube is 1.83 m (6 ft) long which exceeds the deflagration-to-detonation transition length for the test conditions under consideration of reactive gases of interest. Alternate arrangements are to attach extra driver tube sections and a diaphragm section to produce a two-stage shock or piston driver. These arrangements can be used to propagate shocks and detonation waves of high strength into the test section.

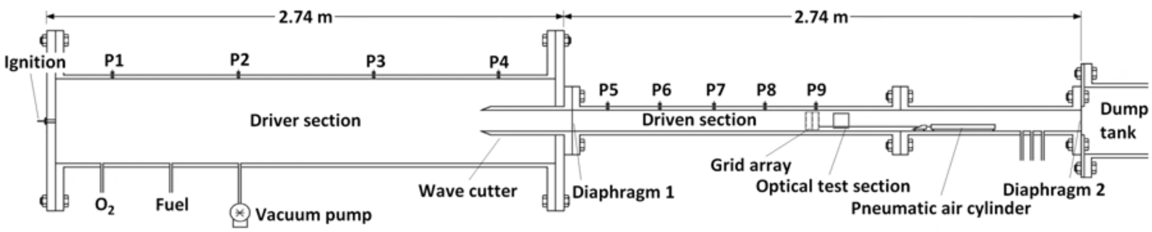

Figure 1. Schematic of test section.

Regardless of the driving technique, the flow entering the driven section (which is a tube with a nominal 7.62 mm, 3 in., square internal section and 0.635 cm, 0.25 in., thick) is intercepted by a “wave cutter.” This arrangement ensures that a well-developed, uniform shock or detonation wave enters the test section. The square cross section allows for good optical access without distortion. Provision is made for a diaphragm between the driver and driven sections. The test section is located within the driven section, the midplane of which is 4.877 m (16 ft) from the igniter location. The driven section is connected to a dump tank. The driven section is separated from the dump tank by another diaphragm if needed under high-enthalpy conditions. This design allows for the driven section to be made with a thin tube. First, the gas does not stagnate in the driven section. Secondly, the large dump tank adds to the overall volume of the shock/detonation tube facility to prevent high final pressures. Finally, a valve is installed in the dump tank which is cracked when the pressure in the tank exceeds about one atmosphere.

Table 1. Axial distances of facility components.

Component	Location (m)
Ignition	0
Wave cutter	2.50
Diaphragm 1	2.74
Diaphragm 2	5.48
Test Section Midplane	4.877
Upstream Face of Pneumatic Cylinder	5.18
P1	0.588
P2	1.143
P3	1.727
P4	2.311
P5	3.159
P6	3.464
P7	3.768
P8	4.074
P9	4.378

Lines for evacuating the driver and driven tubes and for filling them with various gases are available. The evacuation and fill processes are monitored by pressure transducers connected to remote displays in the control room. Should there be an aborted run, the facility can also be safely vented from the control room. Two vacuum systems are available to pump down the various sections of the facility prior to filling with appropriate gases. These gases are supplied by bottles although dried air can also be obtained from the laboratory's compressor system. Some of the more pertinent locations are given in Table 1.

Note that unlike the above-cited references where the grid-generated HIT is produced by the flow from a shock propagating past a fixed grid, the present arrangement is to generate HIT by pulling a system of grids through the test section. This approach allows the turbulence to have time to develop.

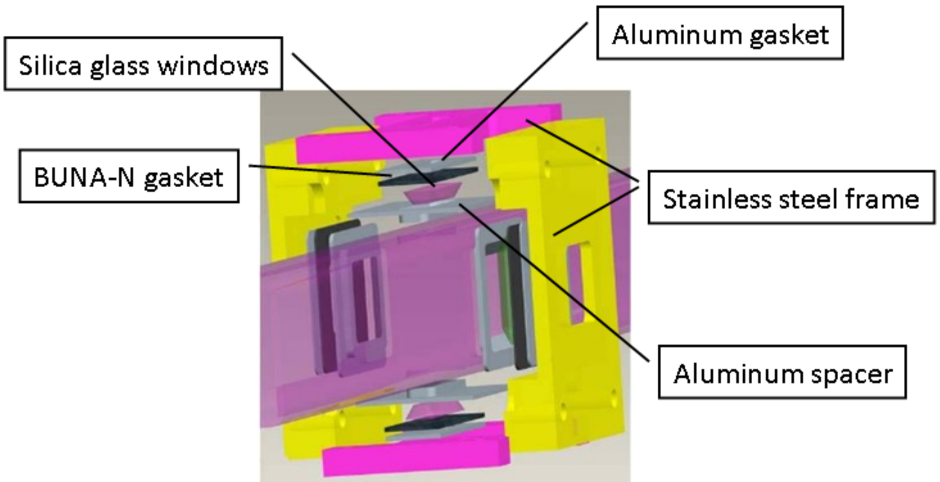

Figure 2. Exploded view of test section.

A. Test Section Design

The optical test section consists of several components. Windows of silica glass, 0.953 cm (0.375 in.) thick, are used on all the four sides due to the anticipated use of optical diagnostics. The dimensions for the side pieces are 7.62 cm (3 in.) square. However, mounting hardware and a 45 deg chamfer on the glass pieces reduced the actual viewing area to 5.72 cm (2.25 in.) square. The top and bottom pieces of glass are 7.62 cm long by 2.54 cm wide (3×1 in.). Similarly, mounting hardware and chamfering reduced the actual open area to 6.52 cm long by 1.44 cm wide (2.567×0.567 in.). These top and bottom ports are expected to be used for introducing a laser light sheet for planar laser-induced fluorescence.

Figure 2 is an exploded schematic of the various pieces needed to mount the windows. The windows are attached to the test section by aluminum and Buna-N gaskets. The joints are sealed and the entire assembly is clamped together by a stainless steel frame with long screws (not shown).

B. Turbulence Generator

The turbulence generator is shown in Fig. 3. Since there is a high likelihood that the turbulence generator will be damaged by the shock or detonation wave, a fast, inexpensive and simple method is needed for its fabrication. The turbulence generator consists of three grids made with stainless steel meshes of 6, 6 and 8 wires per inch with solidities of 0.373, 0.373 and 0.36 respectively.[37] Each mesh is wrapped by styrofoam and these mesh assembles are then attached to four steel rods. The entire assembly is then attached to a flat piece of balsa wood which is then attached to a pneumatic cylinder. The cylinder with a stroke of 20.32

cm (8 in.) is used to pull the entire turbulence generator through the test section. To facilitate movement, the contact surfaces are sprayed with silicone lubricant.

C. Operating Principle

Figure 4 displays wave diagrams of how the facility will operate in the case of an interaction between a detonation wave and HIT. Figure 4a shows a decaying HIT after the turbulence generating grid has been pulled through the test section, filled with a reactive mixture. Numerical simulations[32] show that HIT decays slowly compared to the propagation. After a variable time delay τ_D, the reactive mixture in the driver tube is ignited to propagate a deflagration-to-detonation transition. The driver tube is sufficiently long to ensure that a fully-developed detonation wave is formed prior to impinging the diaphragm. The diaphragm is ruptured by the wave which continues to propagate into the test section. The test section gas, which is by now also turbulent, is then ignited. Figure 4b shows a wave diagram of this process.

Figure 3. Photograph of turbulence generator.

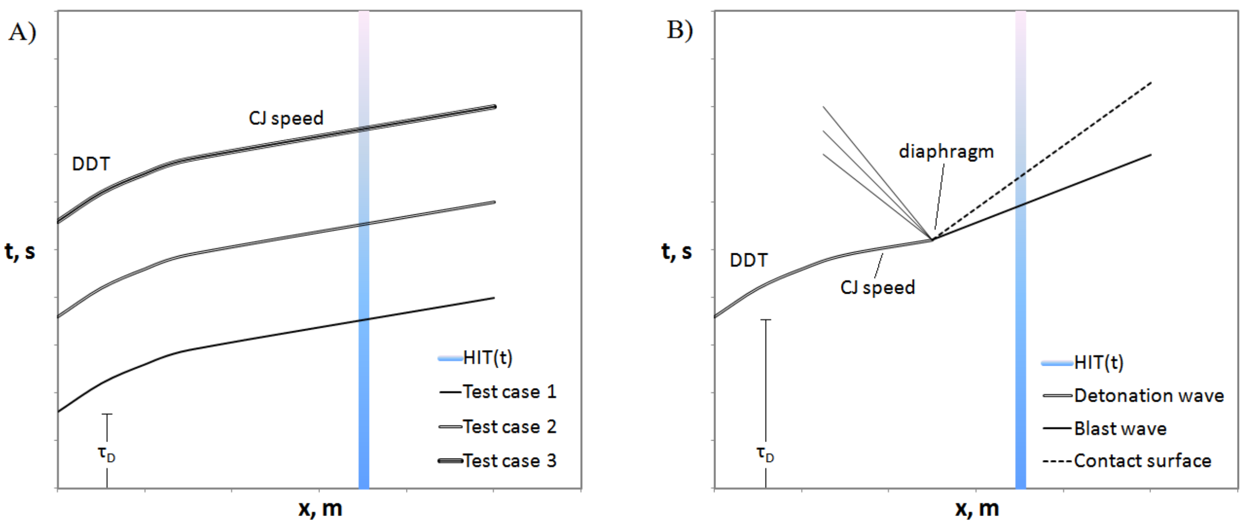

Figure 4. Schematics of time-distance plots for the facility. In A) the grid is moved back to produce the decaying HIT where the ignition delay time τ_D in the driver tube is adjusted so the wave interacts with it at different decay points. In B) a diaphragm is used either at the inlet or between driver and driven sections to produce interaction with a shock or blast wave.

III. Initial Experimental Results and Analysis

Due to problems of adapting new sections to an older facility, only a preliminary result is reported. In this test, the driven section is ambient air at $p_1 = 101$ kPa (14.7 psia) while the driver was charged with air to $p_4 = 414$ (60 psia). The pressures histories from the transducers mounted in the driven section are shown in Fig. 5. The post-shock pressure p_2 compares well with theoretical calculations.[38] Figure 6 is a wave diagram for this experiment. It can be noted that the experimental shock and trailing expansion trajectories are well predicted. The figure shows that the test time is ~10 ms. The test time is expected to decrease with increasing p_4/p_1 as the contact surface leans further to the right in the wave diagram.

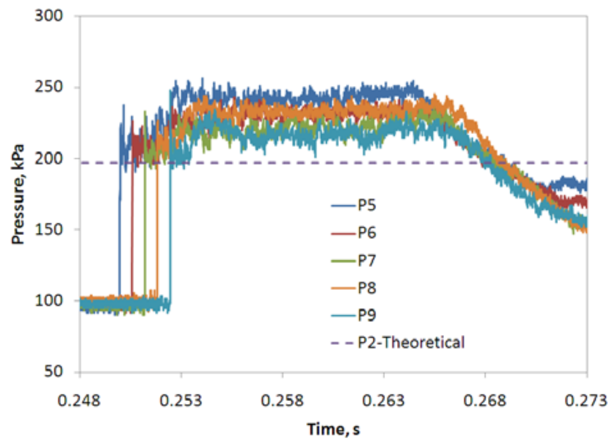

Figure 5. A weak test with $p_1 = 1$ atm and $p_4/p_1 = 4.1$.

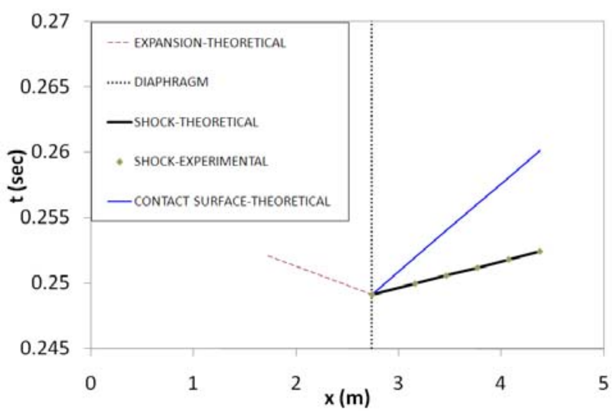

Figure 6. Wave diagram of data shown in Fig. 5.

IV. Conclusions and Future Work

An impulse facility capable of driving shock and detonation waves into a turbulent field was developed. The facility can be used for high-enthalpy testing without requiring a strong structure due to the use of a large dump tank to reduce the final pressure. A relief valve in the dump tank also ensured low post-test pressures. A preliminary test at low pressure without turbulence generation was conducted and it showed that the the facility could produce a test time of about 5–10 ms.

Future work includes the following:

- Testing the turbulence generating mechanism.
- Performing exploratory studies of shock/turbulence interactions including the use of optical diagnostics such as schlieren and laser deflectometry.

- Performing exploratory studies of detonation/turbulence interactions.
- Adapting the facility to study phenomena of interest in the development of pulsed and continuous detonation engines.

Acknowledgments

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