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Experiments in a Combustion-Driven Shock Tube with an Area Change

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1 Introduction

Shock tubes are versatile and useful tools for studying high temperature gas dynamics and the production of hypervelocity flows. High shock speeds are desirable for creating higher enthalpy, pressure, and temperature in the test gas which makes the study of thermo-chemical effects on fluid dynamics possible. Independent of construction and operational cost, free-piston drivers, such as the one used in the T5 facility at Caltech, give the best performance [3]. The high operational cost and long turnaround time of such a facility make a more economical option desirable for smaller-scale testing.

Combustion drivers have been shown to be capable of producing very high shock speeds at low cost [3]. They have been in use in facilities of various sizes since the mid-1950s, [1] and their performance has been studied fairly extensively in the literature. A small combustion-driven shock tube (CDST) has been constructed and tested at Caltech to be used as an economical alternative to facilities with higher operating cost in small-scale experiments. A model was developed using Cantera and the Shock and Detonation Toolbox (SDT) to predict the performance of the tube.

2 Experimental Setup & Results

The CDST consists of two sections, a driver section and a driven section. The driver section was originally built by J. Bélanger for his Ph.D. thesis [4]. It is 1.5 m long with an inner diameter of 50.8 mm. It is constructed of stainless steel to prevent corrosion from contact with high temperature combustion products. Combustion is initiated by simultaneously firing 12 automotive-type spark plugs arranged along

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the length of the tube alternating at 90 degrees from one another at intervals of 10 cm.

The driven section is 1.22 m long with an inner diameter of 25.4 mm. A converging nozzle separates the two sections. This improves the performance of the tube by accelerating the driver gas to sonic conditions before it is further accelerated by a nonsteady expansion [2]. The diaphragm separating the two sections is located at the downstream side of the nozzle. Instead of being ruptured by a pressure difference as in most conventional shock tubes, the diaphragm is ruptured by the electrical discharge of a 5 mf capacitor at 250 V through an electrode pressed against the center of the diaphragm. The center of the diaphragm is melted by the discharge and the pressure difference across the diaphragm opens it fully. Diaphragms are scored to promote more consistent rupture. The diaphragm rupture process is initiated when the peak pressure is reached in the driver section after combustion. Stainless steel with a thickness of 25 µm is used for the diaphragms instead of aluminum because stainless steel's poor electrical conductivity means that a higher temperature is reached upon electrical discharge and a larger area of the diaphragm is melted. Stainless steel is also more brittle than aluminum, which promotes crack propagation during rupture. The thin diaphragms do not form petals upon rupture; they fracture into small fragments which need to be removed between experiments. This system allows for precise control over the time of diaphragm rupture and allows the facility to operate over a wider range of pressure ratios.

The initial gaseous composition inside the driver section was held constant over all experiments while varying the pressure in the driven section to attain different pressure ratios. The driver section was initially pressurized to 140 kPa with a mixture of 79% helium, 14% hydrogen and 7% oxygen by volume. The pressure attained after combustion is approximately 835 kPa with a standard deviation of 27 kPa (3%) between experiments. The driven section was filled with air to pressures ranging from 200 Pa to 4000 Pa.

The burst pressure is measured by a PCB 113A24 piezoelectric transducer located just upstream of the diaphragm in the driver section. Five PCB 113A21 transducers are arranged along the length of the driven section to calculate the shock speed. Four transducers are installed on the length of the tube separated by 25.4 cm and the fifth is mounted in the endwall of the driven section. A typical output from the transducers is shown in figure 1. Transducers are labelled starting from the diaphragm and proceeding towards the endwall. The shock speed is determined from the time of arrival of the shock at transducers 2 and 3 which allows sufficient distance from the diaphragm for shock formation but is not so far that attenuation due to viscosity has a major effect [2]. Using the CDST, incident shock speeds between 2.4 and 4.2 km/s were produced.

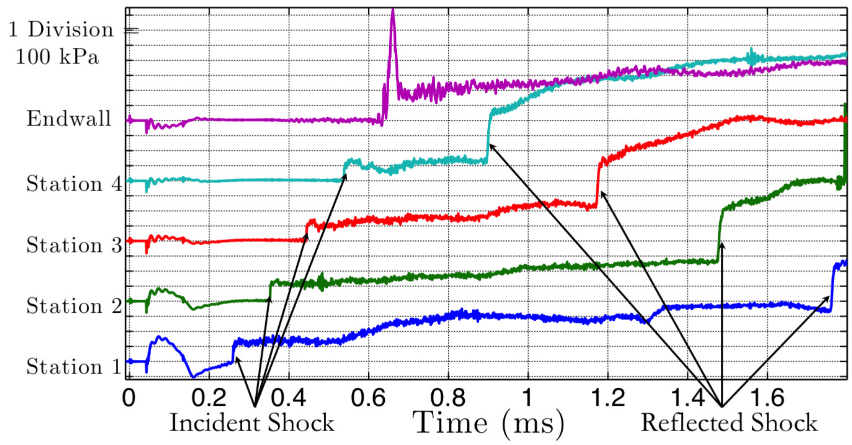

Fig. 1 Pressure transducer output. The oscillations in the signals before the arrival of the incident shock are a result of the electrical impulse of the diaphragm bursting mechanism. Also note the steady pressure rise in all signals because of the downstream nonsteady expansion (see next section)

3 Inviscid Shock Tube Theory

After combustion is complete, the CDST operates like any conventional shock tube and as a first approximation can be modeled under quasi-1D and inviscid assumptions. This model for shock tubes is fully described in the literature, and the reader is referred to chapter 4 of Glass [2] for further details. Conventional nomenclature will be used to describe the states inside the shock tube. Region 1 corresponds to the undisturbed gas in the driven section, region 2 to driven gas processed by the incident shock, region 4 to the undisturbed gas in the driver section (after combustion in the CDST), and region 3 to the driver gas processed by the nonsteady isentropic expansion.

The converging nozzle between the driver and driven sections in this specific shock tube requires state 3 to be divided into two separate states. In all experiments conducted the pressure and sound speed ratios were sufficient to produce supersonic flow in region 3. Thus the nozzle serves to accelerate the subsonic flow produced by the nonsteady expansion in the driver section to sonic conditions via steady expansion, after which it is accelerated by a second nonsteady expansion to supersonic conditions. This nonsteady expansion is detected by the pressure transducers in the driven section as a steady pressure rise in time at a fixed position. The gas processed by the first nonsteady expansion upstream of the nozzle will be called region 3a while the gas processed by both nonsteady expansions and the steady expansion in the nozzle will be referred to as region 3b. The shock speed can then be determined noting that the velocities and pressures in regions 2 and 3b must match across the contact discontinuity between driver and driven gases.

4 Numerical Model

The shock speed and the gas properties in all regions can be computed analytically for a perfect gas, but the perfect gas assumption is a poor predictor of shock tube performance parameters for incident shock Mach numbers greater than 5 [2]. This is the case for all experiments conducted in the CDST, so a numerical model based on iterative solutions of pressure-velocity relations incorporating thermo-chemical effects must be used to obtain an accurate model for the tube. Such a model was developed using Cantera and the SDT using appropriate thermodynamic data from the NASA Glenn database.

The initial conditions are set in both the driver and driven sections. The gas in the driver section is modeled using a mechanism containing helium, hydrogen, and oxygen species, valid for temperatures up to 6000 K. The gas is set to the initial composition and pressure in the experiments and equilibrated at constant volume and internal energy to simulate combustion. The adiabatic assumption does not accurately predict the final pressure in the driver section because of losses during combustion, so the final pressure in this model is set to the measured pressure at diaphragm burst and the mixture is again equilibrated at constant volume. The mechanism used for the driven gas contains oxygen and nitrogen species, valid for temperatures up to 20,000 K. The gases are assumed to be at equilibrium throughout the simulation because the vibrational-translational relaxation times of the molecules involved are much shorter than the other relevant timescales in the problem. The validity of this assumption can be further examined by comparison of the predictions of the model to the experimental data.

The various states described in section 3 as well as the incident shock speed are found numerically using Cantera and appropriate inviscid equations and jump conditions. Gases processed by normal shocks are assumed to reach equilibrium instantaneously.

5 Analysis of Performance

Figure 2 shows the results of the experimental shock speed measurements and the predictions made by the numerical model. Note that the experimental data more closely matches the equilibrium predictions with an area change at the diaphragm station. Equilibrium computation without considering the area change or a computation assuming frozen gas composition result in poor agreement, aiding in the verification of the chosen model.

Quantitatively, the average absolute disagreement between the model and experimental measurements is 0.4 in Mach number with a standard deviation of 0.3. This translates to an average relative disagreement of 4.2%. The total experimental uncertainty is ≈ 0.35 in Mach number, which accounts for the disagreement. It should be noted that the disagreement is systematic. That is, the experimental shock speed is consistently lower than predicted. Because the length-to-diameter ratio of

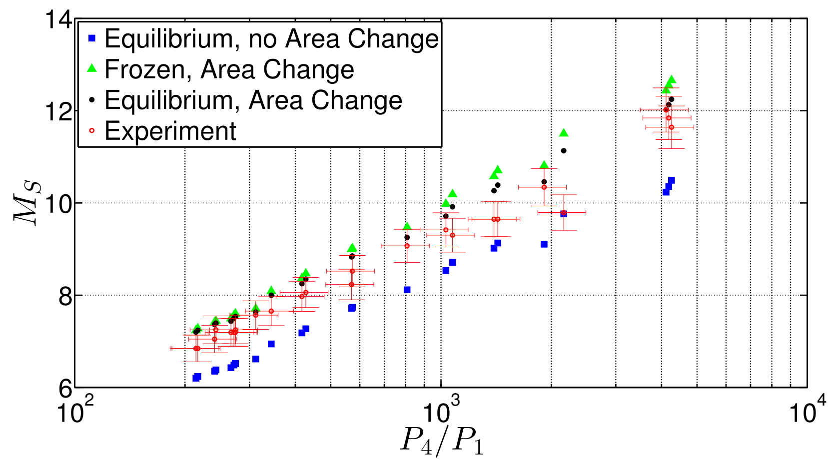

Fig. 2 Comparison of numerical models to experimental data. The equilibrium computation with area change included fits the data best with a consideration for attenuation.

the shock tube is ≈ 30 at the measurement location, shock attenuation is likely to be responsible for much of the disagreement. Shock attenuation due to boundary layers forming behind the incident shock in a shock tube is a well-known phenomenon, but it is quite difficult to model accurately in such a shock tube with very high shock speeds and reacting gases. The diaphragm-opening process is also not modeled numerically, but the combined effects of these two non-ideal phenomena do not significantly reduce the performance of the model.

Based on this encouraging state of affairs, we can use the numerical model to provide estimates of other properties of interest that were not directly measured in the shock tube, such as temperature, species concentration, and enthalpy. These properties are shown in figure 3 and table 1.

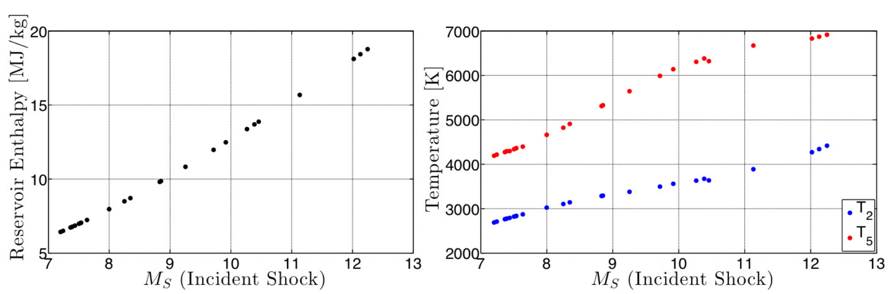

Fig. 3 Plots of post-shock temperatures and reservoir enthalpy calculated from the numerical model

Table 1 Calculated mole fractions of various species behind incident and reflected shocks in air with incident shock Mach number 10.3

Neutral Species	X_{incident}	$X_{\text{reflected}}$	Ions	X_{incident}	$X_{\text{reflected}}$
N_2	6.79×10^{-1}	5.53×10^{-1}	N_2^+	3.66×10^{-13}	9.76×10^{-7}
O_2	5.64×10^{-2}	9.66×10^{-4}	O_2^+	8.79×10^{-10}	2.99×10^{-7}
NO	4.34×10^{-2}	1.77×10^{-2}	NO^+	1.07×10^{-6}	2.03×10^{-4}
N	4.61×10^{-4}	1.15×10^{-1}	N^+	6.57×10^{-15}	1.01×10^{-6}
O	2.21×10^{-1}	3.13×10^{-1}	O^+	1.23×10^{-11}	3.06×10^{-6}
			e^-	1.07×10^{-6}	2.09×10^{-4}

6 Conclusion

This data demonstrates the shock tube's potential for use as a part of a small hypersonic test facility and to test fundamental gas physics. Bakos uses a figure of merit of a total enthalpy of 15.2 MJ/kg for the driver section of an expansion tunnel to produce physically relevant flows [3]. Reservoir enthalpies in excess of 18 MJ/kg can be regularly produced in this shock tube. The Cantera simulation of the shock tube also reveals that the gas behind both incident and reflected shocks is highly dissociated, even at the lower shock Mach numbers in the operational range of the facility. This affords an opportunity for inexpensive investigations of gas dynamics.

The maximum initial fill pressure in the driver section in this series of experiments was limited to 140 kPa due to safety concerns, so low pressures were used in the driven section to achieve high pressure ratios. The driver section is designed to withstand fill pressures in excess of 1 MPa, which translates to pressures after combustion on the order of 20 MPa [4]. This would allow for higher driven section pressures while maintaining the high shock speed performance described here. The other components of the facility are currently being modified to safely accommodate such higher fill pressures.

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