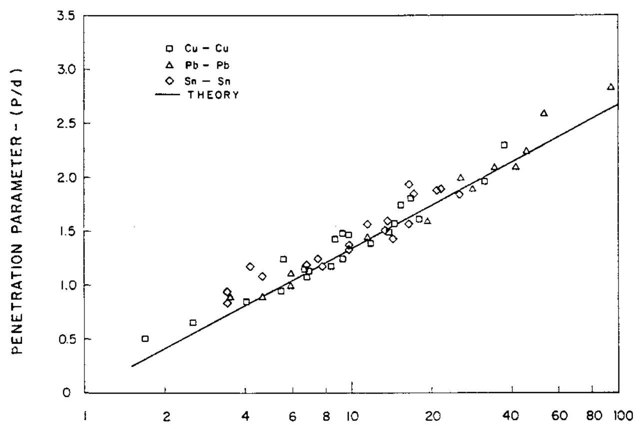

Fig. 5 Impact velocity parameter $(1 + A_2{}^2V^2)$.

state at standard conditions. For a given impact velocity and the corresponding sonic velocity of the material at standard conditions, the penetration parameter can be readily determined without the aid of any specific experimental constant.

Figure 5 summarizes all the three sets of data on hypervelocity impact on projectile and target of the same materials. These data include copper into copper, lead into lead, and tin into tin. On the graph, the ordinate is p/d, and the abscissa is the value of the logarithm of $[1 + A_2{}^2V^2]$ where

$$A_2{}^2\left(\frac{E}{\rho}\right) = \frac{(E/\rho) \times 10^{-4}}{[1.0 + 1.398 \times 10^{-3}\,(E/\rho)^{1/2}]^2} \tag{11}$$

The theoretical expression given in Eq. (10) is represented by a single straight line on the graph. The agreement between this single theoretical curve and available experimental data is surprisingly good.

Conclusions

A more realistic equation of state is introduced to replace the equation of state for a perfect gas in the basic equations for a viscous compressible fluid. The result of the present investigation shows that the use of the equation of state for a perfect gas in the hypervelocity impact analysis is justified.

Future research on the refinements of the present theory is being planned, including the unsteady case, the calculation of the crater volume, and the case of the projectile and target being of different materials.

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Effects of Interface Combustion and Mixing on Shock-Tunnel Conditions

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Introduction

FLOW conditions in the test section of a shock tunnel are usually determined from measured test-section pitot pressures and reservoir pressures and from a reservoir enthalpy calculated from the measured shock speed. In fact, one of the advantages of the shock tunnel is that the reservoir conditions (at least immediately after shock reflection) can be calculated with confidence from the measured shock speed. The flow from the reservoir to the test section is usually assumed to be one-dimensional, isentropic, and in chemical equilibrium. Test-section conditions so computed may be in error because one or more of these assumptions are violated or because of reservoir nonuniformities (e.g., test gas dilution with driver gases) or reservoir losses (e.g., radiation), both of which become more important as reservoir enthalpy levels are increased. In order to assess the accuracy and suitability of the usual method of determining shock-tunnel flow conditions, a program has been undertaken at the Douglas Aerophysics Laboratory (DAL) to measure directly the test-section airflow velocity in a shock tunnel over a wide range of reservoir enthalpies. With this additional measurement, all test-section properties can be determined without resort to any of the previous assumptions.

Experimental Equipment and Interpretation

The experiments were performed in the DAL Hypervelocity Impulse Tunnel (HIT).[1] The driver tube has a 6-in. bore and is 34 ft long, and the driven tube has a 5-in. bore and is 30.67 ft long. The nozzle axis is rotated 90° from the shock-tube axis, they intersect 1 in. upstream of the driven tube end wall. For the series of experiments reported herein, the nozzle throat diameter was 0.840 in. and the time of uniform reservoir pressure was at least 13 msec.

The test-section airflow velocity was measured directly using a technique similar to that described in Refs. 2 and 3. A disturbance in the form of a cylindrical blast wave was generated by the discharge of electrical energy between two electrodes spaced 3 in. apart in the test section. This disturbance was convected downstream with the flow velocity, and its position was recorded a known time later on a schlieren photograph. The accuracy of this velocity measuring technique is primarily limited by the accuracy with which the blast wave displacement can be measured, which was about ±2%.

On some runs, the stagnation-point heat-transfer rate to a 1.25-in.-diam cylinder mounted transverse to the airflow was measured. Thin-film resistance-thermometer outputs were converted into heat-transfer rates by analog circuits.[4]

Test-section velocities also were calculated from the reservoir enthalpy. Conditions immediately after shock reflection (designated 5) were calculated from the measured shock speed extrapolated to the end of the driven tube. When reservoir conditions (designated R) were not the same as conditions after shock reflection (e.g., when tailored-interface conditions[5] were not achieved as is the case illustrated in Fig. 1), the process between 5 and R was assumed to be isentropic, and the reservoir enthalpy h_R was calculated from the measured reservoir pressure record using

$$h_R = h_5(p_R/p_5)^{(\gamma-1)/\gamma} \tag{1}$$

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Table 1 Comparison of measured and calculated test section velocities

Run no.	Driver gas	Driven gas	M_s	Measured velocity V_m, fps	Calculated velocity V_c, fps	V_m/V_c	Time,[a] msec
1	He	air	3.35	5,790	5715	1.012	8
2	He	air	4.87	8,850	8860	0.999	7
3	H_2	air	5.90	12,390	9500	1.306	4.5
4	H_2	air	5.98	12,770	9540	1.338	7
5	H_2	air	6.07	12,690	9670	1.313	10
6	H_2	N_2	5.77	10,020	9670	1.028	8
7	H_2	N_2	5.63	9,820	9440	1.040	11
8	H_2	air	6.00	9,670	9560	1.012	3
9	H_2 and N_2	air	4.70	7,415	7430	0.998	7
10	H_2 and N_2	air	4.76	8,470	7540	1.122	11

[a] Time after incident shock reflection when velocity data were recorded.

Discussion of Experimental Results

Measured and calculated test-section airflow velocities are compared in Table 1. The direct measurements V_m obtained with a cold helium driver (runs 1 and 2) agree very well with the calculations V_c. On run 1, the shock speed was slightly below the tailored-interface value, whereas on run 2, the shock speed was greater than the tailored-interface value. Thus, Eq. (1) appears to be suitable for calculating reservoir enthalpy levels for equilibrium-interface operation.[6]

When cold hydrogen was used to drive air, the measured test-section velocities were indeed surprising. The measured velocities on runs 3–5 are approximately 30% higher than the calculated velocities. This corresponds to an error of about 70% in the reservoir enthalpy as calculated by Eq. (1). When nitrogen was substituted for air as the test gas (runs 6 and 7), the agreement between the measured and calculated velocities was satisfactory. Thus, the anomalous behavior observed with a hydrogen driver appears to be associated with the combustion that takes place at the hydrogen-air interface.[7,8]

Combustion at the hydrogen-air interface is characterized by a reservoir pressure record similar to that shown in Fig. 1. Figure 2 shows a simplified model that explains the observed pressure phenomena. Initially, a constant pressure region of at least partially mixed hydrogen and air separates the hydrogen driver gas and the shocked air. The extent of this zone is affected by the speed of the diaphragm opening, etc. Combustion of the hydrogen and air mixture leaves region b with a higher sound speed a_b and a lower density ρ_b than are found in regions 2 and 3 (which should have the same ρ and a for tailored-interface operation).

The interaction of the reflected shock wave, which was presumably of the proper strength for tailoring in the absence of interface combustion, and region b produces an expansion wave (of strength p_6/p_5), which arrives at the end wall at time t_1 (Figs. 1 and 2). When the reflected shock reaches the end of region b and encounters the higher density of region 3, a shock wave is generated which reaches the end wall at time t_2. When the interactions of this shock wave and the original expansion wave die out, a uniform reservoir pressure p_R is achieved. It should be noted that the time t_1 (which can be easily measured from the reservoir pressure records) is a measure of the extent of the usable slug of test air, and $(t_2 - t_1)$ is a measure of the extent of the region of hot combustion products.

This model only explains the observed pressure phenomena. However, the increase in reservoir enthalpy cannot be explained by any wave processes because, during the wave interaction process, the pressure goes down $(p_R < p_5)$ but the temperature goes up $(h_R \approx 1.7\ h_5)$.

It is postulated that the reservoir enthalpy increase is produced by mixing of the hot combustion products of region b''

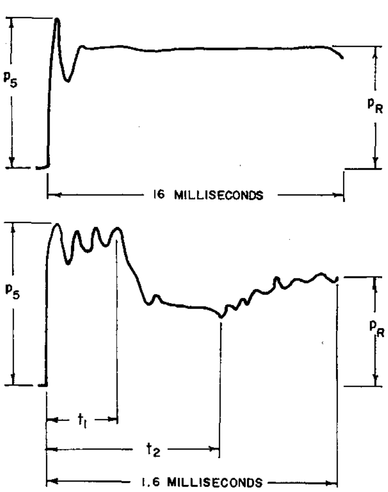

Fig. 1 Reservoir pressure record obtained with cold hydrogen driving air at a shock Mach number of 5.90. The transducer was located in the driven tube end wall. The lower record is the initial portion of the upper record expanded. It shows details of the pressure phenomena associated with combustion at the hydrogen-air interface.

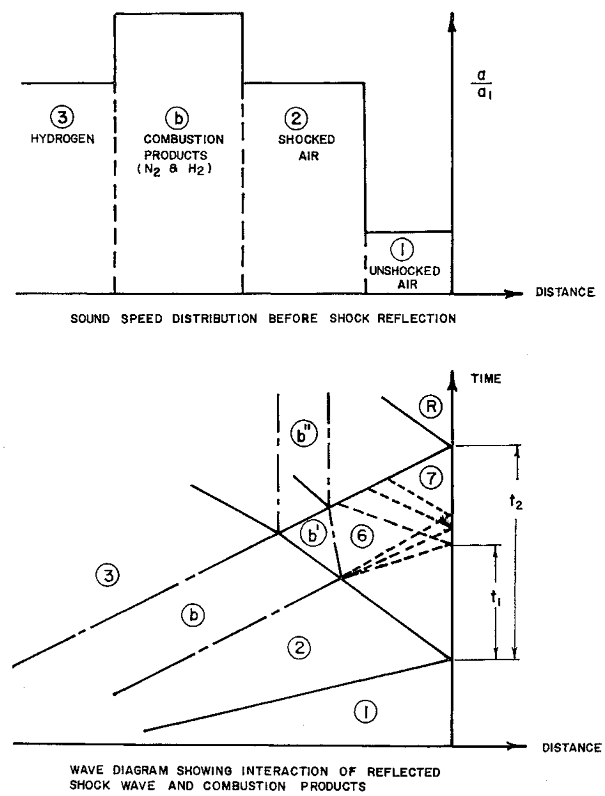

Fig. 2 Model explaining wave processes associated with combustion at the hydrogen-air interface.

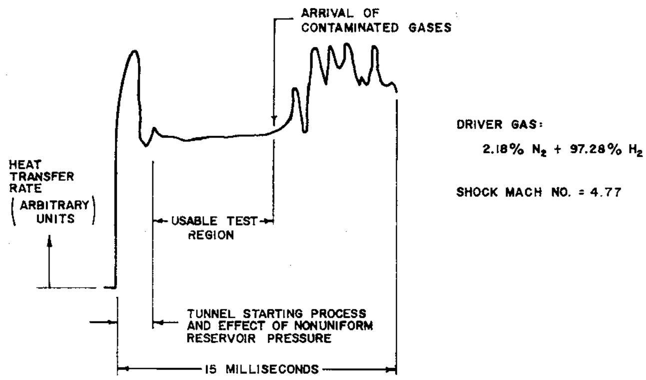

Fig. 3 Test section stagnation-point heat-transfer rate record showing arrival of test gas that has been contaminated and heated by combustion products.

with the cooler uncontaminated test air. Now the time required for these hotter mixed gases to reach the nozzle entrance will depend on the length of the slug of test gas. This is apparent when one compares the runs near $M_s = 6.0$ with the runs near $M_s = 4.7$. For the $M_s = 6.0$ runs, the hot combustion products have not affected the test section airflow velocity 3 msec after shock reflection (run 8), but they have affected the airflow velocity 4.5 msec after shock reflection (run 3). When a less energetic driver, which is produced by diluting hydrogen with nitrogen and which should tailor (in the absence of interface combustion) at about $M_s = 4.7$, is used, the hot combustion gases affect the test-section airflow sometime between 7 and 11 msec after shock reflection (runs 9 and 10). The arrival of the hot gases in the test section is illustrated nicely in Fig. 3. There it is seen that the heat-transfer rate in the test section remains nearly constant until about 10 msec after the arrival of the starting shock wave. After that, it goes up sharply, indicating the arrival of the test gas that has been contaminated and heated by the combustion products.

Of course, contamination of test air by driver gas also takes place when interface combustion is absent (e.g., with a helium driver).[9] However, under tailored-interface conditions without the interface combustion, the driver-gas contamination is more difficult to detect.

So far, technical difficulties have prevented direct velocity measurement when conditions for tailored-interface operation (again, in the absence of interface combustion) were achieved at a shock Mach number near 10 (obtainable in the HIT only by use of an isochoric combustion driver). However, for this case, the amount of hydrogen not consumed in our particular isochoric driver combustion process is about 8% of the total driver mixture, and the reservoir pressure records again show evidence of combustion at the interface. Because of the decreased length of the slug of useful test air at these higher shock Mach numbers, it is expected that the test air will be contaminated by the combustion products at a very early time.

Conclusions

When using a driver containing as little as 8% hydrogen to drive air in a shock tube, combustion takes place at the interface. Initially, because of this interface combustion, pressure waves are generated which perturb shock-tunnel reservoir conditions. These effects can be accounted for by assuming the process is isentropic and calculating the reservoir enthalpy change from the measured pressure change. However, the hot combustion products mix into the test gas and change both its state and composition, thus limiting its usefulness for testing. The time it takes for this contaminated air to first reach the test section decreases rapidly with increasing shock Mach number. Thus, in most cases, this interface mixing, rather than phenomena that can be described on a wave diagram in terms of pressure waves, will limit the usable test time of shock tunnels.

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Correlation of Motor and Strand Composite Propellant Burning Rate

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THE burning rate of composite propellants measured in the Crawford Bomb testing of uncured liquid strands may be correlated with data from small motors by the following equation:

$$P/r_n = (b_n/b_s)P/r_s + K_0 \quad (1)$$

where

r	=	linear burning rate
P	=	pressure
b_n/b_s	=	slope
K_0	=	intercept
s	=	as subscript, strand properties
n	=	as subscript, motor properties

Equation (1) states that the ratio of pressure to burning rate for the motor and strand can be related by two parameters that are independent of pressure when the ratios are

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