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Imperfect Gas Effect in Real Hydrogen Drives

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Nomenclature

a = $(\partial p/\partial \rho)^{1/2}$ = sound speed
f = empirical constant for a given entropy
k = empirical constant for a given entropy
M_s = shock Mach number
p = pressure
s = entropy
T = temperature
u = velocity
v = specific volume
z = compressibility
β = empirical constant for a given entropy
ρ = density

Subscripts

f = final state
i = initial state
0 = reference (p_0 = 1 atm; ρ_0 = 1 amagat)
1 = state of quiescent test gas
4 = state of initial driver gas

IMPULSE facilities (e.g., the shock tunnel) have been extensively used for the production of high-enthalpy flows in various gas mixtures. The use of statically heated hydrogen as a driver has become quite common.[1,2,3] For the upper performance limits, the hydrogen might be compressed to pressures as high as 2000 atm at 800°K. For these conditions, the assumption of an ideal gas is inadequate due to the existence of large intermolecular forces.[4] Huber[5] has calculated performance of a shock tube using unheated hydrogen drivers at pressures up to 125 atm. The development of an expansion tunnel at LRC required more extensive real hydrogen driver performance calculations. These calculations utilized the equations for thermodynamic properties from Ref. 4. Although this data lacks experimental verification above 600°K, it does continue the trend of the most reliably established properties of hydrogen.[6]

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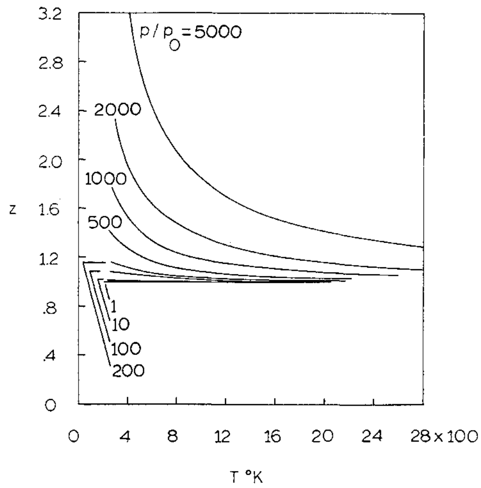

Fig. 1 Compressibility factor for hydrogen.

The effects of considering the intermolecular forces can be seen in Fig. 1 which presents z as a function of T for pressures of 1–5000 atm. For the typical driver conditions cited, a value of $z = 1.5$ is attained. Figure 2 is a plot of p as a function of T along isentropes. The differential equation governing an isentropic one-dimensional unsteady expansion can be written[7]

$$du = -(dp/\rho a)_s \tag{1}$$

Equation (1) can be readily integrated using the semiempirical entropic equation of Ref. 4

$$p^{(\beta - 2)/\beta}(v - f) = k \tag{2}$$

resulting in the following expression

$$\Delta u = [k\beta(\beta - 2)]^{1/2}p^{1/\beta} \tag{3}$$

where Δu is the velocity increment imparted to the flow as it expands from an initial pressure to $p = 0$. Figure 3 presents values of Δu as a function of p at constant entropy. With a

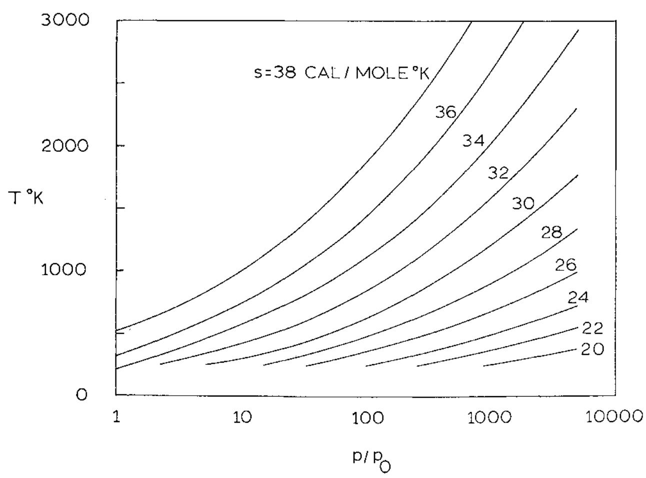

Fig. 2 Pressure-temperature diagram for hydrogen.

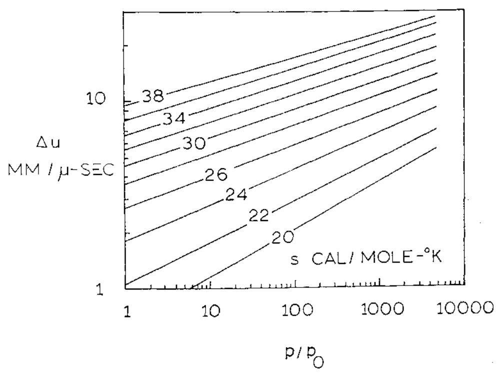

Fig. 3 Velocity increment resulting from a one-dimensional unsteady expansion in hydrogen.

known initial driver pressure and temperature, the corresponding entropy can be found from Fig. 2. Then from Fig. 3, the velocity increment resulting from the unsteady expansion is

$$u_f - u_i = \Delta u(p_i) - \Delta u(p_f) \quad (4)$$

Figure 4 reveals a significant difference between the performance of real and ideal hydrogen driving real air. For example, generation of a shock Mach number of 24 into real air at 300°K and 10^{-4} atm requires a pressure ratio p_4/p_1 about $2\frac{1}{2}$ times that of the ideal driver gas analysis.

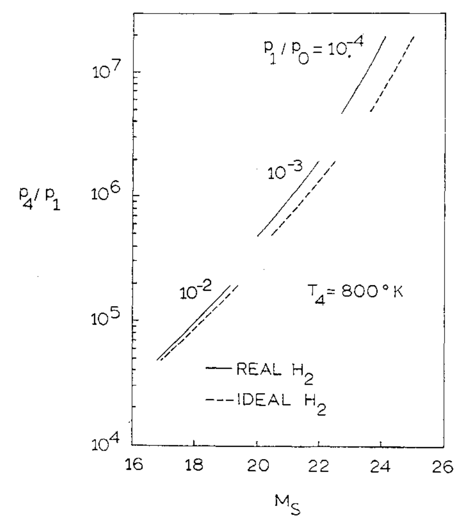

Fig. 4 Comparison of shock tube performance for real and ideal hydrogen driving real air.

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Downstream Pressure Distributions for Two-Dimensional Jet Interactions

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Nomenclature

b^* = slot width, in.
b_e^* = $C_d b^*$, effective slot width, in.
C_d = jet nozzle discharge coefficient
F_{id} = downstream induced force
h_s = jet-shock height, in.
P = pressure, lbf/in.^{2}
x = distance from jet slot, in.

Subscripts

j = jet conditions
o = stagnation conditions
peak = downstream peak conditions
s = separation conditions
∞ = freestream conditions

Introduction

THE general problem considered here is the use of reaction jets to generate control forces in a supersonic environment. A limited-scope, two-dimensional, experimental study has recently been completed at the Naval Ordnance Laboratory. This study is related to the definition of the controlling parameters for the surface pressure distributions aft of a secondary jet blowing normal to the supersonic mainstream. Only the case for turbulent separation forward of the jet was considered. Numerous authors have hinted that the forces produced downstream of the jet may well be beneficial for control purposes.[1,2,3] The only attempt to model this region was by Barnes et al.[1] using a limited amount of experimental data. The NOL study, with additional experimental data, found that the over-all behavior of the pressure distribution was different from that implied by the earlier study.

Equipment and Procedure

The present tests, with adiabatic wall conditions, were run with a freestream Mach number, $M_\infty = 4$, at two freestream Reynolds numbers, per foot, of 6×10^6 and 18×10^6. Shadowgraph pictures were taken of all test runs.[4] The test model was a flat plate 15.5 in. long and 10 in. wide fitted with a half-cylinder boundary-layer trip 0.025 in. high, located 0.75 in. from the leading edge. Surface flow studies using azobenzene, and complementary shadowgraph studies indicated that boundary-layer transition occurred 1.25 in.

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