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Flow Nonuniformity in Low Pressure Shock Tubes under Nonasymptotic Conditions

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Nomenclature

ℓ = distance behind shock front
M = shock Mach number
t = time
u = velocity
ρ = density

Subscripts

m = conditions at maximum test time
1 = conditions ahead of advancing shock wave
2 = conditions in shock heated gas
s = conditions at shock front

Introduction

FLOW nonuniformities associated with the presence and growth of boundary layers behind incident shock waves continue to attract considerable experimental and theoretical attention especially in the context of studying basic collisional and radiative processes in shock heated or shock-generated plasmas. This follows since variations in such fluid properties as temperature and density in the shock heated gas, induced by these nonuniformities, must be known accurately to allow reliable kinetic data to be obtained.[1] Fortunately, an elegant (and tractable) theory has been formulated by Mirels[1,2] and has already been subjected to experimental verification.[3] However, these previously reported experimental studies were restricted to a single gas, argon, and also were concerned with fully developed flow conditions in which a limiting separation, ℓ_m, between the shock front and contact surface, had been established.

However, in many cases of interest, it may be necessary to operate under partially developed flow conditions as a result of constraints in the overall length or diameter of the flow channel itself or the desired range of operating pressures. In such partially developed flows the need to correct for flow nonuniformities associated with the boundary-layer growth can also be anticipated. In the work reported here, experimental data for a range of gases and gas mixtures are presented which confirm the validity of the Mirels treatment in this case. A brief outline of the background theory, experimental approach, and results is presented below.

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Theory

Mirels[1,2] has shown that flow nonuniformities associated with laminar boundary-layer growth in medium and strong shock waves can be derived starting with the mass conservation relationship

$$(\rho_2 U_2/\rho_{2s} U_{2s}) \equiv (U_2/U_{2s}) = (1-(\ell/\ell_m)^{1/2}) \tag{1}$$

In this expression ρ and U denote density and shock velocity, respectively, in shock-front fixed coordinates. The subscript 2 refers to the shock heated gas and the additional subscript, s, refers to the conditions at the shock front. The distance behind the shock front is denoted by ℓ and in a fully developed flow ℓ_m defines the location of the contact surface. Fox et al.[3] integrated Eq.(1) to obtain an expression for t_p the time required for a particle to travel from the shock front to any station ℓ in the shock heated gas. When combined with the expression $t_L(\equiv \ell/U_{2s})$ representing the time (as measured in the laboratory frame of reference) for the shock to move a distance ℓ the following relationship is obtained[3]:

$$(t_p/t_L) = -2(\ell/\ell_m)^{-1}[(\ell/\ell_m)^{1/2} + \ln[1-(\ell/\ell_m)^{1/2}] \tag{2}$$

Valid for laminar boundary layers and strong shocks, Eq.(2) must be applied (in addition to the normal density-ratio factor) to convert laboratory to particle time scales. Although Eq. (2) was initially derived and subsequently experimentally confirmed in the context of fully developed flow regimes,[3] Mirels has indicated that it should be equally valid in partially developed regimes provided shock attenuation effects remain small.[2] A primary objective of the work reported here was to test the validity of this hypothesis. As discussed below this was achieved by comparing particle paths in the shock heated gas with those predicted using Eq. (2).

Experimental

A 4 cm i.d. pressure-driven shock tube of similar design and construction to that described previously by Cunningham and Hobson[4] was used in this study. Spectroscopically pure rare gas samples or gas mixtures buffered with rare gases were introduced into the evacuated-flow tube to a pressure between 1 to 12 Torr. Shock waves in the range Mach 1.6 to Mach 6.0 were transmitted into the low-pressure test gas by rupturing a thin diaphragm.[4] Under these conditions, the shock heated gas was nonionized and had a translational temperature between 500 and 3500 K. Also, at the concentration levels (less than 1%) used, the presence of molecular additives such as N_2, O_2, or H_2O were found not to alter the flow characteristics appreciably. Using the criterion given by Mirels,[1] it was established that the boundary-layer flow remained laminar throughout the measurements reported here. Analysis of the responses of a series of platinum film transducers, mounted flush with and along the length of the flow channel,[3] indicated shock heated gas lengths some 40-60% smaller than those predicted for fully developed flows.[5] In neon, for example, measured shock heated-gas lengths varied between 60 and 20 cm for Mach 2 and Mach 6 shock waves, respectively, and a downstream pressure of 4 Torr. The corresponding values for krypton at the same downstream pressure were 175 and 75 cm, respectively. The length of the shock heated gas was found to scale approximately linearly with pressure as expected.[3]

To map out particle trajectories in the shock heated gas, the approach of injecting a slice of ionization through the shock front and following its subsequent motion was used.[3] This involved creating a 4-6 cm long region of ionization (in the low-pressure test gas) ahead of an advancing (and itself nonionizing) shock wave. A pulse of RF power, of duration between 500 and 1500 μs, applied to a series of electrodes positioned on the outside circumference of the flow channel was used for this purpose.[4] The electrode station was positioned some 3 m downstream of the diaphragm, and the breakdown pulse was terminated prior to the arrival of the shock front at that location. The section of weakly ionized plasma (density $\sim 10^{10}/cm^3$) was swept into the shock heated gas and was transported further downstream and past a series of electrostatic-double probes mounted across the shock tube diameter.[3] A total of 10 probes at an interprobe spacing of 10 cm was used and the first probe was located at approximately 3.5 m from the diaphragm. For a known ion species the current monitored by the electrostatic probe circuitry could be related to the ion density. However, the actual ion composition in the plasma slice varied depending upon the gas being studied. For example, in studies involving the pure rare gases the dominant ion was expected to be the dimer ion of the parent rare gas[4] while in gas mixtures containing N_2, O_2, H_2O, and D_2O the dominant ions were expected to be N_2^+, O_2^+, H_3O^+, and D_3O^+, respectively. Several platinum film thermal transducers were used to define the location of the shock front. These diagnostics allowed both the shock front and plasma slice to be temporarily located to an accuracy of better than ± 5 μs.[4]

Results

An *X-T* diagram allows a convenient comparison between measured and predicted particle paths and several are collected in Fig. 1. For each plot the gas composition, Mach number and downstream pressure, P_1, is indicated and the origin defines the entry of the ionized slice into the shock-heated gas. The solid line labeled SF maps out the variation of the shock front with distance as determined from the responses of the platinum-film gages. For the range of test gas pressures and Mach numbers of interest in this study, shock attenuation was found to be less than 5%. This allowed the use of Eq.(2) to calculate trajectories in the shock heated gas.[2] By taking the maximum of the double-probe signal to correspond to the center of the plasma slice the data points (open circles) were obtained. For the experimental arrangement used, the plasma slice was found to have penetrated to approximately 30 and 70% of the available separation between the shock front and contact surface at the first and last probe station, respectively.

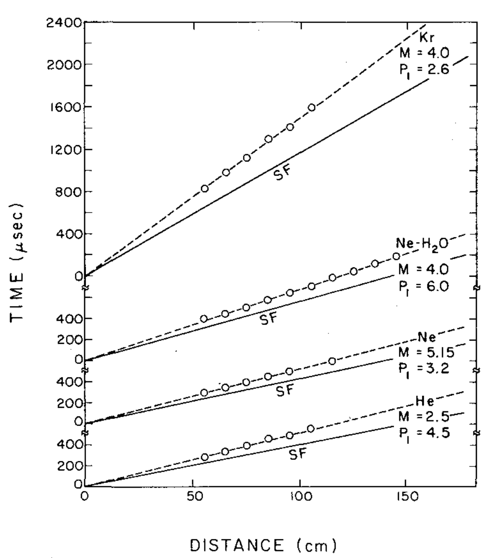

Fig. 1 Particle paths in the shock heated gas (circles represent experimental points).

The dashed line shown in Fig. 1 represents the particle paths predicted using Eq. (2). Similar agreement between measured and predicted paths was obtained for the other rare gases (argon and xenon) and for gas mixtures containing N_2 and O_2.

Summary

It appears that, at least within the limits of experimental accuracy of this study, nonuniformities associated with boundary-layer growth in developing (and nonattenuating) flow regimes can also be described using the theoretical framework presented by Mirels.[2] In situations where this test of comparing measured-particle paths with predicted-particle trajectories can be applied, the need for complex numerical analysis of flow conditions can be circumvented.

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Wing-Body Carryover at Supersonic Speeds with Finite Afterbodies

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Nomenclature

A = wing alone aspect ratio
C_{L_α} = lift curve slope for wing alone, per radian

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