SURVEY OF SHOCK TUBE RESEARCH RELATED TO THE AEROPHYSICS PROBLEM OF HYPERSONIC FLIGHT

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ABSTRACT

In recent years, a considerable volume of research has been undertaken in the field of high temperature gas dynamics in which the shock tube has been employed as the principal experimental tool. In particular, a substantial fraction of this research effort has been devoted to the study of phenomena peculiar to air and its component gases, and is, therefore, directly applicable to many aerophysics problems associated with hypersonic flight through Earth's atmosphere. However, in spite of their omni-existence, most of these works have been published over a period of time in a scattered manner, and hence, appear to be somewhat incoherent.

In the present paper, a preliminary effort is being made to compile these published works under various identifiable (if somewhat arbitrary) topics so as to provide a more convenient reference for investigators in this field. Whenever possible, the advantages and limitations of the shock tube as a research tool for tackling the various topics of interest will also be pointed out.

INTRODUCTION

In contrast to flights at lower velocities, the most distinguishing feature of hypersonic flight is, perhaps, the active participation of the higher internal energy modes of the gas (vibrational and radiative excitations, dissociation, ionization,

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etc.) in a significant part of the flow field. This gives rise to a host of new physical and chemical phenomena (Ref. 1), which, unless properly understood and dealt with, may present a real "thermal barrier" to high speed flight through any substantial part of Earth's (or other planet's) atmosphere.

As one may rightfully suspect, the combined fluid-dynamics and chemical-physics problem of hypersonic flow is generally very complex. However, in many practical situations of interest, there appears to be a natural separation of the entire flow field into regions where either the fluid-dynamics phenomena or the chemical-physics phenomena predominate.[2] A typical example of such separation is the low- and high-entropy regions in the continuum hypersonic flow field around blunt objects.[2] The low entropy region, which is defined by the gas that has flowed through the weak but extensive oblique shock wave, controls the overall pressure and velocity distributions of the flow field. On account of the relatively low temperature, this region has very little, if any, chemical-physics phenomenon of its own.[3] The high entropy region, which encompasses all the chemically active gas that has been heated by the normal (or near-normal) portion of the bow shock wave, on the other hand, occupies only a small fraction of the total volume of the flow field and hence plays only a secondary role in determining the overall pressure and velocity distributions.

The existence of such natural separation between the fluid-dynamics and chemical-physics regions of the flow field offers the possibility for a drastic simplification in the experimental study of many hypersonic flight problems. For, it not only relieves the need for simultaneously reproducing all the flow parameters (e.g., Mach number, stagnation enthalpy and pressure, Reynolds number, etc.) in the laboratory, which is always difficult, if at all possible; but it also often allows one to apply experimental results that have been obtained for various isolated phenomena to the different parts of the flow field with only a minimum amount of reinterpretation. This is

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[2] In the sense that only a relatively crude fluid-dynamics model will be needed in the process of working out the details of the chemical-physics phenomena in a particular region, and vice versa.

[3] For this reason, one may actually treat the gas within this region as a perfect gas of constant specific heats without much error. In other words, all hypersonic flow theories that have been developed for perfect gases of constant specific heats (see Ref. 2) can be applied to this region without further reservation.

also the underlying reason which accounts for the general usefulness of shock tubes in hypersonics research.

SHOCK TUBE AS A TOOL FOR HYPERSONICS RESEARCH

It is well known that normal shock waves of strength comparable to, or even in excess of, those encountered by hypersonic vehicles of current interest (ballistic missiles, satellites, solar system probes, etc.) can easily be generated in the laboratory using high temperature shock tubes such as those described in Ref. 17. By suitable choice of geometry, it is also possible to operate the shock tube at low gas densities corresponding to the condition of flights at fairly high altitudes (Ref. 21). This is illustrated in Fig. 1, which depicts the approximate velocity-density regime within which considerable experimental studies have been performed in connection with the hypersonic flight problem.

Since the early exploration of the shock tube as a scientific instrument (Refs. 3 to 5) it was thought at one time that the shock tube might be an ideal tool for many types of aerodynamics studies on account of the high degree of flow homogeneity that can be achieved with relative ease. Although this has been demonstrated to be the case at the time when the main interest in aerodynamics was in transonic and supersonic flow (Refs. 6 and 7), it was soon noted that, on account of the existence of a limiting Mach number in the shock-induced flow for any gas with finite heat capacities (Ref. 17), the shock tube in its unmodified form would be potentially more useful as a tool for studying the chemical physics aspect of the hypersonic flight problem. This is reflected in the list of published works compiled in Table 1.

When the shock tube is used in this light (i.e., as a generator for high temperature gas samples), it has the obvious advantage over other gas dynamics instruments in basic simplicity and flexibility. As illustrated in Fig. 2, the basic elements of the apparatus consist of just a high pressure chamber and a low pressure chamber connected by a suitable diaphragm. By simple variation of geometry (see Figs. 3 and 4), it can be adapted to perform quantitative experiments over a wide range of temperature, density and chemical composition of the gas samples. With proper care, it is also possible to reduce all the undesirable effects such as wall contamination, flow inhomogeneity (Refs. 8 to 16) etc., to the level of small perturbations, so that the resultant shock-heated gas sample approaches that of an idealized steady one-dimensional flow behind a plane shock wave (see Fig. 5). This is of particular significance in the study of relaxation phenomena behind the shock wave, since the observed one-dimensional relaxation history can now be directly applied to the flight case with simple changes of coordinates (i.e., following the streamlines in Lagrangian coordinates).

When compared with other types of instruments, such as molecular and ion beams, for the study of basic molecular and atomic properties, the shock tube has the drawback that the molecular or atomic samples are available only in the form of randomized ensembles with the normal thermal velocity spread. As a result, the physical quantities that can be observed are always macroscopic quantities that have been averaged over the molecular velocity distribution function, instead of the mono-energetic microscopic quantities which the physicists would like to have. On the other hand, the shock tube has the advantage of being capable of providing relatively pure samples of neutral but chemically active atoms in sufficiently high concentrations for quantitative measurements (which is no trivial matter in molecular beam techniques).

A COMPILATION OF PUBLICATIONS FROM SHOCK TUBE RESEARCH

A compilation of publications from recent shock tube research pertaining to the problem of hypersonic flight through Earth's atmosphere is given here in Table 1. The nature of this compilation is more selective than exhaustive, and hence the author must apologize for the possibility of having left out many important contributions in this field (either due to oversight or insufficient time in the literature search).

The readers are also referred to the papers by Wray (Refs. 39 and 40) and Teare, Georgiev and Allen (Ref. 58), from the Avco-Everett Research Laboratory,for more specific discussions on the chemical kinetics and reaction zone radiation problems.

Table 1 Compilation of published shock tube works according to selected topics

TOPIC	REF.
A. Shock Tube Techniques	
(a) Early exploration of shock tubes	3 - 7
(b) General behavior of shock tube and shock tube flow	8 - 16
(c) Adaptation of shock tube for physical gasdynamics studies	17 - 19
(d) Extension to higher velocities	20
(e) Extension to lower densities	21

B. Quasi-Equilibrium Properties of High Temperature Air and Its Component Gases

(a)	Molecular and atomic transport (heat transfer rates)	22 - 25
(b)	Optical properties (refractive index, absorption and emission spectra, absolute emissivity)	26 - 31
(c)	Electromagnetic properties (electrical conductivity, electron scattering cross-section)	32 - 34

C. Nonequilibrium Properties of High Temperature Air and Its Component Gases (Rate Processes and Relaxation Phenomena)

(a)	Viscous shock structure and rotational relaxation	35
(b)	Vibrational excitation rate	36 - 39
(c)	Dissociation and chemical reaction rates	40 - 48
(d)	Coupling between vibrational excitation and dissociation	49
(e)	Ionization rate	50 - 55
(f)	Reaction zone radiation	56 - 58

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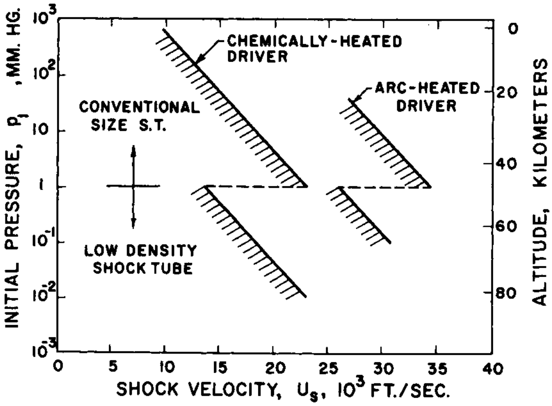

Fig. 1 Typical velocity-density regime covered by shock tubes employed for hypersonic studies. "Conventional size" refers to shock tubes up to several inches in diameter as used by most investigators; "low density shock tube" refers to type described in Ref. 21.

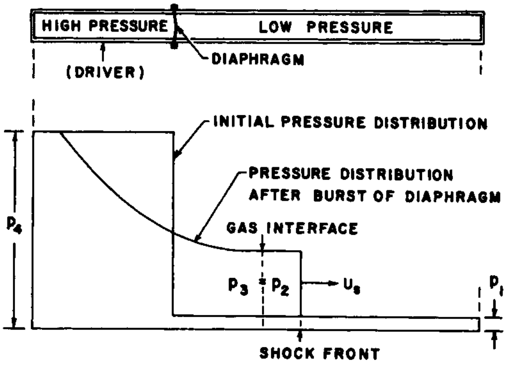

Fig. 2 Basic elements of shock tube. Operating principle of this device is based on nonlinear propagation characteristics of large amplitude pressure waves, which tend to wash out earlier disturbances generated during diaphragm burst, and hence render shock-heated gas sample more homogeneous as shock wave progresses down low pressure chamber.

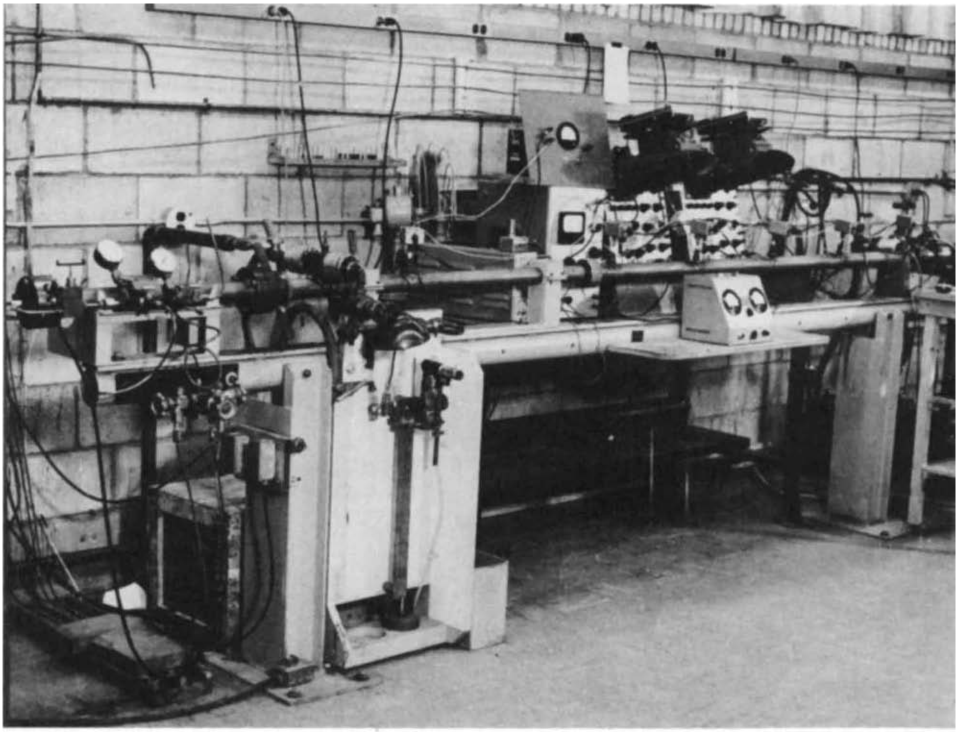

Fig. 3 Example of "conventional size" shock tube.

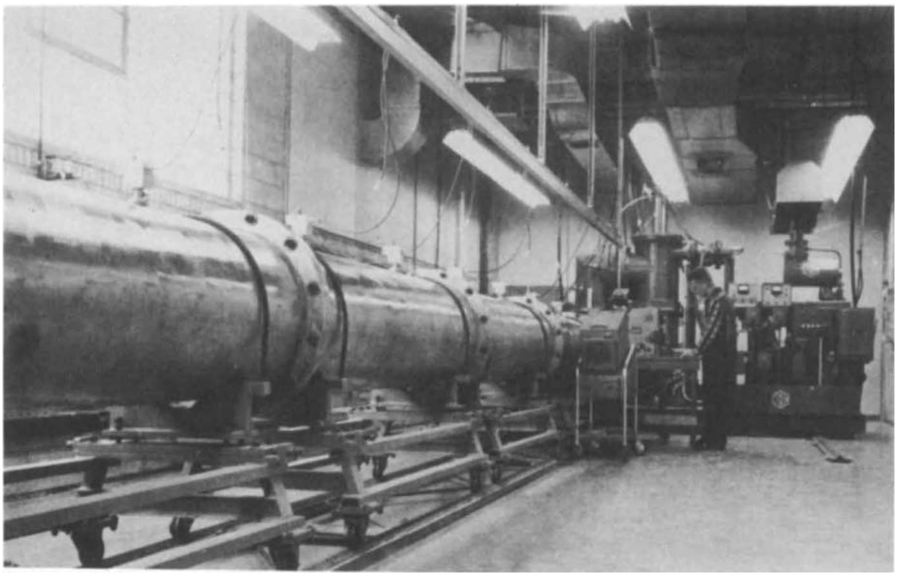

Fig. 4 Example of large diameter, low density shock tube (see Ref. 21).

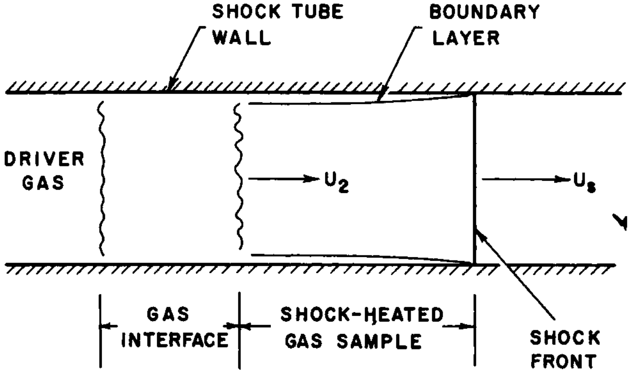

Fig. 5 Instantaneous state of affair in low pressure chamber of shock tube some time after burst of diaphragm, but before shock wave reaches the far end of the tube. For very strong shock waves, shock-induced flow velocity u_2 approaches the propagating velocity of shock front U_s, but flow Mach number u_2/a_2 remains finite and not much greater than unity (a_2 is sound speed of the shock heated gas).