PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Introductory Remarks

E. G. Broadbent

Phil. Trans. R. Soc. Lond. A 1991 **335**, 89-90
doi: 10.1098/rsta.1991.0037

Introductory remarks

By E. G. Broadbent
Department of Mathematics, Imperial College of Science, Technology and Medicine, London SW7 2BZ, U.K.

It is not the intention of this Theme Issue to include any discussion of the pros and cons of hypersonic flight; the existence of a large array of man-made satellites, which seems likely to increase rather than decrease, is a clear indication that hypersonic flight is already with us and likely to stay with us. Since hypersonic speeds are in practice achieved by some form of chemical propulsion, which uses a good deal of fuel, it is important to strive for high efficiency. This in turn suggests that air-breathing engines have an important part to play, by avoiding the weight of the oxidant in comparison with rockets, and furthermore that good lift–drag ratios are important even for hypersonic vehicles by offering a wide choice of trajectory. It is these considerations that have led to the choice of hypersonic aerodynamics as the theme of this volume.

A good starting point is the flight experience that has already been gained by NASA and this is reviewed in some detail by Walberg in the first paper. A glance at the early figures in Walberg's paper shows the wide range of parameters that can be encountered by hypersonic vehicles, with Mach numbers up to 20, heights up to 100 km and beyond and Reynolds numbers from 10^4 almost up to 10^9; later in the paper wall temperatures of up to 1500 K are reported. It is impossible to cover such a wide range adequately in a single volume, and for that reason we have not included any papers on rarefied gas dynamics, which has a large literature of its own.

Many of the features in Walberg's review are, however, strongly reminiscent of conventional subsonic aircraft. Much information is given about stability and control of the various flight vehicles, and although there are differences, much is qualitatively familiar. Boundary-layer transition is still important, perhaps more so because of its significance in heat transfer, and vortices are still found and can be troublesome.

Louie & Okendon discuss inviscid hypersonics in a general way so as to make the most of known results and similarity solutions. They bring out a number of features which are worth further study. For instance, one might expect that chemical reactions would have to be excluded from this type of treatment, but this is not entirely so and some forms of reaction, in particular vibrational relaxation, are illustrated. As the authors point out, an important reason for this type of mathematical work is that it can provide test cases for numerical methods, which if used blind might fail to represent some critical region of the flowfield with sufficient accuracy. The possibility of providing test cases involving chemical reactions could be extremely valuable.

Boundary layers are always important in aerodynamics and hypersonic boundary layers have special features, which are discussed and illustrated by Brown, Khorrami, Neish & Smith. In particular, the flow downstream of a leading-edge shock may contain a viscous layer adjacent to the wall comparable in thickness with the inviscid outer layer. This leads to strong viscous–inviscid interactions that can be awkward to handle numerically, and the paper explores how these difficulties can be overcome, with an illustrated example. The paper goes on to give a detailed discussion of nozzle flow, and finally the important problems of instability and transition to turbulence.

The significance of airbreathing engines has already been mentioned in the context of efficient propulsion and at hypersonic Mach numbers such engines need a large supply of air. For example, if ρ is air density and u flight speed, the power required to provide sufficient thrust to match the drag is $\rho u^3 C_d A_v$ where C_d is a drag coefficient and A_v a typical area of the vehicle. The chemical energy supplied per second, however, is limited to $\rho u A_i C_q$ where A_i is the intake area and C_q the chemical heat release per unit mass of air. It follows that as u increases, so must A_i, and at hypersonic speeds with a ramjet (or 'scramjet', i.e. supersonic ramjet) engine the intake provides a major part of the lift and drag of the vehicle. This is not so surprising when it is remembered that even on *Concorde* most of the thrust (when cruising supersonically) acts on the intake. Studies in the early 1970s had shown the value of a unified treatment of a lifting-propulsion flow field with heat addition, and the method then developed is brought up-to-date in Broadbent's paper, which shows how Mach wave interactions between heated and unheated flows can be taken account of.

One way in which hypersonic flow can differ radically from other flows is through chemical reactions, and Clarke's paper gives a survey of this field of work. Clarke shows that a study of chemically reacting flows does not necessarily entail any departure from the concept of a fluid although the governing equations become more complicated. In particular, new timescales are introduced so that, for example, the flow downstream of a shock may not reach equilibrium for a considerable distance. Clarke discusses the difficulties as they arise in various types of flow-field, and outlines methods of calculation with examples; a section on combustion is included.

In the last paper, Townend brings us back to the complete hypersonic vehicle, as he examines the design trends that current research is leading towards and also the areas where further research is needed. His first figure illustrates the advantage of ramjets and scramjets over rockets, particularly when the fuel is hydrogen, and he then goes on to discuss trajectories, followed by a number of topics of importance in the performance of hypersonic vehicles. This includes taking note of the various constraints that influence a design and which often arise from structural considerations. He concludes with a list of research topics.