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HYPERSONIC FLOW AT LOW REYNOLDS NUMBER

INTRODUCTION

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Mission and energy management requirements dictate that a spacecraft moving at hypersonic speeds in a planetary atmosphere will fly at high altitudes and low Reynolds numbers during a certain portion of its flight path. Two important phenomena arise under these conditions: interaction between the boundary layer and the "external" inviscid flow field; and effect of finite chemical and electronic reaction rates.

Induced surface pressure and heat transfer rates generated by boundary layer displacement effects at hypersonic speeds have been known and understood for several years. Recently, the influence of vorticity in the external inviscid flow associated with curved shock waves has been extensively studied, following an original suggestion of A. Ferri. In the paper by M. Van Dyke, presented in this chapter, a systematic expansion procedure is carried out to obtain all of the second-order effects (first-order correction to ordinary boundary layer theory) on the "locally similar" flow near the stagnation point of a blunt nosed body. Controversy has surrounded this subject respecting the effect of "external" vorticity on the pressure gradient parallel to the body surface. Through later discussion it has become clear that the existence of this effect depends on the procedure employed. In Van Dyke's method the same fixed body surface is employed throughout, and the boundary layer induced velocity normal to the surface gives rise to a "body force" parallel to the surface, which is balanced by an induced static pressure gradient. Other investigators have satisfied the boundary conditions along a "new" body increased by the displacement thickness, so that no vorticity-induced pressure gradient appears in their analyses. When properly interpreted, the studies of Van Dyke, Lenard and Rott, Probstein and Hayes, etc., all agree, but the effect of the density-viscosity product $\rho\mu$ of the fluid has an important effect on the numerical results.

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Although the first step in a systematic expansion procedure such as Van Dyke's is always interesting, significant nonlinear effects which arise at low Reynolds numbers are not taken into account in this procedure. The paper by Levinsky and Yoshihara pushes the Navier-Stokes equations to the limit for the "locally similar" flow in the stagnation region of a sphere. Their numerical calculations include the effect of shock thickening, merged layers, etc., and show the reduction in heat transfer coefficient at low Reynolds numbers as the domain between highly rarefied and low Reynolds number viscous flow is approached. An important question remains as to the possible effect of conditions downstream of the stagnation region on the flow in this region.

When the gas is highly rarefied, the Navier-Stokes equations fail, and use is made of kinetic theory to describe the flow. In order to obtain an approximation to the density distribution along the stagnation line of a "cold" blunt body, H. Oguchi follows an iteration procedure similar to the method developed by D. R. Willis for nearly-free molecule flow. In Oguchi's paper, the Maxwell-Boltzmann equation is replaced by the much simpler Krook equation, and the free molecule flow is taken as the zeroth approximation. This procedure is valid for very small Reynolds numbers and is valuable for showing the departure from free molecule flow. However, true shock wave behavior is expected only for Reynolds numbers of the order of one, almost by definition.

Solutions of Rayleigh's problem have been very instructive in the study of numerous phenomena, including nonequilibrium effects in low density gas flows. The analysis by Moore and Rae utilizes small perturbations and a Lewis number of unity. Nevertheless, this study shows the important effects of a partially noncatalytic surface when there is a "lag" in the species concentrations and temperature of a gas.

In summary, the four papers that follow give a good picture of some main areas of current research in low Reynolds numbers, low density hypersonic flows.