Boundary Layer Blockage in Expansion Tube Nozzles

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Abstract: The results of a first order perfect gas correction for the effects of the boundary layer formation within expansion tubes with nozzles are presented. The analytical model developed to describe the boundary layer formation within the expansion tube and an expansion nozzle located at the end of the acceleration tube is based on the Kármán integral equations. The results of this analytical model are compared with experimental data from an expansion diffuser. The model provides a useful tool for the preliminary design of nozzles for such facilities.

Key words: Boundary layer formation, Boundary layer blockage, Nozzle flow, Expansion tubes, Hypersonic flows, Kármán integral equations

1. Introduction

Scale modelling of hypersonic flows cannot be achieved with complete matching of all non-dimensional scaling parameters. Laboratory testing generally involves only partial similarity and can be justified if the phenomenon of interest is controlled primarily by matchable parameters. For example, the binary scaling parameter allows accurate modelling of binary finite rate dissociation processes, simultaneously reproducing viscous effects.

However, many processes of interest in hypersonic flow do not follow binary scaling, and exact simulation requires full size models. Combustion, recombination and gas radiation are examples of such processes. The size of the test section, therefore, limits the size of flight vehicle which can be tested in this way. Expansion of laboratory test flows enables larger models to be tested, but the associated drop in pressure limits the range of flight conditions which can be reproduced. Because of their high total pressure simulation capability, expansion tubes can potentially provide improved performance over other existing facilities.

In the superorbital expansion tube it is of interest to model rarefied flow phenomena, for which it will be necessary to reduce gas density by means of a nozzle.

The limited test size of an expansion tube may be increased by means of an expansion nozzle located at an appropriate section of the tube (Sudnitsin & Morgan 1994). The starting process associated with nozzle flows reduces the steady test time available (Leyva 1994), and may provide additional limitation on model size.

A nozzle was tested successfully by Miller & Jones 1983 on an expansion tube. However, for their purpose, the unmodified expansion tube was found to be better and the use of the nozzle was discontinued.
Despite the reduction of the binary scaling parameter associated with the use of nozzles, direct simulation over a useful range of flight conditions may still be obtained.

However, certain problems need to be addressed if such nozzles are to be used. Firstly, reservoir pressure must be sufficient to reproduce real flight conditions. A simple ideal gas analysis (Sudnitsin & Morgan 1994) provides a quick assessment of operational conditions in terms of the important non-dimensional parameters. Using this approach, the characteristics of simulated flow in terms of total pressure, driver noise attenuation (Paull & Stalker 1992) and test gas temperature may be found for three different configurations of an expansion tube with the divergent nozzle placed at A - the end of the driver section, B - the end of the shock tube and C - the end of the acceleration tube. Configurations and conditions which may give superior performance and for which further investigation is justified can thus be easily identified.

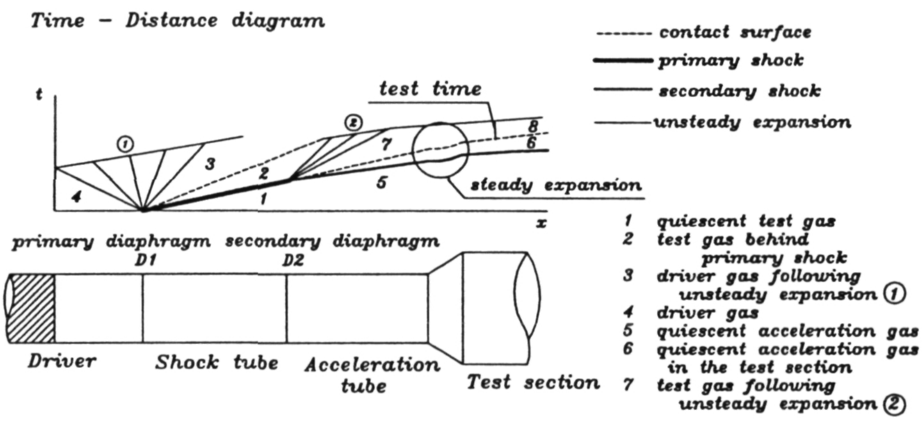

Figure 1. Configuration C

According to the results of the performance comparison in terms of nose-to-tail pressure ratio , configuration C has been chosen for initial investigation (Fig. 1). This configuration is advantageous because it is relatively simple to modify the existing facility and it can be shown that its performance at some operating conditions is comparable to the configurations A and B (Sudnitsin & Morgan 1994).

One aspect of nozzle design concerns the influence of the boundary layers on the effective test flow area achieved in the core flow. This effect is small for low Mach number flows, and is often not corrected for in the design stage, because direct calibration under operating conditions can be used to determine precisely the expanded flow parameters. However, in superorbital expansion flows significant boundary layer blockage may arise, and the nozzle geometric area ratio may be quite different to that seen by the core flow. Consequently, an analysis is presented which couples the boundary layer displacement thickness to the expansion process, giving an improved indication of the state of the core flow.

The present analysis has been done for a small-scale expansion tube at the University of Queensland (X1), and the nozzle is currently under construction.

Experimental data for a diffuser on an expansion tube obtained by General Applied Science Laboratories, Inc (GASL) (Bakos et al. 1992, Bakos 1994) were used to validate the analytical results prior to designing the nozzle for X1 at the University of Queensland.

2. Boundary layer analysis

The present analysis investigates the growth of the boundary layer on the walls of the expansion tube which will reduce the size of the available test core from A_1 to A_1^* (Fig. 3) and change the area ratio of the nozzle, resulting in a decrease in the pressure ratio associated with it.

Flow is assumed to be compressible, and the formation process has been

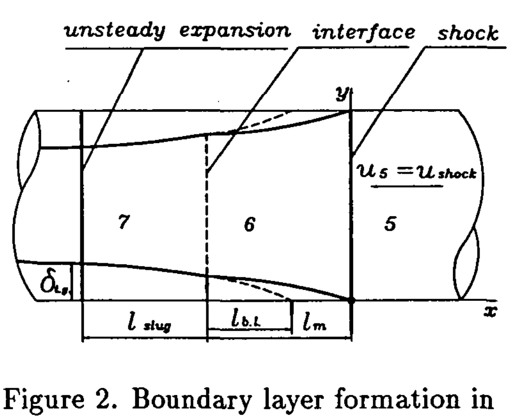

Figure 2. Boundary layer formation in the acceleration tube

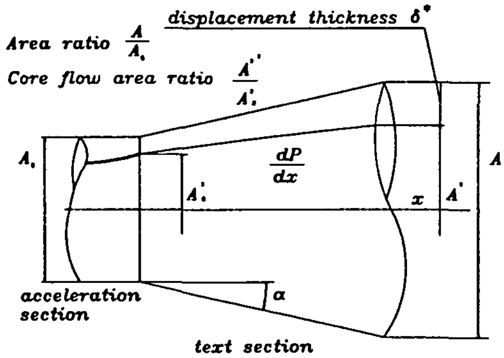

Figure 3. Boundary layer formation in the nozzle

divided into two stages, formation within the tube and growth within the divergent nozzle.

2.1. Boundary layer formation within the acceleration tube

A boundary layer grows between the head of the rarefaction wave and the shock. Fig. 2 schematically demonstrates the different stages of the boundary layer formation and flow for each region.

Boundary layers within the shock tube act as an aerodynamic sink for acceleration gas in region 6 between the shock and interface (Fig. 2). Test gas is also lost by this process in region 7, behind the interface.
The boundary layer at the exit plane of the acceleration tube grows with time. The worst boundary layer thickness occurs with the arrival of the secondary unsteady expansion head (Fig. 2). At this point useful gas flow, in this region is completed.

For the present calculations a worst case approach was adopted, assuming the origin of the test gas boundary layer coincided with the shock location. Therefore, region 6 (Fig. 3) is considered infinitively small and $l_{b.l.} = l_m$, which is a good approximation at high shock speeds. Thus, the test gas boundary layer develops under the influence of conditions behind the interface (region 7 in Fig. 3).

Table 1. Sample predicted condition for X1, targeting supersonic combustion

Regions Fig. 1	Pressure,Pa	Temperature,K	Velocity, m/sec	Speed of sound ,m/sec
4	5E+07	2000	0	1827[a]
7	6E+5	3082	3727	1112[b]
8	25E+3	1250	4200	709

Primary shock speed $U_{sh1} = 3000 m/sec$, secondary shock speed $U_{sh2} = 4500 m/sec$
Speed of sound ratio across the driver gas-test gas interface $\frac{a_3}{a_2} = 0.7$
[a] driver gas is a mixture of He and Ar with $\gamma = 1.67$ and $\mathcal{R} = 1000\, J/(kg\, K)$
[b] test and acceleration gas is air with $\gamma = 1.4$ and $\mathcal{R} = 287\, J/(kg\, K)$

In the sample calculation for X1 (Table 1), it was assumed that the boundary layer behind the interface in the acceleration tube is turbulent. The characteristic thicknesses δ – boundary layer thickness, δ^* – displacement thickness, θ – momentum thickness defining integral deficits were calculated from Hayes & Probstein 1959 and act as starting conditions for the nozzle boundary layer calculation.

2.2. Boundary layer formation within the expansion nozzle

The modelling of the nozzle boundary layer assumed the surface can be represented by a flat plate with a favourable pressure gradient, the flow is compressible, and that the Kármán-Based Method of Walz (1969) may be used to quantify the development of δ^* and θ with x.

The approach used allows the bulk boundary layer properties to be calculated without solving for the internal profiles. These properties can then be used in a one-dimensional approach to calculate nozzle exit conditions.

The physical information required to complete the calculations was incorporated into the differential equation for the velocity, density and area ratio variations along the nozzle. After the initial values of the variable parameters (Walz 1969) were estimated, final bulk properties of the boundary layer were obtained by solving the system of differential equations. A conical nozzle with an area ratio of 9 was used to generate the axial pressure distribution used for the computations. When the effect of the boundary layer displacement thickness was added to the contour, the geometric area ratio needed to expand the core flow to the correct pressure was found to be 20. This illustrates the importance of boundary layer blockage for these flow conditions. The increase of displacement thickness is due to the entrainment of new fluid in the nozzle, and also to the expansion of the boundary layer gas. In this example 66% of the downstream displacement thickness is due to entrainment in the nozzle, illustrating the importance of minimising nozzle length. The experimental validation of this result is yet to be made.

3. Comparison with experimental data

In order to validate the analysis above, it was applied to data from a diffuser placed at the end of the expansion tube at GASL (Bakos et al. 1992). The 0.85 m long diffuser with the initial conditions M17 (Bakos 1994) produced boundary layer with a thickness $\delta_{exit} \approx 6.25\,mm$ (from an exit Mach number profile Bakos et al. 1992). The nozzle starting condition, M17, and the history of the boundary layer were deduced from Bakos et al. 1992 where the boundary layer thickness was measured to be $\delta_0 \approx 25\,mm$ at the acceleration tube exit.

The diffuser was designed to produce a pressure increase of 11.9 (perfect gas approximation) in static pressure relative to the incoming flow. After correction of the contour to account for the displacement thickness, the pressure increase expected is 8. The actual experimental pressure ratio (Table.2) (Bakos et al. 1992) was measured to be 8.8. Therefore it can be seen that the inviscid calculation of a diffuser contour somewhat overestimates pressure ratio, whereas the boundary layer corrected contour can predict the pressure ratio much more realistically. The fact that the viscously corrected and experimental pressure ratios are not exactly the same may be partly due to the fact that the boundary layer thickness was not precisely known from the data available. Further validation will be provided by the planned experiments.

4. Conclusions

The present work indicates the importance of viscous effects in expansion tubes with nozzles. It demonstrates the significant effect of the displacement thickness correction on the contour and the predicted pressure ratio. As the velocities and Mach numbers of the phenomena of interest increase, it will be important to correct for viscous effects right from the earlier stages of nozzle design, rather than calibrating for viscous effects after construction. The simple correction technique is provided to assist with this type of problem.

Acknowledgement. This work was partially supported by the NASA Langley Research Center (Grant NAGW 674, contract monitor R.C. Rogers).

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