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EXPERIMENTAL HEAT TRANSFER AND PRESSURE INVESTIGATIONS OF "DOUBLE APOLLO DISC" INLET AT MACH 10

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Abstract. "Apollo Command Module's" lower heat shield configuration was tested in the RPI 24-in. diameter Hypersonic Shock Tunnel (RPI-HST). A 6-in. diameter aluminum "double Apollo disc" model was fabricated and fitted with the thin-film platinum heat gauges and piezoelectric pressure transducers over its forebody surface. Freestream Mach 10 flow, with a stagnation temperature of 800 K, was selected to conduct the heat transfer and pressure measurements over the "double Apollo disc" model. When the bare 6-in. diameter "double Apollo disc" model was tested, the heat transfer, the pressure ratio measurements and the Schlieren photographs of the shock structure were found to be qualitatively similar to prior experimental and theoretical results.

Keywords: Hypersonic flows, Experimental heat transfer measurements, Experimental pressure measurements, Blunt body

1. INTRODUCTION

The feasibility of transatmospheric flight is limited by phenomena such as aerodynamic drag and heating as well as related thermal management problems. Traditional blunt-nosed hypersonic vehicles generate a strong detached normal shock wave in the nose region, which produces high aerodynamic drag. The temperature behind this strong shock wave increases at hypersonic velocities, although the aerodynamic heating rates are reduced compared with that of an attached shock wave on a conical body. On the other hand, a traditional slender body with a sharp leading edge produces a conical weak attached shock wave with low drag coefficient, but extreme heating is created at the tip of the forebody.

To resolve these difficulties, an efficient transatmospheric hypersonic vehicle design has to combine a low drag coefficient (to maximize the net propulsive thrust) with low heat transfer rates (to minimize thermal protection system mass).

Nagamatsu et al. (1960) have studied experimental blunt body problems at hypersonic speeds since the 1960s. The RPI Hypersonic Shock Tunnel (Minucci, 1991; Nagamatsu et al., 1960; Nagamatsu et al., 1959) has been used to investigate the aerodynamic characteristics of the flow over bodies at conditions comparable to those encountered by ballistic missiles and satellites re-entering the atmosphere. Nagamatsu et al. (1960) presented the results of investigations into blunt bodies at hypersonic Mach numbers and nozzle stagnation temperatures up to 6000 K. The shock detachment distance was found to be smaller at higher stagnation temperatures because of the real gas effects. For hemispherical bodies, the experimentally-derived pressure distribution was found to be lower than that predicted by modified Newtonian theory for all stagnation temperatures.

Experimental pressure distribution at a nominal freestream Mach number of 10 and Reynolds number ($Re_{\infty D}$) of 1.1 10^6 obtained in Tunnel C at AEDC (Bertin, 1996) has been compared with the modified pressure distribution for the Apollo Command Module at a zero angle of attack.

Moretti and Abbet (1966) applied a time-marching Lax-Wendroff finite-difference technique using the unsteady Euler equations to the flow over blunt hypersonic bodies. Also, MacComarck (1969) employed the explicit, predictor-corrector finite-difference MacComarck's method that has been widely used throughout the 1970s and 1980s. Using a classical computational steady flow approach, Lomax and Inouye (1964) have solved the blunt-body problem with an inverse blunt-body method. The numerical results agree very well with the modified Newtonian theory proposed by Lees. Several other investigators (Davis, 1970; Li, 1972; Rakich et al., 1983; Josyula and Shange, 1991) have performed numerical computations on the blunt-body problem with and without real gas effects.

2. EXPERIMENTAL APPARATUS

The model geometry (Figure 1) consists of a "double Apollo disc", wherein the upper and lower contours are identical and are "scaled" directly from the Apollo Command Module's lower heat shield. A 6-in. diameter aluminum model of the vehicle was constructed to investigate the incident hypersonic flow in the RPI 24-in. diameter Hypersonic Shock Tunnel.

The "double Apollo disc" model (Figure 1) was designed to enable the measurement of heat-transfer and pressure drag across a blunt "double Apollo disc" forebody at hypersonic speeds. The heat-transfer-rate was obtained only across the "double Apollo disc" forebody surface. The pressure data was simultaneously obtained in two regions: 1) across the "double Apollo disc" forebody surface, and 2) within the outer annular slipstream region.

3. RPI 24-in. diameter HYPERSONIC SHOCK TUNNEL

The RPI 24-in. diameter Hypersonic Shock Tunnel (Figure 2) was used to obtain the Mach number 10 flow for the present experiment. Minucci (1991) describes in detail the five components of this facility: the driver tube section, the DDS (Double Diaphragm Section), the driven tube section, the nozzle, and the dump tank. The facility is capable of generating reservoir enthalpies up to 6.5 MJ/kg at a stagnation temperature of 4100 K when operating in the equilibrium interface mode with helium in the driver section.

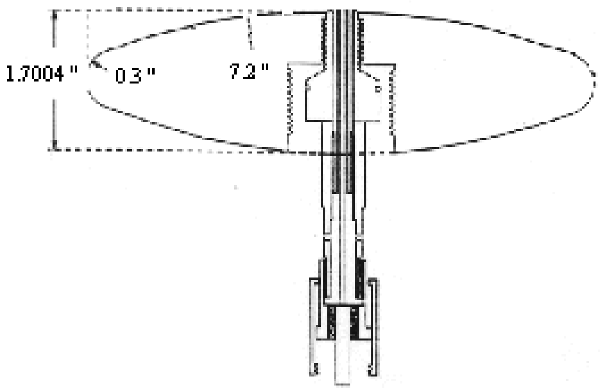

Figure 1. “Double Apollo Disc” Vehicle in Hypersonic Flight and Model

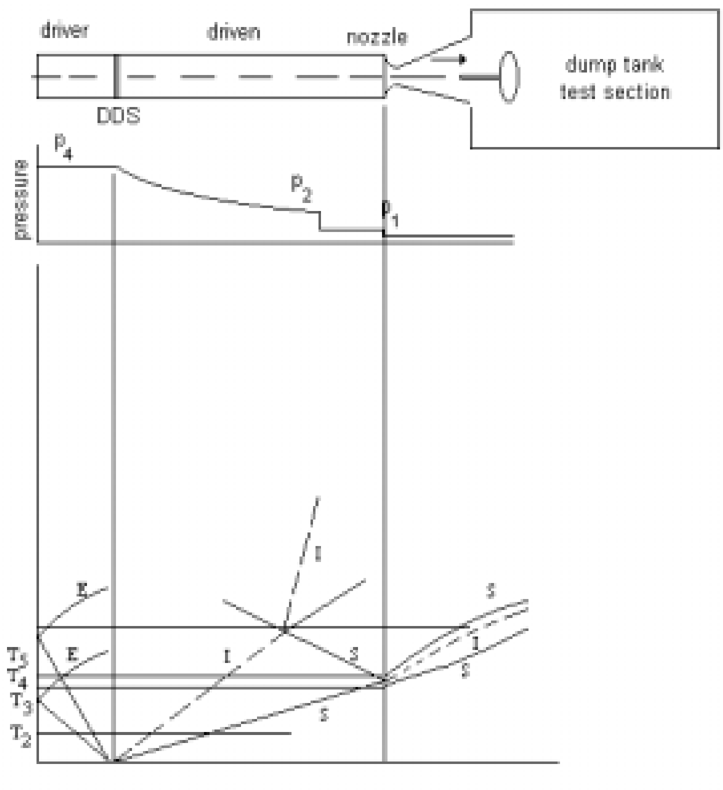

Figure 2. RPI 24-in. Diameter Hypersonic Shock Tunnel

A double diaphragm section (DDS) separates the driver and driven tubes. This section houses one diaphragm at either end. The DDS section controls the rupture of the diaphragms that initiate the shock wave. Stainless steel diaphragms are used to separate the driver and driven gases. For the present investigation, the driven tube was pressurized to about 14.6 psia

(p_1) for Mach number 10. In addition, this section contains the ports for the instrumentation used to analyze the flow, as well as a clamping section that holds a third diaphragm which separates the driven tube from the nozzle and dump tank section. This diaphragm allows the dump tank to have a pressure (p_d) several orders of magnitude lower than the pressure in the driven tube (p_1), facilitating flow establishment in the hypersonic nozzle. Aluminum diaphragms were used in the clamping section.

A 15-degree half angle 24-in. diameter conical nozzle is attached to the end of the driven tube and protrudes inside the dump tank. By using different nozzle throat diameters located in the clamping section, the nozzle area ratio can be varied to produce nominal flow Mach numbers from 8 to 25 for reservoir temperatures of 800 K to 4100 K. The 5-ft. diameter, 200-cubic foot dump tank serves as a large vacuum tank which houses the test section with the model. Two windows in the test section allow flow field visualization by a single pass, spark gap light source. This Schlieren system is located adjacent to the exterior of the dump tank.

Several shock tube conditions are monitored in order to determine the free stream conditions of the flow Mach number in the test section. This data is subsequently transmitted to two RPI-developed flow programs: one to determine reservoir conditions in the reflected region of the driven tube, and a second program to use these reflected conditions and the measured free stream pitot pressure in order to determine the free stream flow parameters. Minucci developed these programs for the RPI Hypersonic Shock Tunnel.

The shock tunnel parameters that are measured are: 1) the elapsed time between two heat gauges; 2) reservoir pressure p_5 located at the position of the nozzle entrance at the end of the driven tube; 3) reservoir/reflected pressure transducer p_2/p_5 located upstream from the aluminum diaphragm; and 4) the free stream pitot probe in the test section located at the same planar position as the central stagnation point of the Lightcraft plasma torch.

Shock tube and free stream data, as well as “double Apollo disc” and pitot rake pressure data are collected with an 18 channel Tektronix Testlab 2520 Data Acquisition System.

4. EXPERIMENTAL RESULTS AND DISCUSSION

When the "double Apollo disc" model was tested, nine thin-film platinum heat gauges and eight piezoelectric pressure transducers were used to measure the heat flux and the static pressure along the frontal surface.

When the "double Apollo disc" 6-in. diameter was tested in the 24-in. diameter Hypersonic Shock Tunnel, the experimental pressure results were found to agree quite well with the analytical results of Modified Newtonian theory (Figure 3). The experimental pressure ratio over the “double Apollo disc” model agrees qualitatively with the experimental pressure coefficient ratio over a flat-nosed cylinder (Kemp et al., 1959). Also, the calculated pressure ratio, using the locally self-similar solutions is qualitatively similar to both, the experimental pressure ratio over a flat-faced body presented by Kemp et al. (1959) and the present pressure ratio results (Figure 3).

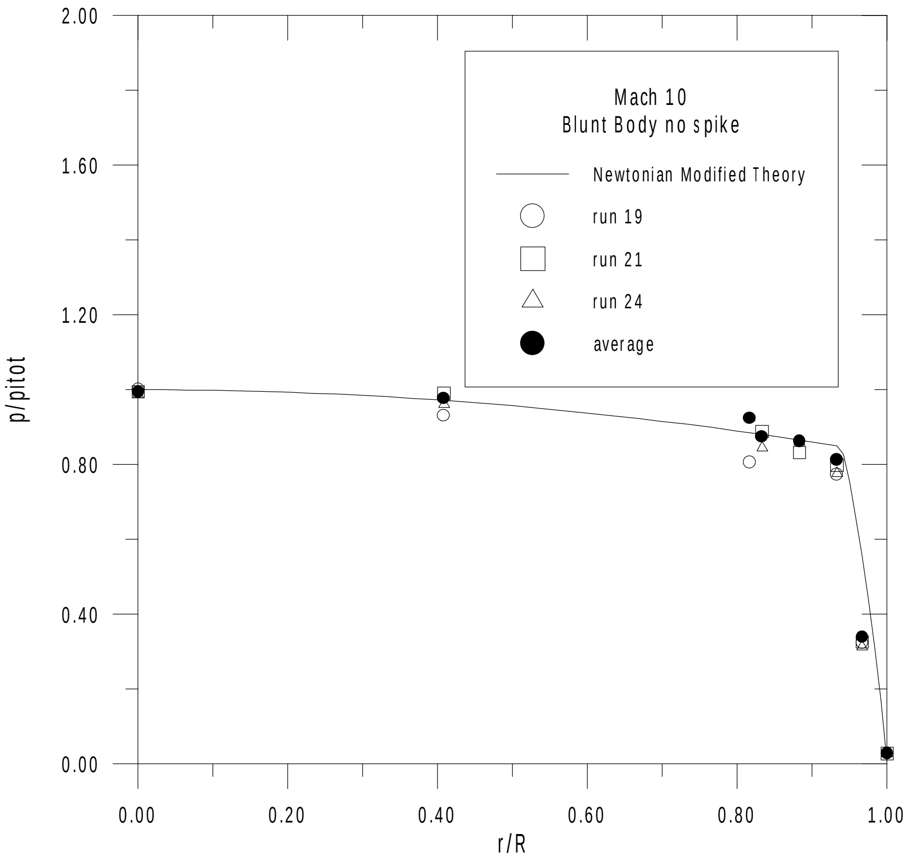

Figure 3. Pressure ratio at “double Apollo disc” model

The Schlieren photograph of Mach number 10 flow over a “double Apollo disc”, shows that the shock is symmetrical, and the shock detachment distance may be estimated by Billing’s correlation (1967) based on experimental data. The stand-off distance of 0.8 in (20.32 mm) agrees with theoretical calculations (Figure 4).

The short test time of the RPI Hypersonic Shock Tunnel, on the order of a few milliseconds, requires the development of fast response heat flux sensors. Thin-film platinum heat gauges are specially suited for use in shock tubes and shock tunnels. Small diameter (2.4 to 3.4 mm) thin-film platinum heat transfer gauges were designed, developed, and constructed to measure the voltage changes when installed on the “double Apollo disc” model. Pyrex and Macor materials were used as a substrate for the thin-film.

Experimental heat transfer measurements across the “double Apollo disc” model surface presents a behavior generally in agreement with available experimental data and theoretical heat transfer predictions (using the locally self-similar solutions, Kemp et al., 1959). Due to rapid flow expansion around the perimeter of a “double Apollo disc” body, the maximum heat transfer is predicted not at the stagnation point, but just at the beginning of the “corner” of the flat-faced nose.

In a very large radius region (i.e., nearly flat surface), the heat transfer trends to the Modified Newtonian theory heat transfer calculation (Figure 5).

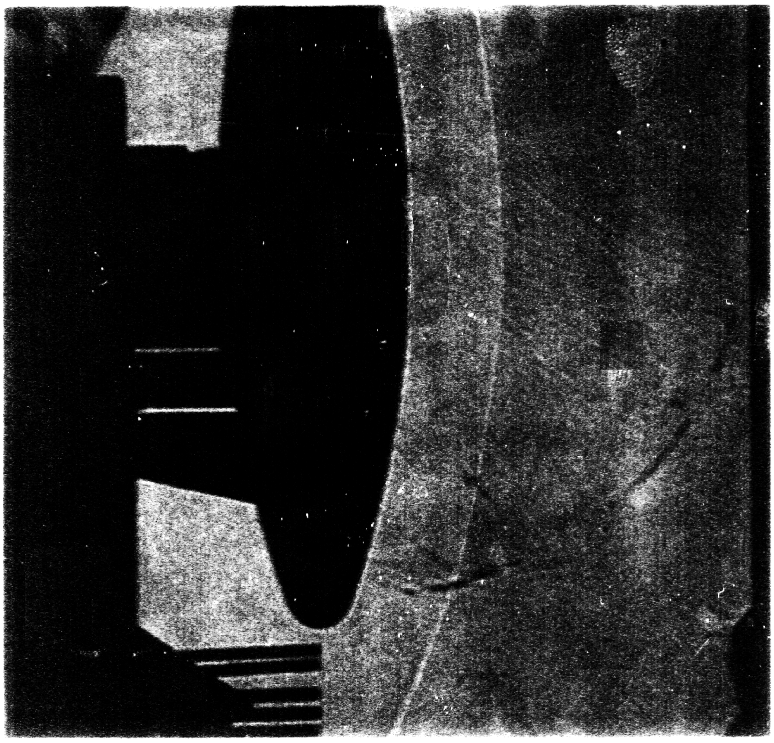

Figure 4. Schlieren photograph of “double Apollo disc” model

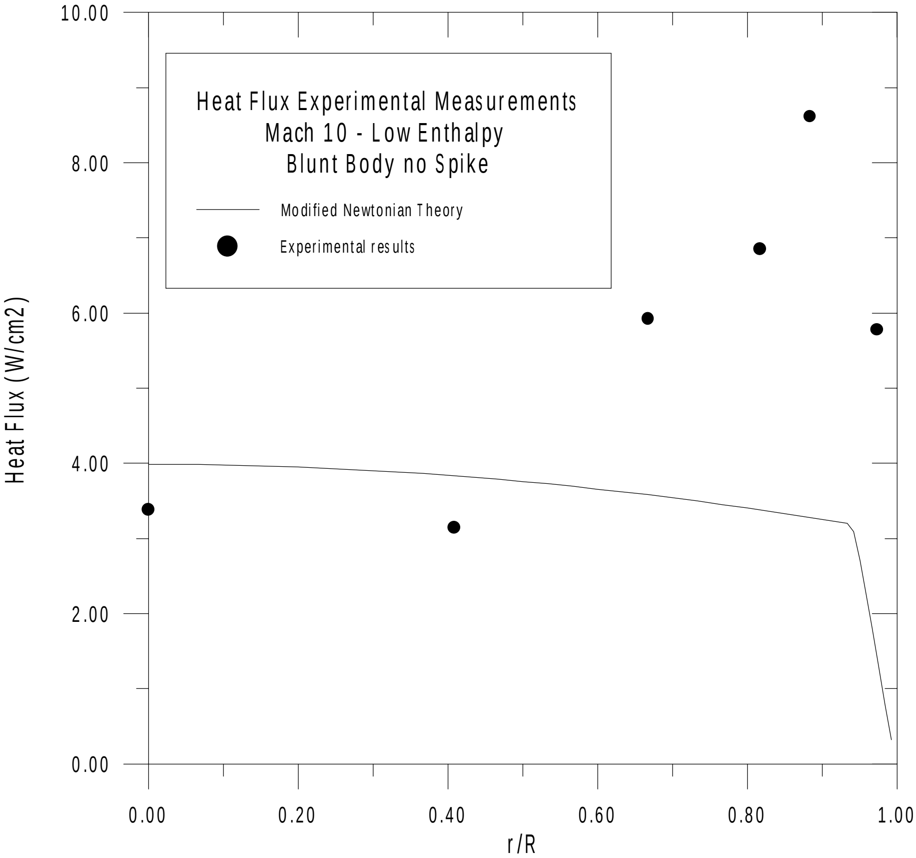

Figure 5. Heat flux at “double Apollo disc” model

The rapid expansion of the inviscid flow around the corner imposes an extremely large favorable pressure gradient on the boundary layer, which results in an actual reduction of the boundary layer thickness. Since the temperature gradient is inversely proportional to the boundary layer thickness, as smaller boundary layer thickness results in a higher temperature gradient, and consequently, higher heat flux at the wall, $q_w = k\left(\frac{\partial T}{\partial y}\right)_w$, therefore, the local heat transfer is expected to increase at the corner (Anderson Jr., 1989).

The pitot pressure measurements taken throughout the outer annular slipstream region, maximum rim diameter, (Figure 4) of Mach number 10 flow over a "double Apollo disc", show that the pressure ratio increases slightly, from the free-stream values r/R = 1.0 to 1.22, and then decreases to nearly free-stream impact pressure (Figure 6).

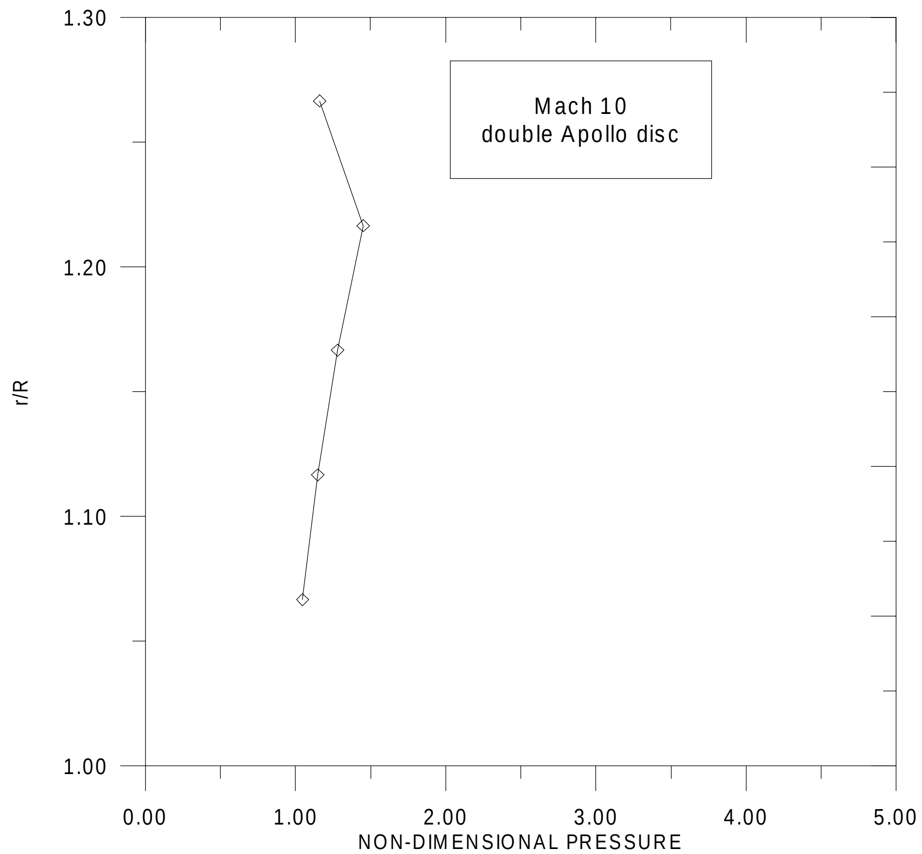

Figure 6. Pitot pressure ratio at rake for "double Apollo disc" model

Toro (1998) presents not only results of pressure and heat transfer measurements of the "double Apollo disc" but also results for the "Directed-Energy Air Spike".

5. CONCLUSIONS

The primary objective of the present experimental investigation was to provide experimental data required for understanding the hypersonic flow characteristics over a "double Apollo disc" for an advanced transatmospheric vehicle.

A 6-in. diameter aluminum model, scaled from the Apollo Command Module's lower heat shield, was fabricated and instrumented with heat transfer gauges and pressure transducers The experimental investigation was conducted in the RPI 24-in. diameter Hypersonic Shock Tunnel on a "double Apollo disc" model configuration. Freestream Mach number 10 flow with stagnation temperature of 800K were selected to conduct the pressure and heat transfer measurements over the "double Apollo disc" model.

Experimental heat transfer measurements across the "double Apollo disc" model forebody present a behavior similar to that of available experimental data and theoretical predictions for hypersonic flow over a flat-faced body. Due to the rapid expansion around the corner of flat faced body, the maximum predicted heat transfer is not located at the central axis stagnation point, but at the beginning of the corner of the flat-hemispherically nosed region.

Schlieren photographs reveal that the flow is symmetrical when a freestream hypersonic Mach 10 flow is established over the "double Apollo disc" model. The pressure data was simultaneously obtained in two regions: across the "double Apollo disc" forebody surface, and within the outer annular slipstream region.

Piezoelectric pressure measurements over the "double Apollo disc" model forebody surface agree quite well with theoretical pressure ratios derived from Modified Newtonian theory. Also, the present experimental pressure ratio results are qualitatively similar to other experimental data for a flat-nosed cylinder, as well as to calculated pressure ratios, using the locally self-similar solutions over a flat-faced body.

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