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A TRANSIENT STAGNATION PRESSURE PROBE FOR TEMPERATURES UP TO 6000K

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ABSTRACT

This paper describes an investigation of the loss mechanisms that occur in free piston compression tubes of the kind used to drive free piston shock tubes, free piston shock tunnels and hypervelocity launchers. The investigation centres around the hypothesis that during the compression stroke of the piston, the thermal boundary layer that forms on the walls of the compression tube is scraped up by the piston and injected forward of the piston as a jet of cooler gas.

To test this hypothesis, a free piston compression tube has been designed to generate pressures of up to 75MPa and temperatures of possibly 6000K in helium. A novel stagnation temperature probe is being developed which will qualitatively study the mode of heat transfer losses and quantitatively measure the magnitude of the losses. The probe operates by sampling a small quantity of gas to measure the temperature.

The performance characteristics of a free piston compression tube is presented. The theory which is used to analyse the experimental data is described. Some preliminary quantitative results are given of the trial of the latest version of the probe.

INTRODUCTION

Free-piston drivers are commonly used for high-enthalpy aerodynamic facilities (Stalker 1966, Stalker and Hornung 1971, Stalker and Morgan 1988, Hornung and Belanger 1990) such as shock tubes and shock tunnels. Free piston drivers are also used to drive two stage hypervelocity launchers. In these devices, reservoir gas propels a free piston down a compression tube as shown in Figure 1. The compression tube is initially terminated by a diaphragm so that the compression tube gas, typically helium or hydrogen, is compressed to high temperature and pressure. As the pressure of the compression tube gas rises, the piston is slowed. When operating at design conditions, the piston stops just as the diaphragm bursts, or soon after. In shock tubes and shock tunnels, the high temperature, high pressure driver gas causes a strong shock wave to propagate along the shock tube compressing the test gas to high temperature and pressure for use as aerodynamic test gas. If the shock tube is replaced by a launch tube with a projectile immediately downstream of the diaphragm, the driver gas can be used to accelerate the projectile to hypersonic speeds.

Such a hypervelocity launcher is of interest when accelerating projectiles to greater than 2 km/s. Unlike chemical propellant launchers which are limited by the temperature and pressure of the propellant gases, free piston driven devices are only constrained by the structural limitations of the compression tube.

Previous studies of the performance of free piston drivers has been mainly concerned with their use in driving shock tubes. Stalker (1966) modelled the compression in this application as an isentropic process. The piston was assumed to be brought to rest at the moment of diaphragm rupture, and the subsequent flow to be based on ideal gas flow in a shock tube with a change of section at the diaphragm. Stalker and Hornung (1971) showed that the so called plateau pressure, the pressure behind the shock reflected at the end of the shock tube was much lower than predicted by this theory. The discrepancy in plateau pressure was observed to increase with increasing compression ratio ($\lambda = L_0/L_1$ in Figure 1). At least part of the energy loss is believed to be due to heat transfer occurring during the compression phase. Knoos (1971) showed that there was significant convective heat loss during compression if piston velocities used were much smaller than the speed of sound in the compression tube gas. Measurements of the actual compression ratios made by Page and Stalker (1983) also showed clear evidence of non-adiabatic compression. Page and Stalker also showed that the plateau pressure deficit correlated well with the clearance volume normalised against the driven tube diameter (L_1/d). The smaller this quantity, the greater the loss in plateau pressure.

In unpublished work, Khatir (1976) showed that a moving piston moving an incompressible fluid scooped up the boundary layer causing a vortex to form in the corner of the piston also causing a turbulent jet of fluid to be injected ahead of the piston. In the present application, this vortex would mean that cold gas adjacent to the wall would be scooped up and directed axially down the centre of the compression tube. This non-homogeneity in the compression tube gas could explain the lower than expected energy in the shock entering the driven tube. It is this hypothesis that is being tested in the present study. It requires simultaneous measurements of the pressure and temperature in the end volume gases in the last stages of the compression stroke.

Transient high temperature measurement in gas dynamic flows is a difficult problem which has no general solution. One approach (eg. Walker & Ng, 1989) is to use a fine sensing element that remains in thermal equilibrium with the changing conditions. Another approach (eg. Schultz & Jones 1973) is to use more robust probes acting essentially as heat transfer gauges the output from which can be mathematically analysed to infer a gas temperature. As is shown below, the conditions of interest in the present work are extremely arduous and so the latter approach has been adopted here.

DESIGN OF EXPERIMENT

Experimental Conditions

The experimental work to study the mode of heat transfer loss from the driver gas in a free piston compressor will concentrate around the compressor shown in Figure 1. This compressor will eventually drive a hypervelocity launcher facility at the University of Queensland. The compression tube is a second hand 4" Leopard Tank Gun Barrel that has had it's rifling removed and been bored to 108mm. The barrel is divided into two sections, the reservoir and the compression tube. The reservoir has been rated to 10MPa and the compression tube has been rated to 75MPa at the high pressure end.

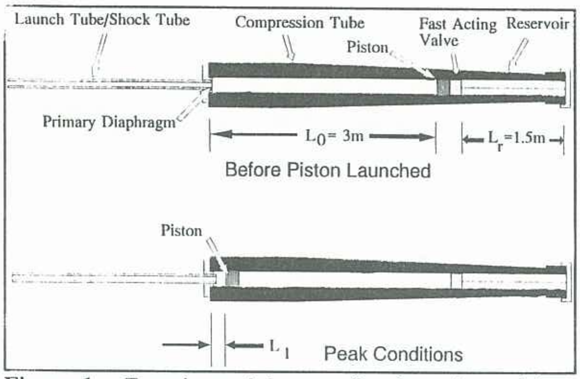

Figure 1 - Experimental layout of a free piston driven shock tube / hypervelocity launcher.

The studies of heat transfer from the compression tube gas will be made using the stagnation temperature probe design discussed below. Five of these probes will be placed in a rake at the end of the compression tube at various radii from the centreline to measure the spatial and temporal variation of temperature of the compression gas.

The physical environment that the probe operates in is very harsh. This environment can cause failure of the probe by two main mechanisms, mechanical failure and thermal failure. The three relevant parameters that determine the severity of the conditions are i) Pressure, ii) Temperature and iii) Duration of test. To be able to adequately design the probe, a simple program was written to simulate the conditions to which the probe is subjected.

The simple analysis was based on conservation of energy between the compression and reservoir gases and the kinetic energy of the piston. It was assumed that the piston velocity was small compared to the sound speed in either gas, and that the combined kinetic energy of the gases was small compared with the kinetic energy of the piston. For the purposes of design, the simplifying assumption was made that the compression and expansion processes were isentropic. With these assumptions, energy conservation leads to,

$$\frac{P_{R0}V_{R0}-P_{R1}V_{R1}}{\gamma_R-1}+\frac{P_{C0}V_{C0}-P_{C1}V_{C1}}{\gamma_C-1}+\frac{1}{2}m_p\ddot{x}^2=Const. \quad (1)$$

Where P is the pressure, V is the volume, γ the ratio of specific heats, m_p the mass of the piston and x its spatial coordinate. Subscripts C and R refer to the conditions in the compression tube and reservoir respectively and the subscripts 0 and 1 refer to the initial and local conditions respectively.

(1) was the basis of a numerical simulation to model the dynamics of the compression process. Given the limiting parameters of (i) Compression Tube Pressure - 75MPa, and (ii) Compression Ratio - 90, the pressure and temperature of the compression tube gases is shown in Figure 2. It can be seen that the transducer has to withstand near peak conditions for about 1 ms (including the first return stroke). Using these peak conditions with the heat transfer relation in (3), to be discussed later, it is found that the a peak heat transfer rate to the probe is around 230 MW/m^2.

To be able to have an adequate resolution of the temporal variation of temperature in the compression tube, it can be seen from Figure 2 that the rise time of the temperature probe must be less than around 0.1ms.

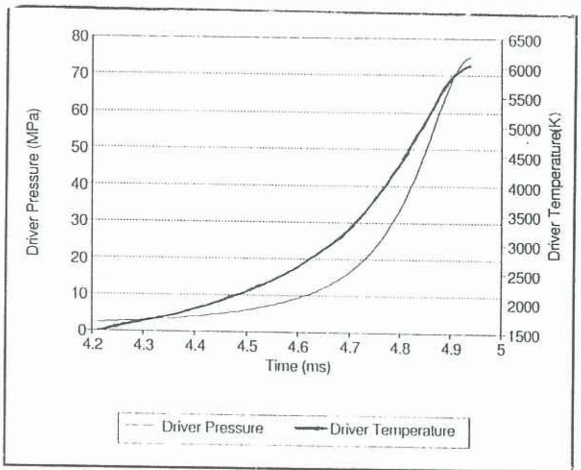

Figure 2 - Simulated Pressure & Temperature variations of the Helium Driver Gas.

From this analysis, several conclusions can be drawn :

(i) The probe must be able to withstand the mechanical loads from a pressure of 75MPa.

(ii) The probe must be able to withstand intense heat fluxes of up to an order of magnitude of 230MW/m^2, and

(iii) The probe must have a response rate of ideally less than 0.1 ms.

Theory of Probe Development

The peak total temperature of the driver gas, in general, is much higher than the melting point of any solid. Therefore it is impossible to measure the temperature of the gas by a probe that comes into thermal equilibrium with it. Instead, the temperature of the gas will be inferred by the simultaneous measurement of heat transfer from the gas and the gas pressure.

In general, the convective heat transfer from a compressible gas to a solid can be described by:

$$\dot{q} = h\,(T_{aw} - T_s) \quad (2)$$

Where $\dot{q}$ is the heat transfer from the gas to the surface of the solid, T is temperature, h is the heat transfer coefficient and the subscripts aw and s refer to the adiabatic wall temperature and the wall surface temperature respectively.

The particular value of the heat transfer coefficient will in general depend on the flow field, the composition and the thermodynamic state of the gas. Hence a formula that predicts h is needed to be able to predict surface heat transfer.

The formula that predicts the heat transfer from high speed gas flowing over the leading edge of a flat plate with laminar flow is of particular interest in predicting h. Holman (1989) gives the expression for these conditions.

$$\left(\frac{h}{\rho C_p u}\right)^{*}_{x}\left(\frac{C_p\mu}{k}\right)^{\frac{2}{3}}_{*} = 0.332\left(\frac{\rho u x}{\mu}\right)^{-\frac{1}{2}}_{*x} \quad (3)$$

Where ρ is the gas density, C_p is the gas specific heat at constant pressure, is the absolute viscosity of the gas, k is the thermal conductivity of the gas, x is the distance from the leading edge and u is the gas velocity. The subscript x denotes that the variables are evaluated at a distance x from the leading edge, and the * superscript denotes conditions evaluated at the Eckert reference temperature defined by-

$$T^* = T_\infty + 0.5(T_s - T_\infty) + 0.22(T_{aw} - T_\infty) \quad (4)$$

with the subscript ∞ referring to conditions immediately outside the thermal boundary layer.

As demonstrated below, this formula was applied to analyse the data from the heat transfer probe. In applying the equation for heat transfer to a flat plate to the case of flow through a circular duct, it is assumed that the boundary layer thickness is small compared with the diameter of the duct.

In other words, by using this analysis, the heat transfer to the probe can be predicted by knowing the Temperature of the gas, the gas Pressure, various transport and physical properties of the gas and the gas velocity. Alternatively, if the heat transfer rate and pressure is measured and the various physical properties evaluated, (2) can be numerically solved for gas temperature. This is the proposed method of determining the temperature of the helium at the end of the compression tube.

A computer program, QDOT, has been written in C++ that solves (2) to determine the temporal variation of the driver gas temperature during the compression stroke and to calibrate each individual probe.

Stagnation Probe Design.

The above analysis of the heat transfer to the probe shows that it is necessary that the gas velocity over the heat transfer gauge be known if the heat transfer signal is to be interpreted correctly. The method of determining the velocity of the gas is to accelerate it through the probe across a pressure difference. The pressure difference across the probe is maintained high enough so that the flow is choked. This ensures that the Mach number of the gas flow at any station upstream of the throat is constant and simply a function of geometry alone. Hence from the equation of state and the Mach number of the gas, the gas velocity can be determined. The original design of the probe (here designated Mk 1) is conceptually shown in Figure 3. Upstream of the annular orifice, the flow is stagnated by a hemispherical probe. At the stagnation point, a thermocouple heat transfer gauge measured the temperature of the gas. This design suffered from several serious problems. The first was the inability of the conventional coaxial thermocouple heat transfer gauge (Schultz and Jones, 1973) to adequately cope with the mechanical and thermal loads. The second was that a tenacious deposit of condensed wear debris formed on the stagnation point of the hemisphere isolating the sensing element from the gas flow.

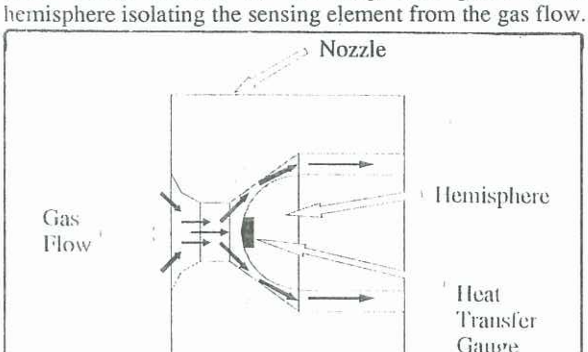

Figure 3 - Original design (Mk 1) for the heat transfer probe.

New designs for the heat transfer probes have been developed to overcome these problems. These new types of gauges must be physically stronger and also able to cope with high heat fluxes. The first new type (here designated Mk 2) is shown in Figure 4. It is constructed by drilling a hole in a layer of constantan then gluing a layer of copper shim over the top. The copper shim is then punched through, extruding to copper through the constantan hole into approximately a 0.040mm thick standard 'T' Type thermocouple junction.

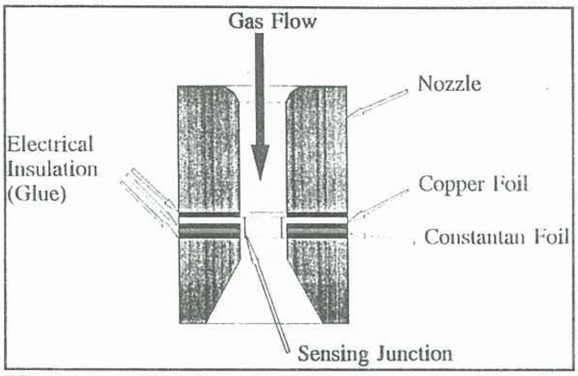

Figure 4 - Revised design (Mk 2) for the heat transfer probe.

To trial this configuration, the probe was tested in the free piston expansion tube, TQ. The tunnel was configured such that the shock from the primary diaphragm reflected at the end of the shock tube to generate conditions of approximately 4.2MPa and 6000K. A piezoelectric pressure transducer was mounted along with the temperature probe in the reflected shock region. The output from the heat transfer gauge was integrated according to,

$$\dot{q}_n(t) = 2\frac{\sqrt{\rho c k}}{\sqrt{\pi}}\left[\sum_{i=1}^{n} \frac{T_s(t_i)-T_s(t_{i-1})}{\sqrt{t_n-t_i}+\sqrt{t_n-t_{i-1}}}\right] \quad (5)$$

which is the "semi-infinite" method of Schultz & Jones (1973), then numerically "smoothed" to determine the heat transfer rate. This data and the signal from the pressure transducer are presented in Figure 5.

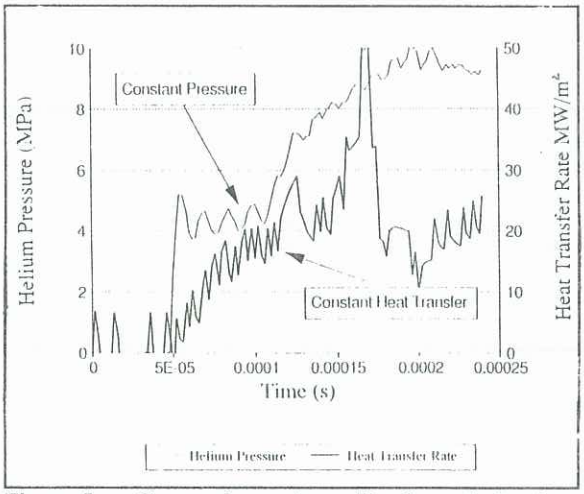

Figure 5 - Output from the calibration of the heat transfer probe (Mk 2) and pressure transducer.

This result indicates that in the reflected shock region, the heat transfer rate is around $18 MW/m^2$. As a comparison, the heat transfer rate was calculated according to (3) with the relevant properties calculated at the Eckert reference temperature as discussed above. The Reynolds number was based on the length of the parallel flow passage upstream of the thermocouple element. For the experimental conditions, the calculated Reynolds number was, $Re_x = 99 \times 10^3$, thus justifying the assumption of laminar flow, and gave a heat transfer rate of $54 MW/m^2$. The discrepancy between the calculated and measured values can be put down to several reasons. Firstly, the heat transfer model from Schultz and Jones (1973) neglects the presence of the copper layer above the constantan. Secondly, the model is for heat transfer to plates in high speed flow, a more accurate model of the heat transfer may be needed. Nevertheless, the figures are of the same order of magnitude indicating plausible results from the heat transfer gauge. With further refinement and proper calibration, this design philosophy has considerable promise.

The next prototype (Mk 3) that is to be tested is shown in Figure 6. It is expected that this probe when comprehensively tested will meet the design specifications as it combines the features of ease and repeatability of manufacture, excellent mechanical strength, small junction mass to junction area and hence a fast theoretical response.

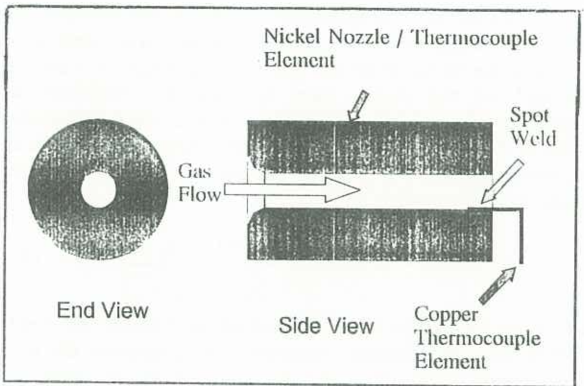

Figure 6 - Most recent design of heat transfer probe.

CONCLUDING REMARKS

Representative conditions have been established for the temperature and pressure in a free piston compression tube. A temperature probe to be used to study heat loss from the compression tube gas must be able to withstand pressures of up to 75MPa, temperatures of up to 6000K and respond in times of less than 0.1ms. It must also be able to withstand peak heat fluxes of about 230 MW/m^2 for about 1 ms.

Several probe designs have been evaluated. The most promising samples the gas through a throat at which there is a thermocouple element. An analytical model has been developed to calculate stagnation gas temperature from a knowledge of the output from the thermocouple and a commercial pressure transducer.

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