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Temperature measurements in a hypersonic gun tunnel using a modified line-reversal method

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Temperature measurements in the test section of a hypersonic gun tunnel using a modified line-reversal two-beam optical pyrometer have been performed. Measurements were made in the shock layer at the front of an 'end-on' flat-faced cylinder using argon or air as the driven gas. The measured temperatures were greater than the calculated isentropic temperatures but much less than the originally predicted shock-heated values. The experimental values agreed reasonably well with the theoretical temperatures for shock-heated air corrected for boundary-layer and heat-loss effects in the gun barrel and also with previously reported experimental values found using heat-transfer methods. Preliminary studies of the vibrational relaxation of nitrogen and air in the test section have been carried out using a flat-sided 'relaxation' tube (a Pitot tube with glass windows). They demonstrated the feasibility of this approach.

1. Introduction

The stagnation temperatures attainable in the FFA hypersonic gun tunnel have been the subject of considerable study during the past two years. Two main lines of investigation have been pursued. One of them has concentrated on heat-transfer measurements using thin-film gauges and calorimeter gauges, and these will be reported by Edney in the following paper (also Edney 1965). The other line has concentrated on an optical method, a modified reversal technique, and is discussed in this paper.

It was of interest to compare the results from these two independent techniques using air as the driven gas. Other gases have been used as the driven gas in the present experiments, namely nitrogen and argon. The nitrogen was used in an attempt to study the vibrational temperature in the test section and through a normal shock, and also to limit contamination due to piston burning. Argon was used to attain higher temperatures at moderate pressure ratios, primarily to test the pyrometer under advantageous conditions of emission and density.

2. Experimental arrangement

The FFA gun tunnel is similar in design to most other gun tunnels, the main difference being the piston, which has been designed to be as light and as strong as possible and, to this end, has been constructed of a polycarbon plastic (see

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Lemcke 1962 and Brown-Edwards 1963, 1965). The piston design was evolved to achieve high piston velocities (and hence temperatures) and, thus, pressure ratios (driving gas pressure/initial driven gas pressure) of the order of 1000 are in common use.

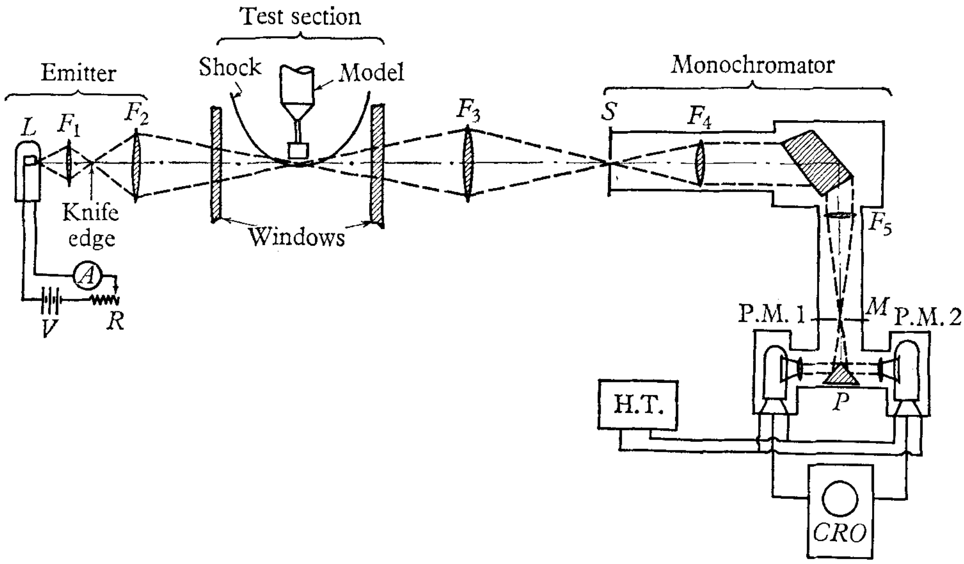

FIGURE 1. Schematic diagram of optical pyrometer.

The optical pyrometer used is shown schematically in figure 1. It has three main components: (1) an emitter which is a calibrated background source of radiation together with suitable optics to produce an image of the source in the hot gas whose temperature is to be measured, (2) a monochromator (constant-deviation prism Pellin–Broca) to give the desired wavelength and bandwidth of the spectrum, (3) a photoelectric recording system consisting of two RCA 1P21 photomultipliers and a Tektronix oscilloscope. The pyrometer operates on the two-beam principle and three quantities are measured simultaneously during a test run. These are: radiation from the hot gas alone, radiation from the calibrated background source alone, total radiation from the hot gas and the background source together. These three measured quantities are then used with the following equation to give the required gas temperature:

$$\frac{1}{T'_G} = \frac{1}{T_L} - \frac{\lambda}{c_2} \log_e \tau, \tag{1}$$

where T'_G = true gas temperature,

T_L = brightness temperature of background source at wavelength λ,

c_2 = radiation constant,

τ = function of the three measured quantities.

The derivation of (1) comes from Planck's radiation law and Kirchoff's law and may be found in many reports on optical methods of measurement (see, for example, Brown-Edwards 1965).

Because the radiation from the test gas is rather small at the temperatures of interest here (< 3000 °K), an additive must be introduced which does radiate sufficiently at these temperatures. In the present experiments, sodium chloride was chosen since this gives high intensity of radiation with only small amounts of additive, and the sodium *D*-line at 5890 Å was selected as the spectrum line. The sodium was introduced into the test gas by depositing a saturated solution of pure sodium chloride and distilled water on to a nichrome spiral mounted inside a glass tube which was connected between the driven gas container and the gun barrel. The barrel and glass tube were evacuated to a low pressure (about 5 mmHg) and a high current passed through the coil. The smoke of sodium chloride

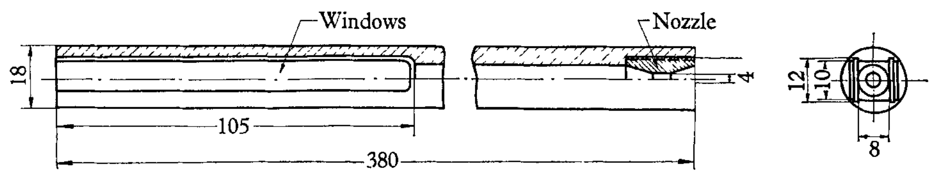

FIGURE 2. Flat-sided relaxation tube with optical glass windows.

evolved was then carried into the driven section of the gun by allowing the test gas to pass slowly over the heated coil and into the barrel. The two-beam method of temperature measurement used here has been assumed to 'follow' the vibrational temperature of the test gas. The evidence upon which this assumption is based has been given in detail by Gaydon & Hurle (1963) and is a fairly common assumption made with reversal methods. In order to study vibrational relaxation behind a normal shock wave in a diatomic gas, a 'flat-sided relaxation tube' has been designed and is sketched in figure 2. It consists, basically, of a tube with a constriction at the downstream end and two flat windows at the upstream end. The constriction provides residence times in the tube which are an order of magnitude larger than blunt body values. The flat windows allow the light beam from the background source to be focused inside the tube. The tube is mounted on a support inside the test section of the tunnel and may be moved axially to allow temperature profiles behind the nose shock to be measured.

3. Results and discussion

3.1. *Measurements using argon as the driven gas*

Because of some early difficulty found in measuring temperatures in air, it was decided to use argon as the driven gas so as to increase substantially the sodium emission at only moderate pressure ratios. The measurements were made at the stagnation point of a 10 mm 'end-on' flat-faced cylinder. However, to obtain successful measurements, the tunnel had to be partially blocked by running with the dump tank at a fairly high pressure (about 50 mmHg). This was due to the nozzle used, which had been designed for a Mach number of 10 in air. Calculations for argon at this area ratio showed that the Mach number in argon would be 20 (from experimental pressure records the Mach number was actually 18·5). The flow was rather unsteady at these conditions (as shown by pressure traces) but the response time of the pyrometer was sufficiently rapid to follow the fluctuations. The shock stand-off distance, or rather the strongly emitting region, was greater than ten times that with steady flow in the nozzle. The temperatures evaluated from oscilloscope records are shown in figures 3 and 4. The time variation of temperature (a typical run is shown in figure 3) shows that the temperature rises gradually over the period 5–10 msec, the first 5 msec of the run with no emission being the nozzle starting time. The temperature then stays approximately steady for the next 7–8 msec and then falls off to the end of the run. The rate of fall in temperature was about 20 °K/msec for all runs and is somewhat higher than the value in air (Edney 1965).

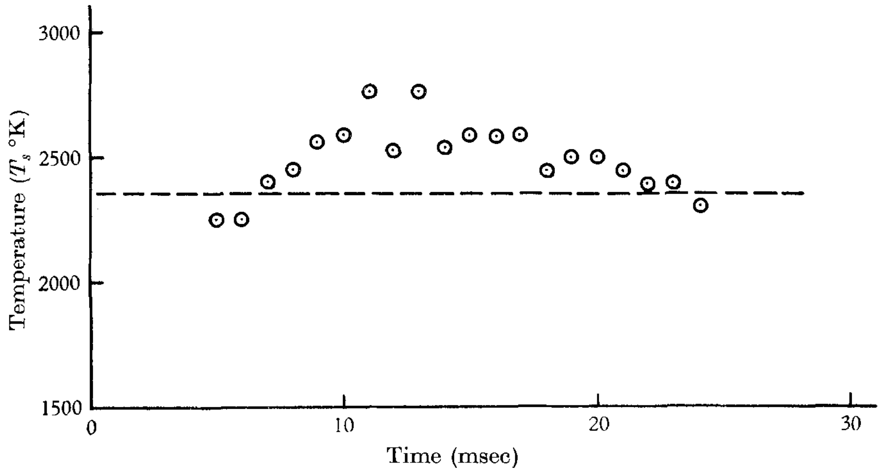

FIGURE 3. Variation of stagnation temperature with time for $p_\alpha/p_0 = 210$ and argon as the driven gas. ———, isentropic; ⊙, experimental.

The experimental temperatures at various pressure ratios, shown in figure 4, are the averaged values taken over the period 10–16 msec after the start. They are compared with three theoretical curves in figure 4, the lower curve assuming isentropic compression of the driven gas from its initial pressure p_0 to the pressure of the driving gas p_α, the middle curve assuming shock compression by the initial shock followed by isentropic compression to p_α after this shock reaches the end of the barrel, and the upper curve assuming one reflected shock followed by isentropic compression after this reflected shock strikes the piston. The experimental temperatures lie somewhat above the isentropic curve but below even the simplest assumed shock compression curve, this effect becoming very pronounced at the higher pressure ratios. This was also found by Edney (1965) for air and was thought to be due to boundary-layer and heat-loss effects in the barrel. The present results show that the losses are also very high for argon.

Finally, it should be pointed out here that, by reason of the method of introducing the sodium chloride, sufficient air is present in the argon to give concentrations between 0·60 and 0·94 % by volume. It is, therefore, almost certainly the vibrational temperature of the air which has been measured and, although the introduction of small amounts of a vibrating gas was accidental, it has subsequently shown to be very fortunate. Other workers have, in fact, carried out

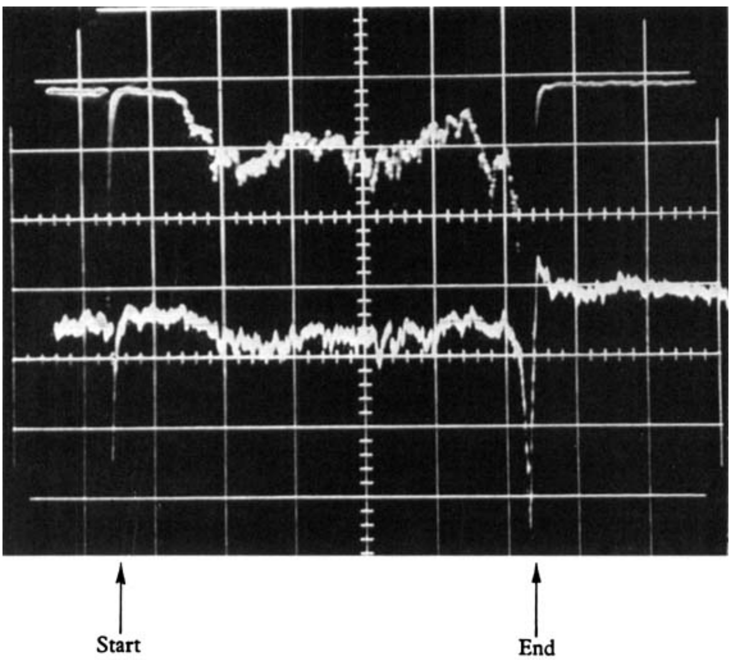

FIGURE 5. Temperature record of the emission from the stagnation point of a 15 mm flat-faced cylinder for $p_\alpha/p_0 = 900$, $M = 12$ and air as the driven gas.

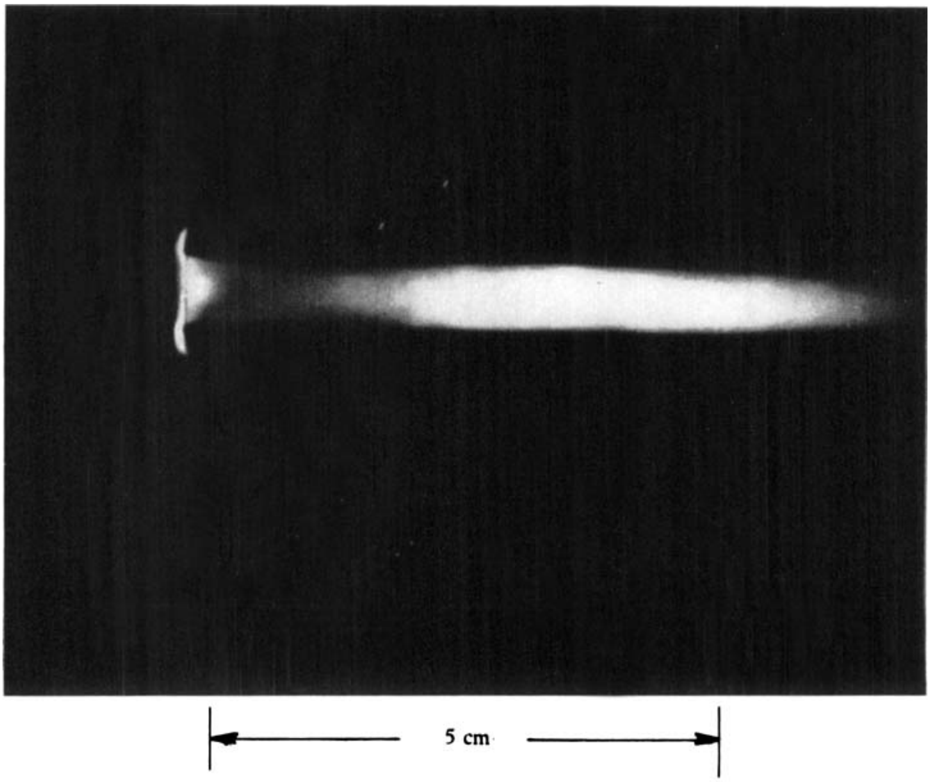

FIGURE 7. Radiation from the flat-sided relaxation tube at a Mach number of 10 showing the relaxation zone. $p_\alpha/p_0 = 750$; driven gas—nitrogen; sodium chloride added.

temperature measurements in argon behind shocks by deliberately introducing small amounts of a vibrating gas. Tsuchiya & Kuratani (1965), for example, used small amounts of carbon monoxide (0·5 % and thus of the same order as the air present in the tests described here) to study temperatures behind a reflected

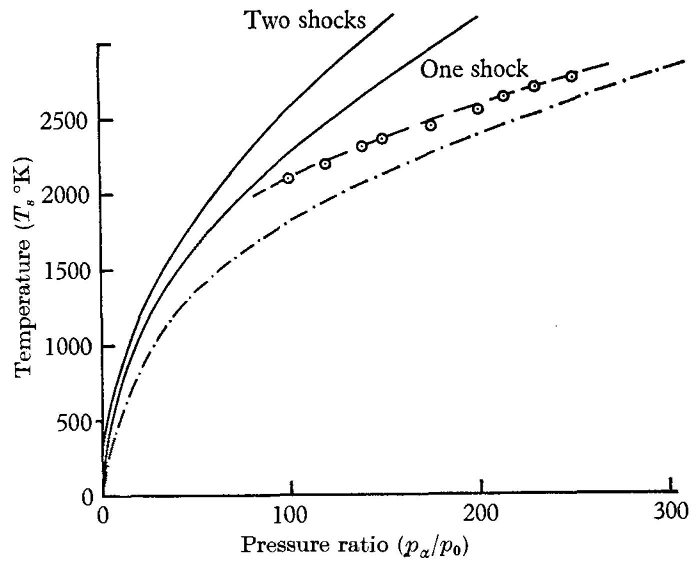

FIGURE 4. Stagnation temperature versus pressure ratio for argon as the driven gas. —⊙—, experimental points; —·—·—, isentropic curve; ——, theoretical.

shock in argon. If extremely pure argon had been used it is probable that large relaxation times or lengths would arise because of the inefficient transfer of energy from the translational mode to the electronic excitation mode, but these were not present in these experiments as has been checked by using a simple form of the relaxation tube described above. It therefore seems reasonable to assume that the temperatures measured at the stagnation point are fairly close to the stagnation temperature of the gas.

3.2. *Measurements using air as the driven gas*

The first measurements attempted with the pyrometer (apart from a simple test on a Meker burner flame) were in the shock layer at the nose of a 15 mm 'end-on' flat-faced cylinder with air as the driven gas. The Mach 12 nozzle was used and either 'Scotch' tape, or shaped Teflon plugs, as nozzle diaphragms. A typical temperature record is shown in figure 5, plate 1. The high noise level is due to the fast response time of the external electrical circuit (about 50 μsec). The upper trace shows the emission from the calibrated background source and the hot gas. The large emission spike at the start of the run is due to nozzle starting effects and the tape diaphragm. No such spike was observed when the Teflon plug was used. Gorowitz (1964) also reports strong emission at the start of a run when studying radiation phenomena in a shock tunnel and concludes that it is caused by relaxation effects during tunnel starting. Since he used a Mylar nozzle diaphragm it seems probable that, in the light of the observations in the present experiments with the tape and plug diaphragms, the radiation was also caused by glowing diaphragm particles. After the initial radiation spike on figure 5, there is a period of 5 msec with no emission which is the tunnel starting time, followed by a fairly steady region of emission (and temperature) for about 20 msec which would be the tunnel running time at this Mach number. Finally, there is a region of very strong emission for the last 3–5 msec of the run probably due to burning piston material.

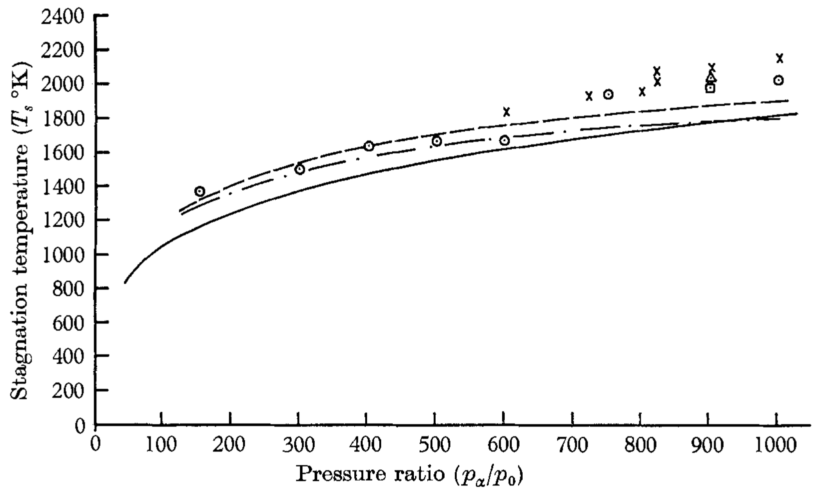

FIGURE 6. Stagnation temperature versus pressure ratio for air as the driven gas. ——, isentropic real gas; — — — —, $p_\alpha = 250$ atm and, —·——·—, $p_\alpha = 150$ atm, theoretical with boundary-layer correction. ⊙, calorimeter gauge. Two-beam method: ×, 15 mm flat-faced cylinder—M 12; ⊡, flat-sided relaxation tube—air; △, flat-sided relaxation tube—nitrogen.

The difference in level of the lamp signal at the start and end of the run was caused by dirt deposited on the test section windows which has come partly from the Scotch tape diaphragm and mainly from the burning piston (this also gives rise to the strong emission signal at the end of the run). Subsidiary experiments using a high-speed camera showed that these glowing particles arrived at the end of the run and thus, in evaluating the temperature records, it has been assumed that the absorbing material on the windows did not affect the initial level of the background source. The temperatures, averaged over the period 10–20 msec after the start, obtained at various pressure ratios are shown in figure 6 and compared there with three theoretical curves and some experimental values from heat-transfer gauges (Edney 1965 and following paper). The two upper broken curves were calculated by Edney, who modified the theoretical values given by Lemcke (1962) by including a correction for boundary-layer and heat losses in the gun barrel for two values of the driving pressure. The temperatures as measured by the two-beam method agree reasonably well with the corrected theoretical curves and also with Edney's experimental values. The small discrepancy is probably due to different driving pressures since Edney used a

$p_\alpha = 150$ atm whereas, in the present tests, values of p_α between 180 and 225 atm were employed. Corrections to allow for vibrational effects were not necessary in this particular series of tests since the 15 mm model was slightly too large to establish Mach 12 flow. Schlieren photographs and emission pictures taken with a Polaroid camera showed that a shock was formed rather far in front of the model (2 or 3 times the normal shock stand-off distance).

3.3. *Relaxation tube measurements*

The final series of tests in air and the only tests for nitrogen were the measurement of the variation of vibrational temperature with distance behind a normal shock produced in the test section (hence in the expanded flow). Figure 7, plate 2, shows a photograph taken with a Polaroid camera of the radiation from the flat-sided

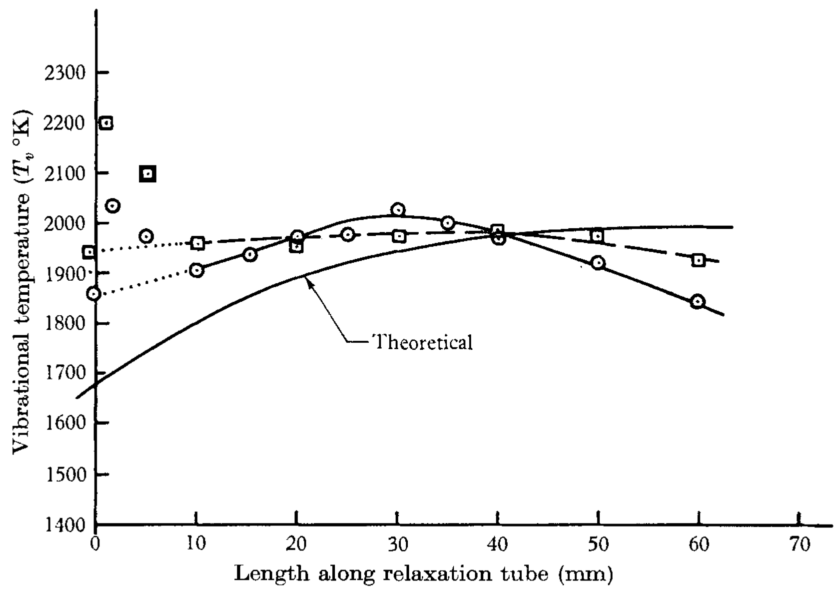

FIGURE 8. Temperature versus distance along the flat-sided relaxation tube $p_\alpha/p_0 = 900$. ⊡, driven gas—air; ⊙, driven gas—nitrogen.

relaxation tube for a pressure ratio of 750 with sodium chloride added to nitrogen. It shows clearly the relaxation zone and the limits of the region of brightest radiation were between 2 and 5 cm from the front of the tube. Several photographs have been taken at various pressure ratios and almost all showed this effect. It was, however, necessary to use Teflon plug nozzle diaphragms or otherwise the relaxation zone could be concealed by radiation from glowing tape particles. No pictures of this type were possible in air as the burning piston obscured all such time-integrated photographs.

The temperatures evaluated from oscilloscope records are shown in figure 8 for air and nitrogen at a pressure ratio of 900. The curve for nitrogen shows a marked relaxation effect, the temperature reaching a peak of 2050 °K at a distance of 3 cm. The values found for both air and nitrogen at 2 and 5 mm were not as expected since it was thought that the temperature, if anything, would fall towards the shock because of relaxation effects in the nozzle and through the shock. Because of these two points, an extra measurement was made between the shock and the front of the relaxation tube (at 0·5 mm in front of the tube). The values found at this point agree with the dotted continuation of the curves. An error therefore seems to exist in the measurements at 2 and 5 mm. Part of this error was found experimentally to be due to absorbing material deposited on the relaxation tube windows, but this only accounted for, at most, 100 °K. It is possible that the rest of the difference is caused by burning or melted piston particles giving a false emission signal or reflexion from inside the cloud of sodium particles. More study is required before this can be answered completely. For air, the temperature stays fairly constant between 1950 and 2000 °K and for nitrogen the maximum temperature was 2050 °K. These values have also been plotted in figure 6 and agree well with the other results shown there. A theoretical curve for the temperature distribution behind the shock has also been shown in figure 8, calculated using the methods given by Stollery & Smith (1962) and Johannesen (1961). The form of the experimental results is similar to the exponential theoretical curve (for a diatomic gas) but the flow seems to have 'frozen' at a higher level than the 1650 °K calculated using Stollery & Park's (1964) data. Hurle, Russo & Hall (1964) have reported that, in order that theoretical and experimental values of the relaxation time measured in an expanding nitrogen flow should agree, it was necessary to postulate a relaxation time fifteen times shorter than that derived from measurements behind strong normal shock waves. However, the results obtained in the present tests do not seem to indicate this and, if anything, the results indicate that a slower relaxation time in the expanded flow would be necessary to make the vibrational temperature freeze at the value of 1840 °K found. Holbeche (1964) has done some measurements of the vibrational relaxation of oxygen through a non-steady expansion and came to a similar conclusion to the present one, namely that the experimental observations suggest that de-excitation proceeds more slowly than usually assumed from shock measurements. The fall in temperature towards the end of the tube is probably due to heat losses and boundary-layer growth in the tube and no allowance has been made for this in the theoretical curve.

4. Conclusions

(i) The modified line-reversal two-beam optical pyrometer could be successfully used to measure temperatures in the expanded flow of a hypersonic nozzle.

(ii) The temperatures attained in both air and argon were greater than the calculated isentropic temperatures but much less than the theoretical shock-heated values.

(iii) The temperatures with air and nitrogen as the driven gas agreed well with the experimental values found by Edney (see following paper) using stagnation-point heat-transfer gauges and also with theoretical values corrected for boundary-layer and heat-loss effects in the gun barrel.

(iv) Photographs taken of the flat-sided relaxation tube showed, qualitatively, the existence of a vibrational relaxation zone in nitrogen but the burning piston made it impossible to see whether such a zone existed in air.

(v) Vibrational temperatures measured along the relaxation tube showed, quantitatively, the existence of a relaxation effect in nitrogen.

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