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AD 294 131

ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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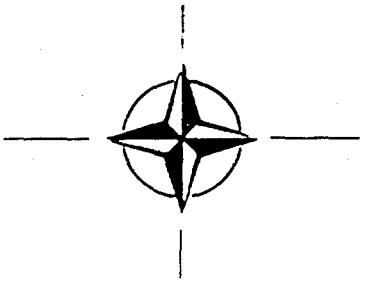
REPORT 327

EXPERIMENTAL MEASUREMENTS OF TEMPERATURE AND RELAXATION TIMES BEHIND SHOCK WAVES

by

A. G. GAYDON and I. HURLE

SEPTEMBER 1959



NORTH ATLANTIC TREATY ORGANISATION

REPORT 327

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ADVISORY GROUP FOR AERONAUTICAL RESEACH AND DEVELOPMENT

EXPERIMENTAL MEASUREMENTS OF TEMPERATURE AND RELAXATION TIMES BEHIND SHOCK WAVES

by

A.G. Gaydon and I. Hurle

This Report is one in the Series 320-333 of papers presented at the High Temperature Gas Characteristics Meeting of the AGARD Wind Tunnel and Model Testing Panel (now Fluid Dynamics Panel) held 21-23 September 1959, in Aachen, Germany

SUMMARY

By using a photomultiplier and cathode-ray oscillograph responsive only to changes in light signal, the sodium-line reversal technique has been adapted for time-resolved studies of temperature behind shock waves produced by a bursting diaphragm. A double-beam system has also been developed, which eliminates changes due to varying concentration of added metal, and interference filters can be used instead of a spectrograph.

General agreement between calculated and observed temperatures is obtained, but both air and oxygen show a high-temperature region due to burning at the interface with the hydrogen driver gas. In nitrogen around 2400°K, a low-temperature region close to the shock front may be attributed to a vibrational energy lag of the order of 100 μs, the sodium excitation following the effective vibrational temperature rather than the translational temperature of the nitrogen. In oxygen, evidence for a dissociation relaxation effect is obtained for shocks, giving temperatures of around 2500°K; this produces an abnormally high temperature near the front. The period of uniform flow is only about half that expected for a real inviscid gas. For carbon dioxide, there are indications of dissociation relaxation. For argon, reversal temperatures are too low because of radiative disequilibrium.

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SOMMAIRE

A l'aide d'un photomultiplicateur et d'un oscillographe cathodique ne sensible qu'aux variations du signal de brillance, la méthode de renversement de la raie de sodium a été adaptée aux études, résolves dans le temps, de la température derrière des ondes de choc produites par un diaphragme éclatant. Une méthode à deux faisceaux a également été réalisée qui supprime les variations dues à la concentration différente du métal ajouté, et des filtres interférentiels peuvent remplacer un appareil spectrographique.

Une concordance générale entre les températures calculées et les températures constatées est obtenue, mais tant l'air que l'oxygène montrent une région à haute température due à la combustion se produisant à la surface de contact avec l'hydrogène utilisé comme gaz d'entraînement. Dans le cas de l'azote à environ 2,400°K, une région basse température au voisinage du front de choc peut être imputée à un retard énergique vibratoire de l'ordre de 100 μs , l'excitation du sodium suivant la temperature de vibration effective plutôt que la température de translation de l'azote. Dans l'oxygène, des traces d'une détente due à la dissociation se manifestent pour des chocs donnant des températures de l'ordre de 2,500°K; ce qui provoque une température anormalement élevée au voisinage du front. La période de l'écoulement homogène n'est que la moitié environ de celle prévue pour un gaz réel non visqueux. L'emploi de l'acide carbonique fait apparaître des indications d'une détente due à la dissociation. Dans le cas de l'argon, les températures de renversement sont trop faibles, en raison du déséquilibre de rayonnement.

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EXPERIMENTAL MEASUREMENTS OF TEMPERATURE AND RELAXATION TIMES BEHIND SHOCK WAVES

A. G. Gaydon and I. Hurle*

1. INTRODUCTION

In recent years the bursting-diaphragm shock-tube has become a powerful tool for high-speed aerodynamic studies and also for the study of high-temperature chemical and physical processes. Among the phenomena studied have been the initiation of combustion, time of attainment of dissociation equilibria, vibrational relaxation times, heats of dissociation, ionization processes and excitation of flame-type and steller-type spectra. In simple theory, a sharp discontinuous temperature rise occurs at the shock front, and then there is a uniform flow region in which pressure and temperature are constant, followed by a sharp temperature fall at the contact surface between the shock-heated experimental gas and the cool expanded driver gas. A variety of techniques, including schlieren photography, interferometry, pressure-sensitive and heat-sensitive gauges, ionization probes and micro-wave attenuation, have been used to study the properties of the gas immediately behind the shock front. Direct measurement of the most important property - the temperature - is, however, difficult. Model[1] made some temperature estimates of very intense shock waves at high gas pressure, produce by solid explosives, using a brightness and emissivity method. Recently Clouston, Gaydon and Glass[2], and Clouston, Gaydon and Hurle[3] have developed a modified sodium-line reversal method for the measurement of temperatures in the 2000 to 3000°K temperature range. Full details of this method are given in the original papers. Here it is our purpose to summarise the method, give some preliminary results on the comparison of predicted and calculated temperatures and on the use of the method for studying molecular relaxation processes, and to put forward certain problems for discussion.

The sodium-line reversal method is commonly used for the measurement of temperature of flames (see Gaydon and Wolfhard[4]). It can be shown from Kirchhoff's law that, for a hot gas in equilibrium viewed against a hot background source emitting a continuous spectrum, the yellow sodium lines will appear bright in emission above the continuous spectrum if the gas is hotter than the background, and dark in absorption if the gas is cooler than the background. When a brightness temperature of the background and the gas temperature are the same, the sodium lines disappear, i.e. are just at the reversal point. In the normal method, the temperature of the background source, usually a strip-filament tungsten lamp, is adjusted until the sodium lines are seen visually in a spectroscope to be just at the reversal point, and then the brightness temperature of the background source is measured with an optical pyrometer calibrated against a black body. In the short time of a shock tube experiment such visual observation is obviously impossible; instead, we have used a photomultiplier system to record the relative brightness of the shock-heated gases against a convenient background source. The light beam from this source is first focused into the shock tube, through quartz windows, and then on to the slit of a monochromator or interference filter which isolates the sodium yellow wavelength prior to collection at the photomultiplier. The output signal from the latter is displayed on a cathode ray oscillo-

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graph and only changes in light intensity are recorded; thus, as the shock front passes the windows the cathode ray trace is deflected positively if there is emission of the sodium lines, and negatively if there is absorption. In these first experiments, information was obtained as to whether the shock-heated gases were above or below the brightness temperature of the background source. To determine the temperature it was necessary to run off a number of similar shocks with the background set at different brightness temperatures. In the later modification of the method, a double-beam system has been used in which two photomultipliers are used to sight effectively on background sources at slightly different temperatures, these temperatures being adjusted so that one cathode ray trace is deflected to indicate emission and the other to indicate absorption. The two beams are adjusted to similar sensitivity and it is then possible to interpolate (or within limits to extrapolate), so that the shock temperature is obtained from the two deflections using a single shock. It is also possible to study variations of temperature with a time resolution of a few microseconds.

2. EXPERIMENTAL

2.1 The Shock Tube

We have used a circular-section shock tube of 2½ inches diameter. The high-pressure section was 2 feet long and the low-pressure section 9 feet from diaphragm to windows. All measurements were made on the primary shock wave, reflections being reduced with a dump chamber. The tube itself was of electrolytic copper, this being spectroscopically fairly clean. The diaphragms were of annealed aluminium, 0.15 mm thick, and were allowed to burst under pressure, i.e. were not stabbed. The normal bursting pressure was about 7 atmospheres, this being measured with a gauge which recorded the maximum pressure reached. Hydrogen was used as driver gas for work with oxygen, nitrogen, air or carbon dioxide; but, with argon as experimental gas, we used helium as driver as this gave temperatures in the 2000-3000^{o}K range, with a convenient initial pressure of argon and with less risk of interference from the rarefaction wave reflected from the end of the high-pressure section. The experimental section was evacuated to about 0.01 mm of mercury pressure, flushed with experimental gas and then filled to the selected pressure, usually between 3 and 20 mm.

2.2 Measurement of Shock Speed

Preliminary attempts to use ionisation probes to measure the shock speed were not very satisfactory as there appeared sometimes to be appreciable delay between passage of the shock front, as detected with heat-sensitive gauges, and the establishment of high ionisation. Much of the work was done with heat-sensitive gauges made of a thin film of gold evaporated on to a film strip. Electrical contacts to these were, however, sometimes unsatisfactory and tended to be sensitive to pressure changes. For the later work we have used heat sensitive platinum gauges, made by painting the end of a short length of 7 mm diameter soda glass rod with a narrow film of colloidal platinum and firing to about 600^{o}C. Acknowledgements are due to R.R.E., Malvern, for advice on this technique.

Three of these gauges were inserted into the tube, two before the observation windows and one just past the windows. The ends of the glass rods were set as flush as possible with the walls of the tube. A constant current of about 15 milliamps was passed through each platinum film, the film resistance being about 20 ohms. The voltage outputs of the first two gauges were differentiated to obtain sharply rising pulses due to the passage of the shock front, whilst the last gauge was allowed to record the full voltage change. The signals from the three gauges were displayed on one beam of a double-beam oscillograph, while the other beam was used for a calibrated time scale. This was obtained from a crystal controlled oscillator circuit adjusted to give large pulses every 100 μ-seconds; these intervals were further subdivided by smaller 20 μ-seconds markers. A typical pair of traces for measuring shock speed is shown in Figure 1a.

2,3 The Optical System

In the original single-beam system, light from a Pointolite background source was focused into the shock tube with a simple lens, through a plane window set as nearly as possible flush with the wall of the tube. The light passed through the tube and out at a second window and was focused with a second lens on to the slit of a spectrograph. The aperture of the second lens was limited with a stop, so that the spectrograph received only the same solid angle of light from the shock-heated gases as from the background source (i.e. the aperture of the second lens was kept smaller than that of the first). In this single-beam work either a large two-prism Littrow spectrograph or a blazed grating spectrograph was used. The stronger sodium line was focused on a second slit placed in front of the photomultiplier.

For the double-beam system, an extra pair of windows at right angles to the first pair were added to the shock tube, and the double beam was obtained with a pair of front-surface aluminised mirrors, M_1 and M_2, as indicated in Figure 2. This indicates the direct beam from the Pointolite lamp, P, passing through lens, L_1, windows, W_1 and W_2, the aperture, A_1 and lens, L_2 on to the first photomultiplier, PM_1. The other beam from the same Pointolite passes through L_3, is reduced in intensity to a lower effective brightness temperature by the neutral filter, NF, and then passes via the mirrors M_1 and M_2 and windows W_3 and W_4, through L_4 on to the second photomultiplier, PM_2.

For this system (Fig. 2), the spectrograph was replaced by two interference filters, IF_1 and IF_2, in front of the photomultipliers. These were a matched pair of filters made by Messrs. Barr and Stroud designed to transmit the sodium yellow lines. They had a maximum transmission of about 35% and a transmission band half-width of 60 Angstroms.

In setting up this optical system it was necessary to use considerable care to see that all lens alignments were accurate and all apertures adequately filled, taking into account the finite size of objects and images. Any loss of light from the Pointolite background will tend to cause an error, the measured temperatures coming too high.

2.4 The Sensitivity of the Method

The sensitivity is determined by the signal-to-noise ratio in the photomultiplier output. The signal amplitude depends on the sodium atom concentration and linearly on the light intensity. The noise is due to statistical fluctuation in the photomultilpier and follows the square root of the incident light intensity. The sentivity is thus most favourable with high light intensity, i.e. with a large aperture in the light beams and a large area of photomultilpier surface illuminated. It is, however, necessary to compromise, as a large image in the shock tube or a wide-angle beam limits the time resolution.

2.5 The Electronic Circuits

The double-beam Cossor oscillographs have been used, a 1035 Mark II for measurement of shock speed and a 1059 for displaying the photomultilpier signals. These oscillographs were triggered by the output from a photocell which viewed a lamp through the aluminium diaphragm; the bursting of the diaphragm permitted light to reach the photocell. An adjustable delay circuit was incorporated between the photocell and oscillograph trigger connections. The cathode ray trace was photographed using F/1.5 Langham-Thomson cameras.

The photomultilpiers were connected to the two traces of the double-beam oscillograph through cathode followers and it was necessary to keep all resistances and capacities as small as practicable to obtain maximum time resolution. Again it was necessary to compromise to some extent between time resolution and sensitivity in the temperature measurements, as the signal-to-noise ratio was improved by using a smaller band width, i.e. by integrating the signal over as long a time as possible. In practice an overall time resolution of about ½ μ-second was possible with adequate temperature sensitivity.

For temperature measurements it was necessary to adjust the amplification in the oscillograph and photomultiplier circuits and the optical apertures to give the same sensitivity for the direct and reflected light beams; the procedure for this has been described in detail by Clouston, Gaydon and Hurle[3].

2.6 Introduction of Sodium

Since there are no readily available volatile compounts of sodium, and spraying of solutions at low pressure is impractical, it was necessary to introduce the sodium as a smoke by passing the experimental gas over salt heated to around its melting point. Sodium chloride seemed more satisfactory than the iodide, although it has a high boiling point and dissociation energy. Various ways were tried, the most satisfactory being to pass the gas over an electrically heated platinum spiral which held a bead of fused salt.

2.7 The Determination of Temperature

The effective brightness temperature of the Pointolite was determined for various heating currents by comparison with a calibtrated tungsten strip-filament lamp. A correction was made for the difference of emissivity at the calibrating wavelength (6500 A) and that of the sodium light, as indicated by Gaydon and Wolfhard[4]. Corrections were also made for reflection losses at optical surfaces.

When using the double-beam system (Fig.2), the effective brightness temperature was reduced by reflection losses in the lens, L_1, and the window, W_1. The indirect beam suffers a similar loss in L_3 and W_3, and additional weakening by the neutral filter NF and the first mirror, M_1. The loss by reflection in M_2 does not affect the reversal temperature, but reduces the light reaching the photomultiplier, PM_2, and so was compensated for by opening the aperture A_2. The first mirror, M_2, had a measured reflection coefficient of 0.85; various neutral filters were used, but one with an optical density of 0.1 was most frequently employed; this gave an effective temperature difference between the two beams, using Wien's law, of about 100 to 150°, according to the initial temperature of the Pointolite.

If the temperature of the shock-heated gas, T_g, is between the brightness temperature of the background as viewed in the direct beam, T_1, and the lower background temperature of the Pointolite as viewed in the reflected beam, T_2, then it can be shown that, when $T_1 - T_2$ is fairly small (less than 200°), a linear interpolation is adequate. Thus, if a is the deflection into absorption against the background T_1, and e the deflection into emission against T_2, then

$$T_g = T_2 + \frac{e(T_1 - T_2)}{a + e}$$

When $T_1 - T_2$ is greater than about 200° or when both traces are deflected in the same direction, then it should be possible to derive the temperature from Wien's law. Thus, if both traces are in emission, the deflections being e_1 against the background T_1 and e_2 against T_2, it follows from Wien's and Kirchhoff's laws that

$$e_1 = K\left(e^{-c_2/\lambda T_g} - e^{-c_2/\lambda T_1}\right)$$

and

$$e_2 = K\left(e^{-c_2/\lambda T_g} - e^{-c_2/\lambda T_2}\right)$$

from which it follows that

$$e^{-c_2/\lambda T_g} = \frac{\left(e_2 \times e^{-c_2/\lambda T_1} - e_1 \times e^{-c_2/\lambda T_2}\right)}{e_2 - e_1}$$

where c_2 is the second radiation constant and λ is the wavelength. In theory it should be possible to extrapolate by this method to temperatures well above that of the background source; for this type of extrapolation, T_2 should be 0, i.e. the background source should be cut off from the reflected beam. In practice we found that this method was inaccurate except over a fairly small temperature range, about 300° being the maximum reliable extrapolation. Sobolev et al[5] have published a preliminary report of a rather similar method, using Wien's law to measure quite high shock temperatures, but they do not give any details of time-resolved studies.

When linear interpolation can be used, it is possible to calculate quite quickly the gas temperature at a number of points behind the shock front and to plot the variation temperature with time. This has been done for a number of records on oxygen and nitrogen. It is also possible to deduce the relative concentration of sodium atoms as a function of time, and thus to get information about the rate of evaporation and dissociation of the sodium chloride.

3. COMPARISON OF CALCULATED AND MEASURED TEMPERATURES

Neglecting relaxation effects close to the shock front, which will be discussed in Section 4, we obtained good general agreement between measured and calculated equilibrium temperatures for air, oxygen and nitrogen.

For air we used the single-beam method to study the temperature for a large number of shocks at Mach numbers between about 5.9 and 7.3, corresponding to calculated equilibrium temperatures of 2050 to 2800°K, and found agreement within about ±30°, the accuracy being set more by the determination of shock speed than by the reversal point. The time for which this temperature was maintained, which was usually around 140 μ-seconds, was however only about a half of that calculated for the time of the uniform flow region, assuming instantaneous bursting of the diaphragm and non-viscous flow. After this period of about 140 μ-seconds of fairly uniform temperature, the traces were usually deflected to indicate a very much higher temperature, often as much as 400° above the equilibrium value. This is attributed to burning at the contact surface between the air and the hydrogen driver; shock-heated air and the hydrogen are in contact and presumably interdiffuse and mix by the turbulence of the flow and so react and produce a further heat release. Although this burning at the interface occurs on most records, a proportion do not show it, the temperature falling sharply in this region, as though ignition had not occurred.

Oxygen behaves similarly, and Figures 1c and 1d show records with and without burning at the interface. Single-beam studies in the temperature range 1900 to 2550°K and some double-beam studies in the range 2500 to 2700°K again show satisfactory agreement between calculated and measured temperature. The shock speeds tend to come rather higher than expected from the pressure ratio across the diaphragm, and there are indications, both from shock-speed measurements and from the temperature distribution - which tends to rise from the front towards the contact region, that there is appreciable attenuation in these shocks in which burning occurs at the interface. It seems that the burning contributes to the force driving the shock in the early stages but becomes less important in the later stages.

Nitrogen again shows satisfactory agreement between calculated and observed temperatures. Single-beam observations have been made in the range 2000 to 2500° and double-beam ones in the range 2300 to 2600°K. We have also[3] made some signal-beam observations between 2900 and 3600°K, using the reversal of the indium blue line and the pole of a carbon arc as background. Nitrogen does not, of course, show the interface burning with hydrogen, and the temperature is found to fall sharply at the contact surface. The time of uniform flow is again only about half the theoretical value.

With argon, temperatures measured by this sodium-line reversal method tend to come appreciably too low, often by as much as 200°; the average, over 35 records, was 140° low. This is attributed to radiative disequilibrium due to the very low efficiency of excitation of the sodium atoms on collision with the monatomic argon atoms. It is known from experiments on quenching of resonance fluorescence of sodium vapour that argon atoms have practically zero effective collision cross-section for deactivation. The population of electronically excited sodium atoms will be reduced by emission of radiation; in complete equilibrium in a black-body enclosure, this loss will be compensated by absorption of radiation, but under the conditions of the shock tube this will not be so and there will be some net depopulation of the excited states by radiation.

In other than monatomic gases, the collision processes will be sufficiently efficient to prevent appreciable departures from equilibrium. It seems to us likely that in the shocks through argon, free electrons formed by ionisation of the sodium chloride smoke are the main cause of such electronic excitation as does occur and that the efficiency of the process depends on the presence of sufficient salt. The effective temperature may thus vary somewhat according to the amount of salt which is present.

We have also made some studies with argon/oxygen mixtures. With both 5% oxygen in argon and 15% oxygen in argon the sodium-line temperatures still tend to come rather on the low side. The discrepancy is around 115° for the 5% and 80° even for the 15% mixtures; the measured temperatures were compared with values calculated by Byron[6]. It seems that collisions with oxygen help to maintain better equilibrium but that their efficiency is only high enough to make the error negligible when oxygen is the major constituent.

In many of the records there are some temperature fluctuations in the supposed uniform flow region. Many nitrogen records show a temperature spike about 70 μ-seconds after the front, while argon records show a similar feature rather closer to the front. Air shows this type of feature less strongly, and records through oxygen show such irregularities even less. In the double-beam records these spikes often come more strongly in one light beam than in the other and at slightly different times (see Fig. 1e); they make detailed interpretations of the records rather difficult. With argon, which gives a much longer flow time, there is some indication that the effect is periodic, successive spikes being regularly spaced but having a decaying amplitude. We are not sure of their cause, but they may be due to transverse vibrations or shocks in the gas. We have suspected that they might be caused by irregularities in the gas flow due to the presence of the gauges iserted for measuring the shock speed; changes in the setting of these gauges do seem to alter the position of these spikes, but we have not succeeded in eliminating them even when the gauges appeared quite flush with the walls.

4. RELAXATION EFFECTS

4.1 Nitrogen

In shocks through nitrogen the reversal temperature close to the front is very low (see Fig. 1b). The rate of rise to the equilibrium value depends on the shock speed. At low shock speeds, giving an equilibrium temperature of around 2200°K, it is very slow and the equilibrium temperature is barely attained during the flow time. At 2600°K with faster shocks, the temperature approaches the equilibrium value in a few microseconds. We have given reasons[2] for believing that this effect is due to delay in the vibrational energy of the nitrogen molecules reaching equilibrium with energy in other degrees of freedom, i.e. to vibrational relaxation. The electronic excitation of the sodium atoms tends to keep in equilibrium with the vibrational energy of the N_2 molecules; this agrees with observations on the quenching of the resonance fluorescence of sodium vapour which show that only molecules possessing vibrational degrees of freedom are efficient. The present work thus gives a method of measuring these vibrational relaxation times at high temperature. The actual molecules in the gas will have been subject to the shock-heated conditions for a time which is the product of the density ratio across the shock front and the time recorded by the

oscillograph trace. This time will apply to the pressure conditions behind the shock front; in our experiments on nitrogen, the density ratio is around 6 and the final pressure about ½ atmosphere. Assuming that the relaxation time is inversely proportional to pressure, we find a time, corrected to 1 atmosphere, of about 70 μ-seconds at 2520°K. Earlier results on nitrogen, which was probably less pure because of small leaks in the vacuum system, gave 80 μ-seconds at 2450°K increasing to 160 μ-seconds at 2250°K. Nitrogen from commercial cylinders has been used, and it is likely that relaxation times would be longer in very pure gas.

4.2 Oxygen

For shocks through oxygen leading to final temperatures of around 2500 to 2700°K, the observed temperature close to the shock front is too high (see Figs. 1c and 1d). This is attributed to delay in dissociation to atomic oxygen, i.e. to dissociation relaxation. Until the oxygen is dissociated, the energy in other modes, including vibration, is in excess of the equilibrium value, and so the sodium excitation temperature, which follows the vibrational temperature, is too high. Again it is possible to use the observations to measure the dissociation relaxation time. Rough values from our results are 25 μ-seconds at 2650°K and 1 atmosphere, increasing to 50 μ-seconds at 2540°K. These values are probably consistent with the much shorter times obtained by Glick and Würster[7], who find 0.06 μ-second at 3800 and 2 μ-seconds at 3100°K, and with the recent data given in a report by Byron[6] which appears to indicate a value of about 7 μ-seconds at 2900°K and 1 atmosphere, falling at higher temperature. This new method of determining dissociation relaxation times from the temperature is likely to be particularly useful in the temperature range of interest for flows through rocket nozzles.

4.3 Carbon Dioxide

Preliminary observations indicate that CO_2 shows effects due to a rather long lag in dissociation. In shocks at observed temperatures below 2600°K, the measured temperature appears to agree with that calculated assuming no dissociation (using data from Griffith and Kenny[8]), while at higher temperatures, around 2800°K, the temperature shows a maximum near the front and then falls towards the contact surface. The dissociation relaxation time has not been measured accurately but is probably of the order 500 μ-seconds at an initial observed temperature of 2800°K. A record of CO_2 showing this effect is shown in Figure 1f.

For CO_2, the density ratio across the shock front is rather high - around 10, and the flow time is only about 70 μ-seconds, but this enables temperatures to be studied over some 700 μ-seconds of gas history.

5. CONCLUSIONS

This sodium-line reversal method of following temperature behind a shock front has established that the theoretically expected temperature is usually obtained, apart from some minor irregularities in the flow, that the actual flow time is less, often around one half of that expected assuming inviscid flow and instantaneous establishment of the shock front, and that, for shocks through oxygen or air with hydrogen as driver gas, there is usually a high-temperature region due to burning at the contact interface. For argon, and presumably for other monatomic gases, there is a significant temperature discrepancy due to lack of radiative equilibrium.

From temperature fluctuations close to the front it is possible to measure vibration or dissociation relaxation times. These measurements are most conveniently made in the temperature range 2000 to 2900°K, an important region for high-temperature chemical reactions and for studying such problems as flow through a nozzle. The time interval during which such effects can conveniently be studied is from about 10 to perhaps 500 μ-seconds. Measurements for very short times are limited by the statistical noise and by the time taken to evaporate and dissociate the sodium chloride.

There are several difficulties which we should like to stress and on which we would welcome suggestions. One of these is on the introduction of sodium; we badly need a controllable way of introducing a predetermined amount. A second obvious limitation is in the temperature range. It may be possible to reach 3800°K with a carbon arc, but we see no obvious way of extending work above this. We are also in some need of clarifying our ideas of definitions of relaxation times; we are not clear whether it is best to take the time for the energy discrepancy to fall to a half or to 1/e of its initial value; we are not sure if the decay is really an exponential type. The flow irregularities which cause minor temperature differences in the two optical beams limit the accuracy with which values of temperature can be interpolated or extrapolated, especially by Wien's law, to values above the background temperature; any improvement in gas flow conditions would enable more accurate measurements to be made.

REFERENCES

1. Model, I.S. — Zh.eksper.teor.Fiz., 32, 714, 1957.

2. Clouston, J.G. et alii — Proc. Roy. Soc. A.248, 429, 1958.

3. Clouston, J.G. et alii — Proc. Roy. Soc. A. (in press), 1959.

4. Gaydon, A.G. Wolfhard, H.G. — *Flames, Their Structure, Radiation and Temperature.* London: Chapman and Hall, 1959 (in press).

5. Sobolev, N.N. et alii — Izv.Akad.Nauk. USSR, Ser.fiz., 22, 730, 1958.

6. Byron, S.R. — *Interferometric Measurements of the Rate of Dissociation of Oxygen Heated by Strong Shock Waves.* Cornell University.

7. Glick, H.S. Würster, W.H. — J. Chem. Phys., 27, 1224, 1957.

8. Griffith, W.C. Kenny, A. — *States of Partial Equilibrium Behind Shock Waves in O_2, N_2, CO, CO_2 and N_2O.* Princeton University, Tech. Report II-23, 1957.

Description of Figure 1.

(a) This shows a typical pair of records used to determine shock speed. The lower trace shows the time base, with marks at 20 μ-second and large marks at 100 μ-second intervals. The upper trace shows the three reflections as the shock passes the temperature-sensitive platinum gauges; the first two pulses are differentiated; the third is not.

The following records, (b) to (f), show pairs of traces from the photomultipliers. In each case the lower trace is of the Na emission or absorption against an unfiltered Pointolite background at temperature T_1, and the upper trace is of the Na emission or absorption against the Pointolite reduced in brightness by the neutral filter to a lower effective brightness temperature T_2. In each case T_c is the shock temperature calculated from the measured Mach number. The approximate time scale is indicated by a white line representing 100 μ-seconds, and the shock front and contact surface are indicated by the letters F and C.

(b) *Shock through nitrogen.* $T_1 = 2625$; $T_2 = 2481$; $T_c = 2520^{\circ}K$.

This shows the low effective temperature near the front due to vibration lag.

(c) *Shock through oxygen.* $T_1 = 2625$; $T_2 = 2481$; T_c about $2865^{\circ}K$.

This shows a high temperature close to the front due to disscoiation lag, and a high-temperature region at the contact surface due to burning of O_2 with the hydrogen driver gas.

(d) *Shock through* O_2. $T_1 = 2565$; $T_2 = 2430$; $T_c = 2645^{\circ}K$.

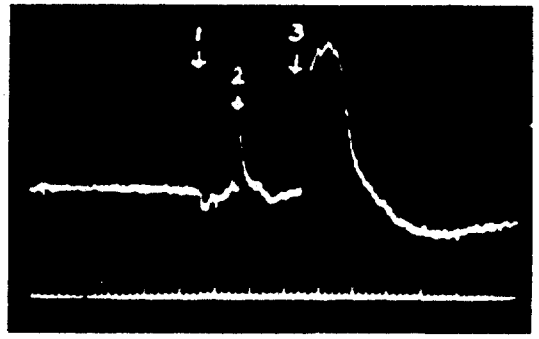
This again shows the dissociation lag, but the burning at the contact surface is absent.

(e) *Shock through argon.* $T_1 = 2587$; $T_2 = 2472$; $T_c = 2645^{\circ}K$.

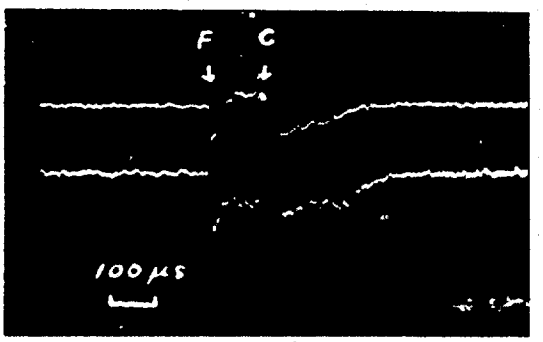
Owing to radiation disequilibrium, the observed temperature is about 173° below the calculated value. In this record, temperature fluctuations due to irregularity in gas flow are small, but some can be seen on the lower trace.

(f) *Shock through carbon dioxide.* $T_1 = 2700$; $T_2 = 2580^{\circ}K$.

The calculated temperature for complete equilibrium is 2400°, and for equilibrium without dissociation 2740°. The observed temperature is near to that calculated without dissociation at the front ($2740^{\circ}K$), but then falls to about 2660° at the contact surface.

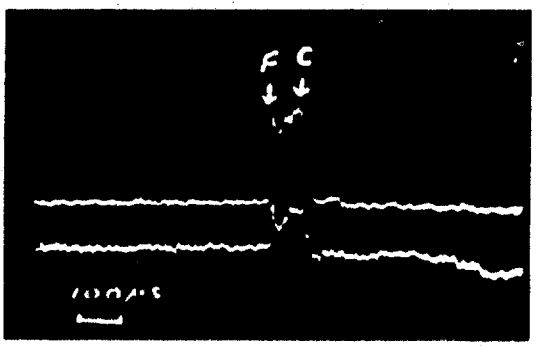


(a.) SHOCK SPEED

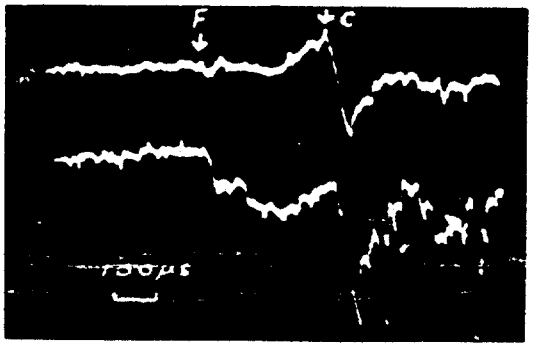


(b.) N_2

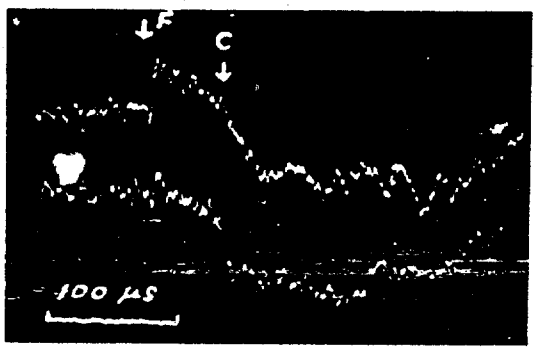
(c.) O_2



(d.) O_2



(e.) ARGON



(f.) CO_2

Fig. 1. Typical traces

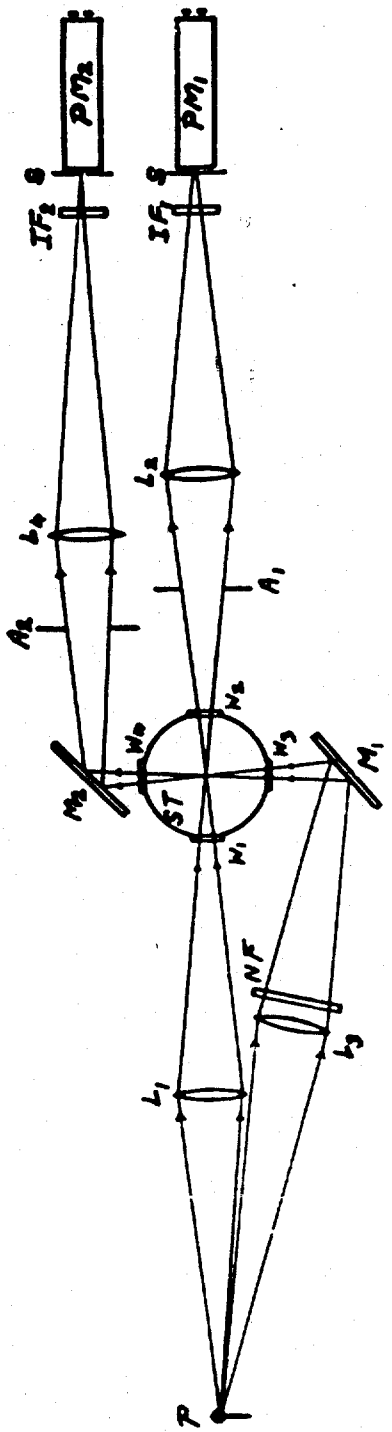


Fig.2 Layout for double-beam optical system

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