EVALUATION OF THE HYPERSONIC GUN TUNNEL

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ABSTRACT

The object of this paper is a critical evaluation of the free piston compression hypersonic wind tunnel known as the "hypersonic gun tunnel."

It is concluded that, although the stagnation temperature is limited to quite low values by piston strength requirements, the gun tunnel offers useful advantages in convenience and economy because of the comparatively long running time which may be obtained.

INTRODUCTION

The problem of providing a source of air at a sufficiently high temperature and pressure to act as the working fluid for a hypersonic wind tunnel has been approached in a variety of ways. One type of equipment which has been used for this and other applications is the free piston compressor. In this device, a piston is propelled down a tube by the pressure of a driver gas contained in a vessel of large volume, and does work on a comparatively small volume of test gas trapped ahead of the piston. The present paper is concerned with a critical assessment of the performance of one type of free piston compressor, the "hypersonic gun tunnel" which employs a piston of low mass in order to heat and compress the working fluid for a hypersonic wind tunnel. Various difficulties have so far limited the performance of these tunnels to conditions well below

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those predicted in early and rather optimistic performance calculations, for example those by Bray, Pennelegion and East (Ref. 1). However, the gun tunnel has been shown to be a useful and very inexpensive type of hypersonic facility. In view of the large number of gun tunnels at present under construction of development, it is hoped that a statement of the working conditions actually achieved will serve a useful purpose.

The following section describes the development of the hypersonic gun tunnel from other types of free piston compressor, and outlines the original concept of gun tunnel operation. Various difficulties which have been met in applying these concepts are mentioned briefly. The third section contains a description of the gun tunnel at the University of Southampton and gives details of experiments which have been carried out to study its performance. The fourth section consists of an evaluation of the gun tunnel in comparison with other hypersonic facilities. Finally, in the fifth section, some examples are given of aerodynamic tests that have been performed in gun tunnels.

FREE PISTON COMPRESSORS

Free piston compressors may be classified according to the mass of the piston.[2] If this is sufficiently large then the piston velocity will always be much less than the speeds of sound in the driver and driven gases. Under these conditions, the pressure behind the piston will be equal to the driver gas pressure p_4, which will remain nearly constant if the driver volume is large. Also, the test gas will be compressed almost isentropically, without the formation of shock waves. When the piston is first brought to rest at the other end of the tube, the work that has been done on the piston $p_4 AL$, where A is the tube cross-sectional area and L its length, is all converted to internal energy in the test gas. For isentropic compression (Ref. 2)

$$\frac{\hat{p}}{p_1} = \left[1 + (\gamma - 1)\frac{p_4}{p_1}\right]^{\frac{\gamma}{\gamma-1}}$$

where p_1 is the initial pressure in the low pressure tube and $\hat{p}$

[2]More accurately, the relevant parameter (Ref. 1) is $m_p a_4^2/p_4 AL$

where m_p is the piston mass, a_4 and p_4 are the speed of sound and pressure of the driver gas, A is the tube cross-sectional area and L its length.

is the peak pressure produced when the piston comes to rest having overshot its equilibrium position. This equation shows that enormous peak pressures can be produced in this way with very moderate driver pressure ratios; the peak temperature $\hat{T}$ may also be very large. $\hat{p}$ and $\hat{T}$ are independent of the piston mass, if this is sufficiently large. However, the piston mass does affect the time history of the compression. The heavier the piston, the longer will be the period of time available for the experiment, in which the pressure is nearly constant and equal to the peak pressure $\hat{p}$.

Compressors of this type have been used successfully by Stalker (Ref. 3) to preheat the driver gas for a small conventional shock tube, in order to obtain very high shock Mach numbers, and by Lalos (Ref. 4) to provide a sample of hot gas for spectroscopic studies. It is also possible to heat the air supply for a hypersonic tunnel in this manner. However, in this application, isentropic compression has an important disadvantage when compared with shock wave compression: it requires a much larger pressure ratio to produce a given temperature ratio. Taking an extreme example, a reflected-shock tunnel will heat a sample of air from room temperature to 5,000 K while raising its pressure by a factor of about 600, assuming perfect gas laws. Isentropic compression to the same temperature requires a pressure ratio of about 24,000, which is 40 times as large. Therefore, to heat a given mass of air from room temperature to 5,000 K at a given final pressure, the low pressure tube of an isentropic compressor would need 40 times the volume of that of a reflected-shock tunnel. Also, in order that conditions in front of the piston may be nearly constant for a sufficiently long time to carry out aerodynamic tests, a very heavy piston must be used and a large recoil force would result. The isentropic compressor does not, therefore, seem to be attractive for high temperature wind tunnel applications. A possible exception may be the simulation of high velocity, high Reynolds number conditions, in which case the very great pressure produced in the isentropic compressor may be an advantage.

In order to convert the work done on the piston more efficiently into thermal energy in the test gas, it is necessary to reduce the piston mass considerably, and so increase its velocity. If the piston velocity is much greater than the speed of sound in the cold test gas, then a strong shock wave will form, and will heat the test gas non-isentropically. Under these conditions, the work done on the piston is much less than $p_4 AL$, and also the peak pressure is much less than the isentropic value given above. However, the peak pressure and temperature may still be very large under some conditions, if large pressure ratios are used.

Piston compressors used to heat a light driver gas for two-stage ballistic model launchers may come into either of the categories considered above. For example, Charters, Denardo and Rossow (Ref. 5) have described a light-gas gun for launching free flight models, in which the helium gas which propels the model is preheated isentropically by means of a heavy, powder driven piston. More recently, Stephenson (Ref. 6) has considered a two-stage launcher is which the compressor piston is light enough for shock wave compression to occur in the driver gas.

A second effect of reducing the piston mass is that the time scale of the piston overshoot past its equilibrium position and the resulting peak pressure is greatly reduced, so that it is no longer feasible to use the peak condition as the testing period for a wind tunnel. It is necessary to allow the piston to move back from its extreme position to an equilibrium position before testing can begin. The equilibrium temperature and pressure, T_e and p_e, are then considerably less than the peak conditions $\hat{T}$ and $\hat{p}$. However, the overall compression process is non-isentropic because of shock wave formation in the test gas, and therefore high temperatures may be produced without prohibitively high peak pressures.

Free piston compression wind tunnels of this type, employing comparatively light, fast pistons, have become known as "hypersonic gun tunnels." The first gun tunnel was built at Ames Laboratory, but was later modified (Eggers, Ref. 1) to a type of shock tunnel operation. The major development of the gun tunnel took place at ARDE, Fort Halstead, where the first of these tunnels (Ref. 7) was built in 1955, and two others have been constructed since then (Cox, Ref. 1). A small gun tunnel was built at Southampton University in 1957 (Ref. 1) with the object of studying this type of wind tunnel and assessing its advantages and disadvantages in comparison with other hypersonic facilities. More recently, gun tunnels have been constructed at a number of other establishments, for example Imperial College (Ref. 8) FFA, Stockholm (Ref. 9) and NAE, Ottawa (Campbell, Ref. 1).

The original concept of gun tunnel operation (Ref. 7) was as follows (see Fig. 1). Tubes containing gas at high and low pressure were separated by a metal diaphragm and a piston. The piston mass was small enough so that, when the diaphragm ruptured, the piston velocity would rapidly approach the equivalent contact surface velocity of a conventional shock tube. This velocity was to be made as large as possible, by the use of a light driver gas such as hydrogen or helium, so that a strong shock wave would form ahead of the piston. Multiple reflections of the shock wave between the end of the low pressure tube and the piston would then compress the test gas non-isentropically, and bring the piston to rest. A second diaphragm, allowing the heated gas to expand through a hypersonic nozzle, was designed to rupture when the compressing process was complete. In this scheme, the piston offered two advantages. First, its motion caused the gas to be compressed through many shock waves, so that a large temperature rise was possible for much less than the isentropic pressure increase. Second, the piston prevented mixing between the driver and driven gases, so that the tunnel running time could be greatly extended by choosing a nozzle of small throat size. Ideal gas (Ref. 7) and real gas (Refs. 1, 8 and 10) performance calculations were carried out for gun tunnels operated in this manner, and indicated that very high stagnation temperature might be achieved, with tunnel running times of the order of tenths of seconds, if helium of hydrogen was used as the driver gas in order to produce a strong primary shock wave.

In attempting to apply these concepts, it soon became obvious that the strength of the light piston would set an upper limit to the stagnation temperature produced in the tunnel. A high stagnation temperature will be reached when a strong primary shock wave is generated, but the multiple reflections of this shock wave also produce a high peak pressure. This is very much less than the isentropic peak pressure for which an equation was given at the beginning of the present section. In fact, the highest peak pressure ever recorded at Southampton was a factor of 10^3 less than the isentropic pressure for the same diaphragm pressure ratio. However, the piston is very severely loaded, and the peak pressure increases rapidly with increase in primary shock strength. The pistons that are available at the present time will only withstand the reflection of fairly weak shock waves, so the maximum stagnation temperature attained to date has been quite low. An order of magnitude improvement is piston strength is required before the very high stagnation temperatures envisaged in Refs. 1 and 7 can be reduced. Most gun tunnel testing has therefore been carried out at very moderate stagnation temperatures, less than 2000 K, using air as the driver gas. Helium and hydrogen will become attractive as driver gases only when pistons can be made strong enough to withstand must higher peak pressures. The first advantage of the piston, that multiple shock reflection produces high gas temperatures, has not therefore been fully exploited, to date.

Difficulties have also been encountered in attempting to make full use of the other advantage of the gun tunnel technique: the long running time. It has been found that the useful running time is severely curtailed by the large rate of fall of stagnation temperature. However, a flow duration greater than that normally produced in a conventional shock tunnel can easily be obtained, and this is useful for some types of aerodynamic tests, as illustrated in the fifth section.

THE UNIVERSITY OF SOUTHAMPTON HYPERSONIC GUN TUNNEL

Several descriptions of the tunnel have been published previously (Refs. 1, 10 and 11). Figure 1 shows a sketch of the major components together with a typical x-t diagram of the first part of the wave motion and Fig. 2 gives a general view of the equipment. The components listed are identified by numbers in Fig. 1.

1) High pressure vessel: 5-ft long section of a 3.7-in. gun forging.

2) Low pressure tube: 10-ft long gun forging of 1.25-in. smooth bore. A 1-ft long high pressure extension screws on to the nozzle end of this.

3) Diaphragm: made from aluminium sheet, can be burst by pressure or mechanically, with the aid of an electrically operated plunger.

4) Piston: the initial acceleration is typically of the order of 10^5 g and the peak retardation may be much greater, so pistons require high strength and resistance to brittle fracture. Resistance to high temperatures is also necessary. Successful pistons have been made from nylon, "Araldite" resin, fibreglass reinforced plastic and "Dural" aluminium alloy. Nylon pistons are quite satisfactory for diaphragm pressure ratios up to about 150, using air as the driver gas, and have been used in most experiments. "Dural" pistons will withstand higher pressure ratios, in excess of 400 using air as the driver gas. Piston weights of between 4 and 15 gm have been used successfully. Development of stronger, lighter pistons is continuing.

5) Nozzle diaphragm: a small piece of "cellotape," which bursts on the arrival of the first shock wave.

6) Nozzle: 7-1/2 in. deg conical expansion ending in a 4-in. diam free jet. A range of Mach numbers between 9 and 15 is available by changing the diameter of the throat insert.

7) Test section: a box with schlieren quality glass windows through which the free jet may be viewed.

8) Diffuser: various types and diameters are available.

9) Vacuum vessel: 70 cu ft capacity, evacuated to a pressure of about 0.1 mm Hg before a run.

Pressure Measurements

Pressure measurements at the nozzle end of the low pressure tube have been made using SLM PZ 14 quartz crystal transducers, with a type HL adapter for pressures above about 2,000 psi. Pitot pressures in the working section of the tunnel have been measured with SLM PZ 6s, PZ 14 and PZ 60 transducers, and a Statham Type PA.222 strain gage transducer has been used for surface pressure measurements.

Figures 3 to 7 show typical pressure-time histories at the end of the low pressure tube, to various time scales. It will be seen from Fig. 3 that, when the tube is fired without a piston, the primary shock wave is considerably weaker than would be predicted from ideal shock tube theory, because of shock wave attenuation and imperfect diaphragm opening. The presence of the piston causes a further large reduction in the primary shock strength. Figure 4 shows the details of the multiple shock wave reflection process for a case with a comparatively heavy piston and high peak pressure $\hat{p}$. The shock reflection process dies out within a few milliseconds, and the pressure then remains nearly constant at a value p_e for a time of the order of 15 ms, as illustrated in Fig. 5. If the cross-sectional area of the high pressure tube is much greater than that of the low pressure tube, as it is for the Southampton tunnel, p_e may be up to twice the driver pressure p_4 . A small fall in pressure occurs at about one-third the duration of this plateau, which is caused by the arrival at the transducer of the backward facing expansion wave in the driver gas resulting from the piston acceleration. At the end of the pressure plateau, a sharp drop occurs, due to the reflection from the diaphragm station of the shock wave in the driver gas caused by bringing the piston to rest. Repeated reflections of this wave occur, causing the steps seen in Fig. 6. Figure 1 may help to clarify these wave reflection processes. If a suitable restriction or reduction in tube area is placed at the diaphragm station, the pressure steps may be almost eliminated (Fig. 7), at the cost of a further reduction in the primary shock strength.

As was explained in the section on free piston compressors, the maximum temperature attainable in the tunnel is limited by the ability of the piston to withstand a very high peak pressure. Figure 8 shows results of a large number of peak pressure measurements, plotted as a peak pressure parameter $\hat{p}A/m_p$ against the calculated primary shock Mach number M_s. The scatter arises partly because of the difficulty in measuring the $\hat{p}$ in the presence of gauge ring and other transient effects, and partly because $\hat{p}$ is also a function of other parameters, in particular the driver pressure p_4. However, Fig. 9 does illustrate the very rapid rise in $\hat{p}$ with increasing primary shock strength. The calculations of Ref. 1, which err on the optimistic side, indicate that to achieve a stagnation temperature of 4,000 K a shock Mach number of about 6.5 is required. Figure 8 suggests that the peak pressure then generated would be at least on order of magnitude greater than those so far resisted by existing pistons.

A satisfactory theoretical expression for $\hat{p}$ has not yet been found by the author. However, the following qualitative statements can be made on theoretical grounds, and have been confirmed experimentally (with the exception of no. 4):

1) $\hat{p}$ increase rapidly with increasing primary shock strength.

2) $\hat{p}$ increases with increasing piston mass.

3) For given primary shock Mach number and piston mass $\hat{p}$ decreases with increasing driver pressure p_4. This is because the piston mass must be compared with the mass of gas compressed. Increasing the pressure level decreases dimensionless piston mass parameter m_p/p_1A and so reduces the peak pressure.

4) If all other conditions are unchanged, $\hat{p}$ will be decreased by increasing the length of the low pressure tube. This is because, in a longer tube, each shock reflection has a longer time in which to slow the piston down before the next shock wave arrives. The piston is therefore brought to rest with less reflections than in a shorter tube.

Figure 9 shows a typical pitot pressure record at the center line of the free jet test section. Kaminoto and Sprinks (Ref. 12) have carried out a detailed survey of the flow in the test section, using pitot tubes and schlieren photographs. They have found that, at the 4-in. diam nozzle exit, a 2-in. diam region of nearly uniform flow exists. Downstream of the nozzle exit, the uniform flow region is smaller than this, because of the formation of a conical compression wave starting from the lip of the nozzle. If the diffuser is too small, or if the test section pressure becomes too high, this conical wave becomes stronger and moves upstream into the nozzle, reducing the region of uniform flow. The schlieren photographs of Figs. 10 and 11, taken under identical conditions, except that the pressure in the vacuum vessel is low in Fig. 10 and high in Fig. 11, illustrate the strengthening of this wave as the back pressure is increased.

Piston Motion

The motion of the piston determines the performance of the light piston compressor and requires detailed study. Cox and Winter (Ref. 7) and East (Ref. 10) have calculated the initial piston motion, and more recently Winter (Ref. 13) has also carried out detailed calculations of the slowing down process under typical conditions. However, in this case experiment has turned out to be simpler than theory, and a microwave technique due to Pennelegion (Ref. 14) has been widely used to measure the piston motion. The low pressure tube acts as a waveguide and the piston, with a metal face, is used as a tuning plunger. The microwave signal strength in the tube is measured as a function of time. Each time the piston position is an integral number of half wavelengths from the end of the tube, the signal reaches a maximum, and so the piston motion can be deduced from measurements of the time intervals between successive maxima.

Parts of typical x-t diagrams obtained in this way by Pennelegion and East (Ref. 15) are shown in Figs. 12 and 14, together with the corresponding pressure-time records. It will be seen that a heavy piston (Fig. 12) considerably overshoots its equilibrium position and so causes a large peak pressure. On the other hand, a very light piston may be brought to rest smoothly without overshoot. If conditions are chosen in order to make the peak pressure small (light piston, high driver pressure, moderate pressure ratio) the piston may be just "dead-beat", and then the peak pressure is approximately equal to the equilibrium pressure , as illustrated in Fig. 14. Figure 15 shows a correlation of the ratio $\hat{p}/p_e$ against the parameter m_p/p_4A, showing that this "dead-beat" condition can be achieved for light pistons and high driver pressures.

Stagnation Temperature

Early estimates by East (Ref. 10) of the stagnation temperature, from the recovery temperature of fine wire thermocouples spanning the hypersonic flow, from stagnation point heat transfer measurements, and by other methods, all indicated that a very large fall in stagnation temperature occurred in flow durations of the order of tenths of seconds.

More recently, measurements of the hypersonic flow velocity have been performed by Merritt (Ref. 16) at the University of Southampton, giving information from which the stagnation temperature has been calculated as a function of time. The method employed to measure the velocity was to create a cylindrical shock wave in the flow, by discharging a 0.02μ F, 8 kv condenser between two electrodes set normal to the flow at the nozzle exit. The electrodes were arranged so that their tips just emerged from the nozzle boundary layer, leaving the central part of the flow undisturbed. Double spark (double exposure) schlieren photographs of the disturbance from the discharge (Fig. 16) showed that the part of the shock wave, which was not passing through the disturbance from the electrodes, was in the form of a circular cylinder giving maximum schlieren sensitivity. The distance moved by the center of the cylinder during the time interval between the two schlieren sparks could be measured accurately. It is claimed that the maximum error in measuring the flow velocity in this way was less than 2%.

Figure 17 shows the results of some velocity measurements by this technique, using air as the driver gas, and pistons weighing about 6 gm. Times are measured from the instant of diaphragm rupture, and $t = 10$ ms soon after the beginning of steady flow in the nozzle. If use is made of the measured pitot and stagnation pressures, in order to calculate the flow Mach number, then the stagnation temperature can easily be deduced from the flow velocity. For the cases illustrated here, the Mach number is eleven, so the Mach number correction to the temperature is small. Figure 18 shows the stagnation temperatures calculated from the same data. The initial temperature, 10 ms after diaphragm rupture, is about 10% below the theoretical value (Cox, Ref. 1) and 15% above the temperature corresponding to isentropic compression to pressure p_e. Also, as shown in Fig. 19, the mean rate of fall of temperature in the interval from 7 to 30 ms is of the order of 8,000 K per second.

Flow velocity measurements by a similar method to that described above, but using a point disturbance to create a spherical shock wave, have previously been reported by Cox (Ref. 1) at ARDE. Cox's initial temperatures are in excellent agreement with those shown in Fig. 18. More recently, Stollery (Ref. 17) has described temperature measurements behind normal shock waves in the test section of a gun tunnel, using the sodium line reversal method. He employed diaphragm pressure ratios of up to 400 and obtained initial temperatures of around 2,000 K, which is consistent with the data of Cox and of Merritt at lower pressure ratios. However, the information on the rate of fall of stagnation temperature is not so consistent. Merritt found a value of the order of 8,000 K per sec in the time interval from 7 to 30 ms after diaphragm rupture. Cox's data using a similar method suggested a value of the order of 1,000 K per sec, and Stollery, using sodium line reversal, quoted a drop of less than 1,000 K per sec during a time interval of 30 ms. The difference is important, because the fall in stagnation temperature is the factor which limits the usable flow duration.

The stagnation temperature may be expected to change during a run for the following reasons.

Heat Transfer

Heat transfer rate measurements at two points on the walls of the low pressure tube, just upstream of the nozzle entrance, have indicated values of the order of 0.5 Btu/sq in./sec during the time period from 10 to 20 ms after diaphragm rupture. Strong vortices must exist in the gas ahead of the piston in order to produce such high rates, and these are presumably caused by the stirring action of repeated shock reflections. If it is assumed that a uniform rate of heat transfer occurs over the whole surface of the low pressure tube in front of the piston, then the rate of fall of stagnation temperature due to heat losses to the tube may be predicted. For conditions in the Southampton tunnel, this calculation gives a value which is about half that deduced by Merritt (Ref. 16) from velocity measurements, but still much greater than the temperature losses measured by Cox (Ref. 1) and Stollery (Ref. 17).

The rate of fall of temperature due to heat losses will decrease with increasing tunnel size, but this effect is not sufficient to explain the discrepancy.

Pressure Changes

Changes in stagnation pressure will produce corresponding changes in stagnation temperature as illustrated by Merritt's results (Fig. 18) during the time interval from 20 to 30 ms, when the pressure falls sharply. However, the pressure is very nearly constant in the interval from 10 to 20 ms and therefore could not be the cause of the large measured temperature drop.

Entropy Changes

As pointed out by Lemke (Ref. 9), the air adjacent to the piston passes through the primary shock wave at an early stage of the piston motion when the shock is weak, whereas air adjacent to the nozzle passes through a much stronger primary shock wave. Because of this effect, Lemke predicts a large gradient in entropy and temperature between the piston and the nozzle, producing a fall in stagnation temperature during a run. Another effect also arises as the piston moves down the low pressure tube behind the primary shock wave. A boundary layer of cold, slow moving air forms behind the shock wave, and the air must be scooped up by the faster moving piston. In this way, a region of cold air will be formed ahead of the piston.

Both of these effects will be reduced by the stirring action of vortices formed as reflected shock waves interact with the boundary layer behind the primary shock wave.

EVALUATION

The various stagnation temperature measurements that have been reviewed show that the temperature actually obtained at the beginning of a run is typically about 10% below the theoretical value (Cox, Ref. 1) and only about 15% above the temperature reached in an isentropic compression to the same equilibrium pressure p_e. The advantage theoretically gained in the gun tunnel due to multiple shock reflections is therefore lost in practice because of the reduction in primary shock strength illustrated in Fig. 3. Also, the inability of the piston to withstand high peak pressures limits the primary shock strength, and therefore the stagnation temperature, to quite low values. Temperatures high enough to study significant real gas effects will not be reached without an order of magnitude improvement in piston strength characteristics.

In view of these limitations, the aim has not been to strive for the highest possible temperature obtainable in the gun tunnel, as other types of facility are more suitable for such work. Once reconciled to this, there is little advantage to be gained from using a heavy piston, or a light driver gas and a large diaphragm pressure ratio in order to produce a strong primary shock wave, and hence a high peak pressure. In the recent operation of the Southampton tunnel (Ref. 15) using air as the driver gas, the investigator used light pistons (about 5 gm), the highest available driver pressure (3,000 psi) and moderate pressure ratios (about 100 to 1). Under these conditions the peak pressure $\hat{p}$ is close to the equilibrium pressure p_e and the piston motion is almost dead-beat, as described in the previous section. In this way the difficulties described by Eggers (Ref. 1) associated with high peak pressures are avoided, and also the pressure reaches its constant value p_e in the shortest possible time, so that the usable flow duration is slightly extended. The penalty in reduced stagnation temperature, because a light piston causes less shock reflections than a heavy piston, is not believed to be significant.

The duration of flow in the gun tunnel may be adjusted at will by suitable choice of the nozzle throat size, but the useful running time is limited by the rapid rate of fall of stagnation temperature. As has been explained, the rate of fall of temperature is still in doubt, but it appears to be at least 1,000 K per sec, so that useful flow durations greater than a few hundredths of a second cannot be expected. It has been found convenient at southampton to use the first pressure plateau (Fig. 5) as the testing period, because both the temperature and the pressure have their highest steady values during this time. The duration of the pressure plateau is about 20 ms. If longer running times are required and a correspondingly larger temperature drop can be tolerated, then the technique of placing a restriction at the diaphragm station may be employed (Fig. 7). Alternatively, a heavy driver gas, such as CO_2, may be used in order to extend the duration of the first pressure plateau by reducing the speed of sound of the gas behind the piston. In either case, the stagnation temperature obtained from a given diaphragm pressure ratio is slightly reduced.

The type of gun tunnel operation described above is very similar to the "equilibrium interface" technique (Ref. 18) for operating a reflected shock tunnel. In this technique the primary shock strength is above the "tailoring" value (Ref. 19) and the interface between the driver and driven gases is brought to rest gradually by repeated wave reflections between the interface and the end of the low pressure tube. The gas sample heated by this process expands through a convergent-divergent nozzle.

Normally, the maximum time available for testing is the interval between the arrival at the nozzle of the primary shock wave, and the arrival of the first reflected wave which has passed up the low pressure tube, reflected from the high pressure tube and returned to the nozzle station. That is, the testing period consists of the first pressure plateau, as in the gun tunnel.

The wave processes occurring in the gun tunnel and in the shock tunnel are therefore very similar. It follows that, for facilities of the same dimensions which use the same driver and driven gases at the same pressures, the theoretical flow durations will be identical. However, if long running times are sought in a shock tunnel, a large amount of mixing is found to occur at the interface between the hot and cold gases, so that a large fraction of the hot gas is wasted and the usable running time is limited. In the gun tunnel, mixing is prevented by the piston and it is for this reason that the gun tunnel can achieve longer running times.

It will be observed that the gun tunnel has lost many of the attractive features originally expected of it, and described in the second section. In terms of stagnation temperature, it has so far given conditions comparable with those obtained in continuously running tunnels, for example, of the pebble bed heater type (Ref. 20), but well below typical shock tunnel temperatures. Does the gun tunnel then have any real advantages? It certainly does provide a workable hypersonic facility very economically and this may be its main virtue. The mechanical construction of a gun tunnel is as simple as that of a shock tunnel, but the instrumentation can be cheaper and more elementary, because of the longer running time available. For example, a very straightforward strain gage balance may be used for measuring aerodynamic forces and moments. Also at the end of a run, the piston acts as a convenient seal preventing the driver gas from escaping through the nozzle, so both the high pressure driver gas and the vacuum in the test section may be preserved for the next run. This is convenient and also economical, because smaller compressors and vacuum pumps may be used. Also, an expensive driver gas such as helium may, if necessary, be recovered.

Economic considerations apart, the gun tunnel is best considered as a modification of the shock tube wind tunnel technique, to be used for tests requiring an extended flow duration but fairly low stagnation temperatures. There are many such tests, and a few examples will be given in the section following. As it has been demonstrated that the piston compression process need not produce a high peak pressure, any shock tunnel may be used in this way when a long running time is required. Whether this is worth while depends on the usable flow duration that can be obtained, which, in turn, depends on the rate of fall of stagnation temperature. Unfortunately, this rate is still in doubt (see the third section).

Finally, it should be noted that the gun tunnel becomes more attractive at higher driver pressures. As explained in the previous section, the peak pressure for a given primary shock strength is reduced as the driver pressure is increased. It may, therefore, be possible to use stronger primary shock waves and to obtain higher stagnation temperatures in this way. The piston strength during acceleration will set a limit to the maximum driver pressure that can be used, so the gun tunnel should be usable with driver pressures up to the maximum peak pressure successfully withstood by pistons. Pistons less well designed than those now in use have stood up to peak pressures in excess of 12,000 psi, so it is reasonable to envisage a gun tunnel driven at a pressure of 1,000 atm. This modification would result in a useful increase in flow Reynolds number.

EXAMPLES OF AERODYNAMIC TESTS IN GUN TUNNELS

It is not the object of this paper to present a detailed report on specific aerodynamic tests. However, a few examples are given of results obtained in gun tunnels, in order to illustrate some types of work for which it is suitable. The following basic aerodynamic measurements have been carried out in various gun tunnels: surface pressure distributions on bodies (Refs. 1 and 21), local heat transfer rates (Refs. 1 and 21), overall forces on bodies (Refs. 1 and 8), gas temperature in the vicinity of the stagnation point on a blunt body (Ref. 17). Many flow visualization studies have been carried out using spark schlieren apparatus.

Force Measurements

With the extended running time available in the gun tunnel, force and moment measurements are comparatively simple. Results have previously been reported by Cox (Ref. 1) and by Stollery et al. (Ref. 8).

The examples[3] of force measurements shown here were obtained in the Number 3 Hypersonic Gun Tunnel at ARDE, Fort Halstead. (See Fig. 19.) Figure 20 shows a view of the 10-in. diam test section of the no. 3 Tunnel and Fig. 21 shows a typical record obtained from the two component strain gage balance in the tunnel. Figures 22 and 23 give data on normal force coefficients and centers of pressure, obtained using this balance, for a typical blunt nosed cone-cylinder-flare model.[4] Theoretical curves obtained from Newtonian theory, with and without an estimate of the effects of separation, are also shown.

Separated Hypersonic Flows

Because of the possibility that a separated flow may require a comparatively long starting time, hypersonic flows involving separation are an obvious choice for study in the gun tunnel. Stollery et al. (Ref. 8) have published schlieren photographs

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[4]The model used was the Standard Ballistic Type Hypervelocity HB-2 suggested in March, 1960, by J. Lukasiewicz, Chief of the Von Karman Gas Dynamics Facility, AEDC, for possible adoption as a standard AGARD model.

of hypersonic flow past blunt bodies with nose spikes and flow up a step with laminar boundary layer separation. They have also studied the stability of the former flow configuration.

Sprinks (Ref. 21) at the University of Southampton has carried out experiments on axisymmetric bodies with cut-out regions to promote flow separation, and has measured pressures and heat transfer rates in the separated region. Schlieren photographs of flow past typical bodies have already been given (Figs. 10 and 11).

Tests on Hypersonic Air Intakes

It is well known that an air intake for a supersonic vehicle will swallow its starting shock only if the ratio inlet area to throat area is less than a certain value, but that, once the starting shock system has been swallowed, the throat area may be considerably reduced before supersonic flow breaks down in the nozzle. It follows that the maximum steady running area ratio can only be found from a test in which the geometry of the inlet is varied during the duration of the hypersonic flow. This area ratio is difficult to calculate because it depends on boundary layer growth in the inlet, which may be greatly affected by shock boundary layer interactions. Experimental results are therefore needed, but require a comparatively long flow duration. Figure 24 shows a sketch of a simple, variable geometry intake used for tests to determine the maximum steady running area ratio. These tests were carried out by Evered et al. (Ref. 22) of the Bristol-Siddeley Engine Company, using the Southampton University gun tunnel. This intake (Fig. 24) was formed by two plates, pivoted near their trailing edges in such a way that the aerodynamic forces tended to swing them outwards increasing the inlet area ratio. Before a run, the plates were set at an area ratio small enough to allow supersonic flow through the inlet to be established. The plates swung outwards, during the duration of the hypersonic flow, past the maximum area ratio for supersonic flow through the inlet. A schlieren record of the run, using a high speed cine camera, determined the maximum running area ratio, from the position of the plates when a normal shock wave first formed in front of the intake. The cine film also showed that the plates took about 5 ms to move out far enough to cause breakdown of the supersonic flow through the inlet. Figures 25 and 26 show the model started and unstarted respectively. A later series of tests have employed glass side plates, so that the details of the flow through the inlet can be studied.

Evered has also reported (Ref. 22) the results of tests, using the University of Southampton gun tunnel, in which plates with effusion cooled leading edges have been tested at hypersonic Mach numbers.

Unsteady Hypersonic Flow

East (Ref. 23) has considered the feasibility of performing experiments on oscillating models in the Southampton gun tunnel, in order to study unsteady hypersonic flow effects. It is hoped that experiments will begin later this year.

CONCLUSIONS

The stagnation temperature achieved in the gun tunnel is limited by the strength of the light piston used to compress the test gas, and the useful running time is restricted by the large heat losses to the cold walls of the tube. In view of these factors the performance of the tunnel is not as attractive as was previously predicted.

However, it has been shown that the high peak pressure due to piston overshoot can be entirely eliminated if a sufficiently light piston is used. Under these conditions any reflected shock tunnel can be used in the manner of a gun tunnel for tests requiring an extended running time at comparatively modest stagnation temperatures.

Within the range of operating conditions for which it is suitable, the gun tunnel is a very convenient and economical hypersonic facility. It becomes more attractive at higher driver pressures and test section Reynolds numbers.

ACKNOWLEDGMENT

This paper describes the work of many people and it is not possible to mention all of them. The author would like, in particular, to acknowledge the assistance of R. A. East during many helpful discussions. The author is also greatly indebted to the Department's workshop staff for their cooperation.

Some of the data presented in the fifth section was reproduced by the kind permission of the Director, ARDE. The cooperation of the Hyperballistics Group at ARDE in making these data available is gratefully acknowledged.

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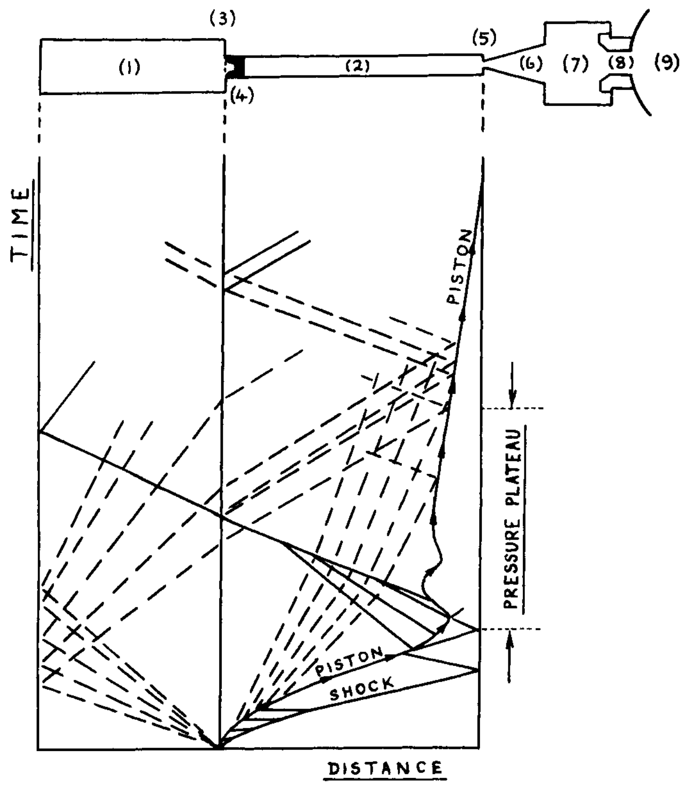


Fig. 1 Gun tunnel and wave diagram.

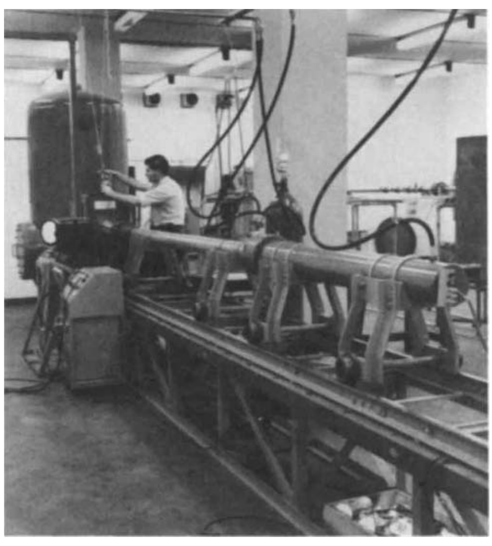
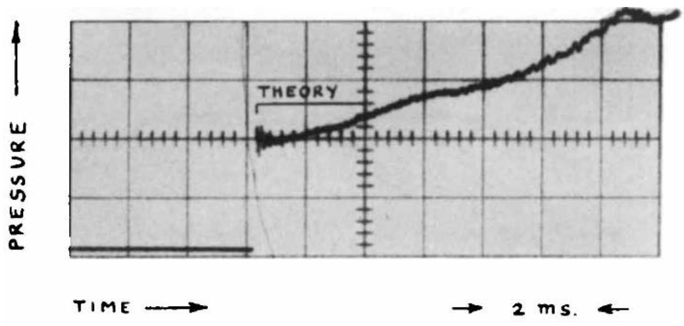
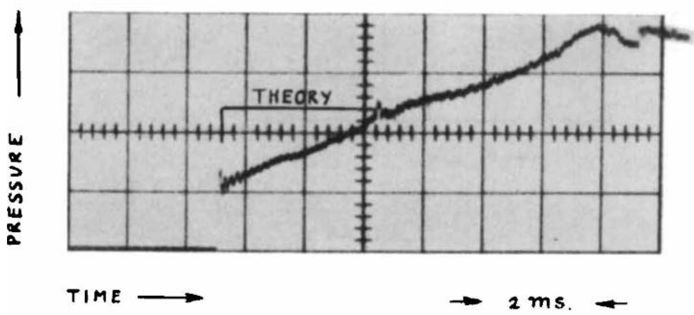


Fig. 2 General view of University of Southampton hypersonic gun tunnel.



"without piston"



piston weight 10 grams

Fig. 3 Pressure - time records at end of low pressure tube - effect of piston on primary shock strength with tube end open. p_4 = 360 psia, p_1 = 14.7 psia.

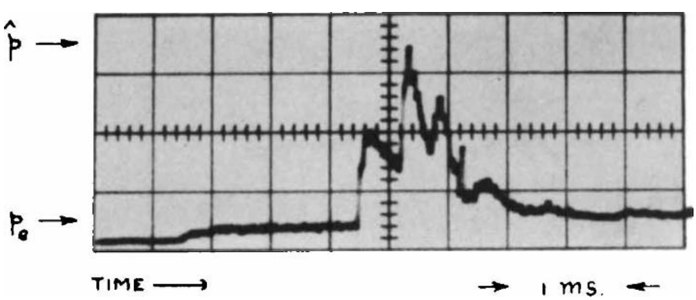


Fig. 4 Pressure - time record at end of low pressure tube - shock reflection process. p_4 = 1940 psia, p_1 = 32.7 psia, m_p = 15 gm.

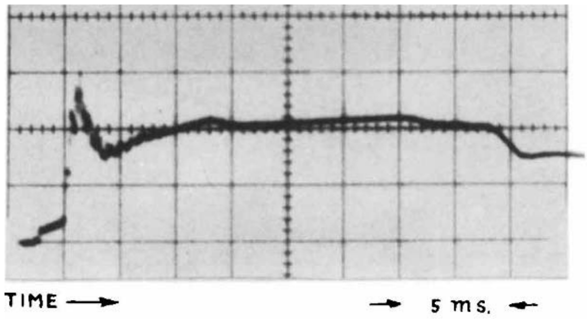


Fig. 5 Pressure - time record at end of low pressure tube - first plateau. p_4 = 2160 psia, p_1 = 35 psia, m_p = 8.35 gm.

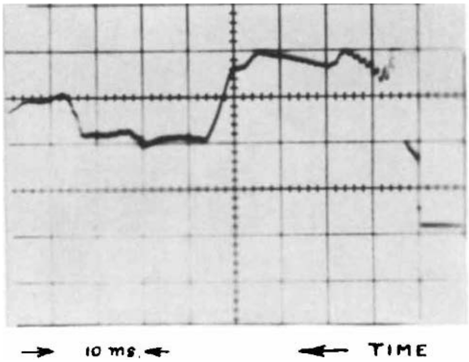


Fig. 6 Pressure - time record at end of low pressure tube - without restrictor plate. p_4 = 1055 psia, p_1 = 34.7 psia, m_p = 5.65 gm.

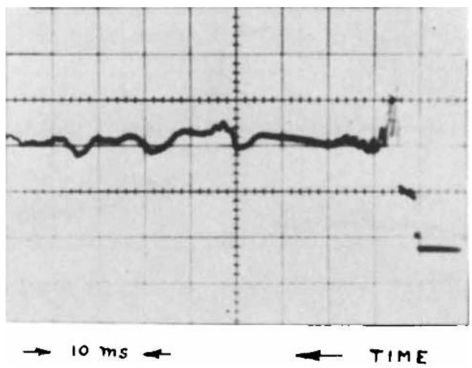


Fig. 7 Pressure - time record at end of low pressure tube - with restrictor plate. p_4 = 1045 psia, p_1 = 34.7 psia, m_p = 5.65 gm.

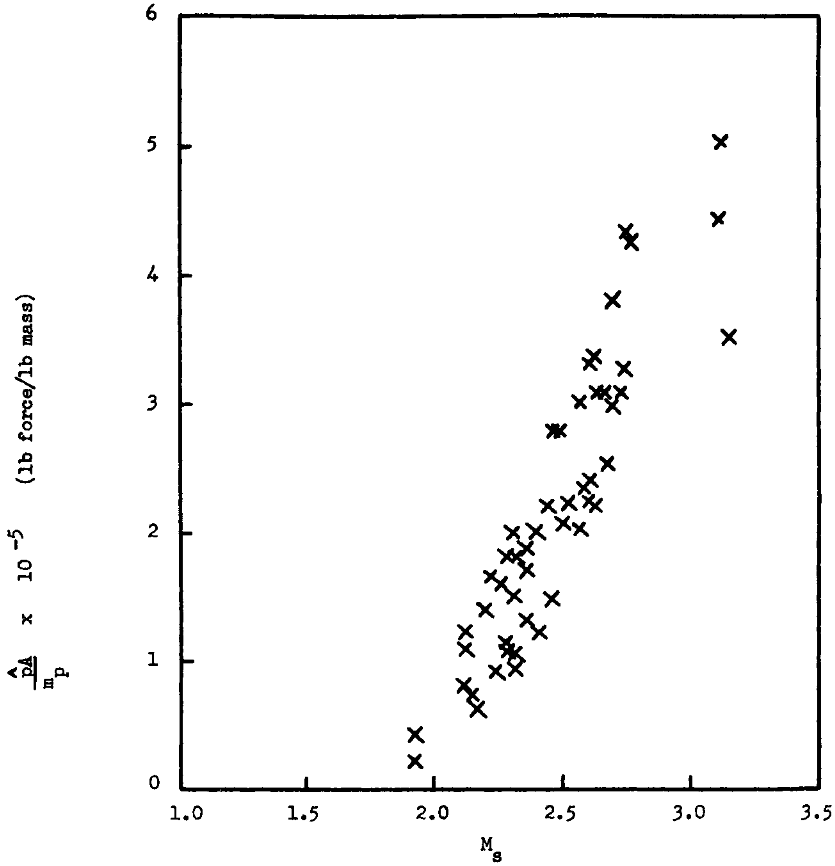


Fig. 8 The variation of a peak pressure parameter with primary shock Mach number.

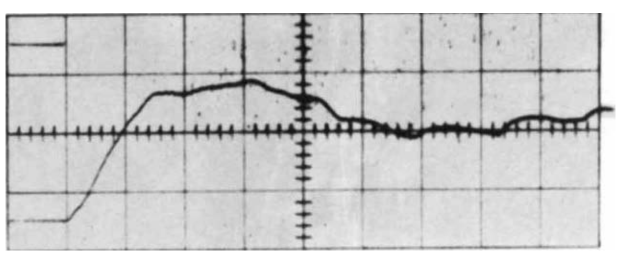


Fig. 9 A typical pitot pressure record on the nozzle center line. p_4 = 2700 psia, p_1 = 54.7 psia, nominal flow Mach number = 11.

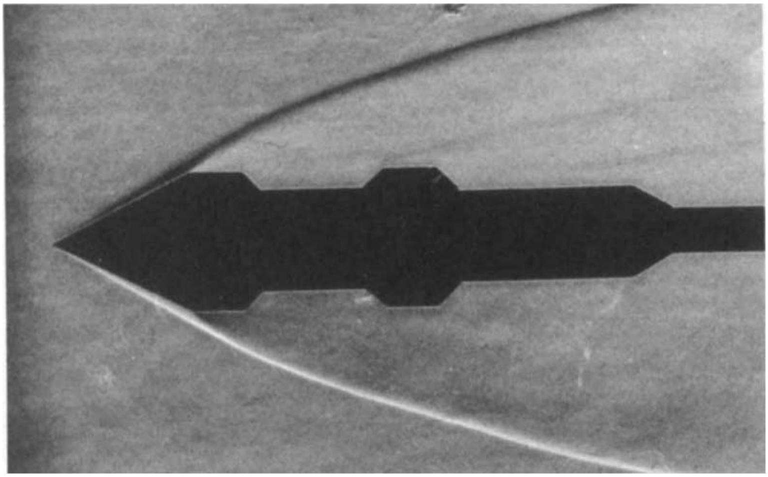


Fig. 10 Typical spark schlieren photograph of flow past axisymmetric body with cut-out to promote separation. Nominal flow Mach number = 11, vacuum tank pressure ≈ 0.1 mm Hg, p_4 = 2930 psia, p_1 = 35 psia.

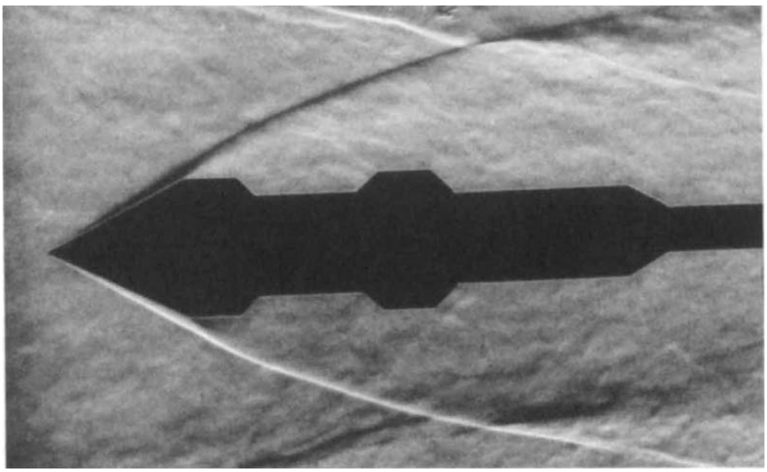


Fig. 11 Spark schlieren photograph of flow past axisymmetric body at a nominal Mach no. of 11. Effect of high pressure (10 mm Hg) in vacuum tank. p_4 = 2930 psia, p_1 = 35 psia.

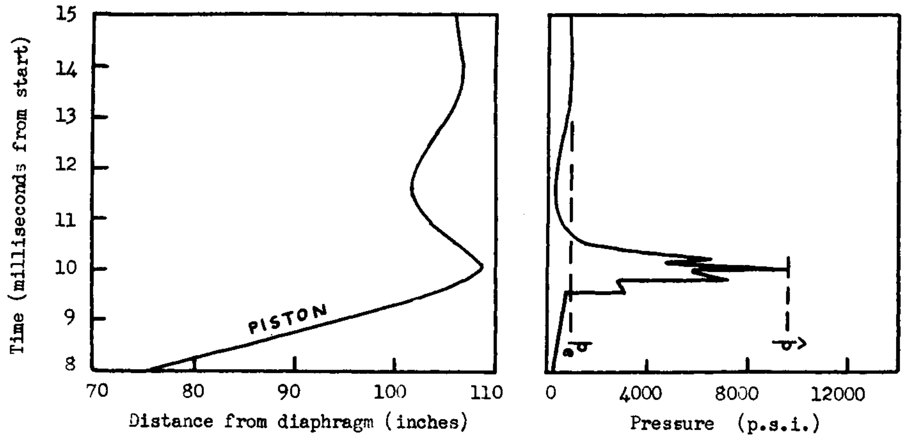


Fig. 12 Portions of x-t and p-t diagrams - heavy piston. m_p = 15 gm, p_4 = 975 psia, p_1 = 15 psia.

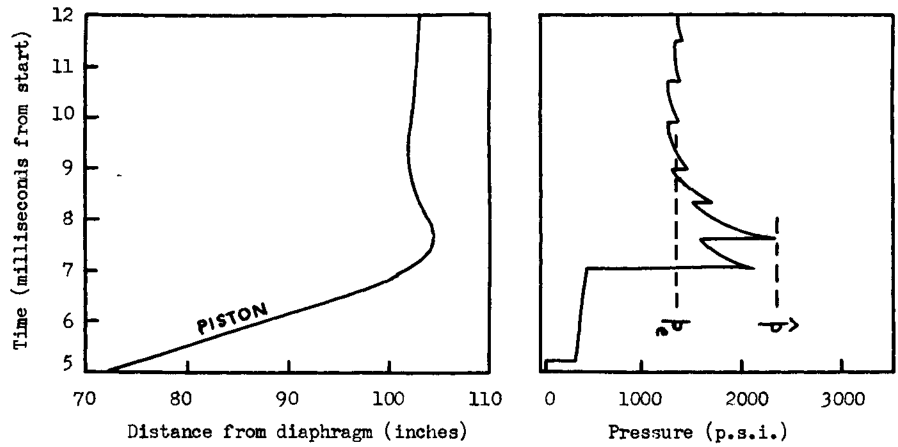


Fig. 13 Portions of x-t and p-t diagrams - medium piston. m_p = 9 gm, p_4 = 1275 psia, p_1 = 40 psia.

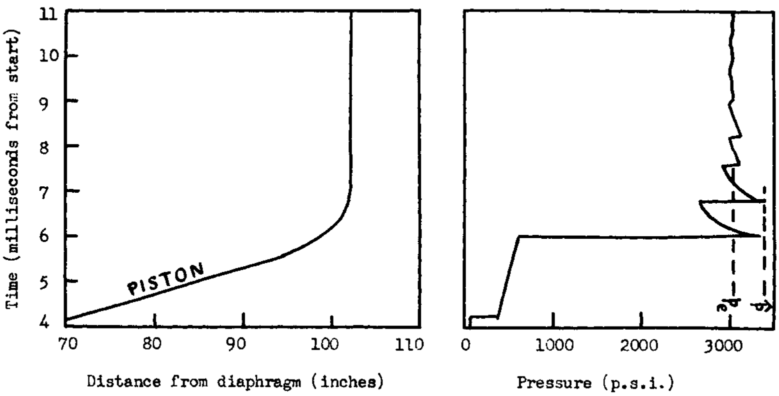


Fig. 14 Portions of x–t and p–t diagrams - light piston. m_p = 5.5 gm, p_4 = 3015 psia, p_1 = 65 psia.

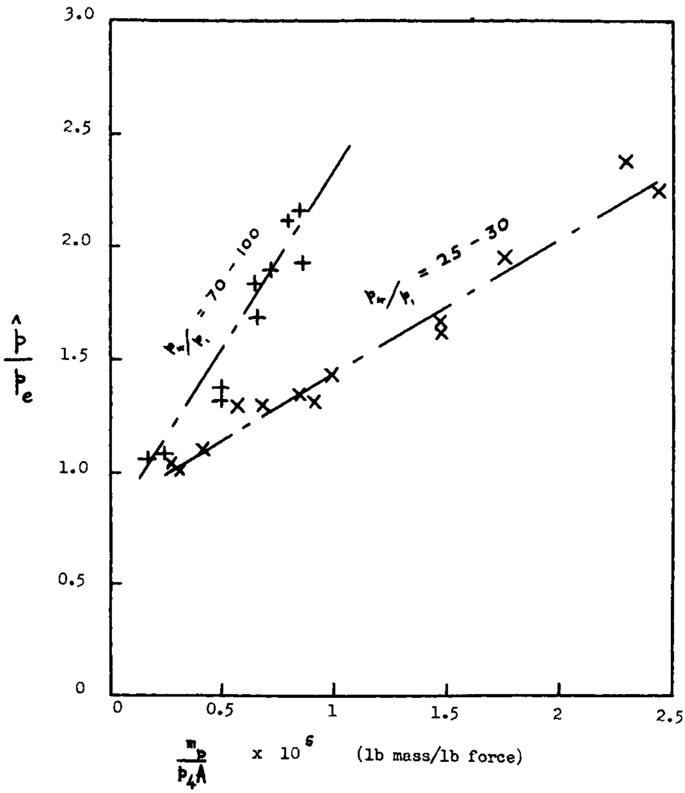


Fig. 15 Ratio of peak pressure to equilibrium pressure plotted against piston mass parameter.

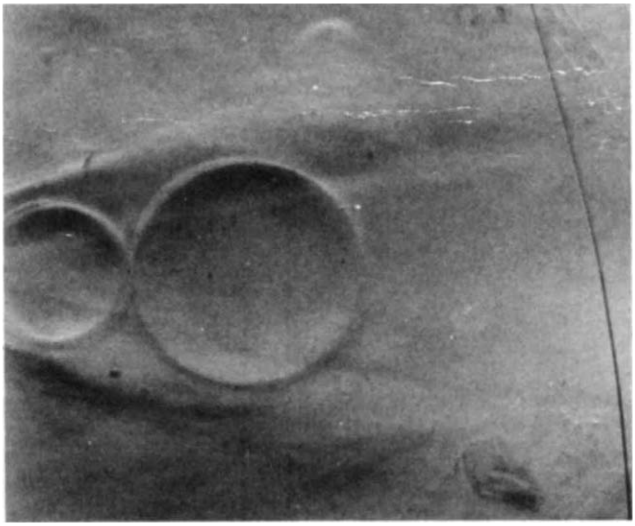


Fig. 16 Typical double - exposure spark schlieren picture of cylindrical disturbance in flow at a Mach number of 11.

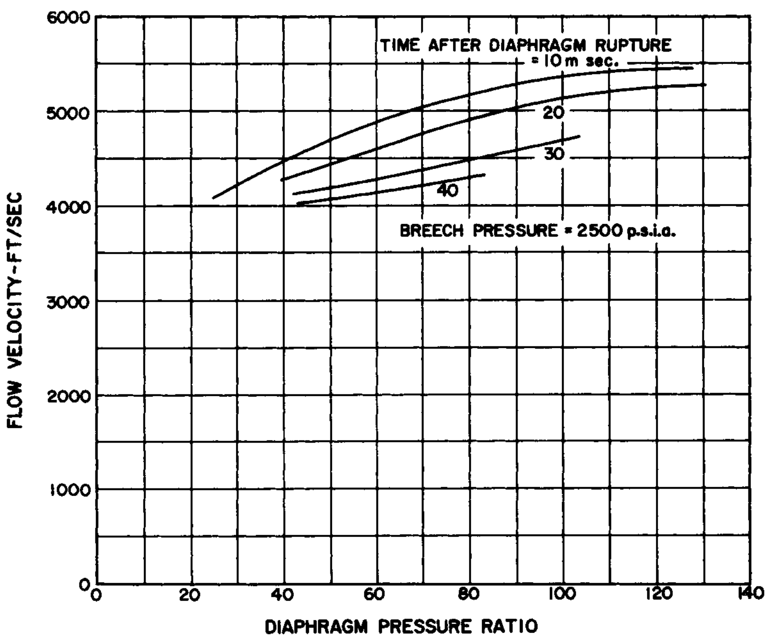


Fig. 17 Flow velocity vs. diaphragm pressure ratio.

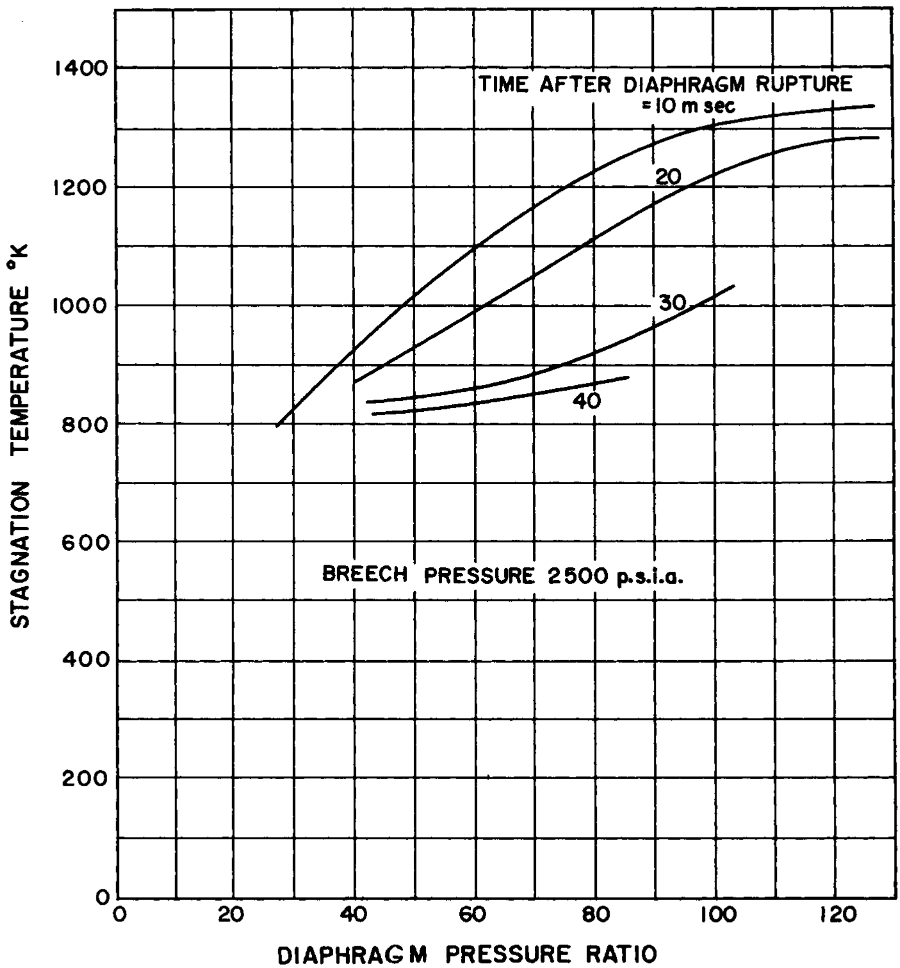


Fig. 18 Stagnation temperature vs. diaphragm pressure ratio.

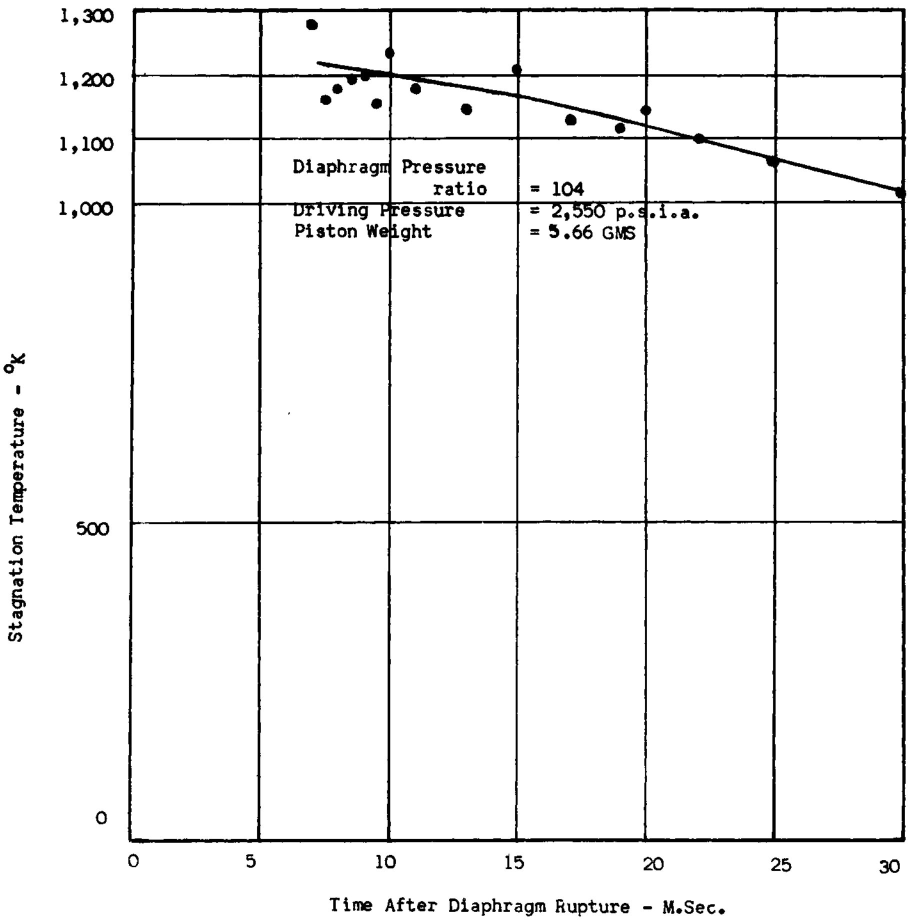


Fig. 19 Stagnation temperature vs. time in run.

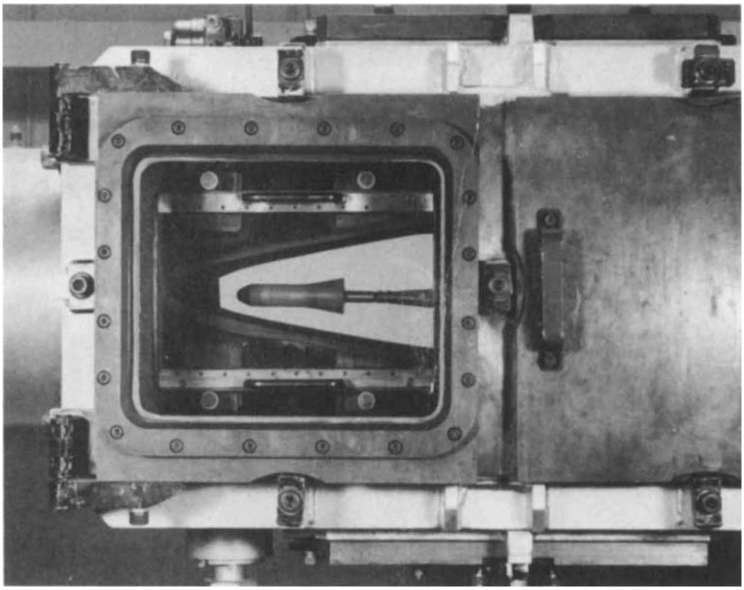


Fig. 20 10-in. diam closed working section of no. 3 hypersonic gun tunnel at ARDE, Fort Halstead.

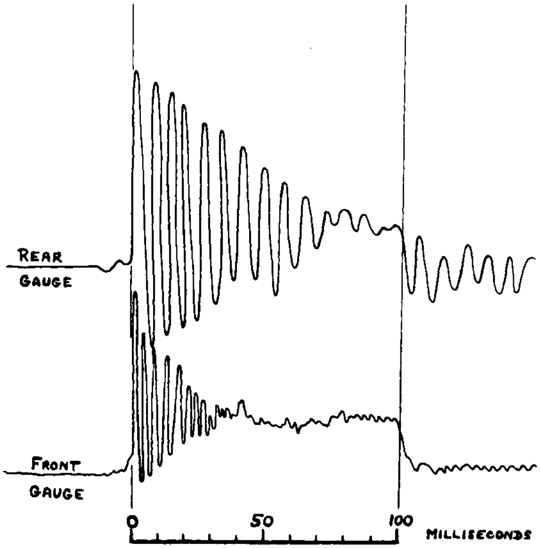


Fig. 21 Typical strain gage balance record for a model in the 10-in, hypersonic gun tunnel at ARDE, Fort Halstead.

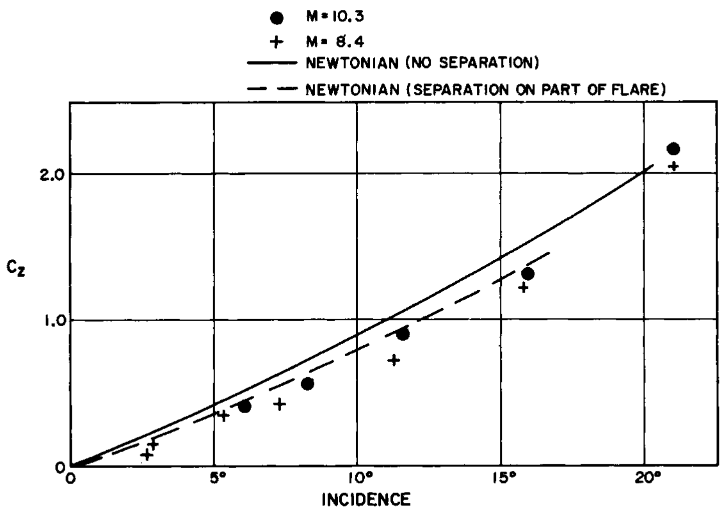


Fig. 22 Normal force coefficient vs. incidence for a standard cone-cylinder-flare model: data from 10-in. hypersonic gun tunnel at ARDE, Fort Halstead.

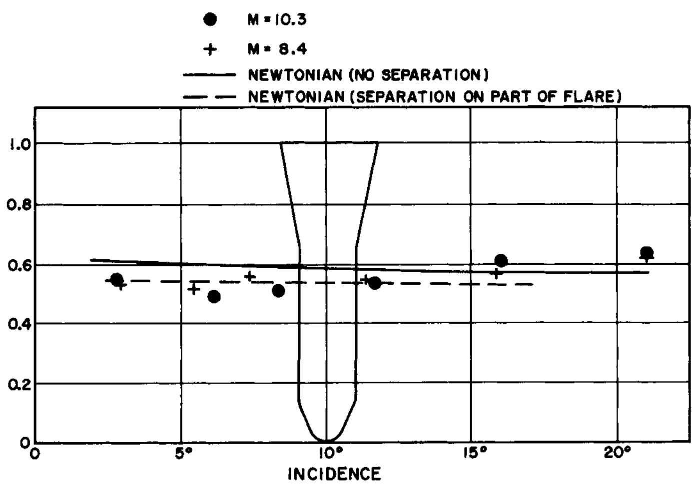


Fig. 23 Center of pressure position vs. incidence for a standard cone-cylinder-flare model: data from 10-in. hypersonic gun tunnel at ARDE, Fort Halstead.

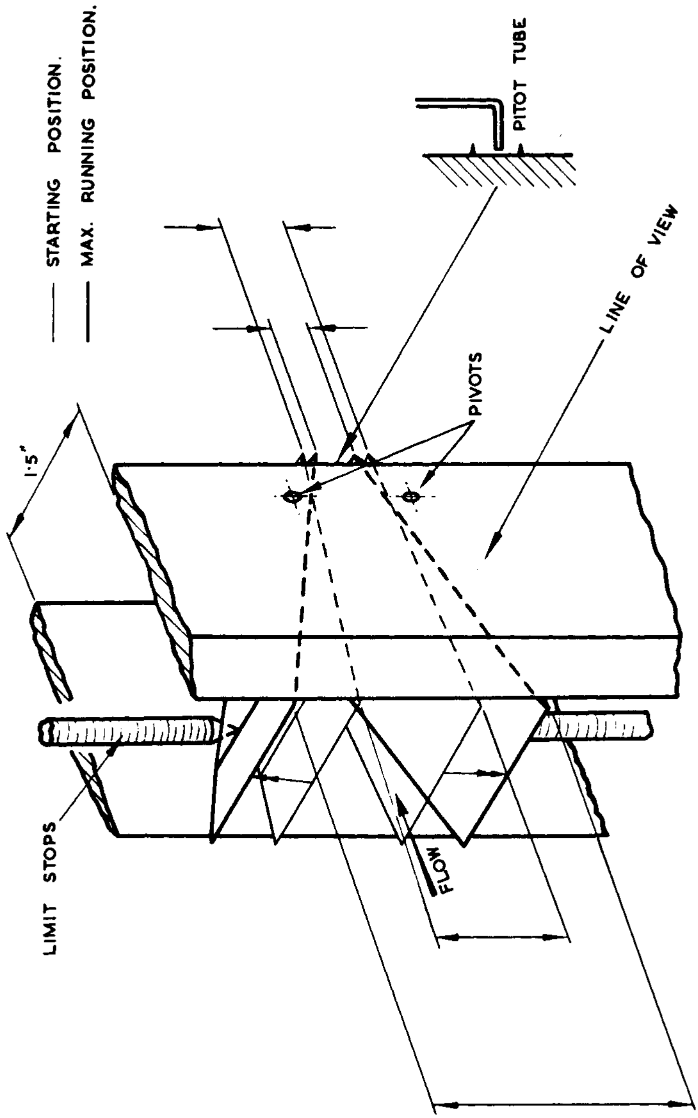


Fig. 24 Diagram of variable geometry intake model (Ref. 22).

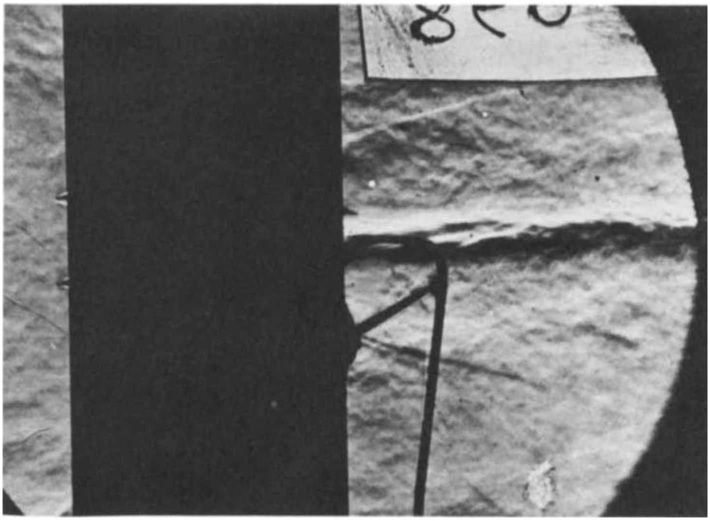


Fig. 25 Schlieren photograph of flow past variable geometry intake (Ref. 22): supersonic internal flow. The position of the movable plates is shown by their leading and trailing edges which project slightly beyond the fixed side plates.

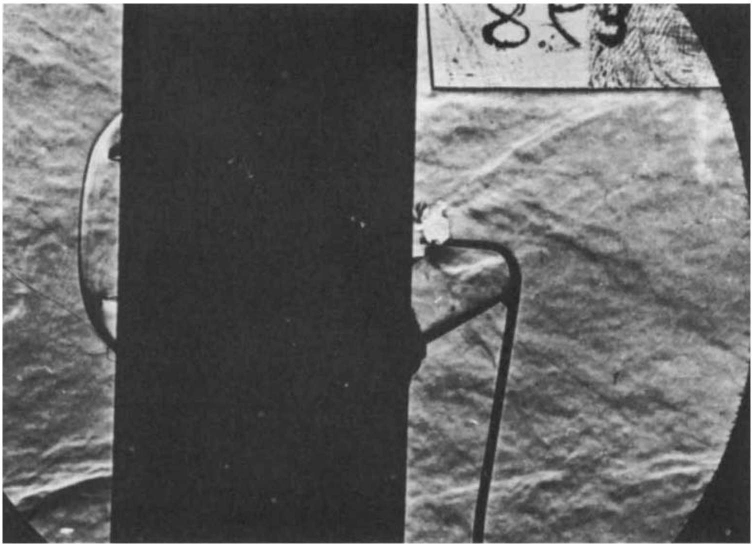


Fig. 26 Schlieren photograph of flow past variable geometry intake (Ref. 22). A strong normal shock wave in front of the intake shows that the internal flow is subsonic.