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A Note on Shock Tubes

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7th May, 1952

1. Introduction

The conventional shock tube (Fig.1) consists essentially of a uniform tube divided initially by a diaphragm into two compartments containing gases at different pressures. When the diaphragm is ruptured by means of a needle or an electric spark, a normal shock wave moves into the low-pressure part of the tube and an expansion wave moves into the high-pressure part. Between these two disturbances, there may be regions in which the gas moves with uniform subsonic, sonic or supersonic speed depending on the initial pressure ratio across the diaphragm. The duration of steady flow in these regions is limited to times of the order of milliseconds in tubes of reasonable length by reflections of the shock and expansion waves from the ends of the tube.

Shock tubes have been used to investigate a wide range of problems in fluid dynamics; for some of these they provide the only convenient method of experiment and for others they are attractive because of their relative simplicity. For the examination of steady flow at high Mach number the shock tube requires less power and is probably cheaper to build than a wind tunnel of comparable size, but has the disadvantage that the duration of steady flow is so short that it is difficult to make observations.

The equations describing the flow in a shock tube have been given in several reports (Refs. 1-6). Here we shall give only a brief physical description of the flow and then pass on to consider some of the problems which have been investigated by using shock tubes.

2. The Flow in a Shock Tube

The motion of the shocks and expansion waves in a shock tube is conveniently described by reference to Fig.2 where the time (t) that has elapsed since the diaphragm was ruptured is plotted against the distance (x) that the wave has moved along the tube from the position originally occupied by the diaphragm. For simplicity we shall assume that the same gas was originally contained in the high- and low-pressure compartments, and that the temperatures in these compartments were initially equal.

When the diaphragm is ruptured, a normal shock moves along OA ; ahead of this shock in region (1) the gas is at rest and behind it in region (2) the gas moves with uniform velocity in the direction of the shock. The gas in the high-pressure compartment expands when the diaphragm is ruptured, and the expansion is propagated in the form of a rarefaction wave of finite extent. The head OB of this wave travels with the speed of

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sound in the high-pressure compartment. The gas is at rest in region (5) ahead of this wave; in region (4) it is accelerated in the direction of motion of the shock wave, and acquires in region (3) downstream of the tail OC of the rarefaction wave a uniform velocity equal to that in region (2) behind the shock. The tail OC of the rarefaction wave moves with the speed of sound relative to the flow in region (3). It, therefore, extends to the left (as shown in Fig.2(a)) for subsonic flow in region (3), and to the right (Fig.2(b)) for supersonic flow in this region.

Since the gas behind the shock wave OA has been compressed while that behind the expansion OC has expanded, the temperature in region (2) is greater than in region (3). A discontinuity of temperature thus occurs at a contact surface OD (sometimes termed "the cold front") which separates regions (2) and (3). The static pressures and velocities in these regions are equal, and in each region the temperature is uniform. The temperature discontinuity moves in the direction of the shock with a velocity equal to that in regions (2) and (3), and there is no flow across it.

It is seen, therefore, that except in the expansion wave (region (4)), the gas throughout the tube is either at rest or in uniform motion in the direction of the shock wave. The strength of the shock and the Mach numbers of the uniform flows in regions (2) and (3) depend on the initial pressure ratio across the diaphragm. The Mach number of the flow behind an isolated shock wave reaches a limiting value for infinite shock strength (static pressure ratio) which depends only on the ratio γ of the specific heats of the gas. For $\gamma = 1.40$ this limiting Mach number is 1.89. In a shock tube the maximum gas velocity which can be reached in region (3) behind the temperature discontinuity is lower than that in region (2) behind the shock because the temperature is lower. Since the velocities must be equal on the two sides of the temperature discontinuity a limit is thus imposed to the maximum shock strength and the maximum Mach number behind the shock. For $\gamma = 1.40$ the calculated values of these maxima are 44.14 and 1.73 respectively. These values cannot, however, be reached in practice as they correspond to an infinite initial pressure ratio across the diaphragm. Values for other initial pressure ratios are given* in Table I, and it is seen that in practice with $\gamma = 1.40$ the upper limits to the shock strength and the Mach number in region (2) are probably of the order of 10 and 1.3 respectively.

Table I

Calculated Values of the Shock Strength and of the Mach Numbers in the Regions of Uniform Flow. $\gamma = 1.40$

Initial Pressure Ratio Across Diaphragm	Shock Strength (Static Pressure Ratio)	Mach Number in Region (2) Behind Shock	Mach Number in Region (3) Behind Temperature Discontinuity
1.0	1.0	0	0
10.38	2.89	0.71	1.00
41.38	4.83	1.00	1.80
100	6.40	1.15	2.41
200	7.80	1.23	2.96
400	9.35	1.31	3.60
600	10.30	1.34	4.00
800	10.90	1.37	4.29
1000	11.50	1.39	4.53
∞	44.14	1.73	∞

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*For more complete and accurate data see Refs. 2, 3.

For a given initial pressure ratio the Mach number is greater (see Table I) in region (3) behind the temperature discontinuity than in region (2) behind the shock because the temperature (and therefore the speed of sound) is lower. In theory the Mach number in region (3) can be increased indefinitely by raising the initial pressure ratio, but in practice a limit* is imposed by the maximum temperature fall that can be tolerated before the effects of condensation become serious. Also since the gas behind the temperature discontinuity was originally contained behind the diaphragm, it is not certain whether the conditions are sufficiently uniform for experimental purposes because of the non-ideal way in which the diaphragm bursts.

The maximum Mach number behind the shock (region (2)) may be increased[2,7] by using a gas of low γ in the tube. If for reasons of similarity it is necessary to produce the shock and the region of uniform flow behind it (region (2)) in air, it is possible[2] to increase the maximum shock strength and the maximum Mach number by using a light gas such as hydrogen or helium in the high-pressure compartment of the tube as this increases the maximum velocity which may be reached behind the expansion wave. If air flow is required in the uniform region behind the temperature discontinuity, the initial pressure ratio can be reduced[2] by using hydrogen or helium in the low-pressure compartment. The uses of gases other than air in a shock tube is comparatively simple because the quantity of gas involved is small, and because the tube must in any case be free of leaks.

It is clear from Fig.2 that in an infinitely long tube the duration of steady flow in either region (2) or (3) can be increased indefinitely by moving the position of the working section. In practice, however, the maximum duration is limited by reflections from the ends of the tube of the shock and expansion waves.

If the high-pressure end is closed the expansion wave is reflected as a second expansion wave. The head of this wave moves along BEF (Fig.3). As far as the reflection from the high-pressure end is concerned, therefore, the maximum duration $t_{3\ max}$ of the flow behind the temperature discontinuity occurs at the point X which for subsonic flow coincides with the position originally occupied by the diaphragm. The maximum duration $t_{2\ max}$ of the flow behind the shock occurs at the point Y. If the high-pressure end is open, the reflection takes the form of a compression wave which tends to build up into a shock; this travels more rapidly than the expansion wave which would be reflected from a closed end, and leads to a reduction of the duration of steady flow.

If the low-pressure end is closed, the shock wave is reflected as a shock. If it is open and the flow behind the incident shock is subsonic, the reflection is an expansion which travels back along the tube less rapidly than the shock reflected from a closed end. If the flow behind the incident shock is sonic or supersonic no reflection passes back along the tube from an open end[3]. Thus if the effects arising from reflection at the low-pressure end are to be minimized it is theoretically best to leave the end open. This is, however, inconvenient in practice because it is usually necessary to use sub-atmospheric pressure+ in the low-pressure compartment in order to achieve the required pressure ratio without overloading the diaphragm. Most shock tubes are, therefore, constructed with both ends closed.

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*Lobb[4] finds that the Mach number reaches a limit of about 5.0. He attributes this to the fact that the rarefaction wave is more complex than assumed in the theory, especially for large initial pressure ratios (> 300).

+This could, presumably, be achieved with an open ended tube by attaching a relatively large airtight surge tank to the end of the tube.

For a given position of the working section the duration of steady flow may be limited by the passage through the working section of the tail of the expansion wave, the temperature discontinuity, or the head of the reflection from either end of the tube. Which of these disturbances actually imposes the limit depends on the initial pressure ratio and on the position of the working section along the tube. The theoretically optimum position of the working section can be calculated readily, but the choice of position in a practical shock tube is also influencedby the following departures[4,7,8] from the conditions assumed in the theory. Since the diaphragm bulges before being ruptured and does not disintegrate instantaneously a plane shock wave is not formed at once. Experimental evidence shows that the uniformity of the shock and of the flow behind it improves as the shock moves along the tube; for observations in the flow behind the shock the minimum distance between the diaphragm and the working section should be from 10 to 20 times the greatest dimension of the cross section[2,6,7]. The temperature discontinuity is in practice a region extending over a length which may be about 6".

In order that the position of the working section may be moved so that it is near the optimum position for each set of initial conditions which are to be used, it is usual to construct the shock tube of several short interchangeable sections.

Most shock tubes are of uniform cross section over their whole length, but calculation shows[9] that the initial pressure ratio across the diaphragm can be reduced by using a larger cross section for the high-pressure than for the low-pressure chamber. The reduction is not, however, very large and it is not yet known how much of it can be realized in practice.

3. Instrumentation

The techniques used for making observations in a shock tube are more elaborate than those commonly used in wind tunnels because the flows are either unsteady or, if steady, of very short duration.

The time scale required for many of the measurements may be provided by means of a drum camera[2,8,10,11] which rotates at a constant known speed and photographs the screen of a cathode-ray oscilloscope connected to pressure pick-ups, or to "light screens" (see below), which indicate the passage of a shock wave or other disturbance past a particular point along the tube. As an alternative to this mechanical method, the time base may be provided by electrical methods involving crystal-controlled oscillators[6] or electronic interval counters. With such methods the shock velocity can be measured very accurately (to within 0.02%).

The passage of the shock wave past a given point along the tube is conveniently indicated by a "light screen"[2,4,7]. This is in effect a miniature schlieren system which actuates a photo-multiplier valve. The apparatus is set up so that when the density in the tube is uniform all light is cut off by a knife edge. When a shock wave enters the optical field the beam of light is deflected away from the knife edge and an electrical signal is produced by the photo cell. This signal may be used in timing the motion of the shock, or it may be fed through an adjustable delay circuit and used to trigger a spark light-source which photographs the flows in the regions of uniform velocity which follow the shock down the tube. An alternative method[12] depending on the change of electric current througha glow discharge when the shock wave passes has been used in cases where the density in the tube is too low for "light screens" to be effective.

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The time at which the diaphragm is ruptured may be indicated[2] by projecting a beam of light along the axis of the tube from a source at one end onto a photo cell at the other. When the diaphragm is intact the beam is interrupted, and a signal is produced by the photo cell when the diaphragm is eliminated.

Since the duration of flow is short, optical methods of observation are widely used in shock tubes. The direct-shadow and schlieren methods are useful for indicating the shape and position of shock waves and other flow phenomena, and the interferometer enables the density to be measured quantitatively. Apart from the synchronization of the light source the arrangement of these techniques is the same as on a wind tunnel.

The "wave-speed camera"[13,14,15] is a useful instrument for obtaining a continuous record of the motion in a shock tube. It consists essentially of a continuous-illumination schlieren or direct-shadow system by which the flow is observed through a pair of long narrow windows running parallel to the axis of the shock tube. The schlieren image of the flow is recorded by a drum camera which produces, in effect, an x, t diagram of the flow similar to those sketched in Figs. 2 and 3.

Pressure measurements in a shock tube are difficult because of the transient nature of the flow, but have been successfully attempted[16] by using a piezo-electric pick-up. The accuracy with which absolute pressures can be measured in this way is not yet known, however, and it is probable that the interferometer provides the best means of quantitative measurement in the flow field. Density measurements have been made[17] by measuring the corona current between the point of a wire and a co-axial ring placed in the shock tube.

The instrumentation may be simplified by an aerodynamic method of triggering and velocity measurement described[18] by Hertzberg and Kantrowitz.

4. Practical Details

The cross-sectional shape of a shock tube depends largely on the work for which it is to be used. Except in special cases a rectangular shape is preferable to a circular one as it facilitates the use of the schlieren and interferometer techniques. The maximum size of the cross section is mainly determined by the loads on the diaphragm which is usually made of cellophane. If the tube is very small, on the other hand, the effects of viscosity may be appreciable[19,20] and it may also be difficult to make optical observations. Sizes varying from about $\frac{1}{2}$" dia. to 18" × 4" have been built, and a size of about 7" × 2" appears to be popular for a general-purpose shock tube.

The length of the shock tube depends on the work to be done and on the time required before the flow is affected by reflections from the ends of the tube. Lengths varying from a few inches to 50' have been used, and a length of about 15' seems popular. It has already been mentioned that the tube is usually constructed with several short interchangeable lengths so that the position of the working section and other components can be altered.

The tube must be sufficiently rigid for the walls not to vibrate under transient loading, and to withstand the pressures which are applied. It should be free of leaks so that it can be evacuated or filled with gases other than air. With air as the working fluid, the usual practice is to obtain the required initial pressure ratio by using atmospheric pressure in the high-pressure compartment and evacuating the low-pressure compartment. The internal surfaces of the tube should be smooth, and care should be taken that discontinuities do not occur where the individual sections join.

Models of aerofoils and other bodies placed in shock tubes must be sufficiently strong to withstand the starting loads and the impact of fragments of the shattered diaphragm. In most cases, it is apparently not difficult to obtain sufficient strength, but when the leading edge of the model is sharp it is necessary[4] to make it of toughened steel to prevent damage.

5. The Uses of a Shock Tube

The shock tube is a highly versatile apparatus and has been used to investigate a wide range of problems in fluid dynamics. These include:-

(i) The Growth, Structure and Motion of Shock Waves

The shock tube provides the most convenient means of investigating these subjects which are of considerable fundamental and theoretical interest and have practical applications to, for example, Civil Defence problems. Examples of the study of shock propagation and reflection are described in Refs. 8, 21, 22 and 23, and examples of the refraction of shock waves in Refs. 24 and 25. The diffraction of shock waves round obstacles has been investigated in Ref.26, and in Ref.27 photo-elastic methods were used to determine the stresses set up in the obstacle. Shock tubes have been used[10,11] extensively to calibrate blast-pressure gauges. Problems of interaction[28] may be studied by using the reflections from the ends of the tube or by using two or more shock tubes in conjunction.

The study of the growth of shock waves is difficult in a conventional shock tube because the diaphragm bulges before breaking, and does not break uniformly, but successful tests have been made[29] in a tube in which the shock was produced by accelerating a relatively massive piston. The thickness of shock waves has been examined[30] by an optical method involving the measurement of the reflectivity of the shock front.

Examples of the use of shock tubes to study detonation processes in combustible gases are given in Refs. 13 and 15.

(ii) The Study of Condensation Phenomena

The condensation of water vapour in rapidly-expanded air has been studied[31] in a shock tube by using air with accurately known humidity in the high-pressure compartment. When the diaphragm was ruptured the presence of condensed moisture was detected by an optical method in which the light scattered by water droplets was observed and recorded electronically. In addition to their fundamental interest the results are of value in the design of supersonic wind tunnels.

(iii) Gas Behaviour at Very High Temperatures and Pressures

Temperatures at which the effects of relaxation time and of dissociation and ionization may be important can be reached in a shock tube. So far, little has been done on this application but some preliminary experiments have been reported by Perry and Kantrowitz[32] and by Petschek[33]. Perry's apparatus (Fig.4) consisted essentially of a 3" diameter, 15" long shock tube fitted with a unit A shaped like a teardrop at the low-pressure end. The plane shock wave formed when the diaphragm was ruptured passed round the channel between the "teardrop" and the wall of the

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tube and formed a cylindrical shock which converged towards the axis. There was a window at the end of the tube, and it was found that sufficient luminosity was produced near the centre of the converging shock to be observed visually and photographed. Schlieren photographs of the shock were taken by polishing the end of the "teardrop" so that light was reflected back through the flow onto the knife edge of the schlieren apparatus. For shocks in argon measurements of the conductivity in the region of the converging shock indicated the occurrence of ionization.

(iv) Steady Flows

As described in section 2, there are two regions in the flow in which the motion is steady, and the use of these regions to examine the flow past aerofoils and other bodies has recently received considerable attention*. Most of the observations which have been reported[2,4,6,34] have been made in region (2) (see Fig.2) behind the shock wave, and it appears that the conditions here are in practice both uniform and steady. With air as the working fluid the Mach number available in this region may be varied in practice from zero to about 1.3. The Mach number behind the temperature discontinuity on the other hand, can in theory be increased indefinitely but the few observations[4,31,35] which have been reported in this region suggest that the flow is less uniform than behind the shock.

Except at very high Mach numbers the Reynolds numbers of tests at a particular Mach number behind the temperature discontinuity are of the same order as those obtained in a wind tunnel with intake conditions similar to those in the high-pressure compartment of the shock tube. The Reynolds numbers of tests behind the shock wave are considerably lower+.

Water vapour present in the air is unlikely to condense in the flow behind the shock because the temperature is high (see also below). Except at very high Mach number the possibility of condensation behind the temperature discontinuity is similar to that in a wind tunnel operating with intake conditions equal to those in the high-pressure compartment of the shock tube. It is, however, easier to dry the air in a shock tube than in a wind tunnel because the quantity of air involved is smaller.

It has been reported[34,36] that choking at free-stream Mach numbers close to unity does not occur when a model is placed in a shock tube and that tests may, therefore, be made at transonic speeds. Further work appears, however, to be necessary before the utility of tests of this kind can be assessed particularly as the difficulties of preventing shock waves reflected from the walls from striking the model are probably similar to those in a wind tunnel.

The limitation to the Mach number which can be reached in air behind the shock wave has been overcome by Hertzberg[37,38] by placing a diverging nozzle upstream of the working section of a shock tube. When the flow is supersonic behind the shock wave reflected waves are continuously formed as the shock travels through the divergent nozzle and these coalesce to form a secondary shock wave. When the strength of the main shock wave is correctly chosen this secondary shock is swept downstream and, after its passage, steady flow is established in the working section. The Mach number of this flow depends on the entry Mach number and on the area ratio of the nozzle. Using this arrangement Hertzberg

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*For a detailed theoretical study see Refs. 2 and 3.

+For example with $M = 1$ and atmospheric initial conditions in the high-pressure compartment, the Reynolds number per foot behind the cold front is 3.2×10^6 whilst that behind the shock wave is 0.4×10^6.

produced a Mach number of 4.2 in air and he suggests that considerably higher values are possible. Since the temperature behind the shock is relatively high, the technique has the advantage that difficulties associated with the liquefaction of the working fluid are less severe than in a wind tunnel.

In addition to observations in steady flow it is possible in a shock tube to examine the development of a flow accelerated rapidly from rest. Some preliminary observations of the development of the laminar boundary layer in the region behind the shock wave are described[39] by Lobb.

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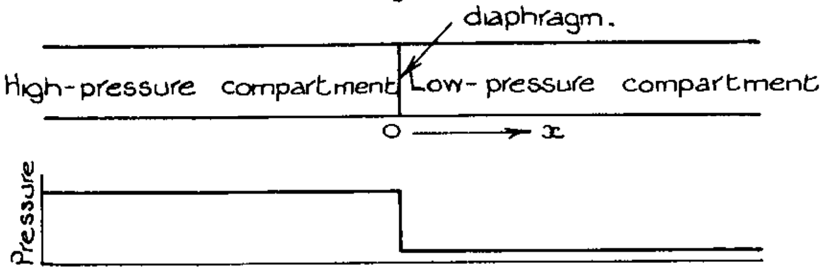
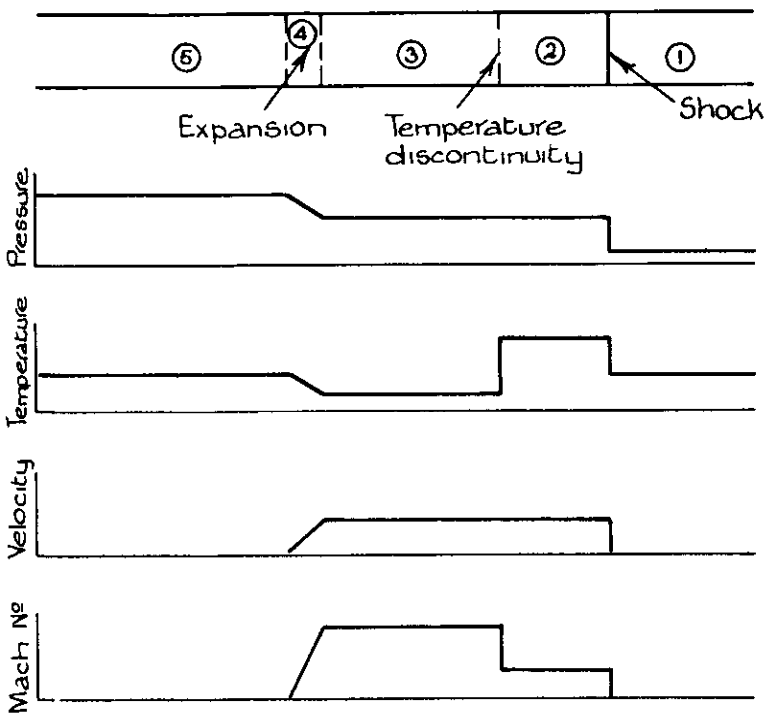
Fig 1



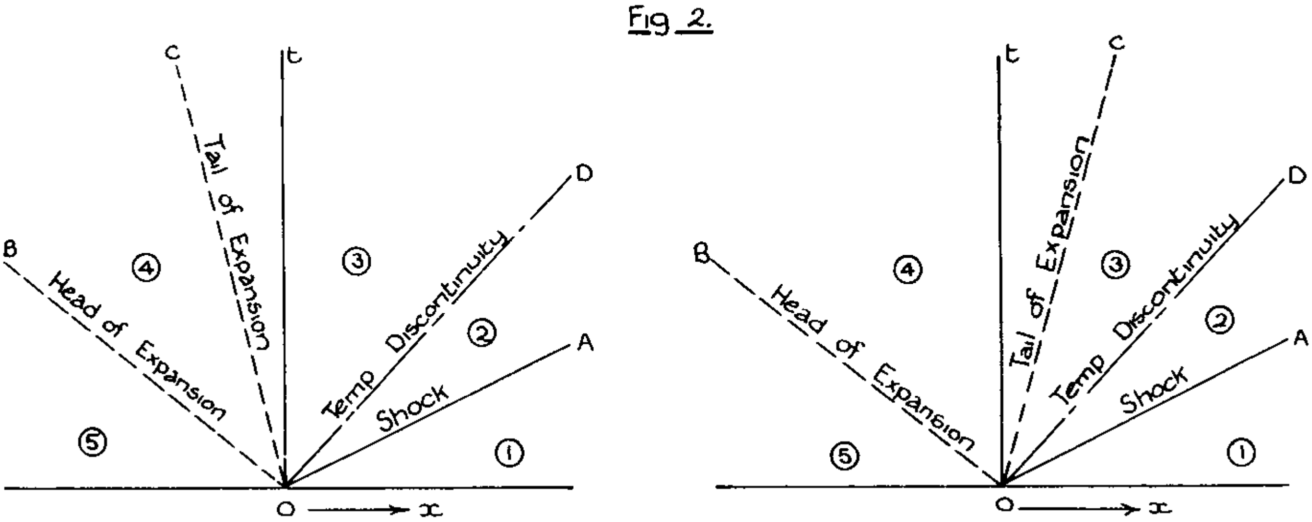
(a) Before Diaphragm is Ruptured



(b) At Time t after Diaphragm is Ruptured
(subsonic flow in region ③)

Sketch showing the Conditions in a Shock Tube

Fig 2.



(a) Subsonic flow in region ③ (b) Supersonic flow in region ③

Sketches of x, t diagrams illustrating the flow in a shock tube

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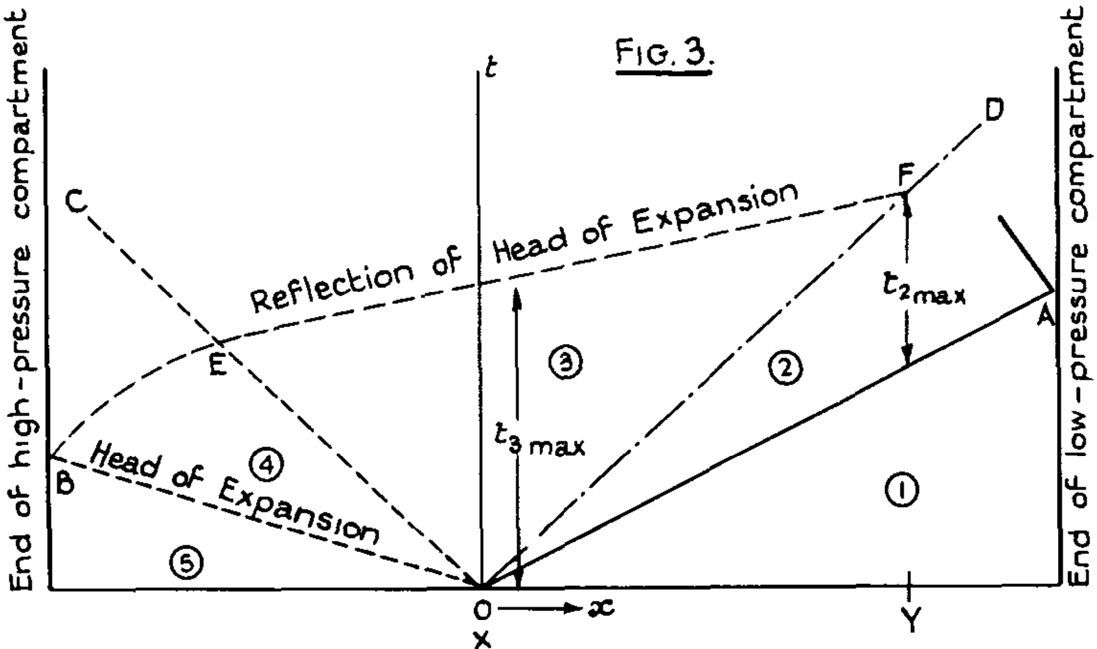
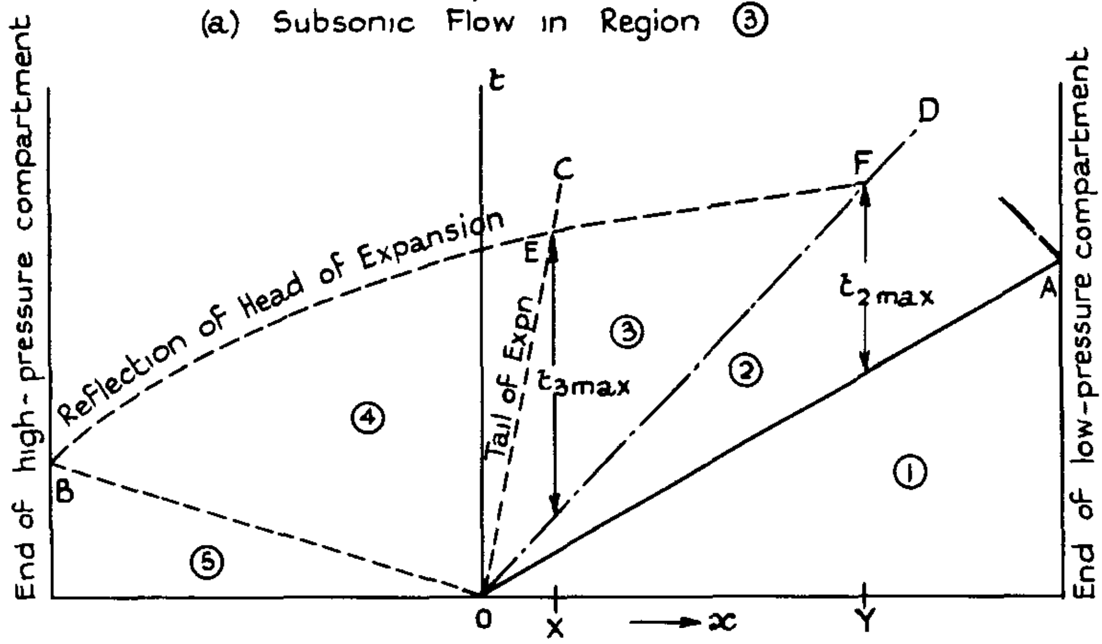
FIG. 3.



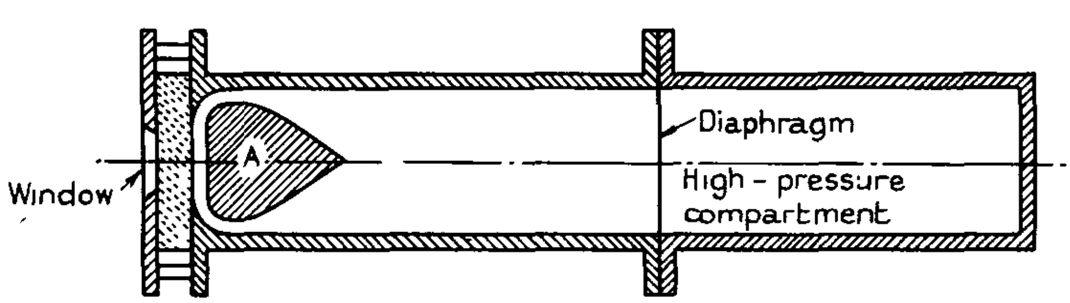
(a) Subsonic Flow in Region ③



(b) Supersonic Flow in Region

Sketches of x, t Diagrams Illustrating the Reflection From the High Pressure End.

FIG. 4



Sketch of Apparatus used by Perry and Katrowitz (ref 32) to produce Converging Shock Waves.

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