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Fabrication and Experimental Study of Shock Waves Generated using a Shock Tube

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Abstract: The prime focus of this paper is to design and fabricate a diaphragm based shock tube and to study the variation of parameters across the generated shockwave. The drastic variation in pressure, temperature and entropy, can be used in various industrial applications. The main objective is to produce a shockwave using diaphragms of varying thickness as well as material, which mainly consists of measuring the speed of the incoming shockwave using microphones and also theoretically calculating the variation of shock waves for different parameters. The diaphragm is placed in an air tight chamber between the driver and driven section. Pressurised air is supplied to the driver section in which the chamber pressure is monitored. The driven section consists of microphones, which measures the velocity of incoming shock. The build-up of pressure in the driver section, causes the diaphragm to rupture, which in turn produces shockwaves. The microphones record the disturbance produced in the surrounding medium and the speed of the shockwave is obtained using the software. The calculated change in parameters for different diaphragm and the speed of shockwave is tabulated corresponding to the diaphragm material used. Using the obtained information, various parameters like pressure, temperature and entropy change is calculated theoretically and the obtained results are analysed.

Keywords: diaphragm, microphones, shocktube, shockwaves.

I. INTRODUCTION

Waves are produced when there is a disturbance in the medium, these waves propagate in the given medium by contracting and expanding the surrounding medium from the point of propagation. Sound waves propagate with a speed of 342.8m/s in air, this speed depends on the gamma value of

air and also depends on the temperature of air. A shock wave is a disturbance which is accompanied by abrupt change in temperature, pressure and entropy, the speed of shock wave is given by Mach number. The application of shock wave process has gained considerable focus in recent years in industries. A variety of industrial applications use shock waves for its property of providing drastic change in pressure, temperature and entropy. There are numerous development not just in application of shock wave but also in the way they are produced. The most reliable and convenient method of producing shock waves is by using a shock tube. There are different types which include diaphragm based, pneumatic based and many more. The most conventional type of shock tube is the diaphragm based shock tube. In conventional diaphragm-type shock tube, the complete setup is economical and the use of diaphragm can be manipulated to obtain the desired results. The following journals was referred and their significance are as follows.

In this paper D.W. Holder [1] describes about the complete theory behind shock tubes which includes the flow in shock tubes, instrumentation, practical details and the uses of shock tubes. Takefumi ikui et.al [2] discovered the use of two kinds of fast acting valves to replace the diaphragm based shock tube. Kazuyoshi takayama [3] highlights the usefulness of shock wave research applied to engineering and medical problems. O.E. Kosing et.al[4] helps us to understand the use of friction controlled, piston actuated diaphragm less shock tube driver over a diaphragm based shock tube. Eric. L. Petersen et.al [5] writes about shock tube attenuation and the variation of temperature and pressure in the region of reflected shock in a shock tube. G. Jagadeesh et.al [6] highlights about the use of shockwaves in biological sciences. Tateyuki Suzuki et.al [7] describes the determination of drag coefficient of an accelerating spherical particle, which was performed using a shock tube. K.Takayama et.al [8] describes about the application and study of shock waves towards the field of medicine. G.Jagadeesh [9] describes how shock waves are used in various industrial applications which include shock wave generated in an underwater shock wave generator. Raymond burn [10] analyses the experimental study of non-equilibrium gases for which two types of facilities are described here, namely shock tubes and shock tunnels. Cui Y et.al [11] throws light on shock wave lithotripsy (SWL) which is the only non-invasive method for stone removal.

Kuriakose et.al [12] has devised methods to eliminate unwanted secondary artifacts in order to obtain pure shock wave waveform in the test section inside of the shock tube. Prof. N.M Reddy [13] shows us the importance and methods to analyze the shockwaves and also tells us about the laboratory of hypersonic research at IIsc Bangalore. M. Kiran singh [14] highlights the importance of temperature calibration of a single pulse shock tube for obtaining precise kinetics data. Some of the commonly used standard reactions for chemical thermometric measurements and their uses in our recent studies are also discussed in this article.

II. METHODOLOGY

As mentioned in the sections above, the shock tube consists of a driver and driven section between which a diaphragm of a known material is placed. The parameters of a shock tube can be varied extensively by varying the diaphragm material as well as its thickness. Shock tubes which use high velocity shocks often use diaphragm made of metals such as aluminium and mild steel sheets, and shock tubes which use comparatively lower velocity shocks use diaphragms made of plastic or high density paper. The properties of the driver and the driven section can be varied by the introduction of different gases such as helium, argon, nitrogen because the main intention is to keep the gamma value and the temperature constant, as the gases are inert at room temperature. By keeping these values constant, it is easy to determine the speed of sound. There are several methods to rupture a diaphragm in a shock tube and these methods depends mainly on the reactivity of the gases used and several other factors. The most common method to rupture the diaphragm is by passing an electric arc or by mechanically breaking it by using a plunger mechanism. The shock tube in this experiment basically uses two types of diaphragms, one made of aluminium and another made up of 85gsm paper. Materials such as mild steel, plastic exhibit yielding under high pressure and do not rupture instantaneously. The diaphragm ruptures due to the differential pressure maintained between the two sections. Two microphones are placed in the driven section at a pre-determined distance so as to measure the velocity of the shock experimentally. When the shock propagates through the driven section of the shock tube, the microphones interprets the disturbance in the medium and displays it as two peaks in an amplitude versus displacement graph, through a software (Audacity). As the distance between the microphones as well as the time difference between two peaks are known from the graph, the speed of the sound wave is calculated. Two pressure gauges (max measurable pressure 10bar), one at the driver section and another at the driven section are placed strategically. By obtaining the above values, the change in properties importantly temperature, pressure and entropy are calculated respectively. The obtained results are tabulated and the predicted results are calculated using formulae. These results are then plotted using MATLAB.

In Fig 1, after the rupture of the diaphragm the shock propagates with a velocity ‘W’ into region 1 which is maintained at STP. This creates a turbulence in region 2 and the flow starts to flow with a velocity of ‘Up’. The velocity of the flow is always less than the velocity of the shock and can attain a maximum Mach number of 1.89. Due to the turbulence created in region 2, the expansion waves, which are weak Mach waves propagate into the driver section region 4.

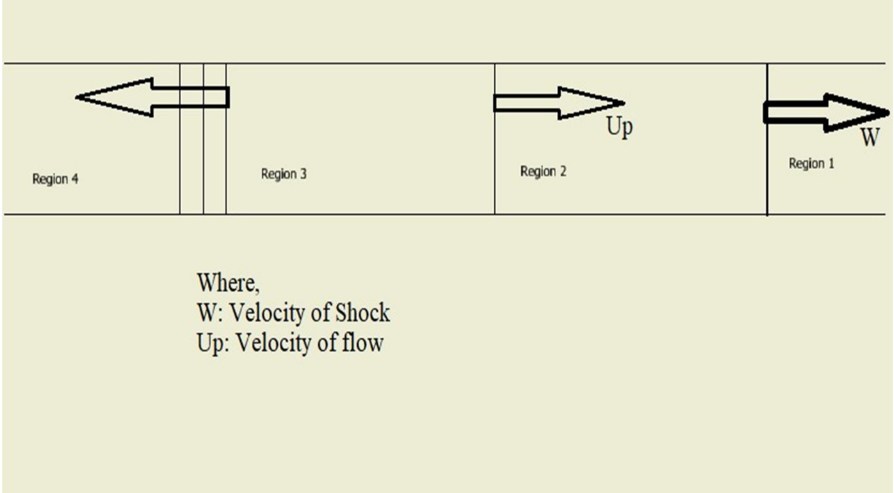

Fig 1. Shock propagation inside a shock tube

The pressure variation is as shown in the Fig 2. Before the rupture of the diaphragm, the differential pressure is maintained in region 4 and region 1 where, pressure in region 4 is greater than the pressure in region 1. After the rupture of the diaphragm the pressure in region 4 gradually decreases to pressure in region 1. As the shock tube used in this experiment is open to the atmosphere, there are no reflections or rarefactions taking place from the end walls of the shock tube.

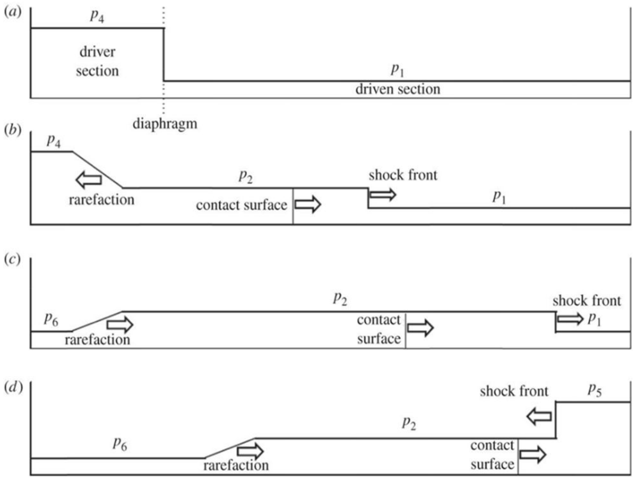

Fig 2. Pressure v/s distance graph

III. DESIGN AND FABRICATION

The fabricated shock tube consists of three main sections, they are the driver, driven and the coupler respectively. The main constraints for the design of the shock tube are Reducing viscous effects of the surrounding medium and to achieve air tight seal.

Thus considering the above factors mild steel was chosen as the material, even though it is comparatively heavier than aluminum, the cost of raw material is significantly less and also the disturbances in the medium are damped due to the heavier material. The parts were galvanized after their fabrication to prevent corrosion.

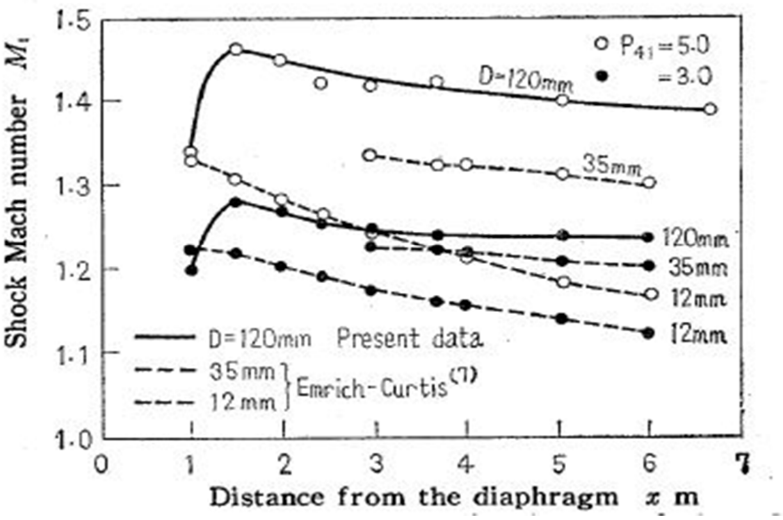

Fig 3. Effect of cross sectional diameter.

As seen above in the graph (Fig3. Effect of cross sectional diameter.), the shock Mach number almost remains constant for a diameter of 35mm and decreases quite sharply for a diameter of 12mm.Thus, a diameter of 19.05mm (ID=0.75in, OD=1in) was chosen. All the sections were designed using Autodesk Inventor, and were simulated for machining using Fanuc coding program to confirm the manufacturing of the respective parts.

To assist ease of handling and air tightness the whole coupler housing is designed to turn and lock rather than using a separate nut and a bolt at various regions in the housing. The mating part is a three-piece design in which the outer coupler has internal thread machined to its inner periphery as shown in the Fig 4. ((3) Coupler). A mating external thread is also machined to the outer periphery of the driven section part, to which driven section chamber is coupled ((1) Driven Section). The driver section ((2) Driver Section) to which the driver section chamber is attached, is placed inside the coupler. The driven section, which also contains the diaphragm, is then screwed on to the coupler creating an air tight seal. The complete assembly with the mounting stand is as shown below.

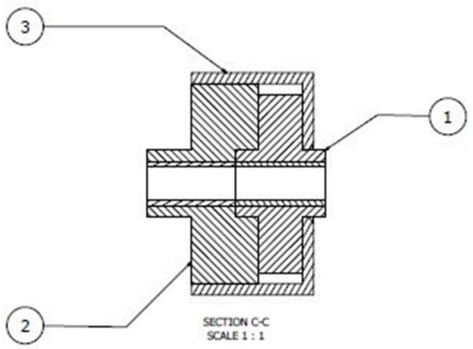

Fig 4. Cross sectional view of the coupling chamber

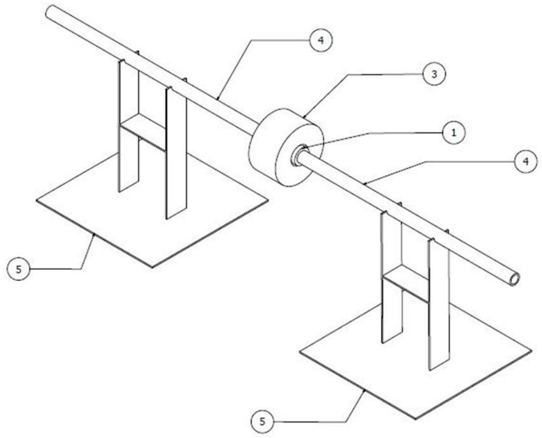

Fig 5. Assembled view of the shock tube setup

IV. FORMULAE USED

$(\rho 1 u1) = (\rho 2 u2)$ (1)

$P1 + \rho 1 (u1)^2 = P2 + \rho 2 (u2)^2$ (2)

$h1 + \frac{(u1)^2}{2} = h2 + \frac{(u2)^2}{2}$ (3)

$\Delta s = Cp \ln \frac{T2}{T1} - R \ln \frac{P2}{P1}$ (4)

$\frac{P4}{P1} = 1 + \frac{2\gamma}{\gamma+1}[Ms^2 - 1]$ (5)

$Ms = \left[\frac{\gamma+1}{2\gamma}\left[\frac{P2}{P1} - 1\right] + 1\right]^{0.5}$ (6) $Up = \left[\frac{a1}{\gamma}\right]\left[\frac{P2}{P1} - 1\right]\left[\frac{{}^{2\gamma}/_{\gamma+1}}{\frac{P2}{P1} + \frac{\gamma-1}{\gamma+1}}\right]^{0.5}$ (7)

$$\frac{Up}{a2} = \frac{Up}{a1}\left[\frac{T1}{T2}\right]^{0.5} \tag{8}$$

$$\frac{T1}{T2} = \left[\frac{1+\left[\frac{\gamma+1}{\gamma-1}\right]\left[\frac{P2}{P1}\right]}{\left[\frac{\gamma+1}{\gamma-1}\right]\left[\frac{P2}{P1}\right]+\left[\frac{P2}{P1}\right]^{2}}\right]^{0.5} \tag{9}$$

The symbols used are of standard notation and are used according to S.I units. The non-standard notations are defined as follows. $P_{1,}$ T_1 refers to the pressure and temperature at respective regions. $a_{1,}$ a_2 refers to the speed of sound in their respective regions. $U_{p,}$ M_s refers to the upstream flow velocity and the shock Mach number.

V. OBSERVATION TABLE

TABLE I

85 GSM PAPER DIAPHRAGM

Sl.no	Thickness (mm)	Inlet Pressure P4 (bar)	Outlet Pressure P1 (bar)	Mach Number	Pressure Ratio (P2/P1)	Flow Velocity Up (m/s)	Temp. Ratio T1/T2	Upstream sound velocity A2 (m/s)	Change in entropy Δs (KJ/kgK)
1.	0.09	2.1	1	1.393	2.097	192.94	0.79	383.491	0.012
2.	0.18	4.6	1	2.021	4.598	436.19	0.58	447.806	0.109

TABLE II

ALUMINUM FOIL DIAPHRAGM

Sl.no	Thickness (mm)	Inlet Pressure P4 (bar)	Outlet Pressure P1 (bar)	Mach Number	Pressure Ratio (P2/P1)	Flow Velocity Up (m/s)	Temp. Ratio T1/T2	Upstream sound velocity A2 (m/s)	Change in entropy Δs (KJ/kgK)
1.	0.064	1.2	1	1.082	1.199	45.063	0.949	352.039	0.0299
2.	0.128	2.6	1	1.539	2.596	254.102	0.728	397.974	0.0452

VI. RESULTS

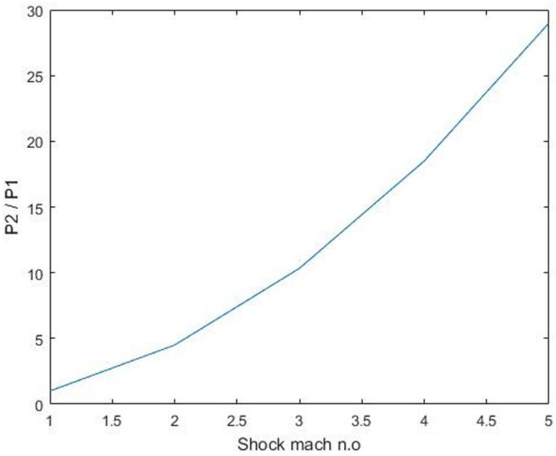

Fig 6. Shock Mach no. vs P_2 / P_1

It can be seen from the graph (Fig 6.) that when the pressure ratio increases, the intensity of the shock wave also increases, as the change in entropy depends on the pressure ratio as well as the temperature ratio. The maximum intensity of the shock is achieved when the flow transits from supersonic to subsonic.

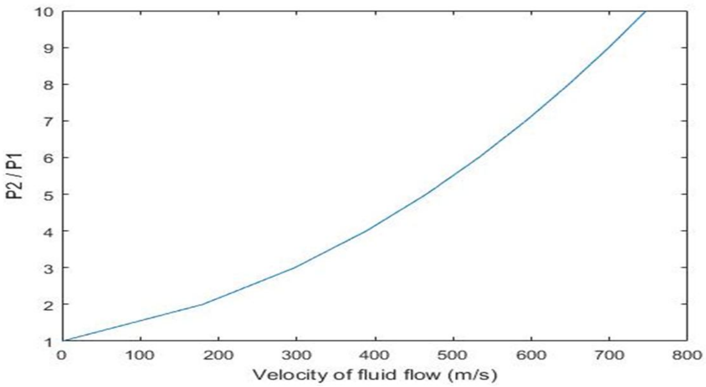

Fig 7. Upstream velocity vs P_2 / P_1

It can be concluded from the graph that, as the velocity of the flow increases, the pressure ratio also increases. But, when pressure ratio tends to infinity, the maximum Mach number
achieved by the upstream fluid flow is 1.89, given that the speed of sound is constant in the upstream fluid.

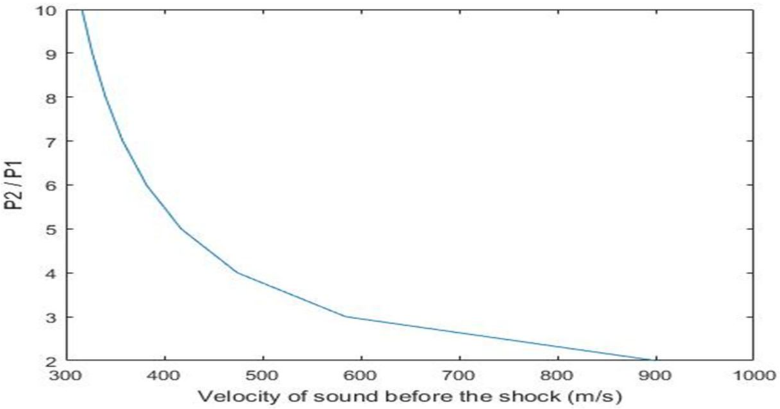

Fig 8. Velocity of sound before shock vs P_2 / P_1

It can be concluded that, higher the pressure ratio, lower the velocity of the sound until it reaches a steady state speed. This can be attributed to the fact that the speed of sound varies inversely to the compressibility of the propagating medium. To lower the velocity of sound before the shock the specific volume of gas can be decreased or the compressibility of the gas can be increased.

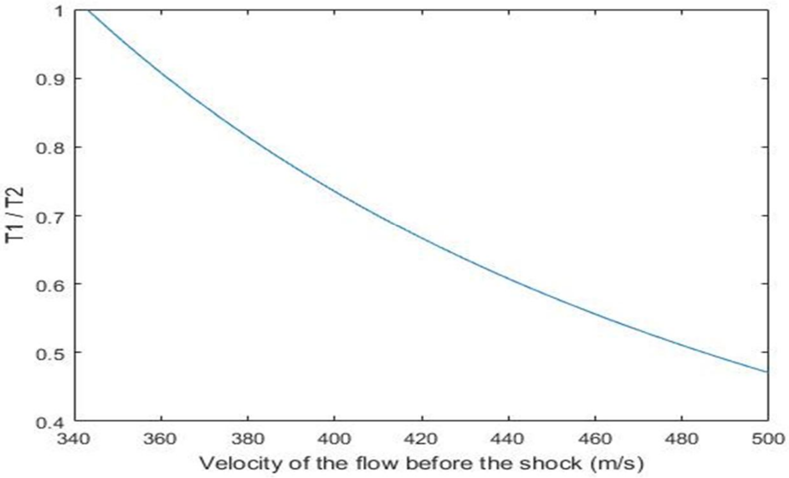

Fig 9. Velocity of flow vs T_1 / T_2

The significance of the graph is that, the velocity of the sound before the shock increases as the temperature before the shock is greater than the temperature after the shock. This can be attributed to the fact that velocity of the sound varies proportionally with respect to temperature. This temperature can be used in endothermic reactions to supply energy to the reactants.

It is to be noted that, the above graphs are obtained for the ratio of specific heats 1.4 as the experimentation is conducted using air as the propagating medium. It can also be observed that the change in entropy is positive, which signifies that the obtained results are predicted correctly.

VII. CONCLUSION

Shock waves are generated using a shock tube which consists of a rupturable diaphragm. The diaphragms used are mainly 85 GSM paper and Aluminium foil. The thickness of the diaphragms is predetermined so as to vary the pressure before and after the diaphragm. A tube of 12 mm was chosen to reduce the viscous effects of the propagating medium.

The diaphragm is placed in an airtight chamber and the diaphragm ruptures due to the differential pressures maintained before and after the diaphragm. The speed of the shockwave is measured using microphones which are placed in the predetermined distance in the driven section.

The change in the properties of temperature, pressure, and entropy are calculated and tabulated in the observation table. The obtained values and the predicted behaviour is plotted in matlab and the following conclusions are drawn.

1) The maximum intensity of the shock is achieved when the flow transits from supersonic to subsonic due to which there is a positive entropy change. The maximum intensity is achieved according to Fig10.

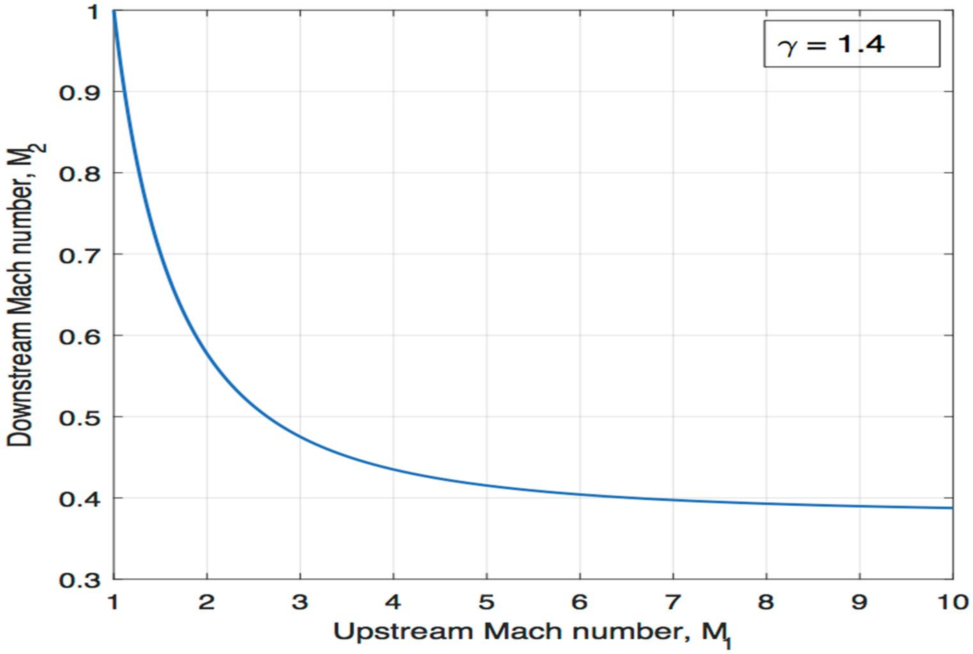

Fig10. Upstream Mach n.o v/s Downstream Mach n.o

2) The upstream flow velocity can reach a maximum Mach n.o of 1.89 only.

3) The pressure, temperature before the shock is significantly greater compared to pressure, temperature in front of the shock, which can be used for various applications.

4) Velocity of the sound varies inversely with compressibility and directly with specific volume and temperature.

VIII. ACKNOWLEEDGEMENT

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