Onset of detonation through a cold flow analysis using metallic diaphragms – an experimental approach

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Abstract. Modern era is looking for high speed transportation systems across globe with due comfort. Innovative design in both aerodynamic and propulsion studies have been made for achieving supersonic to hypersonic speeds ranging a claim of 1km/s under stratosphere limit. The complexity in designing such vehicles in a high-altitude test facility is borne due to the fact that simulation of such conditions as low density, no shock conditions, high rate of dissipation and shock flow comes from unavailability of sufficient technology to pressurize gases to the optimal testing conditions. The prominent ways of constructing a shock tube either involve a blow down type or a vacuum suction type. Here a blow down type shock tube require a built-up pressure comparable to the velocity at the test section. Fibre diaphragms blow out at less critical pressure and are unsuitable for high speed flows. Metal foil are incepted as a concept of diaphragms for this particular problem. Aluminium foils are stacked across a mounting flange on a settling chamber to determine the maximum pressure at which blow down occurs. The results are tabulated for an incremental pressure schema of 1 bar to 10 bar with which it was found that the wave pressure development occurs during each batch of aluminium and recorded to be between 3.5 bar and 9 bar the successive velocities at the exit was found to be increasing with increase of blast pressure.

1. Introduction

Characterization of shock train inside a shock tube by varying the shock tube length, diameter of the diaphragm and pressure ratios has been extensively studied. Investigations were conducted to visualize the interaction between the reflected shockwave and the contact surfaces. The resulting wave expansion produces a supersonic wave which is then decelerated and interacted to produce stronger shockwave [1]. Studies on numerical simulations of flow characteristics in micro shock tube by observing shockwave surface propagation and attenuation has been done at different condition resulting from viscous effects, the friction between shockwave and tube wall aiding in forming boundary layer and micro shocks. Increment of diaphragm pressure ratios have indicated an increment of the Mach number at the exit as well as the shockwave strength. So it can be concluded that higher pressures are required at the settling chamber which affect the exit velocity through jet flow control equation given in equation 1 [2].

\[
\frac{dV}{V} = -\frac{dA}{A} \frac{1}{1-Ma^2}
\]  \hspace{1cm} (1)

Further, shockwave interaction with boundary walls due to the high pressure and velocity involve heat transfer from shock to the wall of pipe. Experimental investigation using various metal foils of
significant thicknesses were used to test the wear rate due to the thermal and fluid boundary layer interaction between the shockwave and surface of the expansion tube. It has been noticed that the heat transfer through the interference or blockage is higher at high Reynold’s number and the erosion effect on the plates were experimentally measured to have a significant change in the demography of the blockages [3]. Fabrics and other materials are also considered for choking the flow from the settling chamber to the jet pipe. At high pressure, singular layers of fabric usage become irrelevant as the cloth permeability ratio is higher and the conversion of subsonic to supersonic flow is generally not possible. However usage of multiple layers of cloth with different orientations make it almost feasible similar to that of metal foils and tracing paper which have been better diaphragm designs under high pressure conditions and has low permeability ratios [4].

Shock flow conditions have also been studied by researchers to describe the flow evolution in an experimental investigation along a flat plate. It has been found that flow structure is important factor which determine the flow evolution and a reflected shockwave may affect the total pressure gradient inside the jet flow thereby inhibiting the flow characteristics stating that heating of gases flowing through the jet occurs due to interaction between fluid, thermal boundary layers and reflected shockwaves [5]. Various inert and standard gases have also been studied inside shock tubes for their sustainability at high pressures due to the compressibility factor of such gases. The gases shows that shockwave formation goes through multiple stages and the pressure gradient always does not follow an incremental schema. The high pressure ratio occurs after the first rise of shockwave due to the propagation effect and the interaction between compressed gases and air. Auto ignition of hydrogen with ambient air at high pressure has been utilized to visualize the effect of compressed gases and the minimum pressure for the auto ignition and subsequent pressure wave has been studied to give an idea about minimum pressure at which the diaphragm should rupture for the maximum exit flow velocities to be achieved and further the type of material must be restricted to lower permeability ratio materials for achieving maximum efficiency of the shock tubes [6, 7].

Acoustic relays play a significant role on measuring the pressure wave strength of shockwaves occurring from diaphragm ruptures as flow velocity measurement instrumentation becomes difficult to construct based on pressure based load cell as the probes for collection of pressure data are themselves considered be micro blockages or cavities in the flow stream as it is affecting the demography of the flow by creating small perturbations in flow stream [8–10]. The small perturbations causes a significant effect in the downstream boundary flow interaction between shockwave and pipe wall where flow mitigation becomes imminent and slipstream reduction occurrence possibility increases. PCB based microphones have been extensively used at multiple lengths and angles across the experimental flow stream to record the soundwave emission and such recordings are then converted to pressure wave strength using a mathematical formulation[11-13].

Mylar 30 woven fabric were also tested as a possible materials for diaphragms in shock tubes and have been found to be resistant to micro cracking for nominal pressures[14]. The panel responses and growth rate of crack have been measured by high rated moving cameras to see the matrix crack fabrication both on and below the surface of the multiple layer diaphragms. Further, it is apparent that rigid diaphragms partitions are better than flexible and expandable materials as they prevent seepage of air pressure at higher pressures [15]. Foils have been used in this study to have the advantages of rigid diaphragms as sealing qualities of a flexible diaphragm material by a defined design change of the mounting flange by replacing normal flange by mating flange arrangement.

2. Design and Methodology

The experimental methodology involved in the testing on oblique shockwaves have a multitude of constraints. The major constraint being physical as the production of shockwaves involved generation
of high settling chamber pressure and maintaining it for the duration of gradual increment till the blast pressure is achieved without disturbing the structural integrity of the settling chamber. Further, high pressure expansion waves generated post blast from the settling chamber expands throughout the delivery pipe or test section in a blowdown shock tube which travel at high speeds causing higher acoustic disruptions in the surrounding areas and presence of any debris in the delivery tube itself will cause such objects at high speeds causing severe damage to property and life.

It was ensured that proper care has been taken during the entire experimentation process so as to avoid any damage either to property or life during the entire duration of the experimentation. Also, the experiments conducted were in a closely monitored conditions wherein, hot flow analysis were avoided to prevent the dangers of expanding combustion gases in closed vicinity and the cold flow can be calibrated to the hot flow analysis using a chemical kinetic model to ensure continuity and repeatability.

The experimental setup has been ensured to withstand high pressures at the settling chamber and to manage the range of pressure inside the chamber, cylindrical structure has been used for even distribution throughout the volume. The thickness of the volume is maintained around 12mm of solid steel in all directions to prevent gaseous expansion even through micro cracks and holes in the surface of settling chamber. Proper welding methodologies are implemented to ensure blockage of micro holes in the surface where the pressure gauge, inlet flange and delivery flanges are attached to ensure maximum pressure building capacity of the settling chamber. A mating flange setup is given to ensure that the leakage of air is not possible through the diaphragm hole to atmosphere and a microphone is attached near the flange plate to ensure radio silence during the surging and pressurizing of the settling chamber before the onset of the blast.

Diaphragm design for micro shock tubes were particularly difficult reason being the economy involved behind the material selection and availability. Soft material selection is generally less that to in metallic components. Foiled diaphragms are an option but metallic foils are also limited to availability and manufacturing. Food grade aluminium foils aids in becoming the best alternate for micro shock tube applications. Further a micro experimental shock tube can also become a detonation tube with the inclusion of high energy materials (fuels).

The onset of such complex problems at low budget is defined in this experimental process where in stacks of compressed aluminium foils are being moulded to a exit flange of settling chamber. Here the settling chamber is pressurized by an external reciprocating air compressor and the air expanding blast open the diaphragm to evolve super-sonic jet flow wave propagation and velocity assimilation due to wave propagation are detailly studied by experimental and numerical simulations in a standard length tube with standard tube diameter aiding in the validation of pressure expansion phenomena in a tubular flow.

The layers of the aluminium foils are then compressed in a standard UTM machine where the air gap between the layers are diminished or completely worn out so that the wave expansion modular will work perfectly. The stacks of aluminium are then cut for the exact shape of the flange and placed in between the mating parts. Experimentation is done in lieu with regression curve based on the data assimilated from the initial analysis between number of layers and explosion pressures. The results evolved aid in selection of number of layers with reference to the pressure of blasts. The instrumentation required for wave pressure modelling in an experimental method is both economically and technologically sound. Here a new instrumentation has been developed where wave pressure has been recorded through acoustic frequencies which can further be numerically endowed as velocity and jet flow. The formulation has been given in Equation 2.
Where \( L_p \) is the frequency of sound in decibels which are found out using the acoustic frequency recording which comprises of attachment of probes on the shock tube at various angles such that to clearly analyse the wave propagation audibility from all the directions of the shock tube at various lengths such as 0mm, 25mm, 50mm, 75mm, 100mm at various angles such as 0°, 90°, 180°, 270°, 360° and \( P \) is the outcome pressure of the wave propagation at the above positions and \( P_o \) is the reference pressure that is considered as the sound pressure that is typically the threshold of human hearing that is \( 2 \times 10^{-5} \) Pa. The experimental setup to determine the onset of detonation is shown in the figure 1.

![Figure 1](image_url)

### 3. Result and Discussion

The experimental investigation of the detonation initiation by cold flow across blowdown from a diaphragm isolated settling chamber and a discharge tube yields an acute understanding of the behaviour of gases at high compressed state and during rapid discharge. The acoustic redundancy was maintained by a noise cancellation test prior to the actual experimentation, wherein an initial test through the pipe was used to record the noise normally occurring at the free state and such frequencies were then removed from the recorded frequencies to maintain the calibrated frequency and then the wave pressure were calculated with reference to the aforementioned equation. It is noted that during the expansion of the pressure wave across the length of the delivery tube there is a continuous decrement of wave pressure signifying expansion of gases through the delivery pipe with rapid increment to attain maximum exit velocity ranging in a supersonic delivery flow. The relationship between the burst pressure and the exit wave pressure are shown in Table 1.

| S. No. | Burst Pressure (bar) | Acoustic Readings (dB) | Wave Pressure (bar) |
|--------|----------------------|------------------------|-------------------|
|        | Mic 1 | Mic 2 | Mic 3 | Mic 4 | Mic 5 | P1 | P2 | P3 | P4 | P5 |
| 1      | 1.213 | 195.6 | 195.3 | 195.4 | 195.2 | 195.1 | 1.2 | 1.16 | 1.17 | 1.15 | 1.13 |
| 2      | 2.913 | 203.2 | 203   | 202.7 | 202.8 | 202.6 | 2.89 | 2.82 | 2.72 | 2.76 | 2.69 |
| 3      | 4.513 | 207.06| 206.8 | 206.4 | 205.9 | 205.6 | 4.5  | 4.37 | 4.17 | 3.94 | 3.81 |
| 4      | 5.913 | 209.4 | 209.1 | 208.4 | 208.1 | 207.4 | 5.97 | 5.7  | 5.26 | 5.08 | 4.68 |
| 5      | 7.213 | 211.1 | 210.9 | 210.8 | 210.6 | 209.7 | 7.17 | 7.01 | 6.93 | 6.77 | 6.1 |
| 6      | 8.713 | 212.7 | 212.5 | 212.2 | 212.3 | 209.9 | 8.63 | 8.43 | 8.14 | 8.24 | 6.25 |
| 7      | 10.013| 213.9 | 212.8 | 211.6 | 210.8 | 210.4 | 9.9  | 8.73 | 7.6  | 6.93 | 6.666 |

Using the above table the exit velocity of such blasts where the expansion of gases leads to higher exit Mach number can be calculated with reference to the pressure wave velocity equation. It is noticed...
that the settling chamber burst pressure is directly proportional to the exit velocity during the supersonic exit phenomena and a stalling is occurring at the higher blast pressure due the back pressure effect due to very low pressure at the exit of the delivery pipe. Since the onset is a cold flow analysis, ionization flow and thereby hypersonic velocities were not recorded and cannot be expected at such low onset pressures. The minimum blast pressure required for a hypersonic flow at the settling chamber may be predicted using the incremental schema of the above table and may be around 16 bar in a cold flow analysis and range around 14 bar using a hot flow condition. The delivery pipe is ensured to have no contaminants or debris to ensure the pressure expansion is even. A sample of the ruptured diaphragm is shown in the Figure 2, below and it shows that the diaphragm rupture is matching with the delivery tube and no material loss does not occur suggesting that the multilayer aluminium foil diaphragm has better structural integrity when compared to composite layered diaphragms and are better suited for hot flow detonation initiation tests.

![Ruptured Diaphragm](image)

**Figure 2. Ruptured Diaphragm**

Using the table we may calculate the various exit velocity values and significant Mach numbers at which the flow is expanding from the isentropic expansion flow equation. The comparative graphs for exit velocity and burst pressure is shown in Figure 3.

![Blast Pressure vs Exit Mach Number](image)

**Figure 3. Relationship between Blast Pressure and Exit Mach number.**
The relation between blast pressure and exit Mach number signify that the maximum velocity at the exit is around 1.4 Mach or 476 m/s in a cold flow isentropic expansion flow conditions where the working fluid is compressed air for a burst pressure of around 10 bar and the corresponding number of layers of aluminium foil required to sustain such high blast pressures in the settling chamber is around 26. The equivalence to exit pressure to the number of layers of aluminium foil required to sustain the pressure is shown in Figure 4 and may be utilized to predict the number of layers of aluminium foil required during a combustion to detonation onset analysis.

Figure 4. Exit pressure vs number of layers of aluminium foil.

4. Conclusion

With reference to the experimental investigation of onset of detonation using a cold flow analysis through multiple layers of metal diaphragm we can conclude the following important points.

1. Food grade aluminium foils stacked in multiple layers and bonded together at high physical loads can be used as effective diaphragms in both cold and hot flow conditions.

2. A predictive model can be realised using the presented data for calculating the thickness of the diaphragm and number of layers required for conducting hot flow experiments.

3. It is found that a maximum velocity of 476 m/s or 1.4 Mach number of exit pressure is possible for a settling chamber diaphragm rupture pressure of around 10 bar.

4. During the expansion of gases through the delivery tube there is a stark decrement phenomena of exit pressure signifying expansion of gases in the absence of any blockages in the delivery tube and an incremental velocity schema.
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