A Major Project

on

DESIGN OF QUICK-ACTING VALVE FOR SHOCK TUNNEL

In partial fulfillment of the requirements for the award of the degree of

Bachelor of Technology in Aeronautical Engineering

by

A. Ravi Prakash	**21N31A2101**
Anthati Keerthi	**21N31A2103**
Nakshita M. Nitalikar	**21N31A2136**
Myakala Pranay	**22N35A2105**

Under the esteemed guidance of

Internal Guide:
Mr. G Sai Sathyanarayana
Assistant Professor

External Guide:
Shri Singh Prakash Rampratap
Sc F, DOAT, (ATF-II), DRDL.

Department of Aeronautical Engineering

Malla Reddy College of Engineering & Technology

(Autonomous Institution- UGC, Govt. of India)

(Affiliated to JNTUH, Hyderabad, Approved by AICTE, NBA &NAAC with A' Grade) Maisammaguda, Kompally, Dhulapally, Secunderabad – 500100 website: www.mrcet.ac.in

2021-2025

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CERTIFICATE

This is to certify that this is the bonafide record of the major project entitled **"Design of quick-acting valve for shock tunnel"**, submitted by **A. Ravi Prakash (21N31A2101), Anthati Keerthi (21N31A2103), Nakshita M. Nitalikar (21N31A2136), Myakala Pranay (22N35A2105)** of B.Tech in the partial fulfilment of the requirements for the degree of Bachelor of Technology in Aeronautical Engineering, Department of Aeronautical Engineering during the year 2024-2025. The results embodied in this major project report have not been submitted to any other university or institute for the award of any degree or diploma.

Internal Guide
Mr. G Sai Sathyanarayana
Assistant Professor

External Guide
Shri Singh Prakash Rampratap
Sc F, DOAT, (ATF-II), DRDL.

Head of Department
Dr. M. Mohammed Mohaideen
Professor

External Examiner

DECLARATION

We hereby declare that the major project titled "**Design of quick-acting valve for shock tunnel**" submitted to Malla Reddy College of Engineering and Technology (UGC Autonomous), affiliated to Jawaharlal Nehru Technological University, Hyderabad (JNTUH) for the award of the degree of Bachelor of Technology in Aeronautical Engineering is a result of original research carried out in this thesis. It is further declared that the major project report or any part thereof has not been previously submitted to any University or Institute for the award of a degree or diploma.

A. Ravi Prakash	**21N31A2101**
Anthati Keerthi	**21N31A2103**
Nakshita M. Nitalikar	**21N31A2136**
Myakala Pranay	**22N35A2105**

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With regards and gratitude,

A. Ravi Prakash	**21N31A2101**
Anthati Keerthi	**21N31A2103**
Nakshita M. Nitalikar	**21N31A2136**
Myakala Pranay	**22N35A2105**

ABSTRACT

DRDL has a ∅ 1 m hypersonic shock tunnel facility capable of simulating high enthalpy at Mach 6 to 10. The facility consists of a conventional shock tube with 180 an internal diameter and 17 m connected to a hypersonic conical nozzle attached to a test section/ dump tank. A single-use CNC-machined aluminium rupture diaphragm with varying thickness forms is used to separate the shock tube's driver and driven tube section. The simulation of the test condition depends on the rupture of the diaphragm at the required design condition.

The design and development of a quick-acting valve for a shock tunnel requires careful consideration of factors like fast actuation, high-pressure capability, and low leakage. Quick-acting valves offer several advantages over diaphragms in shock tunnel applications, including faster actuation times, improved repeatability, and higher reliability. Using a quick-acting valve can achieve more precise control over the shock wave generation process, leading to enhanced experimental results and a better understanding of complex fluid dynamics phenomena.

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1. INTRODUCTION

Experimental setups such as shock tunnels facilitate the exploration of fluid dynamics, particularly at supersonic and hypersonic speeds, which is critical in advancing technologies in aerospace, automotive, and related fields by generating controlled high-speed flows that simulate real-world conditions experienced by vehicles and objects in flight.

This document focuses on the design of a quick-acting valve for shock tunnels—an essential component that not only controls the flow of gases but also dictates the timing and precision of experiments. Understanding the underlying principles of shock tunnels and shock tubes, as well as the role of quick-acting valves, is vital for engineers and researchers aiming to push the boundaries of speed and performance in various applications.

1.1 Understanding the Shock Tube

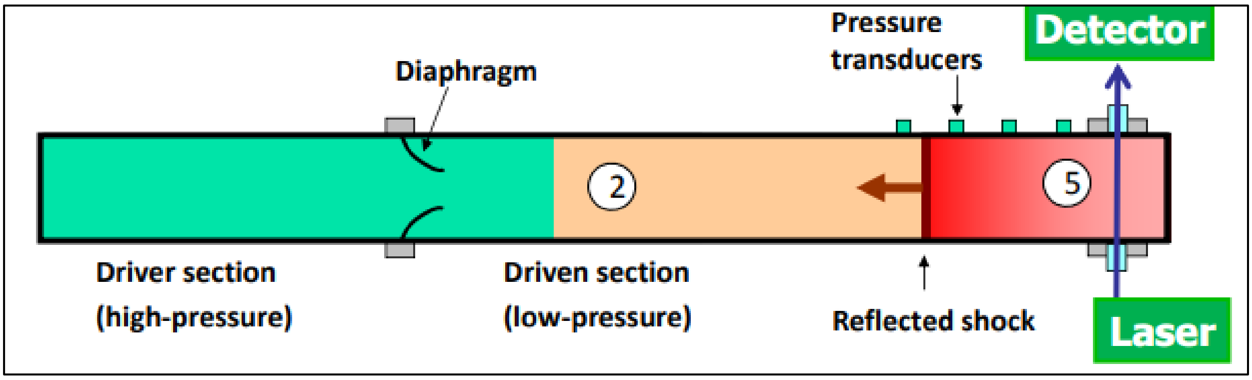


Fig. 1

A shock tube is a device used to generate shock waves for experimental purposes. It consists of two sections separated by a diaphragm; when the diaphragm bursts, the rapid expansion of gas generates a shock wave that travels down the length of the tube. Shock tubes are widely utilized in fundamental research and engineering applications due to their ability to replicate high-speed flow conditions.[1]

Types of Shock Tubes-

1. Conventional Shock Tube: Generates shock waves in gases for fundamental research in fluid dynamics. Used in gas physics and combustion research.
2. Shock Tunnel (Hypersonic Shock Tube): A modified shock tube designed for hypersonic flow studies. A converging-diverging nozzle is used to accelerate gas to hypersonic speeds before reaching the Test Section. Used in aerospace applications to study re-entry vehicles, missiles, and scramjet propulsion.
3. Combustion Shock Tube: Designed for high-temperature chemistry and detonation studies. Used to simulate high-energy explosions and fuel-air reactions.
4. Free-Piston Shock Tube: Uses a piston instead of a gas driver to generate higher shock strengths. Used for high-enthalpy gas dynamics and plasma physics experiments. [2]

1.2 Hypersonic Shock Tunnel:

Fig. 2

A hypersonic shock tunnel is a specialized wind tunnel designed to simulate hypersonic flow (typically defined as Mach 5 and above). The hypersonic shock tunnel is divided into two divisions: Driver tube and driven tube. To connect the driver tube and the driven tube, the diaphragm is used in a hypersonic shock tunnel which is used to separate high- and low-pressure gases. The paper diaphragm is used to separate the tunnel section from the driven tube. In the driver tube, helium gas is stored, and in the driven tube, atmospheric air is stored, and by using both helium and atmospheric air we can produce heat transfer in the tunnel. The flow passes at Hypersonic speed so the overall time for the test section is 1 m/s. To observe the flow visual parameters, Schlieren flow visualisation is used. It is a type of technique that uses light deflection to make small air pressure differences visible. The advantage of using a shock tunnel is that highly energetic flows of high stagnation enthalpy can be generated, which is required to study the features regarding flow around atmospheric re-entry vehicles, ballistic missiles, etc. [16]

1.2.1 Components of Hypersonic Shock Tunnel

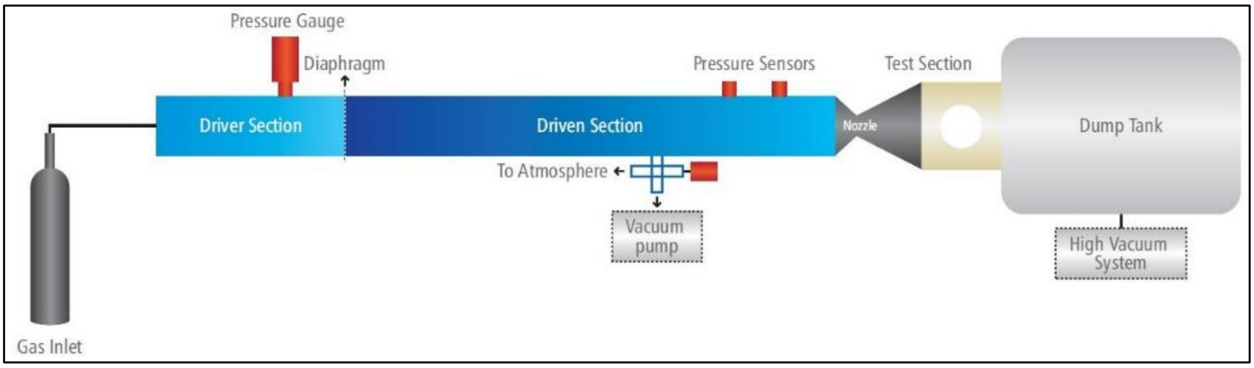


Fig. 3

1. Gas Inlet

The gas inlet is responsible for supplying high-pressure gas (typically helium, nitrogen, or air) into the Driver Section. The choice of gas depends on the required shock strength, flow conditions, and the specific test objectives.

2. Driver Section

This section stores high-pressure gas that serves as the energy source for generating the shock wave. The gas pressure in this section is significantly higher than in the Driven Section. It is equipped with a pressure gauge to monitor the pressure levels before the diaphragm bursts. The stored gas energy is used to drive the shock wave, which propagates through the Driven Section.

3. Diaphragm

A thin metal or plastic membrane that separates the Driver Section from the Driven Section. It remains intact until the pressure difference between the two sections reaches a critical value. Once the diaphragm ruptures, the compressed gas rapidly expands, generating a shock wave that travels through the Driven Section, compressing and heating the test gas.

4. Driven Section

The Driven Section contains the test gas at a lower initial pressure than the Driver Section. When the diaphragm bursts, a shock wave propagates through this section, compressing and heating the test gas to extreme temperatures and pressures. This section may include a vacuum pump to regulate initial pressure conditions before testing.

5. Nozzle

A converging-diverging (Laval) nozzle is used to expand the compressed, high-temperature gas and accelerate it to hypersonic speeds (Mach 5+). The nozzle controls the flow characteristics and ensures uniform conditions in the Test Section. The shape of the nozzle determines the final Mach number of the flow.

6. Test Section

The Test Section is where the model or experiment is placed. It contains pressure sensors to measure important flow parameters, such as pressure, temperature, and velocity. Additional instrumentation, such as high-speed cameras, schlieren imaging systems, and laser diagnostics, may be used to visualize and analyse the flow. The hypersonic flow interacts with the test model, allowing researchers to study aerodynamics, heat transfer, and shockwave behaviour.

7. Dump Tank

After passing through the Test Section, the gas enters a Dump Tank, which acts as a low-pressure chamber to absorb and dissipate the remaining energy. The Dump Tank prevents unwanted disturbances in the test flow by maintaining a pressure differential. It is connected to a High Vacuum System, which ensures that the tank remains at a sufficiently low pressure before each test cycle. [1][8]

1.3 Working Principle of Hypersonic Shock Tunnel

A hypersonic shock tunnel operates based on the shock wave compression principle, where a high-pressure gas rapidly compresses a test gas to generate a short-duration hypersonic flow. The tunnel consists of a Driver Section, Diaphragm, Driven Section, Nozzle, Test Section, and Dump Tank, working together to simulate high-speed flight conditions. The working principle can be explained in the following steps:

1. Gas Charging

The Driver Section is filled with high-pressure gas (such as helium or nitrogen), while the Driven Section contains a low-pressure test gas. A diaphragm separates these sections to maintain the pressure difference. A vacuum pump is used to reduce the pressure in the Driven Section, ensuring a proper expansion ratio for hypersonic flow.

2. Diaphragm Rupture and Shock Wave Formation

When the pressure in the Driver Section reaches a critical value, the diaphragm bursts, releasing the stored high-energy gas. This generates a shock wave, which propagates through the Driven Section, compressing and heating the test gas. The compression increases the test gas temperature to values comparable to those experienced in real hypersonic flight.

3. Flow Expansion through the Nozzle

After being compressed and heated, the gas expands through a converging nozzle. This expansion accelerates the gas to hypersonic speeds (Mach 5 and above). The flow properties, such as velocity, pressure, and temperature, are controlled by the nozzle design.

4. Interaction in the Test Section

The high-speed gas passes through the Test Section, where a test model is placed. Pressure sensors, high-speed cameras, and optical systems measure parameters such as aerodynamic forces, thermal loads, and shockwave interactions. The flow duration is very short, typically in the range of milliseconds.

5. Exhaust into the Dump Tank

After passing through the Test Section, the gas enters the Dump Tank, which absorbs the high-speed gas and prevents disturbances in the system. A High Vacuum System helps evacuate residual gases, preparing the tunnel for the next test.

6. Data Acquisition: Sensors and measurement devices placed in the test section record data related to pressure, temperature, and flow velocity, providing insights into the test model's aerodynamic behaviour. [4][5]

1.4 Diaphragmless Shock Tube

A diaphragmless shock tube is an advanced apparatus designed to generate shock waves without the use of a traditional diaphragm. In conventional shock tubes, a diaphragm—a thin, frangible barrier—separates the high-pressure driver section from the low-pressure driven section. The rupture of this diaphragm initiates the shock wave. However, this method has several drawbacks, including inconsistent rupture behavior, the need for diaphragm replacement after each experiment, and potential contamination from diaphragm fragments. To address these issues, diaphragmless shock tubes employ fast-acting valves or other mechanisms to instantaneously connect the driver and driven sections, thereby generating shock waves with greater repeatability and efficiency. These systems offer benefits such as rapid turnaround between experiments, automation capabilities, and cleaner operation, making them valuable tools in various research and industrial applications. [19]

1.5 Difference between Diaphragm-based and Diaphragmless Shock Tunnel

A diaphragm shock tunnel is a thin membrane (diaphragm) that divides the high-pressure driver section from the low-pressure driven section. Upon reaching a critical pressure, the diaphragm ruptures, creating a shock wave that propagates through the driven section, compressing and accelerating the test gas. This shock tunnel is low-cost and straightforward but involves the manual replacement of the diaphragm after every test, causing delays in operations and variability in rupture timing.[1]

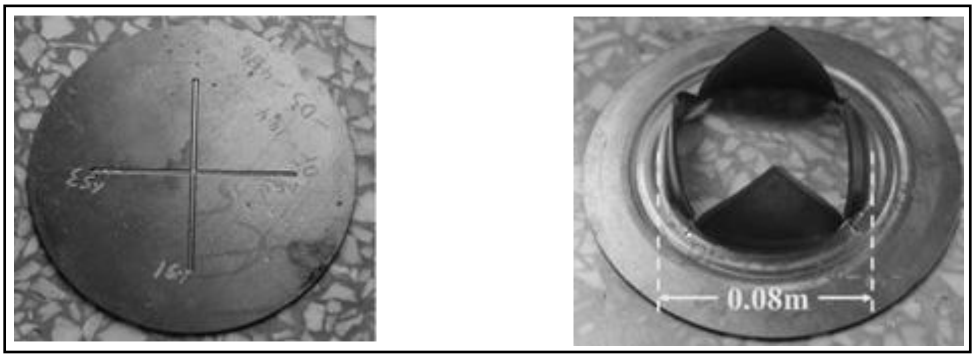


Fig. 4

A diaphragmless shock tunnel eliminates the necessity of a physical diaphragm by employing rapidly acting valves or pistons to generate the pressure difference. Such tunnels provide higher accuracy, reproducibility, and quicker operation as they do not involve diaphragm replacement. They are also capable of providing better control over shock wave generation, resulting in more stable and consistent test conditions. Nonetheless, they are equipped with intricate mechanical systems, which make them costlier and harder to maintain than diaphragm-based tunnels. Diaphragmless shock tunnels are used in sophisticated hypersonic research and aerospace technology where accurate and quick testing is needed. [6]

1.6 Quick Acting Valve in Shock Tunnel

Quick-acting valves (QAVs) in shock tunnels are high-speed valves designed to open and release high-pressure gas rapidly into the driven section without the need for a diaphragm. These valves enable precise, repeatable, and controlled shock wave generation, improving the reliability and efficiency of the shock tunnel operation.

Unlike traditional diaphragm-based systems, which require manual replacement after each test, QAVs operate electronically or pneumatically, reducing test cycle time and enhancing flow consistency. They are commonly used in diaphragmless shock tunnels and free-piston shock tunnels, where precise control of pressure release is essential for hypersonic and supersonic flow research. [7]

1.7 Why are Quick-Acting Valves better?

The quick-acting valve is a critical component in the functionality of shock tunnels. Its design and performance significantly influence the experimental outcomes.

1. Response Time and Control

The quick-acting valve must have a rapid response time to ensure that the gas is released at precisely the right moment. This timing is crucial for generating consistent shock waves. If the valve does not open quickly enough, the shock wave may not form as intended, leading to inaccurate data.

2. Sealing Mechanism

An effective sealing mechanism is necessary to maintain the integrity of the high-pressure environment in the reservoir. Any leaks can lead to a loss of pressure, affecting the performance of the shock tunnel. The design of the valve should incorporate materials and mechanisms that ensure a tight seal, preventing any gas from escaping during the buildup phase.

3. Durability and Maintenance

Given the extreme conditions within shock tunnels, the materials used in constructing quick-acting valves must be durable and resistant to wear. Regular maintenance protocols should be established to inspect and replace components as needed, ensuring reliable operation over time. A well-maintained valve will contribute to the longevity and efficiency of the shock tunnel.

4. Enhanced Repeatability

Diaphragm rupture can be inconsistent, leading to variability in shock wave generation. Quick-acting valves provide precise and controlled opening mechanisms, resulting in more consistent experimental conditions.

5. Reduced Contamination

Traditional diaphragms can produce fragments upon rupture, potentially contaminating the test gas and damaging sensitive equipment. Valveless systems mitigate this risk by eliminating diaphragm debris. [19]

1.8 Objectives for Developing Quick-Acting Valve

Since no experimental work is involved, the objectives will focus on 3D modelling, theoretical calculations, and Computational Fluid Dynamics (CFD) analysis to provide a solid design and performance assessment.

1. 3D Modelling - The system/component will be designed using *Creo Parametrics* software to create a precise and detailed 3D model. Proper geometric considerations and constraints will be incorporated to optimize the design for manufacturability and performance.

2. Theoretical Calculations - Analytical methods will be applied to validate the design parameters, including structural integrity, aerodynamic performance, and fluid flow behaviour. Mathematical models and engineering equations will be employed to estimate pressure variations, temperature, and fluid flow characteristics before simulation.

3. CFD Analysis - A computational approach will be used to simulate fluid flow, heat transfer, and other physical phenomena using *ANSYS Fluent*. The study includes mesh generation, boundary condition application, and solver setup to ensure accurate results. The obtained data will be analysed through contour plots, velocity distributions, and pressure variations to assess the system's efficiency and identify potential improvements.

The combination of these three approaches will guarantee a data-driven, optimized, and validated design, allowing for informed decision-making for future development and implementation.

1.9 Applications of the Shock Tunnel

Shock tunnels serve a multitude of applications across various industries, each benefiting from the ability to replicate high-speed flow conditions:

1. Aerospace Engineering

In aerospace engineering, shock tunnels are pivotal for testing models of aircraft and spacecraft. Researchers can simulate the aerodynamic forces acting on these vehicles during takeoff, flight, and landing phases. Data obtained from shock tunnel experiments inform design decisions, improve fuel efficiency, and enhance overall safety.

2. Automotive Testing

The automotive industry utilizes shock tunnels to evaluate the aerodynamic characteristics of vehicles, particularly high-performance models. By analyzing drag coefficients and airflow patterns, engineers can optimize vehicle shapes for better performance and stability at high speeds.

3. Material Science

Shock tunnels play an essential role in material science by enabling researchers to study how different materials respond to extreme conditions. The ability to generate high temperatures and pressures allows for testing the durability of materials used in aerospace and military applications.

4. Combustion Research

In combustion research, shock tunnels are used to simulate engine conditions, providing insights into the combustion process. Researchers can optimise combustion efficiency and reduce emissions by studying the interaction between shock waves and fuel-air mixtures. This research is vital for developing cleaner and more efficient engines.

2. LITERATURE REVIEW

1. Rupture-disk-less Shock Tube with Compression Tube Driven by Free Piston

Abe et al.. (1997) developed a rupture-disk-free shock tube powered by a moving piston free from constraint, obviating the necessity for a diaphragm. The research aimed to enhance reproducibility and control in generating shock waves by substituting the rupture disk with a high-speed valve triggered by pressurized gas. This method allowed arbitrary shock strength control, posing an improvement over conventional shock tubes where diaphragm breakage causes unpredictability. Experimental tests validated the viability of this system, showing uniform Mach number shock waves. The major benefits of this technique were enhanced repeatability, removal of diaphragm pieces, and decreased setup time. The drawbacks were that complex valve actuation mechanisms existed, and gas leakage could impact long-term stability.

2. Development of a Large-Diameter Diaphragmless Shock Tube for Gas-Dynamic Laser Studies

Rego et al.. (2008) presented a large-diameter diaphragmless shock tube for GDL research. The research was focused on resolving contamination problems due to diaphragm burst, which impacts gas uniformity and flow reproducibility in laser applications. The system utilized a diaphragm-like sliding piston that ensured steady and controlled shock wave propagation. CO_2-N_2 mixture experiments validated that the apparatus could produce shock waves with Mach numbers between 1 and 5, in close agreement with theory. Removal of diaphragm rupture debris, better control of gas flow, and compatibility with long-duration tests were major advantages. The design needed precise control of gas flow and considerable initial setup capital, and its use was thus difficult for typical shock tube applications.

3. A New Friction-Controlled Piston Actuated Diaphragmless Shock Tube Driver

Kosing et al. (1999) designed a piston-actuated diaphragmless shock tube driver with a friction-controlled mechanism, which sought to eliminate the use of diaphragms and maintain high shock wave reproducibility and economy. Their setup employed a brake pad system to lock a piston in position for a controlled and uniform release. The technique overcame inconsistencies based on the diaphragm with Mach numbers between 1.1 and 2. The experimental verification revealed nondimensional formation lengths between 20 and 40, thus verifying the dependability of the system. Key benefits were enhanced piston displacement speeds, reduced operation costs, and minimized risks of contamination. Nonetheless, the method needed precise brake mechanism calibration, and piston release timing variations may slightly influence shock wave consistency.

4. A Rapid-Opening Sleeve Valve for a Diaphragmless Shock Tube

Downey et al.. (2011) presented a rapid-opening sleeve valve to replace conventional diaphragms to enhance automation and operational efficiency. Their pneumatically operated valve rapidly retracted, allowing controlled shock wave initiation without the necessity of frequent replacement of diaphragms. The research built and verified a numerical model for the maximization of valve performance, resulting in an opening time of ~0.5 ms, slower than the ~0.2–0.3 ms of classical diaphragm bursts. The system produced Mach 2.4 shock waves with small losses and reduced preparation times between runs. Benefits comprised fully automatic operation, better repeatability in tests, and a contamination-free environment. Though somewhat reduced valve opening times and possible pneumatic component maintenance were listed as shortcomings.

5. Design of a High-Pressure Single Pulse Shock Tube for Chemical Kinetic Investigations

Tranter et al.. (2001) designed a high-pressure single-pulse shock tube for chemical kinetic investigations, particularly for studying hydrocarbon oxidation and pyrolysis reactions. The system could reach pressures above 1000 atm and temperatures exceeding 1400 K, providing ideal conditions for chemical kinetics studies. It featured an adjustable driven section to precisely control reaction times (0.5–2.5 ms) and an automated gas sampling system for analysing reaction intermediates. This setup ensured isothermal reaction conditions, which are critical for accurate kinetic measurements. The major advantages included high-pressure operation, tunable reaction times, and enhanced reproducibility for chemical kinetics research. However, the system had high operational complexity, required specialized instrumentation, and needed strict control over reaction quenching.

6. A New Fast-Acting Valve for Diaphragmless Shock Tubes

Heufer et al. (2012) designed a high-speed valve for diaphragmless shock tubes that provided a high-fidelity alternative to the standard diaphragm technology. Their system featured a pneumatically actuated piston that opened quickly to produce a clean and repeatable shock wave, enhancing shock formation and pressure stability. The prototype was experimentally tested, showing millisecond-scale valve opening times and high reproducibility of the shock wave. The most significant benefits were removing the diaphragm replacement, minimizing contamination risk, and maximizing test repeatability. Drawbacks like precise pneumatic control, possible mechanical wear, and low energy losses through moving parts needed to be further optimized. Drawing inspiration from this work, the current research uses a comparable design but integrates dimensional and structural adjustments to promote operation efficiency, minimize pressure loss, and optimize shock wave formation for experimental requirements.

Based on the Literature survey, the development of diaphragmless shock tubes has significantly enhanced shock wave reproducibility, operational efficiency, and automation, addressing the limitations of traditional diaphragm-operated designs. Early research, including studies by *Abe et al. (1997)* and *Rego et al. (2008)*, focused on improving flow uniformity and reducing contamination through novel driver mechanisms. Advances by *Kosing et al. (1999)* and *Downey et al.. (2011)* introduced friction-controlled piston drivers and high-speed opening sleeve valves, improving shock wave reproducibility and test repeatability. *Tranter et al. (2001)* explored high-pressure chemical kinetics in shock tubes, while *Heufer et al. (2012)* made a significant contribution with a pneumatically operated valve that eliminates diaphragms, ensuring precise shock wave generation. Building on this work, the current research aims to enhance the diaphragmless shock tube valve design through dimensional and structural improvements for better shock wave stability, energy efficiency, and automation, making these systems more reliable for applications in fluid dynamics, aerospace propulsion, and high-speed gas dynamics research.

3. THEORETICAL FRAMEWORK

Our project is inspired by the work of *Heufer et al. (2012)* on the development of a fast-acting valve for diaphragmless shock tubes. We adopt a similar design approach while incorporating dimensional and structural modifications to optimize performance for our specific DRDL conventional shock tunnel. These changes aim to enhance shock wave reproducibility, reduce pressure losses, and improve operational efficiency, making the system more suitable for our intended applications which will be analysed by CFD analysis. The methodology involves changes in the design of the valve, theoretical analysis, and computational modelling to refine the valve design and shock tube operation.

3.1 Shock Tube Dimensions

The conventional shock tube present in DRDL is 22 meters and has two sections- driver and driven. The driver section is 5 meters long, and the driven section is 17 meters with an inner diameter of 180 millimetres. Shock tubes are primarily used for studying fundamental gas dynamics and chemical reactions. It generates a short, transient shock wave.

The diaphragm, made of aluminium alloy, is placed between the driver and the driven section. A diaphragm, or a thin separating membrane, is used to initially separate the high-pressure driver gas from the low-pressure driven gas. The diaphragm material must be able to withstand the initial pressure difference and rupture reliably when the experiment begins.

Shock tubes, often made of metal like stainless steel (SS-316), are used to study gas dynamics and combustion by generating controlled shock waves and have advantages like precise control over temperature and pressure and the ability to study reacting flows under extreme conditions. [17]

3.2 Shock Wave Theory

A shock wave is a thin region of rapid pressure, temperature, and density change that occurs when a supersonic flow undergoes an abrupt deceleration. Shocks are caused by compressibility effects in high-speed aerodynamics. [1]

Types of Shocks:

Normal Shock (perpendicular to flow) causes a sudden decrease in velocity and increase in pressure and temperature. Example: Flow inside a supersonic diffuser.

Oblique Shock (angled to flow) occurs when a supersonic flow encounters a wedge or ramp. Example: Airflow over a delta-wing aircraft.

Bow Shock (curved shock in front of an object) forms around blunt bodies moving at supersonic speeds. Example: Re-entry vehicles, supersonic aircraft noses. [9],[18]

Shock propagation refers to the movement of a shock wave through a medium. Depending on the conditions, shocks can either strengthen or decay. Key factors that affect shock propagation are medium properties (shocks travel faster in denser or hotter media), initial conditions (stronger shocks weaken over distance due to energy dissipation), and interaction with boundaries (shock waves reflect or refract at surfaces).

3.3 Theoretical Equations

The operation of a shock tube relies on the fundamental principles of compressible gas dynamics, particularly the behaviour of shock waves generated by sudden pressure discontinuities. When high-pressure gas is rapidly introduced into a low-pressure section, it results in the formation of a shock front that propagates through the driven medium.

To accurately analyse the performance of the shock tube and the effect of the Quick-Actuating Valve (QAV), we must use certain equations. These equations form the theoretical foundation for both experimental and computational analysis.

In this document, we have established specific parameters for the shock tube that will also be applied during the Computational Fluid Dynamics (CFD) analysis. These values have been carefully selected to ensure accuracy and reliability in our simulations. Proper attention to these parameters is crucial for achieving meaningful results in the CFD run.

To calculate Mach, we must go through certain steps and calculations. Firstly, calculate the normal shock pressure ratio, [1]

$$\frac{P_2}{P_1} = \frac{2\gamma_1 {M_s}^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)}$$

where,

P_2 = Intermediate pressure after diaphragm rupture.

P_1 = Pressure at driven section (likely before and after the shock).

M_s = Shock Mach number (the Mach number associated with the shock wave)

γ_1 = Specific heat ratio (adiabatic index) of the gas before the shock.

Then gas velocity behind the shock (in lab frame) is:

$$u_2 = \frac{2a_1}{\gamma + 1}(M_s - \frac{1}{M_s})$$

Where,

a_1= speed of sound

The driver gas expands isentropically, so the pressure ratio is:

$$\frac{P_3}{P_4} = (\frac{T_3}{T_4})^{\frac{\gamma}{\gamma - 1}}$$

The flow speed in expansion is,

$$u_3 = \frac{2a_1}{\gamma - 1}[1 - (\frac{P_3}{P_4})^{\frac{\gamma - 1}{2\gamma}}$$

After following these steps, the matching condition should be applied,

$$P_2 = P_3$$

$$u_2 = u_3$$

This is where you iterate over values of M_s To find when both sides match.

Engineers enhance their calculation processes using an online flow calculator, which efficiently generates required values based on input parameters. This tool eliminates repetitive iterations and manual calculations, allowing engineers to focus on more complex tasks. It boosts productivity, ensures accuracy, saves time, and reduces human error, leading to better project outcomes.

Now, for calculation purposes, we have provided values the same as those provided for CFD analysis for both shock tubes with diaphragm and QAV-incorporated shock tubes.

The values are, length = 8m, $P_4 = 40$ bar and $P_1 = 0.4$ bar, then these values were substituted in the online calculator [20], which provided the shock Mach number (M_s), pressure of reflected shock (P_5) and immediate pressure after the diaphragm, i.e. post-shock pressure (P_2) which were $M_s = 2.37$, $P_5 = 10.37$ bar and $P_2 = 2.556$ bar

Then, these same values (length = 8m, $P_4 = 40$ bar and $P_1 = 0.4$ bar) were given in the CFD analysis for both cases, and when the graph was plotted, the values for Mach number (M_s), pressure of reflected shock (P_5) and immediate pressure after the diaphragm, i.e. post-shock pressure (P_2) were obtained,

1. Shock tube with Diaphragm: Measurements recorded

$$M_s = 2.41,\ P_5 = 10.3592 \text{ bar and } P_2 = 2.56 \text{ bar}$$

2. Shock tube with QAV: Measurements recorded

$$M_s = 2.05,\ P_5 = 10.2855 \text{ bar and } P_2 = 2.55 \text{ bar}$$

The data highlights notable differences in performance between the two types of shock tubes. The shock tube with the diaphragm demonstrates higher pressure values at both low and high measurements compared to the shock tube with QAV. This discrepancy suggests that while both configurations have their merits, the diaphragm design may potentially offer superior pressure stability or efficiency under certain conditions. But the shock tube with QAV is close to the efficiency that is provided by a shock tube with the diaphragm. Yet, further modifications and dedicated research and development efforts are essential to refine these systems and aim for optimal performance parameters.

4. METHODOLOGY

4.1 Design and Development of the Shock Tube System

The Shock tube body is a long cylindrical tube that guides the shock wave from the driver to the driven section. It consists of two main sections: the driver section and the driven section, separated by a diaphragm. The driver section contains high-pressure gas, while the driven section contains gas at a lower pressure. Other key components include the diaphragm rupture system, which controls shock wave initiation, and end-wall instrumentation, which captures data on shock wave behaviour.

The working principle of a shock tube is based on the sudden rupture of the diaphragm, causing a rapid expansion of the high-pressure gas into the driven section. This generates a shock wave that travels down the tube, compressing and heating the gas in the driven section. Simultaneously, an expansion wave propagates oppositely into the driver section.

The shock tube used in DRDL has a 5-meter driven section and a 17-meter driven section, and a diaphragm situated in between them. The diameter of this shock tube is 180 mm.

4.2 Quick-Acting Valve Design

The quick-acting valve follows a pneumatic mechanism, using compressed air or gas to transmit and control energy, converting it into mechanical motion, often through devices like cylinders or actuators.

This valve has been designed using Creo Parametric software and features a quick-acting mechanism with an opening speed of approximately 1 ms. It includes an electronic solenoid valve that regulates the opening and closing of multiple valves connected to both the system and the atmosphere. To enhance stability and minimize vibrational disturbances, dampers are incorporated into the design. Additionally, O-rings are used to ensure a secure seal and reduce the risk of gas leakage. If fabricated, stainless steel (SS-316) would be a suitable construction material for the valve and

Viton for O-rings. The system is designed to allow for automated operation, reducing human intervention and improving repeatability.

4.3 Modelling of QAV

The QAV model was designed in Creo Parametrics based on the dimensions of the shock tunnel located at the Defence Research and Development Laboratory (DRDL), Hyderabad. This assembly incorporates various components, including the outer body, slider, center body, O-rings, dampers, and an electronic solenoid valve. All dimensions are taken in millimetres.

4.3.1 Design of Valve Outer Body

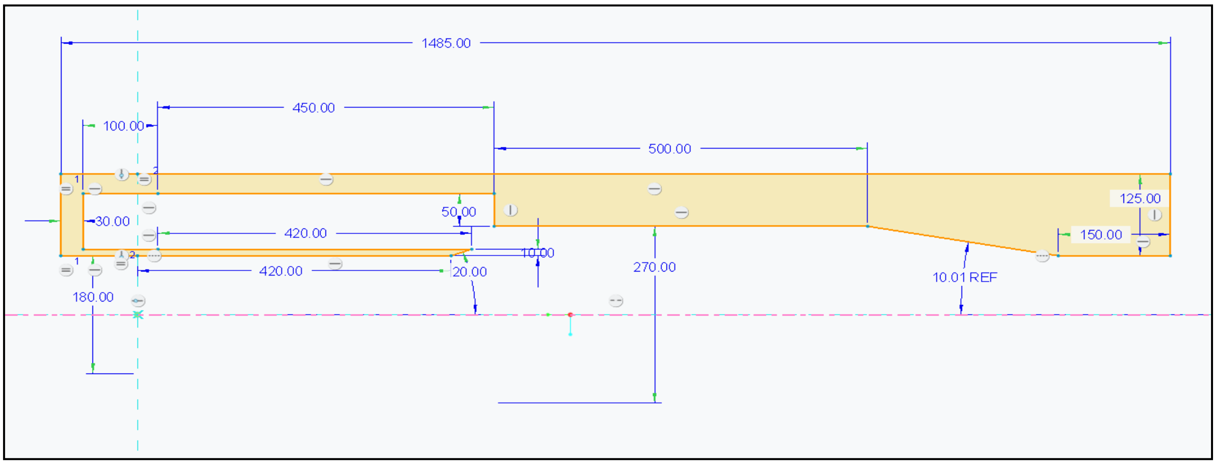


Fig. 5

The mentioned fig.5 is the detailed drawing of key dimensions of the valve's outer body. It includes linear and radial measurements for different sections of the body. The overall length is 1485 mm, and the diameter varies from 180 mm to 370 mm.

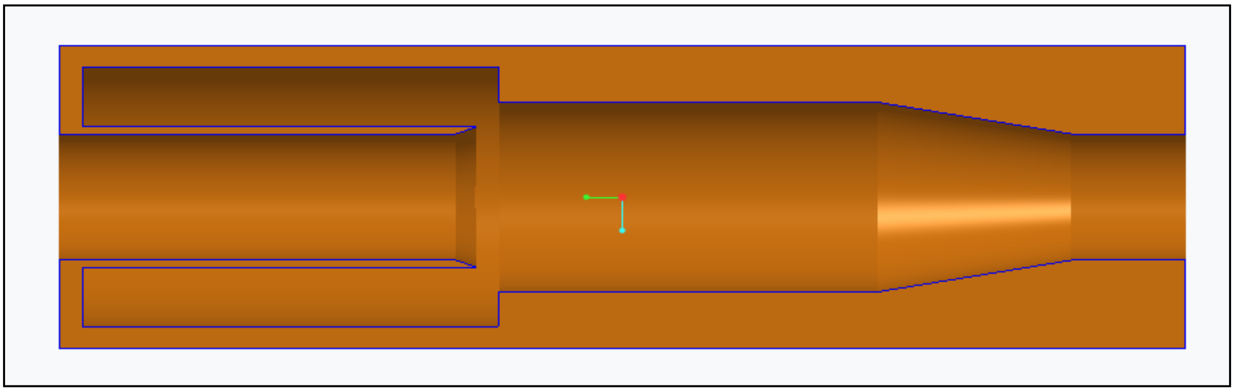


Fig. 6

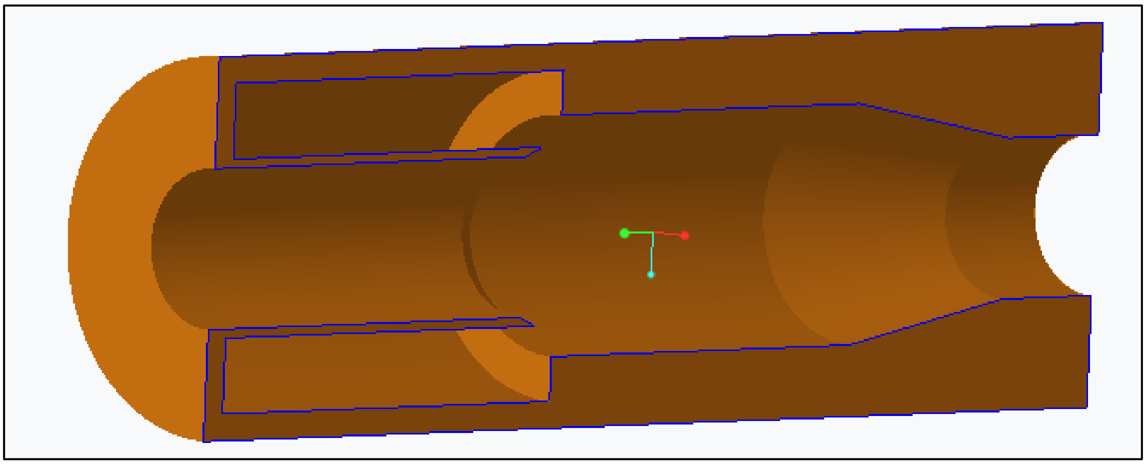


Fig. 7

These (fig. 6 and fig. 7) are the cut-sectional view of the 3-dimensional figure, which is formed when fig. 5 is revolved around the centerline. The central bore and tapered region are for a streamlined fluid movement over the center body.

4.3.2 Design of Slider

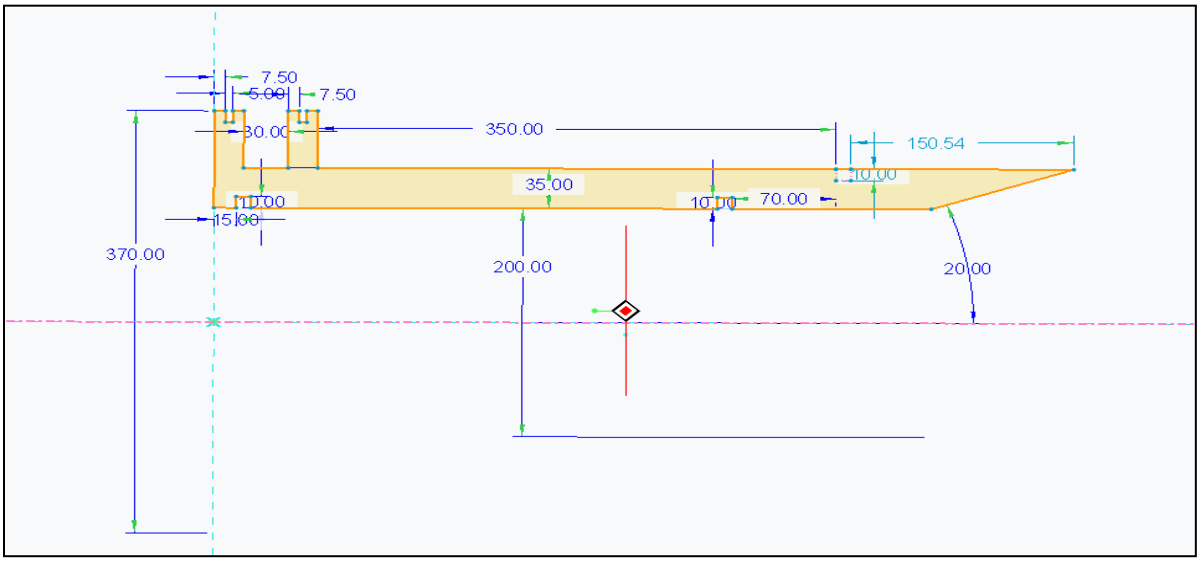


Fig. 8

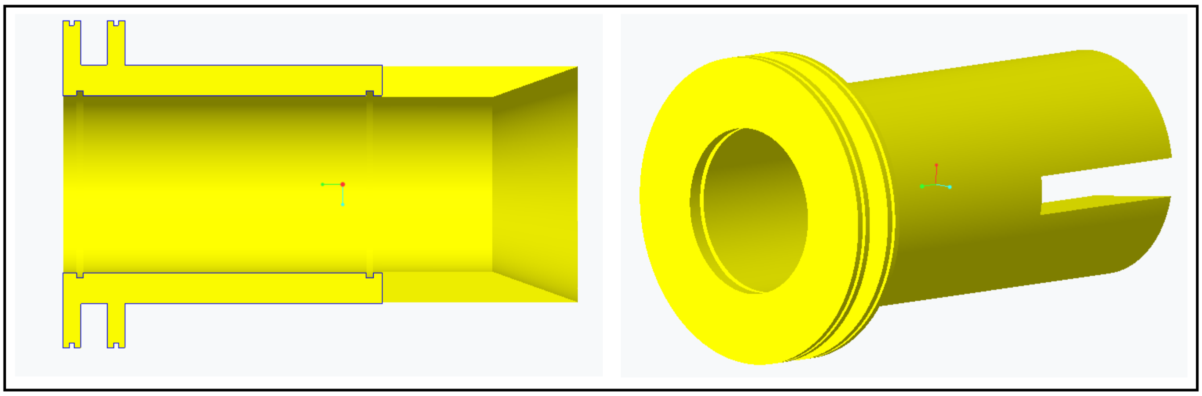


Fig. 9

The illustrated fig. 8 is the sketch of the slider/piston valve with all key dimensions. There are 4 grooves for seals, which will prevent any gas leakage in the valve. Fig. 9 provides a sectional view of the 3D model, offering insight into the internal structure and fluid passage design. It highlights key elements such as the hollow cylindrical shape, internal grooves for potential O-rings, and smooth transitions to for stiffeners present on the center body. The image of the 3D model presents a realistic visualization of the valve, emphasizing its external shape, slots, and machining details.

4.3.3 Design of Center Body

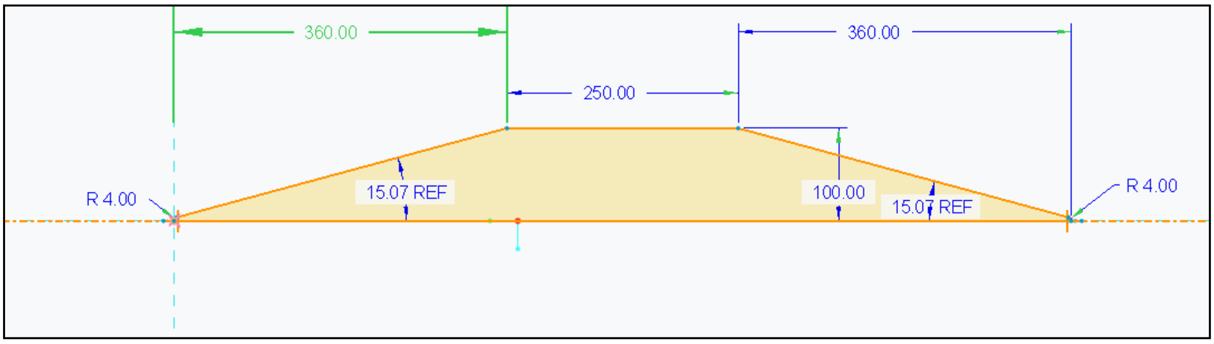


Fig. 10

Figure 10 provides a detailed sketch of the center body utilized in the QAV design. The overall length of the center body measures 970 mm, featuring tapered ends to promote streamlined flow. Fig. 11 provides a 3D image. The structure is reinforced with two stiffeners, strategically placed on both sides, which will be integrated with the outer body of the valve. This reinforcement ensures enhanced stiffness of the body during gas passage.

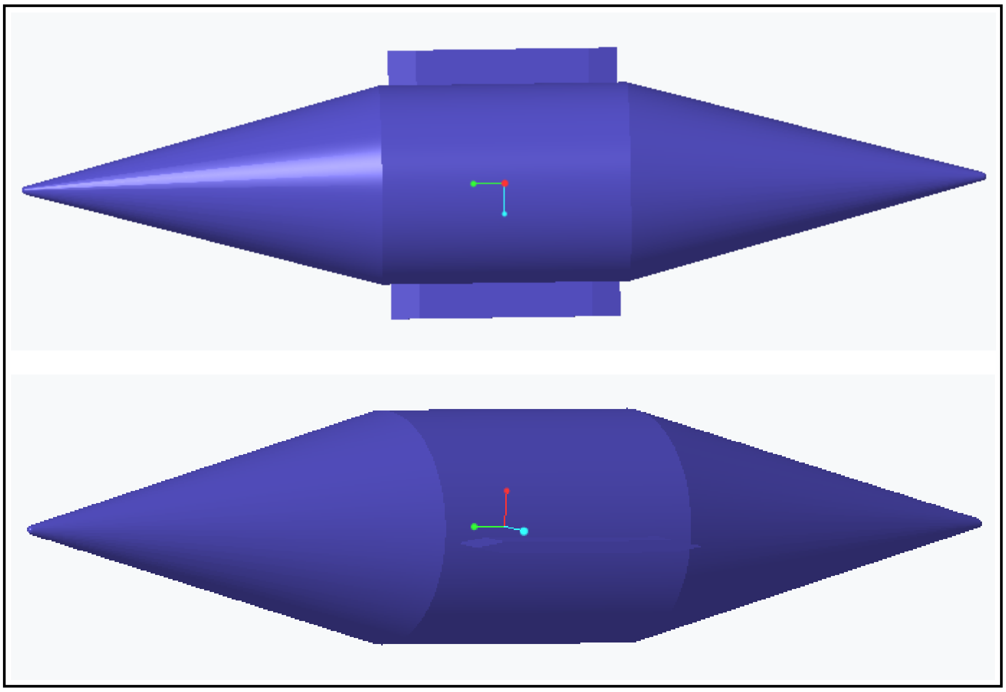
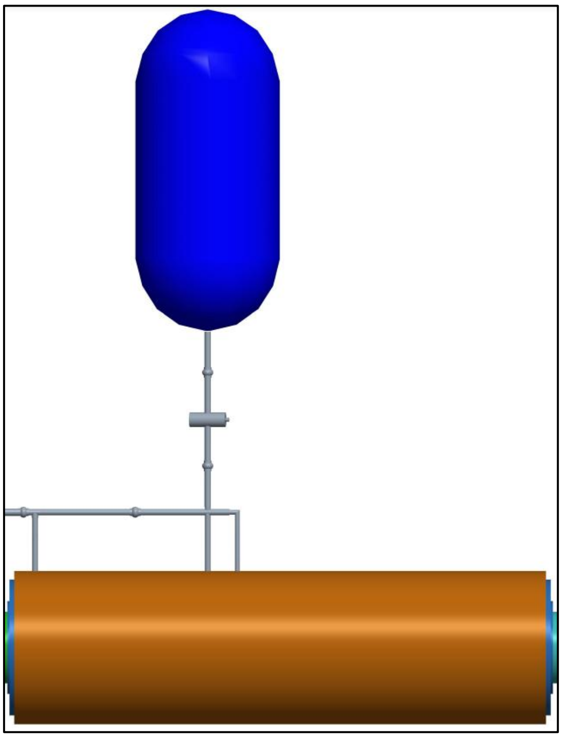


Fig. 11

4.3.4 Assembly of QAV



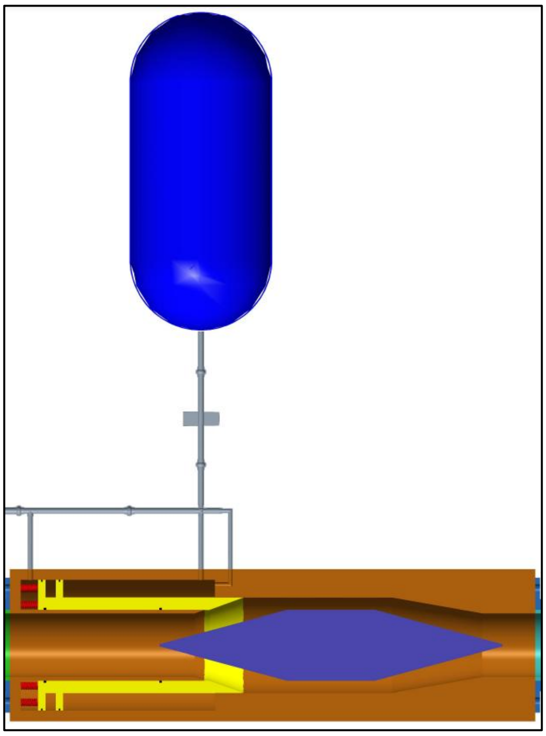


Fig. 12

Fig. 13

The images in Figures 12 and 13 illustrate the assembly of the Quick-Acting Valve (QAV). Figure 12 provides an external view of the fully assembled QAV whereas Figure 13 provides sectional view of the same assembly highlighting various components: the main valve outer body is depicted in brown, the piston valve is shown in yellow, the central body is represented in purple, the pressure vessel is illustrated in blue, and the connecting pipes and valves are indicated in grey, including the electrical solenoid valve. This detailed representation ensures a comprehensive understanding of the assembly and functionality of the QAV.

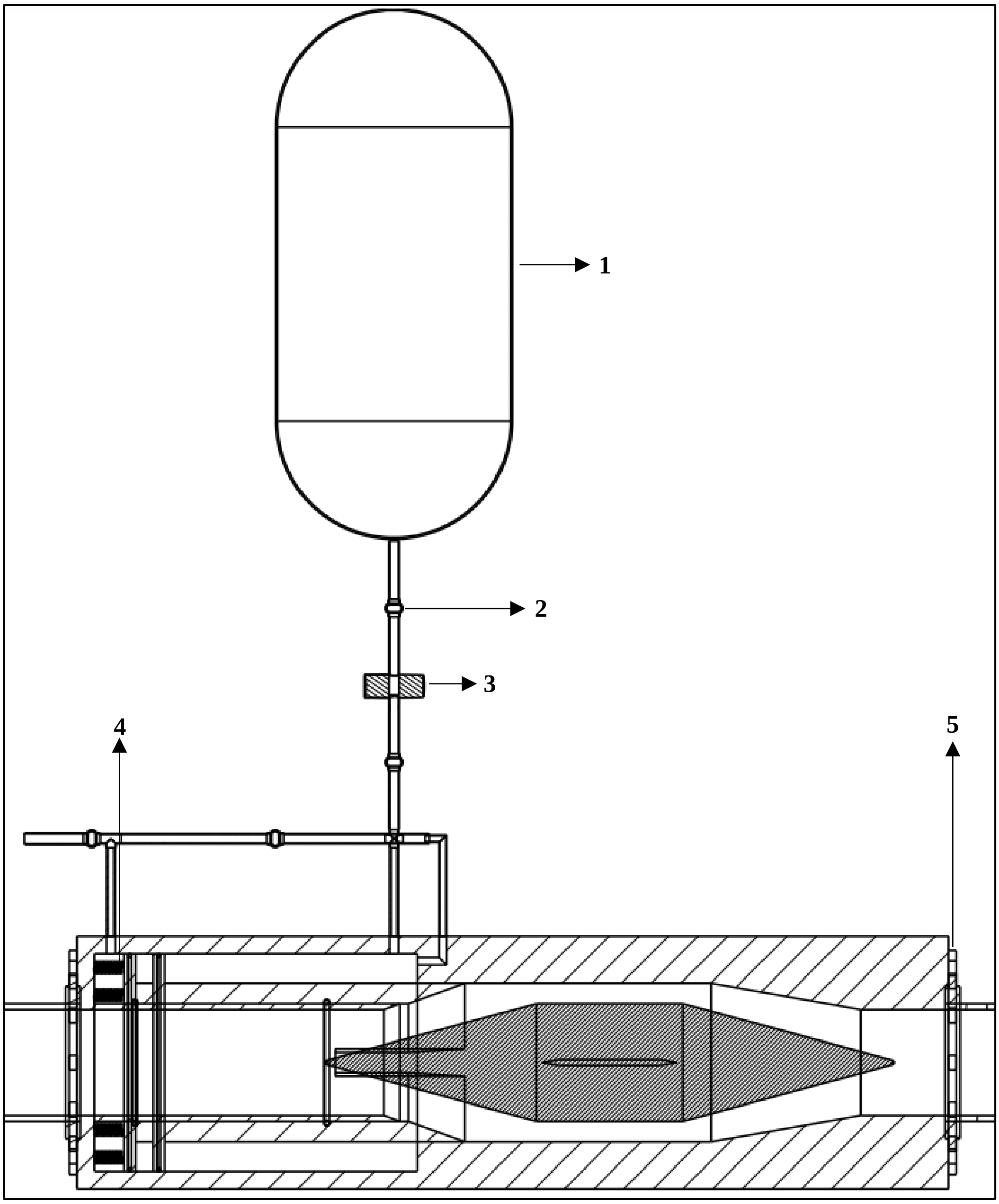


Fig. 14

Figure 14 is the 2D wireframe of the assembled QAV. The diagram shows a system involving a pressure vessel, a valve, a damper, and associated piping.

Components Overview:

1. Pressure Vessel: This component is a large, vertically oriented cylindrical tank located at the system's top. Its primary function is to store the pressurized gas until it is needed for release.

2. Open and Close Valve (Solenoid Operated): Positioned directly beneath the pressure vessel, this solenoid-operated valve regulates the flow of fluid exiting the vessel. Its electric actuation allows for quick and efficient opening and closing.

3. Electrical Solenoid: This actuator controls the opening and closing of the valve mentioned above. When powered, the solenoid opens the valve; when it is not powered, the valve closes.

4. Damper: Situated at the bottom of the system, the damper is a spring-like structure designed to absorb or dissipate energy from the released fluid. This feature helps to prevent sudden pressure surges and potential damage, and its internal design suggests it may effectively restrict or slow fluid flow.

5. Flanges: These circular bolted connections are integral to the assembly, ensuring a secure, leak-proof seal between pipes and other components under pressure.

This concise overview explains the functionality and significance of each component within the system.

4.3.5 QAV incorporated in Shock Tube

The assembled QAV is incorporated in a shock tube that is present at DRDL (virtually) for analysis. The QAV is positioned at the junction of the driver and driven sections, replacing the rupture diaphragm. It is connected to a control system that regulates its opening speed, activation pressure, and response time. The driver section is filled with high-pressure gas, and upon activation, the QAV rapidly opens, causing a shock wave to propagate through the driven section.

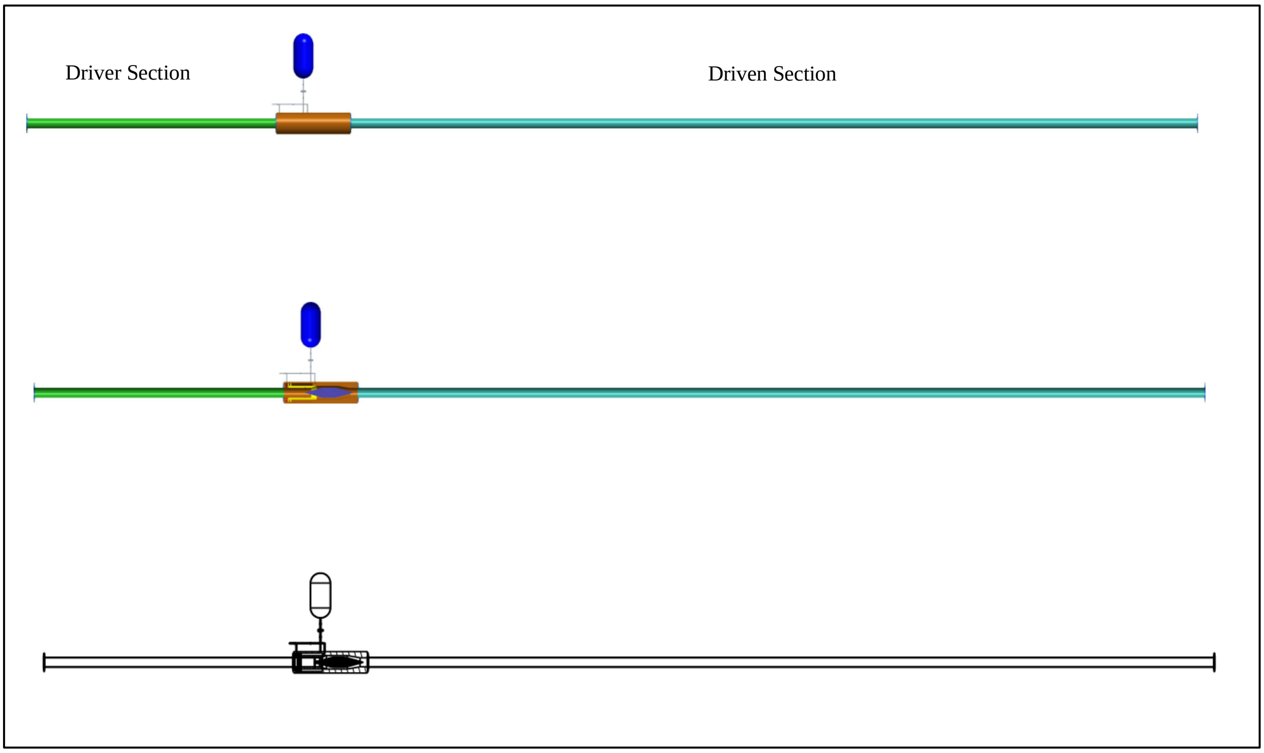


Fig. 15

The dimensions of the driver section and driven section are the same as present in DRDL. By incorporating a Quick Acting Valve (QAV) into a conventional shock tube, we have developed a more efficient, reusable, and controllable alternative to traditional diaphragm-based systems. This innovation enhances shock wave generation accuracy, reduces operational costs, and improves experimental repeatability, significantly advancing shock tube technology.

4.4 Working of QAV

A shock tube is an advanced experimental device employed to investigate shock waves, high-speed aerodynamics, and gas dynamics. The apparatus comprises a high-pressure driver section, a low-pressure driven section, and a precision valve. Notably, a QAV is integrated within the shock tube, although the accompanying images are derived from the truncated portion of the shock tube for illustrative purposes.

The operation of the valve can be articulated in three distinct stages: the closed valve, the activated valve, and the opened valve. The components identified as 1, 2, 3, and 4 represent valves operated by an electrically controlled solenoid.

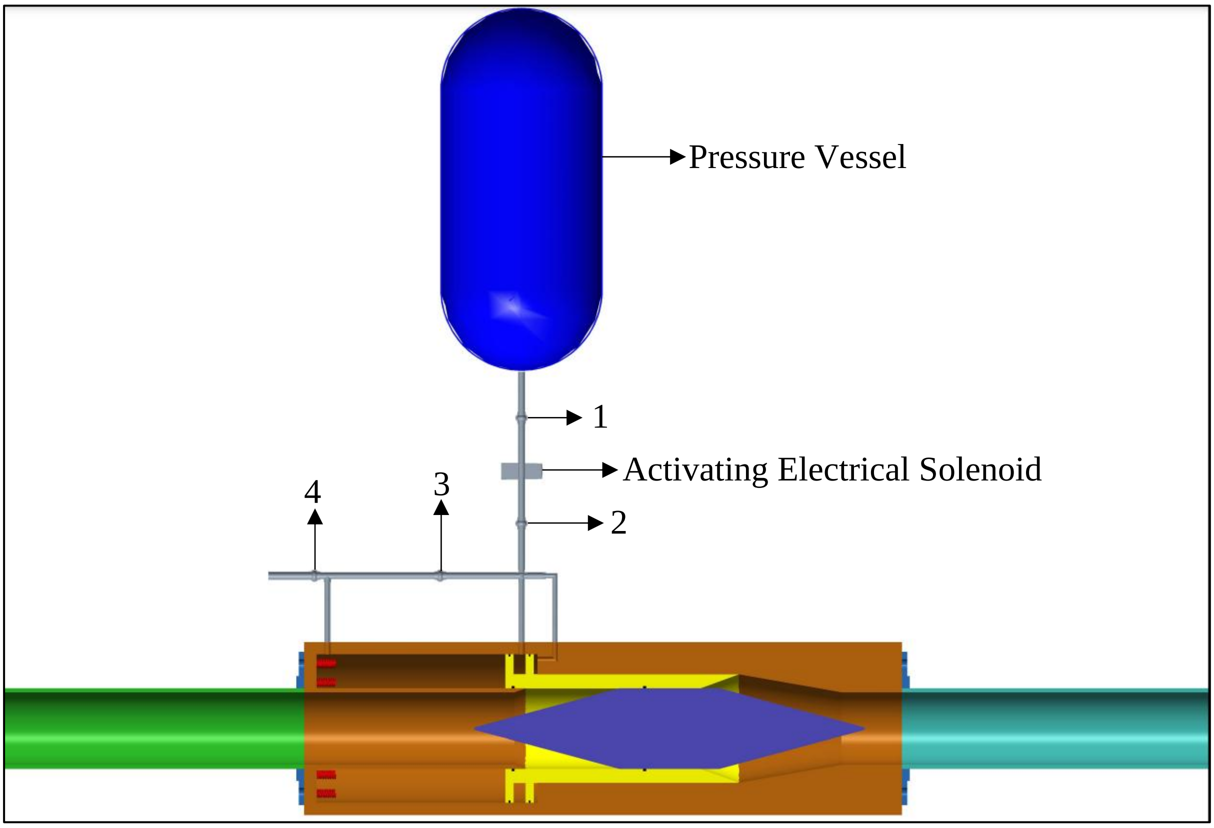


Fig. 16

1. STAGE I -

Figure 16 illustrates the initial state of the system, commonly referred to as the Valve Closed condition. In this configuration, the driver section is filled with high-pressure gas, which is typically stored in a pressurized gas vessel designed to withstand significant pressure levels, and valves numbered 1, 2, 3, and 4 are currently closed, as there is no gas flow present. Conversely, the driven section maintains a lower pressure, usually at ambient conditions or maintained in a vacuum state. The closed valve serves as a critical barrier, effectively isolating the driver and driven sections and preventing any unintended gas flow. This design is integral for ensuring system safety and operational integrity as it maintains pressure stability until the system is activated by a specific mechanism. The valve plays a critical role in the operation of the system by regulating the flow between two different conditions. It acts as a control mechanism that ensures a smooth and secure transition, which is essential for maintaining stability within the system.

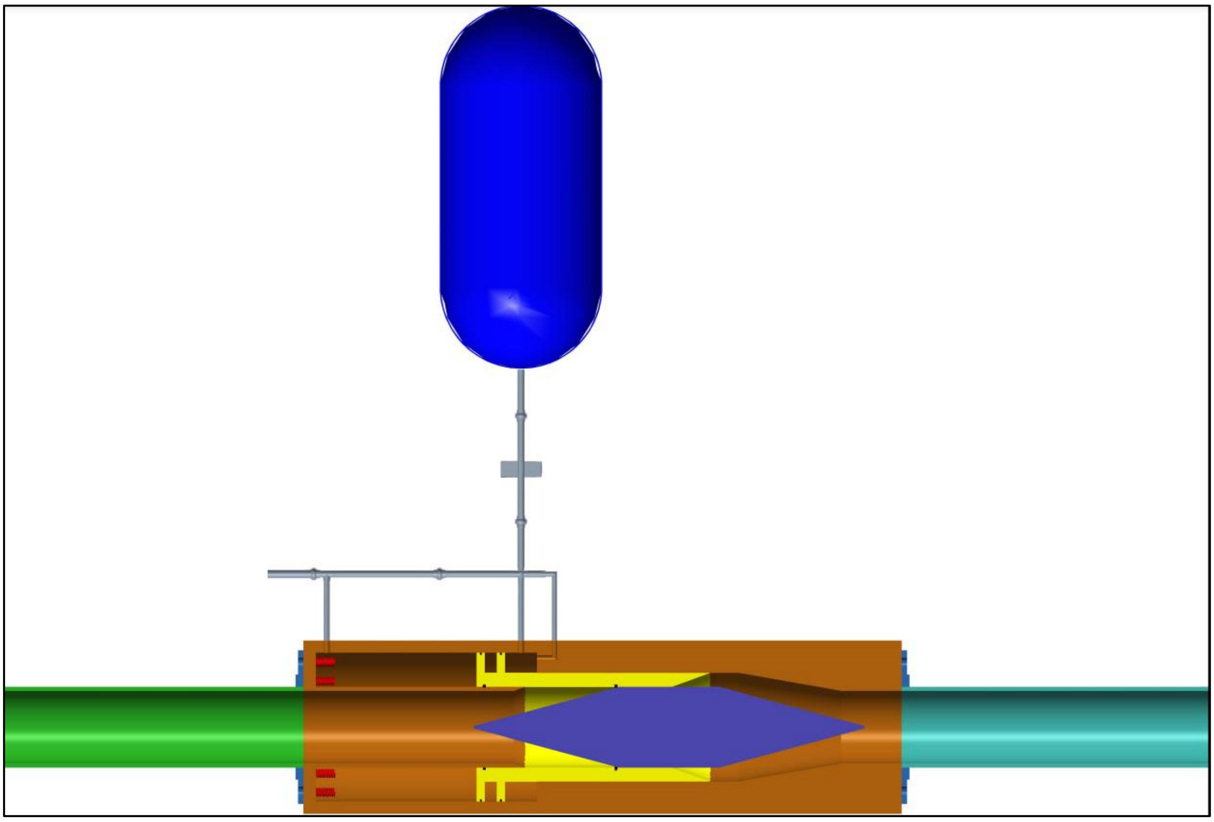


Fig. 17

2. STAGE II -

Fig. 17 represents Valve Activation, i.e. opening the shock tube. When the electronic solenoid valve, connected through a network of pipes, is activated, valves 3 and 4 are closed. It effectively releases the pressure that keeps the main valve securely closed. This release mechanism allows the main valve to open rapidly, within a matter of milliseconds, facilitating the swift expansion of high-pressure gas into the low-pressure driven section. This process ensures efficient fluid management and optimal system performance. Additionally, the quick actuation minimizes the risk of pressure buildup, contributing to the safety and reliability of the overall system. Proper calibration and maintenance of the solenoid valve are essential to prevent operational failures and to ensure consistent performance in applications requiring precise control of gas flow.

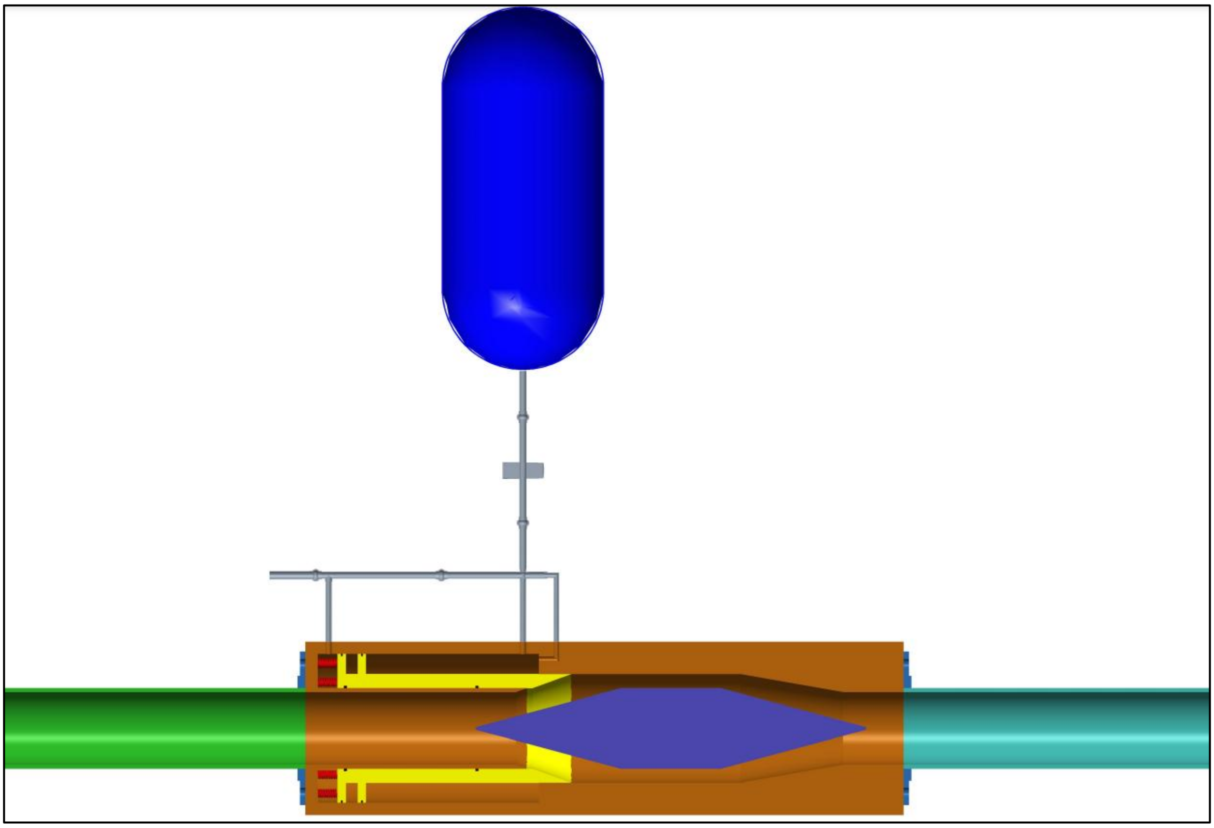


Fig. 18

3. STAGE III -

Figure 18 depicts an open valve, illustrating the generation and propagation of shock waves. The rapid expansion of high-pressure gas induces a shock wave that travels downstream, leading to the compression and heating of gas within the driven section. This process results in the establishment of high-velocity flow.

Upon activation, the Quick Acting Valve, located within the brown and yellow assembly, opens almost instantaneously, allowing the compressed gas to surge into the driven section. This abrupt expansion of gas as it passes through the central body (conical part) produces a shock wave that propagates along the driven tube. The centre body is designed to accelerate the flow to supersonic speeds, thereby enhancing both the strength and stability of the resulting shock wave.

4.5 Computational Flow Dynamics (CFD) Simulations

Computational Fluid Dynamics (CFD) is a powerful tool for analysing the behaviour of high-speed, quick-acting valves. It enables the prediction of shock wave propagation, pressure distribution, temperature changes, and flow velocity without physical experiments. The goal of the CFD study is to optimize valve design parameters to enhance shock wave reproducibility and efficiency.

The quick-acting valve is integrated into the shock tube; however, for computational fluid dynamics (CFD) analysis, a truncated portion of the shock is utilized to optimize computation time, but the performance is not affected.

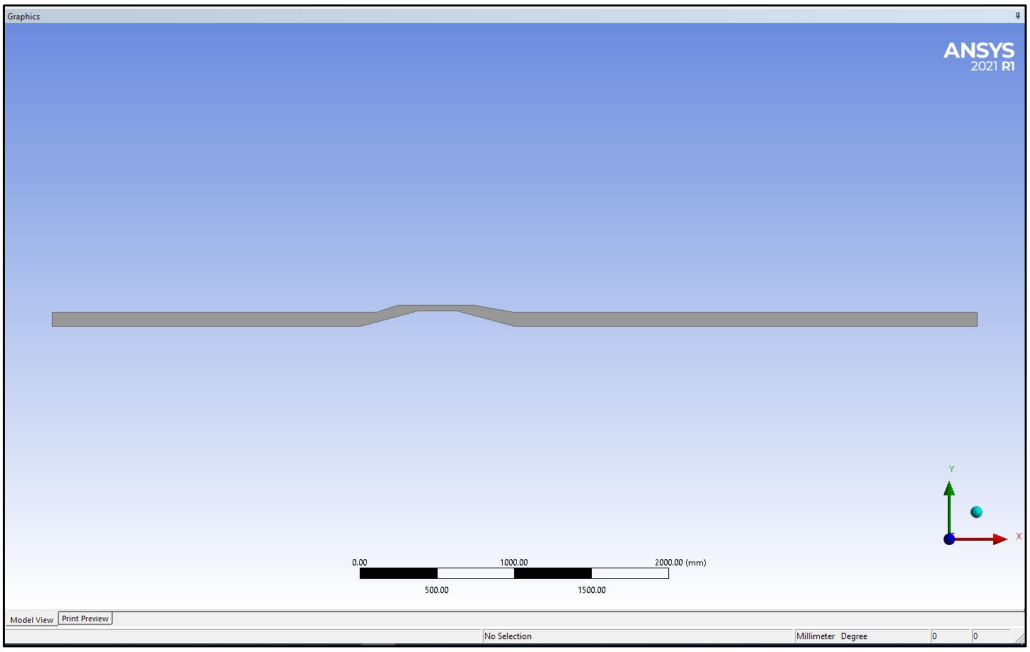


Fig. 19

The geometry of QAV with dimensions was created in ANSYS, as illustrated in Fig. 15. The meshing of element size 1 m is done. The density-based solver is used for compressible flow also time-dependent (transient) simulation, which helps to capture dynamic effects. The turbulence model k-ω SST Model was chosen as it provides better accuracy in shockwave and boundary layer interactions. The pressure in the inlet as well outlet was given 4e5 Pa. The shock capturing scheme that is used is AUSM (Advection Upstream Splitting Method) is used to solve compressible flow equations by accurately capturing shock waves and discontinuities while minimizing numerical diffusion.

AUSM is widely used in high-speed flow simulations, such as aerodynamics, shock tubes, and propulsion systems.

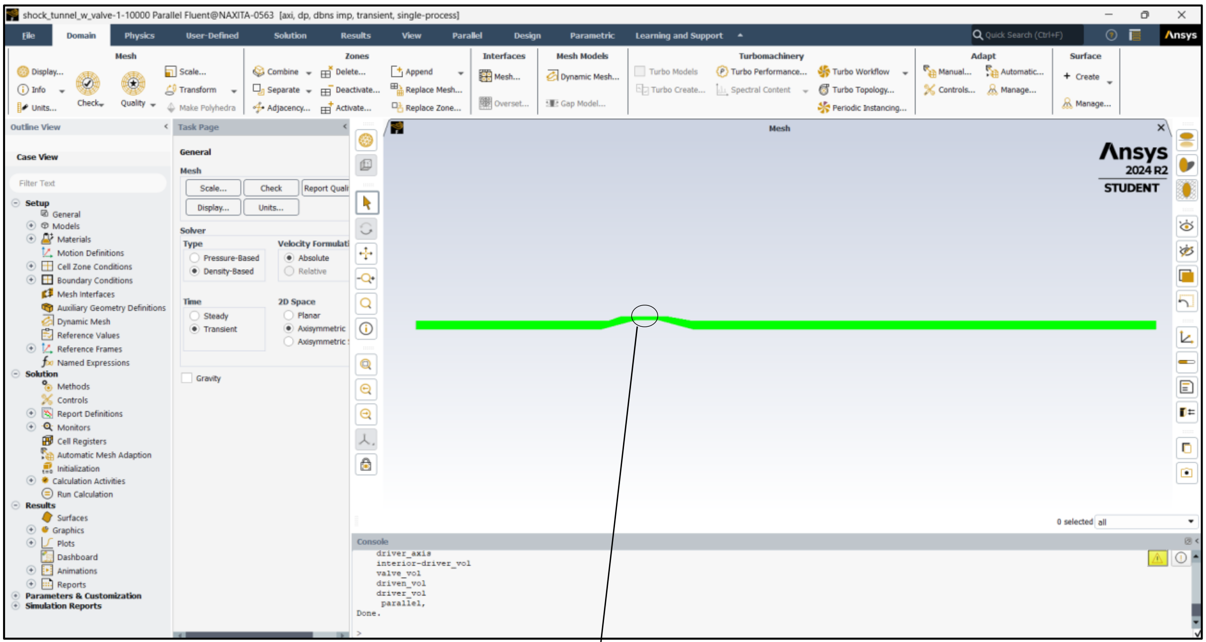


Fig. 20

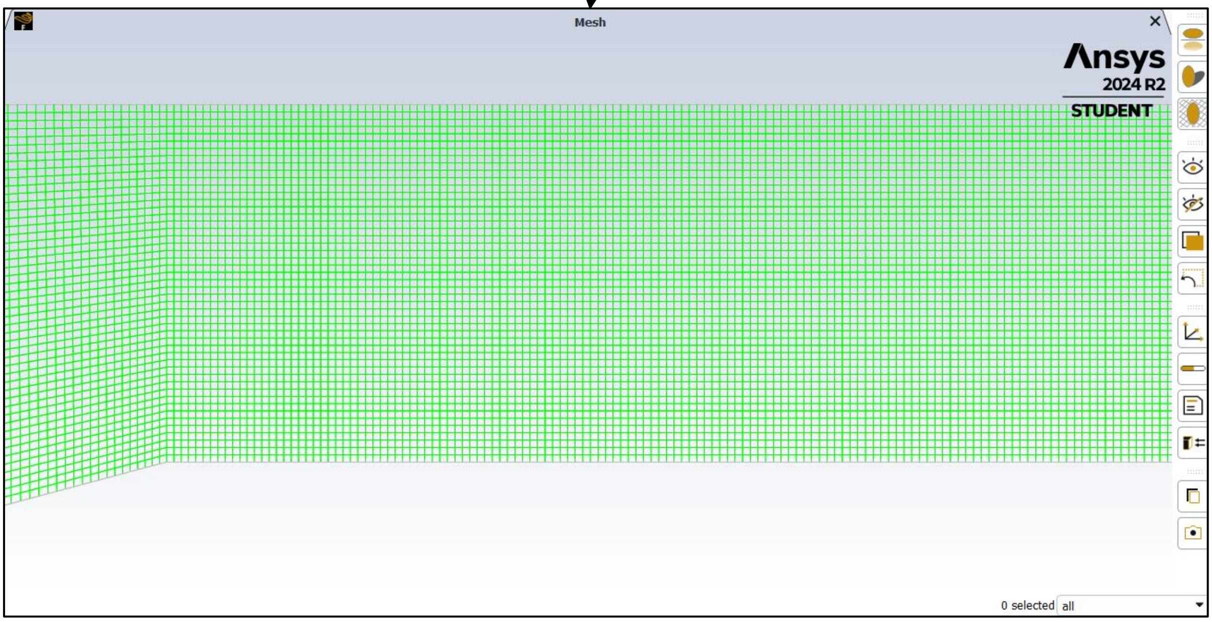


Fig. 20.1

To achieve enhanced refinement in regions subjected to shocks, a structured mesh approach is employed, as demonstrated in Figure 20. Additionally, boundary layer meshing techniques are utilized to ensure precise flow capture. Figure 20.1 presents a detailed view of the generated mesh.

1. Static Pressure

The static pressure contour demonstrates a significant pressure gradient from the driver section (high-pressure region) to the driven section (low-pressure region). Upon actuation of the QAV, high-pressure gas is rapidly released, passing through the valve's convergent-divergent profile. This geometry aids in accelerating the flow and initiating a shock wave, evident by the sudden pressure drop and colour shift from red to blue in the simulation. Figure 21 marks the initiation of computational fluid dynamics (CFD), with Figure 21.1 depicting gas flow before the reflection of shock and Figure 21.2 illustrating the point of shock generation and the completion of the analysis.

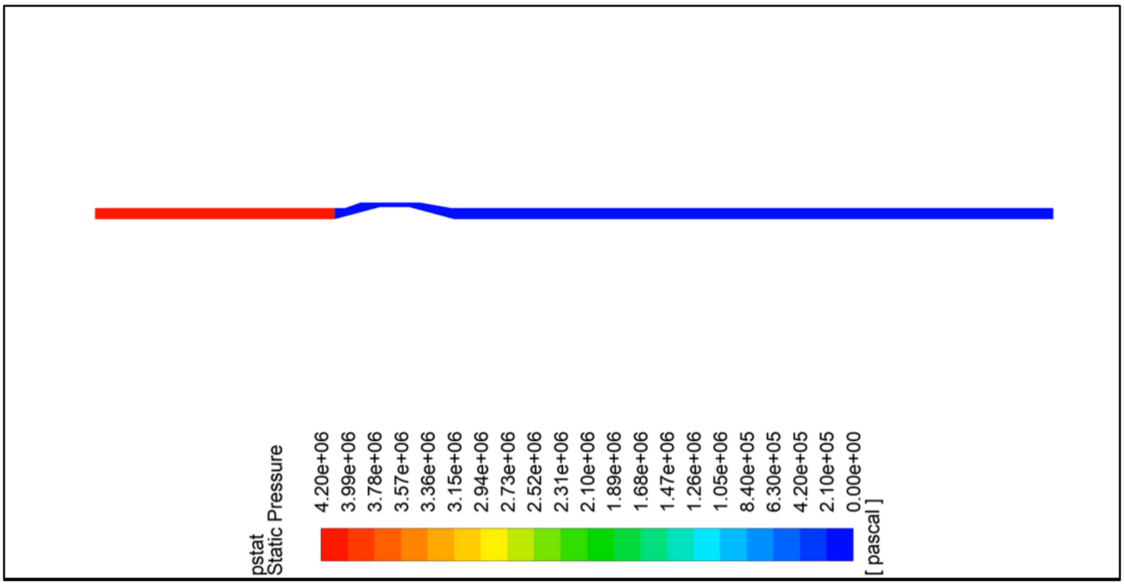


Fig. 21

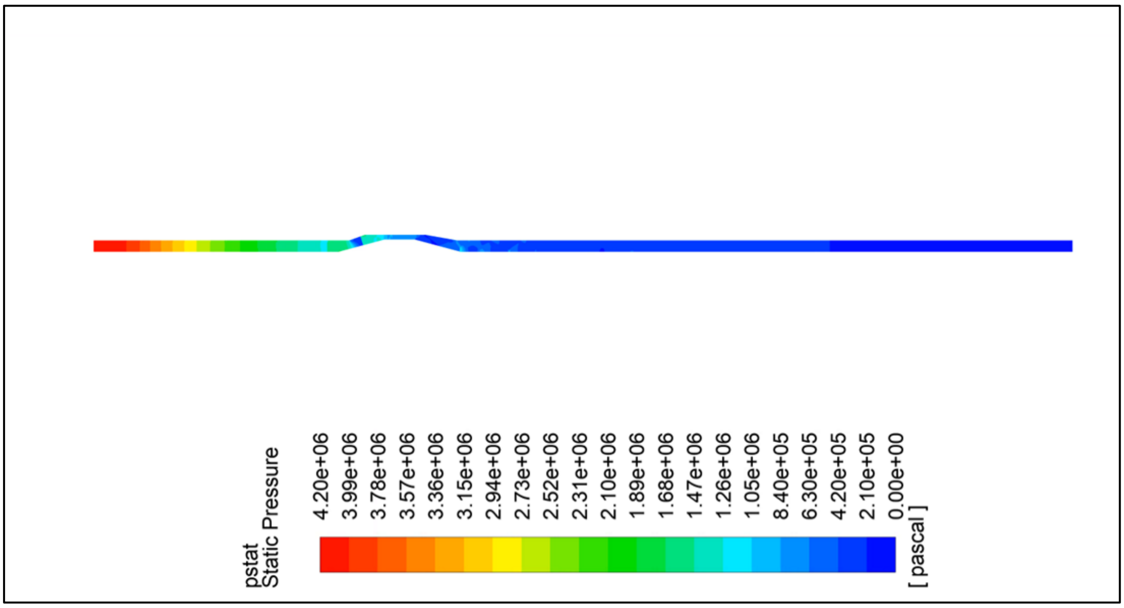


Fig. 21.1

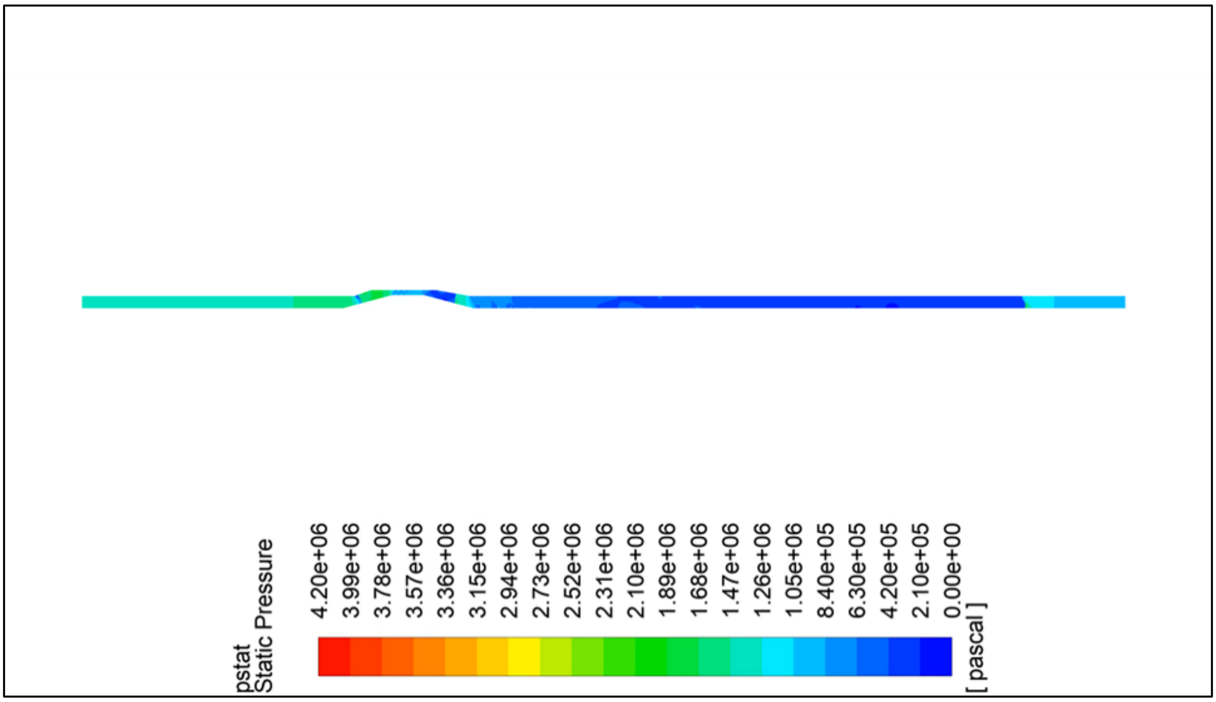


Fig. 21.2

2. Static Temperature

Initially, a high-temperature region is observed in the driver section due to the presence of compressed gas, which is typically stored at elevated temperatures. As the QAV is actuated, this high-energy gas expands and flows rapidly through the converging-diverging section, resulting in a sharp gradient in temperature.

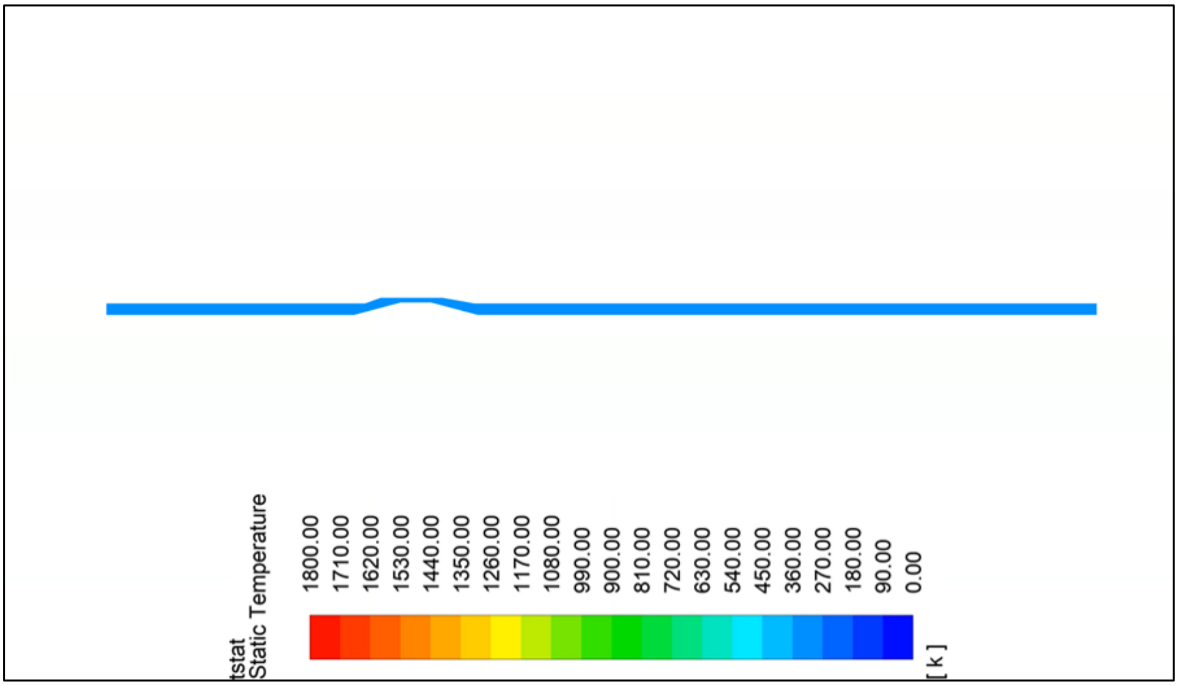


Fig. 22

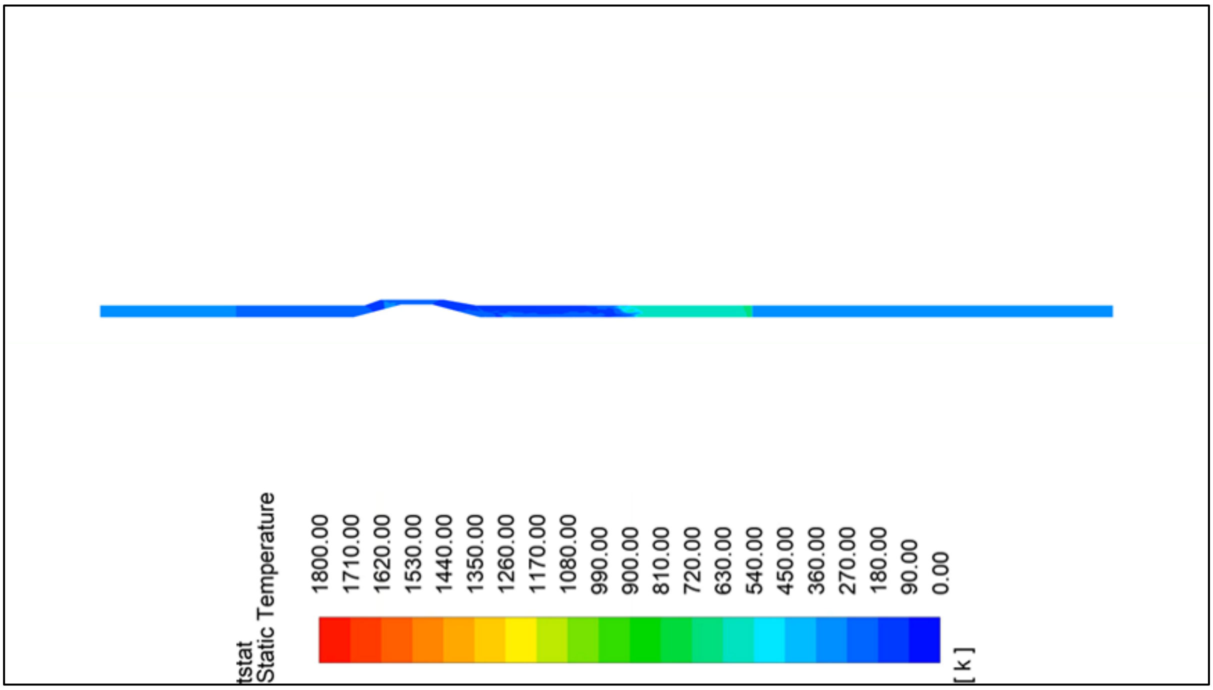


Fig. 22.1

The static temperature contour shown in Fig. 22.1, CFD result provides insight into the shock propagation behavior in a shock tube equipped with a Quick Acting Valve (QAV). This visualization indicates the presence of distinct temperature gradients and flow mixing within the driven section. Immediately downstream of the QAV, the temperature rises slightly, indicating shock initiation.

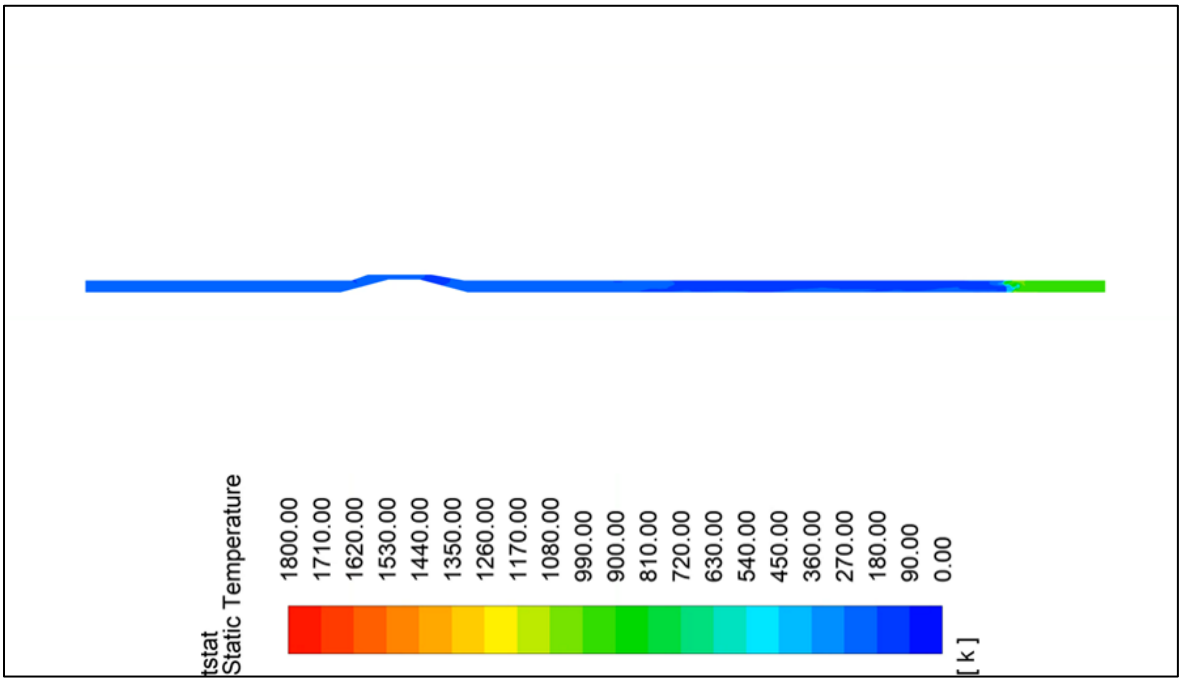


Fig. 22.2

3. Velocity Magnitude

Figure 23 indicates that velocity magnitude is at zero initially, but in fig. 23.1, we can see that the fluid entering the wider section on the left appears to be moving at a relatively lower velocity. The colors transition back towards greenish-blue, indicating a decrease in velocity as the flow expands to a larger area. Whereas Figure 23.2 indicates that the shock is generated and has some velocity magnitude.

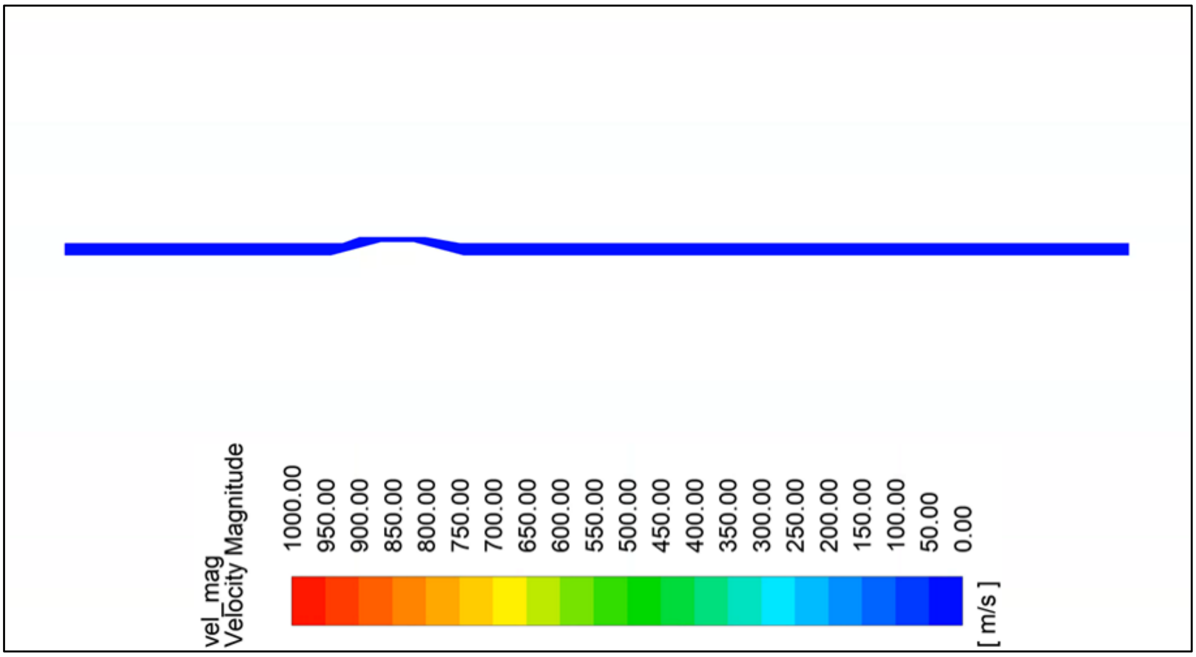


Fig. 23

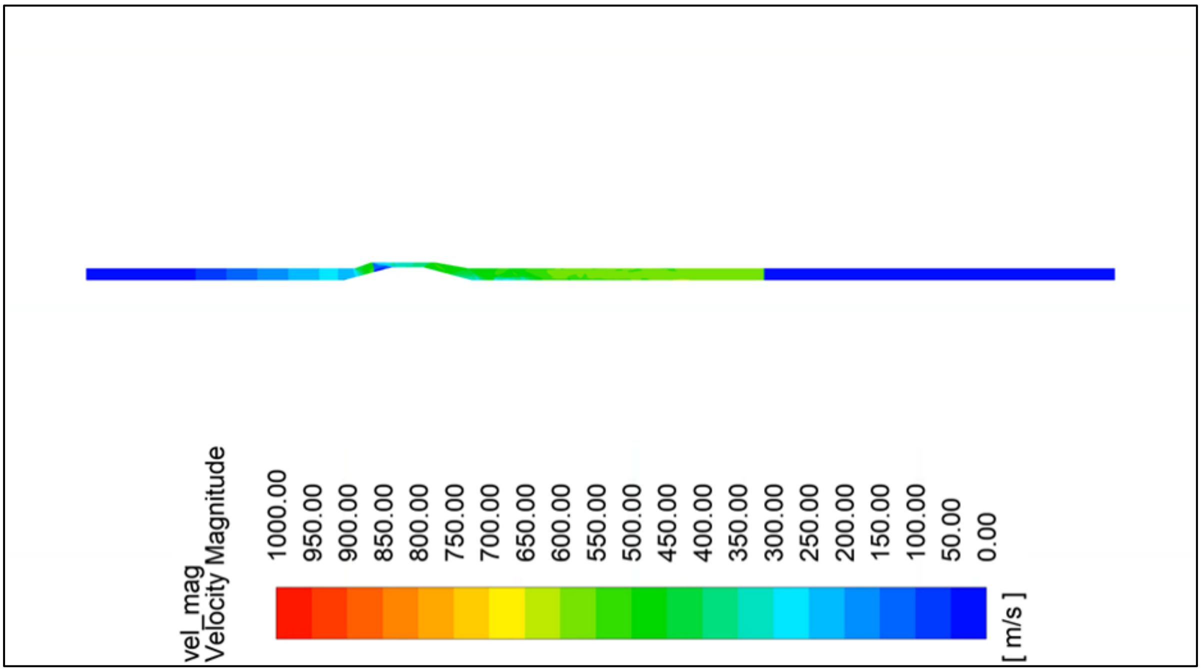


Fig. 23.1

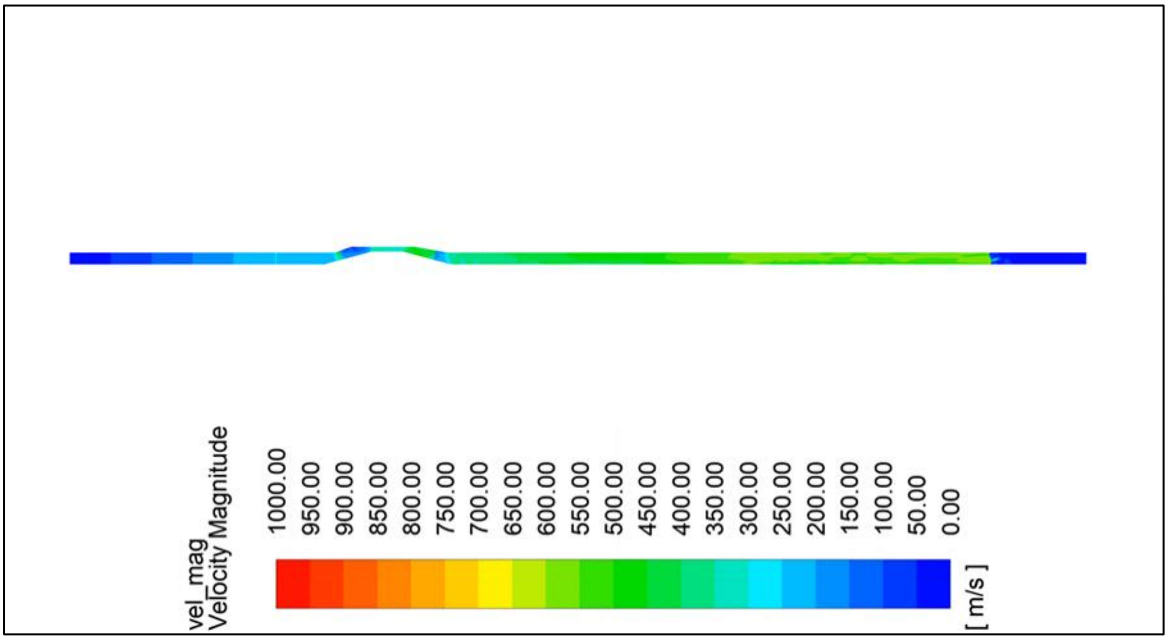


Fig. 23.2

To facilitate a comparison of the parameters we calculated for the QAV, we also generated corresponding parameters for a shock tube with truncated dimensions. Specifically, this shock tube features a driver section measuring 2 meters and a driven section measuring 6 meters.

The boundary conditions and parameters were consistent with those used for QAV. At 2m, a diaphragm is installed that ruptures when high-pressure gas is transmitted from the driver section.

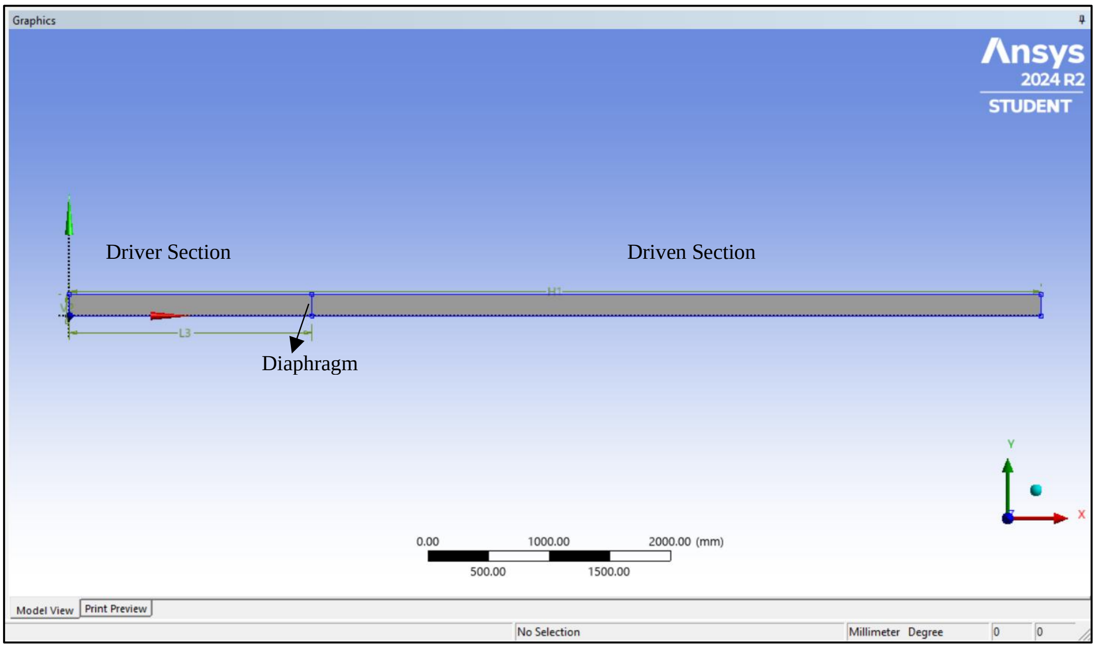


Fig. 24

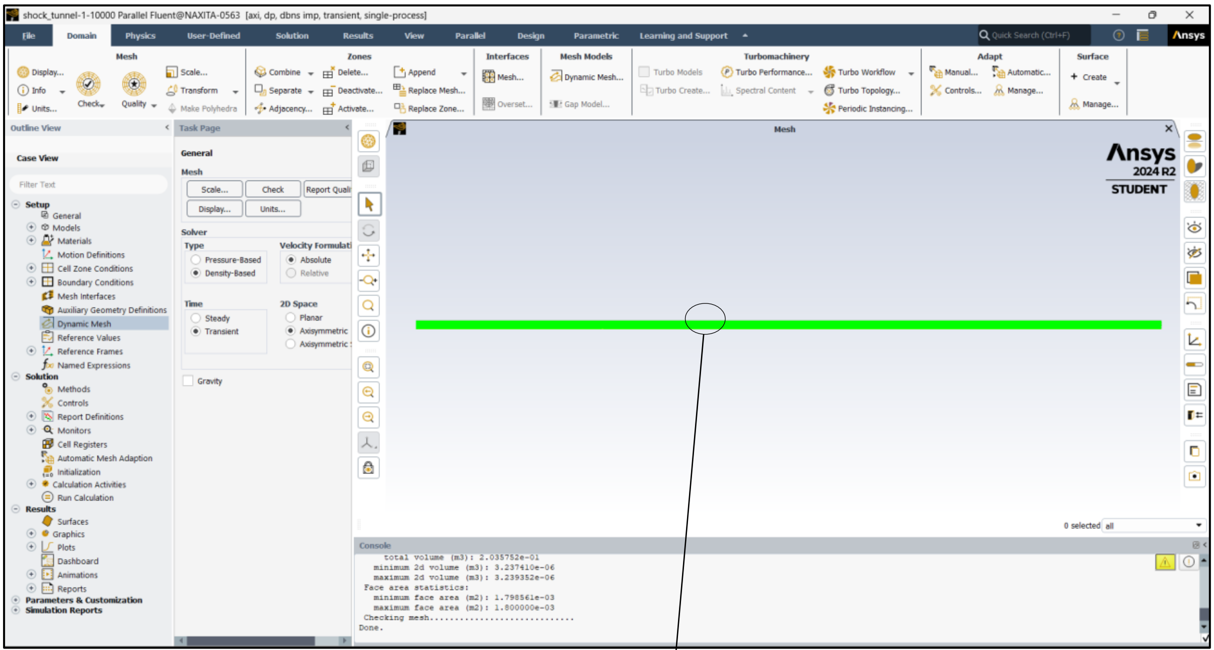


Fig. 25

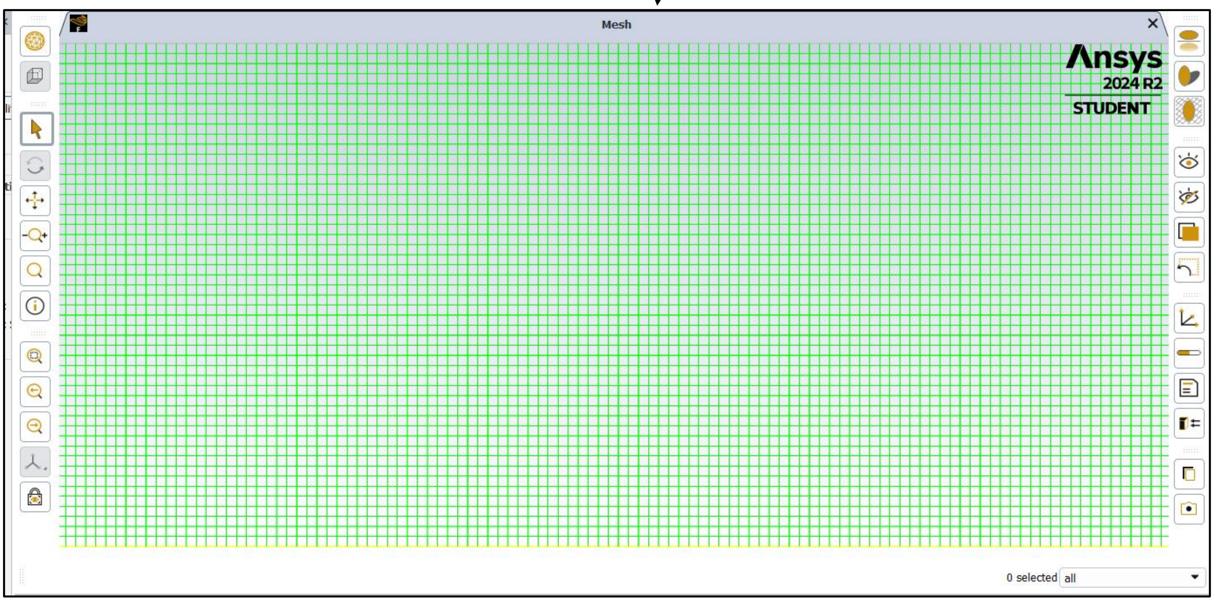


Fig. 25.1

Here for shock tube also the element size for mesh is given 1m and as seen in figures 25 and 25.1 the mesh is structured.

1. Static Pressure

The static pressure contour demonstrates a significant pressure gradient from the driver section (high-pressure region) to the driven section (low-pressure region). The high pressurised gas is passed from the driver section to the driven section in which the diaphragm gets ruptured and accelerates flow, initiates a shock wave, shown in figure 26.

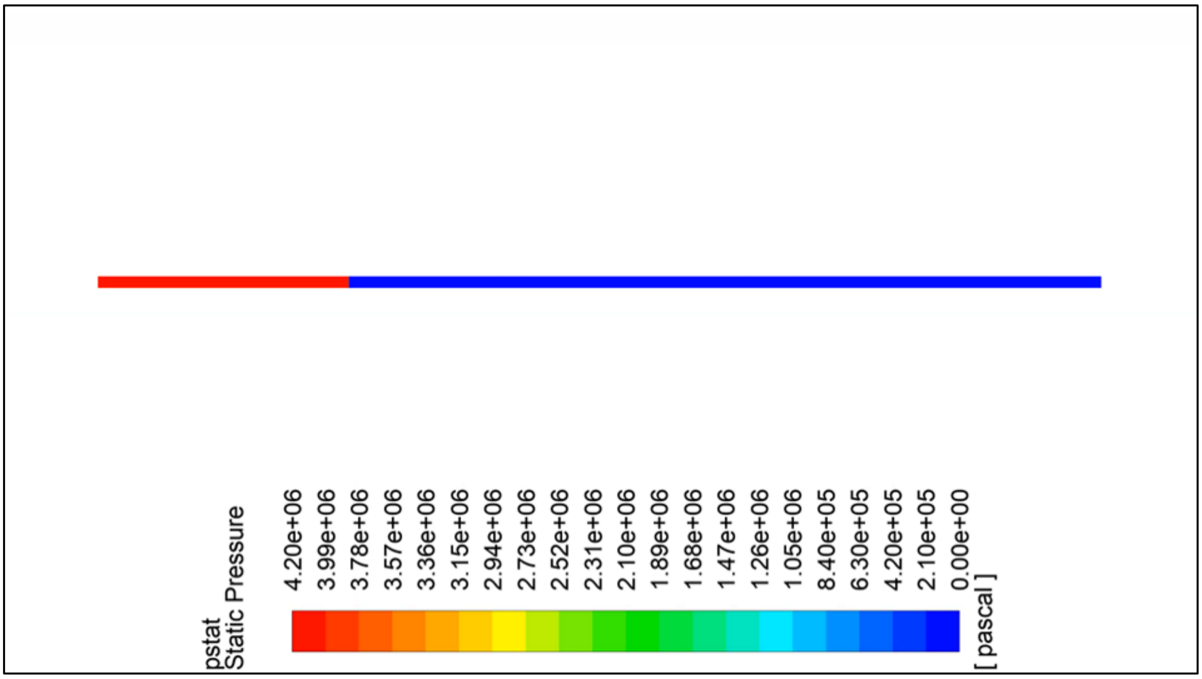


Fig. 26

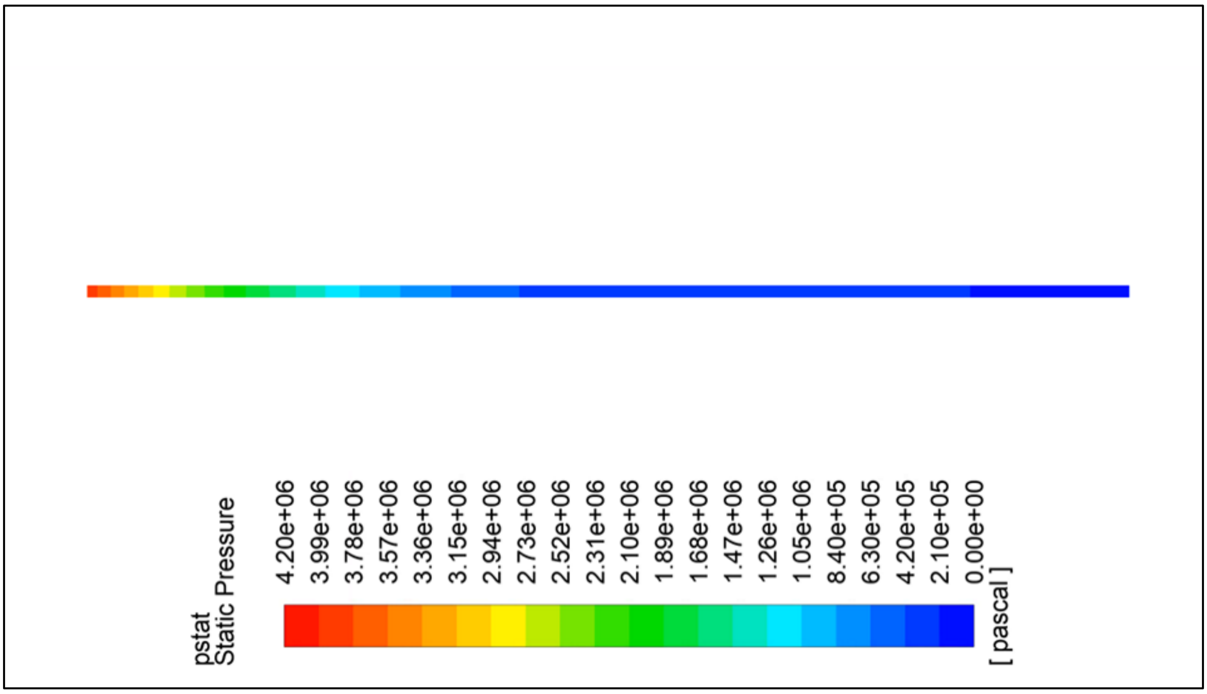


Fig. 26.1

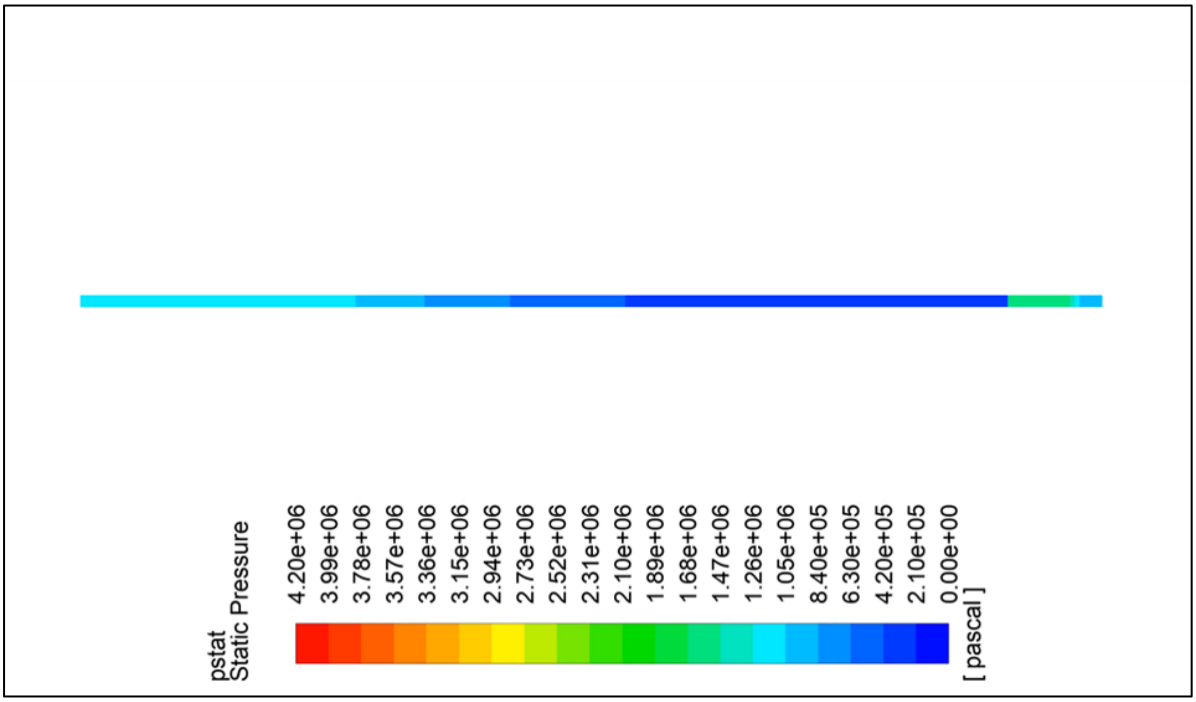


Fig. 26.2

2. Static Temperature

Initially, a high-temperature region is observed in the driver section due to the presence of compressed gas, which is typically stored at elevated temperatures. The static temperature contour shown in Fig. 27 provides insight into the shock propagation behavior in a shock tube.

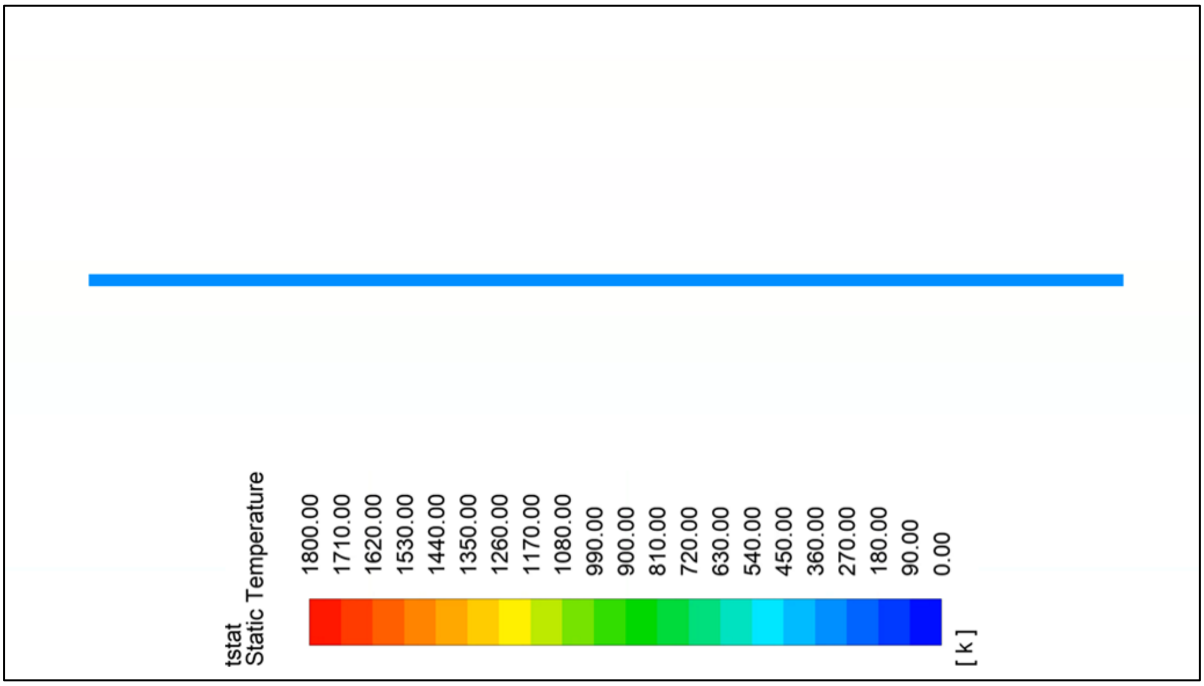


Fig. 27

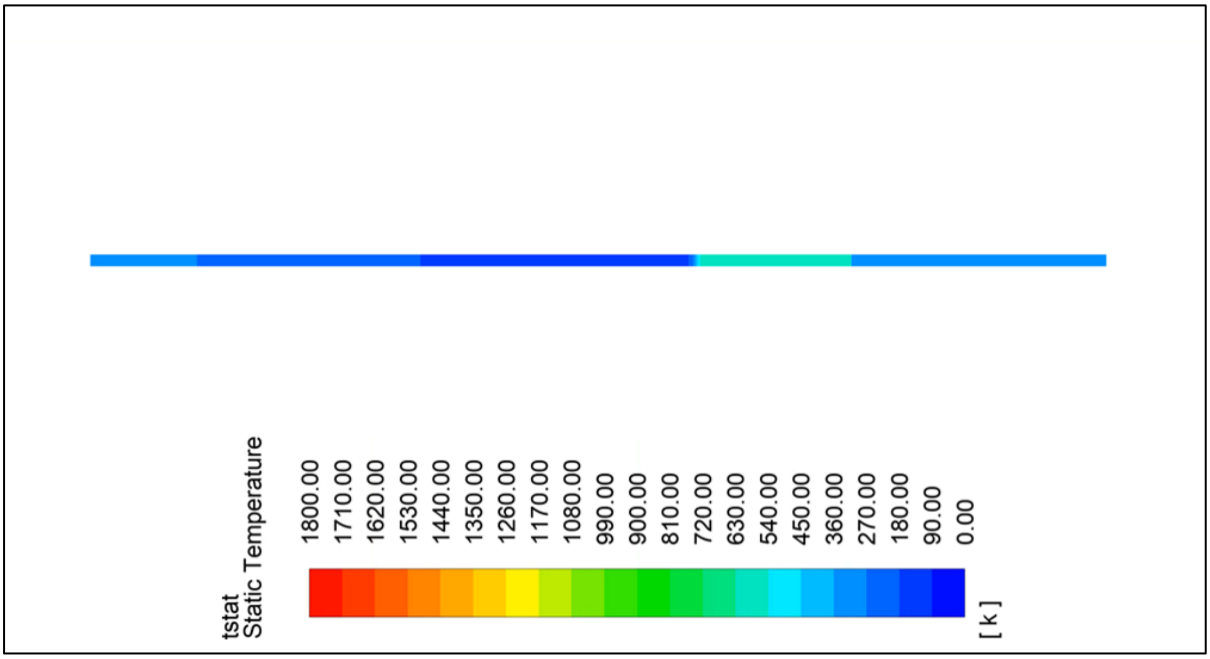


Fig. 27.1

Figure 27.1 depicts gas flow before shock reflection, while Figure 27.2 illustrates shock generation and analysis completion. This visualization indicates the presence of distinct temperature gradients and flow mixing within the driven section.

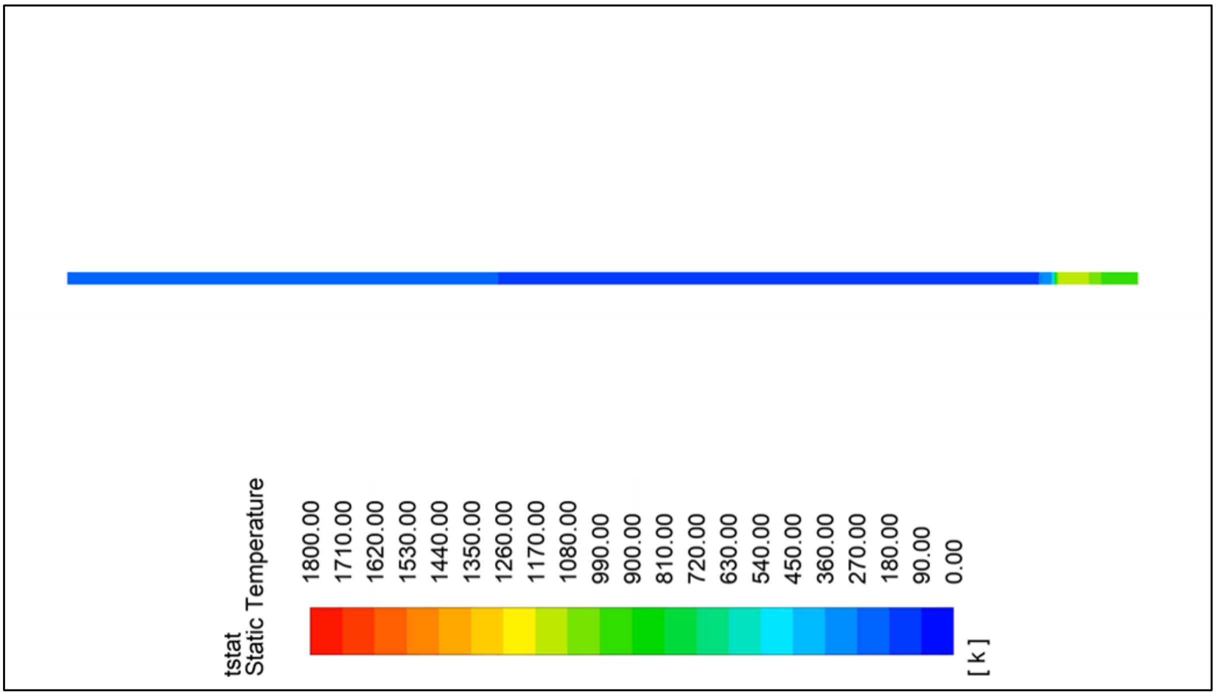


Fig. 27.2

3. Velocity Magnitude

Figure 28 indicates that velocity magnitude is at zero initially, but in fig. 28.1, we can see that the fluid entering the wider section on the left appears to be moving at a relatively lower velocity. The colors transition back towards greenish-blue, indicating a decrease in velocity as the flow expands to a larger area.

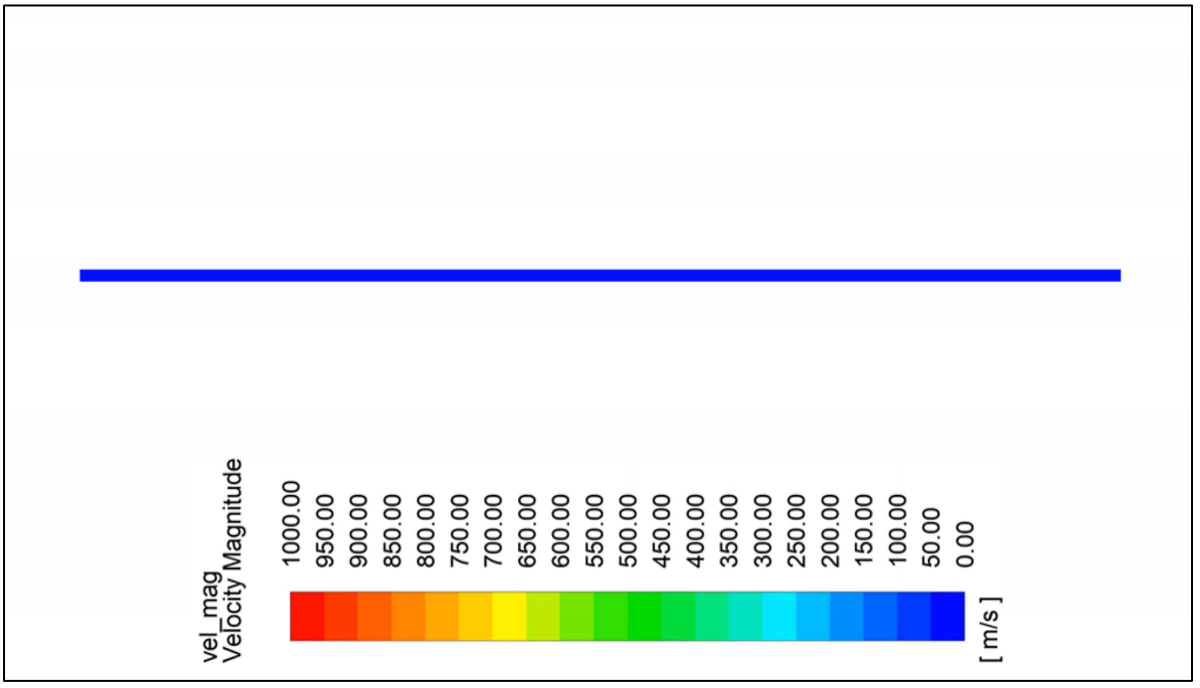


Fig. 28

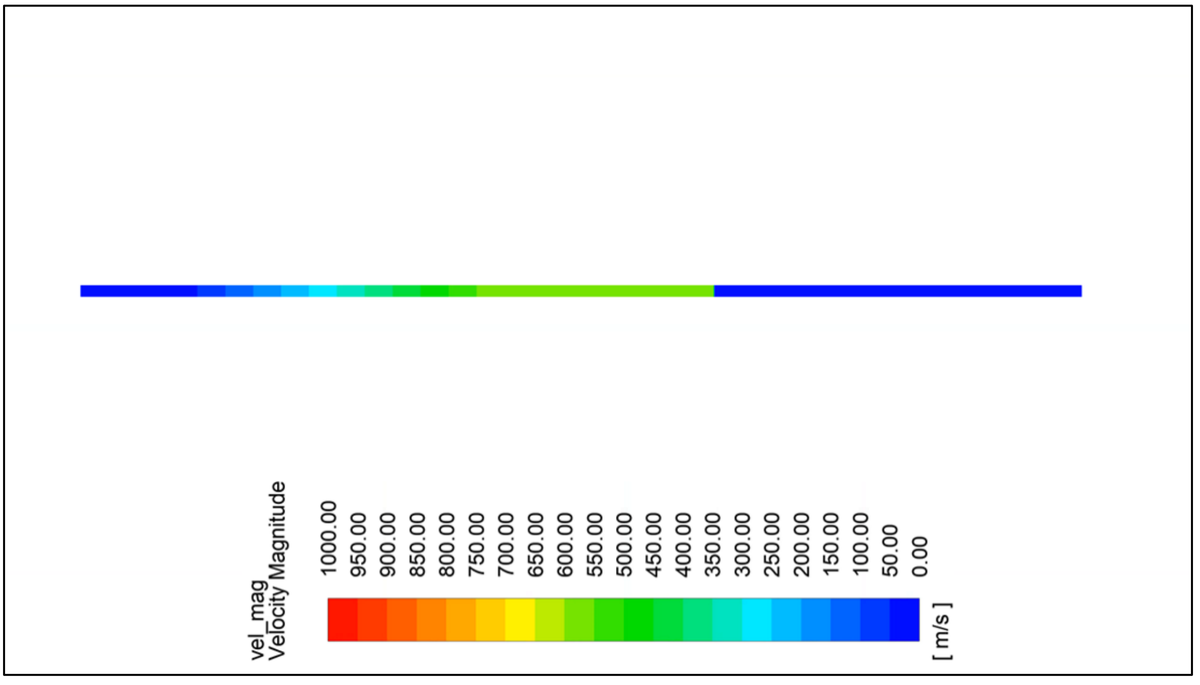


Fig. 28.1

Whereas Figure 28.2 indicates that the shock is generated and has some velocity magnitude. However, the overall impression is that of a steady and uniform flow through the constant area duct.

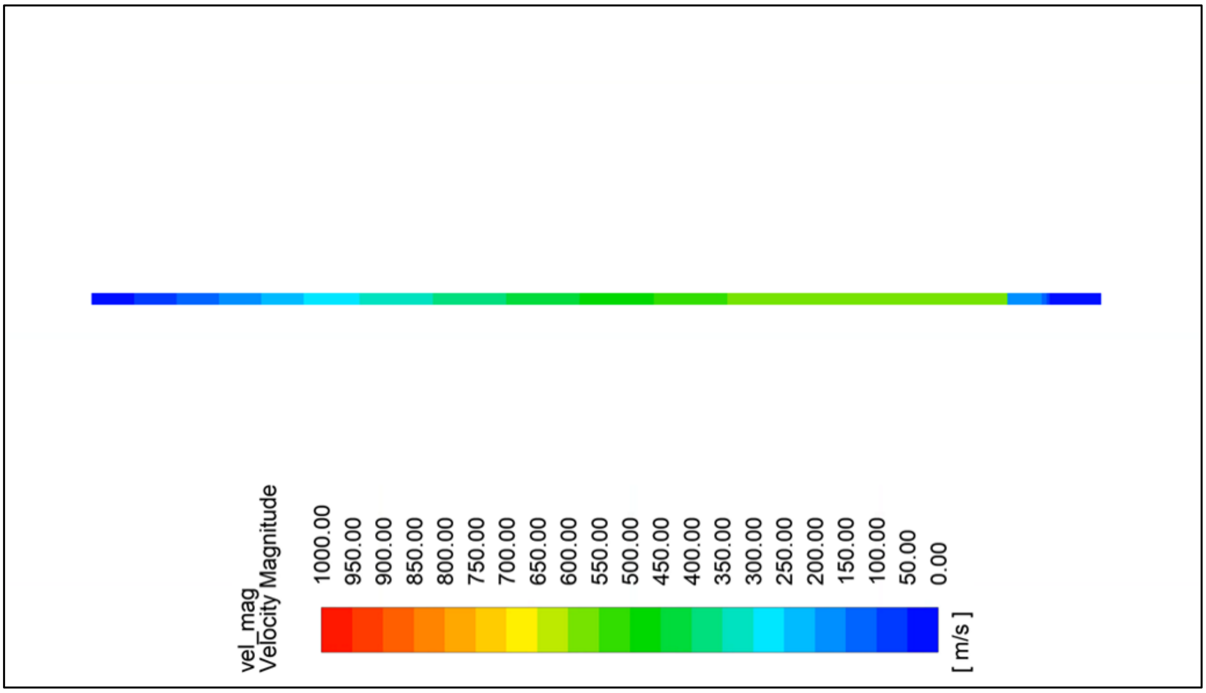


Fig. 28.2

Upon comparing the CFD analysis results of the standard shock tube with those of the shock tube incorporating a Quick Acting Valve (QAV), it has been observed that there are no significant variations in any of the parameters examined. The integration of the QAV does not result in any degradation of performance metrics. However, it is important to note that this analysis represents a preliminary CFD evaluation, and additional analyses will be necessary before fabrication. Notably, structural analysis has not been conducted within the scope of this project.

5. RESULTS AND ANALYSIS

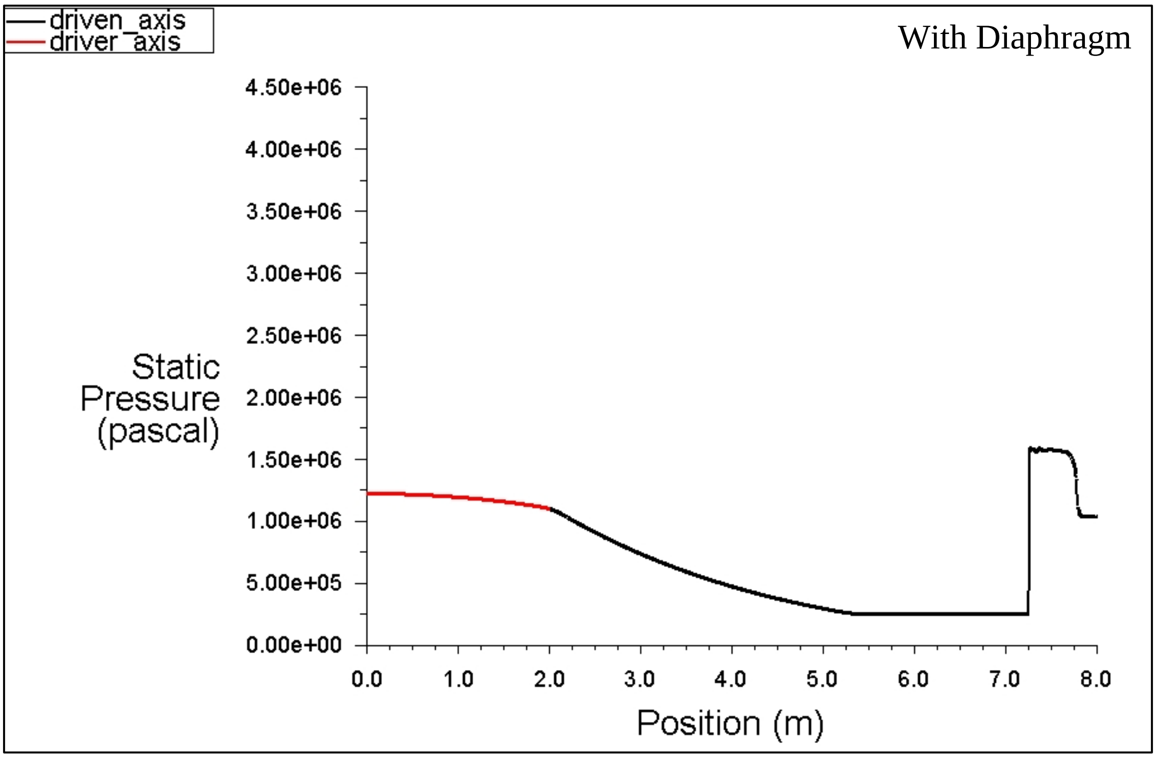


Fig. 29

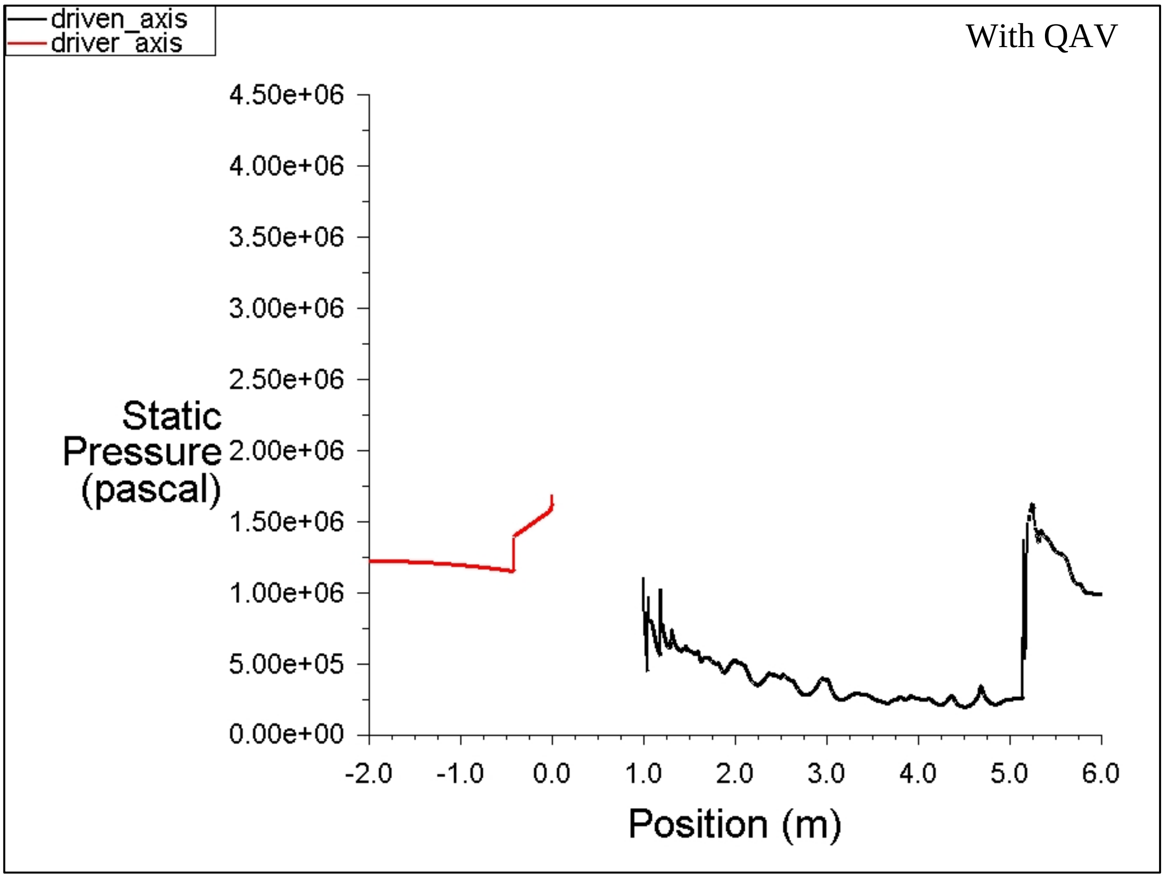


Fig. 29.1

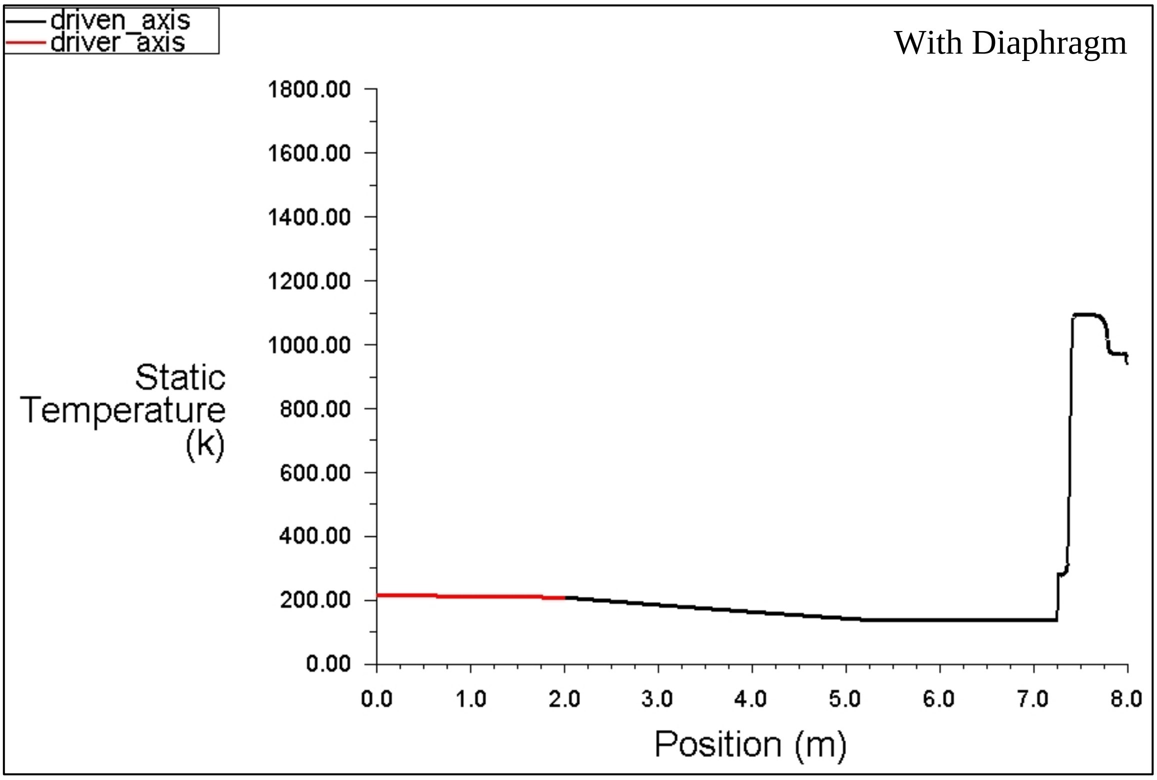


Fig. 30

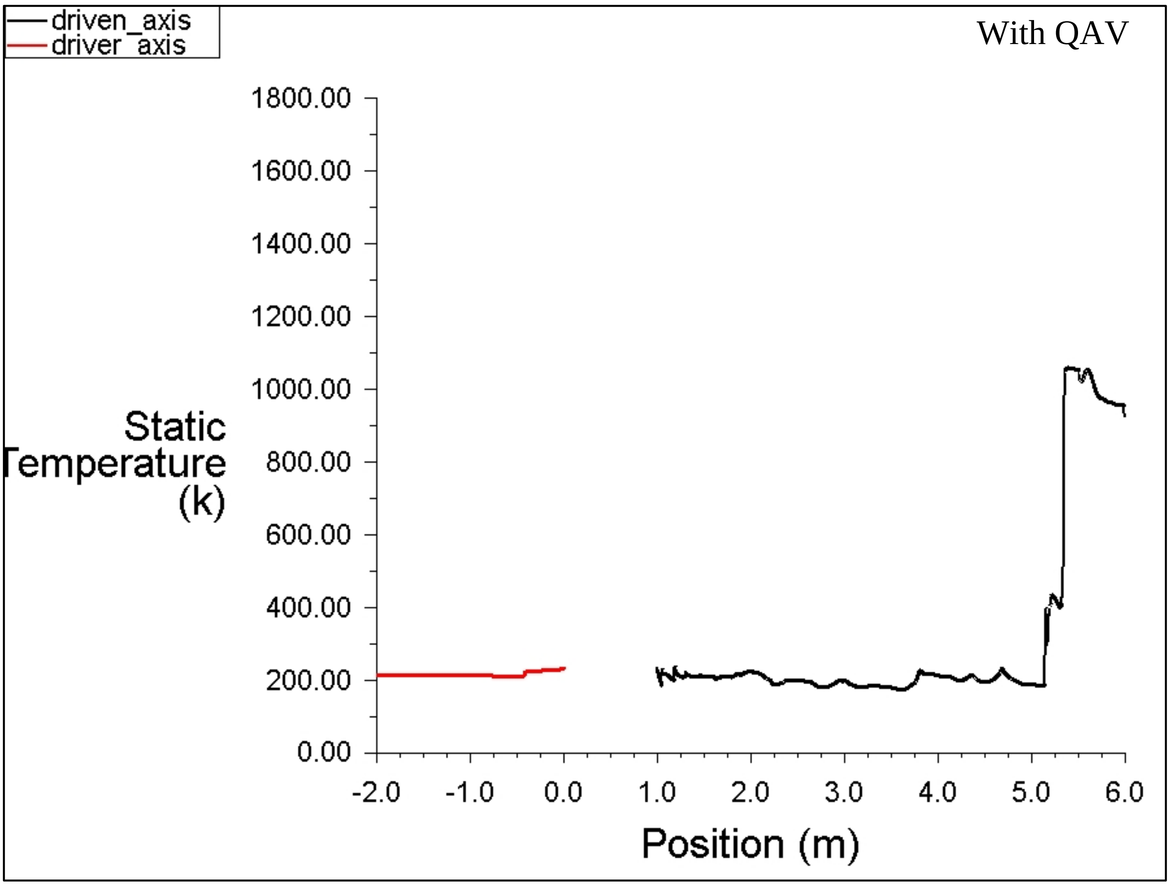


Fig. 30.1

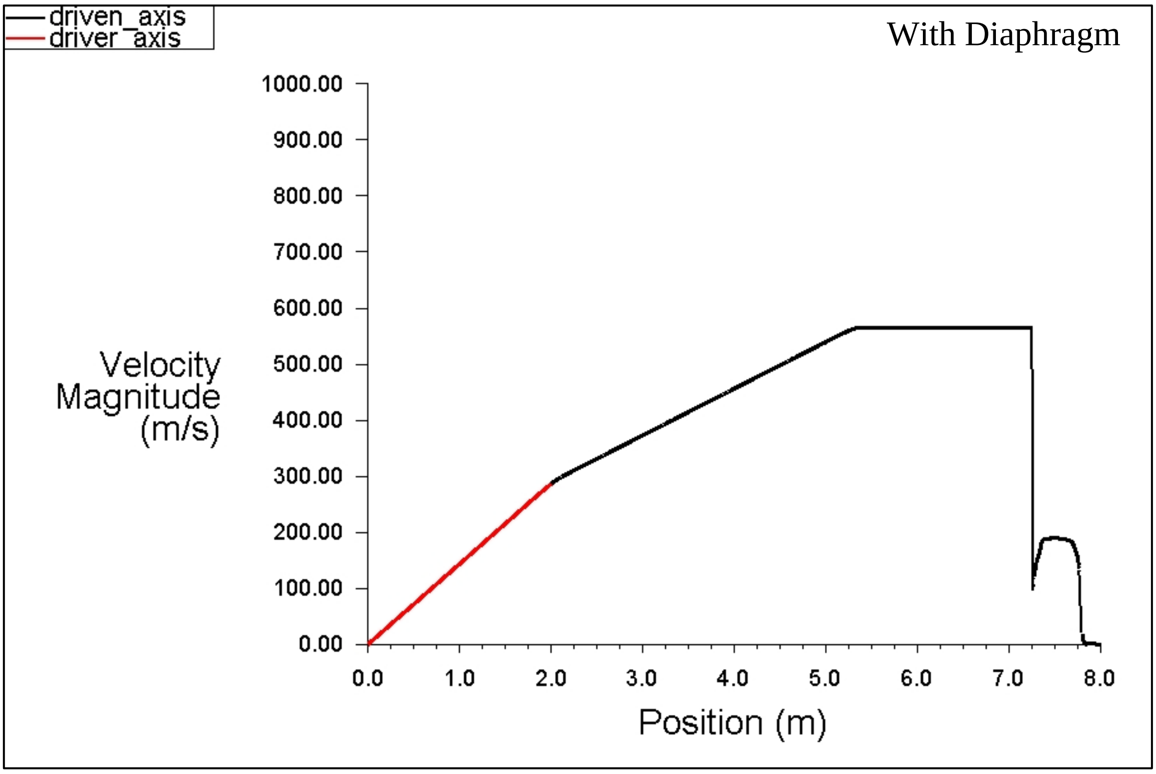


Fig. 31

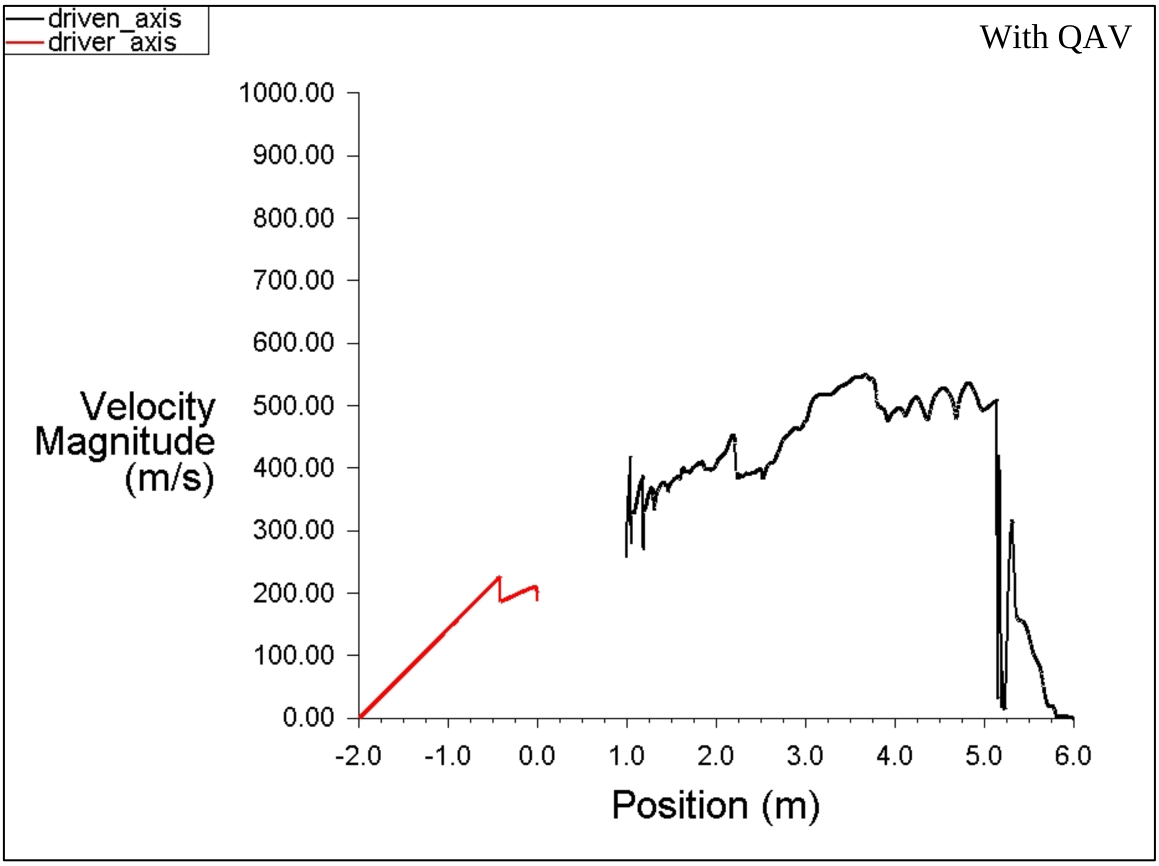


Fig. 31.1

6. DISCUSSION AND PERFORMANCE

The shock tube system presented utilizes a Quick-Actuating Valve (QAV) to facilitate the generation of a high-strength shock wave with minimal delay and improved repeatability. This valve, operated pneumatically, replaces traditional diaphragm-based systems that are typically single-use, manually reset, and prone to inconsistency. The design uses a concentric layout, with the outer tube (high-pressure) surrounding the inner tube (low-pressure). This setup reduces the amount of unused space and helps improve the flow and quality of the shock wave. As the project targeted CFD analysis of the quick-acting valve when incorporated in a shock tube, the basic analysis has been successfully compared with the traditional shock tube (the one with a diaphragm). The observations after CFD are -

1. The flow remained mostly axial with minimal swirl, indicating good design symmetry and flow efficiency.
2. The contours of the shock tube and QAV exhibit a high degree of similarity, with a variance of approximately 2% in certain areas.
3. The QAV demonstrated a smooth and symmetric opening pattern, which was validated by the high-pressure gradients observed following the opening.

Also, from Graphs Section 5, it is evident that there is no major difference visible. This suggests that the trends remain relatively stable across the data sets. Additionally, any fluctuations observed are minimal and do not significantly impact the overall interpretation. Therefore, we can conclude that the variables analysed are likely consistent over the observed period.

Additionally, the improved design of the QAV allows for quicker actuation times, enhancing the overall responsiveness of the shock tube system. The results suggest that the QAV can achieve higher peak pressures compared to the diaphragm-based systems, potentially leading to more powerful shock waves. Moreover, the consistency in performance across multiple cycles highlights the reliability of the QAV in various operational conditions.

7. CONCLUSION AND FUTURE SCOPE

The QAV (Quick-Acting Valve) demonstrates significant benefits across various aspects when properly integrated, as observed in the CFD analysis. However, several crucial steps must be taken before its fabrication and subsequent incorporation into the shock tube. These steps include rigorous testing to ensure compatibility, thorough documentation of all processes to maintain quality, and a detailed evaluation of potential impacts on performance. By following these guidelines, organizations can maximize the effectiveness of the QAV in the final application. Future work may focus on optimizing the valve's geometry further to maximize efficiency. Experimental validations are also planned to corroborate the CFD findings and ensure practical applicability in real-world scenarios.

The results also validated the design features, such as equal pressure operation, area differential control, and the effectiveness of the pneumatic damper in preventing mechanical stress on the system.

Future Scope

To further enhance the design and performance of the QAV-integrated shock tube system, the following areas are proposed for future work:

1. Fluid-Structure Interaction (FSI) Modelling: Implementing FSI in CFD simulations to account for the dynamic interaction between the moving sleeve and fluid forces for more realistic behaviour prediction.
2. Experimental Validation: Complementing CFD findings with high-speed camera imaging, pressure transducer data, and Schlieren photography to validate shock strength, timing, and flow characteristics.
3. Design modification for analysis: The detailed structural analysis may indicate a few modifications in design to obtain the targeted results.
4. 3D CFD Modelling: Developing a three-dimensional CFD model to capture asymmetric effects, swirl formation, and any off-axis behaviour that may not be evident in 2D simulations.

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