

The Characterisation of a Shock Tube System for Blast Injury Studies

Thuy-Tien Ngoc Nguyen

Imperial College London

Department of Physics

This dissertation is submitted for the degree of Doctor of Philosophy

Abstract

In recent decades, improvised explosive devices have been one of the main causes of injuries due to blast effects to military personnel as well as civilians. Such injuries are very complex, with multiple types of injuries happening at once. To understand the nature of such injuries, it is important to be able to re-create the blast waves, isolating their different time-dependent effects (e.g. initial accelerations by shock waves, ballistic impacts, etc.). The shock tube is a versatile apparatus that can generate these elements of blasts in laboratory environment.

The project aims to deepen the current understanding about the shock tube by characterising it over a range of conditions such as diaphragm breakage, and to measure the evolution of the pressure generated. Then, based on these characterisations, additional adjustments and adaptors are introduced to adapt the performance of the shock tube to specific purposes, especially blast injury and mitigation studies. Experiments were performed on an air-driven shock tube system with Mylar[®] and aluminium diaphragms of various thicknesses, and with different lengths of driver section. Single-diaphragm and double-diaphragm configurations were employed, as were open or closed tube configurations. The arrangement was designed to enable high-speed photography and pressure measurements.

Overall, the results from the shock tube are highly reproducible, and show that diaphragm burst pressure is the most influential factor on the output pressure pulses. The diaphragm burst pressure is shown to be linearly related to its thickness in the range studied. Comparing single and double diaphragm systems, both produce similar effects but the latter provides more control over the generation of blast waves. The output blasts were also

characterised against different locations, orientations and sizes of sample mountings. The thesis also reports studies on interactions between produced blast waves and various structures, for both biological sample mounting and blast mitigation purpose. It shows that the shock tube system can allow studies of blast effects on biological samples (e.g. osteoblast and Schwann cell cultures), and blast mitigating properties of different materials and structures (e.g. perforated sheets, reticulated foams). Finally, a computational fluid dynamic simulation for the blast generation in the shock tube has been developed, which gives reasonable agreements with experimental data. Improved versions of the simulation will be coupled with structural program to model interactions between blast waves and different geometries and materials.

Acknowledgements

This project would not have been possible without the help of several individuals who in one way or another contributed and extended their valuable assistance.

First and foremost, I would like to offer my sincerest gratitude to Dr William Proud for his continuous patient support while giving me the flexibility in my project.

Thanks to Dr David Chapman, Dr Daniel Eakins, Dr James Wilgeroth and Dr Katherine Brown for their thorough technical guidance and valuable discussions. They have always found the time to help me despite their busy schedules.

I have been aided by many technicians from both Bio-engineering department and Physics department. Especially, I want to thank Mr Satpal Sangha who has been making and modifying mechanical parts for the shock tube, and Mr Stephen Johnson for his technical advices and help.

Thanks to all the members of the Institute of Shock Physics, especially Miss Chiara Bo, Mr David Sory and Ms Ciara Mulholland, who generously shared their resources and have given me warm encouragements. Ciara has also helped me with all the administration work and orders related to my project.

Thanks to all the members of the Royal British Legion Centre for Blast Injury Studies, especially Dr Emma Burke and Dr Hari Arora, for their constant supports. Hari has given me huge help for the work with computational simulations.

Thanks to the Imperial College Kendo Club, especially Emiko-sensei, for providing me a

place to balance between work and social life, and to relieve all the stress!

Last but not least, I want to thank my family. They have always been the biggest source of encouragement and motivation for me.

My husband, Vincent, has also been my proof-reader and editor for all these years.

Contents

List of Figures	21
List of Tables	23
1 Introduction	25
1.1 Motivations and objectives	25
1.1.1 Overviews of blast injuries	25
1.1.2 Improvised explosive devices	28
1.1.3 Objectives of the project	30
1.2 Thesis structure	30
1.3 Statement of originality	31
1.4 Copyright Declaration	31
1.5 Publications	31
2 Background Theory	34
2.1 Shock waves and blasts	34
2.1.1 The theory of shock wave in gas	34
2.1.2 Blast waves and explosion scenarios	38
2.2 Principles of the shock tube	44
2.2.1 The ideal gas description of the shock tube	44
2.2.2 Deviation from the ideal behaviour	47
2.3 Applications and existing studies of the shock tube	50
2.3.1 Shock tubes in biological studies	52

3	The CBIS Shock Tube System and Diagnostics	55
3.1	The CBIS shock tube system	55
3.2	Dynamic pressure sensors	62
3.2.1	Piezoelectric pressure sensors	63
3.2.2	The mountings of sensors	64
3.3	The schlieren photography for blast visualisations	68
3.3.1	The principle of schlieren photography	68
3.3.2	Visualising the shock tube output	72
3.4	Conclusions	74
4	The Output Blast Waves in the Shock Tube	76
4.1	The blast magnitudes	76
4.1.1	The effect of the diaphragm burst pressure	78
4.1.2	The effect of the stand-off distance from the shock tube outlet . . .	80
4.2	Blast duration	81
4.3	Tailoring blast outputs for different scenarios	87
4.4	Conclusions	89
5	Studies of Blast Interactions and Mitigations	90
5.1	Interactions with perforated sheet structures	91
5.1.1	The perforated galvanised steel sheet	91
5.1.2	The experimental set-up	92
5.1.3	Results and discussions	93
5.2	Interactions with reticulated acoustic foams	96
5.2.1	The reticulated polyurethane foams	97
5.2.2	The experimental set-up	98
5.2.3	Results and discussions	99
5.3	Interactions with reticulated foam - perforated steel sheet combination . .	100
5.3.1	The reticulated foam - perforated sheet sandwich structure	101
5.3.2	The experimental set-up	101

5.3.3	Results and discussions	102
5.4	Interaction with adaptor for tissues and organs	105
5.4.1	The design and test set-up of the adaptor	105
5.4.2	The characterisation results for the adaptor	106
5.4.3	The modifications of the adaptor	110
5.5	Adhesive sealing membranes	114
5.5.1	The use of membranes in blasting of cells	115
5.5.2	The blast attenuating properties of membrane - perforated sheet combination	117
5.6	Interaction with platform for primary blast limb trauma study	119
5.6.1	The design and test set-up of the platform	119
5.6.2	The characterisation result for the platform	121
5.7	Conclusions	124
6	Computational Simulations	127
6.1	Diaphragm rupture simulations	127
6.1.1	The ANSYS finite element method	127
6.1.2	Results and discussions	130
6.2	Shock wave generation simulations	133
6.2.1	Star-CCM+ computational fluid dynamics simulations	133
6.2.2	Results and discussions	140
6.3	Conclusions	142
7	Conclusions	144
7.1	Summary of Thesis	144
7.2	Future work	147
	Bibliography	158
	Appendices	159
A	Lengths of Shock Tube Components	160

B	Matlab code for processing and plotting data from pressure sensors	161
C	Aluminium Foil in Simulation	166
D	Permissions for Reproduction of Images	167

List of Figures

1.1	The TNT equivalence and safe standoff distances for common IEDs. Reproduced from [17].	29
2.1	Thermodynamics of shock front in the medium. The energy from the shock initiation allows the motion of the shock front.	35
2.2	One-dimensional shock wave propagates with velocity U_s from the shocked gas (s) into the ambient unshocked gas (0). Adapted from [19].	35
2.3	The reflection of a shock wave from: A (left) - a normal plane rigid wall, B (middle) - an oblique wall at regular angle, and C (right) - an oblique wall at angle greater than the threshold value. Adapted from [19][23].	38
2.4	The ideal blast wave and its parameters: the ambient pressure P_0 (usually atmospheric pressure), the arrival time at the point of observation t_0 , the peak overpressure ($P_0 + P_s$) followed by the positive phase over time duration t_+ with positive impulse I_+ , the minimum pressure ($P_0 - P_-$) of the negative phase over duration t_- with negative impulse I_-	39
2.5	Various explosion scenarios and their blast loadings: (A) free-air explosion, (B) air explosion, (C) surface explosion, (D) full vented explosion, and (E) fully confined explosion. Adapted from [22][27].	43

2.6	Schematic of a shock tube: (a) A typical shock from the high-pressure region to the low-pressure region initiated when the diaphragm burst suddenly. (b) The motion and evolution of the shock wave, rarefaction wave, reflected wave and the contact surface separating the driver and driven gas. (c) The pressure of gases in different regions inside the tube. (d) The temperature profile of the gases inside the shock tube. Reproduced from [32].	46
2.7	The theoretical prediction for the relationship between the output incident pressure (solid) and reflected pressure (dashed) with the charging pressure in a shock tube. The system is assumed to be at room temperature (293K) initially with the driven gas at atmospheric pressure (1 bar). The red and green curves are respectively for air and helium as driver gas.	47
2.8	Tensile forces on diaphragm in a shock tube	48
2.9	Boundary layer effect: (A) schematic of the development in a shock tube, (B) the drag between the flow fluid and the tube inner wall, and (C) turbulences from the boundary layer problem in a two dimensional flow. Adapted from [19][21][36].	50
2.10	Several types of water shock tube. Adapted from [38].	51
2.11	The shock tube schematics for the study of aluminium 3003 alloy. Reproduced from [39].	52
2.12	Shock tube in studies of ballistic protective vests: (A) schematic of shock tube and torso surrogate set-up, and typical behaviour behind vest responses for low (B) and high (C) blast severity. Reproduced from [41]. . .	53
2.13	Schematic of shock tube with a fluid-filled receiver for <i>in vitro</i> blast testing. Reproduced from [43].	54
2.14	Comparisons between the typical pressure-time histories of experiments and finite-element models for (A) the open shock tube and (B) the fluid-filled shock receiver. Reproduced from [43].	54
3.1	The full schematic of the CBIS shock tube system. Adapted from [61]. . .	56

3.2	A: diaphragm assembly. B: arrangements for high-speed photography. C: a diaphragm with grids.	56
3.3	Left: stages of the diaphragm rupture (A). Right: the rupture of 50 μm Mylar [®] (C) and 100 μm aluminium (B) diaphragms with burst pressures of 4.2 bar and 5.3 bar respectively. Adapted from [61].	58
3.4	Left: the rupture of 40 μm aluminium in single (A) and double (B) arrangements. C: double- (blue) and single- (red) diaphragm systems, both at ~ 2.15 bar burst pressure. Reproduced from [61].	58
3.5	Burst pressure against thickness for Mylar [®] film (blue line) and annealed aluminium foil (red line). Reproduced from [61].	59
3.6	Comparison of pressure profiles for Mylar [®] diaphragm of different thicknesses	59
3.7	A: Overall pressure pulses for closed and open tube. B: detail of coincidence region (grey box). Adapted from [61].	60
3.8	An $x-t$ diagram produced for pressure waves generated with the bursting of a 25 μm aluminium diaphragm, in both open and closed configuration. The blue lines show the locations of the dynamic pressure sensors. The solid orange and dashed red lines show shock waves in closed and open configuration respectively, and green lines refer to rarefaction waves. $x = 0$ is chosen to be the diaphragm location, and $t = 0$ is the time when the diaphragm bursts.	61
3.9	Various sensor mountings: (A) Lateral sensor flange, (B) Outlet flange with head-on sensor mounting for closed shock tube configuration, (C) Head-on bull-nose sensor mount for open shock tube configuration, and (D) Head-on rod sensor mount for open shock tube configuration	62
3.10	Sensor 2 pressure traces from bursting of 50 μm Mylar [®] diaphragm: (A) raw (grey) and low-pass filtered (red) data; (B) raw (grey) and smoothed (red) data	63

3.11	The full schematic of Dytran [®] 2300V piezoelectric LIVM dynamic pressure sensor. Reproduced from [48].	64
3.12	The recessed diaphragm installation will impair the high frequency response and rise time of the sensor. Reproduced from [48].	65
3.13	A - Protruding mounting of sensor. B - Lateral pressure profiles at outlet with sensor mounted flushed or intruded to the inner wall of the ring sensor mount. 40 μm aluminium diaphragm was used for all cases.	66
3.14	Lateral pressure profiles at outlet with sensor mounted at different direction to the shock flow. 40 μm aluminium diaphragm was used for all cases. . .	66
3.15	Head-on pressure profiles at 4 cm from the outlet measured with the bull-nose mount and the rod sensor mount. 40 μm aluminium diaphragm was used for all cases. Full driving volume gives the long plateau trail after the shock.	68
3.16	The principle of schlieren photography: (A) Point light source, and (B) Extended light source. Adapted from [49].	69
3.17	Schlieren fields resulted from different locations of knife-edge cutting in from the same direction. Adapted from [50].	70
3.18	Schlieren photos of turbulent gas jet restuled from different percentage of knife-edge cutoff: (a) 0%, (b) 20%, (c) 40%, (d) 60%, (e) 80%, (f) 90%, and (h) 100%. Reproduced from [49].	71
3.19	Conventional mirror systems: (A) Z-type, and (B) Off-axes. Adapted from [49].	71
3.20	Off-axis Schlieren set-up produced images visualising the blast wave (A), vortex formation with a jet shear layer (B) and the Mach diamond for strong shock (C).	72
3.21	Schlieren snap shots of Mach 1.3 output blast and its features. The inter-frame time was 62.89 μs and exposure time was 2 μs	73
3.22	Schlieren snap shots of Mach 2.4 output blast and its features. The inter-frame time was 62.89 μs and exposure time was 2 μs	74

4.1	Standard shock tube outputs: big samples close to tube outlet (green), small samples (red), and samples lateral to the flow (blue)	77
4.2	Expected peak pressures of output blasts generated from various diaphragm burst pressures	78
4.3	Expected plateau pressures of output blasts generated from various diaphragm burst pressures	79
4.4	Expected shock impulse of output blasts generated from various diaphragm burst pressures	79
4.5	Relationship between the output lateral pressure and head-on pressure for open configuration	80
4.6	Output pressure magnitudes at various distances from the shock tube outlet	80
4.7	A - The effect of driving volume on the drop-off distance. B - Output impulses at various distances from the shock tube outlet.	81
4.8	Polyethylene inserts for reduction of the length of driver volume	82
4.9	The effects of changing driving volume on the blast output. The ‘dip’ feature in the pressure profiles is due to the double-diaphragm set-up as discussed in Section 3.1.	82
4.10	The relationships between the driving volume length with (A) the duration of output plateau pressure, and (B) the output impulse	83
4.11	Drawing of the polyethylene unit insertion	84
4.12	Drawing of the double-headed bolt ring for joining polyethylene inserts together	85
4.13	Drawing of the bolt ring for attachment of the insertion to the inlet flange	86
4.14	The schematic representations of the (A) open field blast, and (B) in-vehicle blast. Reproduced from [53].	87
4.15	Example 1 - Axial output from the bursting of 23 μm Mylar [®] diaphragm with 7% driver volume, and in the open tube configuration	88
4.16	Example 2 - Axial output from the bursting of 23 μm Mylar [®] diaphragm with full driver volume, and in the open tube configuration	88

4.17	Example 2 - Axial output from the bursting of 23 μm Mylar [®] diaphragm with full driver volume, and in the closed tube configuration	89
5.1	The schematic of the shock tube with a perforated sheet and extender tube inserted at the end. Sensor 1 and 2 are approximately 123 cm and 36 cm from the perforated sheet respectively.	93
5.2	Pressure profiles recorded by the second lateral sensor for perforated sheets with different percentage of open area: 22% (blue, lowest), 46% (green, second lowest), 68% (red, middle), 79% (margarita, second highest), and no perforated sheet or 100% (yellow, top). The diaphragms used were 50 μm Mylar [®] . They respective produced loadings of Mach 1.61, 1.78, and 2.15.	93
5.3	A - Pressure transmission ratio calculated using Equation 5.1 of different percentage of open areas, for all three types of diaphragms used in this investigation. B - Transmitted pressure versus incident pressure for different open areas.	94
5.4	Percentage of (A) impulse transmitted and (B) impulse reflected for different perforations	95
5.5	Schlieren snap shots of Mach 1.3 output blast behind a single perforated sheet of open area 22%, 46%, 68%, and 79%. The interframe time was 11.89 μs and exposure time was 2 μs . Extender tube was removed to give better view of the blast wave.	96
5.6	Enlarged schlieren images of transmitted blast features behind 46% perforated sheet as shown in Figure 5.5	96
5.7	A - An Acoustafom reticulated polyurethane foam sample. B - Scanning electron micrograph of an 79 ppi foam, taken by a JEOL JSM-5610LV variable pressure scanning electron microscope, field of view $\sim 10.5 \text{ mm}^2$. C - Acoustic absorbance measurements of reticulated polyurethane foam, taken with a Type 4206 B&K Absorption Tube and a Type 3560 Pulse Analyser. Reproduced from [65].	97

5.8	The schematic of the shock tube with a foam sample and extender tube. Sensor 1 and 3 are approximately 123 cm and 20 cm from the front and back of the foam respectively.	98
5.9	Pressure and impulse transmission versus foam density behind reticulated foam	99
5.10	Pressure and impulse transmission versus foam thickness	99
5.11	Scanning electron micrograph of a blasted 79 ppi foam, taken by the variable pressure scanning electron microscope JEOL JSM 5610 LV (0.5-35kV)	100
5.12	A - Perforated galvanised steel sheet of 22% and 46% open area. B - Reticulated polyurethane foam of 20 mm and 40 mm thickness. C - The sandwich structures combinations of perforated steel sheet and polyurethane foam. .	101
5.13	The schematic of the shock tube with extender tube and the sandwich structure sample (lateral view of nylon tube confinement and axial view). Reproduced from [66]. Sensor 1 and 3 are approximately 123 cm and 20 cm from the front and back of the sample respectively.	102
5.14	Pressure profiles of output blasts behind various mitigation structures for two pressure loadings of (A) Mach 2.15 and (B) Mach 2.60; grey traces collected from reference scenario of no mitigation structure. Reproduced from [66].	102
5.15	A - Percentages of pressure and impulse transmission behind different sandwich structures. B - Schlieren images of output behind a 22% + 20 mm + 22% sandwich panel (i) compared to no structure (ii and iii). Reproduced from [66].	103
5.16	Shock tube adaptor for tissue and cell testing: A - An EVOC sample in a Petri dish. B - The stainless steel adaptor. C - Installation of adaptor in the shock tube system. Adapted from [72].	105
5.17	Sensor mounting in "Petri Dish Housing" - separated parts and as fitted together	106

5.18	Pressure-time profiles from all four lateral sensors. The diaphragm used was 50 μm Mylar [®]	107
5.19	Pressure-time profiles measured by the tertiary and quaternary sensors . .	108
5.20	Peak pressures at the “Petri Dish Housing” compared to blast pressure measured at sensor 3	109
5.21	Impulses at the “Petri Dish Housing” compared to blast pressure measured at sensor 3	109
5.22	Petri dish with 0.5-cm-high PDMS casting	110
5.23	Pressure profiles measured by sensor 3 and sensor 4 for the ‘raised-floor’ Petri dish	111
5.24	Peak pressures at the “Petri Dish Housing” compared to blast pressure measured at sensor 3 for the ‘raised-floor’ Petri dish	112
5.25	Impulses at the “Petri Dish Housing” compared to blast pressure measured at sensor 3 for the ‘raised-floor’ Petri dish	112
5.26	The design and set-up of the bio-compatible mesh for maintaining samples within the Petri dish	113
5.27	Example of pressure-time profiles measured by sensor 4 in a ‘raised-floor’ Petri dish, for with and without the mesh	113
5.28	The averaged peak shock pressure, peak ramp pressure and shock impulse for two cases of with and without the mesh	114
5.29	A - The schematic of Petri dish modification for <i>in-vitro</i> testing of cell and its characterisation test set-up. B - Non-permeable membrane on Petridish. C - Gas-permeable membrane on Petridish.	116
5.30	The pressure profiles measured by sensor 4 in Petri dish for both types of membrane	116
5.31	Peak pressure and shock impulse at the Petri dish compared to blast measured at sensor 3, for both types of membrane	117
5.32	The membrane - perforated sheet combination and their deformation after testing with the side receiving the incoming blast facing up	118

5.33	The pressure profiles measured by sensor 2 downstream of the inserted structure	118
5.34	The percentage of peak shock pressure, peak ramp pressure and shock impulse compared to the case of 79% open area perforated sheet alone, for two types of membranes	119
5.35	The schematic of the limb platform as installed to the shock tube. The limb facing the blast is 5 cm away from the outlet. Reproduced from [74].	120
5.36	The schematic of the shock tube set-up for characterisation of the platform for limb trauma studies	120
5.37	Traces from sensor 2 and 3 (relative to ambient pressure) of four loading configurations	122
5.38	Traces from sensor 1 of the 6 bar - 7% (blue) and 6 bar - 100% (cyan) testing configurations show agreements in magnitude of peak pressures . .	123
5.39	Relationships of the peak and plateau pressures (relative to ambient pressure) between traces by sensor 2 and sensor 3	123
5.40	Improvement of platform for blast limb trauma, and application for traumatic brain injury studies	124
6.1	Flow chart of computational simulations using employing the finite element method	128
6.2	The cut-away section showing the geometry of computational simulation – The model only consists of a holder ring and a diaphragm. The contact surfaces between the holder and the diaphragm were designed to immitate the o-ring shape in order to reduce sharp edge effects. Diaphragm was made to be thicker at the rear to avoid slipping.	129
6.3	Mesh assigned on the design of the simulation – (A) The total view with an element size of 10^3 m. (B) The cut-away shows the mesh inside the diaphragm. Since the element size cannot go below the diaphragm thickness, the mesh is very coarse and the simulations treat the diaphragm as a thin surface.	130

6.4	Pressure load in computational simulations – To avoid using gas and reduce the complexity of the simulation at this stage, a sinusoidal increasing pressure was applied to one side of the diaphragm.	130
6.5	The diaphragm breakage simulations created with ANSYS program using finite element method – top: 14 bar burst pressure, bottom: 50 bar burst pressure. The first figures in each series show the bulging stage. The second figures show the stage when the stress on the diaphragms reach their maximum just before rupture. The third figures show the points when cracks first appear in the diaphragm. Finally, the last figures show the complete breakage of the diaphragms.	131
6.6	Series of high-speed images of the rupture of 40 μm aluminium diaphragm in single-diaphragm (top) and double-diaphragm (bottom) setup. Colour photos show examples of recovered diaphragm after bursting for the two cases, where the single-diaphragm was opened into four petals and double-diaphragm had more cracks with fragments.	132
6.7	Flow chart for the workflow of the Star-CCM+ program	133
6.8	The construction of the simulated shock tube geometry	135
6.9	Parts and regions of the simulated shock tube	136
6.10	Meshing of the simulated shock tube	137
6.11	Initial conditions and post-processing set-up of the simulated shock tube .	140
6.12	Snapshots of the first 0.3 ms of the shock tube simulation with the time interval of 0.05 ms	141
6.13	Pressure traces from the 4 probe points of the simulation, compared with similar experimental result (black trace)	141
A.1	Lengths of shock tube components. The outer and inner radii of all parts are coherently 44 ± 0.1 cm and 5.9 ± 0.1 cm respectively.	160
D.1	Permission for reproduction of Figure 2.11	167
D.2	Permission for reproduction of Figure 2.12	168

List of Tables

1.1	The anatomical distribution of injuries from various conflicts. Adapted from [3][4][5][6][7][8].	26
3.1	Resonance frequency and rise time correspond to various recess length. Reproduced from [48].	65
5.1	Technical specification of perforated steel sheets used [63]	92
5.2	Pore distribution and porosity of foam samples used in this work	98
5.3	Amount of peak pressure mitigation behind different structures	104
5.4	Amount of impulse mitigation behind different structures	104
5.5	Summary of peak pressure, plateau pressure, shock impulse, and duration recorded by sensor 2 for four loading scenarios	122
5.6	Summary of peak pressure, plateau pressure, shock impulse, and duration recorded by sensor 3 for four loading scenarios	122
6.1	Boundary types of simulated shock tube regions	135
6.2	Mesh settings for the simulated shock tube	137
6.3	Comparison between computational results and experimental observations	142
C.1	Properties of aluminium foil used in simulation	166

Chapter 1

Introduction

1.1 Motivations and objectives

1.1.1 Overviews of blast injuries

The blast wave is an outcome of explosions. Even though blast waves only last for few milliseconds, they can cause severe damage to surrounding objects, including human bodies. Blast injuries are very complex, often with multiple types of injuries occurring simultaneously. The injury pathologies are very complicated and not well-understood. The study of blast injuries was started as early as the Balkan war in 1914 by the Swiss scientist Franchino Rusca who noticed that some soldiers were killed from an explosion without any external injuries. He later ascribed the cause to pulmonary embolism. Blast injury studies were the cause to pulmonary embolism. Blast injury studies were continued in World War I (WWI), but not in great depth and the effect was mainly believed to be damage to the nervous system due to prolonged exposure to blasts. Only in World War II (WWII), with significantly high amount of casualties from bombing raids, more effort was concentrated on researching the effects of blast waves on the human bodies by different countries such as Germany, USA (the Atomic Energy Commission, then Lovelace Foundation on casualty and risk criteria), Sweden (on physiological and biochemical alterations), England (the British Chemical Defense Research Establishment on blunt trauma and protective clothing).[1] Ever since, progress has been made to deepen current understanding

of both the blast physics and the pathology of blast injuries.

In modern combat with the increasing use of IEDs, the injury profiles are very different from conventional weapons, and also less well characterised.[2] Studies into blast injury from recent conflicts have analysed injury patterns with regards to wounding mechanisms, anatomical regions, and diagnosis classifications. Ramasamy *et al.* [3] reviewed injury patterns of 104 casualties from 60 different incidents in Operation TELIC (Iraq, 2006), of which 20.2% were killed either at the scene or died in hospital. The study showed IEDs were the main cause of injury (50.6%), and also responsible for 51% of fatalities. Of these casualties, open wounds were the most common type (63.7%), followed by fractures (16.3%), with 67.8% occurring to the extremities and 21% to head/face/neck region. This trend in the anatomical injury distribution also agrees with studies of other conflicts as shown in Table 1.1. Another factor that affects the injury pattern is whether the victim was dismounted (on foot) or mounted in a vehicle. Singleton *et al.* [2] studied 121 fatalities caused by blast effects from IEDs in Afghanistan between 2007 and 2010, of which 42 (34.7%) were mounted and 79 (65.3%) dismounted. They reported that for the dismounted cases, the main causes were injuries to extremities and junctional haemorrhage; while for mounted fatalities, it was severe head injuries. They also found that majority of the mounted casualties, 78.6%, experienced blast lung injuries whereas this number was 31.6% for the dismounted ones.

Table 1.1: The anatomical distribution of injuries from various conflicts. Adapted from [3][4][5][6][7][8].

	Madrid 2004	VN 1964- 1972	Oman 1972- 1973	N. Ire- land 1972- 1974	GW1, Iraq 1990	OIF, Iraq 2003	TELIC, Iraq 2006	Iraq 2006	Iraq & AFG 2001- 2005	Gulf, Iraq 2003	Israel 2000- 2002
Head	9.6							24.5	8	16.5	>53.7
Neck		20.6	18.2	13.2	23.9	18.5	21	28.3	3		4.8
Face	56.8							35.8	10	NA	NA
Chest	38.9										
Back	NA	8.8	25.3	16.6	5.8	9.5	6.3	28.3	6	12.7	12.6
Abdomen	5.5	1.7	NA	8.4	1.9	1.5	4.4	9.4	11	2.5	NA
Upper extr.		27.2			30.3	33.9	29.8	86.8			
Lower extr.	13.9	40.9	55.5	61.8	37.4	34.6	38	81.1	54	81	38.8
Pelvis/Others	NA	0.8	1	NA	0.6	2	0.5	13.2	NA	NA	16.7

VN: Vietnam; GW1: Gulf war 1; OIF: Operation Iraqi Freedom; TELIC: Operation Telic; AFG: Afghanistan.

The type of blast injury inflicted is influenced by the blast loading (peak overpressure, impulse, duration, loading profile, etc.) and the condition of the target (location from the explosion, body mass, protective shielding, exposed body region, etc.). There are four main classes of blast injuries [9][10]:

- Primary blast injuries (barotraumas) occur when a blast wave reaches bodies composed of different densities (e.g. organs and tissues) and accelerates them at different rates, inducing displacements, stress and shear waves.
- Secondary injuries, also called ballistic traumas, are caused via impact of objects debris put in motion by blast (e.g. flying fragments or collapsing structures).
- Tertiary injuries are the result of victims being blown into hard objects by the blast.
- Quaternary injuries are those associated with burns, toxic gases, or environmental contaminations.
- Some medical authors ascribe a “quinary” injuries which are composed of hyperinflammatory behaviours (sweating, hyperpyrexia, low central venous pressure, and positive fluid balance) in the patients. A possible cause is suggested to be unconventional ingredients used during manufacturing explosives.[11]

Body parts such as lungs, bowel and middle ear are the most vulnerable to primary blast injuries because of their air content. As air is more compressible than liquid, different components of air-filled organs are accelerated differently by the blast wave, resulting in serious distortions and tearings. The tympanic membrane perforation is the most common primary blast injury, which can occur with a pressure as low as 0.3 bar relative to the ambience.[12] After the Battles of Europe (WWII), 52% of 292 people surviving from explosions had tympanic membrane rupture [13]; Roth *et al.* [14] reported that 74% of 147 Israeli soldiers experienced sensorineural or mixed hearing loss in their study of the period between 1967 and 1986; Breeze *et al.* [15] found abnormal audiography results from 53% of the 1-13% British soldiers in Iraq and Afghanistan between 2006 and 2009 who actually received the test. These injuries usually heal spontaneously, but

some can result in permanent hearing loss. On the other hand, the pulmonary injury is the most fatal kind which can cause disruption, hemorrhage, contusion and swelling to the lungs.[12] It can be a delayed effect with no indicative makers, and its pathology is not well characterised. There are other wound types of the primary blast injury such as to the eyes (globe rupture, serous retinitis, hyphema) and the central nervous system (blast-induced concussion).[10][12]

The effects of secondary and tertiary blast injuries depend on the projection speed, the nature of the contact, and the proximity of the victim to the explosion source. Those are close to the site and with small body mass (especially children) are vulnerable to these injuries. The injuries can be penetrating or blunt wounds, crushings, traumatic amputations, lacerations, etc.. The brain in particular is vulnerable to these secondary and tertiary blast injuries (concussions and contusions to the tissues).[10][12]

In addition, post-traumatic complications are also significant issues which are not very well understood. They include heterotopic ossification (HO), neurotrauma, stress disorder, recurrent infections, etc. The mechanism of primary blast injuries can be an important factor to HO.[16]

1.1.2 Improvised explosive devices

In recent decades, damage from explosions has become more significant as improvised explosive devices (IEDs) have become more common. These devices can be ‘homemade’ with simple components such as backpacks, pressure cookers, cell phones, etc.. The threat is enhanced by the inclusion of sharp objects like nails, glass or metal fragments. They can come in many forms from simple pipe bombs, suicide belts to more sophisticated devices, and can be delivered in person (suicide vests, suitcase bombs, small packages) or vehicles (cargo vans, trucks). IEDs can pose great risks to both military personnel (Iraq and Afghanistan war) as well as civilians and civil infrastructure (1995 Oklahoma City bombing, 1996 Atlanta Olympic Park bombing, 2004 Madrid train attacks, 2005 London bombings). The TNT equivalence of various common IEDs were published by the US National Ground Intelligence Centre in 2005 (figure 1.1), giving an information that can

1.1. MOTIVATIONS AND OBJECTIVES

be combined with the scale equations to estimate some primary effects of these devices, which can then be used to roughly relate the study scale in laboratory to more realistic situations.

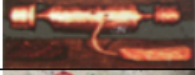
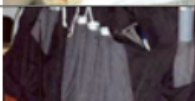
	Threat Description		Explosives Mass ¹ (TNT equivalent)	Building Evacuation Distance ²	Outdoor Evacuation Distance ³
High Explosives (TNT Equivalent)		Pipe Bomb	5 lbs 2.3 kg	70 ft 21 m	850 ft 259 m
		Suicide Belt	10 lbs 4.5 kg	90 ft 27 m	1,080 ft 330 m
		Suicide Vest	20 lbs 9 kg	110 ft 34 m	1,360 ft 415 m
		Briefcase/Suitcase Bomb	50 lbs 23 kg	150 ft 46 m	1,850 ft 564 m
		Compact Sedan	500 lbs 227 kg	320 ft 98 m	1,500 ft 457 m
		Sedan	1,000 lbs 454 kg	400 ft 122 m	1,750 ft 534 m
		Passenger/Cargo Van	4,000 lbs 1,814 kg	640 ft 195 m	2,750 ft 838 m
		Small Moving Van/ Delivery Truck	10,000 lbs 4,536 kg	860 ft 263 m	3,750 ft 1,143 m
		Moving Van/Water Truck	30,000 lbs 13,608 kg	1,240 ft 375 m	6,500 ft 1,982 m
		Semitrailer	60,000 lbs 27,216 kg	1,570 ft 475 m	7,000 ft 2,134 m
	Threat Description		LPG Mass/Volume ¹	Fireball Diameter ⁴	Safe Distance ⁵
Liquefied Petroleum Gas (LPG - Butane or Propane)		Small LPG Tank	20 lbs/5 gal 9 kg/19 l	40 ft 12 m	160 ft 48 m
		Large LPG Tank	100 lbs/25 gal 45 kg/95 l	69 ft 21 m	276 ft 84 m
		Commercial/Residential LPG Tank	2,000 lbs/500 gal 907 kg/1,893 l	184 ft 56 m	736 ft 224 m
		Small LPG Truck	8,000 lbs/2,000 gal 3,630 kg/7,570 l	292 ft 89 m	1,168 ft 356 m
		Semitanker LPG	40,000 lbs/10,000 gal 18,144 kg/37,850 l	499 ft 152 m	1,996 ft 608 m

Figure 1.1: The TNT equivalence and safe standoff distances for common IEDs. Reproduced from [17].

1.1.3 Objectives of the project

With the increasing use of IEDs in both military and civilian situations, injuries and damages by blast effects have become a growing part of modern research. Blast injuries to human are very complex, with multiple types of injuries happening at once. It is important to be able to re-create the blast waves, isolating their different time-dependent effects (e.g. initial accelerations by shock waves, ballistic impacts, etc.). The shock tube is a versatile apparatus that can generate these elements of blasts in laboratory environment. It allows studies of blast effects on biological samples (e.g. osteoblast and Schwann cell cultures), and blast mitigating properties of different materials and structures (e.g. perforated sheets, granular beds, reticulated foams). In many studies of blast injuries, the shock tube is often treated as a ‘black-box’ with many details on operating conditions omitted. Without these precise testing conditions, it is difficult to reproduce their study results.

In response, the main aims of this project are:

- to characterise a shock tube system such as its different driving conditions and their corresponding outputs to enable comparisons across different studies and reproducing of results;
- to develop and characterise various mounting platforms for studying the blast effects on biological specimens ranging from cell culture to whole animal model;
- to investigate interactions between blast waves and various structures to identify their blast attenuating properties.

1.2 Thesis structure

Chapter 2 presents the basic physics of shock waves and blast waves, including blast loadings in different explosion scenarios. The chapter also describes the principles of the shock tube, its applications, and existing studies.

In chapter 3, a shock tube system is presented with its operating features and main diagnostics. The outputs of this system are described in chapter 4 where methods for

tailoring the generated blast waves to different scenarios are also discussed.

Chapter 5 gives some examples for studies of interactions between blast waves and mitigating structures. It also presents examples of platforms for blast injury studies on biological samples.

Chapter 6 highlights the development of computational simulations for blast generations, including the finite element analysis and the computational fluid dynamics method.

1.3 Statement of originality

I hereby declare that, to the best of my knowledge, this submission is my own work and it has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and all the assistance from others in the project's design and conception or in style, presentation and linguistic expression have been properly acknowledged.

1.4 Copyright Declaration

The copyright of this thesis rests with the author and is made available under a Creative Commons Attribution Non-Commercial No Derivatives license. Researchers are free to copy, distribute or transmit the thesis on the condition that they attribute it, that they do not use it for commercial purposes and that they do not alter, transform or build upon it. For any reuse or redistribution, researchers must make clear to others the license terms of this work.

1.5 Publications

- C Bo, N Newell, T-T N Nguyen, B Butler, J Wilgeroth, J Balzer, S D Masouros, A M J Bull, A T M Phillips, A P Jardine, A Williams, S Rankin, K A Brown, and W G Proud, Understanding the Effects of Blast on Biological Systems, in *Proceedings of the 16th Seminar on New Trends in Research of Energetic Materials*,

Czech Republic, 2013, 52-65.

- T-T N Nguyen, J M Wilgeroth, and W G Proud, Controlling Blast Wave Generation in a Shock Tube for Biological Applications, *Journal of Physics: Conference Series* **500**, 142025, 2014.
- J M Wilgeroth, T-T N Nguyen, and W G Proud, Interaction Between Blast Wave and Reticulated Foam: Assessing the Potential for Auditory Protection Systems, *Journal of Physics: Conference Series* **500**, 142005, 2014.
- R J Curry, B Butler, T-T N Nguyen, A P Jardine, W G Proud, and K A Brown, A Shock Tube Adaptor for Blast Studies of Ex Vivo Tissue Models, in *Proceedings of the 4th International Conference on Impact Loading of Lightweight Structures, South Africa, 2014*.
- T-T N Nguyen, T Davey, and W G Proud, Percolation of Gas and Attenuation of Shock Waves through Granular Beds and Perforated Sheets, in *Proceedings of the 17th Seminar on New Trends in Research of Energetic Materials, Czech Republic, 2014, 52-65*.
- T Davey, T-T N Nguyen and W G Proud, Modification of Shock Tube Using Granular Beds, in *Proceedings of the 16th International Conferennce on Experimental Mechanis, United Kingdom, 2014*.
- W G Proud, T-T N Nguyen, C Bo, B J Butler, R L Boddy, A Williams, A Masouros, and K A Brown, The High-Strain Rate Loading of Structural Biological Materials, in *Metallurgical and Materials Transactions A 2015:2975, Springer US, 14th July 2015*.
- T-T N Nguyen, and W G Proud, An Investigation of A Reticulated Foam Perforated Steel Sheet Combination As A Blast Mitigation Structure, in *Proceedings of the 19th Biennial APS Conference on Shock Compression of Condensed Matter, 2015*, manuscript accepted.

- H Badham, M Chalmers, T-T N Nguyen, and W G Proud, The Effect on the Propagation of Blast Pulses of Dry and Dampened Granular Media, in *Proceedings of the 19th Biennial APS Conference on Shock Compression of Condensed Matter, 2015*, manuscript accepted.
- B Butler, D Sory, T-T N Nguyen, R Curry, J Clasper, W Proud, A Williams, and K Brown, Characterization of Focal Muscle Compression Under Impact Loading, in *Proceedings of the 19th Biennial APS Conference on Shock Compression of Condensed Matter, 2015*, manuscript submitted.
- T Eftaxiopoulou, A Barnett-Vanes, H Arora, W Macdonald, T-T N Nguyen, M Itadani, A E Sharrock, D Britzman, W G Proud, A M J Bull, and S M Rankin, Prolonged but not short duration blast waves elicit acute inflammation in a rodent model of primary blast limb trauma, in *The Journal of Trauma and Acute Care Surgery, 2015*, manuscript accepted.
- K A Brown, B J Butler, D R Sory, T-T N Nguyen, A Williams, and W G Proud, Understanding in vivo Strain-Rate Behaviour of Biological Materials, manuscript in preparation.
- R Curry, T-T N Nguyen, B Butler, A W Tucker, A Williams, W G Proud, and K A Brown, A Shock Tube Adaptor for Blast Studies of Biological Cultures, manuscript in preparation.

Chapter 2

Background Theory

2.1 Shock waves and blasts

2.1.1 The theory of shock wave in gas

Shock waves are probably most familiar to us in the form produced by explosions and lightnings. Unlike sound waves which are the result of propagation of small compressions, shock waves are rapid, large-amplitude pressure increases and propagate at supersonic speeds [18]. Shock waves can be represented by propagations of shock fronts. A shock front is a discontinuous change of the thermodynamic state (e.g. temperature, pressure, density) of the medium. A complex shock wave can be represented by a series of shock waves. For acoustic waves, small change in pressure propagate with the constant speed of sound in the medium. For shock waves, this propagation velocity is always greater than the speed of sound of the ambient medium.

Behind the shock front, the density and pressure in the media is much higher than the initial ambient conditions (figure 2.1). The energy deposited in the media can also elevate the temperature, with important results. The temperature of a strong shock can reach to several thousand Kelvin, here dissociation, chemical reaction, electrical excitation, and ionisation can occur. The medium can even transform into a plasma.[19]

A higher pressure gives a higher speed of shock propagation. The shock strength is conventionally defined as the Mach number M :

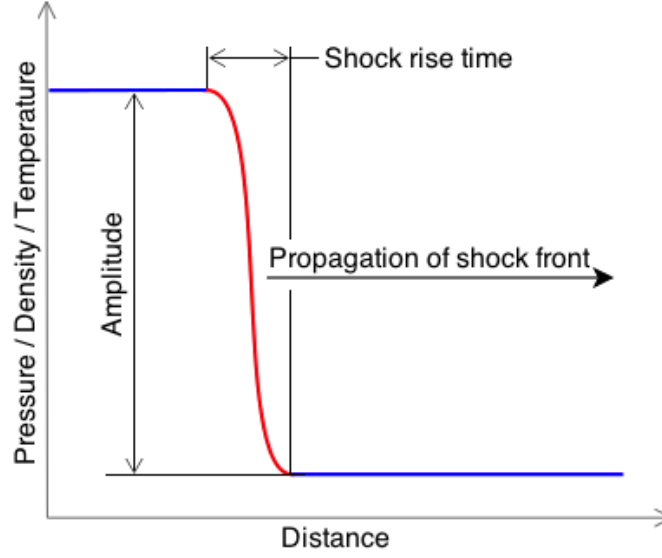


Figure 2.1: Thermodynamics of shock front in the medium. The energy from the shock initiation allows the motion of the shock front.

$$M = \frac{U_s}{a_0}, \quad (2.1)$$

where U_s and a_0 are the shock speed and the sound speed in the ambient medium respectively. As these two speeds vary with the composition of the medium and the local thermodynamics conditions, most importantly pressure and temperature, the shock strength also depends on these factors.[19]

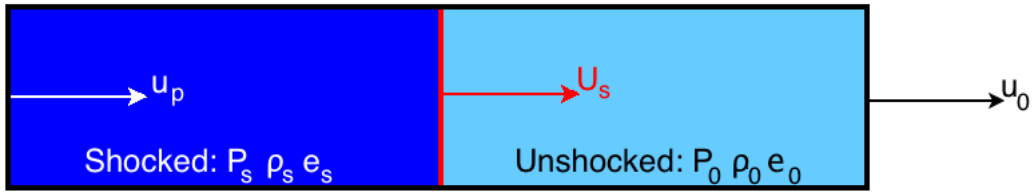


Figure 2.2: One-dimensional shock wave propagates with velocity U_s from the shocked gas (s) into the ambient unshocked gas (0). Adapted from [19].

In the 19th century, the modern theory of shock waves was fully established by William Rankine and Pierre-Henri Hugoniot.[20] The Rankine-Hugoniot equations describing the jump conditions (the changes in variables of state across a shock front), for a one-dimensional shock wave (figure 2.2), can be written as:

Conservation of mass:

$$\rho_s (U_s - u_p) = \rho_0 (U_s - u_0) \quad (2.2)$$

Conservation of momentum:

$$P_s + \rho_s (U_s - u_p)^2 = P_0 + \rho_0 (U_s - u_0)^2 \quad (2.3)$$

Conservation of energy:

$$H_s + \frac{1}{2} (U_s - u_p)^2 = H_0 + \frac{1}{2} (U_s - u_0)^2 \quad (2.4)$$

Here, ρ , P , and H are the density, pressure and specific enthalpy respectively. The shocked and unshocked states are denoted as 's' and '0'. The shock front propagates with velocity U_s ; particles behind in the shocked state and in front in the unshocked state have velocity of u_p and u_0 respectively. Quite often, the unshocked state is the ground state where its particle velocity u_0 is zero. In this theory, body forces (e.g. gravity, centrifugal forces, electromagnetic forces), phase changes and heat exchanges are assumed negligible.[19][21]

The specific enthalpy is the total energy per unit mass of a thermodynamics system including the internal energy E :

$$H = E + RT, \quad (2.5)$$

where R is the gas constant per unit mass and T is the temperature of the gas. For ideal gases where the specific heat at constant pressure c_p and at constant volume c_v are constant and not dependent on temperature, the specific enthalpy can be written as:

$$H = \left(\frac{\gamma}{\gamma - 1} \right) RT = \left(\frac{\gamma}{\gamma - 1} \right) \frac{P}{\rho}, \quad (2.6)$$

where γ is the adiabatic coefficient defined as:

$$\gamma = \frac{c_p}{c_v}. \quad (2.7)$$

This constant specific heat ratio is 5/3 for ideal monatomic gas, 7/3 for ideal diatomic gas and 7/5 for air at room temperature.[21]

Due to different energy modes (translation, rotation, and vibration), for real poly-

atomic gases, specific heat increases with temperature while the adiabatic coefficient decreases. As a result, the temperature of shock waves in real gases is considerably lower than in ideal gases. Given other factors such as dissociation of molecules and ionisation of atoms, the temperature profile of a shock wave may fluctuate with shock speeds. Similar fluctuations occur for the density profile, however, in this case, the density of shocked gases is much higher than the ideal value. This is because density is in general inversely proportional to temperature, and in addition, dissociations and ionisations also lower the average molecular weight.

On contrary, as the shocked pressure mainly depends on the initial gas density and the shock speed (equation 2.3), it has the same behaviour as the ideal shocked pressure, that is a uniform parabolic increase with shock speed, but with a slightly higher magnitude due to the small effect of real gas.[21] For this project, shock pressure is the most important parameter, hence, the theory of shock waves in ideal gases is sufficient for understanding phenomena and predicting outputs of the shock tube.

As with other waves, shock waves exhibit phenomena such as constructive interference, destructive interference and reflection. For this project, it is essential to understand the reflection of shock waves against a plane rigid wall (figure 2.3) since this interaction represents the sealed shock tube as well as in many blast scenarios which are discussed in section 2.1.2.

If the wall is rigid and normal to the flow, the boundary condition dictates that gas immediately adjacent to the wall (regions 1 and 3 in figure 2.3a) must stay stationary both before and after the reflection. Since gas particles behind the incoming shock (region 1, figure 2.3a) are accelerated in the same direction as the shock, they also move towards the wall. As a result, the reflected wave must be strong enough to cause the velocities of these particles to decrease to zero, thus it is a shock wave as well. This also indicates the important point that it is a change in velocity that is associated with a pressure change, higher pressure does not imply a higher particle velocity.

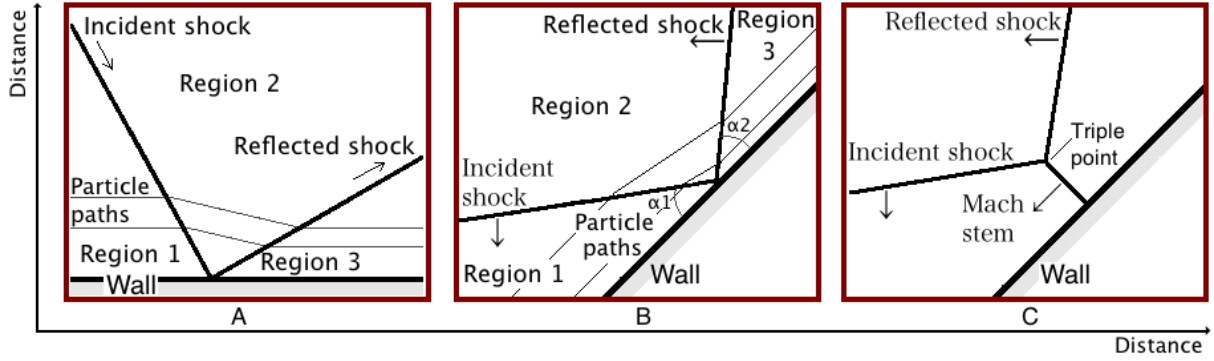


Figure 2.3: The reflection of a shock wave from: A (left) - a normal plane rigid wall, B (middle) - an oblique wall at regular angle, and C (right) - an oblique wall at angle greater than the threshold value. Adapted from [19][23].

In realistic situations, the reflected rigid wall can be oblique to the flow. For a simple oblique wall, the reflection process is essentially the same as the normal wall as discussed above. In this case, the reflecting angle α_2 is very similar to the incoming angle α_1 (figure 2.3b). However, if the incoming angle α_1 surpasses a threshold value ($\sim 40^\circ$ for strong shocks and higher for weak shocks), this simple model is no longer valid. In this scenario, the point of reflection is no longer at the wall (figure 2.3c); this is known as Mach reflection. There is only a single shock connecting the reflected wave with the wall, which is called the Mach stem and is usually normal to the wall or at a slight angle. The triple point is the intersection between the incident, reflected, and Mach waves.

2.1.2 Blast waves and explosion scenarios

The blast wave is a well-known example of a shock wave, which is generated from an explosion (such as denotations of high explosives, ruptures of high-pressure containers, or nuclear weapons) and propagates in a compressible fluid medium (such as air, or water). The simplest form of the blast wave is the classical Friedlander waveform (figure 2.4) which is a good approximation to the free field explosion. In this case, detonation products from the occurrence of an explosion are pushed outwards into the ambient unshocked environment, compressing the surrounding air and resulting in a pressure wave (blast front), hence, a steep rise in the pressure profile. In the case of detonations, this shock pressure P_s can be 10s of GPa inside the detonation products, but quickly decreases down

to MPa scale outside the charge due to the impedance mismatch between the detonation gases and the ambient air surrounding. If this shock front is captured and reflected by a large and rigid surface at a normal angle, peak pressure of the reflected wave can be 2 to 8 times the initial incident pressure.[19] Simultaneously with the formation of the shock front, the gas behind it rapidly undergoes expansion resulting in a release wave moving backwards at an even higher speed than the shock front itself. This rarefaction wave dampens the shock front back to the ambient pressure P_0 , which is usually atmospheric pressure, over a time period t_+ . As the expansion continues, the pressure decays further into a negative phase and behaves like a ‘suction’ region, over the time period t_- . [9][21][22]

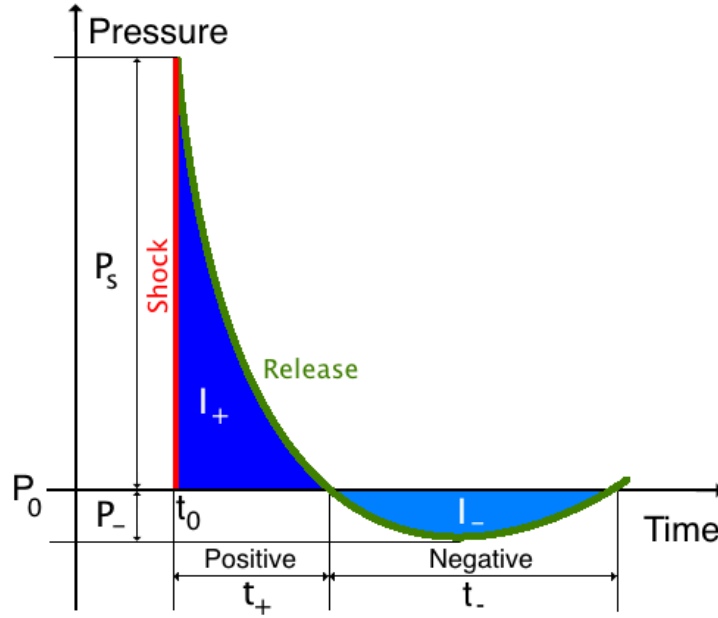


Figure 2.4: The ideal blast wave and its parameters: the ambient pressure P_0 (usually atmospheric pressure), the arrival time at the point of observation t_0 , the peak overpressure ($P_0 + P_s$) followed by the positive phase over time duration t_+ with positive impulse I_+ , the minimum pressure ($P_0 - P_-$) of the negative phase over duration t_- with negative impulse I_- .

The shape of the positive phase can be analytically described by the Friedlander equation [23]:

$$P(t) = P_0 + P_s \left(1 - \frac{t}{t_+}\right) e^{\left(-b \frac{t}{t_+}\right)}, \quad (2.8)$$

where b is a decay constant governing the rate of pressure drop.

The positive and negative impulses of the blast wave, which are the areas between the

curve and the line of ambient pressure value, can be calculated as [23]:

$$I_+ = \int_{t_0}^{t_0+t_+} [P(t) - P_0] dt \quad (2.9)$$

$$I_- = \int_{t_0+t_+}^{t_0+t_++t_-} [P_0 - P(t)] dt \quad (2.10)$$

The profiles of blast waves produced from detonations of high explosives depend greatly on the type and amount of explosive charge, the casing, the ambient environment, the observing location. Since the energy of the shock is distributed over increasing volume as it travels outward, the pressure amplitude reduces with distance. The effects of different explosive charges at different distances can be compared by using equations developed based on the cube root Hopkinson scaling.[23] The peak overpressure P_s at a standoff distance R from the centre of a charge can be estimated by [24]:

$$\frac{P_s}{P_0} = f(Z) = f\left[R/\left(\frac{WT_0}{P_0}\right)^{\frac{1}{3}}\right], \quad (2.11)$$

where P_0 and T_0 are the ambient air pressure and temperature respectively, Z is called the scaled distance, and W is the TNT equivalent weight of the explosive charge. The TNT equivalence is a common tool to scale the mass of any explosive to TNT. There are various ways to calculate this such as using the heat of detonation ratio, maximum pressure or impulse ratio, Berthelot method, or Cooper's method.[24][25][26] The TNT equivalence can introduce a typical error of 20-30% [26] so it is a useful concept that requires care in applications.

Experiments have been done to establish the curve relating the scaled distance Z and the overpressure ratio (P_s/P_0) [24]. Similar relationships have also been identified for the scaled times τ for both arrival time t_0 and positive duration t_+ of the blast wave. From these scale times, the actual timings of the blasts can be calculated as [24]:

$$t_{(0 \text{ or } +)} = \tau_{(0 \text{ or } +)} \times W^{\frac{1}{3}} \left[\left(\frac{P_{ref}}{P_0} \right)^{\frac{1}{3}} \left(\frac{T_{ref}}{T_0} \right)^{\frac{1}{6}} \right], \quad (2.12)$$

where P_{ref} and T_{ref} are the reference pressure and temperature in which these experimental values are obtained.

These scaling equations assume spherical charge, hence, neglecting the effects of the charge geometry and the casing. The UFC-3-340-2 report [25] has showed that the casing could be neglected, but the charge geometry is an important factor, especially for short distances. At a long enough distance, blast waves become homogeneous and behave like generated from a spherical charge. This project does not focus on the explosive charge so the scaling equations 2.11 and 2.12 are sufficient.

Another factor that governs the blast loading is the location of the explosive charge with respect to the ground and its surrounding environment. In this aspect, the loading can be categorised mainly as [22]:

- Unconfined explosions, or external explosions, are those occur in the open air such as empty fields, in which:
 - Free-air explosion (figure 2.5a) happens where there is no obstacles interfering with the produced blast wave. Hence, the blast effects on the target come from the incident wave only, without any amplification.
 - Air explosion (figure 2.5b) happens when the charge is at some height h_{oc} above the ground and at some distance away from the target, such that the incident wave first interacts with the ground surface, producing reflected wave. As the incident and reflected waves propagate forward, a Mach front (or Mach stem) is formed. The height of this Mach front increases with distance, showing by upward path of the triple point (dashed line). If the target is below the triple point, it will experience a plane pressure, where the time history of the loading is similar to the incident blast but of greater magnitude. If the target is above the triple point, it will experience both the incident, and then the reflected waves.
 - Surface explosion (figure 2.5c) happens when the charge is very close or on the ground surface. In this case, a single hemispherical blast wave is generated by

the merging of the incident wave and the reflected wave off the nearby ground.

The loading profile is, like the Mach wave, similar to the free-air case, but with larger blast parameters.

An explosive casing may be present, so the detonation of a spherical TNT charge with no casing is defined as the ideal explosion.

- Confined explosions, or internal explosions, occur in enclosed spaces. The blast profiles in these situations are very complex because of multiple reflections and interactions with different obstacles. There is also the build up of gas pressure adding to the loading, and the leakage of incident wave, reflected waves, and detonation gases depending on the amount of ventilation. The blast effects are dependent on the strength and geometry of the chamber, which is further classified into:
 - Fully vented explosion (figure 2.5d) happens in a cubicle chamber with at least one full side open to atmosphere, or in an urban space surrounded by buildings and structures. As the detonation products are fully vented, there is no gas pressure building up.
 - Partially confined explosion happens in a chamber with limited venting such as small doors or windows. There are complex blast loading with multiple reflections, and leakage similar to the fully vented scenario. However, as the space is confined sufficiently, there is also an increase in baseline gas pressure caused by the detonation products, which is eventually vented out to atmosphere.
 - Fully confined explosion (figure 2.5e) happens in a completely enclosed chamber with no ventilation. The blast loading is remarkably complex with a large sustained gas pressure build up. Pressure drop only occurs if the confining wall(s) of the chamber fails, or as heat conducts out through the walls.

Even though not of direct interest to this project, there are also other common scenarios such as underground explosions and underwater explosions:

- Underground explosions occur in underground cavities generating seismic shock waves transmitting in all directions through the soil. The shape of the underground

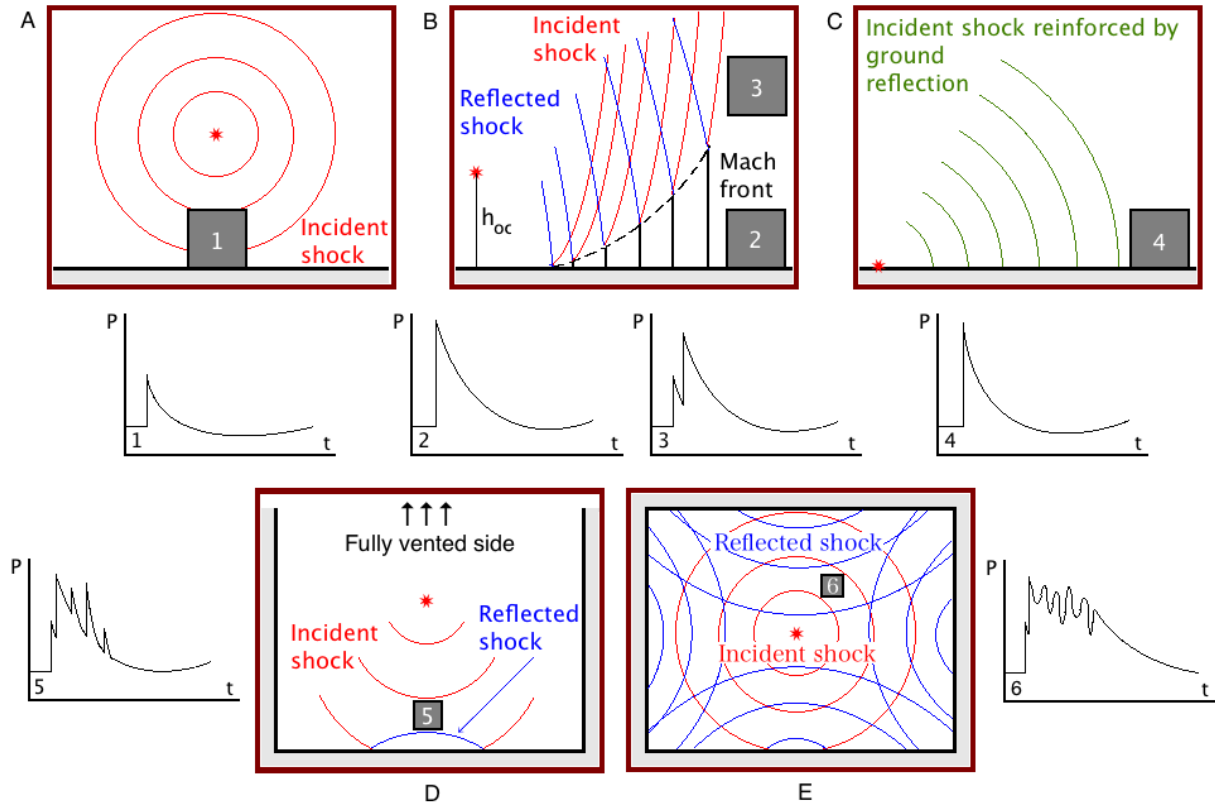


Figure 2.5: Various explosion scenarios and their blast loadings: (A) free-air explosion, (B) air explosion, (C) surface explosion, (D) full vented explosion, and (E) fully confined explosion. Adapted from [22][27].

explosion induced shock wave resembles the charge, approximating a planar wave, and attenuated by its interaction with the surrounding soil.[28]

- Underwater explosions occur in the water, which is considered incompressible. In this case, the detonation products are produced in the form of cavitation bubbles which expand and send out a shock wave. A series of weak pressure pulses are generated as the bubbles collapse and expand as they rise to the water surface. A typical underwater blast wave near the water surface is characterised by a peak overpressure which then decays and cut off by a tension wave from the reflection of the incident compression wave from the surface.[29]

2.2 Principles of the shock tube

2.2.1 The ideal gas description of the shock tube

The shock tube is a device able to generate well-defined pressure outputs of varying intensity and duration. Due to its versatility yet simple construction, shock tubes have been utilised in many fields of research as a tool to probe shock wave structures. The very first application of a shock tube was in the investigation of mine safety. Since then, shock tubes have been used in hydrodynamics studies of shock propagations, tests of aerodynamics and investigations of flows in jet engines, chemical kinetic measurements, heat transfer studies and plasma physics investigations, etc.[30]

The shock tube was first invented in 1899 by the Frenchman Pierre Vieille. It took ten years before the first theory on shock tube operation was published independently, by the Australian scientist Karl Kobes who was cited twenty years later by Hubert Schardin in Germany in a paper about the ignition of combustible gases in a broken pipe line. In early 1940s, in collaboration with the UK Safety in Mines Research Board and the US Bureau of Mines, Payman and Sheppard referenced the paper from Vielle, but instead used the shock tube performance theory by G. I. Taylor [31]. Around this time, a group in Princeton, USA, independently re-invented the shock tube and constructed a new set of theorems for its behaviour. Their design, a long pipe divided into two pressure sections with the higher one created by inducing a large pressure change using chemical explosions, exploding wires or electric discharges or by mechanically building up the pressure using a diaphragm, was published by Griffith and Bleakney [18]. The device was given the name shock tube, and has been used until today. Despite many re-inventions, the shock tube has such a wide range of applications that it is almost impossible to find a paper that discusses solely about the shock tube operation.[30]

The conventional pressure-build-up air-driven shock tube is employed for this project. This shock tube design consists of a high-pressure driver section and a low-pressure driven section which are separated by a diaphragm. Referring to figure 2.6a, the driver section is gradually pressurised to the diaphragm burst pressure P_4 , accompanied with a rise in

temperature to T_4 ; the shock is initiated when the diaphragm bursts. After the rupture of the diaphragm, a compression is driven into the low-pressure region (at an initial pressure P_1 and temperature T_1), which quickly develops into a shock front moving forward at the shock speed U_s . At the same time, a rarefaction (expansion) wave is also created, which travels back into the high-pressure region at the speed of sound in the gas. This wave is not a discontinuity in ambient pressure, but instead, it occurs as a smooth transition between the shock pressure and the input pressure (figure 2.6c). As the tail of the expansion wave travels much slower than the sound speed, the rarefaction wave spreads out with time (the fan shape in figure 2.6b). Figure 2.6b also illustrates the contact surface between the driver and driven gas, which follows the movement of the shock front. The region between this surface and the shock front is denoted 2 whereas the region between the contact surface and the rarefaction wave is denoted 3. In a closed shock tube where the driven section is sealed off, the shock front can reflect back giving rise to a reflected shock with pressure P_5 and temperature T_5 . [21][32]

For a weak shock with a temperature lower than the ionisation temperature (~ 6000 K), the ‘ideal’ description can be applied. This assumes that: (a) the driver and driven gasses are ideal, (b) the diaphragm bursts instantaneously and (c) there is no friction or radiative losses in the flow. Based on the jump conditions (Equations 2.1, 2.1, and 2.3), Gaydon and Hurle [21] presented arguments to relate the pressure, density and temperature gases of different region in the shock tube to the initial conditions of the driven section. For the region right behind the shock front:

$$\frac{P_2}{P_1} = \frac{2\gamma M^2 - (\gamma - 1)}{\gamma + 1}, \quad (2.13)$$

$$\frac{\rho_2}{\rho_1} = \frac{M^2 (\gamma + 1)}{(\gamma - 1) M^2 + 2}, \quad (2.14)$$

$$\frac{T_2}{T_1} = \frac{\left(\gamma M^2 - \frac{(\gamma-1)}{2}\right) \left(\frac{M^2(\gamma-1)}{2} + 1\right)}{\left(\frac{\gamma+1}{2}\right)^2 M^2}, \quad (2.15)$$

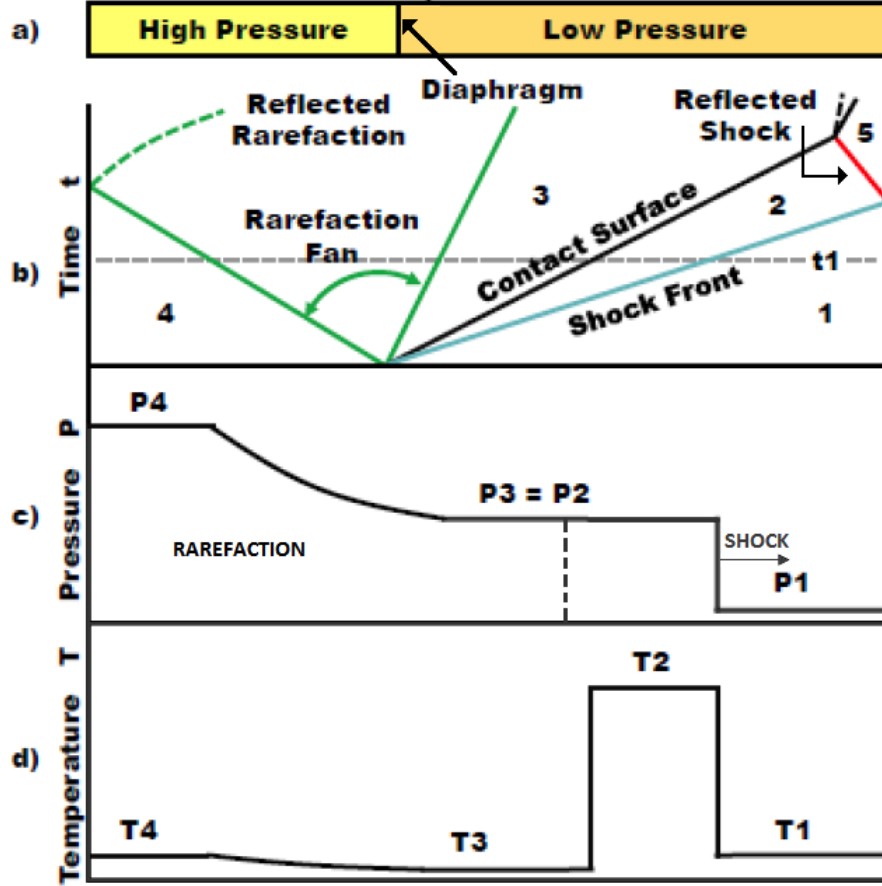


Figure 2.6: Schematic of a shock tube: (a) A typical shock from the high-pressure region to the low-pressure region initiated when the diaphragm burst suddenly. (b) The motion and evolution of the shock wave, rarefaction wave, reflected wave and the contact surface separating the driver and driven gas. (c) The pressure of gases in different regions inside the tube. (d) The temperature profile of the gases inside the shock tube. Reproduced from [32].

$$\frac{P_4}{P_1} = \frac{2\gamma_1 M^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \left[1 - \frac{(\gamma_4 - 1) a_1}{(\gamma_1 - 1) a_4} \left(M - \frac{1}{M} \right) \right]^{-\left(\frac{2\gamma_4}{\gamma_4 - 1} \right)}, \quad (2.16)$$

where γ_1 and γ_4 are the specific heat ratio for the driver and driven region respectively.[21][32]

For the region behind the reflected shock front, the pressure ratio and temperature ratio are [32]:

$$\frac{P_5}{P_1} = \left(\frac{2\gamma_1 M^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \right) \left(\frac{(3\gamma_1 - 1) M^2 - 2(\gamma_1 - 1)}{(\gamma_1 - 1) M^2 + 2} \right), \quad (2.17)$$

hence,

$$\frac{P_5}{P_2} = \frac{(3\gamma_1 - 1) M^2 - 2(\gamma_1 - 1)}{(\gamma_1 - 1) M^2 + 2}, \quad (2.18)$$

$$\frac{T_5}{T_1} = \frac{[2(\gamma_1 - 1)M^2 + 3 - \gamma_1][(3\gamma_1 - 1)M^2 - 2(\gamma_1 - 1)]}{(\gamma_1 - 1)^2 M^2}. \quad (2.19)$$

From these equations, the relationship between the driving pressure (diaphragm burst pressure) P_4 with the incident shock pressure P_2 , and the reflected shock pressure P_5 can be derived (figure 2.7). It needs to be emphasised that all equations in this section are under the assumptions of the ideal gas description, where the adiabatic coefficient γ is constant (e.g. 1.4 for air at room temperature). For a real gas, the specific heats and their ratio are dependent on temperature. While the shock wave has lower temperature and higher density, its pressure is roughly the same.

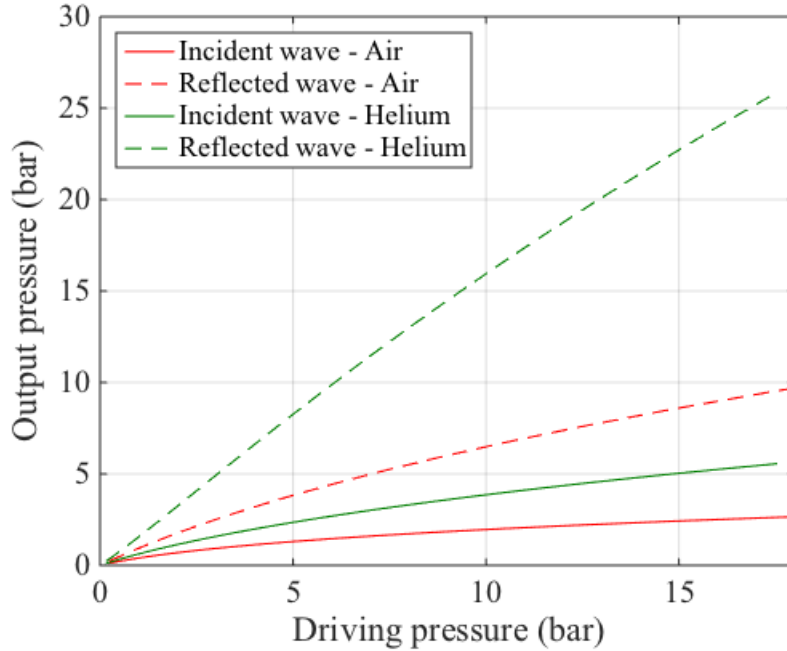


Figure 2.7: The theoretical prediction for the relationship between the output incident pressure (solid) and reflected pressure (dashed) with the charging pressure in a shock tube. The system is assumed to be at room temperature (293K) initially with the driven gas at atmospheric pressure (1 bar). The red and green curves are respectively for air and helium as driver gas.

2.2.2 Deviation from the ideal behaviour

In a shock tube, there are many factors that can make the behaviour of the shock wave depart from the ideal gas description such as non-ideal gas, thermodynamic periodic fluctuations, low initial pressure (less than 0.01 bar), radiative cooling, etc. The two strongest factors are due to the actual rupture process of the diaphragm and the viscosity

of the gaseous fluid.

The diaphragm does not rupture instantaneously but has a finite opening time. When a diaphragm is subjected to a build-up pressure greater than the yield strength of the material, it starts to distort (bulging). This distortion in conjunction with clamping of the diaphragm exerts tensile and shear forces on the surface of the diaphragm (figure 2.8). Once the ultimate strength of the material is reached, the diaphragm fractures. For a metal diaphragm in a shock tube of circular cross-section, the burst pressure is govern by [19]:

$$\frac{P_4}{P_1} = \frac{4d\sigma_{ts}}{r}, \quad (2.20)$$

where r and d are the radius and thickness of the diaphragm, and σ_{ts} is the ultimate tensile strength of the material.

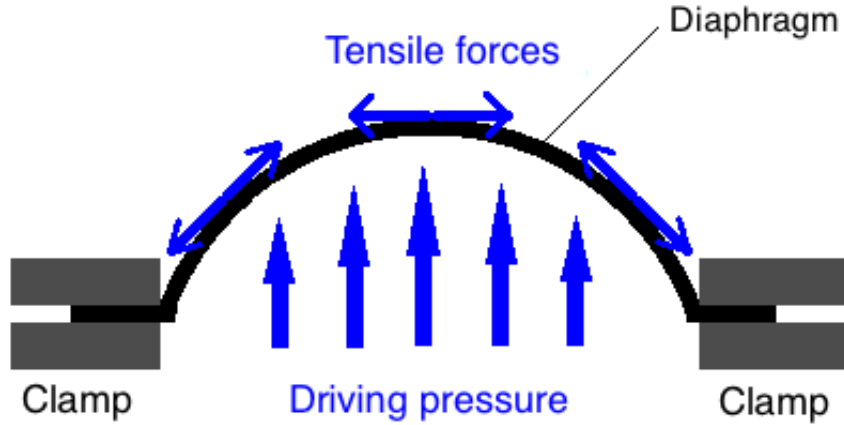


Figure 2.8: Tensile forces on diaphragm in a shock tube

The opening of the diaphragm is a mixture of fracture modes due to combined tension and shear, in which the stress triaxiality (ratio of hydrostatic and the von Mises effective stress) plays a significant role. At high triaxiality, void growth and internal necking are the dominating rupture mechanisms whereas for low triaxiality, internal shearing and simple shear deformation govern the process.[33] Rothkopf and Low [34] showed in their studies that low ductility materials such as aluminium behave more closely to the ideal model of instantaneous and uniform rupture with no prior deformation, where initial bulging is negligible. Ductile materials like copper and brass have considerable bulging

before tearing. In addition, the limit of bulging depends not only on the thickness of the diaphragm, but the applied pressure.

Studies by Campbell *et al.* [35] and Rothkopf and Low [34] demonstrated similar relations between aperture size and time. Results from both photomultiplier and photographic observations agreed on a slow initiation followed by a much more rapid process into full aperture. After about 20% opening, the aperture increases approximately linearly with time. At the end of the process, the opening rate decreases. The rate depends on the materials, shape (square or round) and size of the aperture. It was mentioned that larger amount of time was required for the first 5-10% opening of the 45-mm round and 54-mm square cases and the process in a round shock tube is slower than that in a square one. It also re-confirmed that copper takes more time to reach 10% of full aperture (750 μ s out of 1050 μ s) compared to aluminium (100 μ s out of 180 μ s).

The nature of the diaphragm bursting determines the amount of mixing of gas particles at the contact surface between the driver and driven sections, which affects the flow velocity, and hence, the shock strength. If the driver gas has higher capacity than the driven gas, the produced shock strength will be higher than predicted value. The diaphragm opening time, or the diaphragm complete removal time, critically governs the shock formation distance, especially for a strong shock. The shock formation distance is the distance required for the shock front to accelerate to a stable velocity, which is usually 4 diameters for a weak shock ($M < 1.7$) and 8-10 diameters for a strong shock. If for weak shocks and sufficiently long shock tube, the effects of ‘non-ideal’ diaphragm rupture eventually subside as the shock wave travels further down the tube. [19]

Another phenomenon that reduces the strength and affects the shape of the shock is the boundary layer effect (figure 2.9). This effect arises due to viscosity. The friction between the inner wall of the tube introduces a drag on the boundary between the flow and the wall; the greater this friction, the more convex the shape of the shock front. This drag also leads to the formation of a layer of gas along the tube wall where the flow velocity dropping to zero in a radially outward fashion. The thickness of this boundary layer is zero at the shock front and the rarefaction head, and non-zero in the shock wave

and contact surface in between as shown in figure 2.9A.

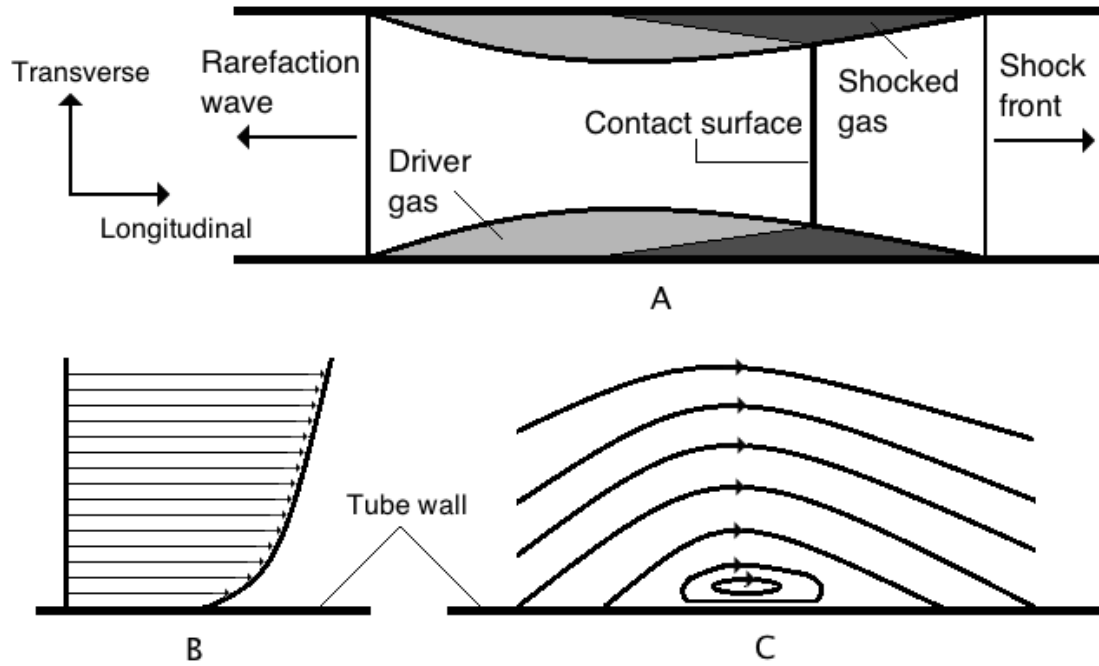


Figure 2.9: Boundary layer effect: (A) schematic of the development in a shock tube, (B) the drag between the flow fluid and the tube inner wall, and (C) turbulences from the boundary layer problem in a two dimensional flow. Adapted from [19][21][36].

The boundary layer effect gives rise to instabilities in the flow, resulting in turbulences at the layer between the tube and the fluid that may affect the reading of lateral pressure gauges installed in the shock tube. It also causes transfer of heat and momentum to the walls, which decelerates the flow. This creates weak pressure waves between the contact surface and the front that attenuates the shock front.[19]

2.3 Applications and existing studies of the shock tube

The shock tube has found a wide range of applications separate from its original use in mine safety studies. As a result, there are many designs of the shock tube to fit different purposes of use.

In 1977, Akamatsu highlighted in his paper [38] different designs of modified gas-liquid shock tubes. They were used for studies of hydrodynamics and liquid properties such as

the shock magnitude in air generated by water vapourisation and behaviours of cavitation bubbles under shock waves or near a solid boundary. Figure 2.10 shows the schematics of several water shock tube types. The modifications were made by filling the low-pressure section with liquids (type (1) and (2), where (2) allowed diaphragm to rupture completely) or by attaching a liquid section to the end of the shock tube (type (3) and (4)). Type (5) produced shock wave by colliding the accelerated water with the end of the shock tube, which also ejected a high-speed flow out of the nozzle.

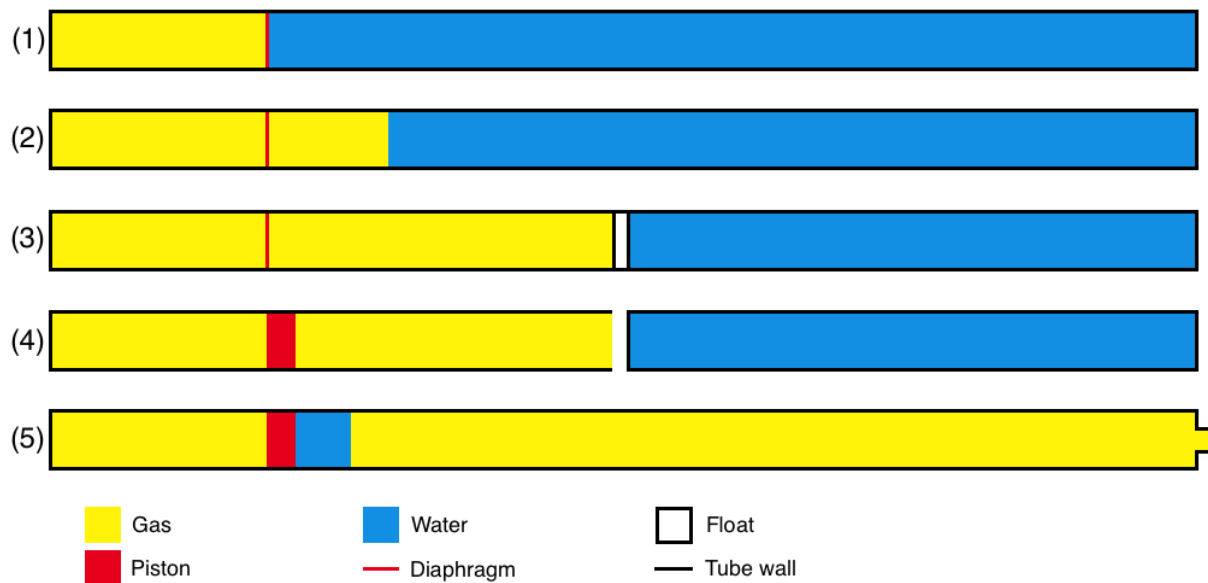


Figure 2.10: Several types of water shock tube. Adapted from [38].

Early 2013, Justusson *et al.* [39] reported the use of a shock tube in the study of the aluminium-manganese alloy - aluminium 3003 material. The author stated that the shock tube had advantages over the traditional bulge test using the split Hopkinson bar system in ranges of intermediate to high rate loadings. The shock tube described in this paper used helium as the driver gas. The aluminium 3003 plate sample was mounted at the end of the driven tube. An empty section was situated behind the specimen to allow the plate to bulge (Figure 2.11). The technique succeeded in accurately determining the yield stress ratio as a function of strain rate, which is in agreement with data from other sources.

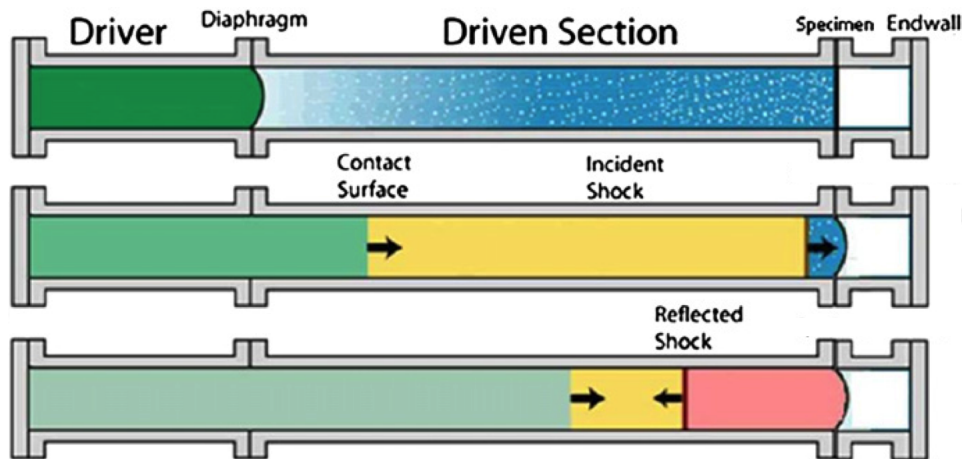


Figure 2.11: The shock tube schematics for the study of aluminium 3003 alloy. Reproduced from [39].

2.3.1 Shock tubes in biological studies

After World War II, shocks tubes have been employed in biomedical studies of blast injuries. In 1968, Bowen *et al.* (1968) [40] performed a series of air blast experiments of thirteen mammalian species and proposed that animals with smaller lung volume had lower blast tolerance. From his study, he assumed that a man could withstand up to a blast wave pressure of about 4.24 bar without incurring severe injury. Recently, Wood *et al.* (2012) [41] showed from his studies on the attenuation of the blast pressure that ballistic protective vests can significantly reduce the pulmonary damage caused by blast exposure (figure 2.12). The study also explained the severity of brain injury even when no pulmonary injuries occurred. Meanwhile, Shridharani *et al.* (2012) [42] studied the cause of blast neurotrauma by exposing unprotected heads of live, anaesthetised pigs to blasts from a compressed-gas shock tube. His investigation suggested that the blast exposure scaling method between animals developed by Bowen cannot be applied on brain trauma of pigs and ferrets. Further studies need to be carried out to verify this conclusion and develop better techniques.

Also in 2012, in their series of papers on blast neurotrauma modelling, Panzer *et al.* [43] and Effgen *et al.* [44] reported the use of a shock tube with a fluid-filled receiver (figure 2.13). This set-up allowed for the investigation of *in vitro* intracranial overpressure response for loading *in vitro* culture preparations. The receiver contained a polycarbonate

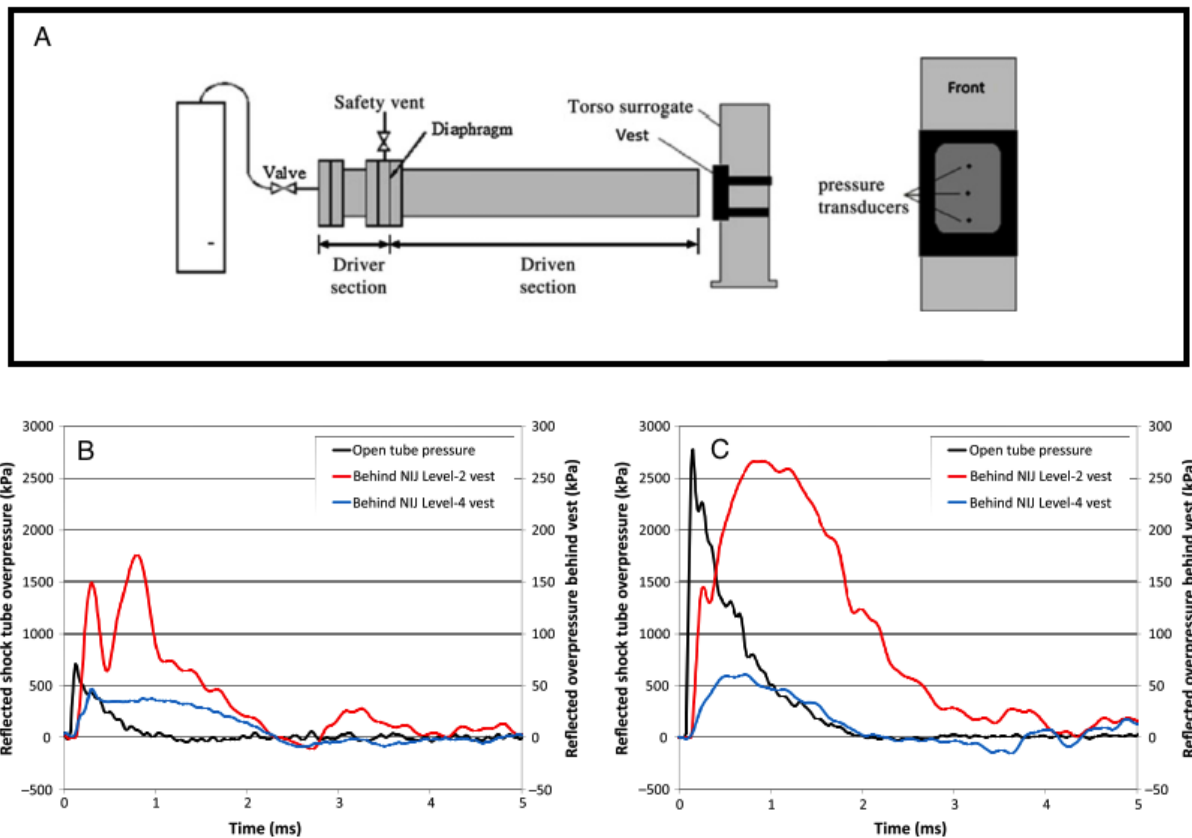


Figure 2.12: Shock tube in studies of ballistic protective vests: (A) schematic of shock tube and torso surrogate set-up, and typical behaviour behind vest responses for low (B) and high (C) blast severity. Reproduced from [41].

tube extending from the top of the reservoir and attached to a diverging HDPE nozzle. The top end of the polycarbonate tube was positioned flush on with the end of the open shock tube, centered on the vertical axis. PTFE (polytetrafluoroethylene) membrane was used between the test column and the reservoir to limit bulk fluid motion. Water at 37 °C was used to fill the receiver for *in vitro* blast characterisations.

When biological specimens are limited, it is more advantageous to use a computational approach. Stuhmiller *et al.* (1996) [45] developed a mathematical model for the generation of strong pressure waves within lungs. This model could predict to a high accuracy the possibility of pulmonary injury by blast waves from the measured or computed pressure profiles. This means less animal testing is required.

In the same paper by Panzer *et al.* mentioned above [43], finite element models of the open shock tube and the fluid-filled receiver were discussed. They were validated using the recorded experimental pressure time-histories without test samples for different

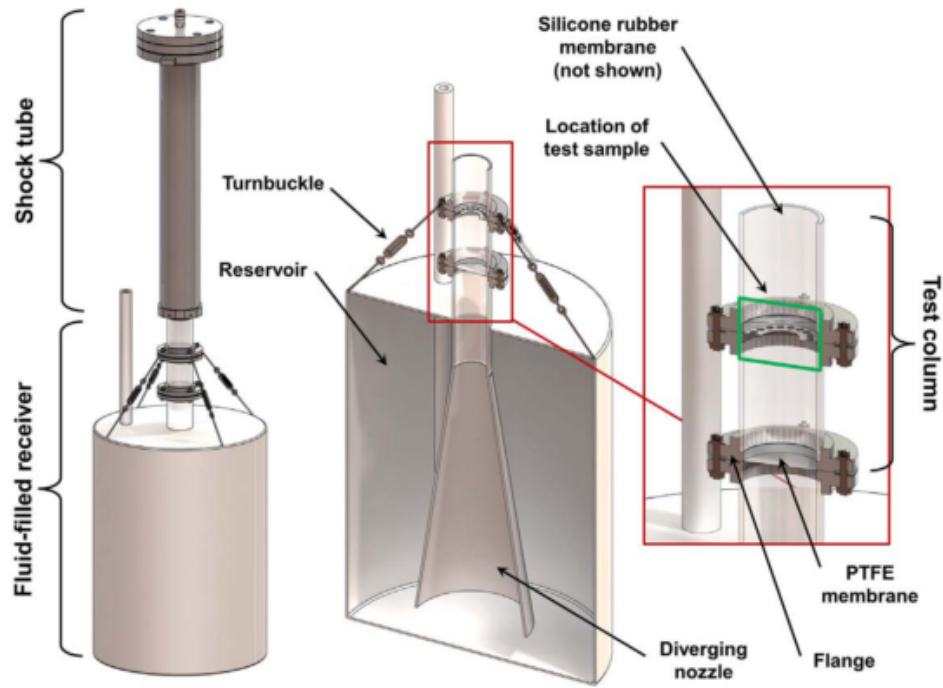


Figure 2.13: Schematic of shock tube with a fluid-filled receiver for *in vitro* blast testing. Reproduced from [43].

levels of blast severity. The model for the shock tube produced results with 90% in agreement with experimental observations (figure 2.14A). The receiver model displayed the same fundamental response to shock propagations and reflections as reality, but the initial pressure pulse was of slightly longer duration (figure 2.14B).

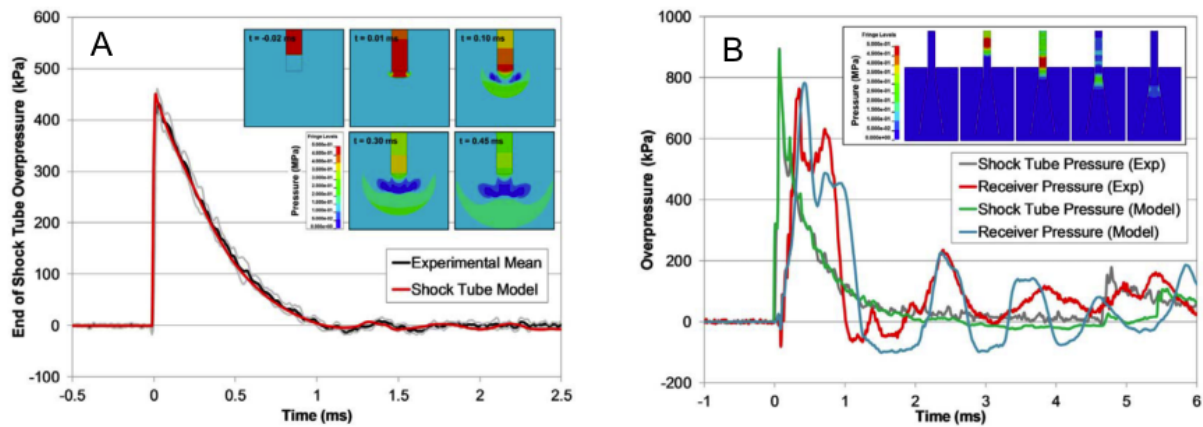


Figure 2.14: Comparisons between the typical pressure-time histories of experiments and finite-element models for (A) the open shock tube and (B) the fluid-filled shock receiver. Reproduced from [43].

Chapter 3

The CBIS Shock Tube System and Diagnostics

3.1 The CBIS shock tube system

The system used in this project is the stainless steel air-driven shock tube at the Royal British Legion Centre for Blast Injury Studies (TRBL-CBIS) at Imperial College London. It was designed by Dr. Chapman in 2010 [32], and brought into use in 2012. The full schematic of the shock tube is shown in Figure 3.1. The basic system, without any adaptor, has a total length of about 4 m and an internal diameter of 59 mm. This shock tube mainly consists of three separate 1.22-metre-long tubes: one of these tubes acting as the driver section, while the other two as the driven section. The driven tubes are joined together by flanges on which pressure transducers are embedded. The driver and driven sections are separated by the diaphragm assembly. The sealing at the joinings of different parts are enhanced with rubber nitrile gaskets and suitable o-rings. The system can be charged up to 18.2 bar (abiding safety regulations). A remote control box connected to the inlet flange, the double breech in the diaphragm assembly and a compressed air bottle using flexible pressure hoses are employed to operate the system.

The diaphragm assembly of the system was designed to facilitate either a single-diaphragm arrangement where diaphragm at A is made to fracture under built-up pressure

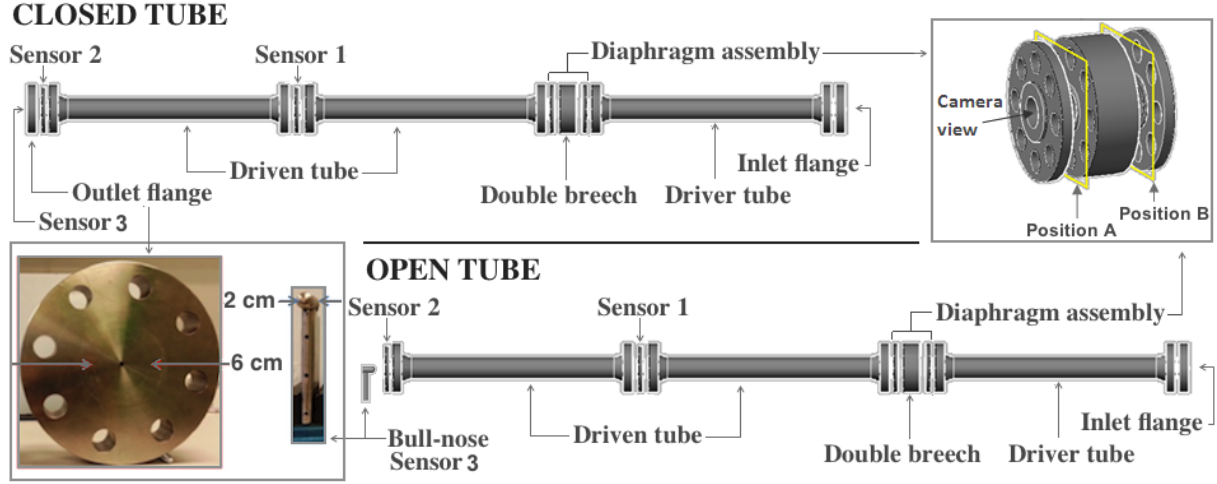


Figure 3.1: The full schematic of the CBIS shock tube system. Adapted from [61].

(no diaphragm at B) or a double-diaphragm arrangement where diaphragm A is ruptured under the blast wave produced from the rupture of diaphragm B. Mylar[®] (polyester) and aluminium diaphragms of different thicknesses are used in both diaphragm configurations (Figure 3.2A). Extra care was exercised during the clamping of the diaphragm assembly. Masking tape was attached to the diaphragm edge as handles to ensure that the diaphragm was positioned axially at the centre. Bolts were sequentially fastened in a diagonally symmetric fashion to avoid any misalignment that would lead to leakage of the driving gas. On the contact faces with the diaphragms of the double breech, o-rings were used to enhance clamping and also to eliminate any sharp edges that could create damage to the diaphragms.

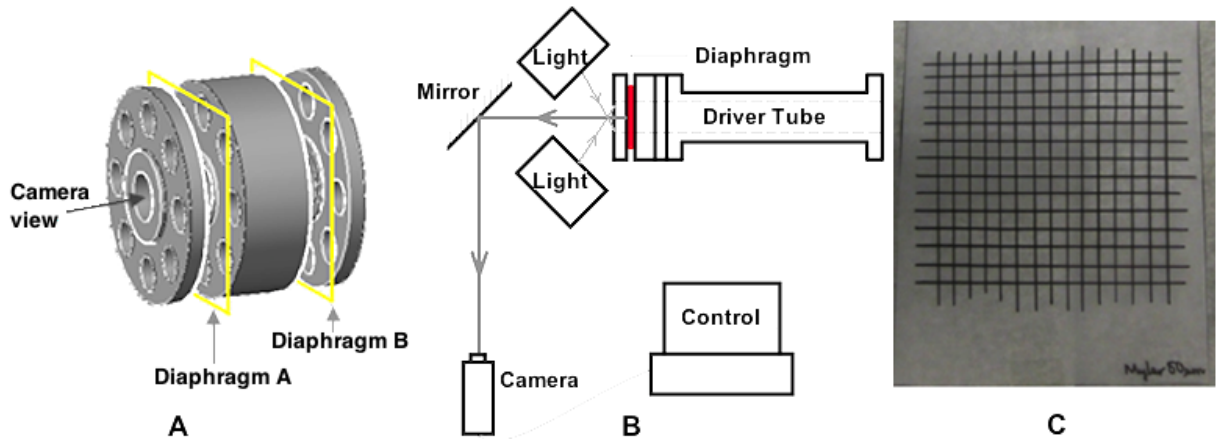


Figure 3.2: A: diaphragm assembly. B: arrangements for high-speed photography. C: a diaphragm with grids.

A Phantom v7.3 high-speed camera [47], with two 500 W static floodlights, were

utilised to observe the breakage process of the diaphragm in both diaphragm configurations. Only the driver tube and the double breech were used. A front-silvered mirror was also employed to direct the image of the diaphragm onto the camera as illustrated in Figure 3.2B. The Vision Research software provided with the camera was used to remotely control and trigger the recording system. Photography umbrellas were also employed to increase the scattering of the light source. As the static light sources warm up the system quickly, they were only switched on when the pressure reached 0.3 bar below the burst pressure in order not to affect the diaphragm breakage process. Grids were gently drawn on the diaphragm using a permanent marker pen to help monitor rupturing of diaphragms (Figure 3.2B). It was verified that these grids did not interfere with the breakage process. The only effect of grids that could be observed was when the crack propagation happened to be on a line of the grid, it would tear the diaphragm along that line (Figure 3.2C). However, this was not a common event.

The set-up conditions produced 54-second recordings with $9\ \mu\text{s}$ inter-frame time and 96×96 pixels resolution, sufficient to see the whole mounted diaphragm. The sound produced from the diaphragm rupture was used as signal to manually trigger the camera to stop recording. The resulting series of images were filtered with their brightness and contrast adjusted to highlight the essential features of the diaphragm breakage process.

In both single- and double-diaphragm set-ups, it was observed that the originally flat diaphragm reached a bulging stage before sudden rupture (Figure 3.3), although it was much faster in the latter. In the single-configuration, the breakage originates from a single surface defect at the centre of the diaphragm, which grows linearly in roughly a two-dimensionally symmetric fashion. The double bursting shows multiple cracks appearing simultaneously within the contact region between the shock front and the diaphragm, and propagate outwards axially in all directions. The circular shape of the contact region suggests that the produced shock wave has a round head. At the moment, crack propagation speed cannot be calculated due to the lack of information about the bulge radius of the diaphragms. The high-speed 3D digital image correlation technique is a possible solution.

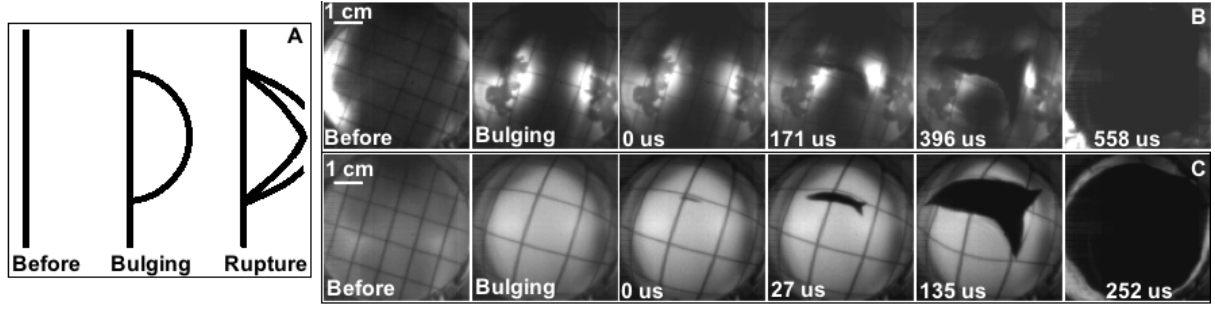


Figure 3.3: Left: stages of the diaphragm rupture (A). Right: the rupture of 50 μm Mylar[®] (C) and 100 μm aluminium (B) diaphragms with burst pressures of 4.2 bar and 5.3 bar respectively. Adapted from [61].

The double-diaphragm set-up is more dynamic, giving higher burst pressure and a more controllable way of producing shock waves. Traces for 40 μm aluminium diaphragms in the double-diaphragm system and 23 μm Mylar[®] diaphragms in the single-diaphragm system are shown together in Figure 3.4. Here, aluminium diaphragms (~ 1.52 bar burst pressure) were made to burst around the burst pressure of Mylar[®] diaphragms (~ 2.15 bar). The dip at the tail of the double-diaphragm trace is a result of the volume between the diaphragms. In this case, the breaking of the rear diaphragm sends a wave back into the main driving volume before the front diaphragm breaks. This small wave is seen at the end of the main pulse.

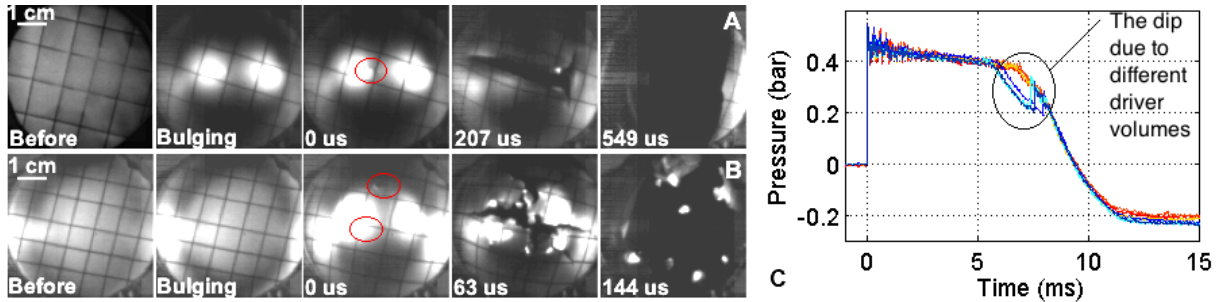


Figure 3.4: Left: the rupture of 40 μm aluminium in single (A) and double (B) arrangements. C: double- (blue) and single- (red) diaphragm systems, both at ~ 2.15 bar burst pressure. Reproduced from [61].

Linear relationships between the average diaphragm burst pressure and the diaphragm thickness for Mylar[®] film and annealed aluminium foil are shown in Figure 3.5. It can be seen that for a given diaphragm material, the burst pressure solely depends on the diaphragm thickness, not the surface texture, manufacturers, or even a slight change in compositions. Using multiple layers to produce the required thickness does not affect this

behaviour. This agrees well with equation 2.20.

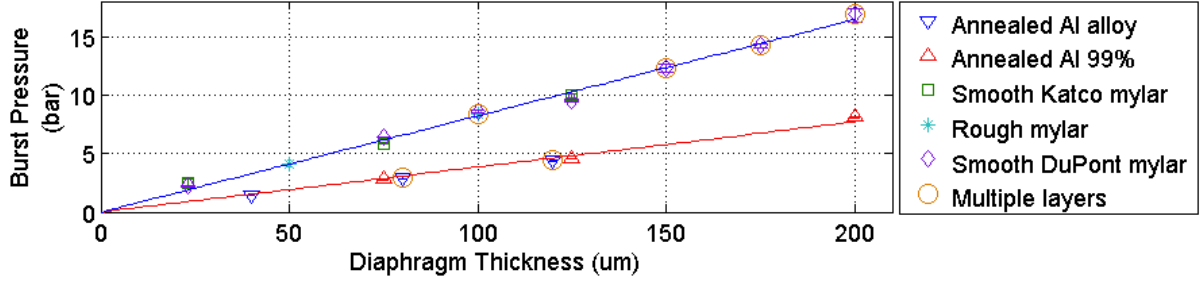


Figure 3.5: Burst pressure against thickness for Mylar[®] film (blue line) and annealed aluminium foil (red line). Reproduced from [61].

Mylar[®] diaphragms give higher burst pressure than aluminium diaphragms of the same thickness. This is because Mylar[®] is more compliant than aluminium, hence it can bulge more and accommodate a higher pressure before rupture. However, cracks propagate much faster in Mylar[®]: 252 μs to reach the diaphragm circumference compared to 549 μs for 40 μm and 558 μs for 100 μm aluminium foil (Figure 3.3). The difference in the fracture toughness of the two materials (24 $\text{MPa}\cdot\text{m}^{1/2}$ and $\sim 1 \text{ MPa}\cdot\text{m}^{1/2}$ for aluminium alloy and polyester respectively) shows that aluminium foils are more resistant to crack propagation, and thus have a longer crack propagation time or diaphragm opening time. Greater levels of thinning resulting from the more bulging seen in Mylar[®] might also be another reason for the faster crack propagation.

The pressure traces for Mylar[®] diaphragms of various thicknesses are displayed in Figure 3.6. It shows that the thinner the diaphragm, the more stable the profile is and the less developed the secondary features.

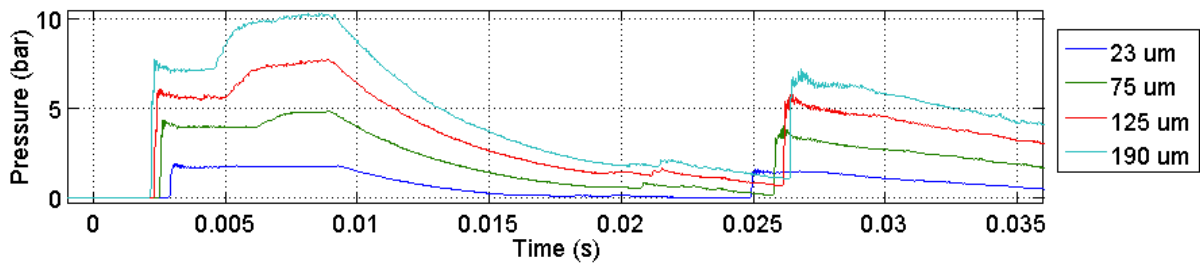


Figure 3.6: Comparison of pressure profiles for Mylar[®] diaphragm of different thicknesses

The shock tube can either be used with the outlet flange sealing the exit (closed configuration) or not (open configuration). The open set-up is more relevant for a sample

subjected to real shock waves (e.g. an air blast); the closed set-up, with reflected shocks from the outlet flange, can give more information about the shock magnitude and average speed. In Figure 3.7, the pressure traces between the open and closed tube configurations with 50 μm Mylar[®] diaphragms are compared. For the open system, the trace is that of a single blast wave with a tail that drops below atmospheric pressure. For the closed system, the initial blast wave produced was reflected between the ends of the tube, resulting in six peaks (from pressure sensor 1 and 3) during the period of 4 ms.

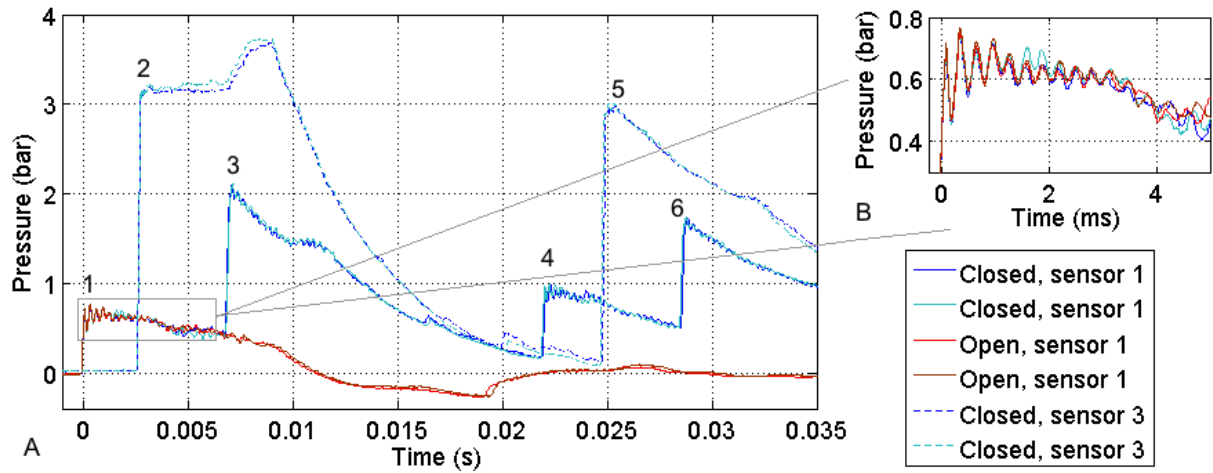


Figure 3.7: A: Overall pressure pulses for closed and open tube. B: detail of coincidence region (grey box). Adapted from [61].

The peaks show the wave magnitude and speed of the shock front. The first peak rises when the blast wave arrives at sensor 1. This wave then travels to the end of the shock tube, hitting sensor 3 to give the second peak and travels back to sensor 1 resulting in the third peak. Afterwards, the wave travels to the inlet of the shock tube and causes the fourth peak on its return at sensor 1. The same process as the beginning then repeats again to produce the last two peaks. Since the shock wave has to travel the longest distance between the third and forth peak, the profile separates itself into two separate groups. At the two ends of the shock tube, the wave experiences mixing that cools the gas down and thus reduces the shock speed, resulting in a longer travelling time between the last two peaks in each group. The final peak in each group is amplified due to constructive interference with the reflected blast wave from the end of the shock tube. Some sub features on the trace such as the bump rising over the first peak of sensor 3 and second peak of sensor 1 may be explained as superposition of the reflected wave with the

secondary shock wave behind the initial wave.

The detail of the coincidence region (Figure 3.7B) between the two profiles shows that the shock waves are highly reproducible, thus what is learnt from the closed tube can be applied to the open tube. In addition, the oscillation observed here suggests that this is a systematic feature of the shock tube, which is very likely to be caused the vibration of the pressure gauge or a component inside the pressure gauge. More tests need to be carried out to verify this explanation, and it may lead to a more accurate way of calibrating dynamic pressure sensors.

The pressure - time histories such as those in Figure 3.7 can also be used to derive the trajectories of the produced pressure waves which can be described in an $x-t$ wave diagram (Figure 3.8). The sharp rises in pressure give information on the shock waves and the decaying features give information on the rarefaction waves. These wave trajectories are all straight lines, thus providing the average velocity of the waves. In reality, these velocities vary as the waves propagate inside the shock tube and interacts with diaphragm remnants and the walls of the tube. Additional wave interaction (with defects and part of the shock tube) can either be observed from the original pressure - time graph or indistinguishable because of noise.

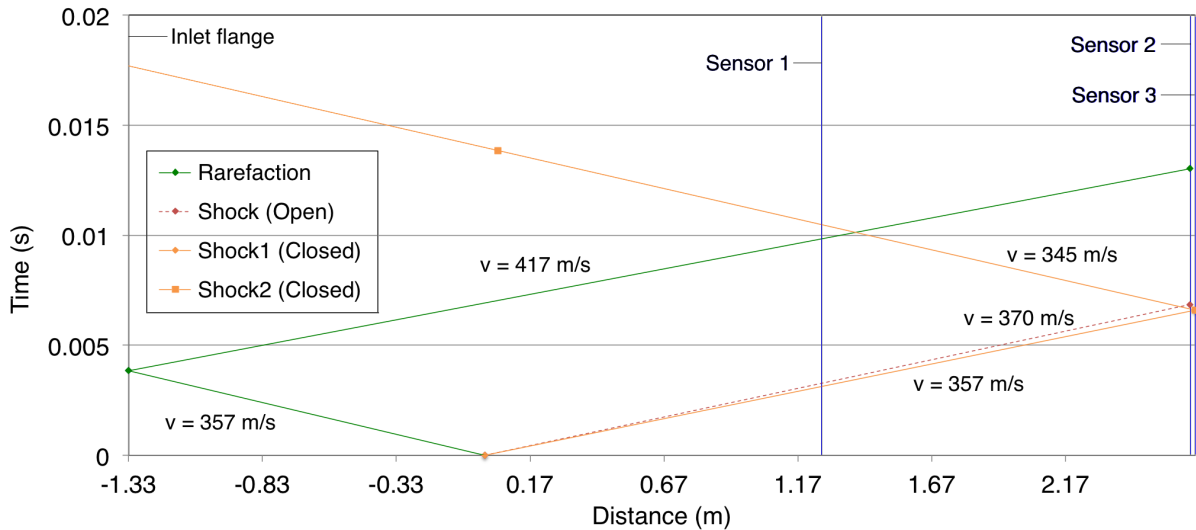


Figure 3.8: An $x-t$ diagram produced for pressure waves generated with the bursting of a $25\ \mu\text{m}$ aluminium diaphragm, in both open and closed configuration. The blue lines show the locations of the dynamic pressure sensors. The solid orange and dashed red lines show shock waves in closed and open configuration respectively, and green lines refer to rarefaction waves. $x = 0$ is chosen to be the diaphragm location, and $t = 0$ is the time when the diaphragm bursts.

3.2 Dynamic pressure sensors

In the CBIS shock tube system, the propagation and evolution of the produced blast wave are monitored by two lateral pressure sensors embedded at the middle and the end of the driven section (Figure 3.1), as well as an appropriate head-on pressure sensor installed on either the outlet flange or additional mountings such as bull-nose mount or rod mount (Figure 3.9).

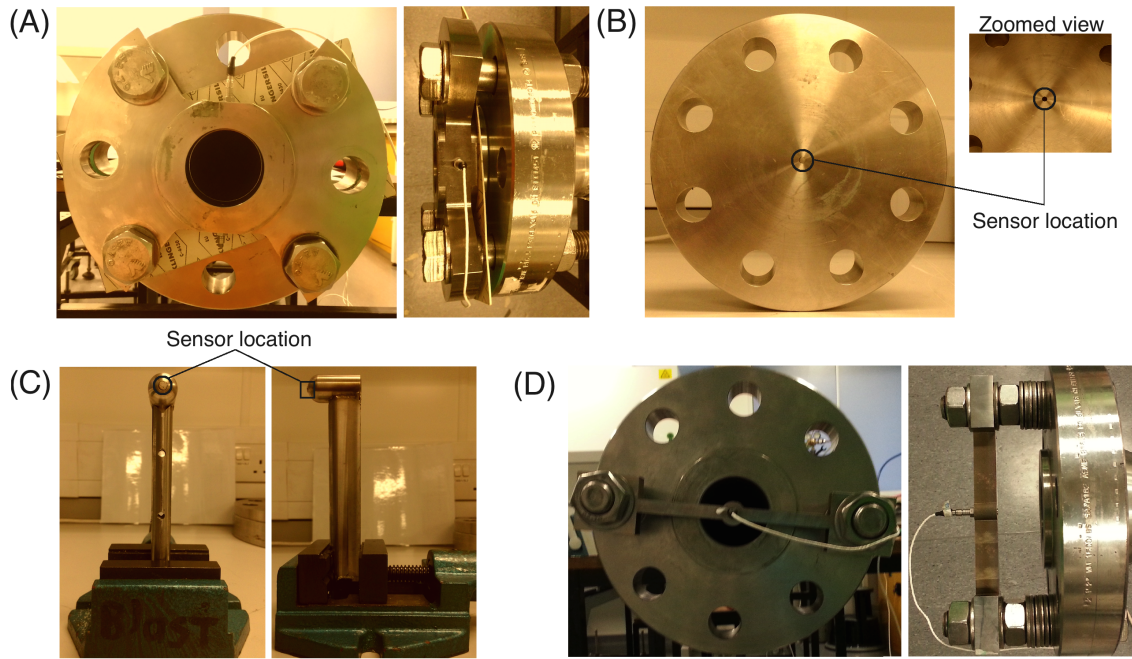


Figure 3.9: Various sensor mountings: (A) Lateral sensor flange, (B) Outlet flange with head-on sensor mounting for closed shock tube configuration, (C) Head-on bull-nose sensor mount for open shock tube configuration, and (D) Head-on rod sensor mount for open shock tube configuration

The pressure transducers are connected to an oscilloscope through a current source. The oscilloscope is sampled for 4 ms at a rate of 25 million-samples/s, triggered by a rising edge in the signal of sensor 1. The sampled trace includes a pre-trigger of five percent of the total sampling time. Data of output voltage against time is then converted to pressure against time using the calibration factor provided by the manufacturer for each sensor. A low-pass filter with a cut-off frequency of 70 kHz is used to process the raw data collected to eliminate random noise in the signal. It is applied with the zero-phase digital filtering Matlab function *'filtfilt'*. This function behaves like the moving average filter which can be performed by the Matlab *'smooth'* function over a span of every 500 data points. They

both result in effectively the same final trace as shown in Figure 3.10.

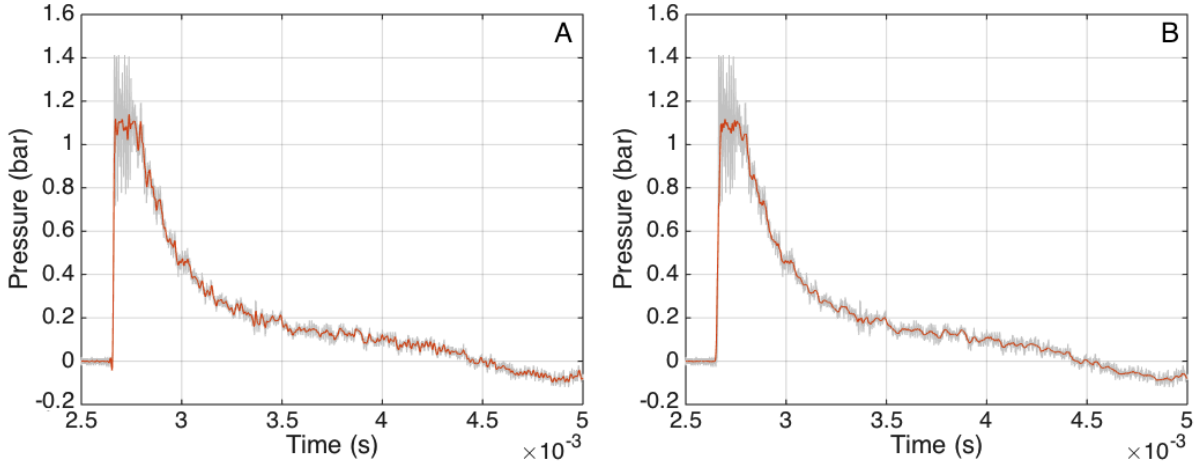


Figure 3.10: Sensor 2 pressure traces from bursting of 50 μm Mylar[®] diaphragm: (A) raw (grey) and low-pass filtered (red) data; (B) raw (grey) and smoothed (red) data

Generally, the first lateral gauge, sensor 1, can be used to trigger the oscilloscope and to compare the produced blast waves of different experiments as it is far enough from the outlet, and essentially independent of additional chambers attached to the outlet of the shock tube. Measurements from the second lateral gauge, sensor 2, and the head-on gauge, sensor 3, are more relevant to samples subjected to the shock tube as they are much closer to the location of the samples. In most cases, these two sensors can be used to characterise set-ups for biological samples.

3.2.1 Piezoelectric pressure sensors

The pressure sensors used in this project are mainly the Dytran[®] 2300V1 piezoelectric LIVM (Low Impedance Voltage Mode) dynamic pressure sensor. These sensors are designed to measure dynamic pressure changes such as in field blast test, pneumatic and hydraulic processes. The exact value of the sensor sensitivity (~ 20 mV/psi) is calibrated at the factory using dynamic calibration hydraulic methods for each individual sensor. Thanks to their high rigidity and small size, they can provide high frequency response and rapid rise.[48]

Figure 3.11 shows the full schematic of a Dytran[®] 2300 sensor. During measurements, the sensor is installed so that the flat diaphragm at the bottom facing the measured

pressure (shock wave in our case). The electrical connector at the top is connected through a general purpose 10-32 plug to BNC plug cable to a current source which is then fed to an oscilloscope.

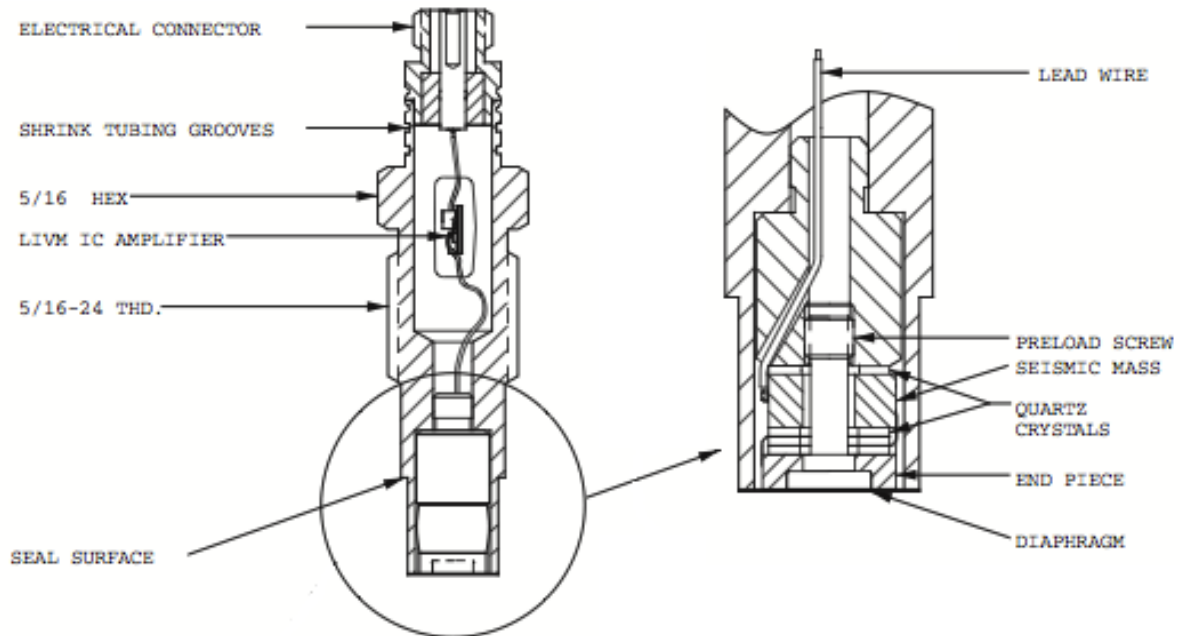


Figure 3.11: The full schematic of Dytran[®] 2300V piezoelectric LIVM dynamic pressure sensor. Reproduced from [48].

As the shock wave hits the diaphragm of the sensor, the pressure is converted to compressive force which strains the stack of thin synthetic quartz crystals linearly with the applied pressure, producing analog voltage signal. This voltage is then transmitted to the LIVM integral impedance converting IC amplifier which reduces the impedance level by 10 orders of magnitude so that long cable drives still have little effect on the frequency response.

In addition, on top of the crystal stack is the integral accelerometer with a seismic mass and a quartz crystal. This part can produce a signal with opposite polarity to the applied pressure to cancel the mechanical motion by vibration or shock on the output.

3.2.2 The mountings of sensors

Mounting of the sensor is important to its performance. In particular, the sealing surface should be smooth without chatter marks or machining imperfections. The position of the diaphragm will also affect the rise time of the sensor. The recessed mounting of the sensor

as shown in Figure 3.12 will introduce a passage of fluid ahead of the sensor diaphragm together with a secondary resonant frequency. This will impair the high frequency response and rise time compared to the sensor in the flush mounting (Table 3.1).

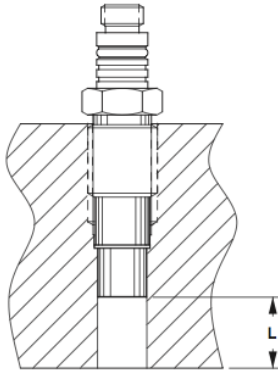


Figure 3.12: The recessed diaphragm installation will impair the high frequency response and rise time of the sensor. Reproduced from [48].

Table 3.1: Resonance frequency and rise time correspond to various recess length. Reproduced from [48].

Recess length L [inches(mm)]	Passage natural frequency	Approx. fastest rise time
.001 (.0254)	3.3 MHz	.1 μ s
.002 (.0508)	1.6 MHz	.2 μ s
.003 (.0762)	1.1 MHz	.3 μ s
.005 (.127)	660 KHz	.5 μ s
.010 (.254)	330 KHz	1 μ s
.050 (1.27)	66 KHz	5 μ s
.100 (2.54)	33 KHz	10 μ s
.200 (5.08)	16.6 KHz	20 μ s
.500 (12.7)	6.6 KHz	50 μ s
1.00 (25.4)	3.3 KHz	.1 ms
2.00 (50.8)	1.66 KHz	.2 ms

The lateral mounting of the sensor is an important aspect of the system. Experiments were performed to investigate the effect of protruded into the flow laterally, in addition to the recessed mounting as advised by the manufacturer. The lateral mount used was one that could accommodate sensors in three configurations: protruded by 1 mm into the flow (1), flushed to the inner wall (2) and protruded by 2 mm into the flow (3). The result shows that the more protruded the sensor is, the more noise produced in the signal (Figure 3.13). It is understandable as the more contact the shock wave has with the side of sensor, the more mechanical vibration induced which the integral accelerometer is not designed to account for. It is also highly important to avoid protruding the sensor into the flow laterally as the crystal stack inside the sensor is vulnerable to force coming side-way.

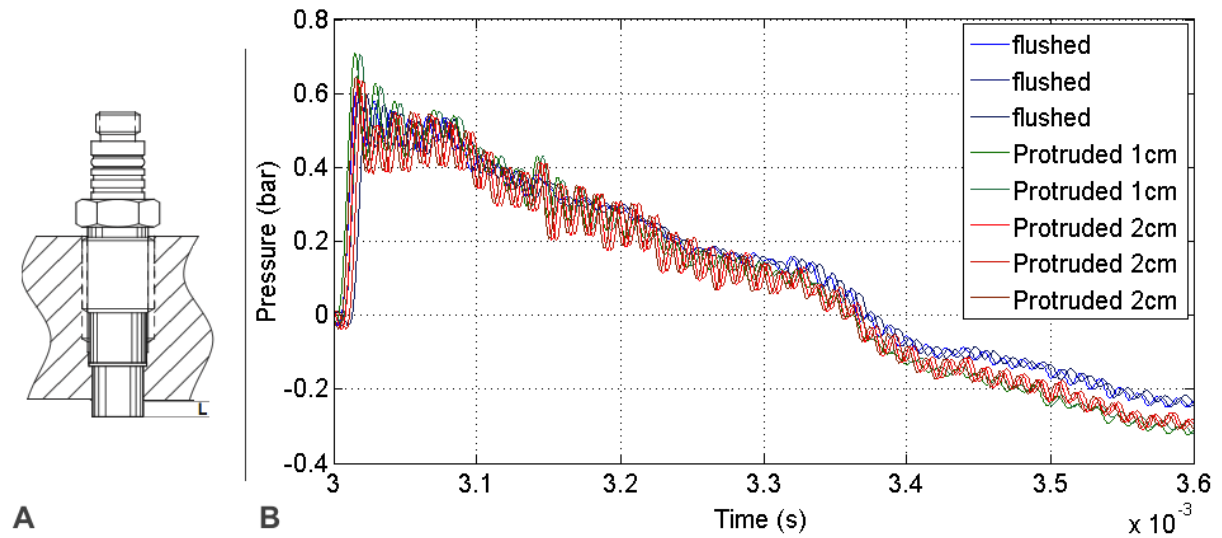


Figure 3.13: A - Protruding mounting of sensor. B - Lateral pressure profiles at outlet with sensor mounted flushed or intruded to the inner wall of the ring sensor mount. $40 \mu\text{m}$ aluminium diaphragm was used for all cases.

The direction of lateral sensor mounting is also an issue to be addressed. Is pressure measured with the sensor looking down to the flow different from one with the sensor looking up to the flow? To answer this, the lateral sensor flange was rotated around so that the sensor looking at the shock flow at the direction of: downwards (0°), left to right (90°), upwards (180°), and right to left (270°). The pressure profiles displayed in Figure 3.14 for these cases are almost identical. It means that generated shock waves are axially symmetric, and it is the same no matter which rotation the sensor is mounted to the shock flow.

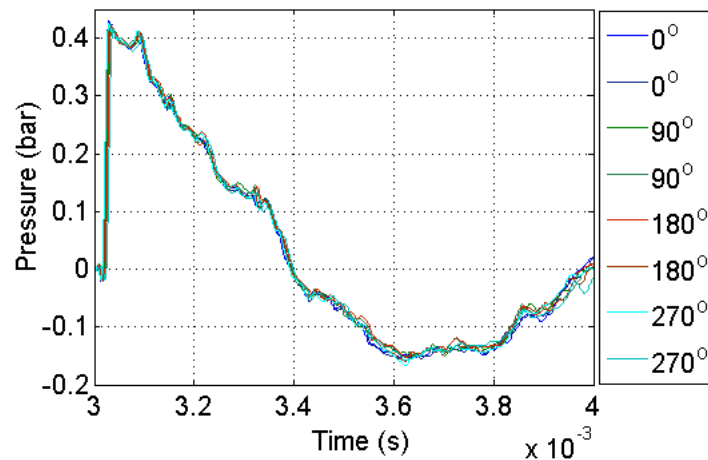


Figure 3.14: Lateral pressure profiles at outlet with sensor mounted at different direction to the shock flow. $40 \mu\text{m}$ aluminium diaphragm was used for all cases.

For head-on measurements of the produced blasts, either the output flange can be used for closed configuration or smaller mounting such as the bull-nose mount can be used for open configuration (Figure 3.1). The bull-nose mount has all its front edges rounded to minimise its interaction with the shock flow, and can be used with a clamp to hold at predecided distances from the outlet of the shock tube. However, noise from vibration of the mounts was unavoidable. For high pressure, the bull-nose could be pushed back or even thrown off its base despite having weights positioned around the clamp, posing risks to the sensor itself. Hence, it is necessary to have a better method of stabilise these mounts or new mounts which are designed to account for vibrations and violent motion when subjected to shocks.

The rod sensor mount (as shown in Figure 3.9D), another design for head-on sensor mounting, can be fixed to the shock tube, thus no risk of it being pushed back or thrown sideways. The standoff distant between the sensor and the outlet of the shock tube can also be adjusted in a more controllable fashion. However, the installation of the rod mount introduces more surface of reflection to the shock flow, and care should be taken to position it horizontally so that it will not interfere with the readings of the secondary lateral sensor at 0° direction. Figure 3.15 compares the pressure traces measured by the bull-nose and the rod sensor mount. Both mounts were positioned so that the sensor diaphragm was 4 cm away from the outlet of the shock tube. No secondary lateral sensor mount was used in these tests. General shapes of pressure profiles are pretty similar between the two cases. However, as the installation arrangement of the rod mount has more surface area for the shock wave to reflect from, it results in higher peak pressure and a slower decay of the overpressure. This effect should become less significant as the further away the sensor is from the outlet.

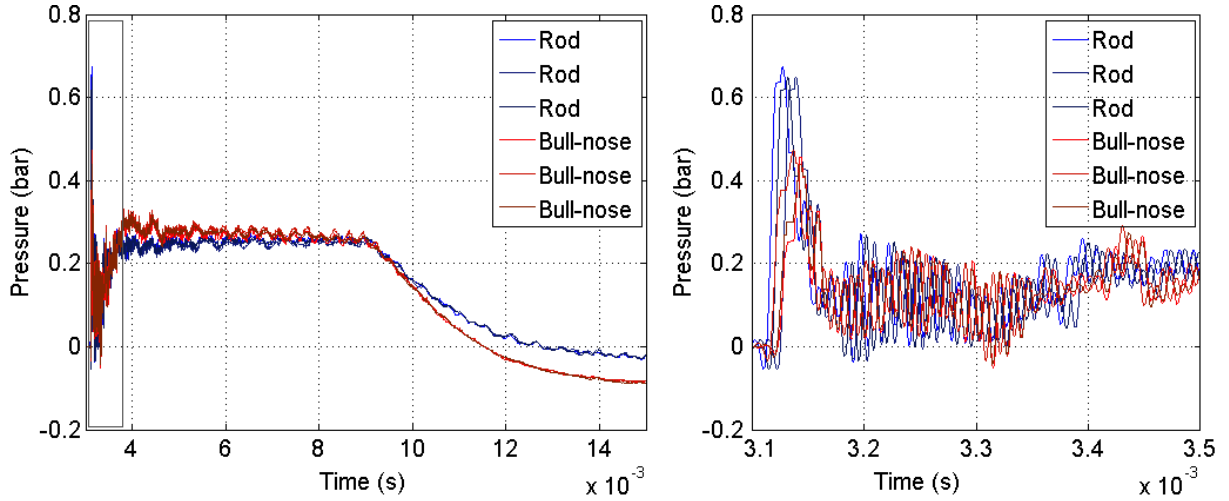


Figure 3.15: Head-on pressure profiles at 4 cm from the outlet measured with the bull-nose mount and the rod sensor mount. $40\text{ }\mu\text{m}$ aluminium diaphragm was used for all cases. Full driving volume gives the long plateau trail after the shock.

3.3 The schlieren photography for blast visualisaions

3.3.1 The principle of schlieren photography

The name schlieren of the technique comes from the German word *schliere* or *striae* meaning streak. This is because of the streak-like appearance of the fluid flow during the visualization process. The history of schlieren technique started from as early as the 17th century with Robert Hooke when first he observed the air disturbance against a distant light-dark boundary. Then he moved on to construct the very first schlieren method with the light-dark boundary replaced by a candle acting as light source, and a second candle was placed very close to the lens which refracts light so strongly that they fall outside the pupil and hence were blocked. With this, the change in light intensity through the convective flow around the candle could be seen by eyes. Then in mid-19th century, the French physicist Leon Foucault invented the next and very important development for the schlieren technique: the first use of an explicit cutoff, distinct from the pupil of the eye. Around this same period, August Toepler re-invented the schlieren imaging technique and gave it its name. His apparatus included a lantern light source, an adjustable knife-edge cutoff, long-focus lens combination that he called schlieren head, and a telescope for viewing the image directly. Failing to see sound with this set-up, he soon used an electric spark to generate sharp acoustic disturbances, and called these sound waves. In fact it is

actually the shock waves which travel faster than sound, giving the first image of shock wave. In early 20th century, a German PhD student named Hubert Schardin worked on his project of the Toepler schlieren technique to study its principle and applications, as well as quantitative evaluation. He was the first to establish a solid theoretical background for schlieren imaging.[49]

The simple schlieren system is one with a point source and object S bends light ray away from their original paths (Figure 3.16A). Second lens focus each point of S to a point on screen. Two light rays from each point are deflected up and down: the upward-deflected ray brightens a point of the screen, but the downward-deflected ray is blocked by the knife-edge giving a dark point against a bright background, making the invisible becomes visible. In reality, light source has a finite size described as an extended source (Figure 3.16B). That means every point in the test area is illuminated by countless rays from the light source and each point in the light source illuminated every points in the test area. This gives depths of focus to the schlieren system, allowing a continuous gray-scale rather than just binary black-and-white.

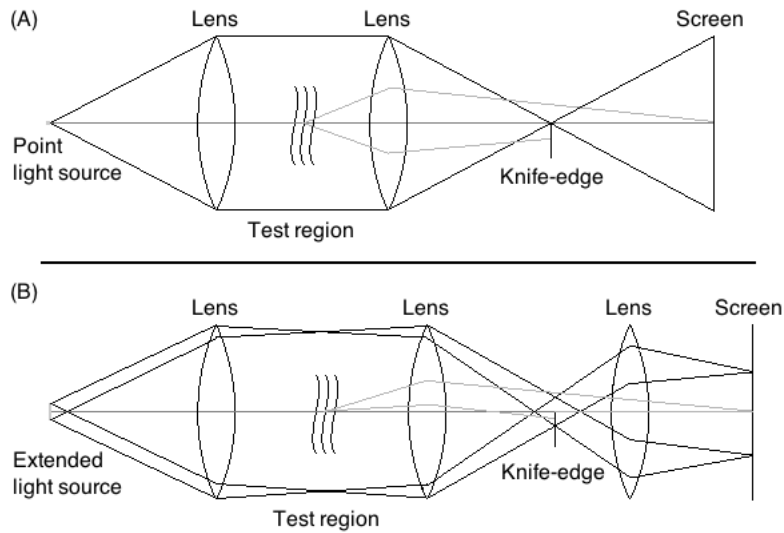


Figure 3.16: The principle of schlieren photography: (A) Point light source, and (B) Extended light source. Adapted from [49].

The knife-edge used in a schlieren system is usually a razor blade that need to be placed at the focus of the second lens, either horizontally or vertically. The knife-edge only detects ray refractions with components perpendicular to its orientation, thus schlieren objects

with purely parallel refractions are not visible. Strictly speaking, two schlieren images of both orientations are needed to fully visualise an object. However, using a circular cut-off will fix this problem; and in practice, a single knife-edge system is normally good enough [49].

The location of the knife-edge is an important and sensitive factor. A perfectly positioned knife-edge at the focus of the second lens (or mirror) will result in the mostly uniform darkening of the schlieren field. Even a small offset of the knife-edge position from this focus, the the darkening of the image of the lens will be darker on one side (Figure 3.17).[50]

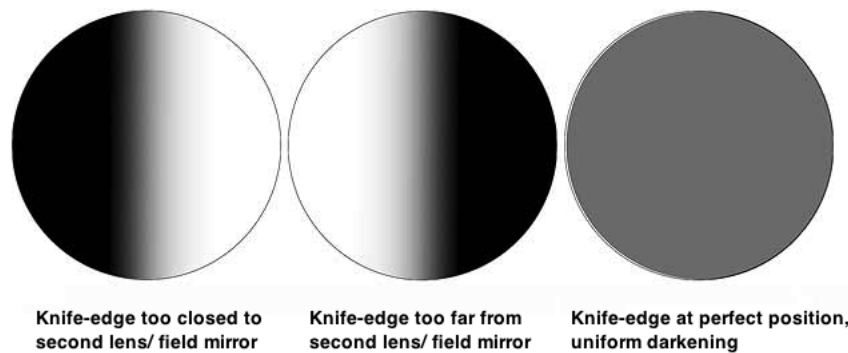


Figure 3.17: Schlieren fields resulted from different locations of knife-edge cutting in from the same direction. Adapted from [50].

As the knife-edge is moved into the image of the source at the focus point, it will uniformly cut off the intensity of the illumination, and increase the contrast of the produced schlieren image. However, high contrast from large cutoff is traded off with loss of information in low density gradient region, hence smaller measuring range. From this aspect, a 50% cutoff is usually recommended even though 90% cutoff is often required for good sensitivity (Figure 3.18).[49][51]

A perhaps more advanced type of schlieren photography is the colour schlieren system with the use of a “white” extended light source and a pair of matched spatial filters (or prism) instead of the traditional knife-edge. This system can give additional data such as multi-gradient magnitudes and directions, which is useful for quantitative analyses. The features in such schlieren images are also more distinguishing. For this project, a colour schlieren system was not used due to the unavailability of a colour high-speed camera.[49]

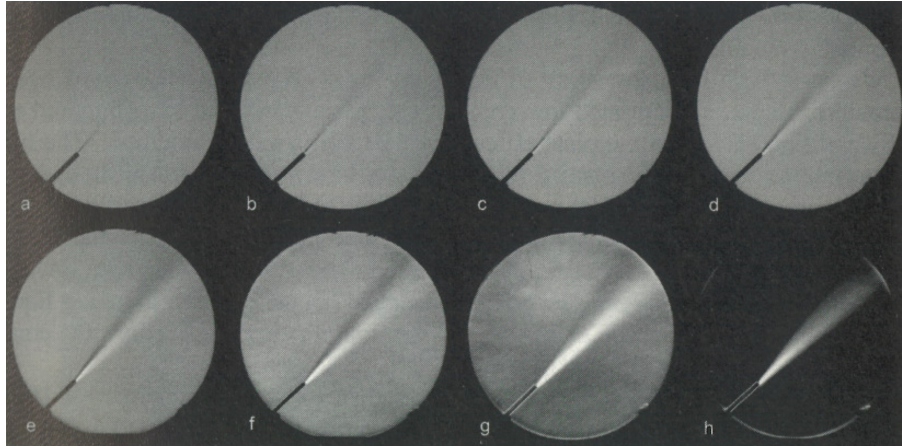


Figure 3.18: Schlieren photos of turbulent gas jet restuled from different percentage of knife-edge cutoff: (a) 0%, (b) 20%, (c) 40%, (d) 60%, (e) 80%, (f) 90%, and (h) 100%. Reproduced from [49].

For the monochrome schlieren photography, two common conventional mirror systems are shown in Figure 3.19: the Z-type mirror system, and the off-axes mirror system. Both of the have their own pros and cons, and are used depending on the experimental conditions. The Z-type system provides a higher sensitivity and accuracy, as well as a larger field-of-view, but it requires multiple mirrors that need to be identical. It is also space-consuming and harder to set up due to its more complicated optical arrangement. On the other hand, the off-axes system only requires a single mirror, and is space efficient and simple to set up. However, its test area is smaller and it also gives more errors as well as shadows in the resulting images.[49]

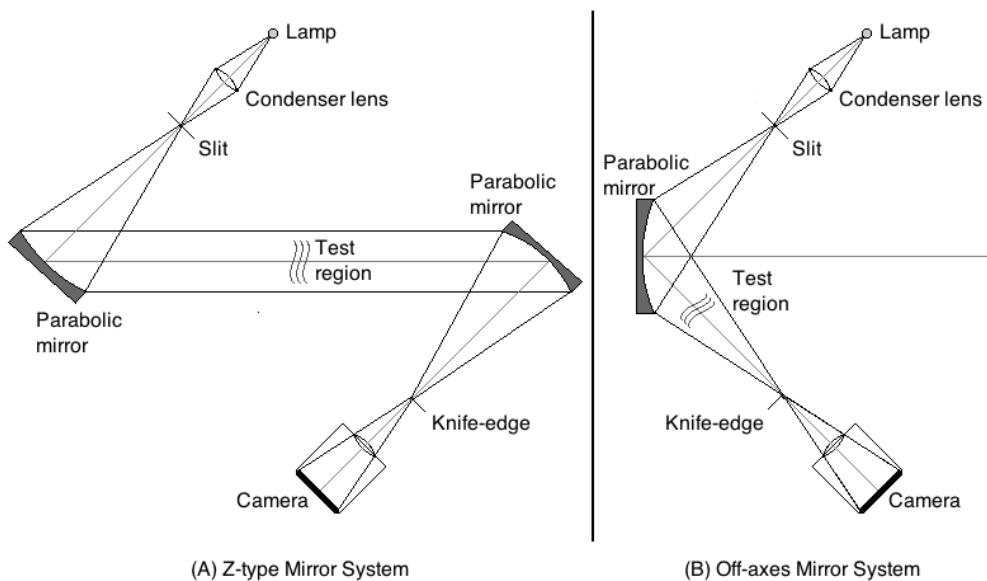


Figure 3.19: Conventional mirror systems: (A) Z-type, and (B) Off-axes. Adapted from [49].

3.3.2 Visualising the shock tube output

The off-axes schlieren system, in conjunction with the high-speed imaging, can be set-up for the CBIS shock tube in the open configuration, as shown in Figure 3.20, to capture images of blast waves as they escape the shock tube and their interactions with platforms used for blast injuries studies as well as various mitigation structures and materials. This aids the understanding of any additional loading features due to the set-up environment on the samples, which may escape the detection of pressure sensors. It can also be used as a validation method for computational simulations.

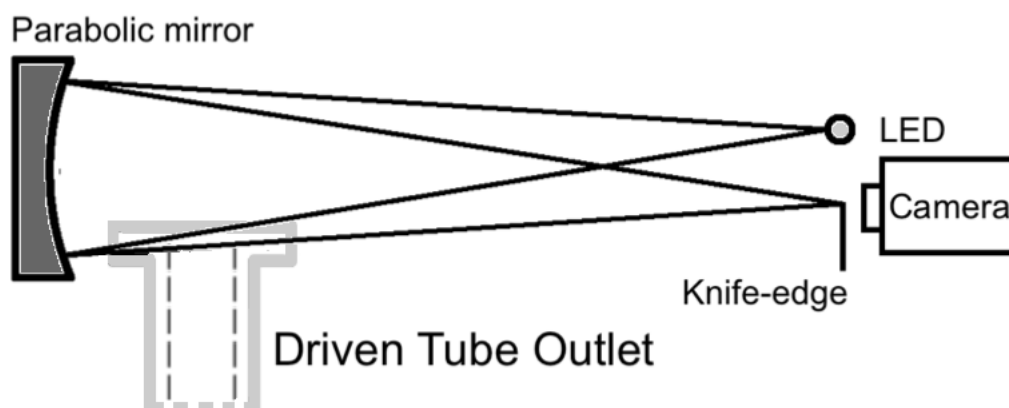


Figure 3.20: Off-axis Schlieren set-up produced images visualising the blast wave (A), vortex formation with a jet shear layer (B) and the Mach diamond for strong shock (C).

This schlieren system was built with a single far field mirror of either 72-inch or 96-inch focal length, with diameter of 8 inches and 12 inches respectively. The illumination source was a Cree[®] CXA2011 X-Lamp[®] LED array, and a razor blade was used as the knife-edge. The knife-edge was placed on a x-y translation stage, at approximately twice the focal length from the mirror, then finely tuned to the focus source image. The camera used was the Phantom v210. The outlet of the shock tube was positioned so that the exiting blasts and/or desired sample mountings are in the test region. The bigger mirror provides a larger field of view so it is more useful in imaging the interaction between produced blast waves with other subjects. However, its greater focal length results in reduction of image resolution.

Two series of snap shots in Figure 3.21 and 3.22 show the blast output from bursting of 50 μm and 125 μm Mylar[®] diaphragm respectively. The earlier generated blast wave with

Mach 1.3, which is quite gentle compared to the Mach-2.4 blast wave produced from the latter. In this strong shock case the blast wave is followed by the formation of vortices and Mach diamond standing wave patterns, and the blast effect lasts for a much longer time period. All objects in these images are doubled as their reflections in the mirror behind were also recorded. This off-axes mirror system is susceptible to the effects of coma as can be seen in the slight distortion of the images here. As discussed, the Z-type Schlieren set-up can eliminate these disadvantages, but it could not be used due to limitation in the laboratory space.

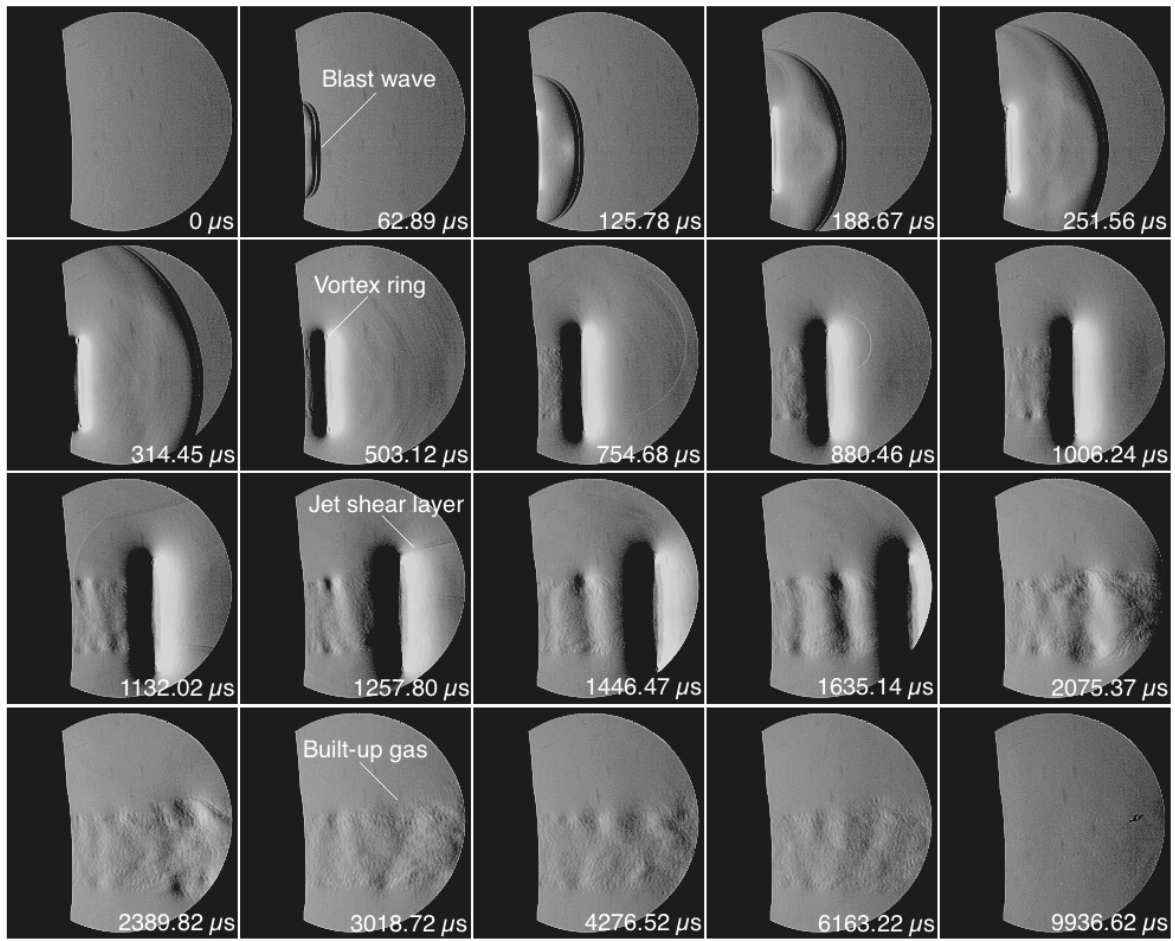


Figure 3.21: Schlieren snap shots of Mach 1.3 output blast and its features. The inter-frame time was 62.89 μs and exposure time was 2 μs .

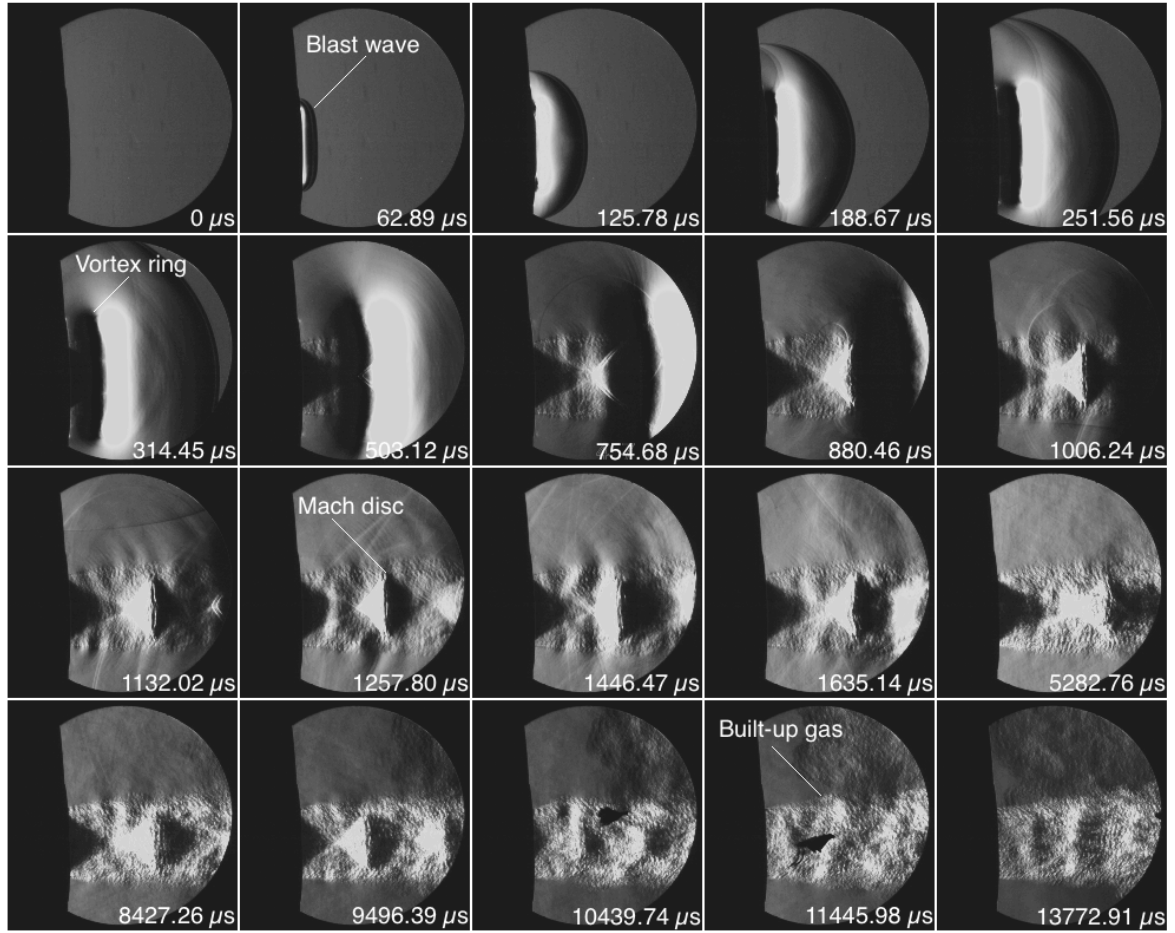


Figure 3.22: Schlieren snap shots of Mach 2.4 output blast and its features. The inter-frame time was $62.89 \mu\text{s}$ and exposure time was $2 \mu\text{s}$.

3.4 Conclusions

This chapter reports a series of experiments with a range of diaphragms, shock tube configurations, and set-up conditions. The results address several issues that highlight the characteristics of the shock tube:

- The high reproducibility of experiments allows the information obtained from the closed set-up to be applied on the open tube case.
- The double-diaphragm system enables the diaphragm to be burst at a specific chosen pressure and time, i.e. giving more control over the output shock wave.
- The diaphragm burst pressure is directly proportional to the diaphragm thickness. The more compliant the diaphragm, the higher the burst pressure.

- The noise in collected pressure signals can be neutralised by reducing mechanical movements of sensor mounts. It can successfully produce ‘cleaner’ pressure profiles, however not without compromises. The head-on rod mount can be bolted rigidly to the shock tube at controlled distance, but the set-up introduces more surface of reflection, resulting in higher pressures detected compared to with the existing bull-nose mount. This effect should be less significant the further away it is from the exit, and its relevance depends on the size of the sample.
- The rotational orientation of the lateral mounting of sensors does not affect the pressure measurement. Furthermore, it is recommended to have sensors flush to the mounting surface. Recessed mountings increase the sensor rise time, and protruded mountings produces more mechanical noises and possibly causes damage to sensors.
- Schlieren photography can be set up in the open configuration of the shock tube to visualise produced blast waves and their interactions with platforms for blast injury studies. It can also be used as a validation method for computational simulations.

Chapter 4

The Output Blast Waves in the Shock Tube

4.1 The blast magnitudes

The blast loading produced by the shock tube is dependent on the sample location, geometry, size, and impedance. The impedance of the sample is an important factor, but often complex to determine if samples are composed of heterogeneous or very complex materials. The mounting of the sample is also a significant factor as it will change depending on the chamber used.

In order to generalise the characterisation of the shock tube output, investigations were performed for standardised locations and sample sizes. Figure 4.1 shows the three most standard cases:

- Large samples comparable to the tube inner diameter ($\sim 60\text{ mm}$, *i.e.* head or chest of a small animal, a mitigation structure, etc.), close to the tube outlet. These samples give a larger area for shock reflection and effectively act as a sealing flange. Hence, they were characterised by the head-on sensor 3 mounted on the outlet flange of the shock tube in the closed configuration.
- Small samples (such as small animal limbs or excised tissue samples) at some small distance from the tube outlet. These samples give less area for shock reflection and

more space for the blast to dissipate. Hence they were characterised by the head-on sensor 3 on a bull-nose or rod mounting at approximately ~ 2 cm from the outlet of the open shock tube.

- Samples mounted laterally to the gas flow in the shock tube using of suitable adaptors. The loadings of this case were measured by the lateral sensor 2 near the outlet of the shock tube.

In the first two cases where samples are subjected axially to the shock tube, they experience the direct effect of the gas flow. They see both the initial peak pressure and the longer duration “plateau” pressure after the peak. This plateau pressure is a small feature for the laterally mounted samples as they do not interfere with the flow of the gas.

It needs to be emphasised that the traces recorded by pressure sensors are not the actual loading experienced within the samples. Nevertheless, this information is useful in the designing of experiments and the comparison of different studies.

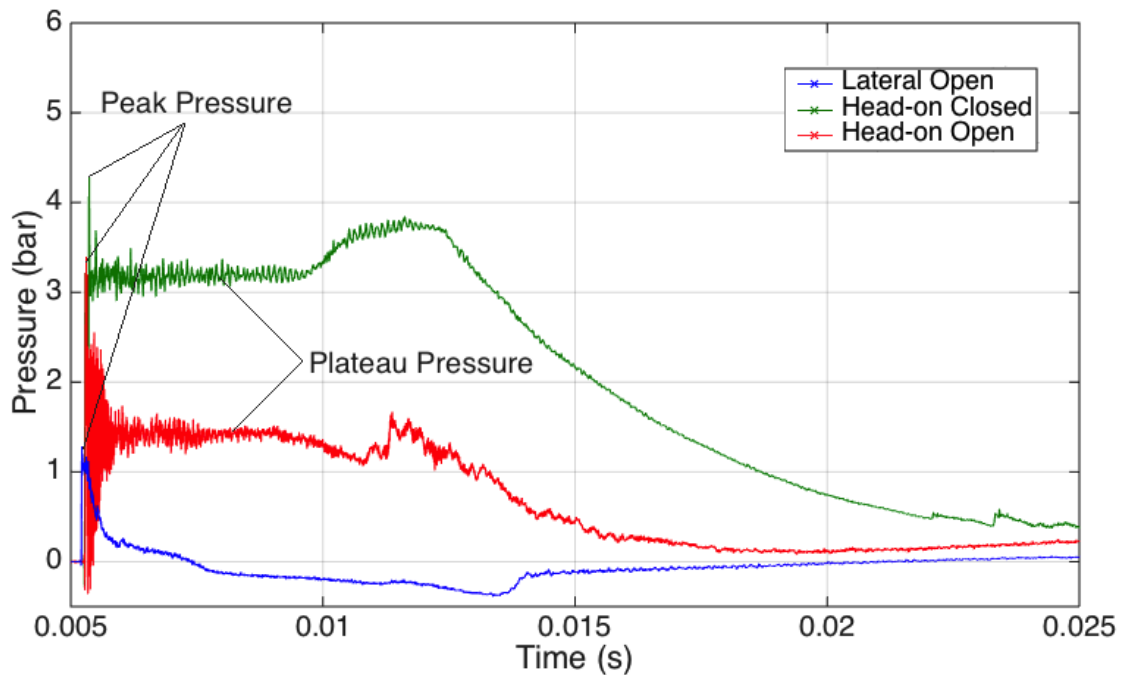


Figure 4.1: Standard shock tube outputs: big samples close to tube outlet (green), small samples (red), and samples lateral to the flow (blue)

4.1.1 The effect of the diaphragm burst pressure

The magnitude of the output shock wave can be controlled by adjusting the diaphragm burst pressure, i.e. the diaphragm material and thickness. Figure 4.2 and 4.3 shows the relationships between the burst pressure and the measured axial and lateral pressures at the end of the shock tube for both closed and open systems. Mountings of head-on sensor 3 introduce reflection surfaces into the shock wave propagation, hence sensor 3 measures the reflected pressure; and the reflected pressure of the closed tube are more relevant to large samples and vice versa. For the same burst pressure, each cases also gives different pulse durations and hence different amount of shock impulse as shown in Figure 4.4.

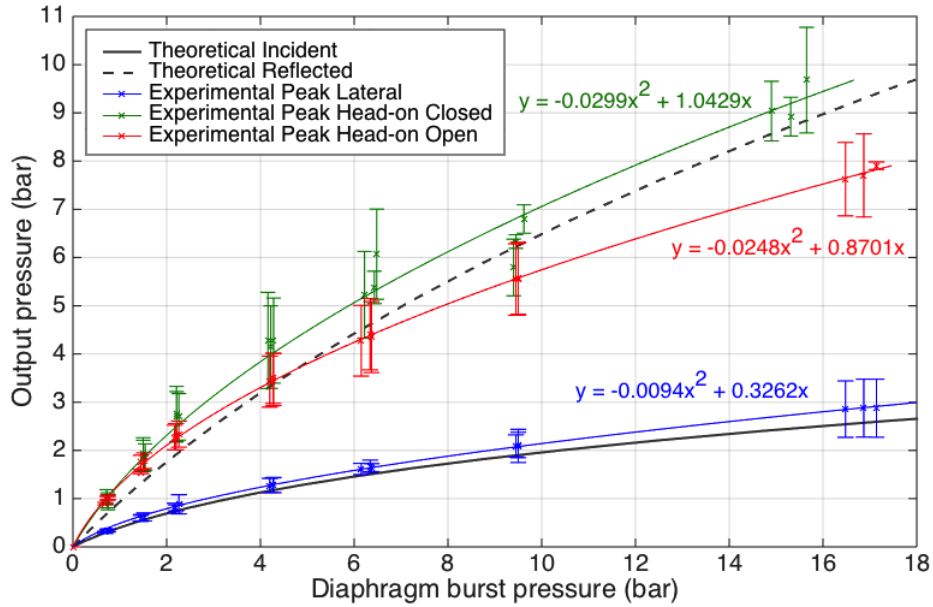


Figure 4.2: Expected peak pressures of output blasts generated from various diaphragm burst pressures

The experimental value of the peak head-on pressure is slightly higher than prediction by the ideal gas description [21]. This is in agreement with the discussion of real gas effects in 2.1.1. In addition, the inner wall of the tube is not smooth and the burst diaphragms also act as an additional mesh that interferes with the shock flow. Radiation effects can also be a reason, in which the low-pressure driven gas at room temperature absorbs the radiative energy of the driving gas behind the shock wave. This raises the temperature of the driven gas, hence the difference between the predicted and actually measured shock.[52]

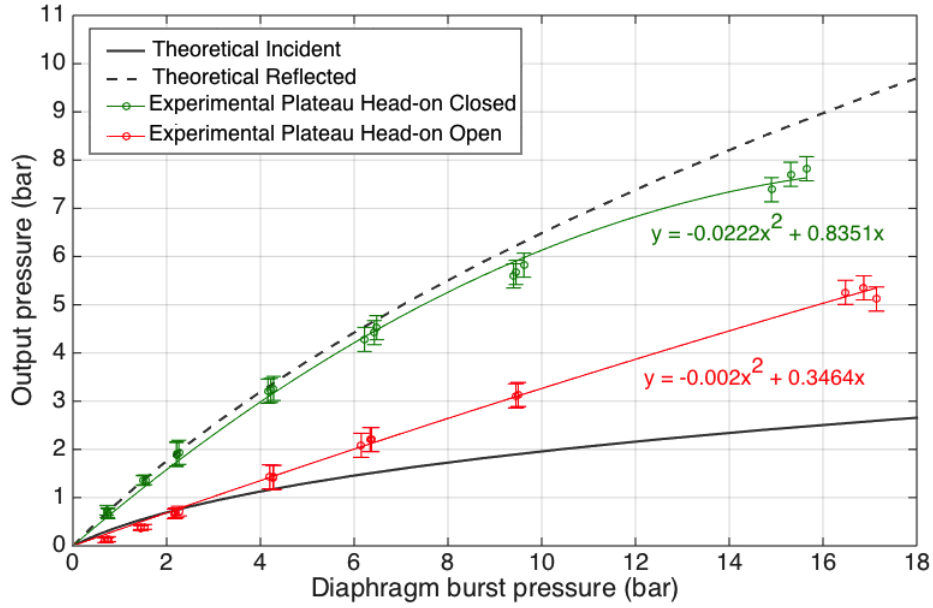


Figure 4.3: Expected plateau pressures of output blasts generated from various diaphragm burst pressures

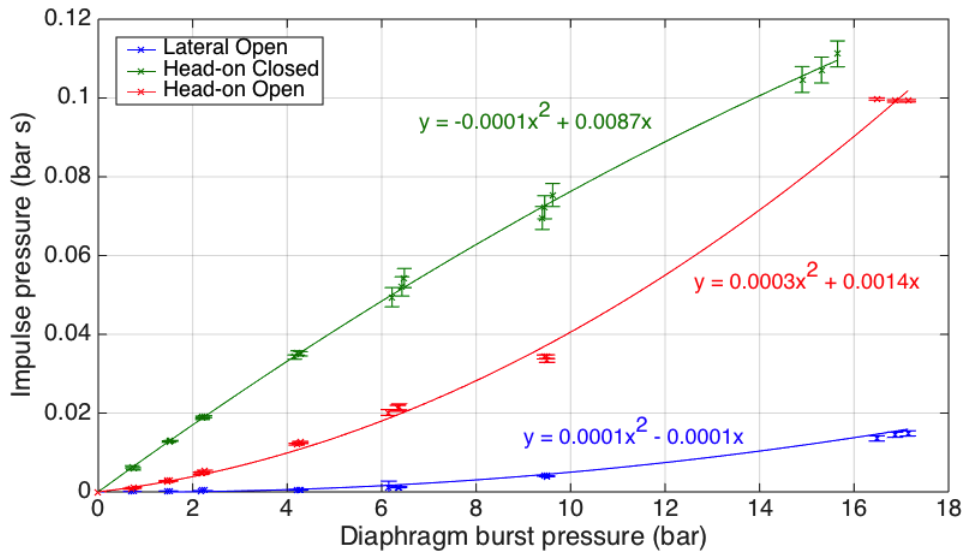


Figure 4.4: Expected shock impulse of output blasts generated from various diaphragm burst pressures

Most of the time, with sample at the outlet of the shock tube, it was not possible to measure the head-on pressure while it was possible for lateral pressure. Hence, the relationship between the lateral and head-on pressure needs to be established so that one can actually estimate the head-on pressure from the lateral pressure. This relationship is linear for both open and closed tube configuration (Figure 4.5). The steeper trend for the closed configuration, i.e. higher head-on pressure corresponding to the same lateral pressure magnitude, is expected as the area of reflected surface is greater in this case.

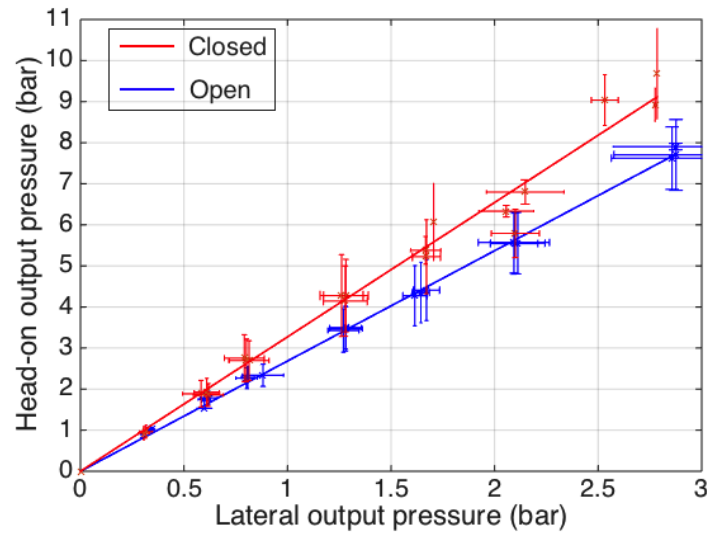


Figure 4.5: Relationship between the output lateral pressure and head-on pressure for open configuration

4.1.2 The effect of the stand-off distance from the shock tube outlet

For samples mounted axially to the open shock tube, the distance from the outlet is an important factor affecting the magnitude of the blast loadings.

Figure 4.6 shows that for full driver volume, at around 40 mm away, the peak pressure goes on a rapid exponential drop while the plateau pressure from the building-up gas remains approximately the same. At sufficient distance, the peak pressure can even drop below the plateau pressure.

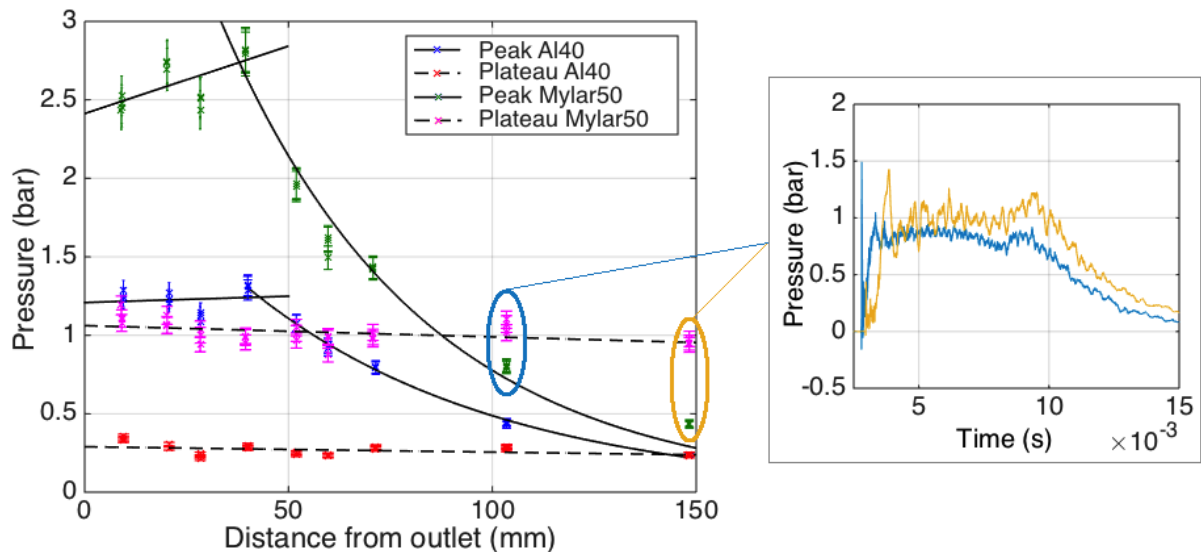


Figure 4.6: Output pressure magnitudes at various distances from the shock tube outlet

The drop-off distance (distance at which the peak pressure starts to decrease) varies with the volume of the driver section. The method of changing this driving volume is discussed in 4.2. Here, the trend in Figure 4.7A shows that as the driving volume decreases, the drop-off distance increases. In all cases, the shock impulse stays approximately the same, just as the plateau pressure (Figure 4.7B).

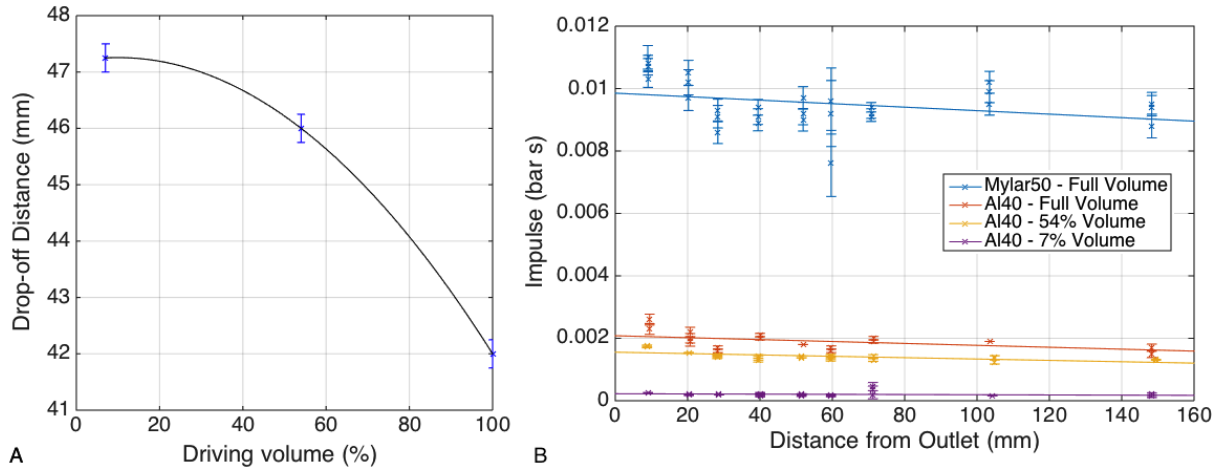


Figure 4.7: A - The effect of driving volume on the drop-off distance. B - Output impulses at various distances from the shock tube outlet.

4.2 Blast duration

If the thickness and material of the diaphragm determine the burst pressure, and hence the magnitude of the blast output, it is the length of the driving volume that controls the duration, and hence shape of the output pressure. In this shock tube system, the charging length can be reduced by inserting different number of 10 – mm – long polyethylene units into the driver section (Figure 4.8). These units are joint together by custom-made double-headed bolts, and the whole length is screwed onto the bolt ring attached to the inlet flange to stop the insertion from moving during experiments. There is a 6.5 mm tunnel running through the whole insertion in order to charge the section from the inlet flange. The detailed designs of these parts are shown in Figure 4.11, 4.12, and 4.13.

Figure 4.9 shows the effects of varying the driving volume on the output of the shock tube. The pressure magnitudes stay approximately the same while the duration of the plateau pressure changes, hence the overall impulse, changes with the charging volume.

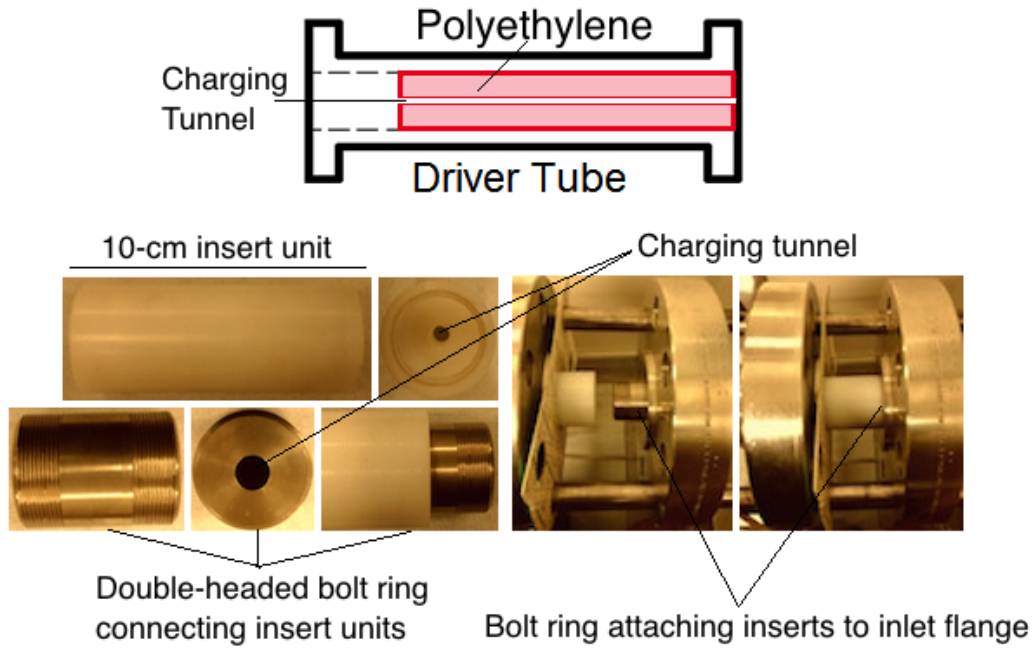


Figure 4.8: Polyethylene inserts for reduction of the length of driver volume

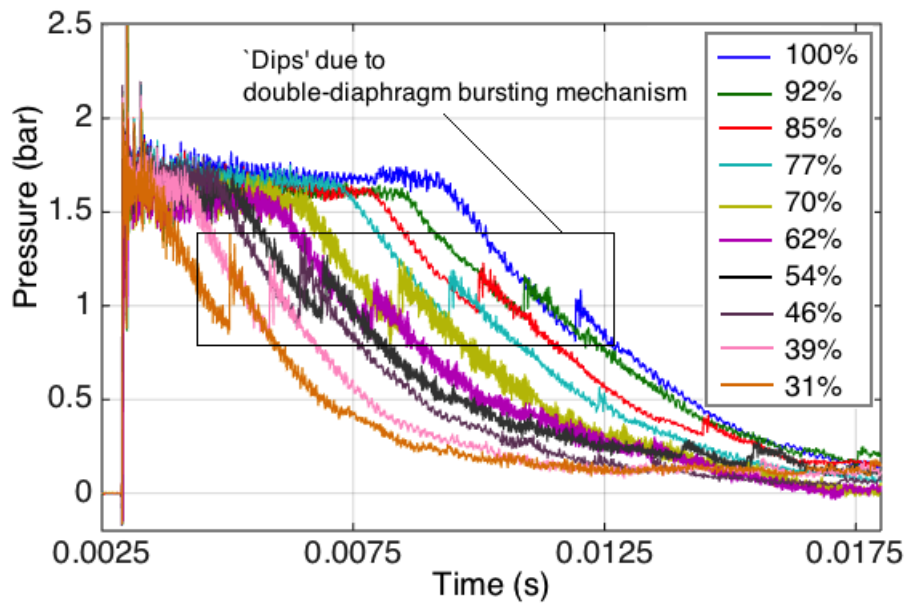


Figure 4.9: The effects of changing driving volume on the blast output. The ‘dip’ feature in the pressure profiles is due to the double-diaphragm set-up as discussed in Section 3.1.

The actual relationships between the volume of the driver section and the output plateau duration and impulse are displayed in Figure 4.10. The ability to change the shock duration without altering the shock magnitude enables the investigation of the effects of different blast features on a sample: for the same impulse, is a stronger and shorter blast or a weaker and longer blast more damaging? As a result, the focus of

mitigation strategies can be addressed for different types of blast injuries.

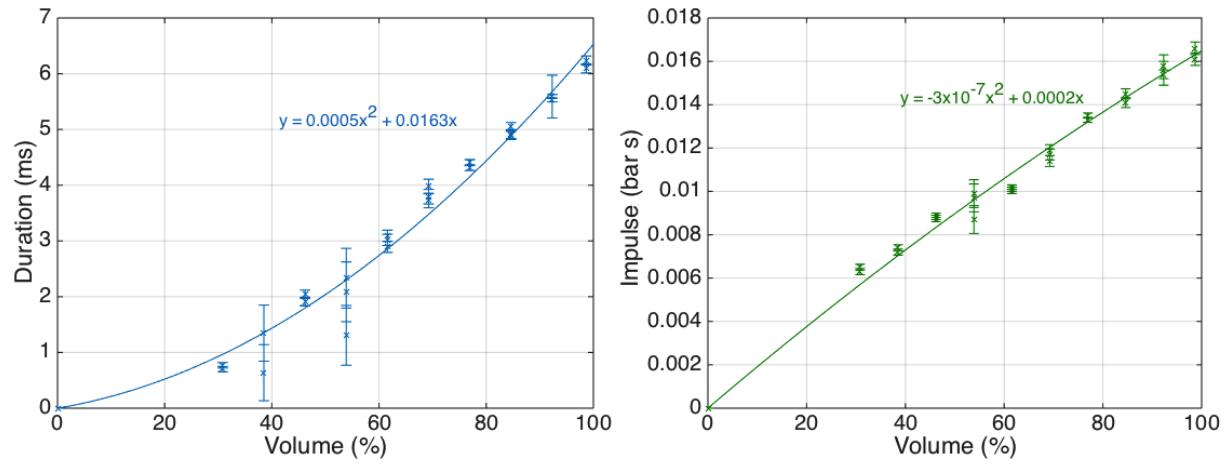


Figure 4.10: The relationships between the driving volume length with (A) the duration of output plateau pressure, and (B) the output impulse

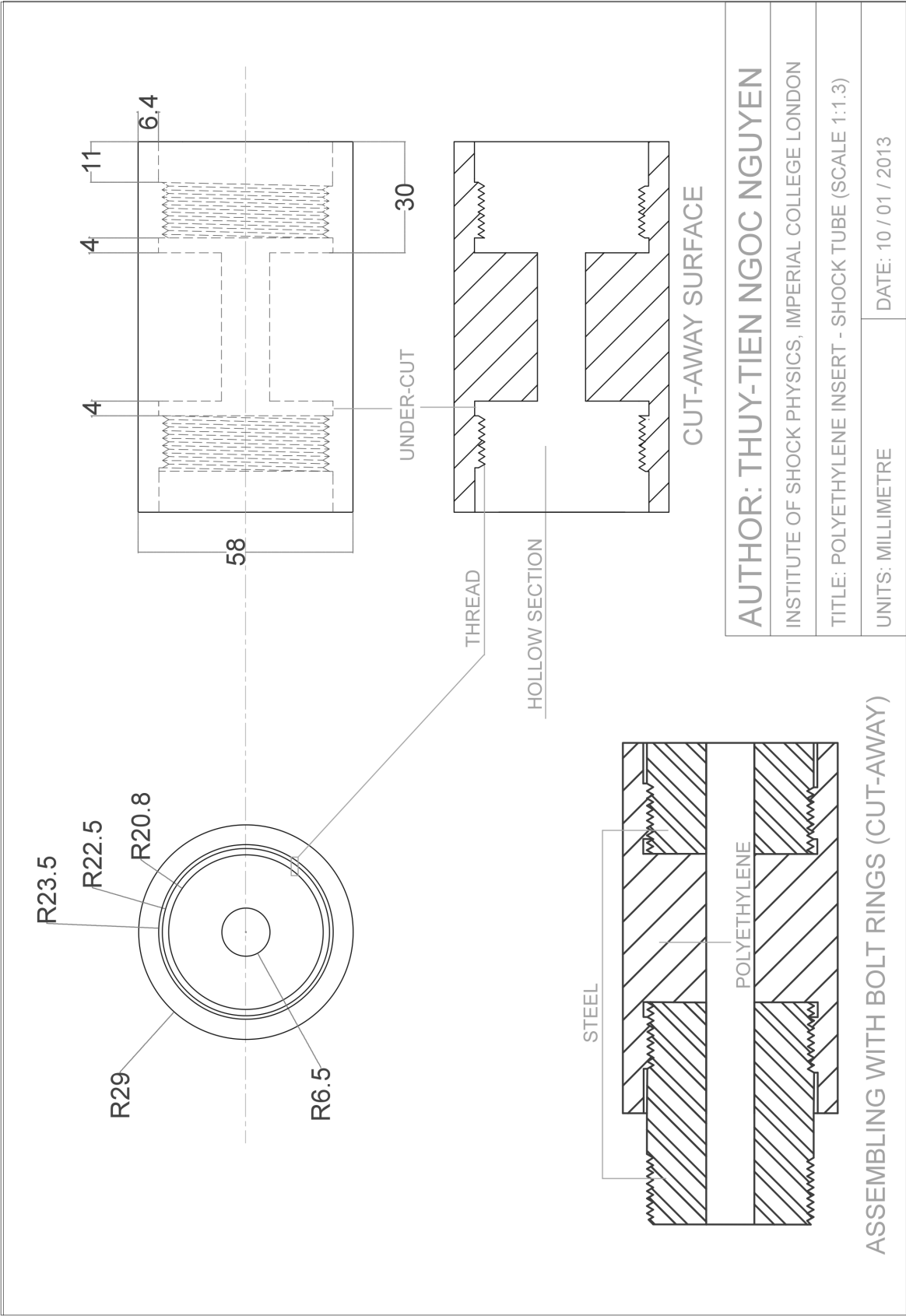


Figure 4.11: Drawing of the polyethylene unit insertion

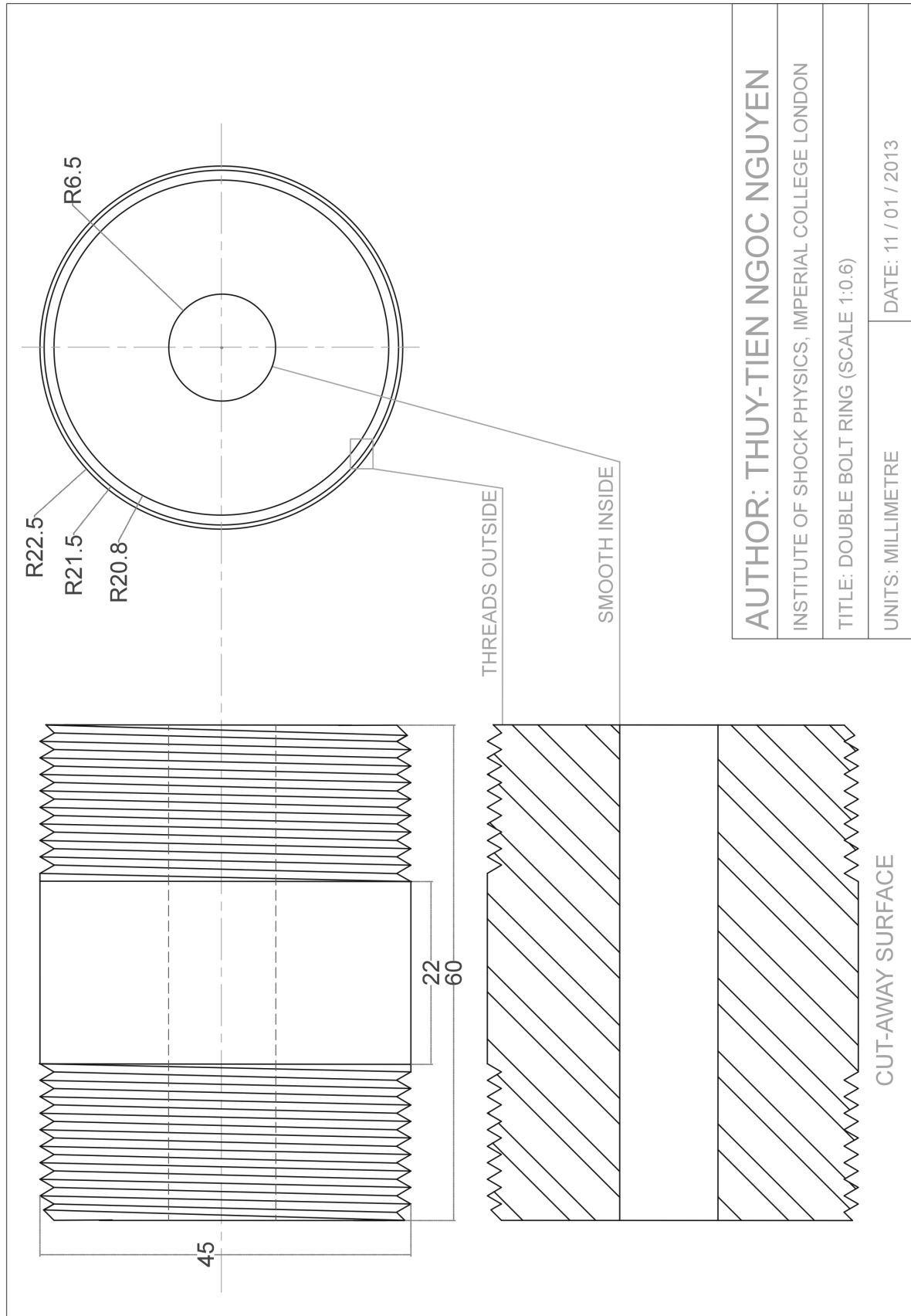


Figure 4.12: Drawing of the double-headed bolt ring for joining polyethylene inserts together

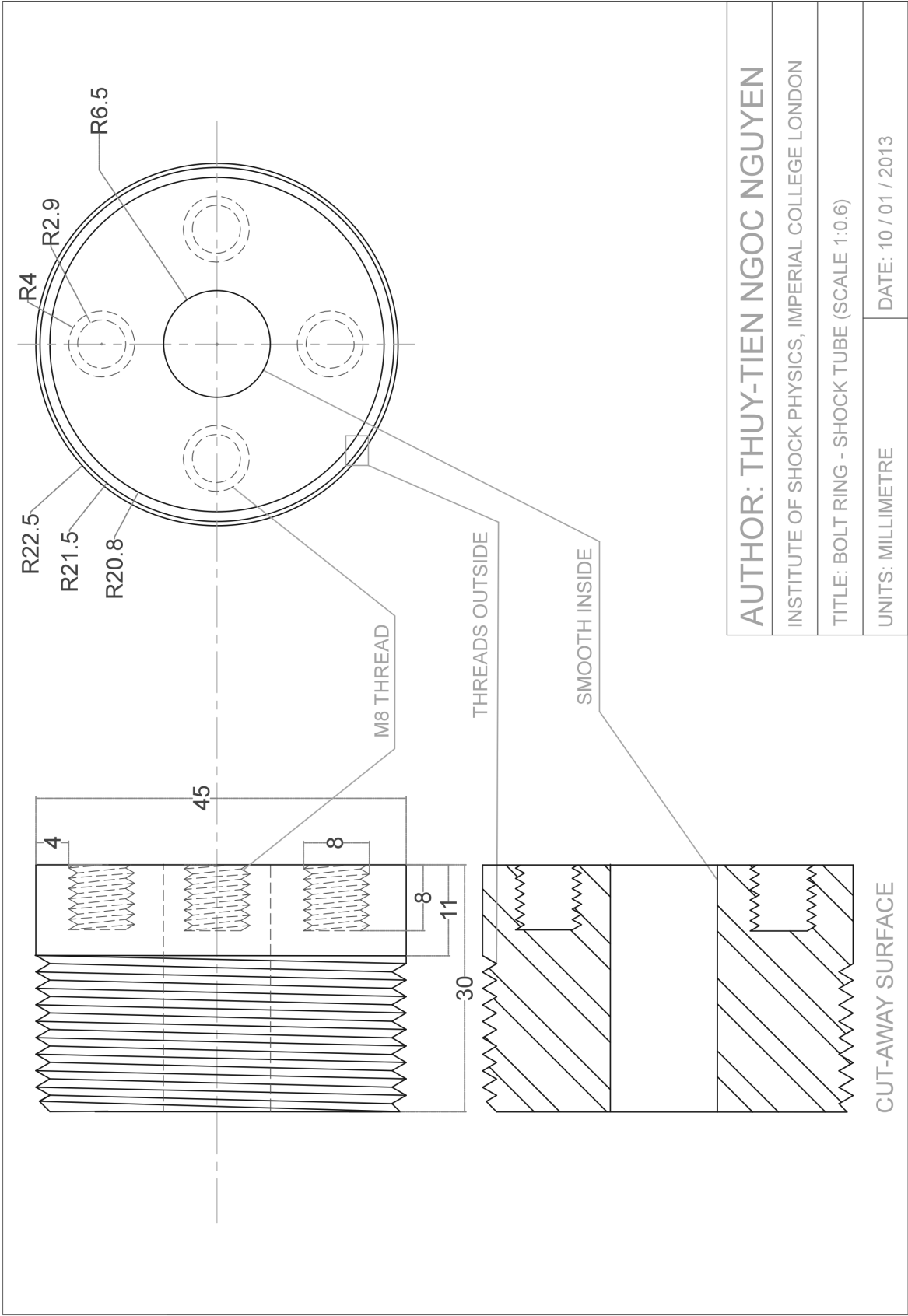


Figure 4.13: Dwaing of the bolt ring for attachement of the insertion to the inlet flange

4.3 Tailoring blast outputs for different scenarios

For blast injuries inflicted during a combat situation, the two most common scenarios are the open field blast simplified as the Friedlander waveform, and the in-vehicle blast simplified as the longer peak duration with secondary pressure spikes as shown in Figure 4.14.[53]

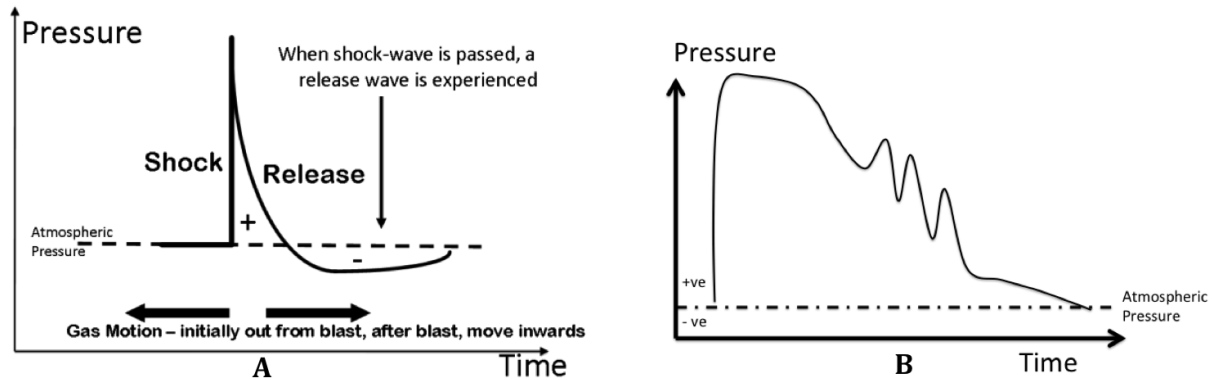


Figure 4.14: The schematic representations of the (A) open field blast, and (B) in-vehicle blast. Reproduced from [53].

In order to reproduce a meaningful blast loading scenario, it is essential that the shock tube system can tailor the blast outputs to desired strength, duration, and shape. This can be done by combining various operating conditions such as the choice of diaphragm, the charging length of the driver section, and the outlet configuration (closed or open) as discussed previously. In this section, three examples are given for three loading scenarios:

- Example 1 (Figure 4.15) - The use of the smallest length of the driving gas volume (giving 7% volume of the driver section) and the open tube configuration generates a blast output very similar to the classical Friedlander waveform. This is relevant to the unconfined explosion such as in an open, empty field.
- Example 2 (Figure 4.16) - The use of the full volume of the driver section and the open tube configuration generates a blast output with a long plateau duration, followed by a decay to the underpressure region. This is relevant to the partially-confined explosion such as in a urban square surrounded by high buildings.
- Example 3 - (Figure 4.17) - The use of the full volume of the driver section and

the closed tube configuration generates a blast output with a long plateau duration (representative of the building-up gas pressure), followed by second blast reflected from the sealed end of the tube making the sample undergoing multiple blasts. This is relevant to the fully-confined explosion such as inside a vehicle or shelter.

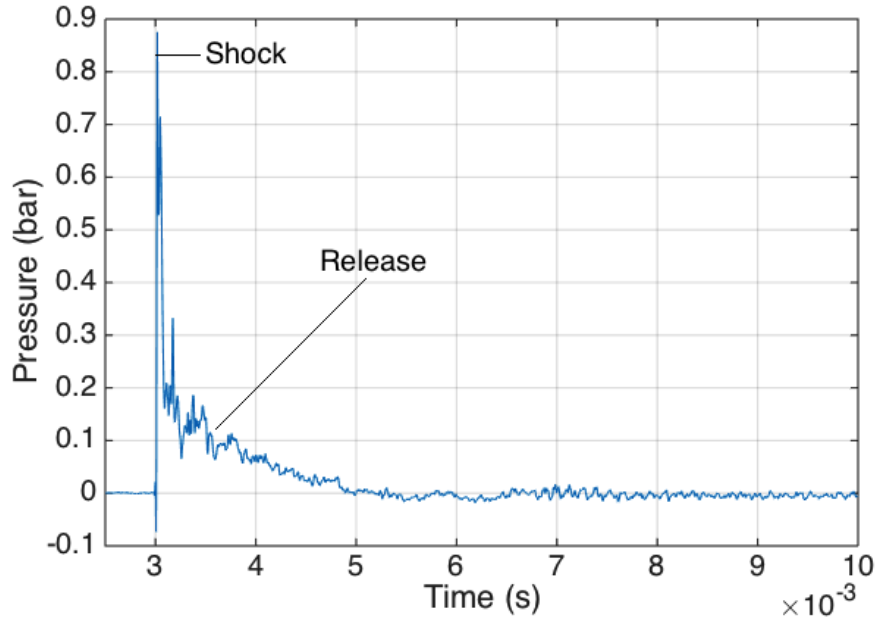


Figure 4.15: Example 1 - Axial output from the bursting of 23 μm Mylar[®] diaphragm with 7% driver volume, and in the open tube configuration

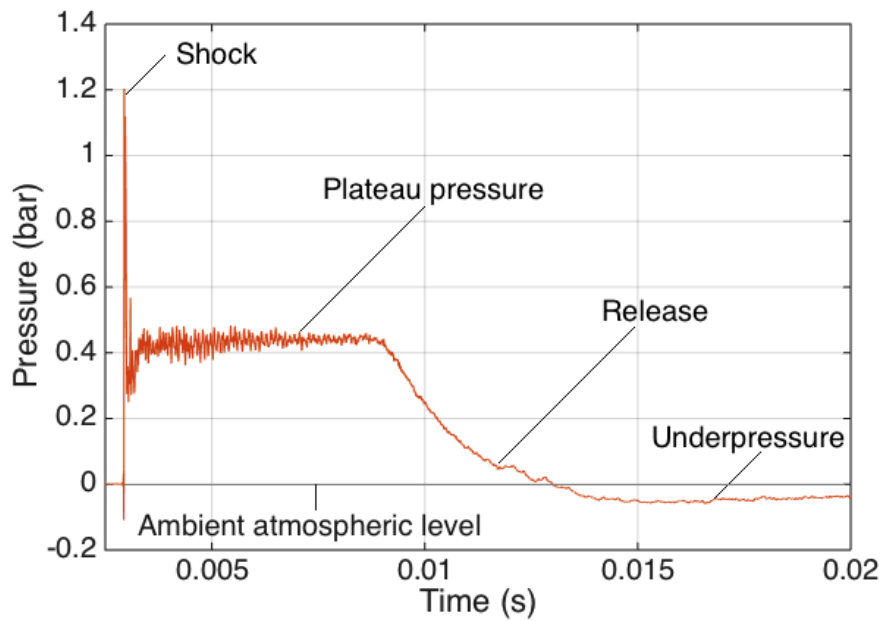


Figure 4.16: Example 2 - Axial output from the bursting of 23 μm Mylar[®] diaphragm with full driver volume, and in the open tube configuration

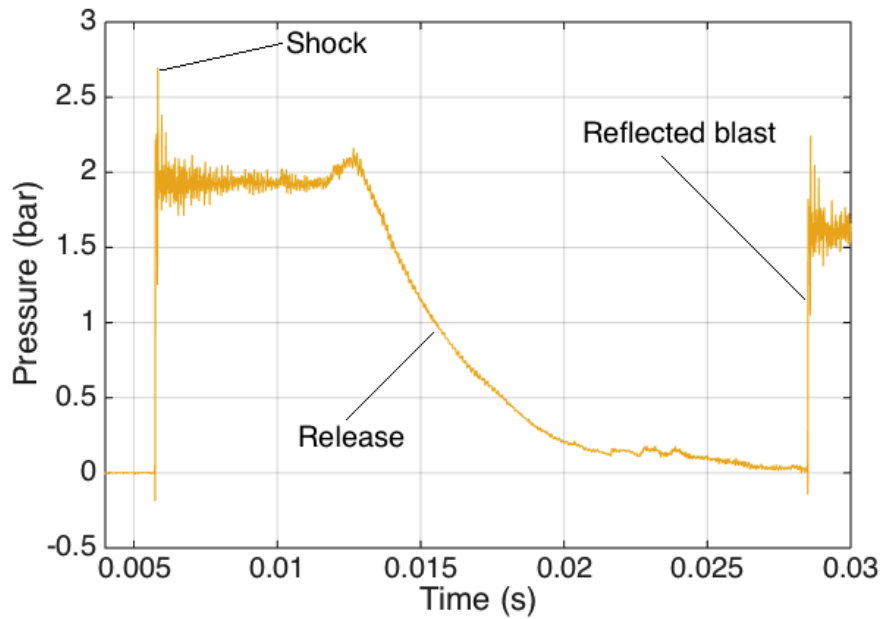


Figure 4.17: Example 2 - Axial output from the bursting of 23 μm Mylar[®] diaphragm with full driver volume, and in the closed tube configuration

4.4 Conclusions

The CBIS shock tube can be used to study blast effects on biological samples representing injuries in open space as well as inside vehicles. Samples can be subjected axially or laterally to the shock tube. The location of the sample, together with its size, govern the pressure loading on the sample. Larger samples experience greater pressure magnitude due to their larger surface of reflection. Axial samples experience more direct effect of the gas flow. At a sufficient distance (~ 40 mm), the pressure magnitude exerted on axially mounted samples drop off quite rapidly.

The magnitude, as well as impulse, of the blast wave generated can also be manipulated with the diaphragm burst pressure which is linearly proportional to the diaphragm thickness. The duration of the shock pulse can be tailored, without significantly affecting its magnitude, by adjusting the volume of the high-pressure driver gas.

The output lateral pressure was characterised against the output head-on pressure, showing a linear relationship. This is useful when samples are at the exit of the shock tube, making it impossible to measure the head-on pressure simultaneously without the sensor mount interfering with the shock wave.

Chapter 5

Studies of Blast Interactions and Mitigations

The effects of exposure of the human body to blast are a growing part of modern research in bio-engineering. As mentioned in Section 1.1, air-filled structures are the most vulnerable to primary blast effects: tympanic membrane perforation occurs at low overpressure and is the most common outcome while pulmonary barotrauma is the deadliest injury [12]. Currently, the CBIS shock tube system is employed for various studies of primary blast injuries such as blast lung trauma, traumatic brain injuries, blast-induced heterotopic ossification, and primary blast limb trauma.

Using the general output characterisation results reported in Chapter 4, the generation of the blast outputs can be controlled. However, most samples (e.g. whole animals, organs, tissues, cells) are placed in different designed-for-purpose mountings. The interactions (such as reflections, diffractions, etc.) with the output blast waves can be complex. This adds more complexity to the blast loading experienced by the samples. Therefore, characterisation is required for each experimental sample mounting.

On the other hand, in order to minimise primary blast effects, it is desirable to reduce the peak overpressure and impulse. Granular and porous materials constitute a key part of protective measures against the damage of blasts. With their shock attenuation properties, granular materials, porous materials and foams are used to provide protection

as well as in air-vents to reduce the amount of blast exposure [54].

The study of shock attenuation is also an important and fundamental aspect of fluid dynamics and engineering [55]. It has applications such as in the structure and flow of gas and oil in the earth's crust, the behaviour of structures during earthquakes, the effect of industrial explosions of buildings, and the processing and transportation of flammable fuels or gases [56][57][58]. The interaction of granular energetic materials with shock waves have been investigated in order to learn about the deflagration-to-detonation transition to improve methods of explosive welding [59] and powder compaction [60].

This chapter addresses some examples of blast interactions with mitigation structures as well as biological sample mounts. These examples are chosen to reflect different application aspects, which can give more insight into the working mechanism of the system.

5.1 Interactions with perforated sheet structures

5.1.1 The perforated galvanised steel sheet

Galvanised steel sheets of triangular-pitched perforation manufactured by Robert Bion & Co. were used in this experiment series. These sheets are easily acquired, light-weight, low-cost materials, and commonly used in ventilation air-ways and facades of most modern constructions. They were all 0.7 mm thick with different percentages of open area, hole sizes and configurations as shown in Table 5.1.

As shock waves arrive at the perforated sheet, they are partially transmitted and partially reflected. The pressure transmission ratio for a perforated sheet of the percentage of open area k can be calculated as:

$$\tau_k = \frac{P_{t,k}}{P_{t,100}}, \quad (5.1)$$

where $P_{t,k}$ is the transmitted pressure behind the perforated sheet with $k\%$ open area, and $P_{t,100}$ is the “transmitted pressure” for 100% open area (no perforated inserted), in other words “incident pressure” measured by the second lateral sensor. This equation was proposed by Kingery *et al.* [62] in their study of parameters affecting the attenuation

of shock waves passing through vented wall plates. Their perforated steel plates were especially made to investigate variables such as hole size, number of holes, and a helium-driven shock tube was used to address the effect of incident peak overpressure. They found (i) no trend regarding the pressure transmission ration or percentage of attenuation, (ii) the hole size did not affect the attenuating performance of the perforated plate, and (iii) the transmitted pressure is directly proportional to the incident pressure for the range of vent areas tested.

% Open area	Hole diameter [mm]	Hole configuration	Pattern
22	1.5	Round, 45°	
46	1.0	Round, 60°	
68	8.0	Round, 60°	
79	6.0 (across flat)	Hexagonal, 60°	

Table 5.1: Technical specification of perforated steel sheets used [63]

5.1.2 The experimental set-up

The single perforated sheet was placed into the CBIS shock tube system as shown in Figure 5.1. An 35-cm-long acrylic extender tube of the same internal diameter as the original shock tube was used to give transmitted shock waves enough distance to stabilise. Piezoelectric transducers (Dytran[®] 2300V1) were positioned laterally, flush to the wall of the shock tube ahead of (sensor 1) and behind (sensor 2) the sheet.

Blast waves of three different Mach numbers were used, produced with three different diaphragms: 40 μm aluminium (Al), 23 μm Mylar[®] and 50 μm Mylar[®].

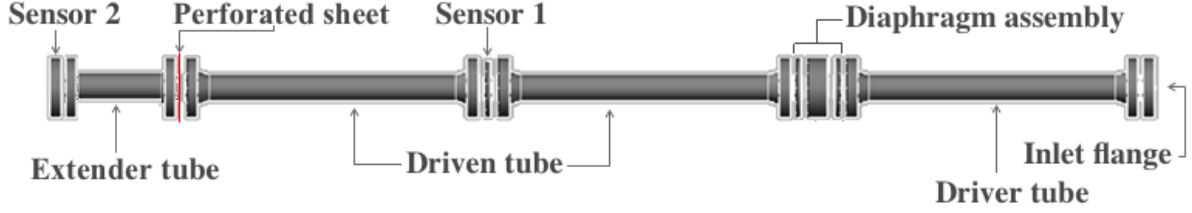


Figure 5.1: The schematic of the shock tube with a perforated sheet and extender tube inserted at the end. Sensor 1 and 2 are approximately 123 cm and 36 cm from the perforated sheet respectively.

5.1.3 Results and discussions

As the shock wave arrive at the perforated sheet, it is transformed into transmitted and reflected waves. Figure 5.2 displays pressure traces of the transmitted waves for different percentage of open areas. With increasing open area, the amount of pressure transmitted increases, and the reflected shock decreases.

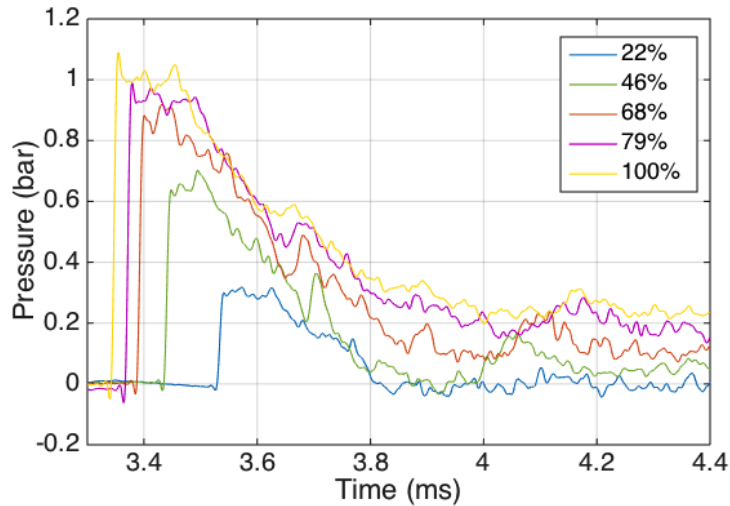


Figure 5.2: Pressure profiles recorded by the second lateral sensor for perforated sheets with different percentage of open area: 22% (blue, lowest), 46% (green, second lowest), 68% (red, middle), 79% (margarita, second highest), and no perforated sheet or 100% (yellow, top). The diaphragms used were 50 μm Mylar[®]. They respective produced loadings of Mach 1.61, 1.78, and 2.15.

The variation of the pressure transmission ratio calculated by Equation 5.1 with percentage of open area of perforated sheets for all incident shock strengths is shown in Figure 5.3A. The trend exhibits an increase in the amount of pressure transmission with increasing open area, which approaches 1, *i.e.* 100% transmission, as the open area reaches 79%. The trend holds regardless of the perforation configuration and the strength of the inci-

dent blast used. Figure 5.3B shows linear relationships between the transmitted pressure with the incident pressure (which is effectively the same as transmitted pressure of 100% open area as the shock attenuation is negligible over such a short distance) for different open areas, in the pressure range studied. This agrees with results from the study by Kingery *et al.* [62], and emphasises again that the amount of mitigation is higher for smaller open area.

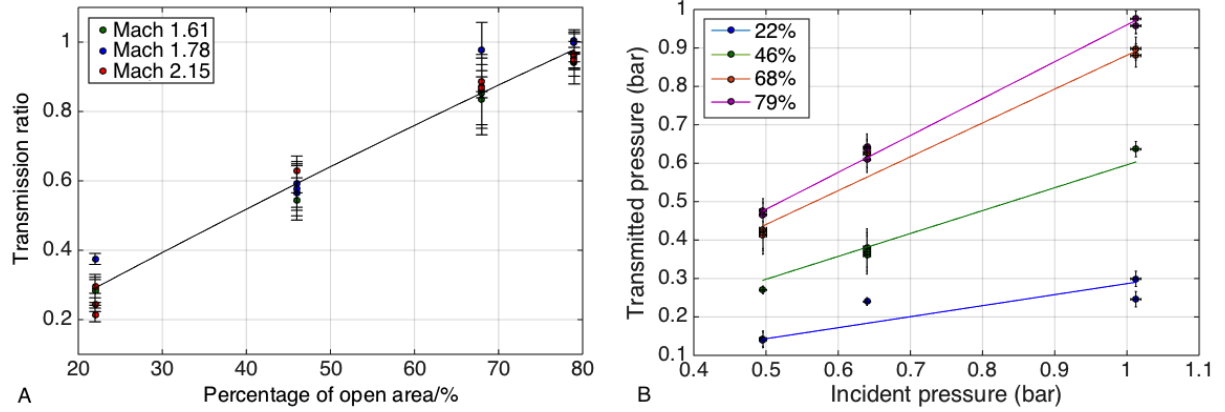


Figure 5.3: A - Pressure transmission ratio calculated using Equation 5.1 of different percentage of open areas, for all three types of diaphragms used in this investigation. B - Transmitted pressure versus incident pressure for different open areas.

Another parameter investigated is the shock impulse. Figure 5.4 display the relationship between the percentage of perforation with the percentage of impulse transmitted and reflected. For the range from 22% to 79% open area, the impulse transmitted increases linearly with the open area and the reverse is true for the amount of impulse reflected as expected. Data from sensor 2 for the 68% open area has a wide spread of value due to the large hole diameter causing unstable mounting, hence more vibration, of the perforated sheet. The same data for sensor 1 is less spread out thanks to the longer distance between the perforated plate and the sensor for stabilisation. For each percentage of open area, there is about 5% of impulse lost, which is likely due to absorption by the vibration of the perforated sheet itself.

Schlieren photography (Figure 5.5) shows that for all perforated sheets, the initial shock wave, vortex formation and escape of gas (just as observed in the basic system) are followed by a small second shock wave, which is the reflected shock wave from the perforated sheet after travelling back and forth once more inside the shock tube, and

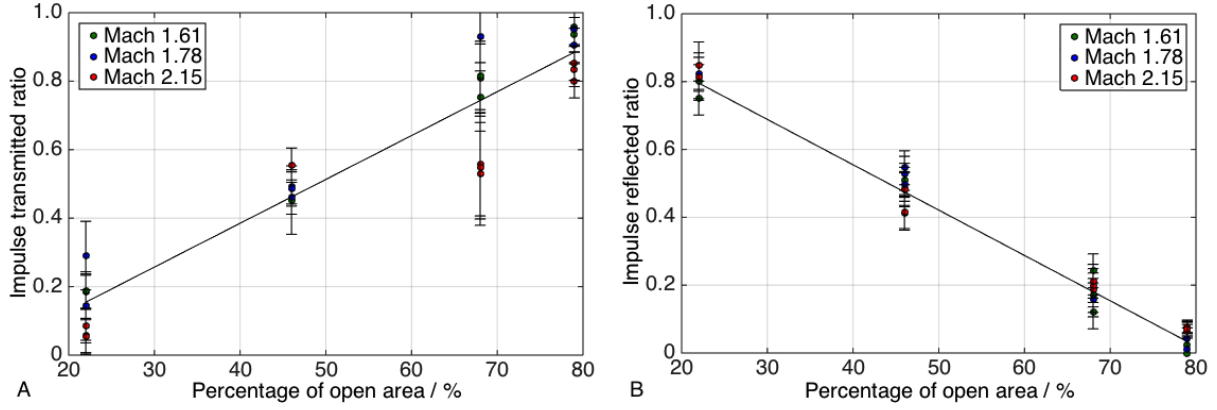


Figure 5.4: Percentage of (A) impulse transmitted and (B) impulse reflected for different perforations

more percolation of gas. The initial shock wave is weaker (dimmer) and decays over a shorter distance as open area decreases. The second shock wave is stronger (more visible) for smaller open area as greater amount of incident shock is reflected from the perforated sheet, which arrives at the sheet again after travelling back and forth in the shock tube. The amount of gas percolating out through the sheet appears to concentrate more in the earlier period for perforated sheet with higher open area explaining the greater impulse of the initial blast wave (the first positive overpressure region) for these cases. Observations from the perforated sheet of 79% open area is very similar to those in the basic system as almost no mitigation effect is offered by this structure.

The work on perforated sheets can be expanded in various directions. In addition to the open area, other aspects of perforated sheets can be characterised such as thickness, holes size, holes distribution, and the materials of the sheet itself. Various arrangements can also be studied: multiple layers of perforated sheets of same and different open areas and orientations, and separated at various distances. These can address the practical application of perforated sheets, e.g. shock reduction in air ventilation: how to attenuate more of the blast, how to reduce more of the transmitted impulse, and the durability of perforated sheets undergoing long-term exposure to multiple blasts.

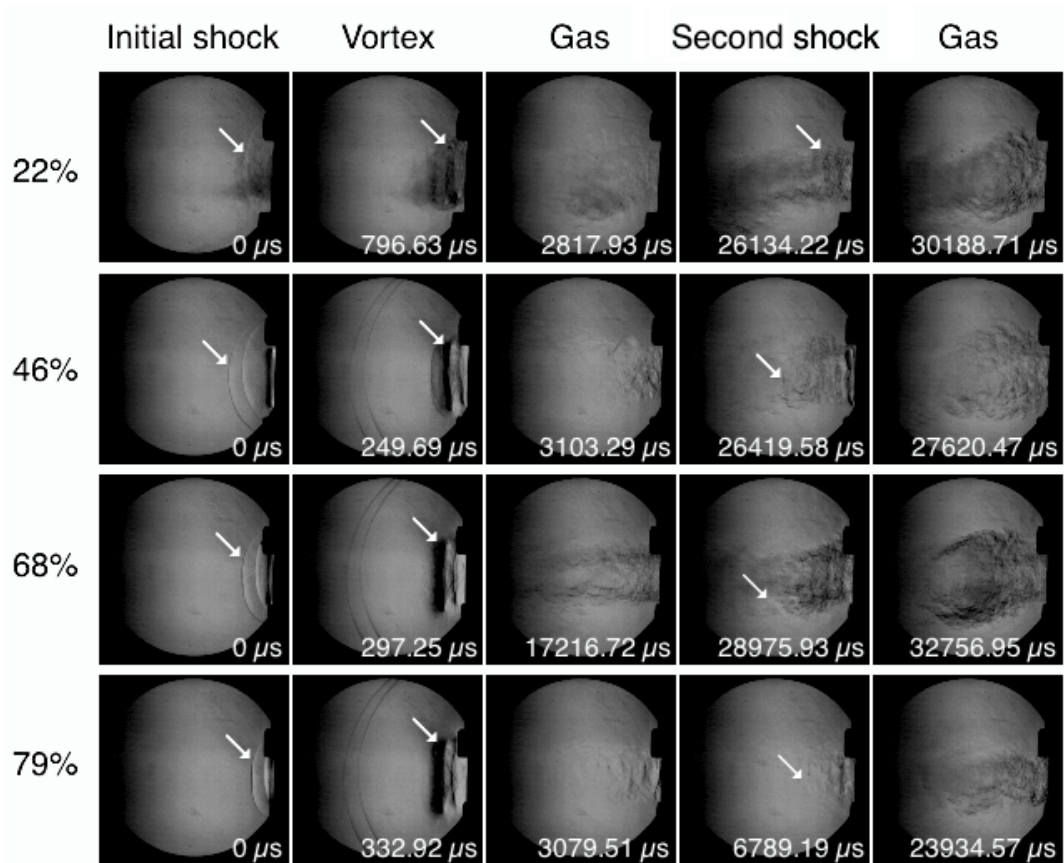


Figure 5.5: Schlieren snap shots of Mach 1.3 output blast behind a single perforated sheet of open area 22%, 46%, 68%, and 79%. The interframe time was 11.89 μ s and exposure time was 2 μ s. Extender tube was removed to give better view of the blast wave.

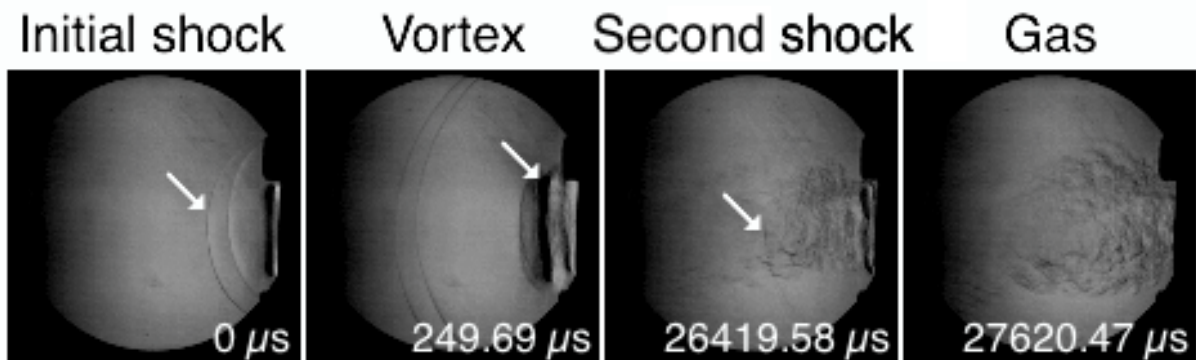


Figure 5.6: Enlarged schlieren images of transmitted blast features behind 46% perforated sheet as shown in Figure 5.5

5.2 Interactions with reticulated acoustic foams

Cellular materials (such as reticulated polymers, pre-crushed honeycomb structures, metal foams, etc.) can be use for blast mitigation due to their compressibility. Introduced between the blast wave and the protected object, these materials can undergo large volume

reduction, attenuate the pressure, and absorb kinetic energy of the blast [64]. In 2014, Wilgeroth *et al.* [65] reported mitigation of $\sim 10\%$ of the incident peak pressure using reticulated polyurethane foam of 40+ mm thickness and porosity between 65 - 79 ppi (pore per inch). This mitigation reduces the pressure to well below the threshold of tympanic membrane rupture. However, due to foam deformation causing secondary ramp loadings, the overall mitigation effect was limited. In this series of experiments, the same reticulated polyurethane foams were used, but with an improved shock tube set-up, to investigate variables such as foam density and thickness in more details. This section is based on the work published in the paper by Nguyen *et al.* [66].

5.2.1 The reticulated polyurethane foams

The materials used were the reticulated polyurethane foams from Acoustaf foam Ltd. (Figure 5.7A). The controlled ignition of gas such as hydrogen was employed to remove faces of a closed-cell foam, leaving a skeleton frame with a very regular pore size as shown in the scanning electron micrographs in Figure 5.7B. According to an investigation of acoustic absorbance by ISO: 10534-2 shown in Figure 5.7C, the peak absorption of an open-cell foam of the type investigated in this work is approximately between 3.5 and 4.5 KHz which is the middle-to-high frequency range of a snare drum [65]. Such foams are characterised in terms of pores per unit length.

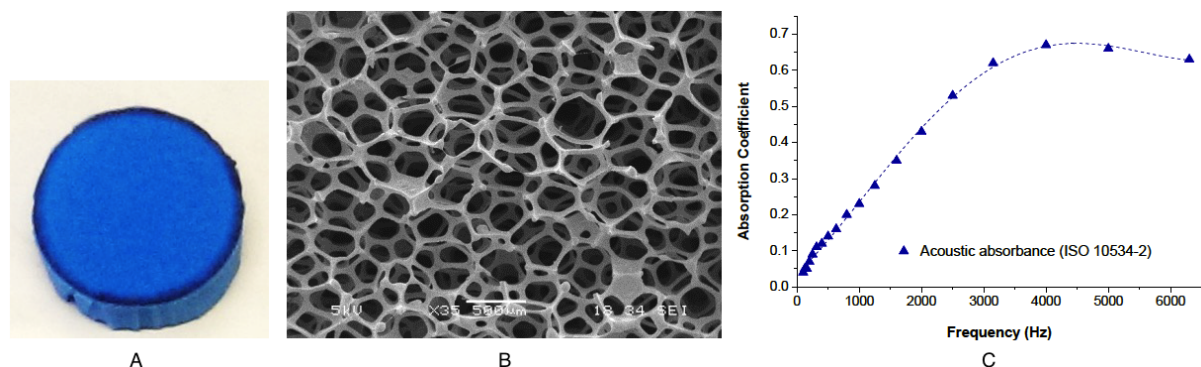


Figure 5.7: A - An Acoustaf foam reticulated polyurethane foam sample. B - Scanning electron micrograph of an 79 ppi foam, taken by a JEOL JSM-5610LV variable pressure scanning electron microscope, field of view $\sim 10.5 \text{ mm}^2$. C - Acoustic absorbance measurements of reticulated polyurethane foam, taken with a Type 4206 B&K Absorption Tube and a Type 3560 Pulse Analyser. Reproduced from [65].

Reticulated foams of 65, 69, 75, and 79 ppi (pores per inch) with average density 29-34 g/cm³ were obtained for experiments. A Micromeritics AccuPyc II 1340 Helium Pycnometer was employed to the density of these samples, hence their solid proportion (*i.e.* porosity) as shown in Table 5.2. Various thicknesses between 20 mm to 60 mm of 79 ppi foam samples were looked at to address the effect of foam thickness in mitigating performance.

Pore per inch [ppi]	Solid proportion [%]
79	1.54 ± 0.05
75	1.94 ± 0.06
69	1.95 ± 0.06
65	1.99 ± 0.07

Table 5.2: Pore distribution and porosity of foam samples used in this work

5.2.2 The experimental set-up

Figure 5.7 shows the adaptation of the CBIS shock tube system, with the use of a 20.5-cm-long extender tube, to minimise the effect of foam deformation. Again, piezoelectric transducers (Dytran[®] 2300V1) were positioned laterally, flush to the wall of the shock tube ahead of and behind the insertion. In this case, lateral sensor 3 downstream was used to monitor and compare the output behind the foam with the case of no foam at all for 100% transmission. For all investigations, 50 μ m Mylar[®] diaphragms were used to produce the incident blast loadings of Mach 2.15.

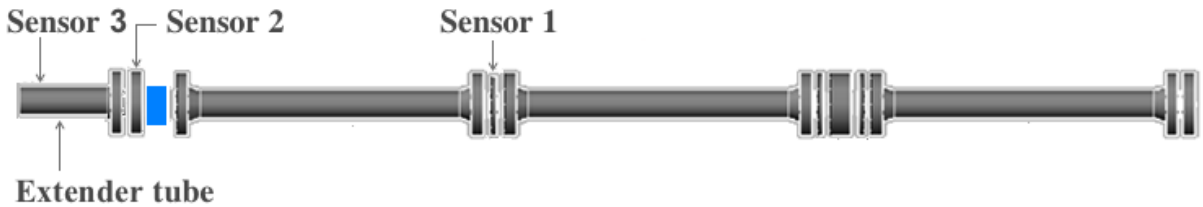


Figure 5.8: The schematic of the shock tube with a foam sample and extender tube. Sensor 1 and 3 are approximately 123 cm and 20 cm from the front and back of the foam respectively.

5.2.3 Results and discussions

Figure 5.9 shows the transmissions of pressure and impulse through reticulated foam against density (pore distribution). The amount of transmitted peak pressure is less for denser foam while the transmitted impulse stays approximately the same for the whole range.

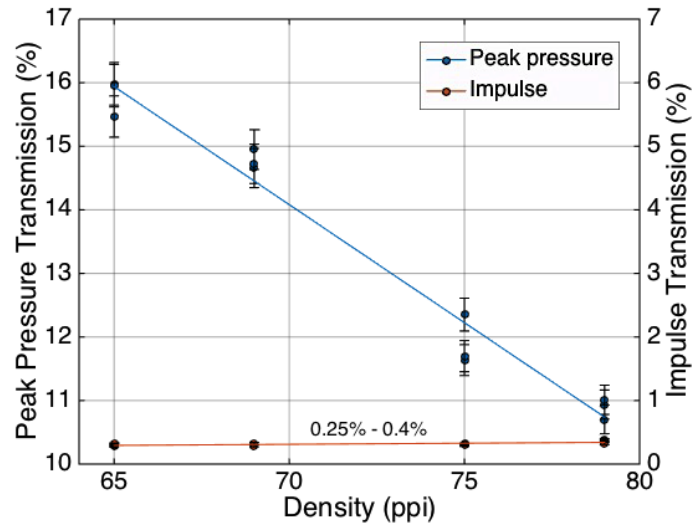


Figure 5.9: Pressure and impulse transmission versus foam density behind reticulated foam

From the density study, 79 ppi foam was chosen for further investigation for mitigation effects of the foam thickness as it offers the highest attenuation performance. As thickness increases, the transmitted peak pressure decreases between 20% to 5% while the shock impulse remains between 0.3% and 0.5%.

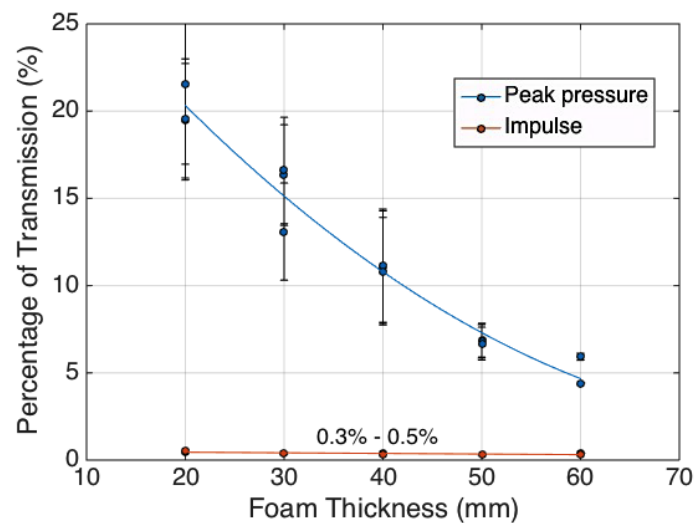


Figure 5.10: Pressure and impulse transmission versus foam thickness

The reticulated foams were observed to slightly reduce in thickness after each test, but they all expanded back to their original thicknesses within 5 minutes and gave the same performances for repeat experiments. A scanning electron micrograph (Figure 5.11) was taken for the blasted sample of 79 ppi foam, which shows no change in the foam structure as compared to the unblasted sample (Figure 5.7B).

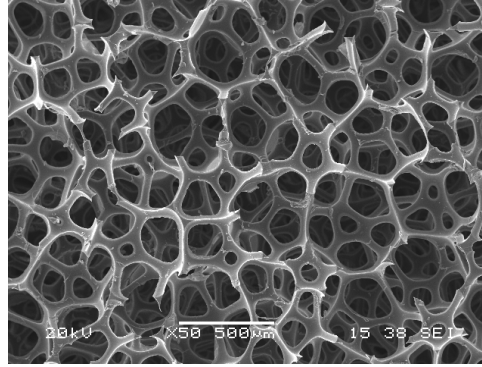


Figure 5.11: Scanning electron micrograph of a blasted 79 ppi foam, taken by the variable pressure scanning electron microscope JEOL JSM 5610 LV (0.5-35kV)

5.3 Interactions with reticulated foam - perforated steel sheet combination

This section is based on the work published in the paper by Nguyen *et al.* [66]. Following the work reported in Section 5.1 and 5.2 on perforated galvanised steel sheets and reticulated polyurethane foam, the combination of these two structures in a sandwich panel was investigated. Similar sandwich structures of metal perforated facesheets and low-density fiberboard or mineral wool core have been commonly used in building construction for their sound insulation and fire resistance abilities [67][68]. Here, the blast attenuation property of such structure is reported.

Other types of sandwich panels are also used in studies of blast mitigation such as E-glass quadriaxial skins (facesheets) with 40-mm-thick styrene acrylonitrile (SAN) foam core [69], E-glass vinyl-ester (EVE) facesheets with Corecell™ A-series foam core [70], and metal square honeycomb core panels with solid-plate facesheets of the same areal density [71]. They all found significant resistance to shock loadings of air blasts.

5.3.1 The reticulated foam - perforated sheet sandwich structure

Based on the study of galvanised steel perforated plates (Section 5.1), two types of perforates sheets were chosen as materials of the facesheets of the sandwich panel: 22% and 46% open area providing attenuation to approximately 30% and 60% respectively (Figure 5.12). These galvanized steel perforated sheets can be considered as stiff (22%) and relatively flexible (46%) structures. For practical applications, thinner foams were used as the core of the sandwich structures: 20 mm and 40 mm foams allowing for 20% and 11% transmission respectively (Figure 5.12).

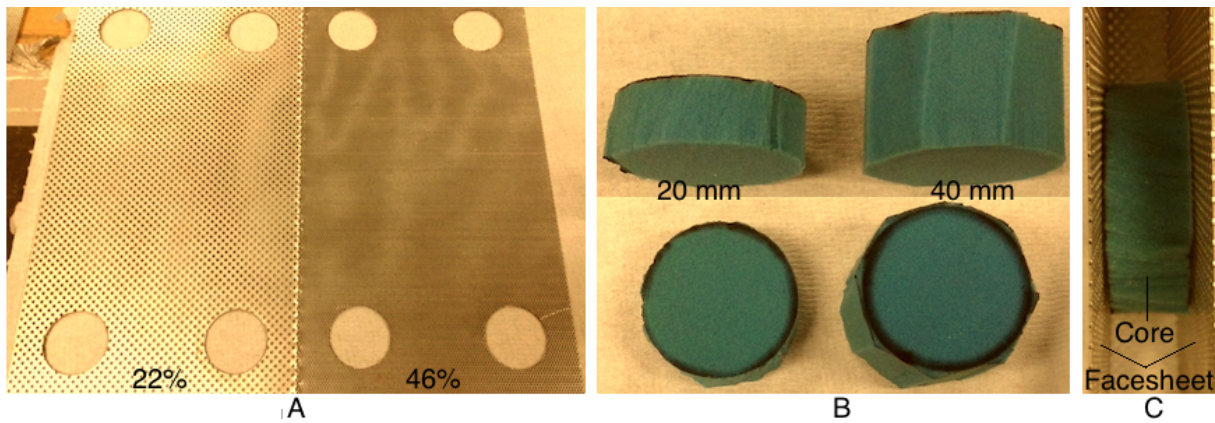


Figure 5.12: A - Perforated galvanised steel sheet of 22% and 46% open area. B - Reticulated polyurethane foam of 20 mm and 40 mm thickness. C - The sandwich structures combinations of perforated steel sheet and polyurethane foam.

5.3.2 The experimental set-up

Sandwich structures of sheet-foam-sheet, where both perforated sheets were of the same open area and not necessarily aligned, were accommodated in the shock tube system as shown in Figure 3a. Reticulated foams were confined laterally using a cylindrical nylon tube to prevent air from escaping from the sides. The piezoelectric pressure sensor 3 (Dytran[®] 2300V1) embedded laterally on the extender tube was used to monitor and compare the output downstream these structures with the case of no structure (100% transmission, no mitigation).

Two pressures were used for investigation: 3.5 bar and 6.8 bar incident magnitudes, produced from the bursting of 50 μm and 125 μm Mylar[®] diaphragms respectively, and

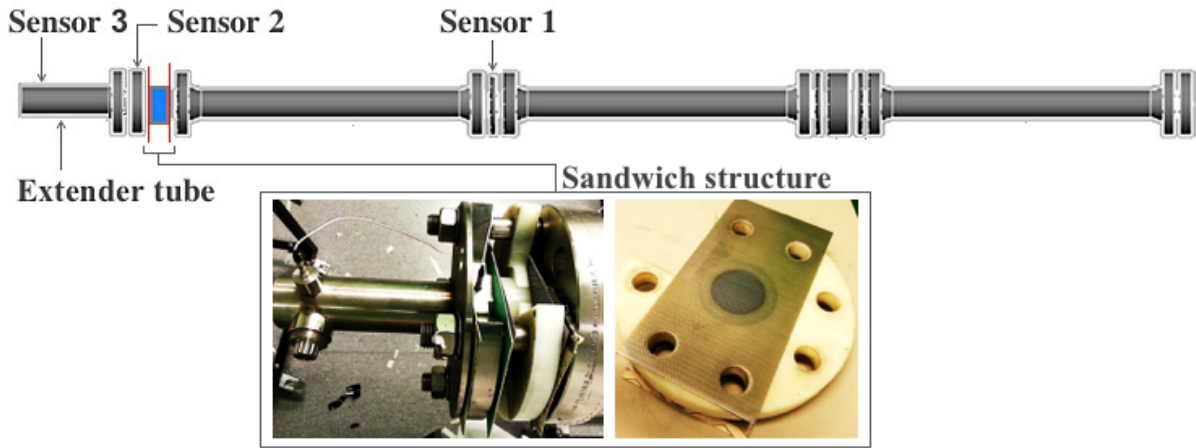


Figure 5.13: The schematic of the shock tube with extender tube and the sandwich structure sample (lateral view of nylon tube confinement and axial view). Reproduced from [66]. Sensor 1 and 3 are approximately 123 cm and 20 cm from the front and back of the sample respectively.

corresponding to two loading levels: Mach 2.15 and Mach 2.60 respectively.

5.3.3 Results and discussions

The results show that these sandwich structure provide attenuations in peak pressures, pulse durations, and hence the shock impulses. As denser structure, i.e. smaller open area and higher thickness, are inserted into the flow, the pulse shape starts to transform into a ramp-like loading following the reduced shock peak (Figure 5.14).

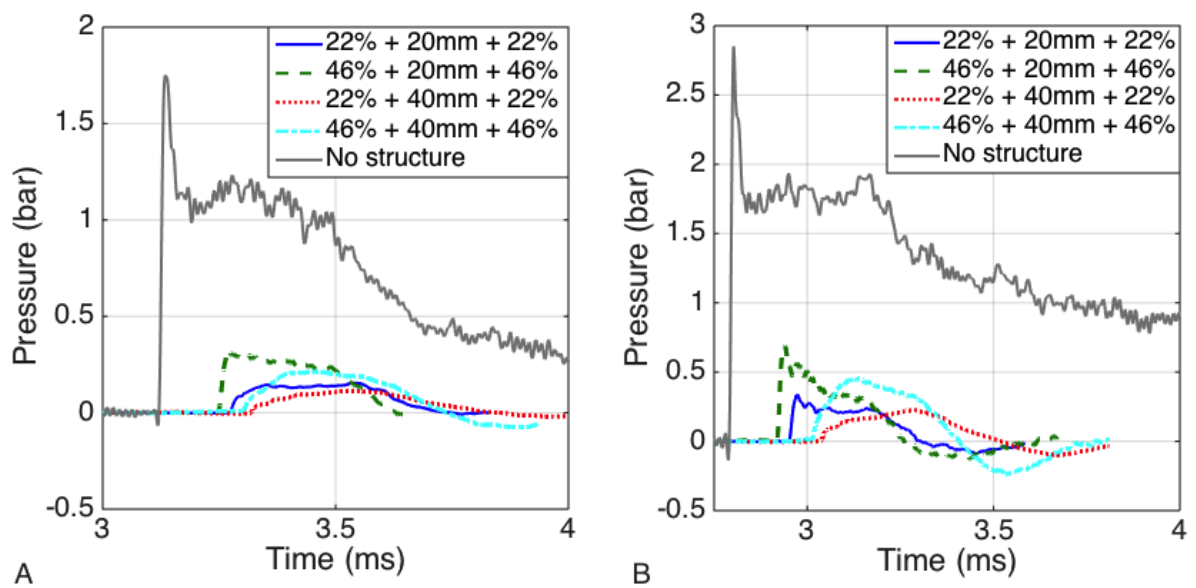


Figure 5.14: Pressure profiles of output blasts behind various mitigation structures for two pressure loadings of (A) Mach 2.15 and (B) Mach 2.60; grey traces collected from reference scenario of no mitigation structure. Reproduced from [66].

Figure 5.15A shows the transmission amount behind these structures. It can be seen that denser structures provide higher peak pressure attenuation. Although the general trends are similar, the pressure mitigation is more effective ($\sim 1-2\%$) against lower incident blasts. In contrast, impulse mitigation is more effective ($\sim 2-5\%$) for higher incident pressure. In this case, the amount of impulse attenuation depends mainly on the perforated structure used and not the thickness of the foam core. Schlieren photography (Figure 5.15B) shows that apart from weakening the shock front, the sandwich structures make the high-pressure gas percolate out in a slow, gradual manner. It needs to be noted that perforated sheets underwent a slight deformation, but it did not affect the mitigation effect when being reused. As for the reticulated foams, they got crushed after each test, but expanded back to the original thickness over a few minutes and behaved the same as initially. For mitigating multiple blasts, crushing of foams may be avoided by gluing of the foam to perforated steel plates. However, this may also result in tearing of the foam.

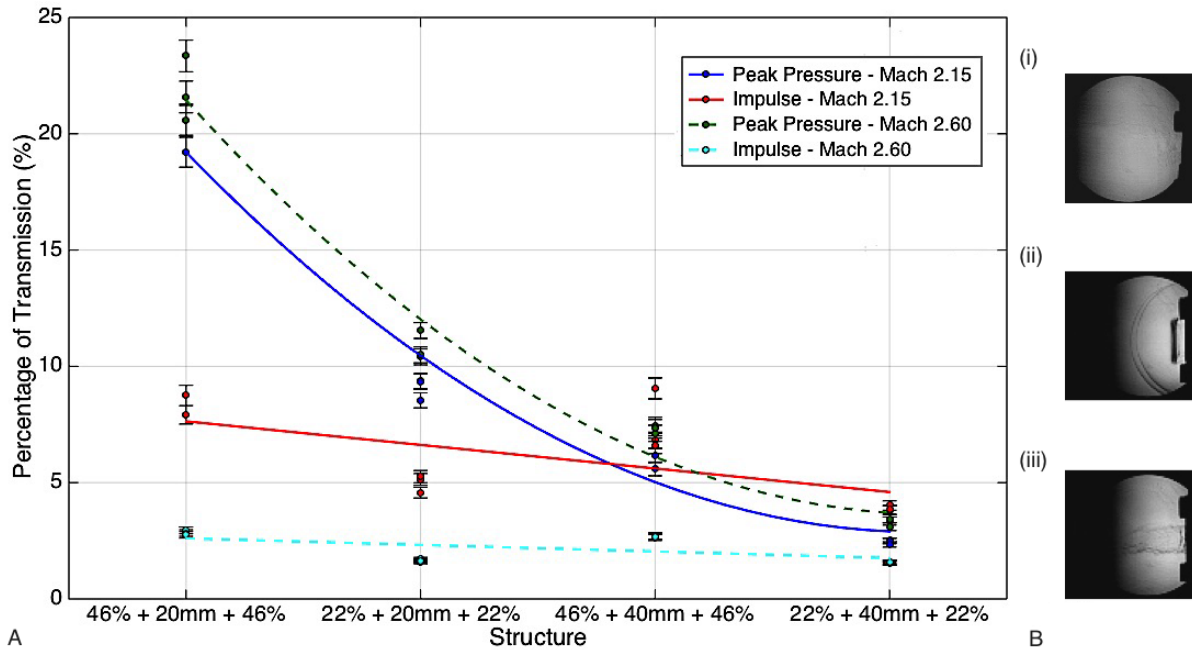


Figure 5.15: A - Percentages of pressure and impulse transmission behind different sandwich structures. B - Schlieren images of output behind a 22% + 20 mm + 22% sandwich panel (i) compared to no structure (ii and iii). Reproduced from [66].

Tables 5.3 and 5.4 show the percentage of pressure and impulse not transmitted (i.e. mitigated) through different sandwich structures. It can be seen that for the perforated plates, using two (without foam in between) does not produce the combined effect ex-

pected from two individual ones added up. It is probably due to the short distance between them. In addition, testing of each individual reticulated foams (without perforated sheets) did not have lateral confinement as in the case of sandwich structure. As a result, the mitigation effects were overestimated, especially for the impulse mitigation. This shows the importance of lateral confinement of foam for an accurate mitigation investigation. For the sandwich structures used in this study, the pressure attenuation achieved was between 75% and 95% (Table 5.3), and the impulse attenuation was achieved to between 90% and 95% (Table 5.4).

	0 mm	40 mm	20 mm
0%	0%	89%	80%
Double 22%	77%	97%	90%
Double 46%	42%	93%	77%

Table 5.3: Amount of peak pressure mitigation behind different structures

	0 mm	40 mm	20 mm
0%	0%	99.5%	99.6%
Double 22%	86%	96% - 98%	95% - 98%
Double 46%	64%	93% - 97%	92% - 97%

Table 5.4: Amount of impulse mitigation behind different structures

More combinations of perforated sheets and foams will be considered for future study to find a theoretical model predicting the mitigation effects of different structures. A computational fluid dynamics model of the shock tube is being developed, which will be coupled with a Lagrange program to simulate the interaction between blast waves and structures. This will resolve limitations of the experimental study due to the size and capacity of the shock tube system.

5.4 Interaction with adaptor for tissues and organs

5.4.1 The design and test set-up of the adaptor

An application of the system is the ability to use the shock tube for the testing of *ex vivo* organ culture (EVOC). For tissues such as swine tracheal explants, it is necessary to have samples stay in contact with the growth medium while subjected to blasts (Figure 5.16A). The 20-cm-long shock tube adaptor (Figure 5.16), designed by Richard Curry from the Blast Injury and Survivability Research Unit of University of Cape Town (South Africa), was made from medical grade stainless steel for that purpose.

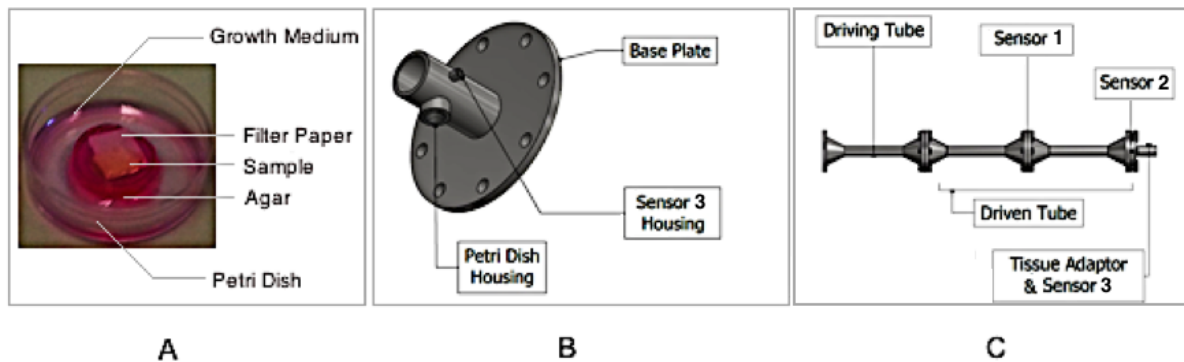


Figure 5.16: Shock tube adaptor for tissue and cell testing: A - An EVOC sample in a Petri dish. B - The stainless steel adaptor. C - Installation of adaptor in the shock tube system. Adapted from [72].

The adaptor can be aligned with the outlet of the shock tube as an extension. In this arrangement, the Petri dish containing the EVOC sample is placed on top of a threaded cap which is then fitted into the “Petri Dish Housing”. A lateral sensor housing was made at the same axial position as the sample housing, with a 90° offset, for estimating the pressure loading undergone by the sample. Both the petri dish and the sensor housing were at ~4.5 cm from the end of the adaptor. This set-up allows for the mounting and testing of samples without contacting other materials, as well as monitoring of the pressure and impulse exerted on biological samples.[72]

The experimental arrangement of the adaptor assumes that pressures measured by the third lateral sensor 3 are what samples mounted at the “Petri Dish Housing” experienced. A series of experiments was performed to investigate the accuracy of this assumption.

In these experiments, the same arrangement as one used for EVOC samples was em-

ployed, but with a fourth lateral sensor (sensor 4) at the sample housing instead of actual specimen. A sensor mount was designed to fit in the Petri dish and the threaded cap of the “Petri Dish Housing”, as shown in Figure 5.17. The sensor mount was positioned, and fixed with epoxy, so that its top was at approximately same height where a typical sample sat in an EVOC preparation (about 0.5 cm from the floor of the Petri dish). This arrangement with four lateral pressure sensors was used throughout the characterisation results of this Section 5.4.

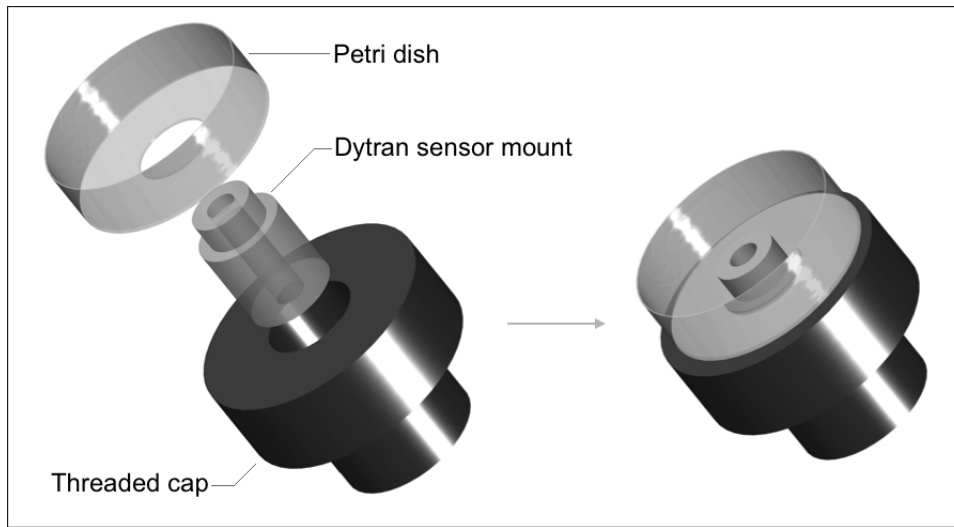


Figure 5.17: Sensor mounting in “Petri Dish Housing” - separated parts and as fitted together

Two scenarios were considered: an empty Petri dish (‘air’) and a Petri dish filled with water to just above the top surface of the sensor (‘water’). They represent the cases where specimen is submerged in the growth medium and where the medium is removed temporarily during blasting. In addition, a range of diaphragm burst pressures was employed: 1.4 bar, 2.2 bar, 4.2 bar, 5.4 bar, and 6.3 bar. They are pressures currently used in the study of swine trachea and lung tissues.

5.4.2 The charactersation results for the adaptor

Figure 5.18 displays pressure profiles from all four lateral sensors used in the set-up. The magnitude of the pulses from sensor 2 and sensor 3 is slightly higher than that of sensor 1. This is because the inner diameter of the R-adaptor is slightly larger than that of the shock tube, resulting in increased pressure by Bernoulli’s effect. The shock durations at

sensor 3 and sensor 4 are shorter as they are nearer to the exit. Pressure profiles from sensor 3 and sensor 4 are not the same, which need to be compared in terms of shape, peak pressure and shock impulse.

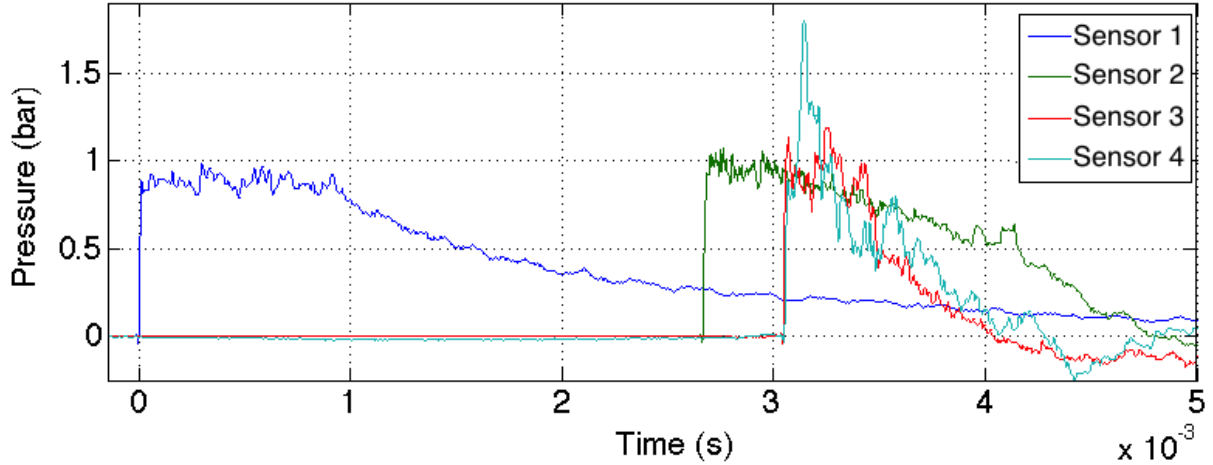


Figure 5.18: Pressure-time profiles from all four lateral sensors. The diaphragm used was 50 μm Mylar[®].

Pressure-time profiles from sensor 3 and sensor 4 are compared in Figure 5.19. Profiles at the “Petri Dish Housing” consist of a shock of smaller magnitude than that from sensor 3, followed by a ramp-like wave reaching a peak pressure greater than the blast at sensor 3. This second feature in quaternary profiles is likely due to the geometry of the Petri Dish whose wall captures blast waves and air, creating secondary wave and turbulences inside the container. It can also be seen that this extra feature is less significant at lower blast pressures, as well as in the ‘water’ scenario. This is understandable as the higher the incident blast, the more amplified the effect is, and with water filled in most of the Petri dish, the capturing volume and contact area of the dish wall are reduced.

For the pressure profile from sensor 4, the maximum pressure reached by the shock-like feature is referred to as the *peak shock pressure*, and the maximum pressure value reached by the ramp-like feature is referred to as the *peak ramp pressure*. Figure 5.20 exhibits the difference in peak pressures measured by sensor 3 and what it is actually at the sample housing. As expected from Figure 5.19, for both ‘water’ and ‘air’ scenarios, the peak ramp pressures hitting sample are higher than the blasts measured at sensor 3 while the peak shock pressures hitting sample are lower. The discrepancy is larger at higher pressure.

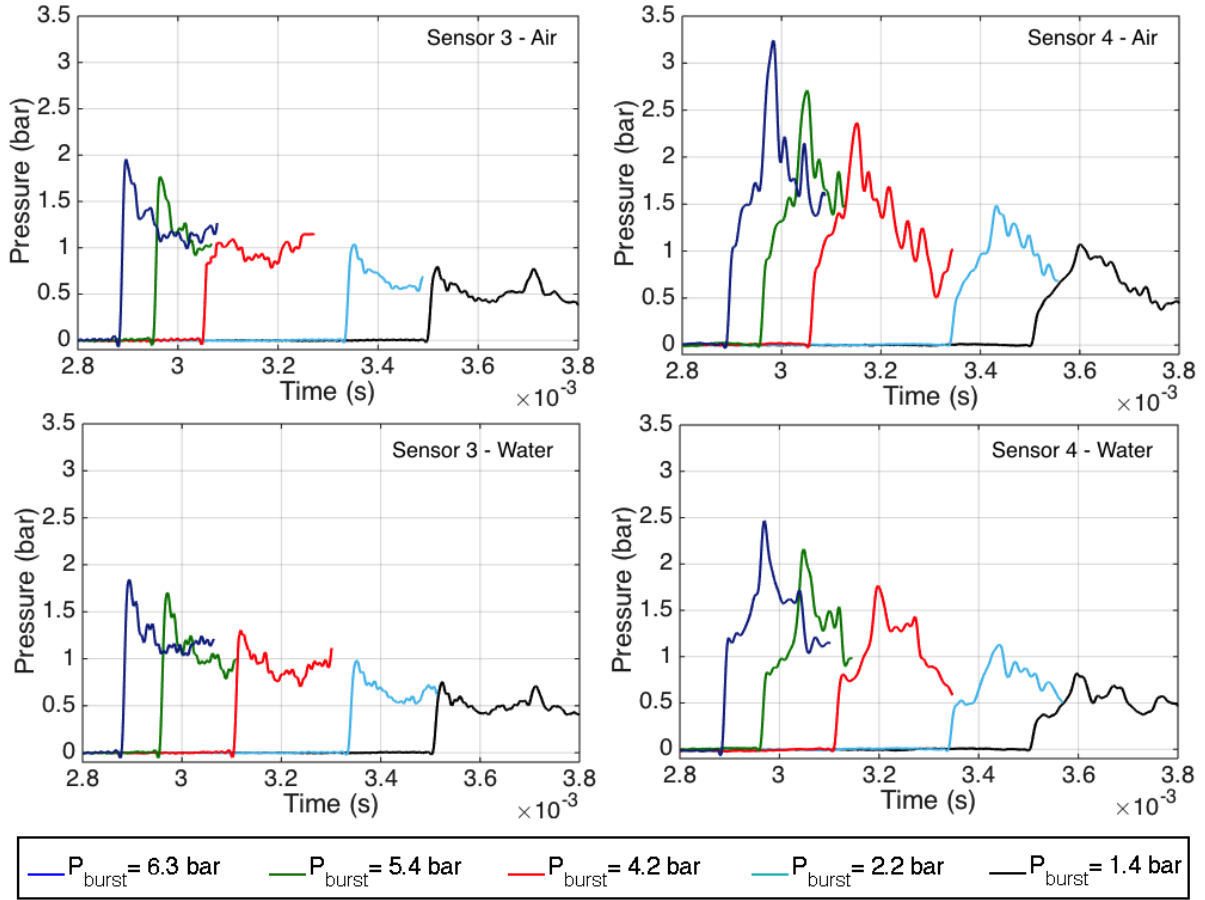


Figure 5.19: Pressure-time profiles measured by the tertiary and quaternary sensors

However, the peak shock pressures in both cases are highly consistent with each other, and around 56% - 60% of the measured pressure at sensor 3. It is quite different for the peak ramp pressures: the measurements at sensor 4 are around 35% higher than the measurements at tertiary sensor for the ‘water’ set-up, whereas these values are around 63% higher for the ‘air’ scenario. This implies that the more liquid filled into the Petri dish, the less ramp-like feature there is. The wide spread of the data for the peak ramp pressures in both scenarios is because this is a turbulent feature, hence not so repetitive and does not follow any obvious trend.

The impulses against burst pressures are shown and compared to that from sensor 3 in Figure 5.21, for both ‘air’ and ‘water’ scenarios. For both cases, the impulses calculated at the sample housing are slightly lower, and around 88-91% of impulses from sensor 3. The secondary features shown in the pressure-time profiles do not have significant effect on the shock impulse as they last for much shorter time compared to the whole pulse

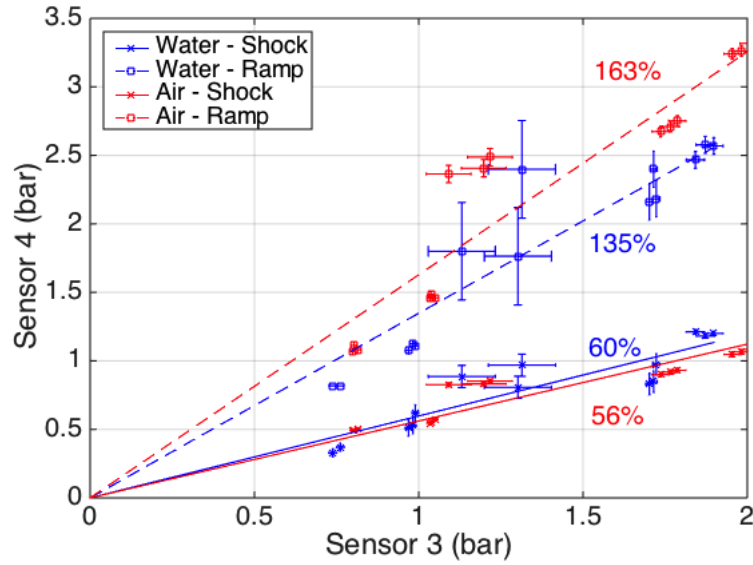


Figure 5.20: Peak pressures at the “Petri Dish Housing” compared to blast pressure measured at sensor 3

width. Hence, the data spreads out less and is quite between the two scenarios.

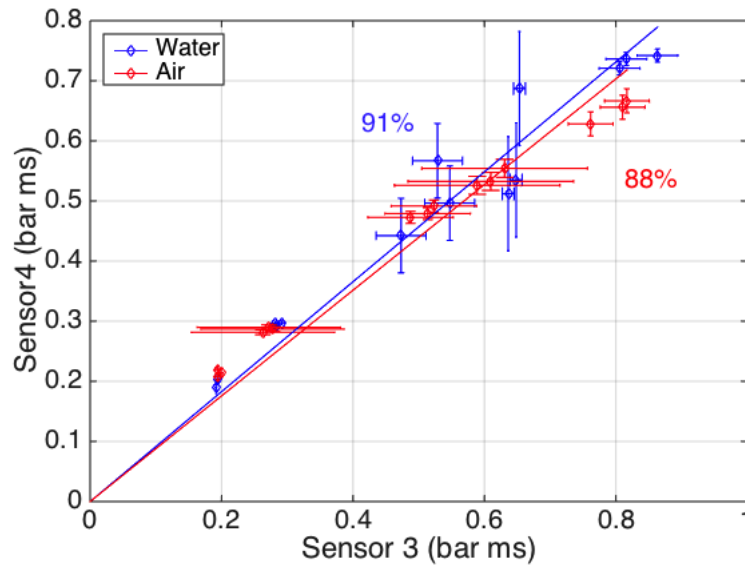


Figure 5.21: Impulses at the “Petri Dish Housing” compared to blast pressure measured at sensor 3

In general, it can be said that the pressure profile and calculated impulse measured from sensor 3 is more relevant to the sample whose container is filled with water than without. Hence, it is recommended that the agar used in EVOC preparation should be as high as possible, and growth medium should be filled up to the top of the agar.

5.4.3 The modifications of the adaptor

PDMS casting

An attempt to reduce the discrepancy between measurements at sensor 3 and sensor 4 is to raise the floor of the Petri dish up by casting a layer of PDMS (polydimethylsiloxane made from Dow Corning® Sylgard 184 with 10:1 base-curing agent mass ratio) to a desired height. PDMS is a silicon-based organic polymer which is transparent, non-toxic, and suitable for working with biological samples. Figure 5.22 shows a Petri dish with PDMS casting of 0.5 cm high, the same height of the sensor housing used for characterisation of EVOC set-up. The surface of the pressure sensor is now level with the new ‘floor’ of the Petri dish.

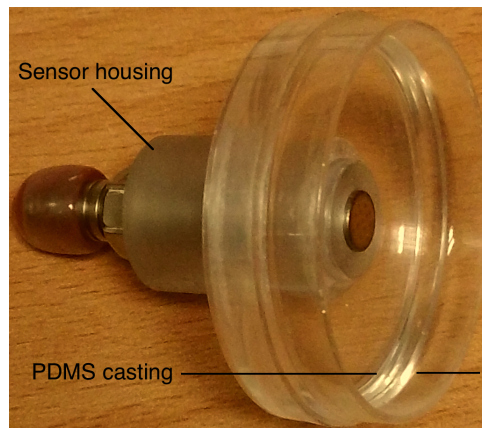


Figure 5.22: Petri dish with 0.5-cm-high PDMS casting

The characterisation for this Petri dish configuration was carried out for a range of diaphragm burst pressures: 2.1 bar, 4.1 bar, and 6.3 bar. Figure 5.23 compares the pressure profiles from third and fourth lateral sensors (in the same set-up as shown in Figure 5.16C) for the ‘raised-floor’ Petri dish. In this case, both the shock-like and ramp-like features of the pressure profiles at sensor 4 have smaller magnitude than the peak pressure measured by sensor 3. The overall shape of the loadings at the ‘raised-floor’ Petri dish is also more ramp-like as compared to the normal Petri dish.

Quantitatively, Figure 5.24 shows that the peak shock pressure and peak ramp pressure at the ‘raise-floor’ Petri dish is respectively 38% and 73% of the peak pressure measured by sensor 3. These figures are only half of that in the normal Petri dish while the pulse

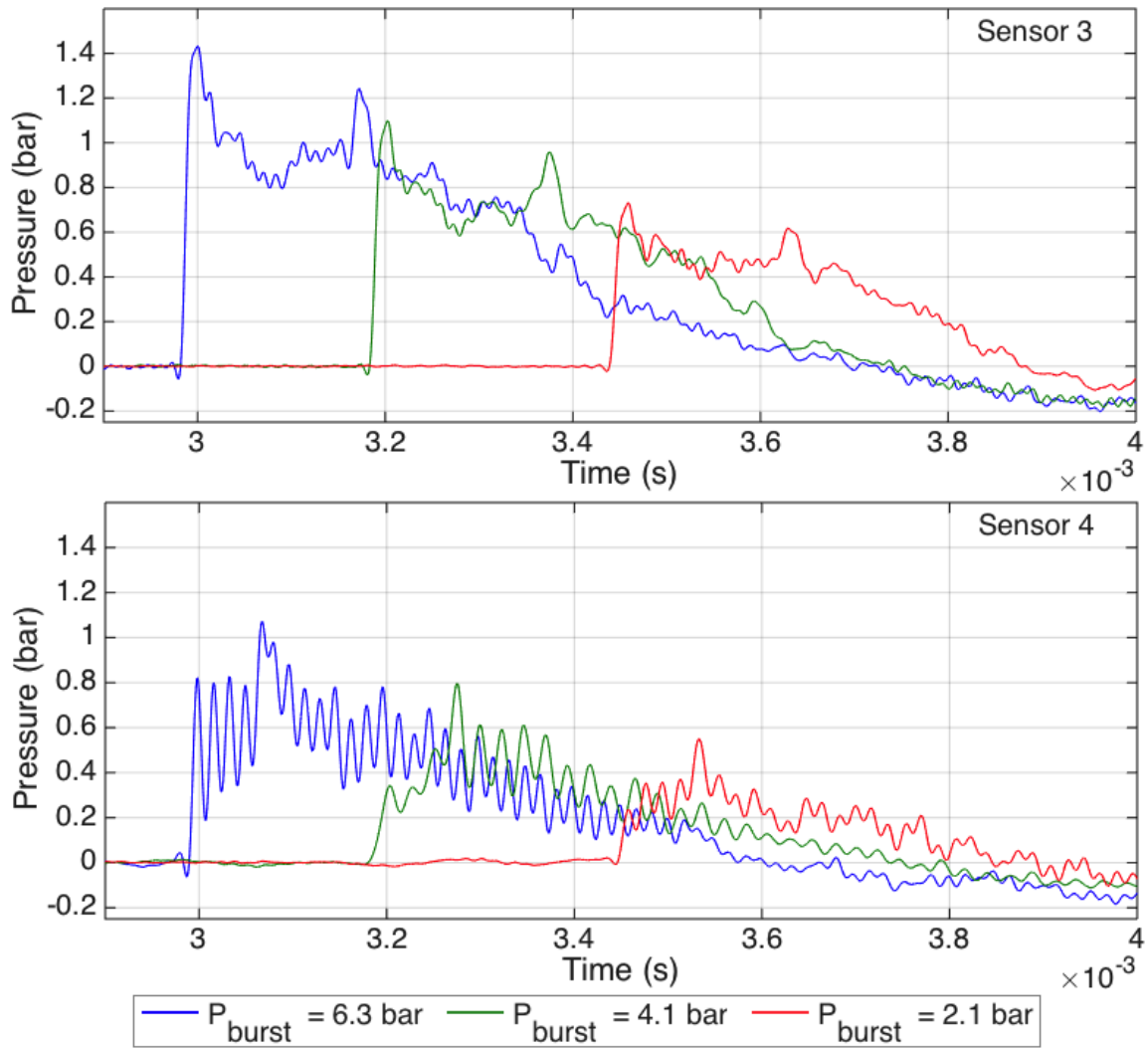


Figure 5.23: Pressure profiles measured by sensor 3 and sensor 4 for the ‘raised-floor’ Petri dish

duration is the similar in all cases (~ 4 ms). As the result, the impulse at the ‘raised-floor’ Petri dish is only 55% of the impulse at sensor 3 which is almost the same as the normal Petri dish’s (Figure 5.21 and 5.25).

It was expected that PDMS casting to raise the floor of the Petri dish would lower the peak ramp pressure, increase the peak shock pressure and the shock impulse closer to that measured by sensor 3. In reality, the peak ramp pressure is indeed reduced since the capturing volume and contact area of the dish wall are reduced. However, the peak shock pressure and shock impulse are also lowered, which is likely due to absorption by the PDMS material itself.

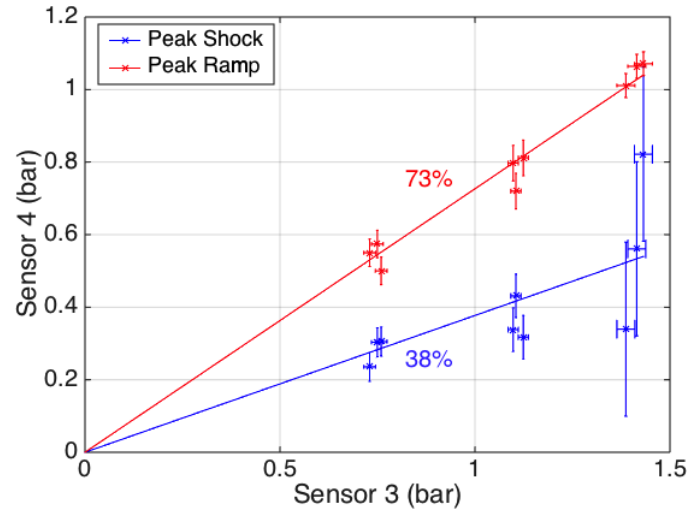


Figure 5.24: Peak pressures at the “Petri Dish Housing” compared to blast pressure measured at sensor 3 for the ‘raised-floor’ Petri dish

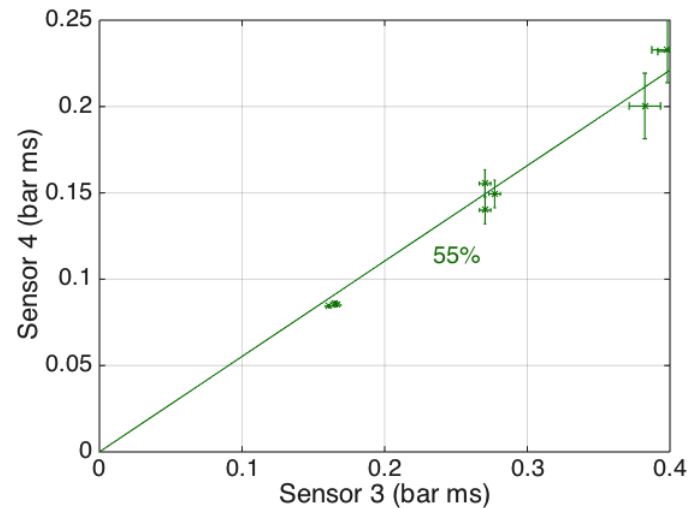


Figure 5.25: Impulses at the “Petri Dish Housing” compared to blast pressure measured at sensor 3 for the ‘raised-floor’ Petri dish

Stainless steel mesh

As the sample of the EVOC set-up is placed in an open Petri dish, it is desired for a physical barrier that can stop it from escaping the Petri dish, but does not significantly alter the blast loading. The study of perforated sheets (Section 5.1) showed that open areas greater than 79% offer almost no attenuation effect, i.e. same as no structure at all. For this reason, a bio-compatible mesh was designed as shown in Figure 5.26. It consists of a 3D-printed ABS (acrylonitrile butadiene styrene) ring with a set of holes for construction of the meshing grids using nylon coated stainless steel wire. This allows for the flexibility of the design to accommodate sample with different sizes. The percentage

of open area can be calculated as:

$$\text{Open area} = \left(1 - \frac{4nt}{\pi d}\right) \times 100, \quad (5.2)$$

where n is the number of grids, t is the grid thickness (or wire diameter), and d is the ring diameter.

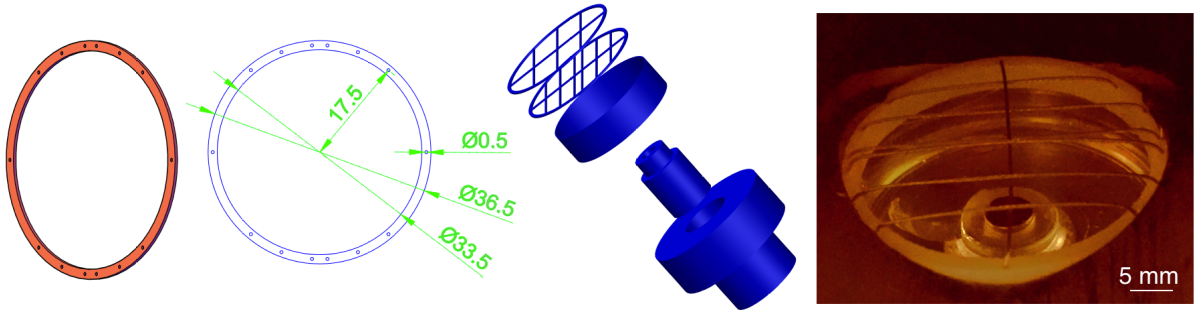


Figure 5.26: The design and set-up of the bio-compatible mesh for maintaining samples within the Petri dish

The brief characterisation for the effect of this type of mesh reported here used one with open area $\sim 95\%$ (7 grids of thickness 0.3 mm), and a burst pressure of ~ 6.3 bar (the most commonly used arrangement for the EVOC adaptor). The Petri dish used here to investigate the effects of this mesh is the ‘raised-floor’ version discussed earlier in this subsection.

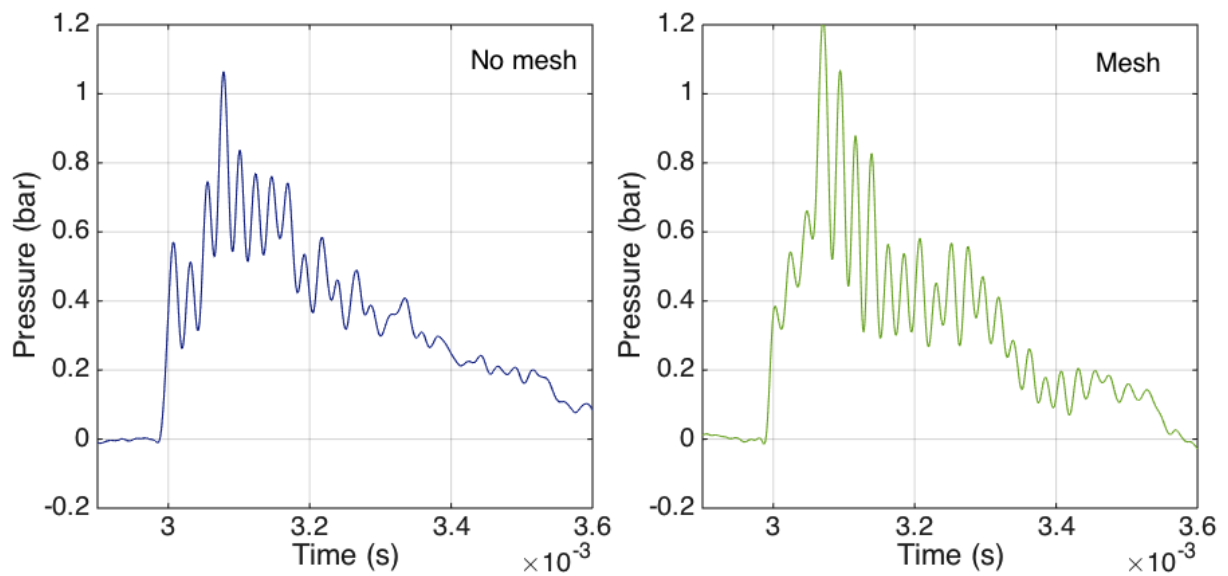


Figure 5.27: Example of pressure-time profiles measured by sensor 4 in a ‘raised-floor’ Petri dish, for with and without the mesh

Figure 5.27 displays the pressure traces recorded by sensor 4 in the ‘raised-floor’ Petri dish with and without the mesh. With the mesh, the peak shock pressure is slightly lower whereas the peak ramp pressure is slightly higher, and the pulse duration is approximately the same. These quantities were averaged over three repeats for each case, and compared in Figure 5.28. It can be seen that the mesh has no significant interference with the blast loading at the Petri dish housing, especially for the shock impulse.

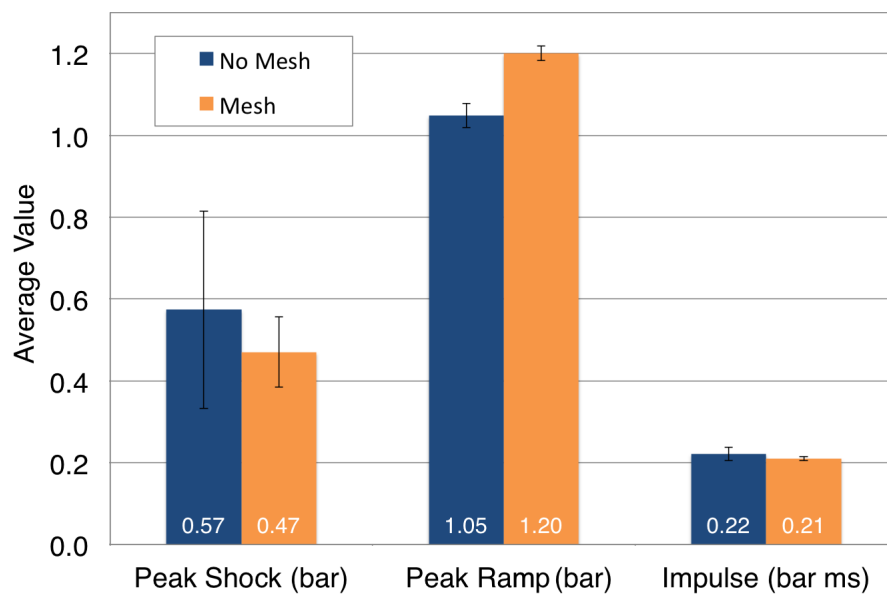


Figure 5.28: The averaged peak shock pressure, peak ramp pressure and shock impulse for two cases of with and without the mesh

5.5 Adhesive sealing membranes

Adhesive membranes are commonly used to seal tissue culture plates for storing. The sterile membranes can be either gas-permeable (gas can pass through for venting) or non-permeable (neither gas or liquid can pass through), and both can provide a barrier against contaminating bacteria.

In-vitro tests in the shock tube also employs such material. Arun *et al.* [73] used the gas-permeable membrane on 96-well tissue culture plates containing SH-SY5Y human neuroblastoma cells and NG108-15 mouse neuroblastoma/rat glioblastoma hybrid cell to study traumatic brain injury in a shock tube system. Bo *et al.* also used the 96-well plates to investigate the effect of blast on stem cell (from the bone marrow of mice) with the

CBIS shock tube [16]. This study employed both the gas-permeable and non-permeable membranes, the performances of each of them were reported and compared thoroughly. In this study, it was reported that the non-permeable membranes produced slightly lower plateau pressure with a larger fluctuation in this pressure value due to the difference in vibration mode of the two membranes. The non-permeable membranes also provide better sealing of the liquid inside the well plate after blasting. The study suggested that the non-permeable membranes can simulate the blast effects on denser tissues (e.g. bone, skin, muscles, etc.); and the gas-permeable membranes can simulate the blast overpressure effects on gas-filled organs (lung, ears, trachea, etc.).

In this section, the two types of membranes, manufactured by Thermo Scientific, were investigated for their application in the set-up of *in-vitro* blast testing of biological cell, as well as their attenuating properties when combined with perforated sheets.

5.5.1 The use of membranes in blasting of cells

The *in-vitro* testing of cells (such as stem cells and endothelial cells from lung vessels) requires the set-up environment to be biocompatible and free of contaminations. In addition, the growth medium may need to be recovered after blasting for post-analysis of microvesicles (fragments of plasma membrane) formation. The amount of growth medium in this case is limited for higher concentration, hence, a physical barrier is required to avoid the removal of this liquid by the gas flow. The set-up of Petri dish is modified, with a gas-permeable or non-permeable membrane for sealing, as shown in Figure 5.29. This Petri dish can then be placed in the Petri dish housing of the adaptor discussed in Section 5.4.

The characterisation of this set-up was done with blast waves produced from 40 μm Al, 50 μm , and 75 μm Mylar[®] diaphragm. Figure 5.30 shows the pressure profiles recorded by sensor 4 (as in set-up in Figure 5.16), placed inside the Petri dish with gas-permeable or non-permeable membrane sealing. The shapes of both loadings are very similar, of approximately same pulse duration, and mainly ramp-like, with almost no shock feature. This replicates the pressure loading inside the body, where the blast wave has passed

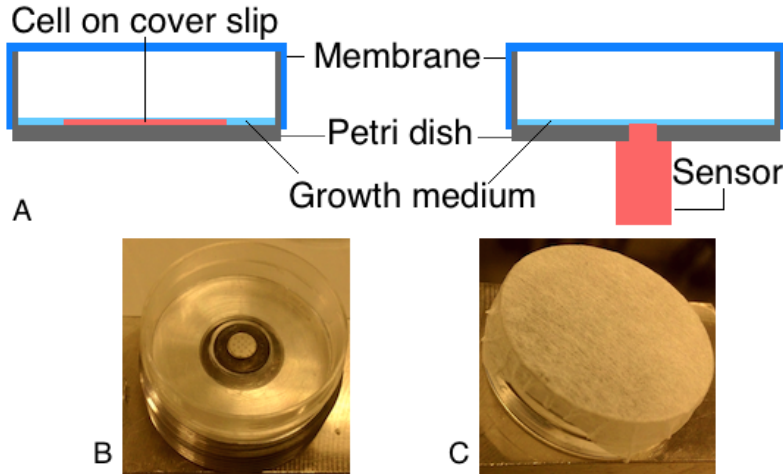


Figure 5.29: A - The schematic of Petri dish modification for *in-vitro* testing of cell and its characterisation test set-up. B - Non-permeable membrane on Petridish. C - Gas-permeable membrane on Petridish.

through layers of outer structures like skins and bones. The oscillations in the traces, which is slightly larger for the non-permeable case, are likely due to the vibration of the membrane themselves.

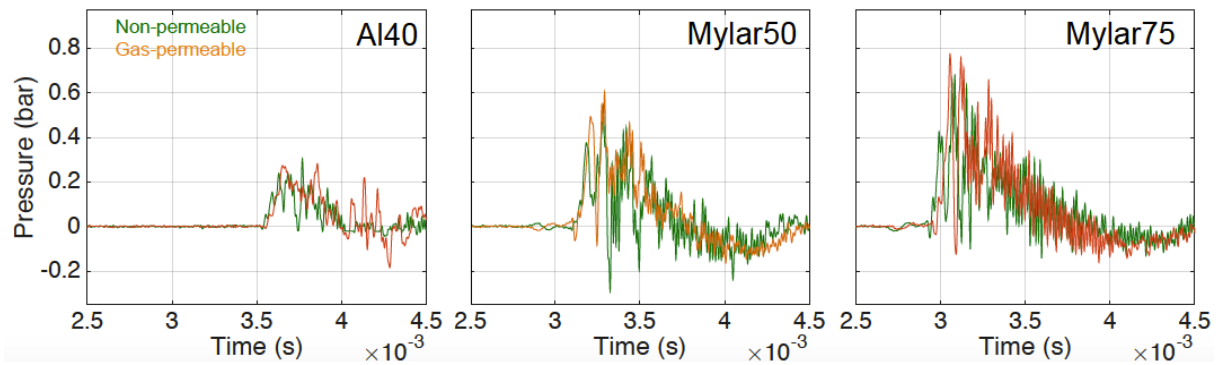


Figure 5.30: The pressure profiles measured by sensor 4 in Petri dish for both types of membrane

Figure 5.31 compares the relationships between the peak pressure (of the whole ramp-like loading) and the impulse of lateral sensor 3 and sensor 4. For both quantities, the gas-permeable membrane allows for higher pressure and impulse to reach the sample, which is in agreement with the study by Bo *et al.* [16]. From these results, it is recommended to use the gas-permeable membrane for this *in-vitro* testing of cell set-up as the benefits of preventing contamination of samples outweigh the added complexity of set-up.

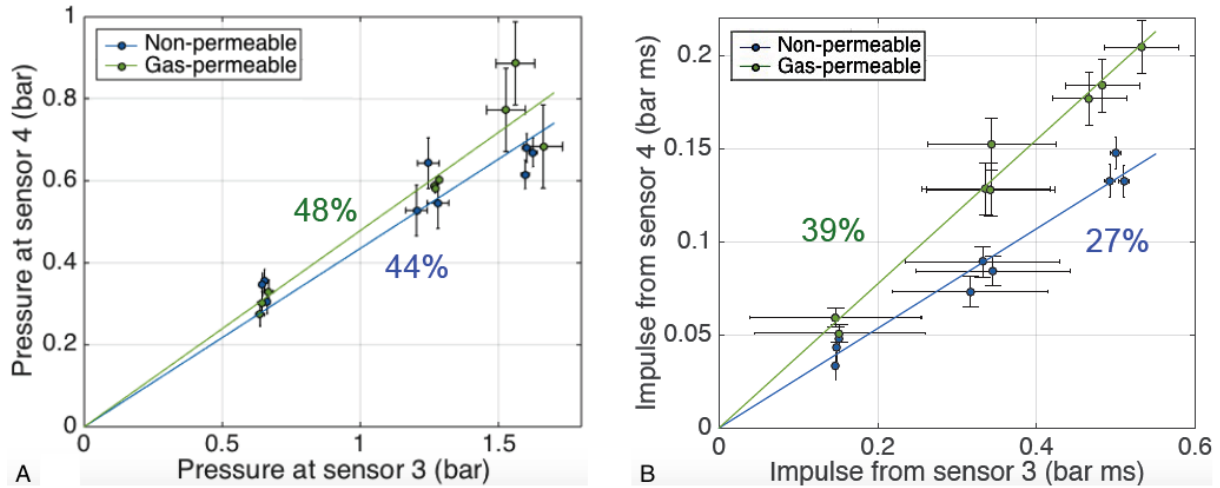


Figure 5.31: Peak pressure and shock impulse at the Petri dish compared to blast measured at sensor 3, for both types of membrane

5.5.2 The blast attenuating properties of membrane - perforated sheet combination

Another use of the membrane is for sealing of fine granular beds inserted horizontally in the shock tube, in conjunction with a perforated plate for supporting. This combination is useful in stopping the granular particles from spilling from the bed and still allowing blast waves to pass through. However, it was observed that this structure also attenuates the blast wave quite significantly.

A preliminary experiment was done to investigate attenuating properties of the combination of a 79% open area perforated sheet (lowest mitigation effect available) with either a non-permeable or gas-permeable membrane under the blast effects from a burst pressure of 5.0 bar. The set-up was similar to that shown in Figure 5.1 (Section 5.1). Features from pressure traces downstream of these combinations were recorded by lateral sensor 2 and compared with the case of perforated sheet only. After undergoing blast effects, the combination deformed significantly (Figure 5.32) and could not be reused even though this was not a problem for perforated sheets alone. This deformation is the factor that absorbs the energy of the blast and provide the passive mitigation.

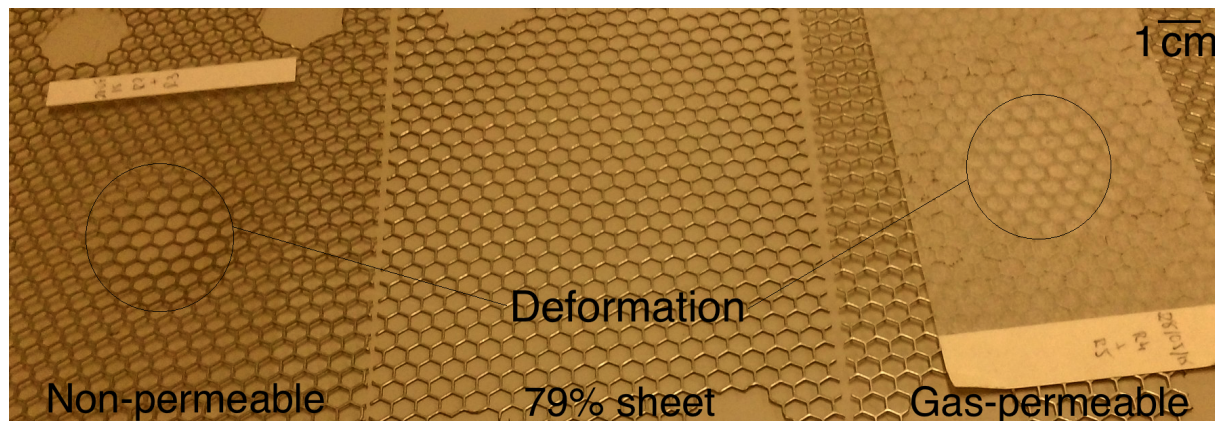


Figure 5.32: The membrane - perforated sheet combination and their deformation after testing with the side receiving the incoming blast facing up

Pressure profiles behind the structures are shown in Figure 5.33. By adding a sealing membrane to the 79% open area perforated sheet which offer almost no mitigation effect (Section 5.1), the structure reduces the transmitted blast greatly in terms of pressure magnitude and impulse. They also transform the pulse shape into one with a ramp loading following the shock feature.

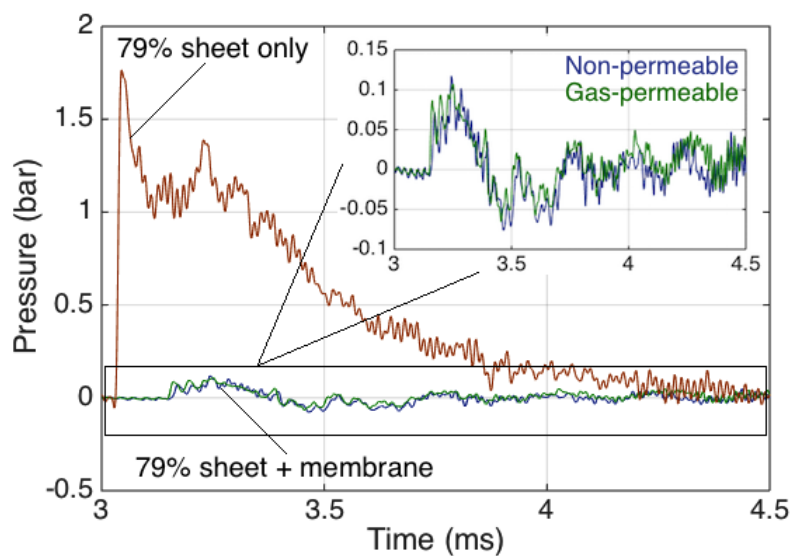


Figure 5.33: The pressure profiles measured by sensor 2 downstream of the inserted structure

Figure 5.34 shows that adding either membrane on the perforated sheet produces very similar effects. They reduced the peak pressure to $\sim 4\text{-}7\%$, and shock impulse to $\sim 2\%$ of the values from 79% sheet only. In addition, the gas-permeable membrane offers slightly lower attenuating effects, but less visible deformation of the structure (Figure 5.32). However, more tests are needed over a greater range of incident pressures to accurately identify

the mitigating properties of these membrane - perforated sheet combinations. Different material of membranes (such as Mylar[®] film, canvas, etc.) can be used on a stiffer perforated sheet to increase the durability of the structure.

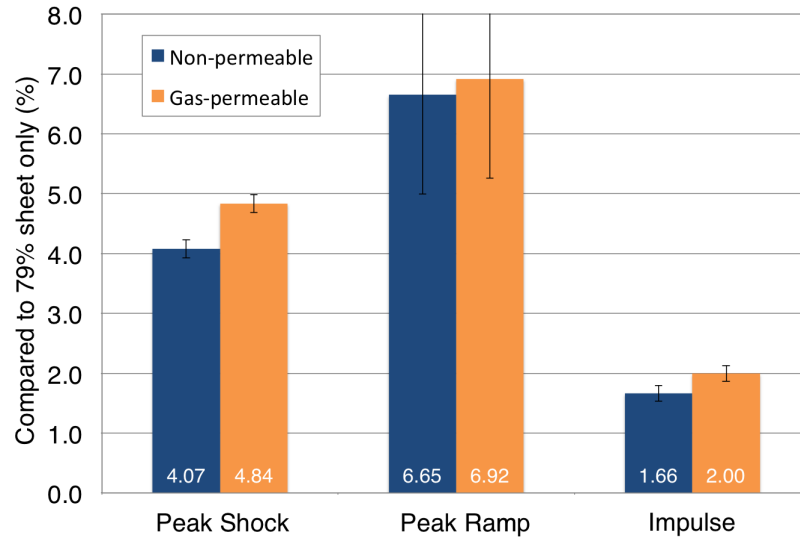


Figure 5.34: The percentage of peak shock pressure, peak ramp pressure and shock impulse compared to the case of 79% open area perforated sheet alone, for two types of membranes

5.6 Interaction with platform for primary blast limb trauma study

5.6.1 The design and test set-up of the platform

The purpose-built steel platform for testing of limb trauma (Figure 5.35) was designed so that the hind limb of the animal is exposed to the outcoming blast wave from the shock tube and the rest is protected by the mounting harness and platform top. Both limbs of the animal can be fixed to a steel bar to prevent undesired tertiary blast effects.[74]

In order to characterise the incoming loading on the mouse limb, the shock tube was set up as shown in Figure 5.36 with three piezoelectric pressure sensors:

- Sensor 1: lateral sensor at the middle of the driven section; for triggering and monitoring the repeatability of tests

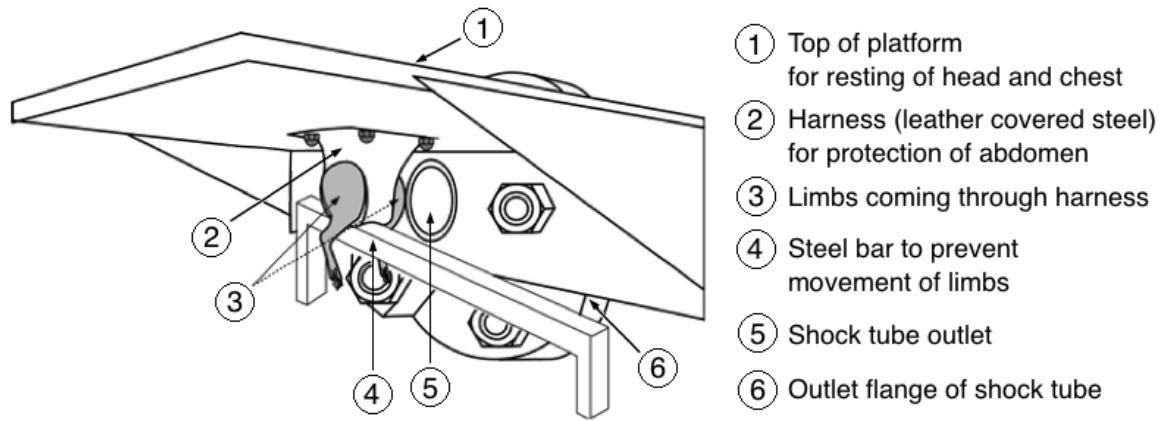


Figure 5.35: The schematic of the limb platform as installed to the shock tube. The limb facing the blast is 5 cm away from the outlet. Reproduced from [74].

- Sensor 2: lateral sensor at the end of the driven section, just before the leg platform; for monitoring the pressure loadings on samples
- Sensor 3: head-on bull-nose sensor mounted in the harness of the leg platform, at the same position of samples; for characterising the pressure loadings on samples

The head of the bull-nose sensor has a cross-sectional area is approximately that of the mouse limb. Hence, it is representative in term of the geometry of the sample.

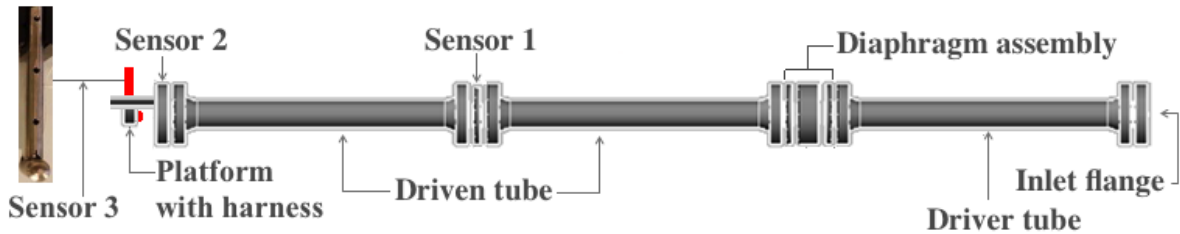


Figure 5.36: The schematic of the shock tube set-up for characterisation of the platform for limb trauma studies

In actual experiments with the sample in place, it is not possible to have the head-on sensor in the system. The lateral sensor 2 is used to identify the magnitude of loading pressure. It is essential to address the relevancy of pressure traces from sensor 2 with that of sensor 3. Characterisation tests of the platform were carried out with four testing configurations, which were also those used in testing of actual samples:

- 200 μm Mylar[®] diaphragm, single-diaphragm bursting at $\sim 15.7 \pm 0.5$ bar with 7% driver volume

- 75 μm Mylar[®] diaphragm, single-diaphragm bursting at $\sim 6.2 \pm 0.2$ bar with 7% driver volume
- 100 μm Mylar[®] diaphragm, double-diaphragm bursting at $\sim 11.9 \pm 0.1$ bar with 50% driver volume
- 50 μm Mylar[®] diaphragm, double-diaphragm bursting at $\sim 6.0 \pm 0.15$ bar with full driver volume

These configurations were chosen to investigate the effects of pressure magnitudes and blast duration in primary blast limb injuries, in order to identify the more damaging factor. The study by Eftaxiopoulou *et al.* [74] reported that “prolonged but not short duration blast waves elicit acute inflammation in a rodent model of primary blast limb trauma” as only the full and the 50% driver volume configurations resulted in expected injury pattern, regardless of the pressure magnitude.

5.6.2 The characterisation result for the platform

Figure 5.37 shows the pressure profiles recorded by sensor 2 and sensor 3 for the four testing configurations. The 7%-volume cases provide Freeland waveform of open-air blasts, while higher volume cases result in blasts with a longer pulse width, similar to those in closed area such as inside a vehicle. Due to the difference in orientation, sensor 3 gives slightly higher pressures than sensor 2, longer overpressure duration, and quite different loading shapes. Sensor 3 measurements are more relevant to samples, and provide upper limits of the pressure loading on samples due to samples’ impedance.

The characteristics of the blast loadings in this platform are described by the shock wave peak pressure, plateau pressure, impulse, and duration from sensor 2 and sensor 3 for all testing configurations (Table 5.5 and 5.6). The higher volume cases provide approximately the same pulse duration and impulse, but different pressure magnitudes; this is useful in investigation of the isolating effect of the acceleration by the shock feature. The middle testing configurations (16 bar - 7% and 12 bar - 50%) provide quite similar pressure measurements, but greatly different impulse and duration values; this is useful

5.6. INTERACTION WITH PLATFORM FOR PRIMARY BLAST LIMB TRAUMA STUDY

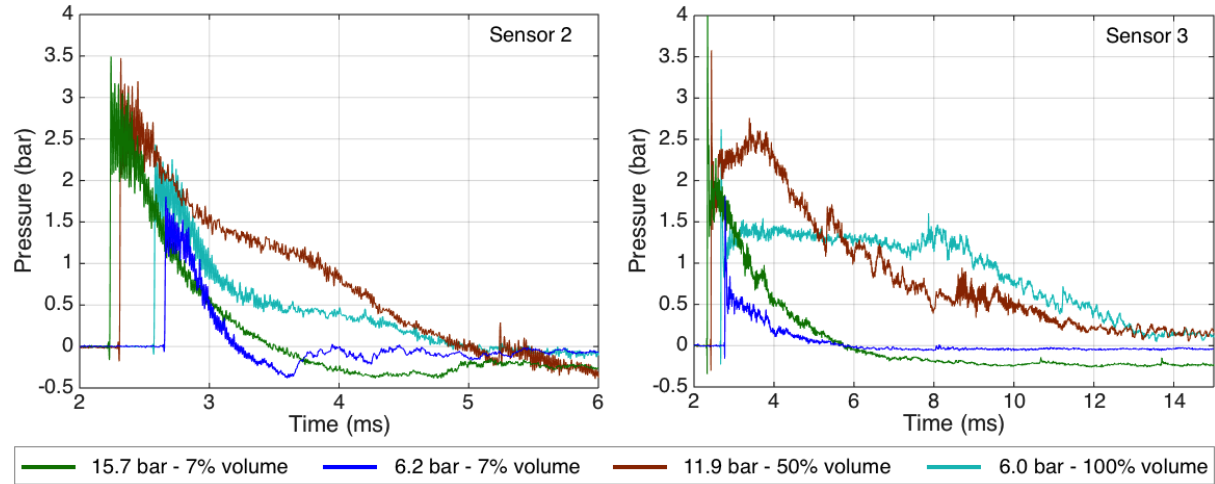


Figure 5.37: Traces from sensor 2 and 3 (relative to ambient pressure) of four loading configurations

in investigation of the isolating effect of the blast wind. Interestingly, the cases of 6 bar burst pressure with 7% and 100% driving volumes, which were meant to provide same pressure magnitudes but different durations, show discrepancy in magnitudes of pressures. As traces from sensor 1 (which is far away and independent of the platform's geometry) of both cases have the same pressure magnitude as expected (Figure 5.38), this unexpected behaviour is likely due to the interaction of the produced blast wave with the platform.

	Peak pressure (bar)	Plateau pressure (bar)	Impulse (bar ms)	Duration (ms)
6 bar, 7%	1.83 ± 0.08	1.36 ± 0.05	0.42 ± 0.03	3.20 ± 0.01
16 bar, 7%	3.28 ± 0.16	2.37 ± 0.12	1.16 ± 0.11	3.47 ± 0.05
12 bar, 50%	3.49 ± 0.05	2.63 ± 0.03	3.05 ± 0.08	5.23 ± 0.20
6 bar, 100%	2.41 ± 0.04	1.81 ± 0.03	1.36 ± 0.06	5.03 ± 0.10

Table 5.5: Summary of peak pressure, plateau pressure, shock impulse, and duration recorded by sensor 2 for four loading scenarios

	Peak pressure (bar)	Plateau pressure (bar)	Impulse (bar ms)	Duration (ms)
6 bar, 7%	1.85 ± 0.11	0.56 ± 0.03	0.72 ± 0.05	5.73 ± 0.05
16 bar, 7%	3.65 ± 0.34	1.60 ± 0.17	2.28 ± 0.21	5.67 ± 0.05
12 bar, 50%	3.79 ± 0.18	2.35 ± 0.06	11.1 ± 0.59	15.0 ± 0.05
6 bar, 100%	2.59 ± 0.06	1.28 ± 0.04	10.1 ± 0.69	15.0 ± 0.05

Table 5.6: Summary of peak pressure, plateau pressure, shock impulse, and duration recorded by sensor 3 for four loading scenarios

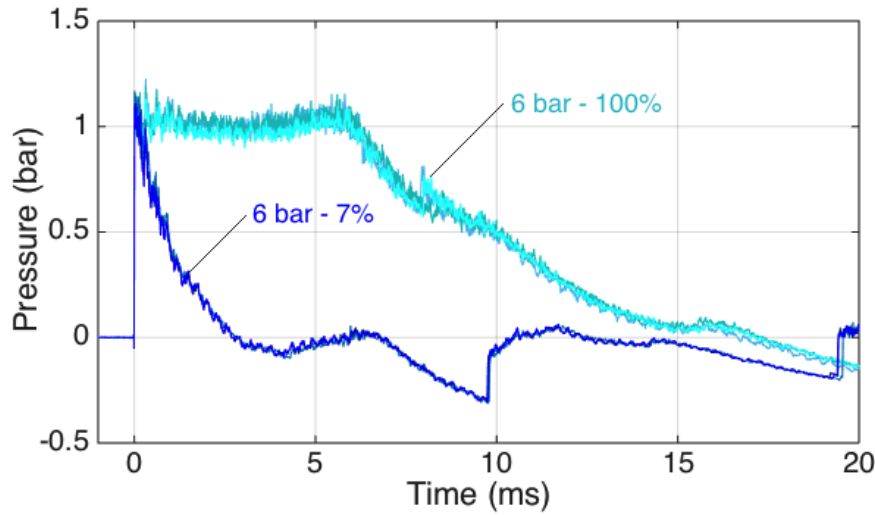


Figure 5.38: Traces from sensor 1 of the 6 bar - 7% (blue) and 6 bar - 100% (cyan) testing configurations show agreements in magnitude of peak pressures

In order to use the lateral sensor 2 to estimate the loading pressure magnitudes reaching the sample, the relationships between the peak and plateau pressures measured by sensors 2 and 3 were identified (Figure 5.39). The relationship is linear for the peak pressure and polynomial for the plateau pressure. As there was no continuous trend in term of change made in driving volume of the testing configuration, the impulse and duration values of these two sensors do not exhibit any clear relationship. These values for each testing configuration can only be estimated by using pressure sensor 3.

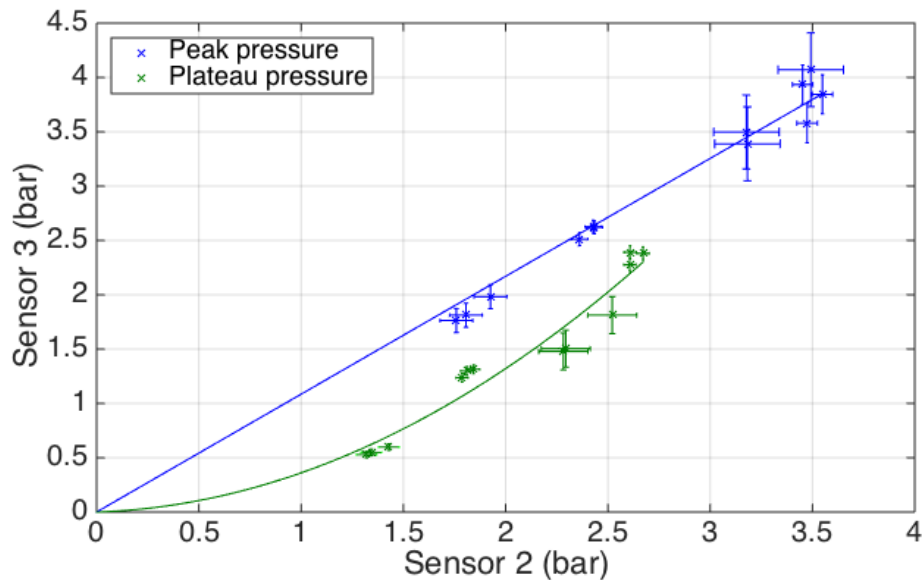


Figure 5.39: Relationships of the peak and plateau pressures (relative to ambient pressure) between traces by sensor 2 and sensor 3

For future development of the platform, a confinement tube (Figure 5.40) can be added to make the loading more controllable as in this case, the sample is subjected to the middle of the flow, not at the outlet, hence fewer unnecessary interactions with the geometry of the platform. It can also provide greater protection for untested body parts from the blast effects. This platform arrangement can also be used for *in-vivo* studies of traumatic brain injuries by rotating the platform 180 ° and removing the harness as shown in Figure 5.40.

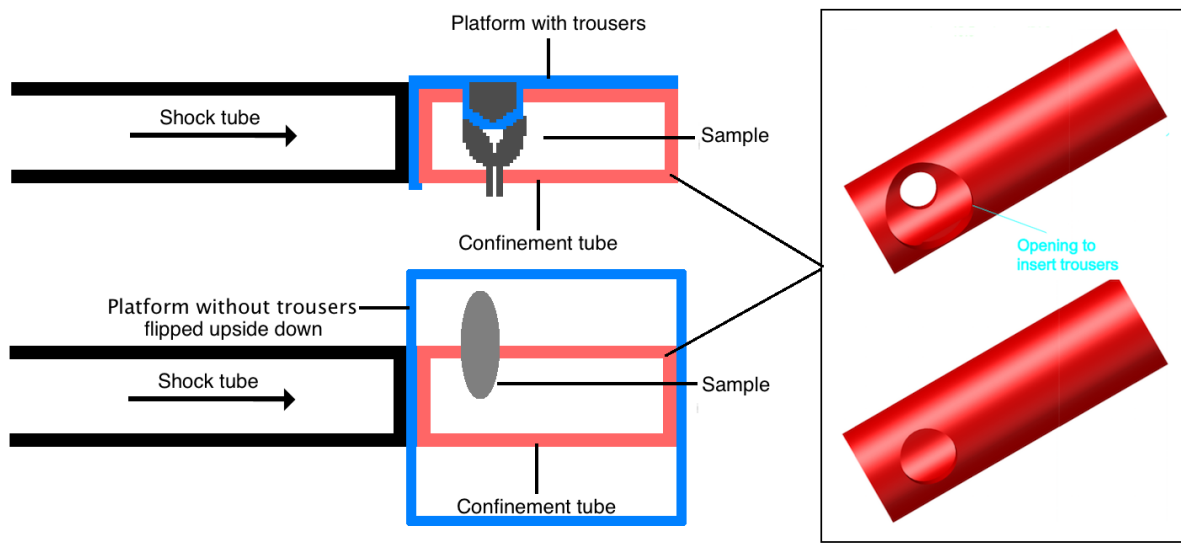


Figure 5.40: Improvement of platform for blast limb trauma, and application for traumatic brain injury studies

5.7 Conclusions

This chapter portrays the usage of the shock tube to investigate the interactions between blast waves and various structures, in the context of blast injuries and mitigations. Mitigating structures addressed include perforated galvanised steel sheet, reticulated polyurethane foams, and the combinations of perforated sheets with reticulated foams or adhesive sealing membranes. The performances of current systems for mounting biological samples (EVOC adaptor, and platform for limb injury studies) as well as potential developments are also discussed.

As shock waves arrive at the perforated sheet, they are transformed into transmitted

waves and reflected waves. The shock magnitude and impulse of transmitted waves increase linearly with increasing percentage of open area while the opposite was found for the reflected shock. 22% open area allows 30% of peak pressure transmission while there is almost no mitigating effect for perforated sheet of 79% of open area. For all open areas tested, about 5% of impulse is lost to absorption by the perforated sheets. To expand the investigation on perforated sheets, other properties can be characterised such as thickness, holes size, holes distribution, and the materials of the sheet itself. Various arrangements can also be studied: multiple layers of perforated sheets of same and different open areas and orientations.

The blast attenuating property of the perforated sheet can be enhanced by adding a layer of adhesive sealing membrane to the front (facing the incident blast). Preliminary tests show that with either the gas-permeable or non-permeable membrane, the 79% perforated sheet of almost no mitigating effect can reduce the transmitted peak pressure to 4-7%, shock impulse down to $\sim 2\%$ and transform the loading to a more ramp-like shape. However, this improvement in blast attenuation has to be traded off with the lifetime of the structure; the more effective it is against blasts, the more damaged post-blast. All the structures tested cannot be reused, which is otherwise without the added membrane.

Perforated sheets can also be combined with reticulated foam as a blast mitigating structure. On their own, reticulated polyurethane foams of pore distribution 65-70ppi and thickness 20-60mm can reduce the transmitted peak pressure to 5-16% and impulse to 0.25-0.5%. The attenuation is more effective with denser and thicker foam. For sandwich structures of 22% or 46% perforated sheets with 20 mm or 40 mm reticulated foam, the pressure attenuation achieved is between 75% and 95%, which is higher for denser structures. The impulse attenuation is achieved to between 90% and 95%, where the open area of the perforated sheets proved to be the more important factor. The pressure mitigation is more effective for smaller incident blasts, while the impulse mitigation is more effective for higher incident pulses. More combinations of perforated sheets and foams will be considered for future study to find a theoretical model predicting the mitigation

effects of different combinations.

The results for interactions of blast waves and mitigating structures reported here are limited by the size and capacity of the shock tube. Bigger structures, hence less support from the mounting, will be weaker especially against blast waves stronger than those used. Stronger blasts can break the structures causing less mitigation and more damages due to fragmentations. In this case, stronger materials are needed for the same geometry of structures. These limitations can be resolved using computational simulations, which can be validated with the available results.

The shock tube can be adapted to study the blast effects on biological specimens with scale ranging from the cell cultures to tissues/ organs, and to the whole animal model. The EVOC adaptor was designed to enable the mounting of tissue in EVOC preparation for direct contact with blast waves. The arrangement also allows for the pressure measurement at the same time and location as the sample. However, due to the shape of the Petri dish containing samples, there is a discrepancy between the measured blast and the actual pressure at the sample housing. This discrepancy can be reduced by elevating the position of the sample in the Petri dish. In addition, with adhesive sealing membranes, a barrier against contaminations can be added to the original EVOC adaptor, making it more suitable for *in-vitro* testing of cells.

For the whole animal model, platforms such as the one for limb trauma reported can be used where only the desired body part is exposed to the blast while the rest is shielded to avoid the post-trauma induced complications. For such platforms, pre-testing characterisation is important to identify any unexpected blast effects due to interactions between the structure and the incident blast wave. The design using a confinement tube is being developed for better mounting and shielding of animals as well as to reduce additional blast effects due to interaction with mounting geometry.

Chapter 6

Computational Simulations

6.1 Diaphragm rupture simulations

6.1.1 The ANSYS finite element method

ANSYS is a tool that is capable of modelling and analysing problems such as static, dynamics, fluid flow, heat transfer and electromagnetism. ANSYS was employed to model the diaphragm breakage process with the finite element method. This method is a numerical procedure using integral formulations to create a system of algebraic equations which can be applied to obtain solutions to various engineering problems.[75]

The simulation stages were outlined in the flow chart in Figure 6.1. Explicit dynamics with principal stress failure was chosen as the analysis system since it gives insight into how a structure behaves under a short-duration high-pressure loading.[76] In the principal stress failure model, the initiation of failure is decided with two criteria: (i) maximum principal tensile stress and (ii) maximum shear stress. When either of the criteria is reached, the material fails instantaneously. In this simulation, the aluminium alloy NL material of the diaphragm was defined with maximum tensile stress and maximum shear stress as $3.3 \times 10^8 \text{ Pa}$ and $2 \times 10^8 \text{ Pa}$ respectively (values provided by built-in library).

The diaphragm system was designed as shown in Figure 6.2, which consisted of a 500 μm thick diaphragm and a holder ring with an inner radius of 58 mm. The thickness of the diaphragm in simulations was chosen to be greater than all the ones used in ex-

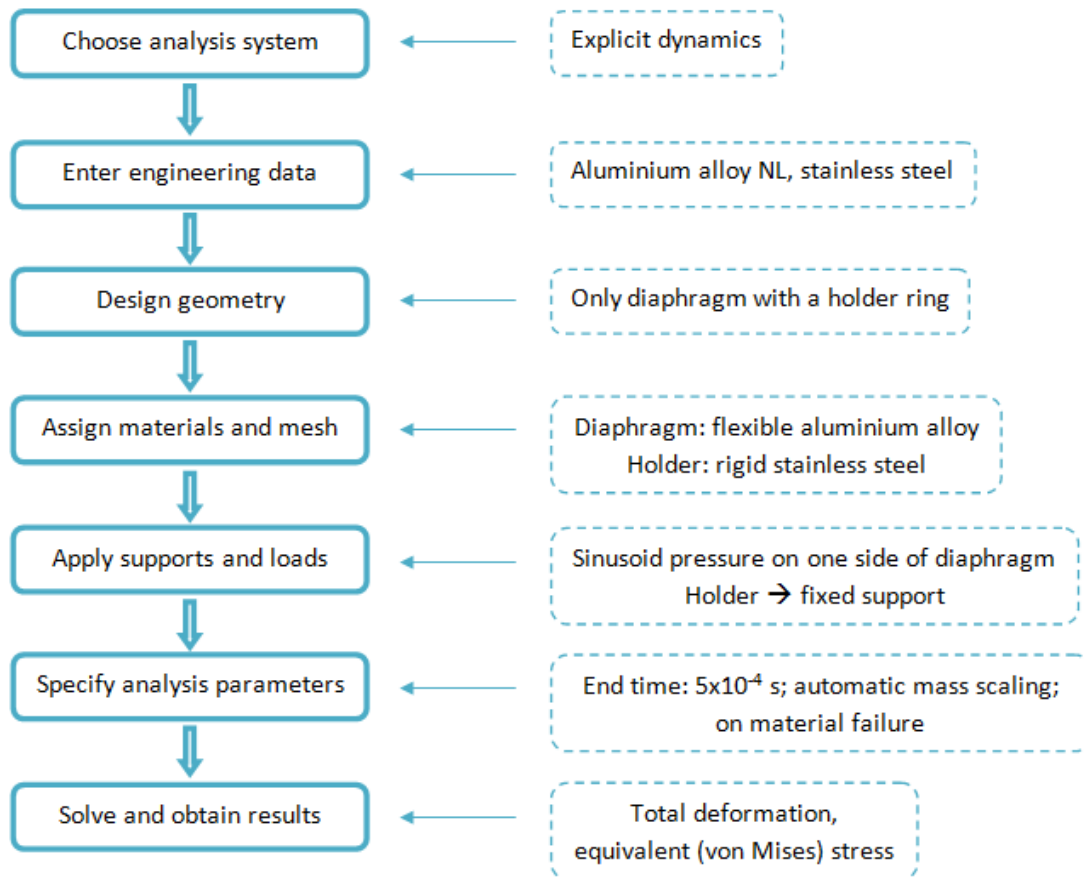


Figure 6.1: Flow chart of computational simulations using employing the finite element method

periments as a compromise with the running time of the simulation. The parts of the holder in contact with the diaphragm had the shape of o-rings in order to avoid sharp edge problems. The part of the diaphragm inside the holder was designed to be thicker to prevent the diaphragm from slipping out when under loading pressure. The interaction between the diaphragm and the ring holder was defined to be frictionless. The material for the diaphragm and the holder was chosen to be aluminium alloy and stainless steel respectively. The engineering data for aluminium alloy was amended according to the specification of aluminium foil. The behaviour of the holder was set to be rigid fixed supporter, i.e. the body would not deform under external loads and kept stationary. A mixture of quadratic and triangular meshes with an element size of 1 mm with a high smoothing effect were used for the model (Figure 6.3). This was the minimum element size that could be achieved for this model and it was good enough for the program to

be executed with an energy error less than 10%. However, since the mesh size is bigger than the thickness of the diaphragm, the mesh inside the diaphragm is quite coarse and the program treats the diaphragm as a thin surface (Figure 6.3B). This mesh configuration divided the bodies into 193000 elements with 43713 nodes. Nodes are the points at which different elements join together and interactions between these elements were programmed by ANSYS to follow the material and structural properties. A boundary condition was applied to all the edges present in the design where the minimum edge length was specified to be 0.18 m. Since the holder and the diaphragm only touched each other but not linked together, boundary conditions did not have to be specified in contact regions.

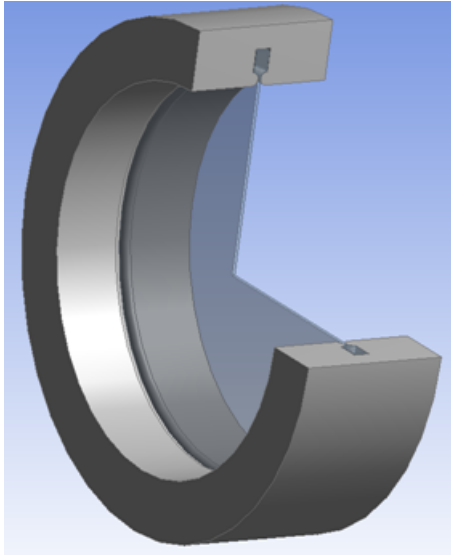


Figure 6.2: The cut-away section showing the geometry of computational simulation – The model only consists of a holder ring and a diaphragm. The contact surfaces between the holder and the diaphragm were designed to immitate the o-ring shape in order to reduce sharp edge effects. Diaphragm was made to be thicker at the rear to avoid slipping.

A sinusoidal increasing pressure load was applied to one side of the diaphragm in order to simulate the effect of pressurised gas (Figure 6.4). A gas fluid was not used since it would significantly increase the computational cost. Various maximum values of pressure, from 5 bar to 50 bar, were used to identify the burst pressure for the simulation and to investigate the effect of increasing pressure.

The simulation was set to last for 0.5 ms with the ‘automatic mass scaling’ , ‘on geometric strain limit’ (value = 1.5 as default), and ‘on material failure’ options for erosion controls enabled. The solution returned information of the total deformation and the equivalent stress of the diaphragm. Since the holder was set to be a rigid body, the stress on it was not calculated.

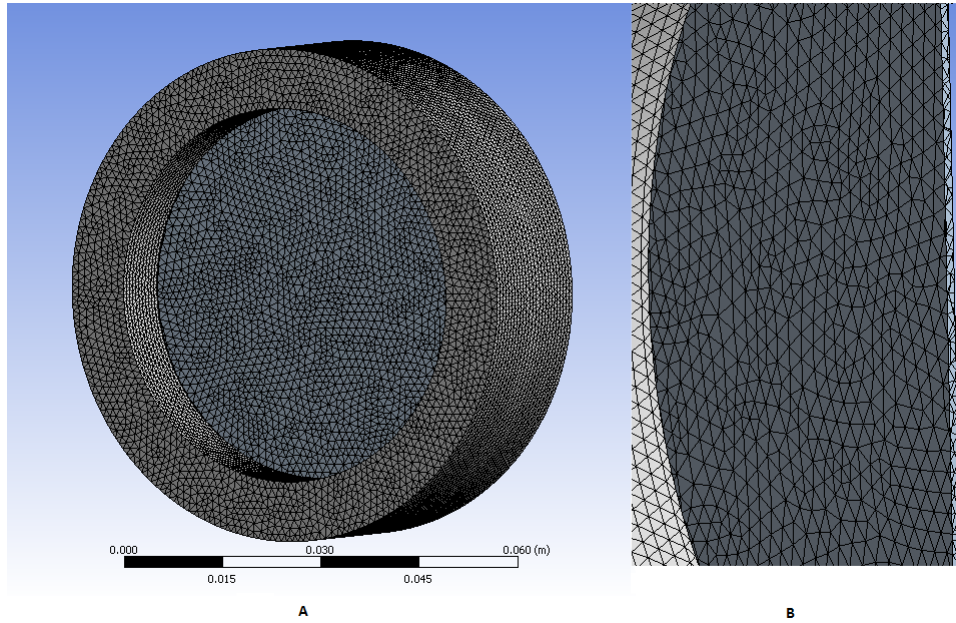


Figure 6.3: Mesh assigned on the design of the simulation – (A) The total view with an element size of 10^3 m. (B) The cut-away shows the mesh inside the diaphragm. Since the element size cannot go below the diaphragm thickness, the mesh is very coarse and the simulations treat the diaphragm as a thin surface.

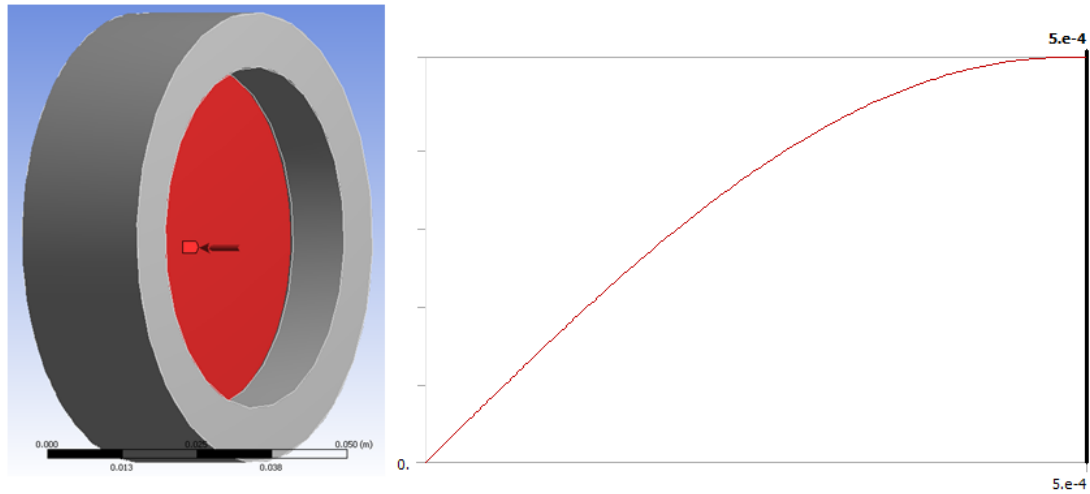


Figure 6.4: Pressure load in computational simulations – To avoid using gas and reduce the complexity of the simulation at this stage, a sinusoidal increasing pressure was applied to one side of the diaphragm.

6.1.2 Results and discussions

Highlights of results from the ANSYS are shown in Figure 6.5. It was found that in these simulations, the diaphragm breaks at a minimum pressure of 13 bar. From the average experimental burst pressures observed for one and two layers of $40\text{ }\mu\text{m}$ aluminium diaphragm(s) ($\sim 1.47 \pm 0.02$ bar and 2.95 ± 0.03 bar respectively), it can be estimated

that an aluminium foil 500 μm thick should break around 18.50 ± 0.05 bar, which is of the same order of magnitude as the minimum breakage pressure observed in this simulation. The top part of Figure 6.5 features the bursting at 14 bar which has a similar rupture process as that of the single-diaphragm setup where the diaphragm petals in the three-dimensional fashion (top, 6.5). The bottom part of Figure 6.5 for the case with 50 bar applied pressure, on the other hand, shows the breakage similar to that of the double-diaphragm bursting where the cracks originate and propagate in an irregular way (bottom, 6.5).

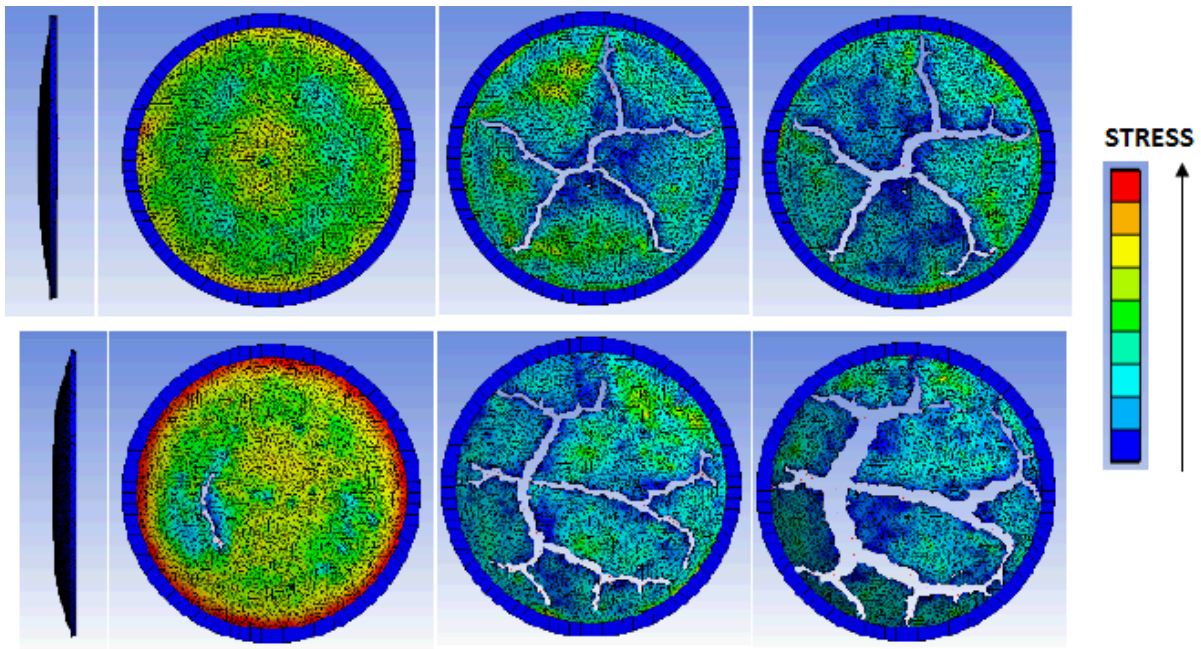


Figure 6.5: The diaphragm breakage simulations created with ANSYS program using finite element method – top: 14 bar burst pressure, bottom: 50 bar burst pressure. The first figures in each series show the bulging stage. The second figures show the stage when the stress on the diaphragms reach their maximum just before rupture. The third figures show the points when cracks first appear in the diaphragm. Finally, the last figures show the complete breakage of the diaphragms.

For both scenarios, bulging occurs, but lasts for a very short time because the simulation was limited to only 0.5 ms and the applied pressure was increased at a much faster rate than during the experiments. Due to the simple model of the holder without the o-rings, stress is more concentrated at the edge of the diaphragm. In addition, the crack initiation and propagation cannot be simulated well because pressure is applied evenly on the diaphragm. This is closer to the case of blast-driven bursting, but for single-diaphragm

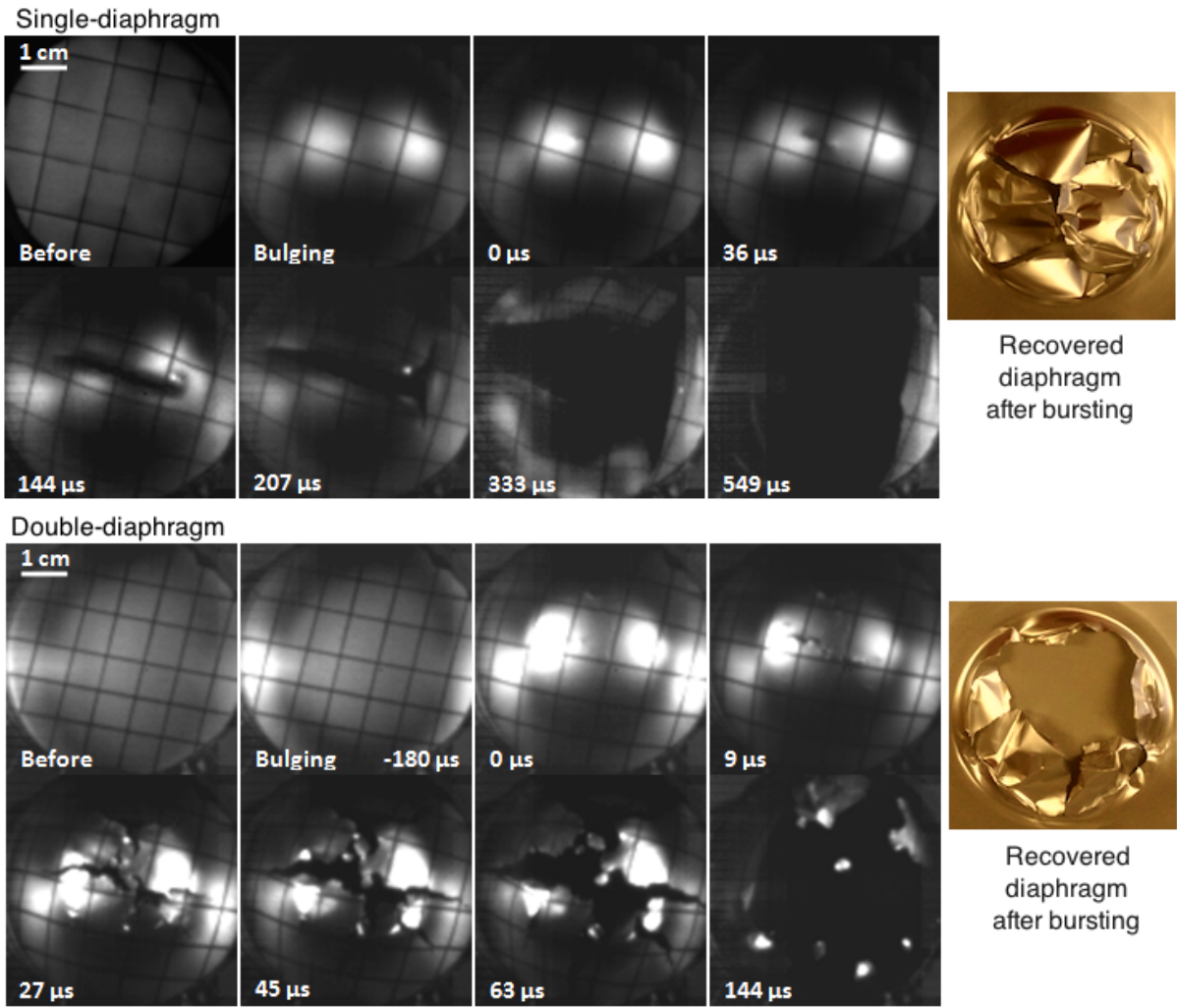


Figure 6.6: Series of high-speed images of the rupture of 40 μm aluminium diaphragm in single-diaphragm (top) and double-diaphragm (bottom) setup. Colour photos show examples of recovered diaphragm after bursting for the two cases, where the single-diaphragm was opened into four petals and double-diaphragm had more cracks with fragments.

rupture, a pressurised air body should be employed. By introducing air into the system, the evolution of the shock along the tube can also be simulated. Finally, during the simulation, the energy error had to be relaxed to double its default value (from 5% to 10%) and the mesh inside the diaphragm was quite coarse. This is because the element size of the mesh was not small enough even though it was the smallest value possible. This can be improved by using a model with better approximations (e.g. scale to a smaller size or use a different design for contact surfaces between the holder and the diaphragm) to reduce any unnecessary complexity. An alternative meshing method could also be used where different meshing sizes are assigned to different bodies to reduce the computational cost but still retaining the accuracy of more important regions.

6.2 Shock wave generation simulations

6.2.1 Star-CCM+ computational fluid dynamics simulations

Computational fluid dynamics (CFD) is the fluid mechanics branch that can solve fluid flow problems using numerical method and algorithms. Star-CCM+ (CCM stands for Computational Continuum Mechanics) is an object-oriented software for CFD simulations, which has a wide range of options for solving various flow regimes (steady or unsteady in time, invicid or laminar, transitional to fully turbulent, incompressible or compressible, subsonic to hypersonic, etc.), as well as heat transfer and stress. It is a useful tool in many engineering applications, especially aerodynamics.

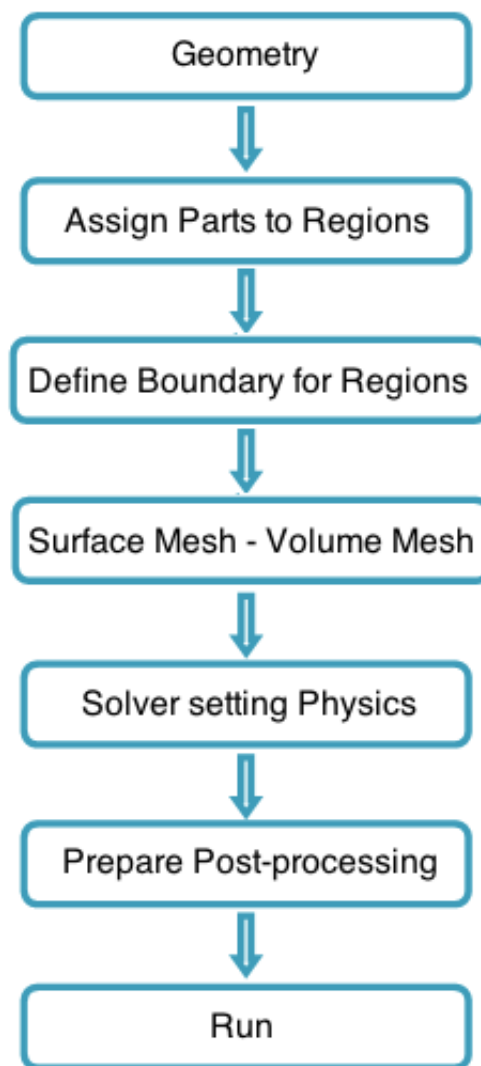


Figure 6.7: Flow chart for the workflow of the Star-CCM+ program

Figure 6.7 shows the workflow of a Star-CCM+ CFD simulation. The first step in the process is to build the object geometry, which can be done using the integrated 3D-CAD module or importing an existing CAD model. The geometry can be edited at any time during the process, and other criteria can be updated accordingly. The 3D-CAD model can then be converted into different geometry parts (an object or collection of objects) so that each can be assigned with their own meshing conditions. In order to use mesh continuum (computational domain where mesh is created by a collection of mesh models) rather than part-based meshing, the geometry parts must be assigned to one or more regions, hence the name region-based meshing. This also need to be done so that the part surfaces can be assigned to boundaries. Then meshing can be carried out either part-based or region-based on surfaces as well as volumes involved in the simulation. The final steps are to define the physics model relevant to the problem and set up measurements for post-processing.

Following the outlined stages, Star-CCM+ was used to model the generation of blast waves in the shock tube of 24-cm-long driver length at 5.2 bar and 36-cm-long driven section at atmospheric pressure. The chosen driver length was the smallest length of the CBIS shock tube driving section. The simulated driven length was 6 times the shock tube inner diameter, sufficient for the formation of blast wave. Smaller lengths were used first to save time and computing resources. Results from the simulation were then compared with experimental data from the case of 5.2 bar burst pressure with 24-cm-long driver section and the full CBIS shock tube driven section (~ 2.5 m long).

The geometry of the simulated shock tube was constructed with the integrated 3D-CAD (Figure 6.8). As the shock tube is axially symmetric, only a quarter of the tube's diameter needed to be model; two symmetric planes could then be used to build the full shock tube cross-section. A 30×30 mm quadrant was made constructed at $(x,y) = (0,0)$, where the 'diaphragm' was intended to be. It was then extruded in the $-z$ direction for 24 cm, i.e. the driver section, and in the $+z$ direction for 36 cm, i.e. the driven section. Afterward, the two extrusions were united as one single body.

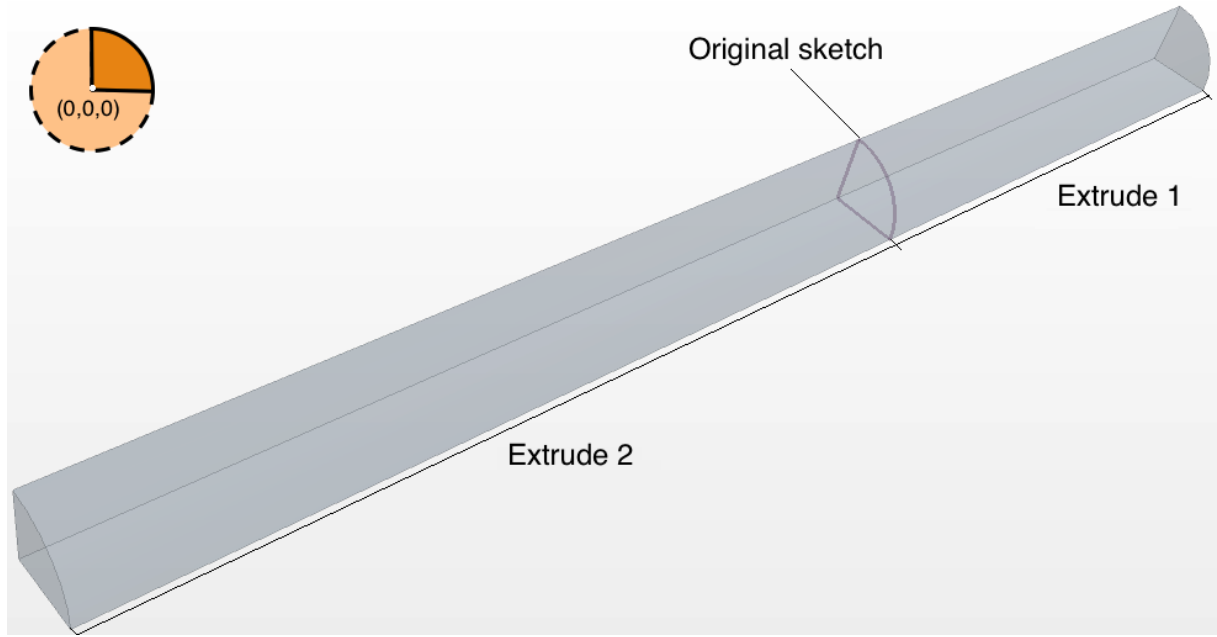


Figure 6.8: The construction of the simulated shock tube geometry

The 3D-CAD geometry was then converted to various parts which were then assigned to different regions and boundaries, through the commands ‘Create a Region for Each Part’ and ‘Create a Boundary for Each Part Surface’, as shown in Figure 6.9 and Table 6.1. There were three types of boundaries involved in the simulated geometry: wall boundary for the inlet and shock tube wall regions, symmetry plane for the two symmetry plane parts, and pressure outlet for the shock tube outlet. As the blast generation was simulated from the moment of diaphragm bursting, there was no need to model the charging of the driver section, hence the inlet is modelled as a closed wall.

Region	Boundary type
Inlet	Wall
Outlet	Pressure outlet
Symmetry plane 1	Symmetry plane
Symmetry plane 2	Symmetry plane
Wall	Wall

Table 6.1: Boundary types of simulated shock tube regions

Meshing of the shock tube (Figure 6.10) was done with the automated mesher function which involved a surface remesher, a polyhedral mesher, and a prism layer mesher. The surface remesher was used to improve the quality of the shock tube surface and hence

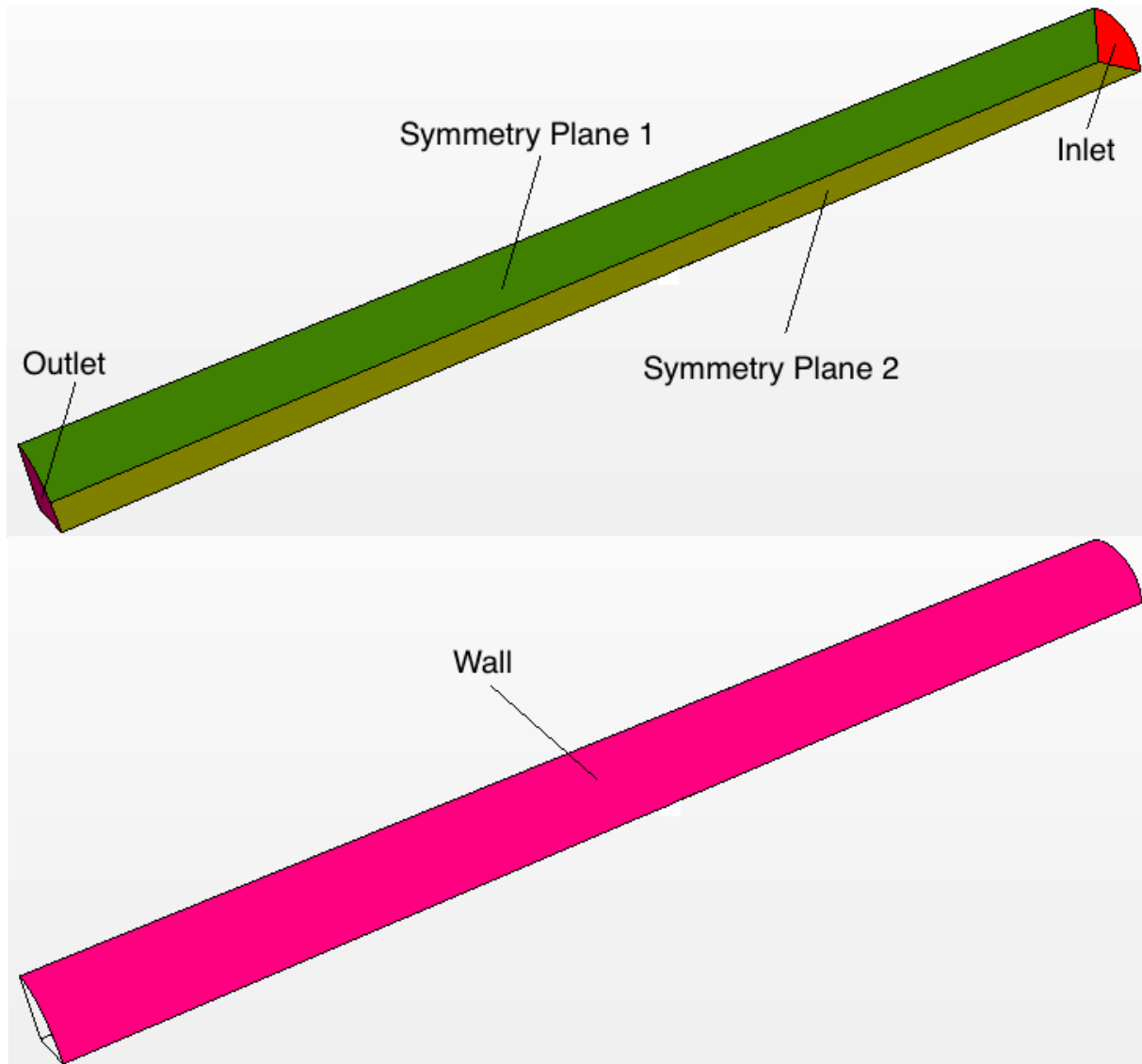


Figure 6.9: Parts and regions of the simulated shock tube

to optimise it for volume meshing of the shock tube body. The polyhedral mesher uses arbitrary polyhedral cell shape to build the volume mesh. It was chosen for this simulation due to its efficiency, especially for complex mesh generations, since it contains about five times fewer cells than a common tetrahedral mesh for the same surface. The prism layer mesher generated orthogonal prismatic cells next to wall boundaries. This meshing model can improve the accuracy of the solution for the flow, which is relevant to the shock tube problem. Values for mesh settings were used as shown in Table 6.2. The element base size was chosen to be 1 mm, which could compromise between the small cross-section of the tube diameter (6 cm) and the large simulated length of the shock tube (60 cm).

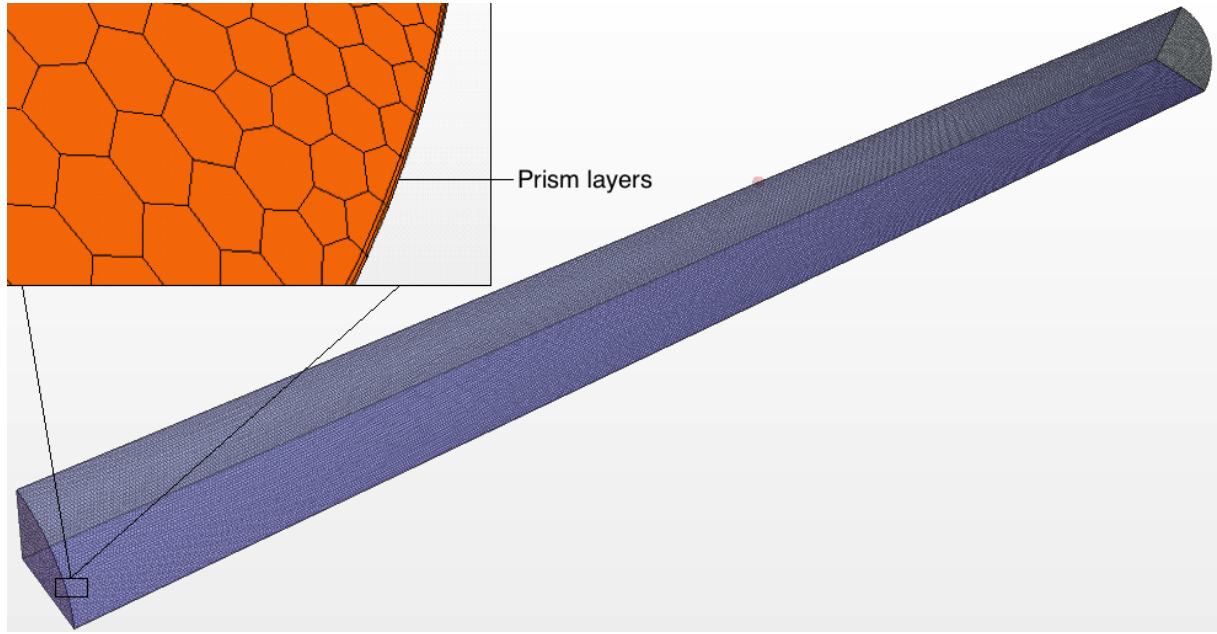


Figure 6.10: Meshing of the simulated shock tube

Property	Value
Base size	0.001 m
Surface growth rate	1.3
Number of prism layer	2
Prism layer total thickness	10% base size

Table 6.2: Mesh settings for the simulated shock tube

A physics continuum was created and applied to the whole simulated shock tube. Within this continuum, various physics models were selected as highlighted below:

- **Model selections:** *Coupled Flow, Coupled Energy, Implicit Unsteady, Reynolds-Averaged Navier-Stokes (RANS), Realisable Two-Layer K-Epsilon (RKE 2L)) turbulence, ideal gas.*

Coupled Flow is the model that can solve the equations for conservations of mass, momentum, and energy simultaneously, using the pseudo-time-marching technique. Its advantages are its robustness for flow problems, and linear scaling of CPU time with cell count (i.e. refining of mesh does not hugely affect the convergence rate). It is also a good combination with the AUSM+ scheme used in the advance setting for this simulation. The Coupled Energy model is an extension of the Coupled

Flow model, which enhance the independence of convergence rate against the Mach number.

For the Coupled Flow and Coupled Energy models, the choice between the implicit unsteady and the alternative explicit unsteady model depends on the time scales of the problem. For most CFD simulations, governing equations are non-linear, and with a large number of unknown variables, the implicit unsteady model is almost always the more suitable approach.

The RANS model consists of time-averaged equations for motions of turbulent fluid flows. This model can be combined with further suitable turbulence models to accurately describe the desired flow problems. In this case, the RKE 2L turbulence model was chosen for the shock tube simulation. The Realisable K-Epsilon (RKE) model uses a function of mean flow and turbulence properties to define the turbulence coefficient instead of the constant value assumption is standard models. Hence, the normal stress is more consistent with the physics of turbulence and the experimental observations of boundary layer problems. The two-layer approach adds in the flexibility of all $y+$ wall treatment, which works well with the fine meshes and viscous sublayer issues.

Finally, the Ideal Gas model was chosen to start with to keep the simulation less complicated. Further adjustments can be added as the simulation progresses.

- **Advanced settings:** *AUSM+ FVS scheme, and Sutherland's law.* The AUSM+ FVS (Advection Upstream Splitting Method - Flux Vector Splitting) scheme is a numerical inviscid flux function that can accurately capture the shock and contact discontinuities. Sutherland's law describes the relationship between the dynamic viscosity and the absolute temperature for an ideal gas. It is commonly used as it can give accurate results with less-than-few-percent error for a wide range of temperatures. Thanks to their relevant benefits, these two advanced optional functions were chosen to improve the accuracy of the shock tube simulation.
- **Initial conditions:** reference pressure was set as 1.01325 bar; initial pressure and

temperature were defined as $(P, T) = (5.2 \text{ bar}, K)$ for $z < 0$; $(P, T) = (0 \text{ bar}, K)$ for $z > 0$. Since it was not yet needed to model the charging process of the driver section, the initial conditions were set as just before the bursting of the diaphragm. In this case, there was no physical diaphragm presenting. Instead, the ‘diaphragm’ was defined as the boundary between the high and the low pressure values, at $z = 0$ (Figure 6.11). Effectively, this means the ideal gas description is assumed for the simulation. In addition, it needs to be noted that there was no big difference between the temperature of the driver and driven sections since the stainless steel driver tube is assumed to act as a giant heat sink, keeping the driver gas from high temperature.

- ***Solver settings:*** 10 μs time-step with 15 inner iterations for a total of 5500 iterations.

The post-processing was prepared with four probe points and a probe plane measuring the pressure magnitude time history as shown in Figure 6.11. The probe points were positioned at 6 cm, 12 cm, 24 cm, and 36 cm away from the ‘diaphragm’ position, which are 1, 2, 4, and 6 bore diameter respectively. They were set up to monitor the evolution of the simulated blast wave along the shock tube (probe point 1, 2, and 3) and at the tube outlet (probe point 4). The probe plane was used to capture the axial profile of the blast wave. After 5500 iterations, the time - pressure data of the four probe points was exported and compared with experimental results.

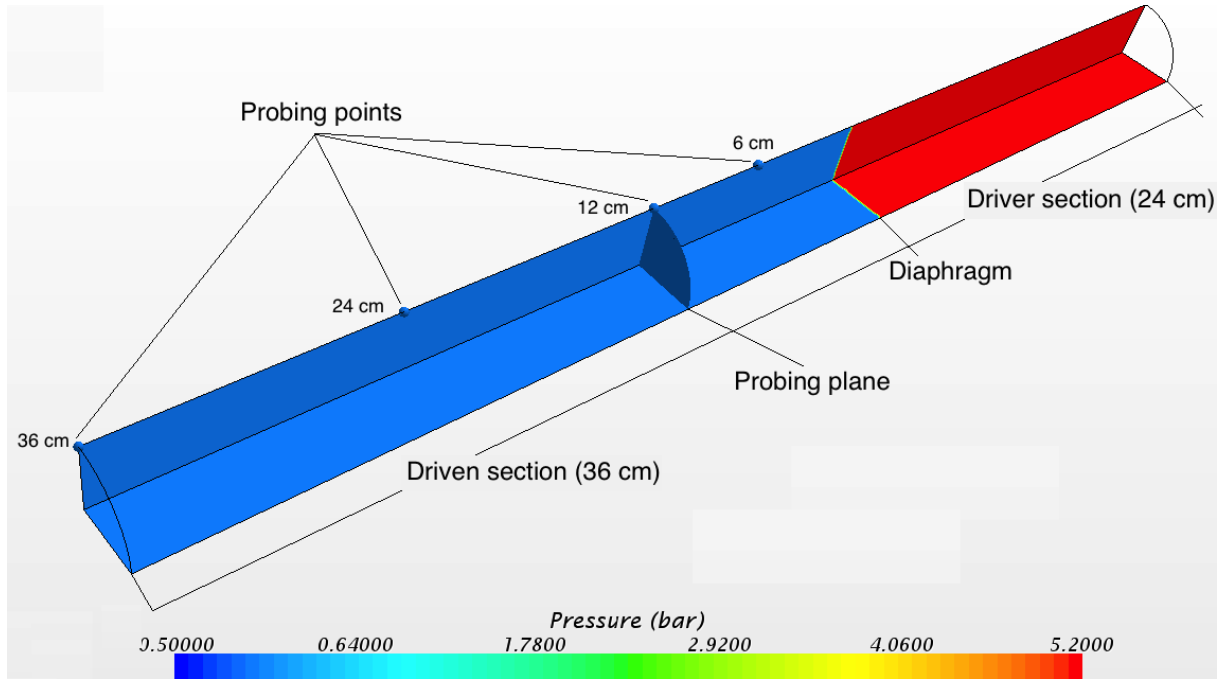


Figure 6.11: Initial conditions and post-processing set-up of the simulated shock tube

6.2.2 Results and discussions

Figure 6.12 shows the computational blast wave generation in the shock tube for the first 0.3 ms. It can be seen that the blast wave simulated was planar, which agrees with observations from schlieren images of the blast wave just exiting the shock tube. The simulation also shows the rarefaction wave (yellow part) expanding while travelling back to the shock tube inlet, as expected from the theory of shock tube.

The computational pressure - time histories from the 4 probe points for the full 5 ms of simulation are shown in Figure 6.13, together with the experimental result of the same shock tube driving conditions. However, the experimental pressure trace was taken from the secondary lateral sensor which was position at 1.25 m from the diaphragm and 12 cm from the shock tube outlet. This gives rise to discrepancies when comparing with the simulated shock tube of only 36 cm driven length. There are good agreements between the computational and experimental results for pressure magnitudes (both positive and negative features), the pulse width (i.e. overpressure time), and the velocity of the shock front (Table 6.3). These agreements are less for probe points further away from the ‘diaphragm’ location. This is likely due to incorrect boundary conditions of the outlet, shown by the pressure profile of probe point 4 very different from the experiment observation.

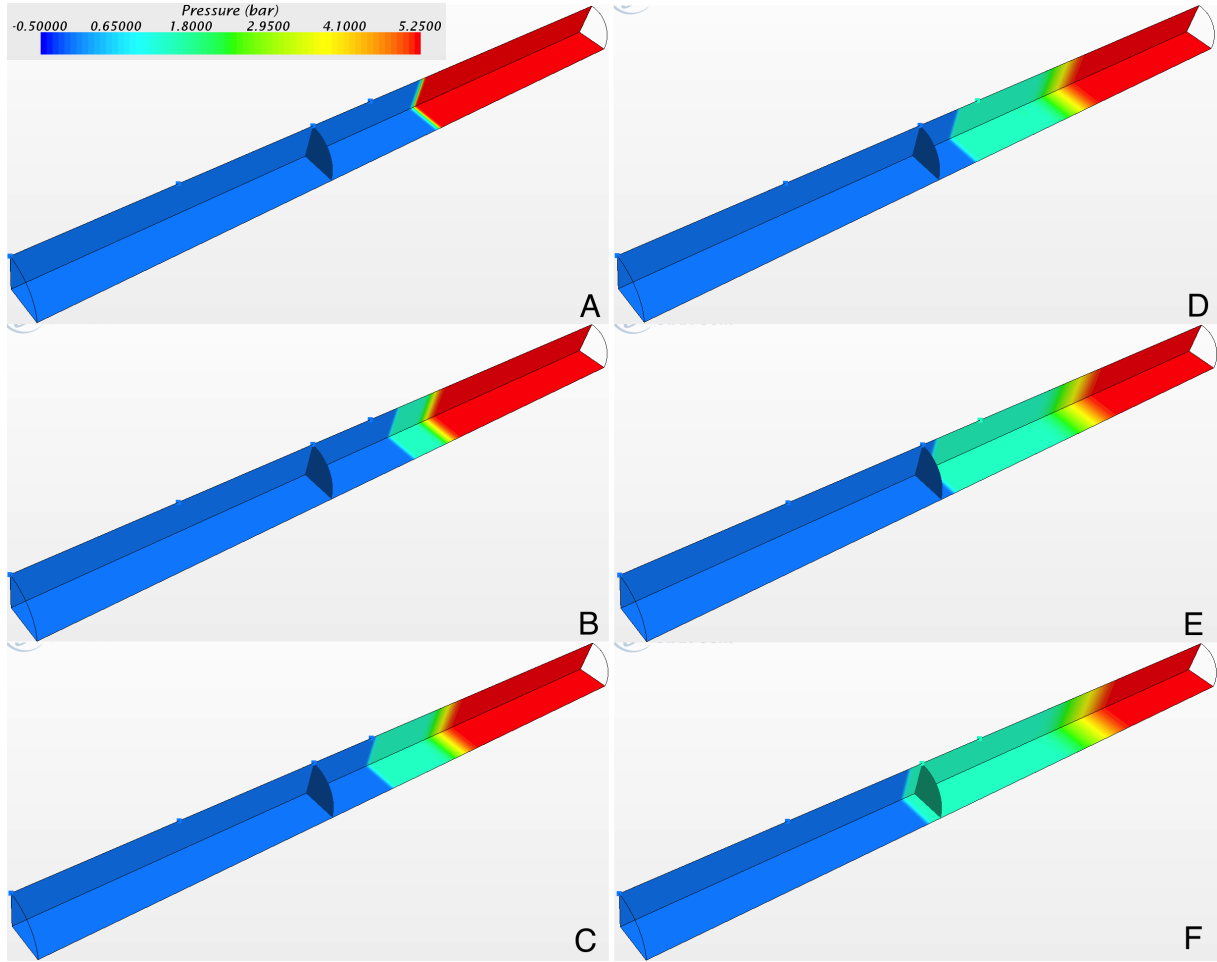


Figure 6.12: Snapshots of the first 0.3 ms of the shock tube simulation with the time interval of 0.05 ms

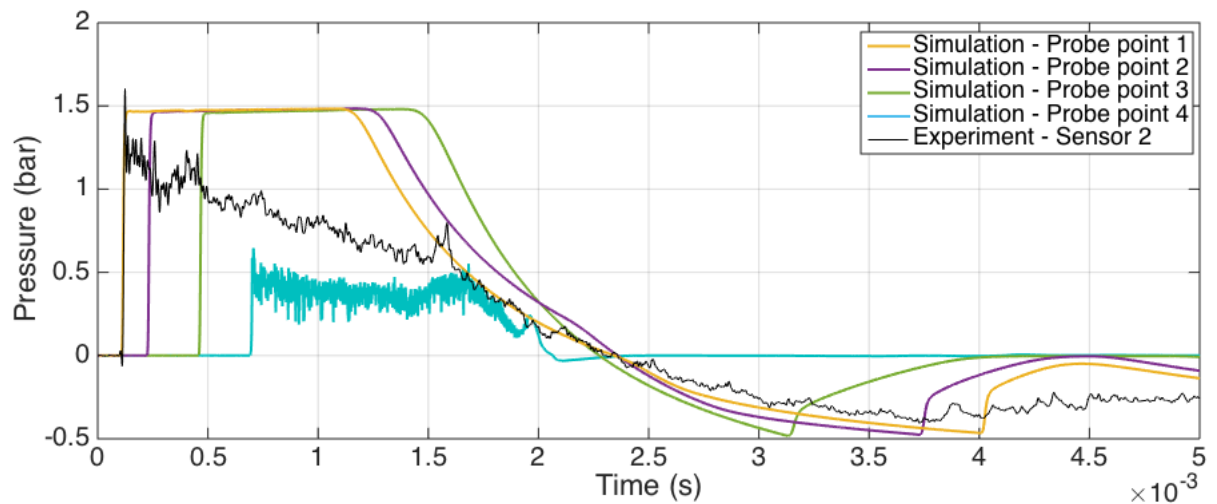


Figure 6.13: Pressure traces from the 4 probe points of the simulation, compared with similar experimental result (black trace)

The duration of the plateau feature, hence the pulse shape, of the simulation does not show the same traits as the experiment. This suggests that the friction setting for the

shock tube wall, i.e. boundary layer setting, was not accurate. This can be improved by using greater number of prism layers with a finer mesh around the tube wall. The dynamic viscosity of the gas should also be re-defined for better results. There is also a discrepancy for the duration of the underpressure feature as the environment outside the shock tube outlet was not modelled in this simulation.

Quantity	Probe 1	Probe 2	Probe 3	Probe 4	Experiment
Pressure magnitude	1.47 bar	1.45 bar	1.45 bar	0.65 bar	1.60 bar
Plateau duration	1.02 ms	0.99 ms	0.95 ms	1.04 ms	0.32 ms
Pulse width	2.23 ms	2.13 ms	1.82 ms	1.38 ms	2.25 ms
Shock impulse	2.16 bar ms	2.16 bar ms	1.97 bar ms	0.46 bar ms	1.50 bar ms
Underpressure mag.	-0.47 bar	-0.48 bar	-0.48 bar	-0.03 bar	-0.40 bar
Underpressure dur.	2.08 ms	2.10 ms	1.85 ms	0.34 ms	5.88 ms
Shock front velocity		518 ms ⁻¹			490 ms ⁻¹

Table 6.3: Comparison between computational results and experimental observations

Finally, the short simulated shock tube length, compared to reality, can also affect the accuracy of the model. The issue with simulating the full length is that the shock tube has very small cross-sectional area, but very long, thus it is tricky to satisfy both fine mesh and reasonable computing time. To go around this, the shock tube can be modelled as various separate lengths, with the output of one being the input of the next length to build up the whole shock tube model.

6.3 Conclusions

For most of the shock tube studies, we only have limited resource of biological samples, and the interactions between the output blast waves with chamber for these samples are very complex. In order to optimise the experiment outcome, and fully understand the loading on these few samples we can obtain, it is important to be able to model this shock tube output computationally, and also simulate the effects of the output blast waves and other structures on each other.

For this purpose, the Star-CCM+ CFD package has been used to model the blast wave generation inside a shock tube. The results so far show reasonable agreement between the computational simulation and the experiment in term of pressure magnitudes and

pulse width. The boundary layer problem, and the boundary condition of the shock tube outlet are being improved to refine the simulation. Lengthwise discretisation will be used to model the full shock tube length.

In order to study the interaction between the blast waves and various structures, two-way coupling with structural programme for finite element analysis (such as Abaqus and ANSYS) is necessary. The gas flow inside the shock tube can also be coupled with the simulation of diaphragm breakage, as shown in Section 6.1, to explain smaller features of the recorded blast waves from experiments.

Chapter 7

Conclusions

7.1 Summary of Thesis

The shock tube is a device that is able to generate well-defined pressure pulses of varying intensity and duration. Since its invention in 1899, it has found application such as aeronautics, chemical kinematics and plasma physics. Inside the shock tube, a blast wave can be produced by the build up of pressure that causes a diaphragm to suddenly burst, bringing the separated driver gas of high pressure into contact with the driven gas of low pressure. This project focused on blast waves, a high-pressure pulse followed by a wind of negative pressure, in the context of biomedical studies. The blast lasts for a very short time, but it can cause severe damage on objects in the surrounding by drastic changes in pressure, flying debris and strong propulsions.

The project performed series of experiments to characterise the working of the CBIS shock tube system with a range of diaphragms, shock tube configurations and set up conditions. Together with high-speed imaging techniques, schlieren photography can be set up in the open configuration of the shock tube to visualise produced blast waves and their interactions with platforms for blast injury studies. The results address several issues that highlight the characteristics of the shock tube:

- The outputs of the shock tube are highly reproducible and can be used to study blast effects on biological samples representing injuries in open space as well as

inside vehicles.

- The double-diaphragm system enables the diaphragm to be burst at a specific chosen pressure, i.e. giving more control over the output shock wave.
- The magnitude of the shock can be manipulated with the diaphragm burst pressure which is linearly proportional to the diaphragm thickness.
- For the same thickness, the more compliant the diaphragm, the higher burst pressure and hence, greater output pressure can be achieved.
- The location of the sample, together with its size, govern the pressure loading on the sample. Axial samples experience more direct effect of the gas flow.
- The duration of the shock pulse can be tailored, without significantly affecting its magnitude, by adjusting the volume of the high-pressure driver gas.
- Lateral measurements can be used to identify the blast incident on a sample mounted axially to the shock tube, thanks to the identified linear relationship between the two orientations.
- The rotational orientation of the lateral mounting of sensors does not affect the pressure measurement.

The CBIS shock tube was also used to investigate the blast attenuating effects of various structures:

- Perforated galvanised steel sheets with 22% open area can reduce the peak pressure magnitude to 30%. For the study range of 22-79% open area, the transmitted shock magnitude and impulse increase linearly with increasing percentage of open area, and vice versa for the reflected values. As the open area approaches 79%, there is almost no mitigating effect.
- Adding a layer of adhesive sealing membrane to the 79% perforated sheet, transmitted peak pressure was reduced to 4-7% while impulse was cut down to $\sim 2\%$. The

shapes of blast loadings were also transformed to be more ramp-like. These extra mitigation was exchanged for the reusability of the structure.

- Reticulated polyurethane foams of pore distribution 65-70ppi and thickness 20-60mm were investigated and found to reduce peak pressure to 5-16% and impulse to 0.25-0.5%. The attenuation is more effective with denser and thicker foam.
- For sandwich structures of 22% or 46% perforated sheets with 20 mm or 40 mm reticulated foam, the pressure attenuation achieved is between 75% and 95%, which is higher for denser structures. The impulse attenuation is achieved to between 90% and 95%, where the open area of the perforated sheets proved to be the more important factor.
- The results for interactions of blast waves and mitigating structures reported here are limited by the size and capacity of the shock tube.

The shock tube can be adapted to study the blast effects on biological specimens. The EVOC adaptor was designed to enable the mounting of tissues in EVOC preparation. With adhesive sealing membranes for preventing contaminations, this adaptor can be used for *in-vitro* testing of cells. A platform to investigate the primary blast limb trauma in rodent was reported. Only the desired body part is exposed to the blast while the rest is shielded to avoid the post-trauma induced complications. The characterisation of the platform was carried out to identify the incident loadings in various shock tube configurations. Such characterisations are important before using these types of platforms with actual biological samples as unexpected loading features due to interactions between generated blasts and platform structures need to be addressed and eliminated to avoid undesired effects on samples.

The Star-CCM+ CFD package has been used to model the blast wave generation inside a shock tube to optimise the experiment outcome, and fully understand the loading on these few samples we can obtain. The results so far show reasonable agreement between the computational simulation and the experiment in term of pressure magnitudes and pulse width. The boundary layer problem, and the boundary condition of the shock tube

outlet are being improved to refine the simulation. Lengthwise discretisation will be used to model the full shock tube length.

7.2 Future work

The development and characterisation of the CBIS shock tube system from this project will enable researches on blast injuries and mitigations to be expanded to different blast loading scenarios. Traditionally, the shock tube is used for whole the animal model. Recently, its usages have been extended to the level of cell culture and animal tissues in order to identify the blast injury mechanism biochemically. This research direction should be enhanced with further development of mounting conditions such as the re-directed shock tube so that the ‘lateral’ samples can experience ‘axial’ loadings, suspensions of tissues closer to the *in-vitro* condition, and the form of blast loading through various outer layers of the body. For the whole animal studies, a design using a confinement tube is being developed for better mounting and shielding of animals as well as to reduce additional blast effects due to interaction with mounting geometry. To expand the investigation on perforated sheets, other properties (such as thickness, holes size, holes distribution, and the sheet materials) can be characterised with various arrangements: multiple layers of perforated sheets of same and different open areas and orientations. The mitigation study will also extend to granular structures of different materials (sodalime glass, sand), with different sizes, porosity, and thicknesses. Finally, to further study the interaction between the blast waves and various structures, two-way coupling between CFD simulations with structural programme for finite element analysis (such as Abaqus and ANSYS) is another important step forward.

Bibliography

- [1] N. M. Elsayed. *Toxicology of blast overpressure* (1997). Toxicology 121 1-15.
- [2] J. A. G. Singleton, I. E. Gibb, N. C. A. Hunt, A. M. J. Bull, and J. C. Clasper. *Identifying future ‘unexpected’ survivors: a retrospective cohort study of fatal injury patterns in victims of improvised explosive devices* (2013). BMJ Open 2013; 3:e003130.
- [3] A. Ramasamy, S. Harrison, I. Lasrado, and M. P. M. Stewart. *A review of casualties during the Iraqi insurgency 2006 - A British field hospital experience* (2009). Injury, International Journal of Care Injured 40 493-497.
- [4] JF. Turegano-Fuentes, P. Caba-Doussoux, J. M. Jover-Navalon, E. Martin-Perez, D. Fernandez-Luengas, L. Diez-Valladares, D. Perez-Diaz, P. Yuste-Garcia, H. G. Labajo, R. Rios-Blanco, F. Hernando-Trancho, F. G-M Nisa, M. Sanz-Sanchez, C. Garcia-Fuentes, A. Martinez-Virto, J. L. Leon-Baltasar, and J. Vazquez-Estevez.. *Injury patterns from major urban terrorist bombing in trains: the Madrid experience* (2008). World Journal of Surgery 32:1168-1175.
- [5] A. Ramasamy, S. E. Harrison, J. C. Clasper, and M. P. M. Stewart. *Injuries from roadside improvised explosive devices* (2008). The Journal of Trauma: Injury, Infection, and Critical Care 65:910-914.
- [6] B. D. Owens, J. F. Kragh, J. C. Wenke, J. Macaitis, C. E. Wade, and J. B. Holcomb. *Combat wound in operation Iraqi freedom and operation enduring freedom* (2008). The Journal of Trauma: Injury, Infection, and Critical Care 64:295-299.

- [7] D. E. Hinsley, P. A. Rosell, T. K. Rowlands, and J. C. Clasper. *Penetrating missile injuries during asymmetric warfare in the 2003 Gulf conflict* (2003). British Journal of Surgery 92[5]:637-642.
- [8] K. Peleg, L. Aharonson-Daniel, M. Stein, M. Michaelson, Y. Kluger, D. Simon, and E. K. Noji. *Gunshot and explosion injuries - Characteristics, outcomes, and implications for care of terror-related injuries in Israel* (2004). Annals of Surgery 239:311-318.
- [9] K. H. Taber, D. L. Warden, and R. A. Hurley. *Blast-related traumatic brain injury: What is known?* (2006). Journal of Neuropsychiatry Clinique Neuroscience 18:2.
- [10] H. R. Champion, J. B. Holcomb, and L. A. Young. *Injuries from explosions: Physics, biophysics, pathology, and required research focus* (2009). The Journal of Trauma: Injury, Infection, and Critical Care 66:1468-1477.
- [11] Y. Kluger, A. Nimrod, P. Biderman, A. Mayo, and P. Sorkin. *The quinary pattern of blast injury* (2007). American Journal of Disaster Medicine 2(1):21-25.
- [12] M. F. Finkel. *The neurological consequences of explosives* (2006). Journal of the Neurological Sciences 249 63-67.
- [13] G. A. Henry. *Blast injuries of the ear* (1945). The Laryngoscope 55: 663-672.
- [14] Y. Roth, J. Kronenberg, S. Lotem, and G. Leventon. *Blast injury of the ear* (1989), Hebrew article with English translated abstract. Harefuah 117(10): 297-301.
- [15] J. Breeze, H. Cooper, C. R. Pearson, S. Henney, and A. Reid. *Ear injuries sustained by British service personnel subjected to blast trauma* (2011). The Journal of Laryngology and Otology 125 13-17.
- [16] C. Bo. *Investigation of the effects of high pressure pulses on biological samples* (2014). Doctoral Thesis, Physics, Imperial College London.
- [17] The US National Ground Intelligence Centre. *The Improvised explosive device safe standoff distance cheat sheet* (2005). Unclassified document.

- [18] W. C. Griffith and W. Bleakney. *Shock waves in gases* (1954). American Journal of Physics 22(9) 597-612
- [19] J. N. Bradley. *Shock waves in chemistry and physics* (1962). London: Methuen & Co. Ltd..
- [20] M. D. Salas. *The curious events leading to the theory of shock waves* (2007). Shock Waves 16:477-487.
- [21] A. G. Gaydon and I. R. Hurle. *The shock tube in high-temperature chemical physics* (1963). London: Chapman and Hall Ltd..
- [22] D. C. Weggel. Blast threats and blast loadings. In: N. Uddin ed. *Blast protection of civil infrastructures and vehicles using composites* (2010). Oxford, Cambridge, New Delhi: Woodhead Publishing Ltd., pp. 3-43.
- [23] W. E. Baker. *Explosions in air* (1973). Austin and Lonfon: University of Texas Press.
- [24] P. W. Cooper. *Explosives engineering* (1997). New York, Chichester, Weinheim, Brisbane, Singapore, Toronto: Wiley-VCH.
- [25] Department of Defense, United States of America. *Unified Facilities Criteria: Structure to resist the effects of accidental explosions* (2014). UFC 3-340-2.
- [26] P. Locking. *The trouble with TNT equivalence* (2011). The 26th International Ballistics Symposium, Miami.
- [27] D. R. Richmond, E. G. Damon, E. R. Fletcher, I. G. Bowen, and C. S. White. *The relationship between selected blast-wave parameters and the reponse of mammals exposed to air blast* (1966). Lovelace Foundation for Madical Education and Research, Albuquerque, New Mexico.
- [28] G. Ma, H. Zhou, Y. Lu, and K. Chong. *In-structure shock of underground structures: A theoretical approach* (2010). Engineering Structures 32 3836-3834.

- [29] J. H. Stuhmiller, Y. Y. Phillips III, and D. R. Richmond. The physics and mechanisms of primary blast injury. In: R. Zajtcuk, D. P. Jenkins, R. F. Bellamy, and M. Quick ed. *Conventional warfare: Ballistic, blast, and burn innjuries* (1991). US Army Medical Department, pp. 241-270.
- [30] M. Rogers. The shock tube - Talisman, tool or techniques?. In proc. *Shock tube and shock wave research : proceedings of the eleventh International Symposium on Shock Tubes and Waves* (1977). Seattle and London: University of Washington Press, pp. 3-11.
- [31] W. Payman and W. F. C. Shepherd. *Explosion waves and shock waves: the disturbances produced by bursting diaphragms with compressed air* (1946). Proceedings of the Royal Society of London A186: 293-321.
- [32] D. J. Chapman. *Design of shock tube facility* (2010).
- [33] I. Barsoum and J. Faleskog. *Rupture mechanisms in combined tension and shear - Experiments* (2006). International Journal of Solids and Structures 44 1768-1786.
- [34] E. M. Rothkopf and W. Low. *Diaphragm opening process in shock tubes* (1973). Physics of Fluids 17 1169-1173.
- [35] G. A. Campbell, G. M. Kimber and D. H. Napier. *Bursting of diaphragms as related to the operation of shock tubes* (1964). Journal of Scientific Instruments 42 381-384.
- [36] B. Holger. *Shock wave-boundary-layer interactions* (2011). Cambridge: Cambridge University Press.
- [37] W. C. Griffith. Research with the shock tube: A case history of science relevant to the needs of society. In proc. *Shock tube research: proceedings of the 8th International Shock Tube Symposium* (1971). London: Chapman and Hall, pp. 1-.
- [38] T. Akamatsu. Applications of shock tube technology to studies of hydrodynamics. In proc. *Shock tube and shock wave research : proceedings of the eleventh International*

- Symposium on Shock Tubes and Waves* (1977). Seattle and London: University of Washington Press, pp. 24-35.
- [39] B. Justusson, M. Pankow, C. Heinrich, M. Rudolph, and A. M. Waas. *Use of a shock tube to determine the bi-axial yield of an aluminium alloy under high rates* (2013). International Journal of Impact Engineering 58 55-65.
- [40] I. G. Bowen, E. R. Fletcher and D. R. Richmond. *Estimate of man's tolerance to the direct effects of air blast* (1968). Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico.
- [41] G. W. Wood, M. B. Panzer, J. K. Shridharani, K. A. Matthews, B. P. Capehart, B. S. Myers and C. R. Bass. *Attenuation of blast pressure behind ballistic protective vests* (2012). Injury Prevention 19(1): 19-25.
- [42] J. K. Shridharani, G. W. Wood, M. B. Panzer, B. P. Capehart, M. K. Nyein, R. A. Radovitzky and C. R. 'Dale' Bass. *Attenuation porcine head response to blast* (2012). Frontiers in Neurology 3:70.
- [43] M. B. Panzer, K. A. Matthews¹, A. W. Yu, B. Morrison III, D. F. Meaney and C. R. Bass. *A multiscale approach to blast neurotrauma modeling: part I – Development of novel test devices for in vivo and in vitro blast injury models* (2012). Frontiers in Neurology 3:46.
- [44] G. B. Effgen, C. D. Hue, E. Vogel III, M. B. Panzer, D. F. Meaney, C. R. Bass, and B. Morrison III. *A multiscale approach to blast neurotrauma modeling: part II – Methodology for inducing blast injury to in vitro models* (2012). Frontiers in Neurology 3:23.
- [45] J. H. Stuhmiller, K. H.H. Ho, M. J. Vander Vorst, K. T. Dodd, T. Fitzpatrick and M. Mayorga. *A Model of blast overpressure injury to the lung* (1996). Journal of Biomechanics 29(2) 227-234.

- [46] T-T. N. Nguyen, J. M. Wilgeroth and W. G. Proud. *Controlling blast wave generation in a shock tube for biological applications* (2014). Journal of Physics: Conference Series 500 142025.
- [47] Vision Research, Inc.. *Phantom v7.3 Datasheet* (2007).
- [48] Dytran Instrument, Inc.. *Introduction to piezoelectric pressure sensors* (Source date: 12th May 2014). Dytran Tech Education - <http://www.dytran.com/tech-education.aspx>, United States of America.
- [49] G. S. Settles. *Schlieren and shadowgraph techniques* (2001). New York: Springer.
- [50] Andrew Davidhazy. *Reflection schlieren photography of liquid surfaces* (Source date: 1st November 2015). Imaging and Photographic Technology, School of Photo Arts and Sciences / RIT. <https://people.rit.edu/andpph/text-reflection-schlieren-two.html>
- [51] P. K. Panigrahi and A. Mazumdar. *Schlieren and shadowgraph methods in heat and mass transfer* (2012). SpringerBriefs in Thermal Engineering and Applied Science.
- [52] H. J. Davis and H. D. Curchack. *Shock Tube Techniques and Instrumentation* (1969). Harry Diamond Laboratories, Washington D. C., United States of America.
- [53] C. Bo, N. Newell, T-T. N. Nguyen, B. Butler, J. Wilgeroth, J. Balzer, S. Masouros, A. Bull, A. Phillips, A. Jardine, A. Williams, S. Rankins, K. Brown, and W. Proud. *Understanding the effects of blast on biological systems* (2013). Proceedings of The 16th Seminar on New Trends in Research of Energetic Materials, Czech Republic.
- [54] A. Britan, G. Ben-Dor, O. Igra, and H. Shapiro. *Shock waves attenuation by granular filters* (2001). International journal of multiphase flow 27(4) 617-634.
- [55] A. Britan, G. Ben-Dor, T. Elperin, O. Igra, and J.P. Jiang. *Mechanism of compressive stress formation during weak shock waves impact with granular materials* (1997). Experiments in fluids 22 507-518.

- [56] A. Levy, G. Ben-Dor, B. W. Skews, and S. Sorek. *Head-on collision of normal shock waves with rigid porous materials* (1993). Experiments in fluids 15 183-190.
- [57] J. G. M. van der Grinten. *An experimental study of shock-induced wave propagation in dry, water saturated, and partially saturated porous media* (1987).
- [58] S. P. Medvedev, S. M. Frolov, and B. E. Gelfand. *Shock wave attenuation by screens composed of granular materials* (1990). Journal of engineering physics and thermophysics (USSR) 55(6) 924-928.
- [59] G. Ben-Dor, A. Britan, T. Elperin, O. Igra, and J. P. Jiang. *Experimental investigation of interaction between weak shock waves and granular layers* (1997). Experiments in fluids 22 432-443.
- [60] Y. Sakamura, and T. Onishi. *Experimental study of scale effects on shock wave interaction with a granular layer* (2011). Proceeding of the 28th international symposium on shock waves, United Kingdom.
- [61] T-T. N. Nguyen, T. Davey and W. G. Proud. *Percolation of gas and attenuation of shock waves through granular beds and perforated sheets* (2014). Proceeding of the 17th International Seminar on New Trends in Research of Energetic Materials , Czech Republic.
- [62] C. Kingery, R. Pearson, and G. Coulter. *Shock wave attenuation by perforated plates with various hole sizes* (1977). USA Ballistic Research Laboratory Memorandum Report No. 2757.
- [63] Robert Bion & Co.. *Technical data sheet: www.bion.co.uk* (Source date: February 2014).
- [64] H. N. G. Wadley, K. P. Dharmasena, M. Y. He, R. M. McMeeking, A. G. Evans, T. Bui-Thanh, R. Radovitzky. *An active concept for limiting injuries caused by air blasts* (2010). International Journal of Impact Engineering 37 317323

- [65] J. M. Wilgeroth, T-T. N. Nguyen and W. G. Proud. *Interaction between blast wave and reticulated foam: assessing the potential for auditory protection systems* (2014). Journal of Physics: Conference Series 500 102005.
- [66] T-T. N. Nguyen and W. G. Proud. *An investigation of a reticulated foam - perforated steel sheet combination as a blast mitigation structure* (2015). Proceeding of the 19th Biennial APS Conference on Shock Compression of Condensed Matter. Manuscript accepted.
- [67] Tamami Kawasaki, and Shuichi Kawai. *Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors* (2006). Journal of Wood Science 52 7583.
- [68] V. Hongisto. *Sound insulation of doors - Part 1: Prediction models for structural and leak transmission* (2000). Journal of Sound and Vibration 230(1) 133-148.
- [69] H. Arora, P. A. Hooper, and J. P. Dear. *Dynamic response of full-scale sandwich composite structures subject to air-blast loading* (2011). Composites: Part A 42 16511662.
- [70] N. Gardner, E. Wang, P. Kumar, and A. Shukla. *Blast mitigation in a sandwich composite using graded core and polyurea interlayer* (2012). Experimental Mechanics 52 119133.
- [71] K. P. Dharmasena, H. N. G. Wadley, Z. Xue, and J. W. Hutchinson. *Mechanical response of metallic honeycomb sandwich panel structures to high-intensity dynamic loading* (2008). International Journal of Impact Engineering 35 10631074.
- [72] R. Curry, B. Butler, T-T. N. Nguyen, A. P. Jardine, W. G. Proud, K. A. Brown. *A Shock Tube Adaptor for Blast Studies of Ex Vivo Tissue Models* (2014). 4th International Conference on Impact Loading of Lightweight Structures (ICILLS), Cape Town, South Africa.
- [73] P. Arun, J. Spadaro, J. John, R. B. Gharavi, T. B. Bentley, and M. P. Nambiar. *Studies on blast traumatic brain injury using in vitro model with shock tube* (2011). Neuroreport 22 379384.

- [74] T. Eftaxiopoulou, A. Barnett-Vanes, H. Arora, W. Macdonald, T-T. N. Nguyen, M. Itadani, A. E. Sharrock, D. Britzman, W. G. Proud, A. M. J. Bull, and S. M. Rankin. *Prolonged but not short duration blast waves elicit acute inflammation in a rodent model of primary blast limb trauma* (2015). The Journal of Trauma and Acute Care Surgery. Manuscript submitted.
- [75] S. Moaveni. *Finite Element Analysis Theory and Application with ANSYS* (2008). New Jersey: Prentice Hall.
- [76] ANSYS Inc.. *Software: Explicit dynamics* (2011).
- [77] G. C. Lowrison. *Crushing and Grinding: The Size Reduction of Solid Materials* (1974). London: Butterworth.
- [78] J. G. Gordon. *The New Science of Strong Materials* (1991). Penguin.
- [79] T. L. Anderson. *Fracture Mechanics - Fundamentals and Applications*, 2nd Edition (1995). US: CRC Press LLC.
- [80] P. A. Thompson and W. F. Loutrel. *Opening Time of Brittle Shock-Tube Diaphragms for Dense Fluids* (1973). Review of Scientific Instruments 40 1436.
- [81] M. Saeed. *Finite Element Analysis - Theory and Application with ANSYS* (2008). US: Pearson Education.
- [82] ANSYS, Inc.. *ANSYS Explicit Dynamics* (2011).
- [83] H. Perry, H. Robert and D. W. Green. *Perry's Chemical Engineers' Handbook, 6th Edition* (1984). McGraw-Hill Company.
- [84] Dytran Instruments, Inc.. *Specifications, Model Series 2300V, High Frequency Probe Type Pressure Sensors* (2002). REV G 07-12-12 ECN 8867.
- [85] Vision Research, Inc.. *Phantom v7.3 Datasheet* (2007).
- [86] N. Recho. *Fracture Mechanics and Crack Growth* (2012). London: ISTE Ltd. ; Hoboken, NJ : John Wiley & Sons.

- [87] L. B. Freund. *Dynamic Fracture Mechanics* (1990). New York: Cambridge University Press.
- [88] KTH Mekanik. *Flow in a Shock Tube* (2007).
- [89] A. Al-Falahi, M. Z. Yusoff, N. H. Shuaib and T. Yusaf. *Flow Instability in Shock Tube Due to Shock Wave-Boundary Layer-Contact Surface Interactions, a Numerical Study* (2009). European Journal of Scientific Research 30(1) 164-176.
- [90] R. P. Benedict. *Fundamentals of Pipe Flow* (1980). US: John Wiley & Sons.
- [91] National Aeronautics and Space Administration. Glenn Research Centre. *Mass Flow Choking*: <http://www.grc.nasa.gov/WWW/k-12/airplane/mflchk.html> (16 Jun 2012).
- [92] P. J. Rae, H. T. Goldrein, N. K. Bourne, W. G. Proud, L. C. Forde and M. Liljekvist. *Measurement of Dynamic Large-Strain Deformation Maps Using An Automated Fine Grid Technique* (1999). Optics and Lasers in Engineering 31(2) 113-122.
- [93] F. F. Abraham and H. Gao. *How Fast Can Cracks Propagate?* (1999). Physical Review Letters 84 3113.
- [94] Federation of American Scientists. Military Analysis Network. *Introduction to Naval Weapons Engineering, Electro-Optical Imaging System*: http://www.fas.org/man/dod-101/navy/docs/es310/EO_image/EO_Image.htm (16 Jun 2012)
- [95] F. Xiao, A. Silverstein, J. Farrell. *Camera-Motion and Effective Spatial Resolution* (2006). Proceedings of International Congress of Imaging Science, pp. 33-36.
- [96] H. T. Goldrein, S. J. P. Palmer and J. M. Huntley. *Automated Fine Grid Technique for Measurement of Large-Strain Deformation Maps* (1995). Optics and Lasers in Engineering 23(5) 305-318.
- [97] J. M. Huntley. *Noise-Immune Phase Unwrapping Algorithm* (1988). Applied Optics 28(16) 3268-3270.

- [98] M. A. Liberman. *Physics of shock waves in gases and plasmas* (1985). New York: Springer-Verlag.
- [99] G. Taylor. *The Formation of A Blast Wave by A very Intense Explosion – I. Theoretical Discussion.* (1949)
- [100] R. A. Bauman, G. Ling, L. Tong, A. Januszkiewicz, D. Agoston, N. Delanerolle, Y. Kim,7 D. Ritzel, R. Bell, J. Ecklund, R. Armonda, F. Bandak, and S. Parks. *An Introductory Characterization of a Combat-Casualty-Care Relevant Swine Model of Closed Head Injury Resulting from Exposure to Explosive Blast.* (2009) Journal of Neurotrauma 26 841860.
- [101] W. A. Martin. *A Review of Shock Tubes and Shock Tunnels* (1958).

Appendices

Appendix A

Lengths of Shock Tube Components

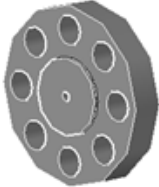
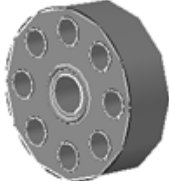
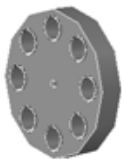
Part	Length (cm)	Quantity	(Not to scale)
Inlet flange	4.15 ± 0.2	1	
Main tube	122 ± 0.2	3	
Small flange in diaphragm assembly	2.65 ± 0.1	1	
Main flange in diaphragm assembly	8.20 ± 0.2	1	
Sensor 1 flange	3.30 ± 0.1	1	
Outlet flange	4.15 ± 0.2	1	

Figure A.1: Lengths of shock tube components. The outer and inner radii of all parts are coherently 44 ± 0.1 cm and 5.9 ± 0.1 cm respectively.

Appendix B

Matlab code for processing and plotting data from pressure sensors

```
%% Program to smooth data
% Input: file 's names, title , legend
% Output: plot of smoothened data
% Author: Thuy-Tien Ngoc Nguyen
% Date created: 04/04/2014

clear all
clc

%% Loading, smoothing and plotting data
NoRun = input('Enter the number of runs: ');
% Number of profiles to be plotted

figure (1)
hold all
grid on
```

```

for i=1:NoRun
    % Load data and choose channel
    Channel = input('Choose channel 1, 2 or 3: ');
    % Specify the recorded oscilloscope channel to be used
    Scale = input('Enter calibration scale [4657:3.430249;
4511:2.616970; 4658:3.298947; 5055:3.167586[3.819834];
5573:3.346990; C4 - 100mV/psi:0.68948; 5686:3.706882;
5685: 3.585439418]: '); % Specify the sensor sensitivity
    Filename = input('Enter filename: ','s');
    File = csvread(Filename,22); % Ignore the first 22 lines
    NoPoint = length(File(:,1))
    TimeStart = File(1,1)
    TimeEnd = File(end,1)
    Time = transpose(linspace(TimeStart,TimeEnd,NoPoint));
    NormalisedValue = mean(File(1:25000,Channel+1),1);
    % So that pressure starts at 0 bar
    Pressure = (File(:,Channel+1)-NormalisedValue)*Scale;

    % Remove -Inf and Inf data
    Time(find(Pressure==-Inf))=[];
    Time(find(Pressure==Inf))=[];
    Pressure(find(Pressure==-Inf))=[];
    Pressure(find(Pressure==Inf))=[];

    % Low-pass filter
    DT = Time(30)-Time(29)
    F = 1/DT
    FNorm = 70000/(F/2) % Cut-off frequency 70 kHz by trials
    [b,a] = butter(4,FNorm,'low');

```

```

    FilteredData = filtfilt(b,a,Pressure);

    %Plot data
    plot(Time, FilteredData)
    xlabel('Time (s)')
    ylabel('Pressure (bar)')
end

```

```

%% Program to calculate impulse against time
% Input: file 's names, title , legend
% Output: plot of I against t
% Author: Thuy-Tien Ngoc Nguyen
% Date created: 31/05/2015

clear all
clc

%% Loading, smoothing and plotting data
NoRun = input('Enter the number of runs: ');
% Number of profiles to be plotted

figure (2)
hold all
grid on
for i=1:NoRun
    % Load data and choose channel
    Channel = input('Choose channel 1, 2 or 3: ');

```

```

% Specify the recorded oscilloscope channel to be used
Scale = input('Enter calibration scale [4657:3.430249;
4511:2.616970; 4658:3.298947; 5055:3.167586[3.819834];
5573:3.346990; C4 (100mV/psi):0.68948; 5686:3.706882;
5685: 3.585439418]: '); % Specify the sensor sensitivity

Filename = input('Enter filename: ','s');
File = csvread(Filename,22); % Ignore the first 22 lines
NoPoint = length(File(:,1));
TimeStart = File(1,1);
TimeEnd = File(end,1);
Time = transpose(linspace(TimeStart,TimeEnd,NoPoint));
NormalisedValue = mean(File(1:25000,Channel+1),1);
% So that pressure starts at 0 bar
Pressure = (File(:,Channel+1)-NormalisedValue)*Scale;

% Remove -Inf and Inf data
Time(find(Pressure==-Inf))=[];
Time(find(Pressure==Inf))=[];
Pressure(find(Pressure==-Inf))=[];
Pressure(find(Pressure==Inf))=[];

% Low-pass filter
DT = Time(30)-Time(29);
F = 1/DT;
FNorm = 70000/(F/2) % Cut-off frequency 70 kHz by trials
[b,a] = butter(4,FNorm,'low');
FilteredData = filtfilt(b,a,Pressure);

% Impulse against time calculation using trapezian rule

```

```

TimeI = Time(1:1000:end);
Impulse = TimeI*0;
for j = 2:length(Impulse)
    n = find(Time==TimeI(j));
    Impulse(j) = 1000*trapz(Time(1:n),FilteredData(1:n));
end

%Plot impulse
plot(TimeI,Impulse)
xlabel('Time (s)')
ylabel('Impulse (bar ms)')

i % Run number
max(Impulse) % Print impulse of overpressure region of i
TimeI(find(Impulse==max(Impulse)))
% Time of end of overpressure region
end

```

Appendix C

Aluminium Foil in Simulation

Table C.1: Properties of aluminium foil used in simulation

Quality	Value	Unit
Density	2680	kg.m ⁻³
Specific heat	800	J.kg ⁻¹ C ⁻¹
Isotropic Elasticity		
Young's modulus	7×10^{10}	Pa
Poisson's ratio	0.33	
Bulk modulus	6.8627×10^{10}	Pa
Shear modulus	2.6316×10^{10}	Pa
Bilinear Isotropic Hardening		
Yield strength	3.25×10^{10}	Pa

Appendix D

Permissions for Reproduction of Images

License Number	3686120597763
License date	Aug 10, 2015
Licensed Content Publisher	Elsevier
Licensed Content Publication	International Journal of Impact Engineering
Licensed Content Title	Use of a shock tube to determine the bi-axial yield of an aluminum alloy under high rates
Licensed Content Author	B. Justusson,M. Pankow,C. Heinrich,M. Rudolph,A.M. Waas
Licensed Content Date	August 2013
Licensed content volume number	58
Licensed content issue number	n/a
Number of pages	11
Type of Use	reuse in a thesis/dissertation
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	>10
Actual number of figures/tables/illustrations	100
Format	both print and electronic
Are you the author of this Elsevier article?	Yes
Will you be translating?	No
Original figure numbers	figure 2
Title of your thesis/dissertation	Characterisation of a shock tube system for blast injury studies
Expected completion date	Dec 2015
Elsevier VAT number	GB 494 6272 12

Figure D.1: Permission for reproduction of Figure 2.11

License Number	3685300789899
License date	Aug 10, 2015
Licensed Content Publisher	BMJ Publishing Group Ltd.
Licensed Content Publication	Injury Prevention
Licensed Content Title	Attenuation of blast pressure behind ballistic protective vests
Licensed Content Author	Garrett W Wood, Matthew B Panzer, Jay K Shridharani, Kyle A Matthews, Bruce P Capehart, Barry S Myers, Cameron R Bass
Licensed Content Date	Feb 1, 2013
Licensed Content Volume	19
Licensed Content Issue	1
Volume number	19
Issue number	1
Type of Use	Dissertation/Thesis
Requestor type	Individual Account
Format	Print and electronic
Portion	Figure/table/extract
Number of figure/table/extracts	2
Description of figure/table/extracts	Figures 1, 2
Will you be translating?	No
Circulation/distribution	1
Title of your thesis / dissertation	Characterisation of a shock tube system for blast injury studies
Expected completion date	Dec 2015
Estimated size(pages)	200
BMJ VAT number	GB 674738491
Requestor Location	Thuy-Tien N Nguyen Imperial College London None None London, United Kingdom SW7 2AZ Attn: Thuy-Tien N Nguyen
Billing Type	Invoice
Billing address	Thuy-Tien N Nguyen Imperial College London None None London, United Kingdom SW7 2AZ Attn: Thuy-Tien N Nguyen

Figure D.2: Permission for reproduction of Figure 2.12