Strong blast wave interaction with multiphase media

by

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“If you only do what you think you can do, you will never be better than what you are.”

Anonymous
Strong blast wave interaction with multiphase media

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Abstract
The interaction of a blast wave propagating in air with different fluids like water column, aqueous foam and thermal/density inhomogeneity have been studied both experimentally and numerically. The blast waves were generated at atmospheric conditions in a newly constructed exploding wire facility. For fixed capacitance and wire size, the intensity of the shock front (measured typically at 200 mm from the wire explosion plane) was varied by controlling the charges stored in the capacitor and the size of the test section. Qualitative features of the interaction were captured using shadowgraph technique. Numerical simulations were performed to better analyze and understand the flow features observed in experiments. The main points across each fluid interactions are as follow:

Water column: A new technique was implemented to create highly repeatable, properly shaped, large diameter water column. The impact of a blast wave with shock Mach number ranging from 1.75 to 2.4 on a 22 mm diameter water column resulted in a complex system of waves propagating inside the column. Due to the concave boundary of the downstream interface, the reflected expansion wave naturally focused at a point before travelling upstream resulting in the generation of large negative pressures leading to nucleation of cavitation bubbles. Through high speed photography, various aspects of the flow features were discussed qualitatively and quantitatively. With the aid of numerical simulation, the effect of size of water column and shock strength on the maximum attainable negative pressures in the absence of cavitation were quantified.

Aqueous foam: The performance of various aqueous foam barrier configurations on the attenuation of externally generated blast wave peak pressure was examined. Here a blast wave with shock Mach number 4.8 was allowed to interact with an aqueous foam barrier of initial liquid fraction 0.1. The dominant process responsible for reduction of peak pressure was the ‘catching up’ of the rarefaction wave with the wave front travelling in the foam barrier. Additional reduction was provided by the impedance mismatch factor at the foam-air interface which was further exploited to achieve greater reduction. A simple numerical model treating the foam by a pseudo-gas approach was used for re-constructing the experimental results.

Density inhomogeneity: The unstable evolution of a 2D elongated, elliptically-shaped inhomogeneity embedded in ambient air and aligned both normal and
at an angle to the incident plane blast wave of impact Mach number 2.15 was studied. The inhomogeneity was created on the basis of ‘Joule heating’ wherein heat produced by a current carrying wire was used to heat its surrounding air. Two counter-rotating vortices primarily due to Richtmyer-Meshkov instability (RMI) and a train of vortices primarily due to Kelvin-Helmholtz instability (KHI) were observed for two different inclination angles. Similarly circulation, calculated from numerical simulation solving Navier-Stokes equation, was also found to vary from a linear to a quadratic function when the inhomogeneity was inclined.

**Key words:** Blast waves, Negative pressure, Cavitation, Blast wave attenuation, RMI, KHI
Växelverkan av starka stötvågor med flerfasmedia

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Sammanfattning

Cylindrisk vattendroppe. Cylindriska vattendroppar med stor diameter och lämplig cirkulär form kunde skapas med hjälp av hydrofobisk ytbehandling. Växelverkan mellan stötvägor med Machtal från 1.75 till 2.4 och en cylindrisk vattendroppe med en diameter på 22 mm resulterar i ett komplext system av vågor inom droppen. En expansionsväg reflekteras från den cirkulära ytan och fokuseras i ett område nedströms nära ytan. Denna fokuseringsprocess leder till stora negativa tryck i droppen och ger upphov till ett område med kavitationsbubblor inom vattendroppen. Undersökningen utförs experimentellt och visualiseras med enstaka bilder och höghastighetsfotograferingen. Inverkan av droppens storlek och den inkommande stötvägens styrka på maximala negativa tryck utan kavitation undersöks numeriskt.


Domän med temperatur- och densitetsvariation. Växelverkan mellan en stötväg

Nyckelord: Stötvägor, negativa tryck, kavitation, stötvägstämpning, RMI, KHI
Preface

This thesis deals with strong blast wave interaction with heterogenous media. A brief introduction on the basic concepts and methods is presented in the first part. The second part contains five articles. The papers are adjusted to comply with the present thesis format for consistency, but their contents have not been altered as compared with their original counterparts.


June 2018, Stockholm

_Sembian Sundarapandian_
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Part I

Overview and summary
Chapter 1

Introduction

Blast waves are encountered in a wide variety of physical situations ranging from the pop of a balloon to supernovae explosions. Sudden release of energy in a finite area by any means results in the generation of strong blast waves with naturally destructive capabilities. As the wave propagates through the medium, damage will be caused to any object in its path by the combination of significant compression behind the shock front and high speed wind that follows it. Of course it can be harnessed to be beneficial to mankind with recent industrial applications like oil extraction enhancement, synthesis of diamonds from carbon, dust removal from surfaces, supersonic combustion, inertial confinement fusion etc.; and medical applications like extracorporeal shock wave lithotripsy, neovascularization and tissue regeneration, targeted drug delivery, tissue necrosis and hemostasis to name a few. They are also of natural interest in astrophysical flows. So not only the nature of the waves but also its interaction with other objects/media has a great impact that fuels further research. Due to the complex nature of blast waves, its interaction with random media can lead to strong coupling of a wide variety of fluid dynamic phenomena that are both beneficial and detrimental. With a surge of recent interest in using such waves across various fields, it is of importance to have a fundamental understanding of the occurring phenomena through basic research. Therefore the aim of the present study is to investigate and develop an understanding of the dynamical characteristics exhibited during blast wave interaction with various media.

This thesis is a collection of basic research on three class of problems - which can be construed as a foundation upon which complex interactions can be studied - that fall under the broad umbrella of blast wave interaction with multiphase media. The problems studied here involve cylindrical water columns (with density 1000 kg/m$^3$), aqueous foams (density 100 kg/m$^3$) and thermal/density inhomogeneities (density 0.39-0.5 kg/m$^3$) with each targeting different application area. A
continuity between the problems can be established when seen from the point of view of their corresponding density with respect to atmospheric conditions. The blast waves are generated using exploding wire technique. A new facility, named Exploding Wire facility, was built at the Shock Wave Lab in KTH Mechanics for this purpose. The experiments are conducted at atmospheric conditions in a specially designed test section. The interaction details and the resulting flow are captured using shadowgraph technique and are aided by numerical simulations.

Thesis structure. The thesis is organized as follows; In Part I, chapter 2 begins with a description of the difference between shock wave and blast wave, followed by descriptions of shock non-linear effects, interface induced and shear induced instabilities, and shock interaction with a bubble. The concept of negative pressure is introduced in the end of chapter 2. Chapter 3 is intended to provide an introduction to exploding wire technique while chapter 4 discusses the in-house built exploding wire facility in detail. An overview of the various techniques used for creating the inhomogeneities are described in chapter 5. Chapter 6 deals with numerical simulation method and the work is concluded with a summary of results in chapter 7. Part II consisting of 5 papers forms the nucleus of the thesis where the results are discussed in detail. The papers appear in the order of the problems studied: Paper 1 and 2 is a study investigating the water column problem; Paper 3 deals with the foam problem; and Paper 4 and 5 discusses the thermal inhomogeneity problem in detail.
2.1. Shock waves

Shock waves are very thin discontinuities, characterised as a wave propagating faster than the local speed of sound of the medium across which flow properties like pressure ($p$), velocity ($u$), density ($\rho$) and temperature ($T$) vary abruptly. The shock process is adiabatic wherein the temperature and velocity gradients internal to the shock provide complex viscous and heat conduction phenomena that increases entropy thereby rendering it irreversible. However for practical purposes, the primary interest is not on the interior of the shock but on the net changes in fluid properties across it. As these changes occur within a very small distance, of the order of a few hundred nm that is comparable with a few mean free path of the molecules, it can be simplified by ignoring the interior of the shock and treat it as a pure line or plane discontinuity. For a flow from right to left passing through a stationary normal shock with conditions ahead denoted by state 1 and behind by state 2 [figure 2.1(a)], pressure, density and temperature increases in state 2 while velocity and stagnation pressure ($P_0$) decreases. Stagnation temperature ($T_0$) remains constant due to the adiabatic nature of the process. For a calorically and thermally perfect gas, the ratio of properties across a normal shock determined by solving the following equations,

\[
\begin{align*}
\rho_1 u_1 = \rho_2 u_2 & \quad \text{(continuity)} \\
p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 & \quad \text{(momentum)} \\
h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2} & \quad \text{(energy)} \\
p = \rho RT & \quad \text{(ideal gas law)} \\
h = c_p T & \quad \text{(enthalpy)}
\end{align*}
\]

(2.1)
Figure 2.1: Properties on both sides of (a) stationary normal shock and (b) moving normal shock.

\[\begin{align*}
\rho_2 &= \frac{u_1}{u_2} = \frac{(\gamma + 1)M_1^2}{2 + (\gamma - 1)M_1^2} \\
p_2 &= \frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1) \\
T_2 &= \frac{T_2}{T_1} = \frac{h_2}{h_1} = \frac{p_2 \rho_2}{p_1 \rho_1}
\end{align*}\]

Here \( M \) is the Mach number, defined as \( u/c \), where \( c \) is the local speed of sound of the medium. The ratio depends solely on the inlet Mach number \( M_1 \) (assuming constant \( \gamma \)) which defines the strength of the shock. This implies stronger the shock, larger is the ratio. In many practical situations, like from an explosion or suddenly opening a valve, the shock wave is moving when viewed from a stationary reference frame. Assuming the gas ahead of the shock to be motionless for such cases as in figure 2.1(b), the gas behind will be travelling with the moving shock at subsonic or supersonic speeds. Since the jump conditions depend only on the strength of the shock, other flow properties like pressure, density, relative velocity (between the shock and gas behind) and temperature will be the same for both stationary and moving shocks.
2.1. Shock waves

2.1.1. Blast waves

Sudden deposition of energy in a very small volume, like detonation of explosives or lightening will result in a blast wave propagating outwards from the source. A shock with ‘blast profile’ or simply called blast wave is basically a shock wave that consists of a leading shock followed by continuous expansion waves which decays its strength at a steady rate. This decay occurs across all the properties behind the leading shock. For a typical shock wave with ‘step profile’ or ‘shock profile’, the properties behind the shock remain constant. Since blast waves were used throughout this thesis\(^1\), a more intuitive understanding between the two is essential and will be provided by means of a piston analogy (Shapiro 1953) and a shocktube analogy. Consider a piston moving from left to right into a motionless gas with a series of impulsive acceleration occurring at equal intervals of time as shown in figure 2.2(a). Each acceleration sends out an isentropic pressure wave of equal strength that slightly increases the pressure of air in the region it has propagated through. For instance, the first acceleration sends out a pressure wave travelling downstream that influences region ‘a’ marked in figure 2.2(a). The second pressure wave from the next acceleration now travels in the region where the flow properties are relatively larger. Since the ratio of increase across the wave is only dependant on its strength, the pressure in region ‘a’ is again slightly increased from its previous value. Also as the second wave travels with the local speed of sound \((c)\) of the fluid, it travels faster compared to the first wave and tends to overtake it. Meanwhile, a succession of accelerations sends out a series of waves that works on the same fluid over and over again until the pressure gradient becomes infinite as shown at step 5 in figure 2.2(a). This also means that all the waves coalesce together to form one single strong wave (a discontinuity) where the viscous and heat dissipation effects within are no longer negligible thereby resisting the infinite steepening of the wave. Thus a shock wave is formed with a constant pressure profile, marked as ‘shock profile’ in figure 2.2(c).

Now lets consider a fully formed shock with the piston position and the state of conditions as in step 5. Now instead of accelerating it rightward, let us accelerate it as before but leftwards [figure 2.2(b)]. This sends out a series of isentropic expansion wave which acts opposite to a compression wave i.e. across an expansion wave pressure, density and temperature decreases while velocity increases. So the propagation of the

\(^1\)Blast waves are typically accompanied by a negative pressure (in gauge) wind. But as will be shown in Sec 4.5, blast waves generated in this work will have a decaying profile but not the negative phase.
2. Important concepts

Piston accelerated rightwards in steps

Piston accelerated leftwards in steps

(a) Shock profile formation

(b) Blast profile formation

(c) Graphical representation of both profiles

Figure 2.2: The formation of (a) shock wave and (b) blast wave using a piston analogy. The corresponding pressure profiles are shown in (c).

first expansion wave slightly reduces the pressure in region ‘a’. Since it travels in the region worked by the shock wave where the local speed of sound is relatively higher, it travels faster and catches up with the shock
2.1. Shock waves

Wave. When waves of opposite families interact, they tend to cancel each other thereby weakening the shock. Meanwhile the second expansion wave travels in a slightly expanded and cooled region with lower speed of sound and will not be able to catch up with the shock until its strength is weakened. This results in a shock wave with a pressure profile that is gradually reducing. Such shock waves are usually defined as ‘shock with blast profile’ or simply ‘blast waves’. A blast profile is as shown in figure 2.2(c). For longer propagation distance, the strength of the wave gradually weakens until it becomes a Mach wave (a pressure wave travelling with the speed of sound).

![Figure 2.3: Schematic representation of x-t diagram for (a) shock profile and (b) blast profile](image)

Shock tube is a device used extensively for the generation of shock waves in a controlled laboratory environment. It is a long tube divided into two regions: a high pressure region called ‘driver’ section and a low pressure region called ‘driven’ section, by a diaphragm of known thickness. When the diaphragm is suddenly removed, a shock wave propagates into the driven section and an expansion fan centered at the diaphragm position propagates into the driver section. A contact surface separating the fluids worked by the shock wave and the expansion wave travels into the driven section. The strength of the shock wave depends on the high pressure to the low pressure ratio while its profile depends
on the corresponding lengths of the driver and driven sections. An x-t diagram is constructed with the shock tube set-up shown in figure 2.3(a). When the diaphragm is removed, a shock wave (indicated by a bold solid line) travels to the right while the expansion fan head travel to the left. Within the domain set for constructing this diagram, the expansions waves reflecting from the driver end wall was never able to catch up with the shock wave. For this scenario, the shock wave propagates with a constant strength and the pressure profile will resemble the shock profile in figure 2.2(c). Now let us reduce the length of the driver section considerably and construct the x-t diagram as in figure 2.3(b). Due to its shorter length, the expansion waves are reflected much sooner and are able to catch up with the shock wave. When the expansion waves interact with the shock, it reshapes its profile thereby gradually weakening it along x.

To sum-up, blast wave is a type of shock wave whose strength and conditions behind it decay at a steady rate during its propagation. In this work only blast waves were used in experiments.

2.2. Shock non-linear effects

Whenever a shock wave encounters different medium it undergoes non-linear effects like reflection, refraction and diffraction at the interface. The incident shock will always be transmitted as a shock wave but will be reflected either as a shock wave or a rarefaction wave depending on the medium characteristics. Generally, for most cases involving gas, they can be classified on the basis of acoustic impedance mismatch as slow/fast or fast/slow configuration and the same on the basis of density are classified as heavy/light or light/heavy configurations. The acoustic impedance ($\mathcal{R}$), given as $\mathcal{R} = \rho c$, is a thermodynamic property of the medium that measures its stiffness. Consider a shock wave travelling in medium 1 with impedance $\mathcal{R}_1$ and encounters medium 2 with impedance $\mathcal{R}_2$. For a case where $\mathcal{R}_2 < \mathcal{R}_1$ as in figure 2.4(a), the transmitted shock will travel relatively faster in medium 2 as it offers less resistance to its propagation. Usually in such a scenario, although the absolute velocity of the shock wave is higher, its Mach number will be lower due to higher sound speed of the medium. As the flow properties are dependant only on Mach number, their corresponding ratios will also be relatively lower in medium 2. Therefore in order to maintain equilibrium of gases across the interface, the incident shock will be reflected as a rarefaction wave. For a reverse case where $\mathcal{R}_2 > \mathcal{R}_1$, the transmitted shock will travel relatively slower. This implies that the gas must contract and therefore the incident shock will be reflected as a shock wave [figure 2.4(b)].
2.2. Shock non-linear effects

Figure 2.4: Shock reflection effects at (a) slow/fast interface and (b) fast/slow interface.

Shock diffraction pattern is categorised into *regular* and *irregular* reflection. Generally regular reflection is a two shock system, consisting of the incident and reflected shock meeting at the reflecting surface. The irregular reflection encompasses various patterns that is subdivided into two major domains: Mach reflection and weak shock reflection domain that includes von Neumann, Guderley and Vasilev reflection. As the focus is only on Mach reflection, the weak shock reflection domain will not be considered here. A thorough treatment of these domains can be found in Ben-Dor (2007). The Mach reflection consists of the incident shock, reflected shock, Mach stem and a slip stream meeting at a single point, called triple point, located above the reflecting surface. Depending on the direction of propagation of the triple point from the reflecting surface, the Mach reflection is further classified as: (a) Direct Mach reflection, where the triple point moves away from the surface; (b) Stationary Mach reflection, where the triple point moves parallel to the surface; and (c) Inverse Mach reflection, where the triple point moves towards the surface. Consider shock wave interaction with a solid cylindrical convex surface shown in figure 2.5. This geometry is chosen as it involves both the regular and Mach reflection patterns and is closely reminiscent of the geometries investigated in this thesis. During this interaction, regular reflection occurs as long as the angle of incidence ($\alpha$) measured between the incident shock and the tangent to the surface does not exceed a critical value, called detachment angle. When the angle of incidence exceeds the detachment angle, a transition from regular to Mach reflection occurs where the incident and the reflected shock no
longer meet at the surface. Typically regular reflection is observed during the initial phase of shock propagation, marked as phase (1) in figure 2.5 and Mach reflection is observed in phase (2). Usually the triple point moves further away from the surface as the shock proceeds through phase (2).

Figure 2.5: Schematic representation of Regular and Mach reflection of an incident shock passing over a solid cylinder at two successive time instants.

2.3. Richtmyer-Meshkov instability (RMI) and Kelvin-Helmholtz instability (KHI)

Richtmyer-Meshkov instability (RMI), named after Richtmyer (1960) who first provided the theoretical analysis and Meshkov (1969) who confirmed it experimentally, is a hydrodynamic instability that typically develops when a material interface separating two fluids is impulsively accelerated by passage of a shock wave. The instability develops as a result of baroclinic vorticity generation, due to the misalignment of pressure and density gradient across the interface, given by the following vorticity transport equation:

$$\frac{D\omega}{Dt} = \frac{1}{\rho^2} (\nabla \rho \times \nabla p)$$  (2.3)
2.3. Richtmyer-Meshkov instability (RMI) and Kelvin-Helmholtz instability (KHI)

The disturbances initially present in the interface, however small it may be, are amplified by the deposition of vorticity that finally develops into regions of intense mixing. RMI can be considered as the impulsive-acceleration limit of a constant acceleration environment as in Rayleigh-Taylor instability (RTI). The evolution of the instability can be easily understood following figure 2.6 taken from Brouillette (2002). Consider a sinusoidal interface separating a light from a dense fluid (with the light fluid on top) is impacted by a shock wave travelling in the light fluid. A distorted shock wave is both transmitted and reflected at the interface which is impulsively accelerated in the direction of the transmitted wave. The misalignment of pressure gradient of the shock and density gradient of the interface results in the formation of an unstable vortex sheet of varying strength due to the generation of counterclockwise and clockwise vorticity on the right and left side [figure 2.6(b)]. This leads
to a nonlinear regime with the penetration of heavy fluid into the light fluid and vice versa, termed as ‘spike’ and ‘bubble’ formation respectively. The vortices then roll-up due to the onset of Kelvin-Helmholtz instability (KHI) eventually resulting in intense mixing of the fluids.

![Image of cloud pattern depicting KHI](source: amusingplanet.com)

The KHI is also a hydrodynamic instability that is induced by shear between fluid layers or a velocity difference/discontinuity across an interface. It means that any sharp velocity gradient in a shear flow is unstable leading to the amplification of disturbances thereby resulting in rolling up of the layers/interface. KHI can be seen occurring naturally in real life scenarios, like the cloud pattern as shown in figure 2.7.

2.4. Shock-bubble interaction

When a shock wave interacts with an isolated gas bubble, strong coupling of several of the previously described fluid dynamics phenomena occur. Due to the plethora of information contained within a shock-bubble interaction, it has been researched extensively making it a fundamental yet vital configuration for studies pertaining to shock accelerated inhomogeneous flows. Shock refraction pattern over a geometrically well defined gaseous bubble, from the experiments of Haas & Sturtevant (1987), for both slow/fast and fast/slow cases are as shown in figure 2.8. For the slow/fast scenario, irregular refraction occurs - similar to that of a solid cylinder - with the addition of a faster travelling transmitted
shock through the bubble and a reflected rarefaction wave. The transmitted shock is connected to the incident shock through a precursor shock initiating a quadruple point at its intersection with the Mach stem and reflected wave. The refraction follows a Direct Mach type as the quadruple point moves away from the interface during shock passage. In case of fast/slow scenario, the incident shock is directly connected to the transmitted shock at the interface due to the slow nature of the transmitted shock.

During this process, baroclinic vorticity is deposited at the interface between the two fluids due to the misalignment of pressure and density gradients. The circular shape of the bubble covers the complete range of angles between the pressure and the density gradients with the maximum misalignment at the diametral plane. This phenomenon is classified into two phases: (a) vorticity deposition phase where the incident shock wave is in contact with the interface; and (b) vorticity evolution phase which drives the flow after the incident shock leaves the interface. Depending on the outward or inward radial density gradient at the circumference of the bubble, the sense of rotation of the vorticity on the top half and
bottom half is either clockwise (negative) or counter-clockwise (positive). After several shock-passage times, this leads to the formation of two counter-rotating vortices - the primary instability often referred to as RMI. The rotation of the vortices also induces ‘jetting’ in the channel between them. Further investigation by Tomkins et al. (2008) using planar laser-induced fluorescence measurements (figure 2.9) revealed evidence of secondary instabilities appearing on the structures causing rapid transition to turbulence enhancing mixing. Appearance of coherent structures of KH type instability is observed at 650 \( \mu \text{s} \) but it soon evolves into a well-mixed incoherent state at 1000 \( \mu \text{s} \).

![Figure 2.9: Concentration (mass fraction) maps with time obtained using planar laser-induced fluorescence (Tomkins et al. 2008)](image)

### 2.5. Negative pressure induced cavitation

Cavitation is a phenomenon observed in liquids. In Engineering literature, cavitation in liquids is usually stated to occur when the pressure of the liquid falls to its vapour pressure. In a more general sense, this statement is true. But the more correct statement is that cavitation occurs when tiny bubbles are formed due to pressure reduction usually below 0 Pa (in absolute scale), termed as ‘negative pressures’. Any liquid can be brought to such states by either superheating it above its boiling temperature or by stretching it below its saturated vapour pressure. Water, unlike gas, is held together by cohesive forces that can sustain such positive stress or negative pressures when subjected to tension. Under tension, it behaves differently from those at compressed or ambient pressure as attractive forces, rather than repulsive forces, dominate their behaviour. When the tension in water exceeds a certain limiting value, it fractures resulting in cavitation. This statement becomes reasonable if thought
2.5. Negative pressure induced cavitation

in terms of density where negative pressures corresponds to a reduced liquid density compared to equilibrium. Molecules are further away but their mutual attraction allows the system to remain in ‘metastable’ state. For too large intermolecular distance, the system becomes mechanically unstable resulting in cavitation. Theoretical treatment for prediction of the threshold for nucleation of bubbles in pure homogeneous water (without impurities) was provided by Classical nucleation theory (CNT). It is based on the fact that when the liquid reaches its vapour pressure, the nucleation of bubbles is delayed due to the cost associated with the surface energy required to form the liquid-vapour interface. This leads to the metastable state that sustains negative pressures. The competition between the energy gained from the formation of bubble and the energy cost associated with the creation of interface results in an energy barrier which decreases as the pressure is further reduced. Upon reaching a critical value, the barrier is low enough to be overcome thereby generating bubbles resulting in cavitation. CNT predicts that water can get upto -150 MPa at atmospheric conditions before it begins to cavitate (Caupin 2005). A few other theories predicting this threshold have been developed over the years and figure 2.10 - extracted from Caupin & Herbert (2006) - gives an overview of those limiting values. However experimentally determined values are usually lower than predicted by theory and scattered between various experiments because of the heterogeneous nature of nucleation at dissolved gases, solid impurities and tiny crevices in walls of the vessel containing the liquid which acts as nucleation sites.

Traditionally numerous experimental techniques have been developed for creating tension in water that broadly fall under three categories viz. (a) static (b) dynamic and (c) ultrasonic stressing. A summary of the techniques can be found in Trevena (1984). The methods falling under static stressing are, (a) Berthelot tube method (Worthington 1892): a vessel almost completely filled with water is first heated until it expands and fully fills it. Upon cooling, the liquid sticks to the wall of the vessel preventing it from contracting thereby inducing tension and sustaining negative pressure if the temperature is low enough; (b) Centrifugation (Briggs 1950): a Z-shaped capillary tube, open at both ends, is filled with water and rotated at high speeds resulting in negative pressures due to centrifugal forces; (c) mineral inclusion method (Zheng et al. 1991; Azouzi et al. 2013): this method to similar to Berthelot method wherein water is trapped inside crystals (like quartz, calcite and fluorite) in the 10-100 µm range. It is then heated to remove any vapour bubbles and cooled until nucleation occurs. Most of the negative pressure reported for homogenous cavitation in water were obtained using this method.
We will now review the experimental results on $P_{cav}(T)$. Of course, the answer to the question about the minimum measured at positive pressure (see Section 2.2).

In this paragraph we consider specifically the spinodal of water. As we shall see, its behavior may be different from that of other liquids. We also discuss the theoretical predictions for the homogeneous cavitation line $P_{cav}(T)$.

Figure 2.10: Graph showing theoretical - CNT (dotted line, Caupin 2005); Density functional theory (solid line, Speedy 1982); and Molecular dynamics simulations (short-dashed line, Yamada et al. 2002) - and some experimental - Mineral inclusions (filled diamonds, Zheng et al. 1991); and acoustic method (empty circle, Herbert et al. 2006) - cavitation threshold pressure as a function of temperature extracted from Caupin & Herbert (2006).

While static stressing takes a few minutes for nucleation, dynamic stressing utilizes shock waves for creating tension where nucleation is rather immediate. It can be generated on the basis of (a) reflection principle: Underwater explosion (Trevena 1967; Wilson et al. 1975) resulting in shock wave which gets reflected as an expansion (tension) wave at the free surface, bullet-piston method (Overton & Trevena 1982; Williams & Williams 2000) in which the mode of generation of shock is by a bullet fired at a cylinder containing water; (b) tube arrest technique (Overton & Trevena 1981): a tube filled with water is pushed upwards by springs and is stopped suddenly creating a shock wave; and (c) Water shock tube method (Richards et al. 1980): expansion wave is produced in the liquid either directly or by converting a shock wave by a reflection method. Usually low values of negative pressures were reported as the free surface of water was not a perfect reflector and it was also difficult to avoid heterogeneous cavitation. Ultrasound stressing (Lauterborn & Cramer 1981; Herbert et al. 2006) makes use of an acoustic wave that can
quench water to negative pressure during its negative swing. The waves were usually generated using a spherical or hemispherical piezoelectric resonator immersed in water.
Chapter 3

Exploding wire technique

The blast waves in this work are generated using ‘Exploding Wire (EW)’ technique which offers the following advantages: table-size experimental facility; high intensity blast generation with relatively less resources compared to a more predominantly used shock tube; ease of operation; and ability to generate shocks in any medium. This technique works on the principle of ‘Joule heating’ wherein passage of current through an electrically conducive wire produces heat. A much simplified version of EW mechanism can be observed when a fuse blows where a slight pop sound is accompanied with a bright flash of light. Owing to relatively low current, the fuse wire melts under the generated heat forming liquid droplets that arcs resulting in a bright flash. But when a few hundred kilo amps of current is suddenly deposited at a very high rate in the wire, it undergoes violent detonation accompanied by shock waves.

The study of wires exploded by means of large current pulses has a long history after Nairne (1774) published the first paper on exploding wires. Singer & Crosse (1815) reported later with interest in explosive force. Later large amount of contributions, like Pugh et al. (1951); Allen et al. (1953); Zarem et al. (1958) to name a few, were put towards the improvement of high speed photography during the mid and late 1950’s following the development of Kerr cell photography. Bennett (1958) studied the shock waves associated with EW, relating the shock wave, electrical and heat energy. A comprehensive review of EW phenomena research until 1963 can be found in McGrath (1966a). Vaughan (1963) used the exploding wire technique to generate shock waves in water following which works on underwater explosion appeared on a consistent basis. McGrath (1966b) discussed the similarity existing between EW and chemical underwater explosions (CUE). Alenichev (1972) compared the strength of the shock wave generated in water by wires of different sizes by virtue of the deformation of the diaphragm. More recent studies in underwater exploding wires include works of Krasik et al. (2008); Veksler et al. (2009); Fedotov-Gefen et al. (2010); Bazalitski et al. (2011).
Usually the charges were stored in a capacitor with the conducting wire being made of aluminum, copper, constantan, iron or gold. The size of the wire used, like its length and diameter, are dependant on the rating of the capacitor. A typical EW process - occurring within the microsecond scale - comprises of the following steps:

- Heating of wire due to dumping of electrical energy at a very high rate.
- Liquid metal replaces the wire and in some cases develops an instability that forms a spherical broken series of the liquid metal.

Figure 3.1: Shock fronts and associated vapour cloud resulting from a wire explosion at two time instants.
These were responsible for the striated pattern observed in the vapour cloud resulting from wire explosion.

- The liquid metal vaporize after which a period of very low conductivity immediately follows, reported as ‘dwell time’ or ‘dark time’.
- Following restrike, a very high current again flows that converts the vapour into plasma. A sudden flash of light is also observed.
- One or more shock fronts are also produced during this interval.

Figure 3.1 shows the shock fronts and the associated vapour cloud striation patterns for two wire lengths of 20 mm and 40 mm respectively at two time instants. The tests were made with a 0.2 mm diameter copper wire suspended in the middle of a $80 \times 80 \times 8$ mm square test channel.
CHAPTER 4

Exploding wire facility

The experiments were conducted in a newly built Exploding Wire (EW) facility at the Shock Wave Lab, KTH Mechanics. The initial 30% of the total time in the Doctoral programme was devoted to the design and construction of the EW facility which consists of three main units, namely (a) high current generator, (b) test cell unit, and (c) optical unit. A general outline of the setup is shown in figure 4.1. The facility along with the associated equipments used are described in detail in this chapter.

![Figure 4.1: General outline of the EW facility.](image-url)
4. Exploding wire facility

4.1. High current generator

As the name suggests, the primary function of this unit is to generate and deliver high current to the wire to be exploded. This unit, as shown in figure 4.2, consists of a high voltage power supply, a capacitor, a spark gap assembly, 8 co-axial cable assembly, and a safety circuit consisting of a charging resistor, discharging resistor, manual and automatic safety switches. The high voltage power supply is a Spellman SL300 that provides well regulated, low ripple high voltage with a maximum output rating of 60 kV at 5 mA current in an efficient and compact design. The DC output voltage and current are adjustable from zero to maximum rating either through two front controls with status indicators or through remote programming. To preset the desired output voltage and current manually, the HIGH VOLTAGE OFF switch should be pressed and held and then the corresponding control dial is rotated while noting its meter reading. Once the voltage and current is set to a desired value, pressing the HIGH VOLTAGE ON switch will start the charging process. During this process, the light inside the switch will be lit green indicating that power is being generated. To terminate the power generation, the HIGH VOLTAGE OFF is pressed. All these operations and monitoring can also be performed remotely by sending signals through the 26 pin interface situated at the rear panel. Majority of the experiments in this work are
performed using a preset voltage of 11-13 kV unless otherwise specified. The power generated by the power supply is utilized to charge a 6 $\mu$F capacitor with a maximum voltage rating of 30 kV. A charging resistor of resistance 3 k$\Omega$ and a high voltage coil intercepts the line between the power supply and the capacitor, thereby completing the charging circuit.

Figure 4.3: (a) Spark gap assembly; (b) Safety circuit for discharging left-over or stored charges in the capacitor.

The discharging circuit is either through the spark gap and the wire or through a discharge resistor and the manual and automatic safety switch. The spark gap (Series T-670), shown in figure 4.3(a), acts as a fast switch consisting of two brass electrodes at opposite ends with a flat brass disc in the middle, all separated by a small gap between them. The T-670 is a compact pressurised spark gap originally designed to operate in the 20-100 kV range and can handle a peak current of 100 kA. But as the test unit is not designed to handle such high voltages, the distance between the electrodes are adjusted manually so that self-breakdown of air occurs around $\approx 9$ kV at atmospheric conditions. Self-breakdown, also termed as dielectric breakdown, is said to occur when current flows through an
insulator when the voltage applied across exceeds the breakdown voltage. So the minimum voltage at which the spark gap is functional is 10 kV. The spark gap can be operated in two modes (a) External trigger mode, and (b) Pressure release mode. In the external trigger mode, a TM-11A Trigger module designed to provide a 30 kV trigger pulse of fast rise time is connected to the middle brass disc. Also two resistors of resistance 10 MΩ are connected between the charged electrode and the disc and between the disc and the uncharged (zero initial potential) electrode respectively to distribute the potential difference evenly. The trigger module can be operated using a pushbutton, remote female jack or the oscillator BNC input connector. Each output lead is fitted with a 500 pF capacitor rated for 30 kV DC providing D-C isolation to prevent damage to the module due to discharge from the disc. Since self-breakdown occurs at 9 kV at atmospheric pressure, the spark gap is slightly pressurised with 0.5-1 bar overpressure to operate at higher voltages. The pressure is controlled accurately by a pressure regulator. When a 30 kV trigger pulse is applied to the disc, the potential difference shoots up breaking the air insulation, initiating rapid discharge of the capacitor. In the pressure release mode, the middle disc is removed and the spark gap is initially pressurised to 3 bars to prevent self-breakdown during the charging process. When the experiment is to be made, the pressure is released through a one-way solenoid valve initiating rapid discharge of the capacitor making it a simple method for firing. Both the modes can be operated manually as well as remotely. When the capacitor is discharged via the spark gap, the current is delivered to the wire by 8-parallel, short RG-213 co-axial cables in order to reduce the circuit inductance.

Depending on the type and size of the wire used for explosion, there may be some left-over charge in the capacitor after the shot is made. Also occurrences where the shot has to be aborted after charging the capacitor cannot be ruled out. In order to short-circuit either the left-over charge (when the shot is made) or the stored charge (when it is aborted) in the capacitor, a safety circuit consisting of a resistor and safety switches housed in a wooden box with aluminium casing as shown in figure 4.3(b) is included. The discharging resistor with a resistance of 100 kΩ connects the main of the capacitor with the safety switches. The automatic switch, controlled by a 5-port solenoid valve, is a pneumatic controlled actuator connecting the main and the ground. Another line from the pressure regulator pressurizes the actuator piston in turn opening the circuit while releasing the pressure retracts it, thereby closing the circuit. The manual switch, again connecting the main and the ground, can only be
4.2. Test cell unit

opened and closed by flipping the lever located on the side of the box [figure 4.3(b)]. It cannot be operated remotely and hence the name. Both the manual switch and the actuator must be open in order to charge the capacitor while closing even one discharges it, providing two layers of safety.

![Diagram of the automation process](image)

Figure 4.4: General outline of the automation process using NI-USB 6009 DAQ.

The entire process starting from setting the desired output voltage and current level, opening the actuator, charging the capacitor, firing the spark gap and then closing the actuator was at first automated using NI USB-6009 DAQ and LabVIEW software. A general outline of this automation set-up is shown in figure 4.4. After repeated operations, the DAQ was burnt presumably by the electromagnetic fields induced by the long closed circuit loops. Full automation was then discarded and a manual procedure that avoids the loop was followed thereafter. In the manual process, due to safety concerns two physical switches for opening/closing the actuator and firing the spark gap were set-up at the other end of the room far away from the facility.
Figure 4.5: (a) Test cell consisting of the exploding chamber and test chamber; (b) Schematic drawing of the test cell; (c) Cut-section view of the test cell.

4.2. Test cell unit

The test cell unit is the heart of the facility where the experiments are performed. The test cell, shown in figure 4.5, consists of two chambers namely exploding chamber and a test chamber. Both the chambers are made of 12 mm thick steel wall and are rigidly connected to each other through flanges. A cut-section view of the test unit showing the construction is shown in figure 4.5(c). The chambers are designed in a way that a uniform channel of width 74 mm and height 5 mm runs throughout. The overall length of the channel is 360 mm. The exploding chamber [figure 4.6(a)], as the name suggests, is the chamber where the blast waves are generated by exploding the wire by subjecting it to the very high current from the capacitor. This chamber houses the electrodes which are 74 mm apart across which the wire to be exploded is screwed. The other end of one of the electrode is connected to the capacitor via 8-parallel co-axial cables while the second electrode is grounded (also through the co-axial cables). The inner walls of the exploding chamber are insulated with PolyOxyMethylene (POM) thermoplastic of varying
4.2. Test cell unit

Figure 4.6: (a) Exploding chamber (b) Test chamber windows.

thickness (across all walls) to avoid sparking between the electrodes and the steel body. In addition, two 13 mm wide, 5 mm thick POM railings with a L-cut to fit the electrodes (figure 4.6) runs throughout the sides of the channel providing a straight, uniform rectangular $74 \times 5$ mm test area. When high current passes through the wire, it undergoes rapid Joule heating resulting in the generation of a cylindrical blast wave. Since the generated blast wave is confined within the narrow rectangular section, it undergoes multiple reflections from the top and bottom walls and eventually modifies itself into a plane blast wave. A description of the modification is dealt in Sec 4.5. This plane blast wave then propagates into the test chamber where the shock interactions are investigated.

The test chamber is a section providing a field of view of about 200 mm in length and 74 mm in width. The top and bottom of the test chamber are either fitted with transparent plexiglas windows or glass windows for capturing shocks and shock interactions optically. While the plexiglas windows are relatively cheap, easy to fabricate and more importantly offer a degree of freedom with mounting of pressure sensors at desired locations, glass is superior in avoiding stress waves (Paper 1) with excellent optical properties. Owing to the construction of the
test chamber, the glass windows were specially fabricated by gluing it into a steel housing as shown in figure 4.6(b). As the steel housing was designed to provide access for mounting the sensors on the sides, the glass windows only provide a field of view of 140 mm in length and 40 mm in width. Note that the overall dimensions for shock propagation is still 200 × 74 mm. The windows are secured rigidly in place by a steel rim screwed along the edges of the top and bottom wall of the channel. The entire test unit is properly sealed using o-rings wherever necessary.

4.3. Optical unit

The shock interaction and its subsequent flow field exhibiting density variations are captured using a Shadowgraph optical setup. The shadowgraph technique is based on the principle that when a light passes through a density gradient, it deflects due to the variations in refractive index of the medium. A shadow effect is generated due to this deflection resulting in a dark area at the recording plane. The optical unit, shown in figure 4.7, is set-up to pass light through the test chamber. The main components making up the set-up are laser light source, camera, plane mirrors and optical lens assembly. The general arrangement is that the beam from the laser head is expanded horizontally to 180 mm in diameter and rendered parallel by a combination of concave (L1) and convex lens (L2) of focal length -6 mm and 1350 mm respectively. The resulting parallel beam is then redirected vertically by the top plane mirror tilted \(45^\circ\) to pass through the transparent test chamber and then redirected back to the horizontal plane by the bottom \(45^\circ\) mirror. The image of the shadowgraph plane is focused on the camera sensor by convex lenses L3 and L4 of focal length 1350 mm and 100 mm respectively.

Two types of camera with either high temporal or spatial resolution are used for capturing the flow structures. For temporal resolution, a Shimadzu HPV-X2 high speed camera with the capability to capture at the rate of 60 - 10 million frames per second (fps) is used. It is equipped with a 10 bit, monochromatic FTCMOS2 sensor with pixel count of 100,000 (400 X 250 grid) and recording capacity of 128 frames (full pixel mode) or 256 frames (half pixel mode). The camera is triggered by an external TTL-level (5 V) signal from the digital delay generator. For spatial resolution, a 12.3 megapixel Nikon D90 camera is used. As the shutter of the Nikon D90 cannot be triggered without internal modification, it was simply left open for 30 s due to which it can only be operated with a pulsed (single-shot) light source. As it is left open for long, a neutral density filter was placed close to the camera sensor that is opaque enough to damp the light coming from the explosion flash, room
and other equipment illumination while transparent enough to pass the light pulse.

Two types of laser light source are used: one continuous and the other pulsed, to be used in conjunction with the high speed camera and the Nikon D90 camera respectively. The pulsed laser is an Orion Nd:YAG laser (532 nm) with a pulse energy of 17 mJ and a beam diameter of 2.75 mm. With a frequency of 1 Hz coupled with a very short pulse width of 4-6 ns, it’s ideally suited to be used with the Nikon D90. To trigger the laser, two TTL signals are sent: the first to fire the flash lamp at a preset time and after a time interval of about 200 µs, the second signal follows to fire the Q-switch. Upon receiving the second signal, the laser is fired typically around 850 ns. Two energy modes, LOW and HIGH, with variable scale range from 0-100 are available for controlling the maximum transmitted energy. Since the light reaches the camera via a strong neutral density filter of optical density 3, the laser is operated at its highest transmission i.e HIGH 100. The continuous laser used is a Spectra-Physics BeamLok 2060 argon-ion with an output power of 10 mW.

4.4. Trigger unit and sensors

Once the charges are released, the events that follow are very fast requiring an accurate and reliable system to trigger the equipments. The triggering unit consists of a high voltage probe and a digital delay generator (figure 4.8). The high frequency high voltage probe is a HVP-39 pro
model with a very short rise time of 1.6 ns and can handle upto 40 kV. It has a division ratio of 1000:1, meaning the output voltage at its maximum (40 kV) is 40 V. Since the capacitor is mostly charged around 10-13 kV, its output voltage of 13 V acts as the main trigger signal. One of the terminals of the probe is connected between the 8 co-axial cable assembly and the EW while the other is grounded. The probe’s sensor lead is connected to the trigger terminal of a Stanford Research Systems DG-535 delay generator, consisting of 4 digital delay outputs which in turn triggers the pulsed laser or the high speed camera depending on the set-up. Since the charges released from the capacitor reaches the wire almost instantly, the only uncertainty revolves around the probe’s sensor to report the potential difference. But due to its very fast rise time, this way of triggering using the probe was found to be highly repeatable with an uncertainty of $< 1 \mu s$.

![Figure 4.8: (a) HVP-39 pro high voltage probe (b) Stanford Research Systems DG-535 digital delay generator.](image)

The shock pressure profiles are recorded by mounting three PCB piezoelectric sensors (113B24, PCB Piezotronics) at desired locations. The diaphragm diameter of the sensor is 5.54 mm and it has a response time of 1 $\mu s$ with a frequency response of $\leq 100$ kHz. The sensors are driven by a 482C series signal conditioner, connected through a 10-32 co-axial jack. The signal conditioner has 4 individual channels and supply a regulated 26 VDC at 2-20 mA excitation voltage to the connected sensors. The output signal from each channel of the signal conditioner is read by connecting it to an oscilloscope.
4.5. Blast wave formation

Figure 4.9: Modification of a cylindrical wave into a plane blast wave for a 12 kV, 74 mm wire length case.

The formation and transformation of the initially cylindrical wave to plane blast wave is demonstrated using numerical density gradient images in figure 4.9, taken along the exploding chamber cut-section view. The real wire explosion is numerically simulated by replacing it with an equivalent high pressure region. The value of this high pressure region here is chosen by trial-and-error method to represent a 12 kV, 74 mm channel width case by juxtaposing the obtained numerical pressure profiles with the experimental trace from the pressure sensors. The numerical simulation method will be presented in Sec 6. The wire is mounted 3 mm away from the walls and the generated cylindrical wave is captured in figure 4.9(a). Due to the confined rectangular geometry, this cylindrical wave undergoes multiple reflections at the top, bottom and back walls. This complicated process, also responsible for the absence of negative phase in the blast wave profile, is shown in figure 4.9(b)-(f). The emergence of the second wave reflected from the back wall can be seen clearly in figure 4.9(g)-(h). Since the second wave propagates in an environment worked by the first wave, it travels relatively faster and eventually both the waves coalesce into one plane wave as shown in figure 4.9(k). This plane wave then propagates into the test chamber.
Table 4.1: Shock Mach number measured at 200 mm from EW as a function of charging voltage and length of wire for a 0.4 mm diameter copper wire

<table>
<thead>
<tr>
<th>Length of wire (mm)</th>
<th>Voltage (kV)</th>
<th>Energy stored (J)</th>
<th>$M_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>10</td>
<td>300</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>432</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>507</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>675</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>867</td>
<td>3.8</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>432</td>
<td>4.65</td>
</tr>
</tbody>
</table>

Since this being a blast wave, its intensity reduces as it propagates through the channel. For a given capacitance, the strength of the wave at a particular location depends on the charging voltage, the length and diameter of the wire. Several tests were performed and based on the charge left in the capacitor after the explosion and physical observations of the exploded wire residues in the channel, a 0.4 mm diameter copper wire was deemed optimal for this set-up. The summary of charging voltages, the energies stored and the shock Mach number measured at
around 200 mm from the EW for a 0.4 mm diameter copper wire are as shown in Table 4.1.

Figure 4.11: Experimental pressure profiles measured by two sensors for (a) 74 mm wire length and (b) 10 mm wire length; (c) Numerical pressure drop for both wire lengths as a function of propagation distance \(x\) and (d) Corresponding shock Mach number as a function of \(x\).

The transformation for a 10 mm wire length is shown in figure 4.10. The corresponding shock profiles measured using two shock sensors for a 12 kV charged, 74 mm and 10 mm wire length is as shown in figure 4.11(a)-(b). Notable differences are the leading shock strength and the rate of decay of pressure behind it. While the 74 mm case is characterised with a relatively weaker leading shock with moderate decay, the 10 mm case is characterised with a strong shock and very steep decay. So for a constant initial voltage, the reduction in length of the wire induces two compromising effects: (a) increases the leading shock strength and, (b) increases the rate of decay. The rate of decay is directly related to the expansion waves ‘eating into’ the leading shock thereby reducing its
strength. This effect for the overall propagation distance ($x$) is plotted in figure 4.11(c)-(d) as a function of pressure and shock Mach number respectively.
Inhomogeneity creation techniques

The crux of the present work relies on the ability to generate good, repeatable, geometrically well-defined inhomogeneities. Each problem investigated here required a new solution to break through the dominantly used techniques in their corresponding area. The procedure used to create the inhomogeneities in the test chamber are described in this chapter.

5.1. Water column

Although various techniques have been employed previously to produce water droplets/columns (Nicholls & Ranger 1969; Hirahara & Kawahashi 1992; Hsiang & Faeth 1995; Joseph et al. 1999; Igra & Takayama 2001), the diameter of the column is limited to a maximum of 7 mm. When the interest is to study in detail the wave motions inside the column along with its associated instabilities, columns of larger diameter are a necessity. Also with such small diameter, no measurements inside the column are possible. But creating such large columns posed a problem as water tend to splash sideways resulting in non-uniform shapes. Also as only one high spatial image per column can be obtained, it was also important to produce them with good repeatability. This required an external force that does not interfere with the flow or optics, to hold the column in place. To overcome this issue, a technique of using super-hydrophobic coating on the windows was implemented. Hydrophobicity is a property of a molecule to repel water. When such materials are coated on a surface, it becomes a superhydrophobic surface where the water contact angle exceeds 150° primarily due to surface tension effects (eg. water on lotus leaf).

A superhydrophobic paint was specifically chosen with a hydrophobicity level that just about prevents the splashing of water and is also transparent enough to pass light. The coating is applied on a limited area on the bottom window and the coating procedure is as follows: An O-ring of 22 mm diameter is placed at a suitable location on the bottom window and is pressed firmly using a solid mass (called as O-ring mould)
Figure 5.1: (a) Image showing the setup before painting the surface; (b) Shadowgraph image depicting the rim of the coating immediately after removal of the O-ring; (c) Side view (taken using normal still camera) of the water column; (d) Top view (shadowgraph image) of the water column.

and lever as shown in figure 5.1(a). The superhydrophobic paint is then coated around the area surrounding the O-ring using a brush. Since the O-ring is firmly pressed, excess paint collects on the outer circumference of the O-ring and does not seep through it. It is then allowed to dry rapidly using an air gun for approximately 30 minutes. Upon carefully removing the O-ring, a perfectly circular rim of hydrophobic coating is formed as shown in figure 5.1(b). Now the top window is placed in position and rigidly secured. Note that the top window is not treated with any coating. A syringe with its top end modified to fit a small, long tube is filled with water and then inserted through a small opening from the back end flange of the test chamber. The water is then carefully and very slowly injected into the uncoated area, thereby creating a cylindrical water column of 22 mm diameter as shown in figure 5.1(d). A slightly larger wet area is observed in figure 5.1(c) at the bottom due to weight of the water. Nevertheless, the variation in diameter is less than 2%
indicating a geometrically well-defined cylindrical water column. The thickness of the coating is negligible compared to the thickness of the channel. The paint just about holds the column in place and even slight vibrations to the test unit would allow the water to flow over the barrier. This procedure of creating columns worked really well that during the course of this experiment, a total of 150-200 columns were prepared with excellent repeatability.

5.2. Foam barrier(s)

Aqueous foam is a two-phase system where gas bubbles are enclosed within thin liquid (usually water) films (Weaire & Hutzler 2001). On the basis of volume liquid fraction ($\alpha$), defined as $\alpha = V_l/V_f$ where $V_l$ and $V_f$ are the volumes of liquid content and foam sample respectively, foams are generally classified as dry foams ($\alpha < 0.05$) where the shape of the gas bubbles resemble polyhedrons with very thin films; and wet foams ($0.05 < \alpha < 0.36$) where the bubble shape approaches a circle. For $\alpha > 0.36$, the bubbles will no longer be in contact with its neighbours thereby becoming a bubbly liquid (Britan et al. 2007). Mechanical properties of the foam mainly depend on the liquid volume fraction and size distribution of the bubbles. When being impacted by very strong shocks, dry foam gets shattered into fine liquid droplets with transfer of momentum and heat occurring between the gas and liquid phases. These processes result in flow non-equilibrium. But wet foams are characterised with smaller bubbles where the net momentum and heat transfer between the liquid and gaseous phases are negligible. The relaxation effect becomes less pronounced resulting in rapid flow equilibrium (Britan et al. 2013). This makes numerical modelling relatively simple as the flow can be represented by a single component approach since both the phases are in dynamic and thermal equilibrium which is in contrary to dry foams where multiphase models are a must for accurate prediction (Britan et al. 2014). Also for applications concerning blast mitigation by absorption of energy, wet aqueous foams comprised of fine bubbles with significantly larger liquid total surface area is advantageous as water, owing to its large specific heat and latent heat of vaporization, is one of the best substance for absorbing energy.

For creating the foam barrier(s), a conventional shaving foam from Gillette, Procter & Gamble was used for the following reasons (Liverts et al. 2015):

- Wet aqueous nature of the foam with a density of $\approx 100 kg/m^3$ ($\alpha = 0.1$).
• No pre-preparation required as it was readily available commercially.
• Microscopic observation of the foam revealed a uniformly distributed, fine polydisperse bubbles with an average diameter of 50 µm.
• The foam was stable and $\alpha$ remained constant for close to 2 hour of foam aging.

Figure 5.2: (a) Shadowgraph image showing broken shock structure due to interface instability in a 74 mm width foam barrier; (b) Normal still camera image showing the reduction of width by insertion of POM rails and the created foam barrier; (c) Schematic drawing of the test section with POM rails; (d) The conditions before (top) and after (bottom) incident shock impact with a 10 mm width foam barrier. The stabilised straight shock wave structure is indicated in the bottom shadowgraph image.

In order to form a barrier of specified length $l$, two T-inserts of height 5 mm and length 10 mm are placed at a distance $l$ between them. Foam is then uniformly filled within the space and excess foam on the top is wiped away. Care was taken to properly fill the foam without any voids. The T-inserts are then lifted in one swift motion to ensure a plane uniform interface. The most important criteria for creating the foam barrier was to maintain straight, smooth interface particularly in the downstream to avoid RM instability. However initial efforts proved futile as to no matter how carefully the barrier was created, it still resulted in non-uniform broken shocks emerging from the foam due to RMI [figure 5.2(a)]. For the sake of analysis, a relatively uniform shock
was expected to emerge from the foam. Since this being a 1D study, this problem was then alleviated by reducing the initial width of the channel to 10 mm by inserting POM rails [figure 5.2(b)-(c)]. Due to this reduced width, the shock transmitted from the foam quickly stabilised to form a uniform shock front as seen in figure 5.2(d). This technique was also suitable for creating multiple barriers.

5.3. Density inhomogeneity

Shock accelerated inhomogeneous flows were traditionally explored using cylindrical/spherical bubbles (from herein referred to as circular inhomogeneity). Techniques like spark discharge (Rudinger & Somers 1960), soap film (Haas & Sturtevant 1987), fine jet (Jacobs 1992) etc., were predominantly used in creating single or multiple circular inhomogeneities. Despite the shear volume of progress, experimental investigation on shapes other than circle are very scarce.

What is an inhomogeneity? Simply put, any collection of matter which is not uniform or consistent with the surrounding mass is defined as an inhomogeneity. A simplest way to create such difference is just by introducing heat. For example when gas is heated, its density drops and becomes lighter thereby creating an inhomogeneous system. Markstein (1957) in his pioneering study, utilized a reactive flame front to create an oblong shaped bubble. Similarly Rudinger & Somers (1960) also used heat to create a density inhomogeneity. Inspired from their works, a new technique of heating the surrounding gas on the basis of ‘Joule heating’ is implemented here to create elliptically shaped inhomogeneities. The setup is as shown in figure 5.3(a)-(b). For creating straight inhomogeneities, two brass electrodes of 3 mm diameter with one being solid (anode) and the other hollow (cathode) are screwed into the bottom plexiglas window at a distance of 145 mm between them. The anode is mounted at 200 mm from the wire explosion plane and cuts through the entire 5 mm channel while the cathode is positioned at half height. A variable external power supply is connected across the electrodes. A 0.2 mm diameter copper wire is suspended in the middle of the 5 mm channel with its one end tied rigidly at the anode while the other end is connected to a freely suspended weight after passing it through a guide cylinder and the hollow cathode. As the wire will expand when subjected to heat, the guide cylinder and the freely suspended weight makes sure that it is always suspended in the middle of the channel by maintaining it in a state of tension. The wire is then subjected to 15-24 V, 2.8-3.6 A current resulting in heating of the wire. This in turn heats the surrounding air, producing a density inhomogeneity. Heat from the wire will be
5. Inhomogeneity Creation Techniques

Figure 5.3: (a) Schematic drawing of the set-up seen from top view; (b) Cut section view corresponding to (a); (c) Current supplied time versus heat spread.

emanating cylindrically until it reaches the top and bottom plexiglas windows. When the plexiglas surface comes into contact with heat, it becomes soft and pliable at the contact region. This affects its optical properties thereby making it partially opaque as indicated by the dark region (termed ‘Hot gas’) in figure 5.3(c). The effective thickness of the dark region (or the inhomogeneity) is influenced by the amount of time the wire is subjected to conduct current. Figure 5.3(c) shows heat spread as a function of current supplied time for a 24 V, 3.6 A current. After about 60 s, the heat has spread to a thickness of ≈10 mm with an overall shape resembling an ellipse. Inclined elliptic inhomogeneities are created using similar mechanism but by placing the anode and cathode at an angle to the incoming shock front.
Numerical simulations, performed to complement the experimental data, play a vital role by providing assistance in interpreting and analyzing the flow features observed in experiments. It also provides practically unlimited level of details of the results which are difficult to achieve in experiments. The numerical simulations in this work are performed either using a commercial CFD package (StarCCM+) or one of the two in-house codes solving compressible Euler and Navier-Stokes equations respectively. The first in-house code solving the compressible Euler equation is based on an artificial upstream flux vector splitting scheme (AUFS) while the other is based on a hybridised AUFS scheme with Roe’s solver (AUFSR). Each method exhibit certain strengths suitable for the class of problems investigated in this work. A description of the in-house codes are provided in this chapter.

6.1. Foam - AUFS

Wet foams are characterised with smaller bubbles where the net momentum and heat transfer between the liquid and gaseous phases are negligible resulting in rapid flow equilibrium. Here the flow can be represented by a single component approach as both the phases are in dynamic and thermal equilibrium. As the main focus is on the macroscopic characteristics of the foam, the strategy to simulate foam problem is by treating it using a pseudo-gas approach in which it is considered as a perfect gas with high molecular weight incorporating an effective adiabatic index ($\gamma$) for simulating the real water content in foam (Liverts et al. 2015). The description of the flow was based on liquid volume fraction ($\alpha$) formulation based algorithm which provides an approximate treatment for mixture of fluid component within a grid cell (Shyue 2006). The full set of compressible Euler equations along with the $\alpha$ based equation solved are as follows:

$$\mathbf{U}_t + \mathbf{F}_x = 0 \quad (6.1)$$
where $\mathbf{U}$ and $\mathbf{F}$ are vectors of conservative quantities and fluxes, respectively,

$$
\mathbf{U} = \begin{pmatrix} \rho \\ \rho u \\ \rho E \\ \rho \alpha \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho E u + pu \\ \rho u \alpha \end{pmatrix}
$$

(6.2)

$\rho$ is the density, $u$ is the particle velocity, $p$ is the pressure and $E$, the total energy per unit mass given as the sum of specific internal energy and the kinetic energy $E = e + u^2/2$. The foam density is a mixture of density of water ($\rho_w$) and air ($\rho_a$), and is calculated using $\rho = \alpha \rho_w + (1 - \alpha) \rho_a$. The water density is set to be incompressible with a constant value of $1000 \text{ kg/m}^3$. The system of equations are completed by modeling the following Noble-Abel equation of state:

$$
p(\rho, e) = \left( \frac{\gamma - 1}{1 - \alpha} \right) \rho e
$$

(6.3)

The adiabatic index ($\gamma$) of the fluid mixture is updated using the following equation:

$$
\frac{1}{\gamma - 1} = \frac{\alpha}{\gamma_w - 1} + \frac{1 - \alpha}{\gamma_a - 1}
$$

(6.4)

The equations are solved using the AUFS method, proposed by Sun & Takayama (2003), which is a special flux vector splitting scheme. It introduces two artificial wave speeds into the flux decomposition for adjusting the direction of the wave propagation. Its strength lies in exactly resolving pure entropy waves without the associated carbuncle problem (instabilities in shock capturing) and it is a simple, accurate and robust upwind scheme. The flux vector $\mathbf{F}$ can be rewritten as,

$$
\mathbf{F} = u \mathbf{U} + \mathbf{P}
$$

(6.5)

where $\mathbf{P} = (0, p, pu, 0)^T$. Marching explicitly through time, the discretised governing equation yields in conservation form:

$$
\mathbf{U}_i^{n+1} = \mathbf{U}_i^n - \frac{\Delta t}{\Delta x} (\mathbf{F}_{i + \frac{1}{2}} - \mathbf{F}_{i - \frac{1}{2}})
$$

(6.6)

where $\Delta t$ is the time step and $\Delta x$ is the grid size. The numerical flux vector $\mathbf{F}_{i + \frac{1}{2}}$ is defined by the left and right cells. The fundamental idea of the AUFS scheme is to split $\mathbf{F}$ into,
\[ \mathbf{F} = (1 - S)\mathbf{F}_1 + S\mathbf{F}_2 \]  \hspace{1cm} (6.7)

Here \( \mathbf{F}_1 \) and \( \mathbf{F}_2 \) are the intermediate flux vectors. Eq. (6.7) reduces to Eq. (6.5) when \( S = s_1/(s_1 - s_2) \), where \( s_1 \) and \( s_2 \) are the artificially introduced wave speeds. Depending on the value and sign of \( s_1 \), \( \mathbf{F}_1 \) and \( \mathbf{F}_2 \) are calculated from,

\[ \mathbf{F}_1 = \frac{1}{2}(\mathbf{P}^L + \mathbf{P}^R) + \delta \mathbf{U} \]  \hspace{1cm} (6.8)

\[ \mathbf{F}_2 = U^\zeta(u^\zeta - s_2) + \mathbf{P}^\zeta, \zeta = \begin{cases} L & \text{for } s_1 > 0 \\ R & \text{for } s_1 \leq 0 \end{cases} \]  \hspace{1cm} (6.9)

The artificial viscosity \( \delta \mathbf{U} \), determined from Steger-Warming formula is represented as,

\[ \delta \mathbf{U} = \frac{\gamma}{2\bar{c}} \left( \frac{p^L - p^R}{\gamma(pu)^L - (pu)^R} + \frac{1}{2}[(pu)^L - (pu)^R] \right) \]  \hspace{1cm} (6.10)

where \( \bar{c} \) is the intermediate speed of sound given by \( c^2 = \gamma p/\rho(1 - \alpha) \). The numerical values of \( s_1 \) and \( s_2 \) are chosen as

\[ s_1 = (u^L + u^R)/2 \]

\[ s_2 = \begin{cases} \min(0, \min(u^L, u^R) - \max(c^L, c^R)) & \text{for } s_1 > 0, \\ \max(0, \max(u^L, u^R) + \max(c^L, c^R)) & \text{for } s_1 \leq 0 \end{cases} \]  \hspace{1cm} (6.11)

The final intercell flux is given as,

\[ \mathbf{F} = (1 - S)\left[ \frac{1}{2}(\mathbf{P}^L + \mathbf{P}^R) + \delta \mathbf{U} \right] + S\left[ U^\zeta(u^\zeta - s_2) + \mathbf{P}^\zeta \right] \]  \hspace{1cm} (6.12)

The numerical geometry creation, mesh generation and the solver were coded using Matlab. Since this being a 1D problem, the domain was meshed with 36000 grid points with a uniform spacing of \( \Delta x = 0.01 \text{ mm} \) and run on a single desktop computer. The calculations were quite cheap but since this being an explicit scheme with relatively small stability bounds, the time step was chosen to fall strictly within the Courant number limit. A detailed description of the domain, initial and boundary conditions along with the validation of the code are found in Paper 3.
6. Numerical simulation method

6.2. Density inhomogeneity - AUFSR

Compressible flow problems often involve complex flow phenomena, like strong shocks, shock wave refraction and reflection, shock-shock interaction and shear layers. While the AUFS is an efficient method for solving compressible inviscid flows, the scheme yields large values of viscosity in the presence of shear waves, leading to poor resolution of boundary layers Kemm (2015). This is mainly due to the choice of artificial viscosity \( \delta U \) in Eq. (6.10). For the density inhomogeneity problem where shear induced instability is expected, solving a full set of 2D compressible Navier-Stokes equations given in Eq. (6.13) using the AUFS scheme as such will produce unacceptable results.

\[
\begin{align*}
U_t + (F_a + F_b) - (G_a + G_b) &= 0 \quad (6.13) \\
U &= \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix}; \\
F_a &= \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho E u + pu \end{bmatrix}; \\
F_b &= \begin{bmatrix} \rho v \\ \rho vu^2 + p \\ \rho E v + pv \end{bmatrix} \\
G_a &= \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ u \tau_{xx} + v \tau_{xy} - q_x \end{bmatrix}; \\
G_b &= \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ u \tau_{xy} + v \tau_{yy} - q_y \end{bmatrix} \\
\end{align*}
\]

where

\[
\begin{align*}
\tau_{xx} &= 2 \mu u_x - \frac{2}{3} \mu (u_x + v_y); \\
\tau_{yy} &= 2 \mu v_y - \frac{2}{3} \mu (u_x + v_y); \\
\tau_{xy} &= \mu (u_y + v_x); \\
q_x &= -\kappa T_x; \\
q_y &= -\kappa T_y \\
\end{align*}
\]

Here \( U \) represent the vectors of conservative quantities, \( F_a \) and \( F_b \) the vectors of inviscid flux, and \( G_a \) and \( G_b \) the vectors of viscous flux in \( x \) and \( y \) direction respectively. \( T, \mu, \kappa \) denote temperature, dynamic viscosity and thermal conductivity respectively. \( \mu \) and \( \kappa \) are temperature dependent and are calculated using the following relations:

\[
\begin{align*}
\mu &= \mu_0 \left( \frac{T}{T_0} \right)^{1.5} \frac{T_0 + 110}{T + 110} \\
\kappa &= 1.527 e^{-11T^3} - 4.8574 e^{-08T^2} + 1.0184 e^{-04T} - 0.00039333 \\
\end{align*}
\]

Given an interface with normal vector \( n = (n_x, n_y) \), \( U \) and \( F \) can be expressed in the direction of normal face \( n \) as,
\[
\tilde{U} = \begin{bmatrix}
\rho \\
\rho q_n \\
\rho q_t \\
\rho E
\end{bmatrix}; \quad \tilde{F} = \begin{bmatrix}
\rho q_n \\
\rho q_n^2 + p \\
\rho q_n q_t \\
\rho E q_n + pq_n
\end{bmatrix}
\] (6.18)

where the normal \((q_n)\) and tangential velocity \((q_t)\) through the interface is given as,

\[
q_n = u n_x + v n_y; \\
q_t = v n_x - u n_y
\] (6.19)

The system of equations are closed by modeling the ideal gas law. Formulations of flux difference splitting (FDS) schemes, like Roe’s scheme, are proven to accurately resolve shock waves with the capability to correctly deal with density or shear layers but suffers from carbuncle problem (MacCormack 2011) and also sometimes lead to unphysical flow solutions. Tchuen et al. (2014) proposed a new scheme that combines the efficiency of AUFS with the accuracy of FDS approach by hybridising the AUFS flux and Roe flux. The scheme, termed AUFSR, utilizes the modified wave speed approach from AUFS and applies it to Roe solver, thereby introducing numerical dissipation to shear waves while negating the carbuncle problem. By this, the AUFSR scheme becomes not only robust for shock capturing but also accurate for resolving shear layers.

Basically the AUFSR follows a similar path until Eq. (6.7) where \(F_1\) and \(F_2\) for a 2D system are given as,

\[
F_1 = \frac{1}{2}(P^L + P^R) + \delta U
\] (6.20)

\[
F_2 = U^\zeta(q_n^\zeta - s_2) + P^\zeta, \zeta = \begin{cases} 
L & \text{for } s_1 > 0 \\
R & \text{for } s_1 \leq 0
\end{cases}
\] (6.21)

The significance of the scheme appears in the formulation of \(\delta U\) which is defined on the basis of Roe-averaged values,
\[ \bar{\rho} = \sqrt{\rho^L \rho^R}; \quad \bar{u} = \frac{\sqrt{\rho^L u^L} + \sqrt{\rho^R u^R}}{\sqrt{\rho^L} + \sqrt{\rho^R}}; \]
\[ \bar{v} = \frac{\sqrt{\rho^L v^L} + \sqrt{\rho^R v^R}}{\sqrt{\rho^L} + \sqrt{\rho^R}}; \quad \bar{q}_n = \frac{\sqrt{\rho^L q_n^L} + \sqrt{\rho^R q_n^R}}{\sqrt{\rho^L} + \sqrt{\rho^R}}; \]
\[ \bar{H} = \frac{\sqrt{\rho^L H^L} + \sqrt{\rho^R H^R}}{\sqrt{\rho^L} + \sqrt{\rho^R}}; \quad \bar{c} = \left[ (\gamma - 1) \left( \bar{H} - \frac{1}{2} \bar{u}^2 \right) \right]^{\frac{1}{2}} \]

(6.22)

expressed as,

\[ \delta U^{\text{AUF}} = \frac{1}{2} \left( \frac{(q_n^L - s_1)\rho^L + (q_n^R - s_1)\rho^R}{(q_n^L - s_1)(\rho u)^L + (q_n^R - s_1)(\rho u)^R} \frac{(q_n^L - s_1)(\rho v)^L + (q_n^R - s_1)(\rho v)^R}{(q_n^L - s_1)(\rho E)^L + (q_n^R - s_1)(\rho E)^R} \right) - \frac{1}{2} \sum_{k=1}^{4} \left| \lambda_k \right| \eta_k R_k \]

(6.23)

Here \( \lambda_k, \eta_k, \) and \( R_k \) are the eigenvalues, characteristic variables and eigenvectors respectively. For this case,

\[ \lambda_k = (\bar{c}, 0, 0, \bar{c}) \]
\[ \eta_{1,A} = \frac{(P^R - P^L) \mp \bar{c}(q_n^R - q_n^L)}{2\bar{c}^2} \]
\[ R_{1,A} = \begin{pmatrix} 1 \\ \bar{u} \mp \bar{c} \\ \bar{v} \mp \bar{c} \\ \bar{H} \mp q_n \bar{c} \end{pmatrix} \]

(6.24)

The numerical values of \( s_1 \) and \( s_2 \) are set as,

\[ s_1 = \bar{q}_n \]
\[ s_2 = \begin{cases} \min(0, q_n^L - c^L, \bar{q}_n - \bar{c}) & \text{for } s_1 > 0, \\ \max(0, q_n^R + c^R, \bar{q}_n + \bar{c}) & \text{for } s_1 \leq 0 \end{cases} \]

(6.25)

The final intercell flux through the interface is expressed as,

\[ F = (1 - S) \left[ \frac{1}{2}(P^L + P^R) + \delta U^{\text{AUF}} \right] + S \left[ U^\zeta (q_n^\zeta - s_2) + P^\zeta \right] \]

(6.26)

Depending on the case studied, the domain was meshed with 2.5 - 5.5 million unstructured triangular cells refined along the zone of interest
with the mesh size varying slowly and smoothly as we go outwards. The overall smallest and the largest cell size were 0.025 mm and 0.15 mm respectively. The calculations were expensive and memory consuming that it was run on resources provided by the Swedish National Infrastructure for Computing (SNIC) at High Performance Computing Center North (HPC2N) requesting a RAM allocation of 90 GB. A detailed description of the domain, initial and boundary conditions along with the validation of the code are found in Paper 5-6.
The study began with the construction of an Exploding Wire (EW) facility in which the experiments presented in the papers in Part II were performed. The facility had the capacity to generate strong blast waves in atmospheric conditions with shock Mach number typically varying from 1.75 - 4.8 and also provided flexibility for altering the test geometry depending on the case investigated. The shock wave-multiphase interaction and its associated flow field was captured optically using shadowgraph technique. The experiments were always accompanied with numerical simulation, performed using Star-CCM+ CFD package and two in-house numerical schemes, to better understand and analyze the distinctive flow features observed. A short and concise summary of the contributions and conclusions drawn from the investigations are presented in this section.

7.1. Water column

The studies were conducted on a 22 mm diameter water column impacted with a blast wave of shock Mach number 1.75-2.4. Images were captured with both the Nikon D90 single-shot camera for spatial resolution and Shimadzu HPV-X2 high speed camera that was set to capture 1 million frames per second for temporal resolution. The concluding remarks are as follows:

- A new technique of treating the bottom transparent plate with super-hydrophobic coating proved powerful and effective in creating highly repeatable, properly defined, large diameter water columns. Normal tap water was used for creating the columns.
- Upon impact, the incident shock wave was reflected, diffracted and transmitted at the upstream interface boundary. The reflection and diffraction were similar in nature to that of a shock interaction with a solid cylindrical wall. The transmitted wave was a shock wave seen propagating through the water column.
On reaching the downstream boundary of the water column, the transmitted shock wave was reflected back as an expansion wave. Due to the convex nature of the reflection, the expansion wave naturally focused at a point before travelling upstream. This focusing of expansion wave resulted in negative pressures initiating heterogenous cavitation. The cavitation bubble cloud was observed for shock impact with Mach number 2.4 and not for Mach number 1.75 case suggesting that the threshold negative pressures were not reached.

High speed camera images obtained for Mach number 2.2 revealed that cavitation was initiated during the converging path of the expansion wave. Time taken to complete all dynamical processes like cavitation bubble nucleation, growth and its subsequent collapse was 35 µs.

### 7.2. Foam

The efficiency of well characterized aqueous foam barrier configurations on the attenuation of strong blast waves was investigated. The foam barriers were impacted with a blast wave of shock Mach number 4.8. A PCB piezoelectric pressure sensor was placed at the target location to measure face-on pressure. Numerical simulation was performed through an Euler equation model that treats the foam using a pseudo-gas approach. The concluding remarks are as follows:

- The dominant mechanism responsible for the reduction of the peak pressure of the shock wave propagating in foam was the ‘catching up’ of the rarefaction wave with the wave front resulting in constant re-shaping of its profile. This process proved particularly effective in foams due to its very low speed of sound of ≈ 40 m/s. This provided sufficient time for the rarefaction wave to reduce the energy of the wave front at shorter distances. Additional reduction of peak pressure was also observed due to ‘impedance mismatch factor’ at the foam-air interface.

- For various configurations with single foam barrier, both the mechanisms provided a combined pressure reduction in the range of 86% - 96.5%. The advantageous effect of the impedance mismatch factor was exploited by splitting the barriers into two so as to provide additional interfaces. For same thickness, this resulted in relatively large pressure reduction as compared to single foam barrier. For various configurations with twin foam barriers, an overall peak pressure reduction in the range of 96.5% - 97.2% was obtained.
7.3. Density inhomogeneity

The unstable evolution of an elongated elliptically shaped inhomogeneity aligned both normal and at angle to the incoming blast wave of Mach 2.15 was investigated. The 2D inhomogeneities were generated by heating the air around a current conducting wire suspended between two electrodes. Through the positioning of electrodes, this technique provided the flexibility to generate inclined inhomogeneities. Images were again captured using both the single-shot and high speed camera that was set to capture at 0.5 million frames per second. Numerical simulation was performed by solving a 2D Navier-Stokes equation with air as test gas. The concluding remarks are as follows:

- Due to the high speed of sound in the inhomogeneity, the transmitted shock wave travelled relatively faster than the diffracted incident shock. Both shocks were connected to each other through a precursor shock (a wedge shaped disturbance). At the junction of the precursor shock and the incident shock, a quadruple point was initiated that additionally consisted of the Mach stem and a reflected shock.

- Concerning the straight case, the flow was symmetric about the inclination axis and the ‘broadening’ of the pressure profile along the center plane was identified to be caused by three physical features namely shock jump, precursor region and vorticity induced flow. The structures observed were similar to that of a 2D circular bubble where two counter-rotating vortices were formed primarily due to RMI. The variation of normalized width, length and circulation of the vortices with both distance and time were found to be linear. Also the normalized circulation was independent of inhomogeneity density and thickness thereby enabling formulation of a unique linear fit equation.

- Regarding the inclined case, although the transmitted shock adjusted itself to travel normal to the inhomogeneity, the precursor shock regions were asymmetric about the inclination axis. For the case studied here, the size of the top precursor region was larger than the bottom precursor region. Most striking observation was the vortex trains generated primarily due to KHI phenomenon. The initial velocity of each individual vortex in the train was dependent on the strength of the transmitted wave and it was observed to lose its velocity linearly with time as it grows in size. The normalized circulation followed a non-unique quadratic function influenced by two factors: the reduction in strength of the transmitted shock thereby generating vortices with reduced
vorticity along with the gradual loss of vorticity of the earlier generated vortices.
• The qualitative features observed in both cases were largely unaffected by temperature variations and shock curvature phenomenon.
Chapter 8

Papers and authors contribution

The main advisor for the project is Prof. Nicholas Apazidis (NA). Dr. Michael Liverts (ML) and Dr. Nills Tillmark (NT) acts as co-advisors.

Paper 1

*Plane shock wave interaction with a cylindrical water column.*
S. Sembian (SS), M. Liverts (ML), N. Tillmark (NT) & N. Apazidis (NA)

SS set-up and performed the experiments with assistance from ML and NT. Numerical calculations were planned and performed by SS. The obtained data was analysed by SS with guidance from ML, NT and NA. The paper was written by SS with feedback from ML, NT and NA. Parts of this work have been published in or presented at:

*On the refraction of shock wave by a cylindrical water droplet*
S. Sembian, M. Liverts, N. Tillmark, N. Apazidis
30*th* International Symposium on Shock Waves
19-24 July 2015, Tel Aviv, Israel.

Paper 2

*An experimental time-based analysis and numerical parameter study on shock-water column interaction.*
S. Sembian (SS), M. Liverts (ML) & N. Apazidis (NA)
*manuscript in preparation.*

The experiments and numerical simulations were set-up and performed by SS. The paper was written by SS with feedback from ML and NA. Parts of this work have been published in or presented at:

*On the focusing of expansion wave due to shock interaction with*
cylindrical water column
S. Sembian, M. Liverts and N. Apazidis
22nd International Shock Interaction Symposium
4-8 July 2016, Glasgow, Scotland.

Paper 3
Attenuation of strong external blast by foam barriers.
S. Sembian (SS), M. Liverts (ML) & N. Apazidis (NA)

SS set-up and performed the experiments with assistance from ML and NA. Numerical calculations were planned and performed by SS. Analysis of the data and the preparation of figures used in the paper was done by SS with guidance from ML and NA. The paper was written by SS with feedback from ML and NA.

Paper 4
Plane blast wave propagation in air with a transverse thermal inhomogeneity.
S. Sembian (SS), M. Liverts (ML) & N. Apazidis (NA)

The experiments and numerical simulations were set-up and performed by SS. The obtained data was analysed by SS with guidance from ML and NA. The paper was written by SS with feedback from ML and NA. Parts of this work have been published in or presented at:

Revisiting shock propagation through temperature gradients
S. Sembian, M. Liverts and N. Apazidis
31st International Symposium on Shock Waves
9-14 July 2017, Nagoya, Japan.

Paper 5
Plane blast wave interaction with an elongated straight and inclined heat-generated inhomogeneity.
S. Sembian (SS), M. Liverts (ML) & N. Apazidis (NA)

The experiments and numerical simulations were set-up and performed by SS. The results were analysed by SS with guidance from ML and NA. The paper was written by SS with feedback from ML and NA.
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As a newbie coming from a region with different work culture, it's natural to get intimidated or overawed at a new place. In that respect, my previous officemates Ramin and coworkers Renzo, Sohrab, Marco, Julie, Sissy, Karl, Mathias (all are titled Dr.) and Chetan are gratefully acknowledged for their warm and welcoming demeanour that made the transition instant. My current officemate Krishne also deserves a special mention for all those interesting discussions on anything under the sun and sometimes even beyond that during our spare time. I would also like to extend my thanks to current colleagues for their support and a delightful working environment.

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