An Experimental Study on the Dynamics of Melt-Water Micro-Interactions in a Vapor Explosion

Licentiate Thesis
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Abstract

Vapor explosion as a result of Molten Fuel-Coolant Interactions (MFCI) postulated to occur in certain severe accident scenarios in a nuclear power plant presents a credible challenge on the plant containment integrity. Over the past several decades, a large body of literature has been accumulated on vapor explosion phenomenology and methods for assessment of the related risk. Vapor explosion is driven by a rapid fragmentation of high-temperature melt droplets, leading to a substantial increase of heat transfer areas and subsequent explosive evaporation of the volatile coolant. Constrained by the liquid-phase coolant, such rapid vapor production in the interaction zone causes pressurization and dynamic loading on surrounding structures. While such a general understanding has been established, the triggering mechanism and subsequent dynamic fine fragmentation have yet not been clearly understood. A few mechanistic fragmentation models have been proposed, however, computational efforts to simulate such phenomena generated a large scatter of results.

In order to develop a mechanistic understanding of thermal-hydraulic processes in vapor explosion, it is paramount to characterize dynamics of fragmentation of the hot liquid (melt) drop and vaporization of the volatile liquid (coolant). In the present study, these intricate phenomena are investigated by performing well-controlled, externally triggered, single-drop experiments, using advanced diagnostic techniques to attain visual information of the processes. The methodology’s main challenge stemming from the opaqueness of the molten material surrounded by the vapor film and rapid dynamics of the process, was overcome by employing a high-speed digital visualization system with synchronized cinematography and X-ray radiography system called SHARP (Simultaneous High-speed Acquisition of X-ray Radiography and Photography).

The developed image processing methodology, focus on a separate quantification of vapor and molten material dynamics and an image synchronization procedure, consists of a series steps to reduce the effect of uneven illumination and noise inherited of our system, further segmentation, i.e. edge detection, and extraction of image features, e.g. area, aspect ratio, image center and image intensity (radiography).
Furthermore, the intrinsic property of x-ray radiation, namely the differences in linear mass attenuation coefficients over the beam path through a multi-component system, which translates the image intensity to a transient projection of the molten material morphology, was exploited. A methodology for the quantitative analysis of the x-ray images, i.e. transient maps of the fragmented melt, was developed. Its uncertainties were evaluated analytically and experimentally pointing towards the need to minimize the X-ray scattering and noise inherited from the optical system, for a more accurate quantification and a larger calibrated thickness range.

Analysis of the data obtained by the SHARP system and image processing procedure developed provided new insights into the physics of the vapor explosion phenomena, as well as, quantitative information of the associated dynamic micro-interactions.

The qualitative analysis, based on the matched radiograph and photographic images, describe the bubble and melt interrelated progression granting information on the phenomenological micro-interaction of the vapor explosion process. The dynamics of the initially disturbed vapor film is composed by multiple cycles, where the vapor bubble grows to a maximum diameter and collapses. X-ray radiographs show that during the first bubble expansion, the melt undergoes deformation/pre-fragmentation but does not follow the bubble interface during the subsequent expansion; suggesting no mixing between coolant and melt. Coolant entrainment occurs when the expanded bubble collapses leading to fine fragmentation of the molten material due to explosive evaporation. The vapor bubble expansion, fed by these fragments at the boundary, reaches its critical size, and start collapsing. The remaining melt is accountable for the following cycle.

Bubble dynamics analysis shows a strong correlation between energetics of the subsequent explosive evaporation and the high temperature molten material drop (tin) deformation/partial fragmentation during the first bubble growth. The data suggest that this pre-fragmentation may have been responsible in providing an adequate mixing condition that promotes coolant entrainment during the bubble collapse stage. The SHARP observations followed by further analysis leads to a hypothesis about a novel phenomenon called pre-conditioning, according to which dynamics of the first bubble-dynamics cycle and the ability of the melt drop to deform/pre-fragment dictate the subsequent explosivity of the so-triggered drop.
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<tbody>
<tr>
<td>A</td>
<td>area</td>
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<tr>
<td>a</td>
<td>distance source-to-specimen, m</td>
</tr>
<tr>
<td>b</td>
<td>distance specimen-to-detector, m</td>
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<tr>
<td>Bi</td>
<td>Biot number</td>
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<tr>
<td>Cp</td>
<td>specific heat, J/Kg°C</td>
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<td>equivalent diameter, mm</td>
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<td>E</td>
<td>error</td>
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<td>Eo</td>
<td>internal thermal energy, J</td>
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<td>focal spot</td>
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<td>W</td>
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# Greek Letters

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<tr>
<td>α</td>
<td>proportional constant</td>
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<tr>
<td>β</td>
<td>calibration constant</td>
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<tr>
<td>δ</td>
<td>thickness, m</td>
</tr>
<tr>
<td>ε</td>
<td>radiation emissivity</td>
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</table>
\[ \eta \quad \text{conversion ratio} \]
\[ \mu \quad \text{mass attenuation coefficient} \]
\[ \mu \quad \text{viscosity, kg/m.s} \]
\[ \rho \quad \text{density, kg/m}^3 \]
\[ \sigma \quad \text{surface tension, N/m} \]
\[ \tau \quad \text{time, s} \]

*Subscripts*

A \hspace{1em} \text{attenuated}

a \hspace{1em} \text{air}

b \hspace{1em} \text{bubble}

conv \hspace{1em} \text{convection}

DC \hspace{1em} \text{dark current}

L, l \hspace{1em} \text{liquid}

LM \hspace{1em} \text{liquid pool with melt}

M, m \hspace{1em} \text{melt}

NM \hspace{1em} \text{no melt}

NS \hspace{1em} \text{no scattering}

p \hspace{1em} \text{projected}

rad \hspace{1em} \text{radiation}

S \hspace{1em} \text{scattered}

t \hspace{1em} \text{total}

TS \hspace{1em} \text{test section}

V, v \hspace{1em} \text{vapor}
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1. Introduction

1.1. Physics of Vapor Explosion

Vapor Explosion, also referred to as steam explosion, thermal detonation or fuel-coolant interaction (FCI), may occur when a high temperature liquid, e.g. molten material, comes into contact with a cold volatile liquid, e.g. water. In this process a rapid heat transfer between the two liquids leads to an explosive vaporization of the superheated volatile liquid. In an energetic vapor explosion, the high temperature liquid undergoes fine fragmentation which enhances the heat transfer area. The heat transfer and phase transition occurs in such small time scale that pressure relieve is unfeasible. As a result, the expanding high pressure vapor produces strong shock waves, which provide hydrodynamic loading to the surroundings.

Conceptually, large scale vapor explosions are characterized by four distinctive phases, Fig. 1.1: (i) premixing, (ii) triggering, (iii) propagation and (iv) expansion:

![Figure 1.1 Vapor explosion phases.](image)

Typically driven by gravity, the molten hot melt falls into the cold liquid (or else coolant injected into the melt), during this stage the temperature of the melt and coolant is such as to immediately form a vapor layer that works as a thermal blanket preventing the direct contact between the liquids. Hydrodynamic instabilities, generated by the velocities and densities differences as well as vapor production, breaks up the molten jet dispersing it into the coolant to form a coarse mixture: *premixing phase* (on the scale of 1 cm in the case of molten corium and water). This metastable stage of dispersed droplets of melt undergoing film boiling in the coolant persists until the vapor film destabilizes (spontaneously or externally induced) in
some localized region allowing the direct contact: *triggering phase*. The subsequent rapid heat transfer generates and explosive vaporization create a local pressure rise establishing a shock wave. The disturbance pulse travels through the premixture leading to hydrodynamic and thermal fragmentation of the melt: *propagation phase*. Finally, the high pressure vapor generated expands against the inertial constrain of the surroundings: *expansion phase*.

The yield of the vapor explosion is due to the mechanical energy associated with the multiphase thermal detonation. In other words, the stored thermal energy of the high temperature liquid is converted to produce work by the high pressure vapor.

This phenomenon can be observed in the nature, such as volcanic eruptions where lava mixes with sea water (Naoyuki Fujii, 1993), and it is a safety concern in many industries that involve such a hot-liquid/cold-volatile-liquid system, e.g. steel and aluminum casting, paper, transportation of liquefied natural gas, as well as nuclear [1].

### 1.2. Molten Fuel Coolant Interaction: Nuclear Industry Safety Concern

Particularly in a nuclear power plant, FCI is an important issue for safety design and assessment of risk of a severe core-melting accident, which although accounted as a very low probability event, poses a catastrophic potential hazard.

Specifically in a hypothetical severe accident scenario where a complete and prolonged failure of normal and emergency coolant flow occurs, the core would be exposed and the fission products decay heat will cause its meltdown. Vapor explosion could then occur as the molten fuel relocates and eventually interacts with the coolant either in the vessel, *in-vessel*, or in the cavity, *ex-vessel*, as represented in Figure 1.2. If an energetic interaction is to occur, the containment integrity would be threatened with the subsequent of radioisotopes into the environment.

*In-vessel* FCI could take place in the reactor vessel during flooding of the degraded core or when corium (molten mixture of the vessel components, e.g. nuclear fuel, cladding, structures and etc) relocates to the lower plenum filled with residual water where vapor explosion could take place.
Deterministic and probabilistic methods provided a consensus (SERG-2, 1995) that the so-called alpha-mode failure, containment failure due to the impact of the reactor vessel upper head launched as a missile against the containment wall as a result of steam explosion, is of very low probability with little significance to the overall risk. Moreover, for BWR, whose forest of penetrations in the lower plenum would have a damping effect on the propagation of shock waves, the lower head integrity would not likely be challenged by a FCI.

**Figure 1.2** Scenarios of in-vessel and ex-vessel vapor explosion in a postulated severe accident.

*Ex-vessel* progressions start with the reactor vessel failure followed by the pouring of molten corium into the containment cavity. The molten material could then interact with the coolant present in the containment pavement, e.g. water delivered from a primary LOCA (loss of coolant accident)\(^1\) or present due to a Severe Accident Management (SAM) procedure, which is the case for the Swedish BWR’s. The ex-vessel case initial conditions, which involve a large discharge rate of superheated corium into highly subcooled coolant,

---

\(^1\) A recent study of two typical ex-vessel steam explosion cases in a PWR cavity with energy conversion ratio 1% and 10% showed that the collapse of the cavity walls is not probable. However, future analyses should be addressed to high-pressure melt ejection scenarios and the consequences of successive steam explosions. [30]
favor an energetic FCI, leaving this issue still unresolved. Additionally, the SERENA (Steam Explosion Resolution for Nuclear Accidents) program exercise [2] on the assessment/validation and application of the FCI computer codes re-indicated that the complexity of the phenomena largely hindered a high-fidelity prediction of FCI energetics in reactor accident conditions.

1.3. Previous Studies on Vapor Explosions

An extensive amount of work motivated by safety concerns on the nuclear industry [1,2,3,4,5,6,7] has been conducted in the past to develop a basic understanding of physical phenomena involved in vapor explosions.

Experimental studies of vapor explosions are usually classified in two categories, namely small and large scale. The difference between them is the amount of fuel and coolant involved in the interactions.

Recent well controlled large scale experiments show mixed results on the triggability of various molten materials (from pure metallic melts to prototypic corium melts). The KROTOS and FARO tests [8,9] revealed no or mild propagation for interaction of corium composite melt (non eutectic UO₂-ZrO₂) with water, even by applying strong triggers. On the contrary, energetic explosions were observed in KROTOS tests with pure alumina melt [10] and in TROI [11] with an eutectic mixture of UO₂-ZrO₂. Although some mechanisms were proposed, e.g. steam absorption, hydrogen release, crust/mushy zone presence etc, the relationship between the material type and its triggability remains unclear.

On the other hand, such large scale experiments provide an integrated picture of all phases of the explosion. The key in a modern understanding of vapor explosion is the micro-interaction concept pioneered in Yuen et al [12]. Specifically, mixing of volatile coolant into the hot melt, which is responsible for the local pressure increase (in a confined bubble domain or so-called m-fluid) that drives the escalation and propagation of a vapor explosion. As to say, the understanding of the microinteractions is paramount to accurately model the phenomena.

The explosivity largely depends on the fine fragmentation of molten material during the vapor explosions since it defines the high rate of heat transfer.
Many fragmentation models have been proposed to depict the fine fragmentation of a hot liquid in a cold liquid. The models are commonly classified in two groups; thermal and hydrodynamic. The thermal fragmentation models were based on the idea that fine fragmentation occurs due to the formation of micro coolant jets that penetrate into the hot drop [13,14] and due to the generation of a local high pressure region which stretches and breaks up the melt [15,16,17]. In the thermal fragmentation models with micro jet formation, the micro jets penetrate the drop surface and are trapped within the drop. Rapid vaporization of this encapsulated coolant jet disperses the drop into fine particles. Although this kind of vapor bubble collapse and jet formation was observed in the cavitation phenomena [18], there was no direct experimental evidence in vapor explosions to support this model.

The hydrodynamic fragmentation model explains the fine fragmentation of a hot droplet in terms of the hydrodynamic acceleration of the droplet with respect to the coolant. In the hydrodynamic models, intensive slip flow over the drop strips its surface and breaks them into fine particles, e.g., boundary layer stripping, surface instabilities [19,20,21]. Requiring the strong relative velocity between the drop and ambient fluid, these models would be plausible for the case of large-scale vapor explosions where multiple vapor explosions and propagation occur. However, they are not appropriate models for small-scale single drop vapor explosion where no intensive slip flow apparently exists.

Verification or development of such models relies heavily on the visual information of the vapor explosion triggering process. Early visualization efforts with regular high-speed photography, such as tests performed by Duda & Nelson [22], provided insights of the fine fragmentation process based on the image data of vapor bubble dynamics, while unable to characterize the molten material which is enclosed by the vapor layer. To overcome this visual impeding effect, radiographic methods were considered as a promising instrument for flow visualization in such multiphase and opaque medium [23,24,25,26,27,28].

Radiography uses attenuation or absorption of a radioactive source in a medium, and is classified as X-ray, Gamma ray and Neutron radiography according to the radiation source. Neutron radiography, combined with a high-speed CCD camera system, was applied to vapor explosion research [26,28], though limited to the study of melt jet breakup and mixing
phenomena. For the visualization of a multiphase medium, where the volume fraction of dispersed high-density component (melt drop in this study) is considerably smaller than that of a continuous low-density component (water in this study), the X-ray radiography has an advantage over the neutron radiography since the absorption of neutrons in water is considerable. In addition, the X-ray radiography is more accessible than the neutron radiography, which requires a high flux neutron beam source normally available from a nuclear reactor.

Using X-ray radiography, Ciccarelli [16] successfully visualized the fragmentation of the high temperature liquid during vapor explosion. However, the employed snapshot flash X-ray system provided one still image per test due to the X-ray recharging time, inhibiting the acquisition of a consistent sequence of the phenomenon.

Experiments to characterize micro-interactions in steam explosion were performed in the SIGMA-2000 facility for study of droplet explosion under a very strong shock wave, using a high-speed video camera and a flash X-ray imaging of the melt drop [29].

Notably, due to the intensity and microscopic scale of processes of importance it has been very difficult to obtain data on micro-interactions for the basic understanding. A mechanistic treatment of micro-interactions remains elusive.

1.4. Research Objectives

Triggering is the event that initiates the rapid local heat transfer and pressure rise, which is necessary if a propagating wave is to develop leading to the rapid transfer of heat from the melt to the coolant. Furthermore, the explosivity largely depends on the fine fragmentation of molten material during the vapor explosions, given that it governs the overall heat transfer rate. Adding to the fact that most of the developed codes built to simulate the entire process depends heavily on such fragmentation rates, which is an unknown parameter, leading us to stress that a detailed knowledge of the steam explosion mechanisms, in particular the triggering phase, is required to obtain theoretical prediction of the hydrodynamic loading to the surrounding system.
The purpose of this study is to improve the understanding of the dynamic characteristics of vapor explosions that involve micro-interactions among multiphase and multi-component flows, by scrutinizing a single molten drop interaction with water which is representative to one cell on the metastable pre-mixture.

The scientific objectives of the present experimental program on droplet explosion are twofold. First, the aim is to obtain high-quality experimental data in well-controlled single drop experiments. Such data are useful for the development and validation of mechanistic models, including CFD-based simulation methods. Second, process the attained data to gain new insights into the physics of micro-interactions.

In addition, the programmatic objective of this work is to establish the hardware and software infrastructure, which are instrumental for future experiments using a broad range of simulant melt materials and under conditions beyond triggering.

1.5. Technical Approach

The present work is an experimental investigation of the triggering and fragmentation process of a single molten metal (Sn) droplet in water, realized on well-controlled conditions at the developed MISTEE facility (Micro Interactions in Steam Explosion Experiments), which is described in Chapter 2.

Given that the qualitative and quantitative understanding of such multi-fluid multiphase interactions requires visualization of both material dynamics and interface dynamics, a new approach has been developed at the Royal Institute of Technology. The focus is placed on the development of a synchronized high-speed visualization by digital cinematography and X-ray radiography. The resulting system named SHARP (Simultaneous High-speed Acquisition of X-ray Radiography and Photography), enables the continuous and simultaneous visualization of the “entire” process of droplet explosion phenomenon, which was not possible in previous investigations.

Chapter 3 scrutinizes the SHARP image processing methodology, which includes a separate quantification of vapor and molten material dynamics and an image synchronization procedure, consisting in a series steps to
reduce the effect of uneven illumination and noise inherited of the imaging system, and further segmentation, i.e. edge detection, which enable the extraction of relevant image features.

Furthermore, we exploit an intrinsic property of X-ray radiation, namely the differences in linear mass attenuation coefficients over the beam path through a multi-component system, which translates the image intensity to a transient projection of the molten material morphology.

Chapter 5 includes a discussion of new insights gained from synthesis of behavior of melt deformation/fragmentation and vapor film dynamics observed over a range of coolant temperature.
References


Theofanous, T. G., Angelini, S., Chen, X., Luo, R., and Yuen, W. W., Quantitative radiography for Transient Multidimensional Multiphase


2. Experimental Method

2.1. Overall Description of the Experimental Approach

The aim of the established experiments is to simulate a single molten drop undergoing vapor explosion in a well-controlled environment, where the melt thermo-physical properties, temperature and mass of melt-simulants, coolant temperature, and strength of the external trigger pulse are the main experimental parameters.

The general plan is to perform tests that should cover a range of corium simulant materials, from metallic melts, e.g., Tin, to medium-temperature oxidic melts, e.g. MnO₂-TiO₂, WO₃-CaO, and later also high-temperature metal, e.g. Steel, and ceramic oxide materials, e.g. Al₂O₃; in the pursuit to identify the possible key thermo-physical properties, which would be responsible for the higher triggerability and explosivity of metallic and some oxidic melts over others. The present thesis, however, will be based on the experiments realized with Tin with the coolant temperature ranging from room temperature to near saturation at an ambient pressure of 1 atm.

As typical for the study of vapor explosion phenomena, the qualitative and quantitative understanding requires visualization of both material dynamics and interface dynamics. An intrinsic challenge arises due to opaqueness of such media, presence of convoluting interfaces, and need for high-speed, high-resolution imaging.

To overcome this complexity, a new approach has been developed with the focus placed on the development of a synchronized high-speed visualization by digital cinematography and X-ray radiography, which enables the continuous and simultaneous visualization of the “entire” process of droplet explosion phenomenon, which was not possible in previous investigations.

Furthermore, we exploit an intrinsic property of X-ray radiation, namely the differences in linear mass attenuation coefficients over the beam path through a multi-component system, which translates the image intensity to a transient projection of the molten material distribution.
The collected data on the molten droplet and vapor film morphology and interrelated dynamics will be synthesized and serve as basis for the analysis of the vapor explosion micro-interactions, which in turn will provide a concept on the physics of the phenomena.

2.2. MISTEE Test Facility

The MISTEE facility (Micro Interactions in Steam Explosion Experiments), used for performing single drop experiments, was located inside a 700mm thick reinforced concrete containment (4x4x4m) which provided the X-ray radiation shielding during the tests. The facility, Fig 2.1, consists of a melt generator, Fig 2.2, a test chamber, Fig 2.3, an external trigger system, a visualization system, Fig 2.4, an operational control system, Fig 2.5, and a data acquisition system, whose individual description is given below.

![Figure 2.1](image)

**Figure 2.1** The schematic diagram of the MISTEE facility.

2.2.1. Melt Generator

The melt generator, Fig 2.2, purpose is to melt and heat up the sample to a desirable temperature, and then release it to the water tank beneath.

---

2 The facility has been moved to a new bunker, where the walls were fortified with 5mm lead sheets, approved by KTH.
It consists of an induction furnace (HeatTech GT6, 6kW, 80-180kHz) where its copper coil enfold a graphite cylinder (40mm O.D. x 50mm), which is the element that is actually heated by induction, with an alumina crucible (20mm I.D. x 30mm) with a 5.0mm hole at the center of the bottom. Insulation, ceramic fiber (Cerablanke), is placed between the coil and the crucible to ensure the integrity of the furnace, and to hold the crucibles in place. An extra support is given by a refractory ceramic piece located underneath the crucibles. A boron-nitride melt release plug (10 mm O.D. x 20 mm) is used to block the crucible bottom hole during the melting and it is lifted by a pneumatic piston to release the melt drop.

![Schematic of the melt generator.](image)

The whole system is housed inside a Teflon cylindrical chamber with an aluminum lid, with all the walls padded with insulation material, where Argon gas is purged in to prevent the sample and the boron nitride plug from oxidizing during heating. A guide-tube was mounted through the aluminum lid to deliver the sample to the crucible without compromising the inert atmosphere.

To measure the sample’s temperature a K-type thermocouple is used, since the chamber and small size of the sample makes it difficult to measure it by an optical pyrometer. The thermocouple’s tip contacts the alumina crucible wall near the bottom, since the sample is very small compared to the
crucible size, which unable to embed the thermocouple in it. For this reason, a dwell time at the desired temperature is necessary before release. The temperature was not recorded by the data acquisition system; instead, it is displayed on the control room for reference.

### 2.2.2. Test Chamber

The test chamber, Fig 2.3, is placed below the melt generator with a 4 cm gap to allow the placement of a laser beam (ELFA TIM201) and a photo sensor (ELFA BPX43-3).

![Figure 2.3 The schematic diagram of the MISTEE test section.](image)

The test section is a rectangular Plexiglas tank (180x130x250mm) that enables direct visualization, i.e. photography, and avoids a large X-ray attenuation, since its density is close to the water. A piezoelectric pressure transducer\(^3\) (PCB Piezotronics 102A03, sensitivity 75.0 mV/MPa, rise time

---

\(^3\) Although the pressure transducer is delivered with a calibration certificate from the vendors, a second calibration was performed for verification. A small cylindrical metal piece was fabricated where the transducer and an inlet for pressurized air were mounted. By using a barometer as reference, one could find the relationship between the pressure transducer signal, i.e. voltage, and equivalent dynamic pressure. Indeed, the results were the same as the calibration chart given by the vendor.
< 1.0μs) and a K-type thermocouple are flush-mounted at the center of the test section in opposite walls. The pressure transducer is connected to the four-channel ICP signal conditioner (PCB Piezotronics 442A04). The water temperature is displayed in the control room, whether the pressure and laser signals are acquired by a 2 channel 10^6 Hz data acquisition system (National Instruments PCI-6111E) and downloaded into a PC, where LabView software was used to convert the signal and record the data.

At the bottom of the test chamber is located the external trigger system, which is next described.

2.2.3. External Trigger System

The triggering phase of the vapor explosion is of main concern; therefore the interaction is initiated by applying a weak pressure wave, contrary to the classical shock tube experiments which reproduces the propagation phase of the phenomenon.

The external trigger system can be described as a piston located at the bottom of the test section, which generates the sharp pressure pulse (rising time of 50 μs at the full width half maximum) up to 0.15 MPa that travels through the coolant. The trigger hammer that impacts on the piston to generate a pressure pulse, is aligned underneath the latter, and is driven by a rapid discharge of a capacitor bank, consisting of three capacitors of 400 Vdc and 4700 mF each.

2.2.4. Visualization System

The fast synchronous visualization system, SHARP (Simultaneous High-speed Acquisition of x-ray Radiography and Photography), shown in Figure 2.4, consists of a continuous high-speed X-ray radiography and photography.

The continuous high-speed X-ray radiography is composed by a X-ray source tube, a X-ray converter and image intensifier and a high-speed video camera. The X-ray source tube (Philips continuous X-ray, MCN 323) has a voltage up to 320 keV and a current up to 22mA. The X-ray converter and image intensifier (Thomson TH9436 HX) powered by a high voltage power
supply (Thomson TH 7195) has a view window of 290 mm and three magnification modes. X-rays are detected on the input phosphor screen with a CsI crystal layer and converted into photoelectrons that are accelerated, amplified and converted at the output phosphor screen into visual light, where the images are acquired by a high-speed camera (Redlake MotionScope HR 8000), that enables to record up to 1 second at 8000 frames per second. The aim is to visualize the melt fragmentation process during the explosion phase of vapor explosion. This image data will provide the visual information on the fine fragmentation and triggering processes and eventually be quantified after a series of calibration tests, which will be discussed in the section 3.2.

Figure 2. 4 The schematic diagrams of the SHARP visualization system.

The high-speed CMOS digital camera (Redlake HG50LE) with a recording speed up to 100000 frames per second\(^4\), and tungsten lightning are used for the visualization of the dynamic behavior of the vapor film that surrounds the melt droplet during the vapor explosion process. Two spot lights (DedoCool) were used and placed on the back of the test section, to have a good contrast of the interface, and on the front, to see details of the vapor film surface. A mirror is placed 45° in front of the test chamber so to acquire the same face of the vapor film and melt droplet during the interaction, configuring the simultaneous visualization system.

\(^4\) For the actual experiments, the recording speed of 20000 frames per second was used.
2.2.5. Operational Control System

The high speed cameras’ resolution, which is a function of the number of pixels in the sensor and their size relative to the projected image, is inversely proportional to the recording speed. Consequently, to maintain a reasonable spatial resolution, the cameras have to be set as to have a smaller field of view, giving rise to the need of a precise control of the experiments.

![Schematic diagram of the control system. LS: Laser, PD: Photo Detector, HSC: High-Speed Camera, TC: Thermocouple, and PT: Pressure Transducer.](image)

**Figure 2.5** Schematic diagram of the control system. LS: Laser, PD: Photo Detector, HSC: High-Speed Camera, TC: Thermocouple, and PT: Pressure Transducer.

As a result, the control system, Fig. 2.5, with a set of precision timers (1ms time resolution) was developed and employed to provide the accurate operation signals to the subsequent automatic sequences of experiments such as: triggering of the high-speed cameras, the data acquisition system, and the external trigger system at preset time delays. Moreover, due to the impossibility to stay in the containment during the experiments because of the X-ray radiation, remote operations of the Argon, induction furnace, melt-release plug and X-ray system control; were necessary and implemented in the control system.
2.3. Experimental Procedure

At present, about 0.6-0.7 g of Tin is melted, heated at 1000 °C and released into the test section filled with tap water at temperatures of approximately 20~80 °C.

The experimental procedure is as follows:

i. Warm up the x-ray
The X-ray tube has its on automatic sequence for warming up, and depends on the time that it was last used. During the warm up a lead piece should be placed on the source window, to avoid unnecessary radiation.

ii. Start charging the capacitor bank

iii. Turn on the laser beam

iv. Assemble the melt generator
The induction furnace coils are inserted in the insulation padded Teflon housing. The ceramic insulation is wrapped around the graphite crucible, which is then placed in the induction furnace coil. The alumina crucible is put into the graphite and the argon tube is inserted through the Teflon housing.

v. Turn on the X-ray converter and choose magnification

vi. Camera positioning and focus
A phantom is put through the crucible hole and positioned at the same water depth as the interaction should be initiated. This piece serves as a reference to position, focus and regulate the lens aperture of the high speed cameras. As well as readjusting the placement of the laser beam/detector.

vii. Open the Argon gas valve

viii. Open the feed water to the induction furnace refrigeration system

ix. Turn on the pressure transducer signal conditioner
x. Put the cameras in stand by mode

xi. Close the lid on the Teflon housing and purge Argon
   Connect the release plug with the pneumatic piston and position the
   thermocouple so to touch the bottom wall of the crucible. Close the
   aluminum lid and start the Argon flow.

xii. Put the Tin through the guide tube and start the induction furnace

xiii. Close the containment door

xiv. When reaching the desired temperature start the X-ray, turn of the
     induction furnace and lift the release plug

xv. Automatic sequence
    Sets of timers (1 ms time resolution) operate the subsequent automatic
    sequences, which are triggered by a signal from a photo-detector when
    the molten drop interrupts the laser beam. The timer triggers the high-
    speed cameras, data acquisition system, and external trigger capacitor
    bank at preset time delay.

xvi. After the interaction the X-ray turned off

xvii. Save data on the PC
     The pressure and laser history were saved on the PC. The images from
     the high speed digital cameras were downloaded and saved on the PC.

2.4. Assessment of Uncertainties and Source of Errors

2.4.1. Temperature and Pressure measurements

The thermocouple used in the melt generator and test section did not give
indications of high frequency electrical noises\(^5\). Adding to the fact that the
measurements were made under the device’s allowed range, up to 1300°C,
one can assume that the measurement error is corresponded to the vendors:
2.2°C.

\(^5\) The device reading time was Hz, where high frequency noise might not be registered. Nonetheless, no
oscillations on the displayed temperature were observed.
The pressure measurements however presented high frequency noises, 40 kHz, even after proper grounding of the equipment. The uncertainty is then determined by the noise amplitude when analyzing the pressure signal, which is found to be $\pm 0.05\text{MPa}$.

### 2.4.2. Camera Synchronization

In the absence of a synchronization board for the cameras, phase lock between them was not possible. Hence, a series of tests were performed to determine the cameras timing offset. A set-up was assembled consisting of a rotating disc with a pinhole and a careful aligned laser beam$^6$ behind it. The two cameras where trigger at the same time and the offset between the frames were determined by the time that the light shined through the pin-hole. Tests were performed by setting up the cameras with the same and different recording frame rates. The offset between frames were found to vary in every test even for the same conditions, however it never exceeded 4 frames. For this reason, the reference frame used to synchronize the images, radiography and photography, was chose to be the time of bubble collapse on the fist cycle, which it is easy to define from the melt and vapor film side. In the actual experiments the cameras are set for different recording rates; meaning, one X-ray frame is equivalent to 5 frames of the photographic images. So, considering the camera different recording speeds and the event chosen to be used as a reference, the uncertainty was determined to be of 0.125 ms.

### 2.4.3. Image Resolution

The uncertainties related to the image quantification will be discussed in chapter 3.

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$^6$ The same laser beam used in the experiment.
2.5. Discussion of Needs for Improvement of Equipment and Procedure

2.5.1. Visualization System

Although image processing is a valuable tool to enhance the images, it does not substitute a high quality raw image. Thus, one should always pursue the optimization of the visualization system, which can be translated in improvements on the illumination, lenses and peripheral noise sources.

Specifically to the X-ray system, efforts on the minimization of the scattering should be addressed. At present, there are two suggestions proposed: the use of a collimator in front of the X-ray source and/or a grated lead sheet placed on the converter side, similar to the ones used on medical CT imaging. Any of those modifications would decrease the image brightness, thus the gain should be pondered by evaluations on the signal-to-noise ratio and image contrast.

Another improvement was the design of a remote controlled positioning rail that moves the high speed camera facing the fluorescent screen at the back of the converter, allowing a more meticulous focusing.

2.5.2. High Temperature Experiments

The following step on this experimental work is to perform single drop experiments for a variety of materials, including high temperature melts. Consequently, the melt generator and external trigger should be modified accordingly.

2.5.2.1. Melt Generator

To measure the temperature of the melt material in the crucible, C-type thermocouples will be used and the inert atmosphere will be maintained, since such thermocouple is sensitive to oxidizing environment at high temperatures. Preliminary tests using a high quality graphite as crucible were performed and proven to be efficient. However, its increasing porosity during its life-
time could be a problem; hence graphite crucibles coated with Zirconium oxide and molybdenum crucibles will also be considered.

The delivery system would be the same as described for the Tin experiments, except for the material of the plug and argon injection tube which will be substituted by Tungsten.

2.5.2.2. External Trigger

The higher the molten droplet temperature the thicker and more stable the vapor film that surrounds it will be. For this reason, in order to destabilize the vapor film to trigger the vapor explosion, the need of a stronger trigger arises.

The planed modification to the current external trigger set-up is to place the piston inside the test section and when the hammer, driven by the capacitor bank discharge, impacts on it, it will create an upward motion of the coolant similar to a water slug. Modifications of the cables that connect the capacitor bank to the hammer piece are also planed to optimize the efficiency of the discharged current.

A more outlying plan is to also consider other external triggers possibilities, e.g. exploding wire, exploding caps, shock tube and etc.
The quantitative information of micro-interaction dynamics is built upon the separate quantification of vapor and molten material dynamics by attaining relevant features of the acquired images. In this chapter, we describe an image processing procedure developed to extract such information, which includes a series of steps for noise reduction and edge detection, and an image synchronization procedure.

Optical measurements are difficult to perform and have its limitations. Depiction of their range of validity preserves its appropriate application, accordingly, image quality is also investigated and quantitative measurements obtained by the high-speed X-ray radiography and cinematography are evaluated for the actual setup of the MISTEE facility.

**3.1. Method for Photographic Image Processing**

Initially, the photographs illustrates the equilibrium between the droplet surface superheat, bulk subcooling and external velocity field that determines the shape and stability of the vapor film. Following to the external disturbance posed into the system, a sequence of vapor bubble growth and collapse leads to high convoluting interfaces where the main interest for quantification lays.

Bellow, are three examples of images acquired representing the period before, Fig. 3.1 a, and during the interaction, Fig. 3.1 b and c:

![Figure 3.1](image)

**Figure 3.1** Photographic images emphasizing different aspects as (i) light reflection and (ii) foreign interfaces
A typical sequence of a single droplet undergoing vapor explosion is on the range of 10 ms. Considering that the recording speed were set to be 200000 fps, one experiment would produce 200 images to be enhanced and quantified, which would be unfeasible to do one-by-one in a mouse-clicking fashion. Hence, the main task is to develop an algorism to analyze the whole sequence at once. The challenge is that it should be general enough as to be able to take care of images like Fig 3.1a, b and c, which has very different characteristics, e.g. brightness, contrast, foreign interfaces, etc. Moreover, although not obvious to the human eyes, noise is present in each image and it can hinder the accurate identification of the bubble interface.

3.1.1. Noise Sources

The vapor film progression during the vapor explosion is recorded by a CMOS high speed camera whose sensor not only carries the useful signal, but includes a variety of noise components such as photon noise, fixed-pattern noise (FPN), amplifier noise, which can seriously restrict the ability to achieve high-quality images.

Photon noise is related to the random fluctuation of photon flux arriving at the camera sensor. FPN is due to the differences in individual pixels’ responsivities. This type of noise is more prominent at higher intensities and it is signal dependent. Read out noise is introduced to the signal during the process of measuring the signal.

In addition, high speed imaging suffers from low light collection, small exposure time, producing images with a significantly reduced signal to noise ratio. Even if one accomplishes to set up a system with a satisfactory and uniform illumination, there is still to consider noise sources as the camera sensor, imaging screen, etc. Consequently, before any attempt to segment such images, some steps are necessary to optimize the definition and contrast in respect to the inherited noise.

---

7 Water is an imperfect medium for transmission of light/photons, where scattering and absorption take place. Moreover, high heat fluxes at boundaries causes large gradients of the refractive index on the liquid that deflect light rays, which are also absorbed by the liquid and refracted and reflected at the liquid-vapor interfaces [1].
3.1.2. Image Processing Procedure for Noise Reduction and Segmentation

Figure 3.2 shows the image processing procedure applied to the images presented in Figure 3.1, and the detailing of the image procedure is given bellow.

Unfortunately, high speed imaging can not use the advantages of averaging multiple exposures to reduce noise. Hence, shading correction or background subtraction, Fig. 3.2(1), must be carried out by dividing the current image by the referent background image, i.e. average of a defined number of images of the test section without the molten droplet. This procedure would reduce noise inherited from the system and smooth out the uneven illumination.

However, random noises are not eliminated and image filtering is necessary. From a large array of possible filters, e.g. median, average, etc, an adaptative filter was considered since it reduces noise by smoothing, while preserving useful details of the image. The selected Wiener filter is applied to an image adaptively, Fig. 3.2(2), which is based on statistics estimated from the neighborhood of each pixel, i.e. local image variance. Where the variance is large, i.e. edges, the filter performs little smoothing and where the variance is small it performs more smoothing. Such filter tailors itself to be the “best possible filter” for a given local region of the image.

Edge detection is accomplished by segmenting the images to separate the individual objects from the background, i.e. selecting a threshold that separates the gray levels of these dominant modes, Fig. 3.2(3). In this process, also known as binarization, each pixel of the gray scale image is tested independently: if the pixel value is greater than the threshold it is set to 1 (white), while pixels with a value bellow the threshold are set to 0 (black). However, thresholding alone may not always be able to determine the vapor bubble region. Sometimes the lighting brightens one edge and darkens the opposite edge, producing a break in the perimeter of the bubble, Fig.3.2(3)a; sometimes a bright glint in the center produces a hole in the area determined by the bubble boundary. These problems can be solved then by performing a morphological closing.

A morphological closing is defined as dilation, Fig. 3.2(4), followed by erosion, Fig 3.2(5). Dilation is an operation that grows and thickens objects
in the binary image by changing every background pixel that is touching an object pixel into an object pixel. This operation will link breaks on the bubble contour and fill holes inside the bubble perimeter.

Conversely, erosion shrinks objects in a binary image by changing every object pixel that is touching the background into a background pixel. By doing so, the bubble is returned to its original size, although now with a smoothed periphery and joined breaks. The following morphological opening, Fig.3.2(6), which is the inverse of the morphological closing, i.e. erosion followed by dilation, will finally remove any foreign interfaces, Fig. 3.2(5)b and c, and random noise, Fig. 3.2(5)c, left in the image.

As can be seen in Figure 3.2, the image processing procedure developed works very well for cases like Figure 3.1a and b; however, not as well for cases like Figure 3.1c. Although some improvements on the lightning would help to get a clearer image, the presence of the fragments will always introduce an uncertainty on the exact definition of the bubble boundary.

### 3.1.3. Quantification of Image quality

Four parameters are useful in considering the image quality: the spatial resolution, the time resolution, the noise and the contrast. The spatial resolution can be defined as the distance at which 2 structures can be distinguished, and the time resolution is the exposure time of the image. The noise, consider to be a combination of the noise components referred in section 3.1.1, is the mean grey level amplitude of the statistical fluctuations of a homogenous area. The contrast is the grey level difference between two areas and determines if we recognize a detail or not.

The image spatial resolution pared with the image contrast, i.e. image blur, can be determined in a integral manner by obtaining the point spread function (PSF) of the imaging system, which provides a quantitative description of the system’s resolution and directly depicts the image degradation [3,4,5].

PSF can be measure directly from the projection of a carefully aligned exact pinhole; it also can be taken from the derivation of the gray scale profile along the transverse direction (edge spread function) across the phantom image, as shown in Figure 3.3.
Figure 3.2 Image processing procedure applied to images acquired in the MISTEE facility.8

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8 In Figure 3.2c, after background subtraction, some brightness adjustments were made as to enhance the bubble interface.
Figure 3. 3 Edge spread function and respective point spread function for the photographic image.

Typically, the PSF will have a Gaussian shape due to the zoom optics of the camera, and the light beam divergence. Therefore, its full width at half maximum (FWHM) will be taken as the parameter to define the image blur.

Accordingly, for the photographic images, with a spatial resolution of 0.1863 mm/pixel, the fitted Gaussian curve, i.e. point spread function, gives a FWHM of approximately 3 pixels.

Besides the spatial resolution, the noise characteristics are also of interest for image quantification, and as mentioned earlier, it can be identified from the background mean grey level amplitude and its fluctuations. Therefore, a region of interest is extracted and the uniformity within the image background, between pixels, and between frames was analyzed by means of standard deviation/mean gray values ratio, Table 3.1.

After the mentioned image processing steps for noise reduction, the photographic images showed a clear increase on the signal-to-noise ratio (SNR), but less significant increase on the uniformity between frames. The later is due to the lights used on the experiment, which has a frequency of 100Hz and when imaging a 10 ms transient, brightness variations will take place.
Table 3.1 Photographic images non-uniformity between pixels and frames

<table>
<thead>
<tr>
<th>Non-uniformity</th>
<th>Raw Image</th>
<th>Background Subtraction</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>between pixels</td>
<td>10.95</td>
<td>2.09</td>
<td>0.52</td>
</tr>
<tr>
<td>between frames</td>
<td>1.98</td>
<td>0.89</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Temporal resolution, defined as the smallest increment of time over which a change in an imaged dynamic process can be observed, can be a limiting factor when dealing with such high-frame rate imaging system. However, since it is determined by the shutter speed of the camera, arrangements were made in the SHARP actual set up as to exclude this limitation. The temporal resolution is then determined by the recording speed: 0.05 ms.

3.1.4. Data Extraction of MISTEE Images

The primary target of the bubble dynamics quantification is to characterize the bubble interface that envelops the molten material. By acquiring image features such as area, aspect ratio and center of mass, one can determine the falling velocity, the aspect ratio and equivalent diameter of the vapor bubble.

The molten droplet falling velocity establishes the initial conditions of the system, e.g. Reynolds number, necessary for the convection heat transfer calculation when estimating the molten droplet temperature prior to the interaction, see Appendix A.

The aspect ratio characterizes the morphology of the vapor bubble, whether the equivalent diameter represents the history of vapor bubble growth and collapse. The latter is used for estimating the pressure inside the bubble, which in turn is used for calculating the work done on the surroundings by the expanding bubble, see Appendix B.
3.1.4.1. Image Processing Procedure for Data Extraction

Figure 3.4 illustrates the general schematic of the image processing procedure for noise reduction, segmentation and extraction of image features of interest.

Figure 3.4 Image processing procedure for noise reduction, segmentation and extraction of image features of interest.

The vapor bubble, which encompasses the molten droplet, trajectory in water is extracted from the processed images by tracking the coordinates of the center of mass during the process. Such data is acquired by getting the Euclidean distance transform from the segmented images, i.e. for each pixel in the segmented image the distance between that pixel \((x_1, y_1)\) and the nearest nonzero pixel \((x_2, y_2)\) is assigned, Fig. 3.5, and the center, \(c\), is then determined by the pixel which has the maximum value:
\[ c(x, y) = \max \left[ \sqrt{(x_i - x_2)^2 + (y_i - y_2)^2} \right] \]  

(3.1)

**Figure 3.5** Segmented image of the vapor bubble and the correspondent Euclidean distance transform.

Considering that the trajectory is mainly in the vertical direction, the \( y \) coordinate is then plotted to obtain the falling velocity. Figure 3.6 shows a linear fit of such data, hence the average velocity. One can also observe the time of the external trigger pressure wave arrival and subsequent interaction, where the droplet is brought to a standstill and it is represented by the plateau in the data set.

**Figure 3.6** Vapor bubble trajectory in water extracted from the photographic images.
The aspect ratio, shown in Figure 3.7, is extracted by taking the center of mass as a reference point, \( c(x,y) \), and determining the distance between the lateral peripheries, and the distance between the high and low periphery.

![Figure 3.7 Vapor bubble aspect ratio.](image)

The reason not to use this information for estimating the transverse area is due to the fact that the interface is quite irregular and noisy leading to a greater error and unrealistic oscillations. As shown in Figure 3.7, the vapor bubble is nearly spherical, aspect ratio \( \sim 1 \), particularly during the relevant interaction. Hence, a smoother way to describe the dynamics of the phenomena is to estimate the equivalent diameter, correspondent to the projection of a sphere, directly from the binarized image by assuming it to be symmetric. The projected area is determined by the number of off-pixels, i.e. pixels of value 0 (black), in the segmented image. The equivalent diameter, Fig. 3.8, is then determined by:

\[
Deq = \sqrt{\frac{4 np \cdot sr^2}{\pi}}
\]  

(3.2)

where, \( np \) is the number of off pixels and \( sr \) is the spatial resolution.
Figure 3.8 Vapor Bubble equivalent diameter history.

3.2. Method for Radiographic Image Processing

X-ray radiography enables the visualization of the molten droplet dynamics during the vapor explosion, providing visual information on the triggering processes and fine fragmentation. The X-ray has a unique characteristic, which allows the molten material dispersal quantification after a series of calibration tests.

The intensity of the detected X-rays, $I$, after the transmission of the incident X-ray beam, $I_0$, in a medium, obeys the attenuation law as follows

$$I = I_0 \exp\left\{ -\sum_i \mu_i \delta_i \right\}$$

(3.3)

where, $\delta_i$ and $\mu_i$ are the thickness and the mass attenuation coefficient of $i$-th materials. However, the total x-ray intensity detected at the converter, Fig 3.9 consists of the intensity of the X-rays that penetrated through the test section and were attenuated, $I^A$, and the intensity of the x-rays that were scattered by the object and surrounding shields $I^S$,

$$I = I^A + I^S$$

(3.4)
Figure 3.9 The schematic diagram of the x-ray components detected by the converter.

The transmitted X-ray beam enters the input window of the converter and strikes the input phosphor. The input phosphor scintillates and light photons strike the photocathode, which emits electrons. These electrons are accelerated and focused by the electron optics onto the output phosphor, which emits light that is recorded by the high-speed CCD camera. The image contrast, proportional to the transmitted X-ray beam, is transformed into digitized gray levels. Therefore the digitized gray level, $G$, can be generally expressed as,

$$G = \alpha I + G_{DC} = \alpha (I^A + I^S) + G_{DC}$$

$$= \alpha I_0 \exp \left\{ -\sum_i \mu_i \delta_i \right\} + G^0$$  \hspace{1cm} (3.5)

where $\alpha$, $G_{DC}$, and $G^0$ are the proportional constant, dark current of the imaging system and the image offset, which represents the gain of the image gray level due to the scattered X-rays and the CCD dark current, i.e., $\alpha I^0 + G_{DC}$, respectively.

The basic arrangement of the SHARP X-ray system (X-ray tube and converter) consist of a test section that has a multiphase mixture of water, vapor and melt during the vapor explosion process. In this configuration, the X-ray intensities with and without melt droplet surrounded by vapor film, $G_M$ and $G_{NM}$, respectively can be obtained as follows,
where the subscripts \( a, TS, L, LM, \) and \( V \) are denoted as the air, the test section, the liquid pool, the liquid pool with a melt droplet and the vapor, respectively. Since the projected area of the melt droplet in the test-section filled with liquid is significantly smaller than that of the test-section, \( \alpha_M \sim \alpha_{NM} = \alpha, G^0_M \sim G^0_{NM} = G^0 \) and \( \delta_{LM} \sim \delta_L \) will be valid. In addition, since the attenuation of X-ray beam in the very thin vapor film around the melt droplet is negligible, the equations (3.4) and (3.5) become

\[
G_M \approx \alpha M_0 e^{-\mu_M \delta_M - \mu_T \delta_T - \mu_L \delta_L - \mu_V \delta_V} + G^0_M \quad (3.8)
\]

\[
G_{NM} \approx \alpha_{NM} I_0 e^{-\mu_M \delta_M - \mu_T \delta_T - \mu_L \delta_L} + G^0_{NM} \quad (3.9)
\]

Combining equations (6) and (7), the normalized gray level of the image can be expressed in terms of the thickness of the melt droplet as

\[
\Delta G \equiv \frac{G_M - G^0}{G_{NM} - G^0} \approx e^{-\mu_M \delta_M} = \beta e^{-\mu_M \delta_M} \quad (3.10)
\]

Therefore, the thickness of the melt droplet during the vapor explosion process can be quantified after the determination of \( \beta \) in a series of calibration tests by,

\[
\delta_M = -\frac{1}{\mu_M} \ln \left( \frac{\Delta G}{\beta} \right) \quad (3.11)
\]

### 3.2.1. Noise Sources

X-rays interact by elastic (Thompson and Rayleigh), inelastic (Compton) scattering and by photoelectric absorption, the relative amounts of each being material and wavelength dependent. X-rays are also scattered in the surroundings shields. But for the purpose of this work, we will consider the total scattering without discerning between them.
Similarly to Hibiki and Mishima’s work for neutron radiography [6, 7, 8], one can describe the influence of scattering for X-ray radiography as it follows.

The gray levels for the test section with and without the tin phantom are given by equations (3.6) and (3.7). From equation (3.9), one can obtain the thickness of the object considering the scattering:

\[ \delta_M = -\frac{1}{\mu_M} \ln \left( \frac{G_{Mix} - G^0}{G_{NM} - G^0} \right) \]  

(3.12)

And for the thickness without the scattering correction:

\[ \delta_{M}^{NS} = -\frac{1}{\mu_M} \ln \left( \frac{G_{Mix} + G^S}{G_{NM} + G^S} \right) \]  

(3.13)

where, \( G^S = \alpha^S \), \( G_{Mix} = G_{Mix} - G^0 \) and \( G_{NM} = G_{NM} - G^0 \).

Combining the above equations with equation (3.8), we obtain:

\[ \delta_{M}^{NS} = -\frac{1}{\mu_M} \ln \left\{ e^{-\mu_M \delta_M} \left( 1 - \frac{G^S}{G_{NM} + G^S} \right) + \frac{G^S}{G_{NM} + G^S} \right\} \]  

(3.14)

Finally, one can estimate the error if the scattering is neglected by:

\[ E_\delta = \frac{\delta_M - \delta_{M}^{NS}}{\delta_M} \]  

(3.15)

Figure 3.10 shows the error in respect to the tin thickness and scattering ratio, \( \frac{G^S}{G_{NM} + G^S} \), for the current X-ray settings of our system (120kV) for the current arrangement.

For such high energy x-rays, scattering becomes of a great importance and must be taken into account. The scattered photons create a loss of contrast and definition, incurring into large measurement errors.
Figure 3. 10 Error dependent on the tin thickness and scattering ratio.

Experimentally, one can depict such system characteristic by taking and image of a highly attenuating object, i.e. lead, which ideally should provide an optical brightness equal to zero. However, scattering (light, x-ray and electron) results in the radio-opaque object not being completely opaque in the image. This offset can be determined, as shown in Figure 3.11, for subsequent correction.

Figure 3. 11 Lead phantom optical brightness on the transverse direction.
The amount of signal from a CCD detector may vary in a complicated way with the X-ray energy and angle of incidence. But if one concentrates on the noise inherent from the CCD camera, then it should be considered its dark current and background nonuniformity, the later as mentioned earlier for the photographic images.

**Figure 3.12** Background gray level and offset gray level on the longitudinal direction.

The CCD dark current noise consists of two parts, the first one is thermal noise distributing in Poisson stochastic process and forming the background noise; another one presents impulses, called CCD dark current nonuniformity, which is cased by CCD pixel defects. The CCD dark current noise behaves as the one that superimposes into the practical image [9, 10].

In order to analyze the CCD dark current noise, an experiment was made capturing 20 frames with the x-ray off. The average gray levels in a row, transverse direction, shows a quite low fluctuation, around 4.8%, but on the average in a column, longitudinal direction, it rises to around 29%. This characteristic will reflect on the $G^0$ values, Figure 3.12b, which are determined by the scattering and dark current, and background, $G_{nm}$, Figure 3.12a, by superimposition.
3.2.2. Quantification of Image Quality

Geometric unsharpness in the image is caused by the fact that X-rays are emitted from an area rather than from a point. Regions at the edges of an object will be formed in which the x-ray intensity will be gradually increasing (or decreasing) producing a more diffuse edge due to the penumbra.

The size of the X-ray tube focal-spot, \( f \), and the magnification factors, namely the source-to-specimen distance, \( a \), and specimen-to-detector distance, \( b \), that determine its magnitude:

\[
U_g = f\left(\frac{b}{a}\right)
\]

To minimize the penumbra, the test section should be placed as close as possible to the detector and the source placed some distance from the test section. The greater the distance between the source and the test section the more the geometric unsharpness is reduced. However, the intensity of the source decreases as distance increases. Therefore, the source should be placed only as far away as necessary to control the penumbra. Using the equation above, the geometric unsharpness for our system, \( U_g \), is around 0.16 mm in the converter, which corresponds to 0.018mm on the output phosphor screen. Since, this value is lower than the spatial resolution of the output phosphor screen for the current setup of our X-ray system, the geometric unsharpness is negligible.

Using the same methodology described earlier for the photographic images to determine the its quality, the radiographic images, with a spatial resolution of 0.126 mm/pixel, showed a point spread function of approximately 5 pixels. And the noise characteristics, showed in Table 2, indicates that random noises, which are more difficult to remove, are higher in the radiographic images; as a result, even after having achieved an enhanced SNR, further improvement is still desirable. Conversely, variations of the background between frames are minimal, substantiating no build-up of the background intensity due to luminescence decay which could limit the temporal resolution.
3.2.3. Data Extraction of MISTEE Images: Fragmentation Map

3.2.3.1. Image Processing Procedure for Data Extraction

Due to the previously mentioned background nonuniformity, for the purpose of calibration, the background subtraction and offset correction should be performed pixel by pixel and not using an average number.

Since the scattering is also influenced by the size of the object being imaged (large lead piece, large absorption), the lead piece used to determine $G^0$, does not cover the whole window. To apply the equation (8), one has to have a matrix of $G^0$ values of the same size as the image. Because of that, an artificial $G^0$ matrix based on the scattering rate and dark current variation was created by using the gray values on the longitudinal centerline of the lead piece.

No smoothing filter, e.g. median or adaptative, was applied since the exact thickness of each pixel would be smeared during the process.

3.2.3.2. Calibration Assessment

Figure 3.13a shows the brightness distribution of the radiography image of a tin piece, and Figure 3.13b shows the same image after the background and $G^0$ correction. Figure 3.14a and 3.14b show their respective transverse line, where significant improvement on the image contrast and signal-to-noise ratio can be seen.

Nevertheless, there are variations of the tin gray level between pixels of the image, ranging from 2 to 25% depending on the thickness of the phantom. Conversely, the variation of the average gray level between frames is lower than 0.6%, suggesting no buildup of background intensity due to luminescence decay, e.g. afterglow [11], of the output phosphor screen.
Figure 3.13 Tin phantom gray level; (a) before and (b) after image processing.

Figure 3.14 Gray levels of a 0.5mm thick tin phantom on the transverse direction, before (a) and after (b) image processing.

Figure 3.15 is the final calibration curve to convert gray images taken by X-ray radiography to the correspondent thickness of the tin.
The achievable measurement accuracy depends on the statistical error of the x-ray beam $\Delta \varepsilon_{\text{stat}}$, contrast ratio on the fluorescent screen $\Delta \varepsilon_{\text{screen}}$, on the fluctuation of the optical brightness between pixels $\Delta \varepsilon_{\text{pixel}}$, and the deviation between the actual and measured thickness, $\Delta \varepsilon_{\delta}$. The correlation for the total uncertainty $\Delta \varepsilon_{\text{tot}}$ is given by [12]:

$$
(\Delta \varepsilon_{\text{tot}})^2 = (\Delta \varepsilon_{\text{stat}})^2 + (\Delta \varepsilon_{\text{screen}})^2 + (\Delta \varepsilon_{\text{pixel}})^2 + (\Delta \varepsilon_{\delta})^2
$$

(3.15)

The X-ray tube current, $A$, is equal to the number of electrons flowing from the cathode to the anode per unit of time. The exposure of the beam for a given tube voltage (kV) and filtration is proportional to the tube current [13]. Since a constant-potential generator provides nearly constant voltage, the statistical error is then given by [14]:

$$
\Delta \varepsilon_{\text{stat}} = 0.002A + \text{resolution}
$$

(3.16)

where the tube current resolution for our system is 0.05mA.

The image intensifier is commonly used as a converter device. The X-ray beam emerging from the sample first passes through the input window of the tube, which is made of a special low-absorption, low-scatter glass. It is then
absorbed by the input detector screen, where the X-rays photons are converted into light photons.

A photoemissive layer, coupled to the input screen, is excited by these light photons and produces electrons. The electrons are accelerated and focused by appropriate electric fields, and then impinged upon a fluorescent screen (type P20), which converts them into light photons, giving a demagnified high brightness output image.

The contrast ratio is defined as the ratio between the luminescence in the center of the output image if no object is present, and the residual luminescence at the same point if the central zone of the entrance plane is covered with an X-ray opaque lead disk under exactly the same exposure time. This characteristic gives the $\Delta \varepsilon_{\text{screen}}$.

The final $\Delta \varepsilon_{\text{total}}$ will have the following trend:

Figure 3. 16 Total uncertainty of the calibration.

The reason why the error decreases for higher thickness can be explained by the fact that the optical brightness approaches its saturation, represented by the asymptotic part of the calibration curve, giving an almost constant gray level. And for the thinner phantom, scattering and overexposure leads to a larger lost of contrast and consequently larger errors.
As a result, for an accurate quantification and for a larger calibration range, efforts on the minimization of the X-ray scattering are required.

### 3.2.4. Data Extraction of Mistee Images: Droplet Mass Estimation

The initial mass of the molten material is used to calculate its internal energy for the estimation of the conversion ratio for single drop steam explosion.

In some cases, the molten material is delivered resulting in a multiple drop system, which unable the use of the total delivered material mass measured prior to the release. Instinctively, one would consider the radiographic images to estimate the droplet mass, which is the common procedure applied. However, when such information is not available, one has to turn to the photographic images to estimate the initial mass. This procedure is justifiable in the current experiments were the vapor rear is quite negligible.

To estimate the volume of the melt droplet, it was assumed that the distance from the melt droplet surface and the bubble interface at the separation point is negligible. The center of mass, determined by distance transform of the image, is established; \( y \), is then determined by the distance from the center to the lower periphery in order to avoid the influence of the vapor rear; and \( X \), is determined by the distance between the lateral peripheries. The volume is extracted by considering \( X \) and \( 2y \) the axis of an oblate ellipsoid, Fig.3.17, and the droplet mass is then estimated by multiplying the molten material density.

This method showed an error of around 15% when comparing to the measured droplet mass, which is 3 times higher than by estimating it through the radiographic images using the same routine, but reasonable enough to use on the internal energy assessment\(^9\).

\(^9\) Whenever this method for estimating the molten material mass is applied, it will be indicated in the future data analysis.
3.3. Method for Photographic and Radiographic Image Synchronization

The simultaneous high-speed visualization by digital cinematography and x-ray radiography was carried out to identify the interrelated dynamics of vapor bubble and melt fragmentation which is paramount on the understanding of vapor explosion. Accordingly, an image synchronization procedure was developed to depict the phenomenon micro-interactions progression.

To match the images from the two different cameras, with different resolutions, field of view and position relative to the test section, one needs to characterize the spatial resolution, coordinates offset and rescaling factor of the images. This was accomplished by acquiring a simultaneous image of a reference phantom. The images were then optimized and segmented as described previously, the Euclidean distance transform was computed, which is equivalent to the radius of the spherical phantom, to identity the center of mass and spatial resolution. The images are then adjusted in agreement to the difference in resolution and position and matched accordingly; see Figure 3.17.
Figure 3.18 Image processing procedure for the synchronization of the photographic and radiographic images.
References


4. Experimental Results

In this chapter, experimental results of the simultaneous visualization of the bubble and melt dynamics during a vapor explosion are presented. The selected experiments were performed under the same trigger conditions, i.e. ~0.15MPa pressure pulse, and initial melt temperature, 1000°C, but under different water subcoolings, as shown in Table 4.1.

Table 4.1 Tin single drop experimental conditions

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<th>Run ID</th>
<th>T\text{melt}\textsuperscript{10} \degree C</th>
<th>m\text{melt}\textsuperscript{11} g</th>
<th>T\text{water}\textsuperscript{12} \degree C</th>
<th>Visualization</th>
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<td>0.504</td>
<td>54.0</td>
<td>x</td>
</tr>
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<td>0.7384</td>
<td>45.0</td>
<td>x</td>
</tr>
<tr>
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<td>0.6895</td>
<td>52.0</td>
<td>x</td>
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<td>0.7094</td>
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<tr>
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<td>0.7298</td>
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4.1. Bubble Dynamics: Experimental Observations

Still pictures, recorded by the high speed camera, with a temporal resolution of 0.05 ms per frame, are presented in Figure 4.1 to 4.3 revealing the vapor bubble progression during its interaction with a 0.6-0.7 g of molten tin droplet at 1000°C.

The vapor explosion evolution can be depicted into 3 cycles, which represents an initial expansion and the succeeding collapse of the vapor bubble. τ=0 ms is defined as the time when the vapor bubble collapses in the first cycle.

\textsuperscript{10} At the time of release.
\textsuperscript{11} Initial measured Tin mass.
Figure 4.1 Bubble dynamics of a ~0.6 g of Tin at 1000°C in water at 30°C undergoing vapor explosion.

Figure 4.2 Bubble dynamics of a ~0.6 g of tin at 1000°C in water at 73°C undergoing vapor explosion.
A vapor film is immediately formed at the time that the molten tin droplet enters the water and endures as it descends into the water. Figure 4.1 shows a vapor explosion sequence in highly subcooled water. One can directly observe that the vapor film that surrounds the molten droplet is so thin that it can not keep the droplet in a spherical shape as one can observe in Figure 4.2 and 4.3 where the water temperature is higher.

The *first cycle*, 4.1-2 b to f, initiates when the pressure wave produced by the external trigger destabilizes the vapor film, 4.1-2b, initiating the interaction with the melt droplet. Nucleation takes place leading to the first bubble expansion. At 4.1-2d, the overgrown bubble reaches its maximum and it starts to collapse, accelerating towards its center until reaching the hot droplet, 4.1-2f. The direct contact leads to a violent evaporation and second bubble growth, i.e. initiating the *second cycle*. Once more, the overgrown bubble reaches its maximum, 4.1-2h, and collapses into the possible remaining molten material, 4.1-2i leading to the *third cycle* and final bubble collapse.

*Figure 4.3* Bubble dynamics of a ~0.6 g of tin at 1000°C in water at 80°C undergoing vapor explosion.
Figure 4.3 shows the special case when coolant temperature is closer to saturation, specifically 80°C. As described earlier, the vapor film is destabilized initiating the first cycle. During expansion one can notice that the vapor has a smooth characteristic and its asymmetry becomes more obvious. During contraction phase the extremely overgrown bubble collapses, the coolant is accelerated towards the molten droplet reaching a Weber number of proximally 250 upon impact. That is to say that the accelerating interface hits the molten droplet with such kinetic energy, i.e. water hammer, as to hydrodynamically fragment it. The still hot fragments, undergoing film boiling, are then dispersed into the coolant and direct liquid-liquid contact does not occur. The vapor explosion per say is hindered setting an upper limit for the actual experimental conditions.

The photographic images, Fig. 4.1-3, provide the integral vapor dynamics, however having limited information on the structure of the molten droplet and its fragmentation during the vapor explosion process.

### 4.2. Melt Dynamics: Qualitative Fragmentation Map

As established previously in the section 3.2.3., calibration attempts were made for the precise quantification of the transient melt fragmentation [1,2], however for achieving such an objective minimization of the X-ray scattering and optimization of the image quality is thus far required.

Nonetheless, keeping in mind that X-ray radiography gives the projection of the molten droplet, superimposing fragments that are aligned in the X-ray beam direction, a qualitative transient mass distribution, i.e. fragmentation map, can be achieved, granting valuable information on the molten material morphology, which is instructive to the basic understanding of the vapor explosion mechanisms.

Figures 4.4-7 are typical fragmentation maps with a scale from 0 to 100% representing the molten material mass fraction integrated over the incident X-ray beam line. More specifically, 100% represents the thicker part of the molten droplet prior the interaction.
**Figure 4.4** Qualitative fragmentation map of a tin droplet at 1000°C undergoing vapor explosion in water at 45°C.

**Figure 4.5** Qualitative fragmentation map of a tin droplet at 1000°C undergoing vapor explosion in water at 50°C.
Figure 4.6 Qualitative fragmentation map of a tin droplet at 1000°C undergoing vapor explosion in water at 54°C.

Figure 4.7 Qualitative fragmentation map of a tin droplet at 1000°C undergoing vapor explosion in water at 73°C.
The transverse profile history, Fig 4.8, taken from regularly spaced points along a horizontal line segment path defined by the center of the droplet, was also attained as a manner to represent the whole sequence of events.

**Figure 4.8** Profile history of a tin droplet at 1000°C undergoing vapor explosion in water at 37°C. The top-down direction depicts time evolution of melt effective thickness (integrated along the X-ray beam) taken at the droplet centre mass horizontal slice. (a)-(f) correspond to different stages of micro-interactions. (a) droplet falling into the coolant until shock arrival; (b) 1st expansion/droplet deformation/prefragmentation; (c) mixing with coolant; (d) 2nd expansion/fine fragmentation; (e) coolant inflowing, mixing; (f) 3rd expansion/fine fragmentation.

Figure 4.4-7 show the initial elliptical shape of the molten droplet prior the interaction. After external triggering, the first bubble expansion takes place along with the molten droplet deformation as shown in Figure 4.4-7 b.

At this stage, Ciccarelli [3] observed the formation of so-called melt fingers, melt jets, during the first vapor bubble growth and he related these behaviors to local generation of high-pressure vapor at the drop surface. During the bubble collapse, these fingers would be exposed and direct contact with the liquid coolant is re-established, leading to the explosive vaporization. Surprisingly, for the current experimental set up in MISTEE, the same droplet distortion and melt fingering were not observed; on the contrary, the deformation occurs in a quite uniform manner, similar to swelling.
The subsequent vapor bubble collapse leads to the direct contact of the inrushing water mostly on the near surface of the droplet, Fig 4.4-7c, where the explosive vaporization of the entrained coolant fragments the molten material. The fine fragments generated by the stratified explosion on the melt surface are ejected radially, Fig 4.4-7d, whether the inner part appears to be compacted by opposite compression forces due to such discrete vapor expansion. Subsequently, during the second bubble collapse, the coolant is accelerated towards the remaining melt, Fig 4.4-7e, where further mixing takes place, leading to the second explosive evaporation, Fig 4.4-7f, and final melt fine fragmentation.

In Figure 4.9, one can in fact observe the coolant entrainment, Fig. 4.9c, and subsequent violent vaporization, Fig. 4.9d, which leads to the fine fragmentation of the molten droplet. Once again, the remaining melt is responsible for the second interaction, Fig. 4.9e-f.

Figure 4.9 Qualitative fragmentation map of a tin droplet at 1000°C undergoing vapor explosion in water at 37°C

In this respect, it is worth noting that in an early work of Kim & Corradini [4] on droplet explosion, where coolant entrainment mechanism impelled by the growth of Rayleigh–Taylor instabilities during vapor film disturbance were proposed. This mechanism was later disputed as unlikely, when Inoue et. al. [5] analytically showed that the difference of densities was too high rendering a great difficulty for the coolant to entrain in the molten material.
Agreeably, from the images acquired, one may stipulate that the initial disturbances do not lead to a violent interaction, but a “slow” homogenous nucleation, where the molten droplet undergoes deformation/prefragmentation. However, the initial conditions of the subsequent bubble collapse are established, given that, the latter will provide the kinetic energy sufficient to overcome the droplet surface tension, i.e. coolant entrainment.

In order to scrutinize any internal structures of the droplet that might facilitate the water entrainment, close-up X-ray radiographies of a molten droplet undergoing deformation were acquired as shown in Figure 4.10, by using the artifact of magnification given by the distance object-to-converter.

![Figure 4.10](image)

**Figure 4.10** Partial close-up of a molten droplet qualitative fragmentation map of a typical single drop vapor explosion.

One can clearly observe the non-homogeneities on the melt surface, Figure 4.10b, showing density/mass decrease up to 50%, which define the points of coolant entrainment, Figure 4.10c and respective violent evaporation, Figure 4.7d-e.
4.3. Bubble and Melt Interrelated Progression

Scrutinizing the vapor film and molten material dynamics separately provides a solid ground to the interpretation of their interrelated progression depicted by the matched simultaneous X-ray radiographic and photographic images.

Figure 4.11 shows a typical vapor explosion sequence tin droplet, in red, vapor film in white. The whole process takes place in less than 10 ms, and even with some remaining noise, one can clearly identify the convoluting interfaces.

**Figure 4.11** Synchronized X-ray radiography and photographic images of a 0.5g tin drop at 1000°C into water at 73°C undergoing vapor explosion.

Initially, the undisturbed molten droplet with a diameter of 4.8 mm, undergoing stable film boiling, falls freely into the water with a velocity of 0.6 m/s. At t=-3 ms, the system is disturbed by an externally triggered
pressure pulse of 0.15 MPa, as indicated by an arrow in Figure 4.11. Liquid-vapor interface instability, induced by the arrival of the pressure wave, leads to the coolant contact with melt/superheated vapor zone and homogeneous nucleation takes place commencing the first cycle.

During the subsequent bubble growth, $t=-2.75$ to $-1.25$ ms, the molten droplet surface is deformed/pre-fragmented and no apparent fine fragments are observed on the vapor interface, i.e. no major fragmentation. The vapor bubble then reaches its maximum, $t=1.25$ms, and starts collapsing. The coolant is accelerated towards the deformed droplet, initiating the mixing/direct contact, $t=0$ ms, which leads to the second cycle explosive evaporation and fine fragmentation of the droplet. It can be observed that the fine fragments set off in the radial direction following the interface of the growing bubble, $t=0.25$ to 0.75ms. As the vapor bubble decelerates, the inertia of the fine fragments causes them to go through the bubble surface. The latter reaches its critical size, $t=0.75$ms, and the subsequent bubble collapse leaves the fine fragments behind, $t=1$ to 1.5ms, whereas a fraction of them is redistributed into the center of the initial melt location. At this point, the bubble dynamics can not be precisely discerned since the cloud of fine fragments unable the exact resolution of the bubble interface.

Nevertheless, the third cycle can be clearly observed, when the collapsing bubble promotes the mixing of the coolant and the remains of the molten material, $t=1.50$ms, leading to a secondary explosive vaporization. A shell-like region of finely fragmented melt particles is formed just about the water vapor interface during the expansion period, $t=1.75$ to 2.75ms. The fine fragments are then dispersed within the coolant after the bubble has finally collapsed, $t=4.25$ms.
References


5. Data Analysis

The aim of the following investigation is to gain an understanding on the mechanisms that govern the energetics of the vapor explosion by scrutinizing the bubble and melt dynamics during the interaction.

The data analysis is based on the quantitative information acquired from the photographic and radiographic images of the associated micro interactions. The radial progression of the vapor film is the basis for the bubble dynamics assessment, as well as the estimation of the conversion ratio, i.e. the amount of the melt thermal energy converted into the work done by the expanding bubble, which is the main objective of a typical vapor explosion analysis. Following, the melt dynamics will be analyzed regarding its deformation/fragmentation.

5.1. Bubble Dynamics

The radial history of the vapor bubble is represented by the equivalent diameter, $D_{eq}$, estimated by the image projected area, $A_p$:

$$D_{eq} = \sqrt{\frac{4A_p}{\pi}}$$ (5.1)

The normalized equivalent diameter, $D_{eq}$ divided by the equivalent diameter prior to the external shock wave arrival, for different coolant temperatures is shown in Figure 5.1, where one can easily identify the 3 cycles mentioned previously: first, $-4 < t < 0$ ms; second, $0 < t < 1.55$ ms; third, $t > 1.55$ ms.

The work done by the expanding vapor bubble, $PdV$, is calculated by estimating the internal pressure using the classical Rayleigh-Plesset equation\(^{12}\) for bubble dynamics [1]:

---

\(^{12}\) Since the energetic part of the vapour explosion interaction is an inertia driven rapid transient, the mass/heat transfer through the interface was neglected [2,3].
\[
W(t) = 4\pi \rho_l \int_{R_0}^{R} \left[ R^3 \dddot{R} + \frac{3}{2} R^2 \dddot{R}^2 + \frac{2\sigma R}{\rho_l} + 4\mu R \dot{R} \right] dR
\] (5.2)

where \( \rho_l \) stands for density of the liquid; \( R \) for the bubble radius; \( \sigma \) for surface tension; \( \mu \) for viscosity, see appendix A for particulars.

![Figure 5. 1 Radial vapor film history of a single tin drop at 1000°C in different water subcoolings.](image)

The fraction of the melt thermal energy that could be converted into mechanical work done by the expanding bubble, namely conversion ratio, \( \eta \), can be estimated by the ratio of the total energy transfer from the molten droplet to the vapor bubble and the total initial available thermal energy of the droplet:

\[
\eta(t) = \frac{W(t)}{E_{melt}^0}
\] (5.3)

The latter is estimated by the following equation:

\[
E_{melt}^0 = m_{drop} \left[ C_{p,melt} (T_{melt} - T_{coolant}) + h_{fus} \right]
\] (5.4)

where \( m_{drop} \) and \( C_{p,melt} \) is respectively the mass and the specific heat of the molten droplet; and \( h_{fus} \) is the heat of fusion.
Figure 5.2a shows, for different coolant temperatures, the cumulative work done by the expanding bubble and Figure 5.2b the respective cumulative conversion ratio for each cycle.

![Figure 5.2a](image1.png)  
![Figure 5.2b](image2.png)

**Figure 5.2** (a) Cumulative work and (b) Cumulative conversion ratio for different water subcoolings.

The clear dependence of the bubble dynamics, and hence the conversion ratio, on the coolant temperature grants a direct parameter which influences the vapor explosion, thus worth evaluating.
The following considerations will be based on the 1\textsuperscript{st} and 2\textsuperscript{nd} cycles, given that during the 3\textsuperscript{rd} cycle the fine fragments are dispersed in the coolant restricting the accurate resolution of the bubble interface, especially during the collapse phase.

### 5.1.1. 1\textsuperscript{st} Cycle

As mentioned earlier, the first cycle corresponds to the initial liquid-vapor interface instability induced by the imposed external pressure wave, the direct contact heat transfer that generates the first bubble expansion, and the subsequent bubble collapse.

After the melt-coolant contact heat transfer, the coolant boundary layer is heated and expands dramatically due to nucleation generating the first vapor film expansion.

As a thermally driven process, it is understood that the water subcooling will be a factor. One can observe on the photographic images 4.2d, 4.3d and 4.4d that the expanded vapor film in the first cycle has a larger and smoother characteristic for the lower subcooling runs. These features can be rationalized by the very high nucleation rate during spontaneous nucleation, which as a result, as soon as nucleation occurs, no more contact points are activated; and adding to the fact that the lower the subcooling, the easier will be for the coolant to evaporate. In other words, in the case of low subcooling, the vapor film is more stable, leading to fewer contact points, i.e. less ‘nucleation sites’, and in conjunction with a rapid evaporation, a smoother growing vapor film will be then generated.

Accordingly, the quantification of the vapor film dynamics for the first cycle, Fig. 5.3, substantiates the prompt evaporation and larger bubble expansion rate character of the low subcooling runs.
However, being a ‘slow’ process where neither violent interaction nor fine fragmentation of the melt droplet is observed, the resulting work done by the expanding vapor film on the surroundings is minor, thus presenting a small contribution to the overall conversion ratio, Fig. 5.2. Nevertheless, the water subcooling effect on the bubble dynamics is noticeable, Fig. 5.1, and as expected, it shows a direct correlation to the first cycle conversion ratio, Fig. 5.4.

The outward motion of the vapor film continues beyond the equilibrium position. As a result, the vapor film pressure falls below the ambient pressure leading to deceleration of the interface, until a point where the interface outward movement reverses and it starts collapsing. Higher subcooling is expected to facilitate condensation, thus increasing the collapse acceleration.

Figure 5.3 First cycle bubble expansion rate and duration for different water subcoolings.
An interesting disclosure emerges when quantifying the final velocity of the collapsing interface, where low subcooling creates a larger momentum near the impact onto the molten droplet than the anticipated high subcooled runs. This points out to a dominant factor: the preceding vapor film expansion. Low subcooling generates a larger first expansion, Fig. 5.1; accordingly, the collapsing bubble has a longer contraction period, thus reaching larger velocities at the time of impact onto the molten droplet, Fig. 5.5, in a liquid hammering manner. Consequently, the accelerating interface reaches the droplet with a larger kinetic energy which determines the extent of coolant entrainment.

**Figure 5.4** First cycle cumulative conversion ratio for different water subcoolings.
Figure 5.5 First cycle bubble contraction rate for different water subcoolings.

By merely considering this observation, one would expect a larger mixing/entrainment for the lower subcooling case which would result in a more energetic interaction in the subsequent cycle.

5.1.2. 2nd Cycle

The second cycle is characterized by the coolant entrainment into the melt droplet, portraying a new scenario where, instead of having the molten droplet surrounded by the coolant, one now has the inverse situation of coolant droplets surrounded by the hot molten material.

The direct contact coolant-melt dwelling time cannot be precisely determined. Nonetheless, the photographic images indicate a contact period in the order of 200μs (4 frames) which would allow the coolant to be heated far beyond its boiling point, i.e. superheat limit, leading to a so-called homogeneous nucleation regime given the absence of nucleation sites [4].

The flash evaporation of the entrained coolant leads to a large local pressurization, since the constrained superheated vapor cannot expand sufficiently fast. In trying to escape, it breaks through the molten droplet
causing the catastrophic hydrodynamic fragmentation of the host molten
droplet. Accelerated by the internal vapor flow, the fine fragments do not
remain dispersed in the bubble, the larger drag force in water than in vapor
makes the particles to stop and accumulate on the vapor-water interface,
forming a shell of finely fragmented particles, which in turn supplies vapor
to the growing bubble by high heat flow from the fragmented particles to the
liquid\textsuperscript{13}.

The pressure build up and consequent expansion ratio at this stage shows a
strong correlation to the coolant subcooling, Fig. 5.6., where larger rates are
associate to lower subcooling, which leads to higher conversion ratios, Fig
5.7.

Previous works [6,7,8] concluded that higher subcooling should lead to a
more energetic steam explosion and this conception is indeed reinforced by
the analysis of MISTEE experimental data, Fig. 5.2b and 5.7. However,
keeping in mind that the initial conditions of such a violent inertia driven
interaction were established by the thermally driven first cycle; an
inconsistency arises since the so-reinforced energetics trend contradicts the
perceived picture given by the bubble dynamics during the first cycle: low
subcooling would promote a better mixing due to the higher kinetic energy
of the collapsing bubble into the melt droplet. This finding implies that the
bubble dynamics alone can not explain the subcooling effect on vapor
explosion.

\textsuperscript{13} Homogeneous nucleation alone is known to be a 100-200 $\mu$s process [5] where, in the water case, would
lead to a bubble growth rate of approximately 23 m/s\textsuperscript{4}. In the performed single droplet vapor explosion
experiments, the vapor film growth rate reaches its maximum during the same time period; however the
total expansion period is of about 1ms, which points out to a contribution of the fine fragments at the vapor-
coolant interface during bubble growth.
Figure 5.6 Second cycle bubble expansion rate and pressure build up for different water subcoolings.

Figure 5.7 Second cycle maximum instantaneous conversion ratio for different water subcoolings.
5.2. Melt Dynamics

As shown in Figure 5.8, after the external pressure disturbance, the molten droplet successively undergoes deformation/pre-fragmentation during the first cycle. Recalling the relation between the image gray level, $\Delta G$, i.e. intensity, and the density/thickness of the molten material, one can qualitatively represent such a deformation by taking a horizontal line segment, i.e. transverse profile, through the droplet’s center. The red and black lines show the profile ‘thickness’ distribution of the molten droplet prior the interaction and by the end of the first cycle expansion, respectively.\(^{14}\) It is apparent that the droplet is deformed in the radial direction, i.e. enlargement of the projected area, and becomes less compact, analogous to a porous element.

The non-occurrence of a drastic fine fragmentation of the molten droplet and the moderate characteristic of the bubble growth during the first cycle suggest no coolant entrainment during the initial coolant-melt contact. With that in mind, several mechanisms\(^{15}\), or their combination, have been postulated to be responsible for such deformation:

i. Taylor instabilities: When the vapor film is compressed by the passage of the external trigger the vapor pressure and the heat flux from the hot droplet surface to the coolant increase abruptly even though the surfaces are separated by the vapor film. Local high pressure in the vapor film generates high acceleration from the vapor to the fluids, water and melt, which causes instabilities of both interfaces.

ii. Turbulent internal vapor flow [8]: Shortly after the initial contact, the nucleation itself could cause highly turbulent oscillations on the droplet surface.

iii. Acoustic cavitation [9]: rapidly changing pressure at the surface of the molten droplet would produce propagation/reflection of pressure waves within the droplet leading to localized subatmospheric pressures, i.e. cavitation. This phenomenon would

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\(^{14}\) One should keep in mind the that the actual X-ray system can only resolve thicknesses up 2mm, as presented in section 3.2.3.2, which means that one can not resolve accurately the melt thickness in its center since it exceeds this value.

\(^{15}\) These mechanisms were proposed as phenomenological models for droplet break-up during vapor explosion. However, they are here associated to the initial phase where the molten material is deformed/pre-fragmented.
be enhanced in the presence of dissolved gases in the molten droplet.


The deformation/ pre-fragmentation of a molten droplet can be quantified by its average density/thickness and/or by its projected area evolution during the 1st cycle. It can be seen from Figure 5.9 that the droplet deformation/pre-fragmentation decreases with the increase of coolant temperature. Although the exact cause(s) of the melt deformation is not yet known and still purely speculative, the effect of coolant temperature points to a strong relation to the stability of vapor film.

Figure 5.8 Melt deformation/prefragmentation under the first cycle.
The higher the coolant temperature, the thicker and more stable the vapor film is. The energy transfer to the liquid vapor is proportional to the difference between the vapor-liquid interface temperature (saturation) and the bulk coolant temperature. More water is vaporized as the coolant temperature increases, thereby increasing the film thickness. When the external pressure pulse is applied for a low subcooled water case, the vapor film does not condense as much since the energy transferred across the film...
starts vaporizing more liquid. Accordingly, pressure oscillations in the vapor-liquid interface would be damped effectively on a thicker film (such as in low-subcooling case) [12,13,14], hence minimizing local coolant-melt contacts and resulting in a more limited deformation/pre-fragmentation of the molten droplet.

It is logical to suggest that the greater the melt drop’s deformation/prefragmentation the easier it is for the coolant to entrain. That is to say that the pre-fragmented melt drop allows a larger mass of volatile coolant to permeate deeper into the melt interior upon the bubble collapse. The enhanced mixing environment is more favorable to subsequent explosive vaporization, which reflects on the second bubble dynamics cycle and melt material dispersal, namely the energetics. This hypothesis is substantiated by the MISTEE tin-drop explosion data, which exhibits a strong correlation between the droplet deformation/prefragmentation and the second cycle instantaneous and cumulative conversion ratios as respectively shown in Figures 5.10a and b.

Thus, the MISTEE X-ray data on melt dynamics provides resolution to an apparent controversy about the effect of water subcooling on the first-cycle bubble dynamics vs. explosion energetics discussed in Section 4.1. In fact, the MISTEE data shows how the data on bubble dynamics alone could be misleading. Remarkably, most previous models and theories of droplet explosion were derived and validated from images on the bubble dynamics. Simply put, data on evolution of melt material and its relation to bubble dynamics and energetics did not exist prior to the present study. The MISTEE X-ray data of the melt droplet undergoing vapor explosion shown in this paper lead to a discovery of the dominant role of melt dynamics over bubble dynamics in understanding fundamental mechanisms of micro-interactions.

The observations made in MISTEE experiments and the correlation established between the explosion energetics and the droplet deformation provide a basis to suggest that the deformation/prefragmentation of the molten droplet during the first cycle is prerequisite for an energetic vapor explosion in thermal fragmentation regime. We name this mechanism “preconditioning” of melt droplet for explosion.
Implications of the governing role of melt preconditioning on vapor explosion are broad and far-reaching. For instance, one can arguably relate the oxidic corium’s lower explosivity to corium drop being less “preconditioned” to trigger an explosion than a drop of other molten materials used in FCI testing, typically alumina or steel. On the melt-drop side, due to corium’s higher temperatures (compared to alumina and steel),

Figure 5.10 Second cycle (a) maximum instantaneous and (b) cumulative conversion ratio in respect to molten droplet deformation/prefragmentation.
the radiation heat flux is more intense, promoting a rapid surface cooling prior to pressure perturbations. Surface of molten metal (e.g. steel) drops remains in the liquid phase for a longer period (than corium) due to the lower temperature level, lower emisivity and significantly higher thermal conductivity which effectively transfers the heat from the droplet interior toward the surface region. Formation of a thin crust or even a mushy layer on the drop surface would significantly increase the viscosity and effective surface tension, rendering the drop resilience to external forcing, including disturbances due to local melt-coolant contacts. In fact, for non-eutectic materials, it suffices to remove only a fraction of the latent heat of fusion to bring the melt into a mushy state. On the coolant side, the higher radiative heat flux leads to a higher evaporation rate, thicker vapor film and effectively lower subcooling due to energy deposition in water region adjacent to vapor-liquid interface. Correspondingly, a binary non-eutectic oxidic corium melt drop can form a more stable vapor film and a deformation-resistant mushy surface layer in a much shorter time than a droplet of molten alumina, steel or even eutectic corium [15].
References

6. Summary

6.1. Experimental Setup and Image Processing

A single drop vapor explosion experimental facility, named MISTEE, along with a synchronized high speed digital cinematography and x-ray radiography system, named SHARP, was developed to pursue the basic understanding of the phenomena. Jointly, an image processing methodology was established for the image synchronization and for the vapor and molten material dynamics quantification.

Investigations of image quality, for the quantitative measurements evaluation, of the high-speed X-ray radiography and cinematography (SHARP) were performed for the actual setup of the MISTEE facility. It was found that the point spread function FWHM were 3 and 5 pixels for photographic and radiographic images respectively. The noise characteristics were identified from the background mean grey level amplitude and its fluctuations before and after the image processing steps committed to noise reduction. The uniformity within the image background between pixels showed a clear improvement on the signal-to-noise ratio (SNR) for the photographic images, but not so impressive for the x-ray images where the random noises were difficult to remove without degrading the image. Conversely, variations of the background between frames for the x-ray images are negligible, suggesting no build up of background intensity due to luminescence decay, contrary to the photographic images that suffers from the illumination amplitude variation.

Investigations for the evaluation of the quantitative measurements for high-speed x-ray radiography were performed, analytically and experimentally. From the numerical analysis, it was shown that: X-ray scattering generates high measurement errors if not taken into account, and the geometric unsharpness can be neglected, since it is less then the spatial resolution of the output phosphor screen. From the experimental analysis, after a series of image processing steps, a calibration curve was obtained, where variations of the tin phantom gray level between pixels and frames were evaluated, in addition to other fluctuations inherited from the X-ray system. The total
measurement error was then estimated as varying from 6.6% to 26% depending on the thickness of the tin phantom, which points out to the need for the minimization of the X-ray scattering, if a more accurate quantification and a larger calibrated thickness range is to be achieved.

Although an improvement of the image quality and a more advanced image processing technique to reduce the image noise are desirable for an accurate quantification is desirable, the developed visualization system, SHARP, is already capable of delivering valuable information on the physics of the vapor explosion phenomena.

6.2. Vapor Explosion Triggering Phenomenology

The triggering of a vapor explosion was investigated by performing single drop experiments initiated by a very weak external pressure wave, as to promote the destabilization of the vapor film, which is characteristic of such phase.

The qualitative analysis, based on the coordinated radiograph and photographic images, depicted the bubble and molten material interrelated progression granting information on the phenomenological micro-interaction of the vapor explosion process:

![Figure 6.1. Vapor explosion triggering phenomenology.](image-url)
Moreover, translated from the X-ray radiography image intensity, the qualitative two dimensional transient distribution of the fragmented particles and profile history were attained revealing the melt droplet internal dynamics, i.e. deformation/pre-fragmentation and subsequent fine fragmentation.

Based on the attained information, one could describe the triggering of a single drop vapor explosion as follows:

i. the melt droplet, which undergoes stable film boiling, is perturbed by the arrival of the external pressure wave;
ii. the collapse of the vapor film causes the coolant-melt contact and consequent evaporation;
iii. the vapor film expands while the molten droplet undergoes deformation/pre-fragmentation;
iv. when reaching a critical size, the over-expanded vapor bubble starts collapsing. The accelerating vapor-coolant interface hits the deformed droplet in a water hammer manner, causing the coolant to entrain into the pre-fragmented molten droplet;
v. the entrained coolant vaporizes violently fine fragmenting the molten droplet which in turn feeds the expanding vapor.

Coolant encapsulation has been proposed in earlier works; however, no experimental evidences were ever produced to support such theories. Furthermore, although similar to past phenomenological models, the one proposed in this thesis is unique regarding the molten droplet preconditioning, i.e. deformation/pre-fragmentation during the first cycle, and the driving mechanism in which the coolant is encapsulated, i.e. bubble collapse at the end of the first cycle.

### 6.3. Data Analysis

The analysis of data obtained in MISTEE on vapor bubble dynamics shows that, in low subcooling runs, a favorable initial condition for a more energetic interaction (large kinetic energy of the collapsing bubble, i.e. water hammer) is established during the bubble’s 1st cycle – a notion contradicting the results obtained in the bubble’s 2nd cycle and the conventional wisdom where lower conversion ratios are expected in low-subcooling cases. Since the bubble dynamics alone does not explain the subcooling effect on vapor
explosion energetics, detailed analysis of the melt droplet dynamics becomes crucial.

The MISTEE images point to *coolant entrainment* into the droplet surface as the mechanism for direct contact/mixing ultimately responsible for energetic interactions. Furthermore, the data exhibits an inverse correlation between the coolant temperature, which characterizes the dynamics of the first cycle in bubble dynamics, and the molten droplet deformation/pre-fragmentation. The latter named *melt preconditioning* is in turn found to be directly proportional to the vapor explosion conversion ratio.

The newly established insight about the role of melt droplet dynamics paves way to speculation that a mechanistic treatment of the droplet preconditioning can lead to a basic understanding and quantification of how melt physical properties influence steam explosion’s triggerability and energetics.
7. Future Work

There are two main issues that remain to be scrutinized on the path to understand the vapor explosion micro-interactions:

I. The melt physical properties that dictates the molten droplet preconditioning
II. The effect of non condensable gases in the vapor explosion anatomy and energetics.

7.1. Material Property Effect

Single drop experiments using different materials are necessary to establish the property effect related to the melt preconditioning and hence its energetics in a vapor explosion. Therefore, a range of metals, oxides and binary-oxides (eutectic and non-eutectic) will be chosen as to cover different melt physical properties.

Scoping single drop experiments were performed by using MnO-TiO$_2$ (eutheic) at approximately 1500$^\circ$C and water temperature of 22-30$^\circ$C. It was observed, Fig.7.1, that after the imposed pressure wave disturbs the system, it initiates a sequence of vapor film expansion and collapse, which endures until the initial film boiling regime is re-established. As a result, in order to initiate a vapor explosion, one would need to apply a stronger external trigger to effectively destabilize such an established vapor film. Efforts on optimizing the actual external trigger system will be addressed.
Figure 7.1 Scoping single drop experiments with eutectic MnO-TiO$_2$ at 1500°C and water temperature at 22°C

7.2. Non-Condensable Gases Effect

In a realistic severe accident scenario, non-condensable gases will be present and its influence should be assessed.

This issue will be address by selecting Tin single drop experiments where a considerable amount of air is trapped in the vapor film during the droplet entrance in water. The presence of the non-condensable gases will then be translated into the vapor morphology, i.e. aspect ratio.

Scoping experiments show that the presence of non-condensable gases affects directly the bubble dynamics, as can be seen in Figure 7.2 and 7.3. Whether in Figure 7.2 the vapor explosion is hindered by the collapsing rear, in Figure 7.3 it appears that the vapor explosion is enhanced by the rear dynamics.

Quantification of such processes is paramount to attend the effect of non-condensable gases in vapor explosions.
Figure 7.2 Bubble dynamics of a ~0.6 g of tin at 1000°C in water at 42°C with a large rear of entrapped air.
Figure 7.3  Bubble dynamics of a ~0.6 g of tin at 1000°C in water at 45°C with a rear of entrapped air.
Appendix A

A.1. Molten Droplet Temperature

A series of single drop vapor explosion tests were carried out by using 0.6 to 0.7g of tin, initially at 1000°C. The coolant, tap water, temperature was from 30 to 80°C. To determine the molten droplet temperature at the time of interaction, the calculation of how much the drop cools as it falls through the air gap and later to the water depth where it is triggered is required. The heat loss results in a decrease of internal energy of the molten droplet, which has to be estimated for the subsequent vapor explosion energetics calculation.

As the drop free falls, it passes through a 5 cm air gap before reaching the water level. The heat loss is mainly by forced convection and the heat transfer coefficient can be estimated by:

\[ h_{\text{conv}} = \frac{Nu_{\text{c}} \cdot k_{\text{air}}}{d} \]  

(A.1)

where

\[ Nu_{\text{c}} = 2 + 0.6 \text{Re}^{1/2} \cdot \text{Pr}_{\text{air}}^{1/3} \]  

(A.2)

Since the droplet temperature is quite high, 1000°C, radiation will also play a part on the heat loss and its heat transfer coefficient can be estimated by:

\[ h_{\text{rad}} = \varepsilon \sigma \left[ \frac{T_{\text{tin}}^4 - T_{\text{air}}^4}{T_{\text{tin}}^4 - T_{\text{air}}^4} \right] \]  

(A.3)

Following, the total heat transfer will then be:

\[ h_{\text{t,air}} = h_{\text{conv}} + 0.75h_{\text{rad}} \]  

(A.4)
To determine whether the lumped capacitance method can be used, the Biot number is calculated:

\[ Bi = \frac{h_c \cdot d}{k_{tin}} \]  

(A.6)

Accordingly, the lump capacitance method can be used, Biot < 0.1, which means that the temperature is nearly uniform throughout the droplet, and the molten droplet temperature can be estimated as follows:

\[ T_{tin,air} = T_{air} + (T_{tin} - T_{air}) \cdot e^{-\left(\frac{6 \cdot h_c}{\rho_{tin} \cdot d \cdot C_{p,in}} \cdot \tau_{air}\right)} \]  

(A.7)

When the droplet enters the water, film boiling, with its poor heat transfer characteristics, takes place. The falling droplet will lose heat by forced convection film boiling at subcooled conditions and radiation. Based on Liu and Theoanous work on film boiling on spheres in single and two-phase flows [1], the Nusselt number can be defined as:

\[ Nu_{film} = Nu_{sat} + 0.072 \cdot Re^{0.77} \cdot Pr_t^{0.5} \cdot \frac{\mu_l}{\mu_v} \cdot \frac{Sc}{Sp} \]  

(A.8)

\[ Nu_{sat} = 0.5 \cdot Re^{1/2} \cdot \frac{\mu_l}{\mu_v} \left[ \frac{\rho_l \cdot (d / 2)^4}{\rho_v \cdot Sp} \right]^{1/4} \]  

(A.9)

The total heat transfer is then calculated by applying the equation A.1, A.3 and A.4.

To determine whether the lumped capacitance method may also be used for the second step of the cooling process, the Biot number is again calculated and it is found to be well below the critical value. Hence, the final temperature of the molten droplet at the time of interaction, i.e. water depth of 11 cm, is obtained by:

\[ T_{tin,water} = T_v + (T_{tin,air} - T_v) \cdot e^{-\left(\frac{6 \cdot h_{water}}{\rho_{tin} \cdot d \cdot C_{p,water}} \cdot \tau_{water}\right)} \]  

(A.10)

The Figure A.1 shows the molten droplet temperature for different water subcoolings at the time of interaction:
Figure A. 1 Molten droplet temperature at the time of interaction for different water subcoolings.

References

Appendix B

B.1. Energy Conversion Ratio of Single Drop Vapor Explosion

One of the main objectives of the steam explosion studies is to determine what fraction of the total heat content of the melt can be converted into mechanical work done by the expanding vapor, i.e. conversion ratio. Considering the droplet temperature at the time of interaction, one can estimate the total available thermal energy by the following expression:

\[ E_{melt}^0 = m_{melt} \left( c_{p,melt} (T_{melt}^0 - T_{coolant}) + h_{melt, fus} \right) \]  

(B.1)

where \( m, C_p, T \) and \( h \) are mass, heat capacity, temperature and heat of fusion.

The radius history extracted by the photographic images is used to estimate the pressure inside the bubble. Since the initial energy deposited in the vapor bubble occurs in a time that is short relative to the time for the bubble expansion, then a good approximation to the subsequent bubble growth will be given by the classical Rayleigh-Plesset equation for bubble dynamics:

\[ R \dot{R} + \frac{3}{2} R^2 = \frac{1}{\rho_l} \left\{ (P_b - P_{\infty}) - \frac{2\sigma}{R} - \frac{4\mu \dot{R}}{R} \right\} \]  

(B.2)

which is derived from the conservation mass and momentum applied to the surrounding water and does not consider any mass flux across the bubble surface due to evaporation or condensation.

Condensation may play a role in the late stages of the bubble expansion, when the bubble growth slows down and the bubble pressure and temperature drop. However, the most significant amount of the energy is transferred during the bubble collapse on the first cycle where the entrained coolant forms a high pressured vapor. The violent expansion of the vapor, as

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16 For a molten Tin droplet of 0.6g at approximately 990°C (corresponding to the state just before the interaction is initiated), the available thermal energy will be around 200J.
an inertia driven process, justifies the use of equation (2) to estimate the pressure inside the bubble.

The mechanical work, as the pressure-volume integral of the bubble growth, is then calculated in the following manner:

\[
W(t) = 4\pi \rho \int_{R_0}^{R} \left( R^3 \dot{R} + \frac{3}{2} R^2 \ddot{R}^2 + \frac{2\sigma R}{\rho_l} + 4\mu \dot{R} \dot{R} \right) dR
\]  

(B.3)

Since the energy loss to the water through the bubble surface is negligible, all the energy transferred from the drop goes into \( PdV \) type work done by the expanding bubble. Therefore, the conversion ratio is determined by:

\[
\eta(t) = \frac{W(t)}{E_{\text{melt}}}
\]  

(B.4)

**B.2. Rationale for the Conversion Ratio Estimation Method Used for Single Drop Vapor Explosion**

The radial history of an experiment, with 0.6g of molten Tin droplet at an initial temperature of 1000°C and coolant temperature of 73°C, was chosen for the following calculations. The analysis will be based on the first and second cycle, where the bubble interface can be well resolved.\(^{17}\)

**B.2.1. Sensitivity to Data Oscillations**

A smoothing of the radius history, \( R(t) \), was performed by using Savitzky-Golay method (4th order, 12 points), and shown bellow:

\(^{17}\) In the 3\(^{rd}\) cycle, the fine fragments are dispersed in the coolant restricting the accurate resolution of the bubble interface.
Figure B. 1 Original and smoothed radius history.

The oscillations were damped, especially for the calculated pressure inside the bubble, Fig. B.2.

Figure B. 2 Calculated pressure inside the bubble for the original and smoothed radius history.
Nonetheless, when calculating the cumulative work done by the vapor bubble, Fig. B.3, it was found that: for the 1st cycle (-5 to 0 ms) the smoothed experimental data show divergences up to 3% of the original experimental data; and for the 2nd cycle (0 to 1.5 ms) these differences were up to 8%, which will then be reflected on the conversion ratio:

**Figure B. 3** Calculated cumulative work for the original and smoothed experimental data.

**Figure B. 4** Calculated cumulative conversion ratio for the original and smoothed experimental data.
That is to say that the calculated work and conversion ratio are not particularly sensitive to experimental data oscillations.

**B.2.2. Effect of the Ambient Pressure**

After the external trigger pressure pulse passes the molten droplet surrounded by the vapor film, it is reflected to the interaction zone. The ambient pressure varies with time in a complicated way, due to the nature of the trigger and test section set-up. Whether this parameter should be taken into account for the energetics’ calculations, it will be addressed by comparing two cases: considering the ambient pressure as constant, ~0.1MPa, and as varying with time as shown by the pressure transducer\textsuperscript{18}, Fig. B.5. The smoothed pressure signal used for the following calculations, was attained by FFT filtering (3Hz), where high frequency noises were eliminated.

![Original vs Filtered Pressure Signal](image)

**Figure B. 5 Ambient pressure signal**

In Figure B.6, one can observe the influence of the surrounding’s pressure oscillations to the pressure inside the vapor bubble, as indicated (blue circle).

\textsuperscript{18} Data from the pressure transducer provides the dynamic pressure, i.e. the resulting total pressure is given by summing the atmospheric pressure to the dynamic pressure.
However, this divergence tends to minimize towards the energetic interaction (after the bubble collapse, t=0 ms).

**Figure B. 6** Calculated vapor bubble pressure considering a constant and varying ambient pressure.

**Figure B. 7** Calculated cumulative work done by the expanding vapor bubble considering a constant and varying ambient pressure.
The influence of considering the varying ambient pressure is even more smeared when calculating the work done by the expanding bubble, and it can be considered negligible.

**B.2.3. Comparing to Cicarelli’s Work**\(^{19}\)

Ciccarelli [1] developed a model for the bubble dynamics to calculate the work done in the surroundings by the single drop vapor explosion. In his model, the Rayleigh equation for bubble dynamics was used without considering the mass transfer in the interface, ideal gas behavior was assumed and heat transfer from the distorted droplet surface into the bubble was added, and the resulting equation for estimating the pressure inside the vapor bubble is:

\[
\frac{dP}{dt} = \frac{3(\gamma - 1)}{4\pi} (R^3 - R_0^3) Q - \frac{3\gamma P\dot{R}}{(R - R_0)} \tag{B.5}
\]

To reproduce the experimental bubble dynamics, 2J was added before the 2\(^{nd}\) expansion.

When reproducing Ciccarelli’s experimental data, Fig. B.8, and calculating the work done by the expanding vapor bubble using the same routine as the one proposed for MISTEE, Fig. B.9, an interesting finding came to light: the 2\(^{nd}\) expansion gives \(~2J\), corresponding to the same energy that was artificially added to the model to fit the experimental bubble radius history. In short, although using a simplified method to calculate the energetics, the results from both works are similar.

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\(^{19}\) This work was chosen due to the similarities to the actual study.
Figure B. 8 Ciccarelli’s radius history for a 0.5g of Tin at 700°C and water temperature of 65°C.

Figure B. 9 Cumulative work calculated by using the same routine as the one proposed for MISTEE.

The rationale presented in this appendix, gives a strong indication that the method used to estimate the steam explosion energetics can be applied to the analysis of the MISTEE data.
References