IMPACT OF HEATED SOLID SPHERES ON A LIQUID POOL

THESIS SUBMITTED IN PARTIAL FULFILMENTS OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF ENGINEERING IN MECHANICAL ENGINEERING UNDER FACULTY OF ENGINEERING AND TECHNOLOGY

Submitted by
SK HASAN RAJA
Class Roll Number: 002111202020
Registration No.:160286 of 2021-2022
Exam Roll No.: M4MEC23015
Academic Session: 2021-2023

Under the guidance of
Prof. Achintya Mukhopadhyay
Dr. Sourav Sarkar

Department of Mechanical Engineering,
Jadavpur University

Dr. Aranyak Chakravarty
School of Nuclear Studies & Application,
Jadavpur University

DEPARTMENT OF MECHANICAL ENGINEERING
JADAVPUR UNIVERSITY

DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that the thesis entitled "**IMPACT OF HEATED SOLID SPHERE ON A LIQUID POOL**" contains literature survey and original research work by the undersigned candidate, as a part of his *MASTER OF ENGINEERING IN MECHANICAL ENGINEERING under the DEPARTMENT OF MECHANICAL ENGINNERING*, studies during academic session 2021-2023.

All information in this document have been obtained and presented in accordance with the academic rules and ethical conduct.

I also declare that, as required by these rules of conduct, I have fully cited and referenced all the material and results that are not original to this work.

Name: **SK HASAN RAJA**

Class Roll Number: **002111202020**

University Registration No: 160286 of 2021-2022

Examination Roll No: M4MEC23015

Date:

Signature:

FACULTY OF ENGINEERING & TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING
JADAVPUR UNIVERSITY
KOLKATA

CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled " **IMPACT OF HEATED SOLID SPHERE ON A LIQUID POOL**" is a bonafide work carried out by SK HASAN RAJA under our supervision and guidance in partial fulfilment of the requirements for awarding the degree of Master of Engineering in Mechanical Engineering under Department of Mechanical Engineering, Jadavpur University during the academic session 2021-2023.

THESIS SUPERVISOR
Prof. Achintya Mukhopadhyay
Department of Mechanical Engineering
Jadavpur University, Kolkata

THESIS SUPERVISOR
Dr. Aranyak Chakravarty
School of Nuclear Studies and Application
Jadavpur University, Kolkata

THESIS SUPERVISOR
Dr. Sourav Sarkar
Department of Mechanical Engineering
Jadavpur University, Kolkata

Prof. Amit Karmakar
Head of the Deparment
Department of Mechanical Engineering
Jadavpur University, Kolkata

Prof. Ardhendu Ghosal
Dean
Faculty Council of Engineering & Technology
Jadavpur University, Kolkata

FACULTY OF ENGINEERING & TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
JADAVPUR UNIVERSITY
KOLKATA-700032

CERTIFICATE OF APPROVAL

The foregoing thesis, entitled "**IMPACT OF HEATED SOLID SPHERE ON A LIQUID POOL**" is hereby approved as a creditable study in the area of Automobile Engineering carried out and presented by SK HASAN RAJA in a satisfactory manner to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

Committee of final evaluation of thesis:

Signature of Examiners

ACKNOWLEDGEMENT

I would like to record here my gratitude to all who supported me and gave constructive suggestions during the completion of this paper.

Separately, I express my deepest gratitude to **Prof. Achintya Mukhopadhyay**, Department of Mechanical Engineering and co-supervisor **Dr. Aranyak Chakravarty,** School of Nuclear Studies and Application and **Dr. Sourav Sarkar**, Department of Mechanical Engineering, for their invaluable guidance. The regular discussions and idea-sharing with my thesis supervisors really helped me to improve my knowledge day by day my research related problems. At the beginning of this work, they gave me the valuable instruction that properly guided me in right path to accomplish this paper. It was really a pleasure work under their supervision.

I sincerely believe that I was fortunate enough to have come across **Prof. Achintya Mukhopadhyay**, who can inspire someone to work wonders. It would really have been not possible for me to complete this thesis without his assistance, proper guidance and motivation. He always helped me during the critical phase of this thesis and was always available for me for any query, whether it's a telephonic or a face to face discussion. Above all he enhanced my confidence and guided me throughout my work.

I firmly believe that I was fortunate to have met **Dr. Aranyak Chakravarty**, School of Nuclear Studies and Application, who has the ability to motivate people to do great things. Without his aid, the right direction, and the determination to finish this thesis, it would not have been feasible for me to do so. He always supported me as I worked through the revision process for this thesis and was always there to answer any questions I had, whether they were best answered over the phone or in person. Above all, he boosted my confidence and helped me get the job done.

I truly think it was a stroke of luck that I met **Dr. Sourav Sarkar**, Department of Mechanical Engineering, who has the ability to motivate others to achieve great things. Without his help, the right direction, and the inspiration he provided, I definitely would not have been able to finish this thesis. He always supported me as I worked through the key stage of my thesis and was always accessible to answer any questions I had, whether they required a phone call or a face-to-face meeting. Above all, he boosted my confidence and assisted me while I worked.

I also tender my sincere gratitude to **Mr. Sudipta Saha,** PhD scholar, whose continuous guidance helped me a lot in carrying out a major portion of my work. Without his wise and valuable advices, it would not be possible to prepare such a thesis.

I would like to thank **Mr. Saumendra Nath Mishra**, PhD scholar, for giving me valuable suggestions and the instant ideas which played an important part to process the thesis.

I also like to thank **Mr. Ajit Das**, Department of automobile engineering, for implying his knowledge in the experimental work and his assistance in all over the work.

I would like to thank **Mr. Joy Mandal** and **Mr. Manish Kumar Manna**, PhD scholar, Department of Mechanical Engineering, for their instant help and providing ideas.

I am highly indebted to all my professors of **NEPTUNE** lab, their guidance and supervision as well as for providing necessary information regarding thesis and also for their support in completing my master's thesis.

I would like to thank all the working personnel of HYDRAULICS and HEAT POWER lab for allowing me to carry out the experiments and for giving access of the necessary equipments.

I would like to express my gratitude towards my parents and my younger brother for their kind cooperation and encouragement which helped me in the completion of my master's thesis.

Finally, my thanks and appreciations also go to my dear friends in developing my master's project and people who have willingly helped me out with their abilities.

SK HASAN RAJA

M.E ("Mechanical Engineering")

2nd Year, Final Semester

Department of Mechanical Engineering

Jadavpur University, Kolkata

TABLE OF CONTENTS

NOMENCLATURE

A : Area (m^2)

C : Specific heat capacity of sphere material (J/kgK)

D_0 : Diameter of the steel sphere (m)

Fr : Froude number

g : Gravitational acceleration (m/s^2)

H : Drop height of the sphere above water surface (m)

h_{fg} : Latent heat of evaporation of water (J/kg)

h : Convective heat transfer coefficient of air (J/m^2K)

Ja : Jakob Number

$\overline{Nu}_D$: Nusselt number over diameter

Pr : Prandlt Number

R_0 : Radius of the sphere (m)

Ra_D : Rayleigh number over diameter

T : Temperature (K)

ΔT_{sat} : Superheat (K)

t : Time (s)

t^* : Non-dimensional pinch-off time

V_o : Impact Velocity of the sphere on water surface (m/s)

Z : Pinch-off depth

Z^* : Non-dimensional pinch-off depth

α : Thermal diffusivity (m^2/s)

β : Thermal expansion coefficient (K^{-1})

ρ_s : Density of sphere material (kg/m^3)

ρ_w : Density of water (kg/m^3)

ν : Kinematic viscosity (m^2/s)

List of Figures

List of Tables

Chapter 1

INTRODUCTION

The study of cavity formation during impact of hot solid sphere (steel) is important in various engineering applications. Lots of researches are done in this field or similar fields. In many technical applications, the interaction between high-temperature solids and liquid media is a topic of great interest. Having a better understanding of the intricate phenomena that arise during these interactions can lead to better designs, safety precautions, and performance improvements. The impact of a hot solid sphere (steel) inside a liquid (water) pool is one such fascinating event. The goal of this experimental investigation is to examine and evaluate the impact dynamics, heat transfer, and subsequent hydrodynamic consequences of a hot solid sphere (steel) submerged in a liquid (water) pool.

The interaction of a hot solid sphere with liquid is encountered in numerous industrial processes, such as steel manufacturing, metal casting, and energy production. During these processes, molten or high-temperature steel is often transferred to water pools for cooling, solidification, or quenching purposes. The impact of the hot steel sphere onto the water surface triggers a series of complex physical phenomena, including heat transfer, fluid flow, and energy dissipation, which influence the overall cooling efficiency and material properties.

Gaining a thorough understanding of the impact dynamics and subsequent heat transfer mechanisms involved when a hot steel sphere enters a water pool is the main goal of this study. By analysing the intricate interactions between the solid projectile and the liquid medium, we hope to pinpoint the essential variables and conditions that control the heat transfer procedure and the water pool's subsequent hydrodynamic reaction.

The experimental approach used in this study will help to accomplish these objectives. The design and deployment of a controlled setup that enables the monitoring of some parameters during the impact event will be part of experimental investigations. A high-speed camera is utilised to record the dynamics, thermocouples are used to monitor the sphere's temperature at the furnace exit, and a mathematical formula is employed to determine the impact temperature of the sphere.

At early stages the formation of splashes due to the impact of solid are studied [1]. Then to measure impact force some experiments are done [2]. Then to capture and visualize the very quick phenomena high-speed cameras are used to capture and for further investigation using image of every instants [3, 4, 5]. Different shapes of objects are used to study the nature of the cavity formed. Object shapes like cylinder [3], disc [6].

When a liquid droplet is placed on a heated surface that is much hotter than the liquid's boiling point, the droplet becomes extraordinarily mobile due to a vapour cushion, which makes the droplet appear to "levitate" above the solid surface. The entire rebound of liquid drops that are impacting can also result from this heat-induced non-wetting impact [7]. The Leidenfrost effect is the name given to these phenomena. According to a recent study by [8], the drag force acting on a sphere descending through a liquid can be decreased by up to 85% when it is heated to a temperature over the Leidenfrost temperature of the liquid and then released below the free surface. Meyer conducted experiments with a collective mass of tiny, heated spheres striking a water body. The spheres struck the free surface as a cylindrical jet, but they dispersed at the bottom of the resulting air cavity.

The purposes of these studies are mainly for underwater machinery, ship machinery, turbines, naval application, military applications and many others. Another important part is the heat transfer part which is most important for the molten fuel coolant interaction in nuclear power plants, which can cause an accident scenario.

In this thesis, the cavity formation process during the impact of hot steel spheres into water is investigated using experimental techniques. Cavity formation due to impact of a heated object into a liquid depends on the total energy contained in the heated object. The energy is either in form of kinetic energy or heat energy or may be combination of both kinetic and heat energy. Three types of cavities can be seen due to this phenomenon – (a) open cavity, the opening of the cavity is opened in atmosphere, (b) sealed cavity below liquid surface, the opening of the cavity is sealed below the top surface of the liquid and (c) sealed cavity above the liquid surface, the opening of the cavity is sealed but above the top surface of the liquid and outer liquid surface of the sealed part is in contact with the atmosphere. The temperature from which film boiling starts is called the Leidenfrost temperature. Inverse Leidenfrost effect on the sphere happens due the continuous cooling inside the water pool. When the sphere is heated above the Leidenfrost point and then dropped into water pool, first film boiling occurs and after a certain time of nucleate boiling starts. The total impact, cavity formation and cavity pinch-off phenomena are shown in Fig. 1 below.

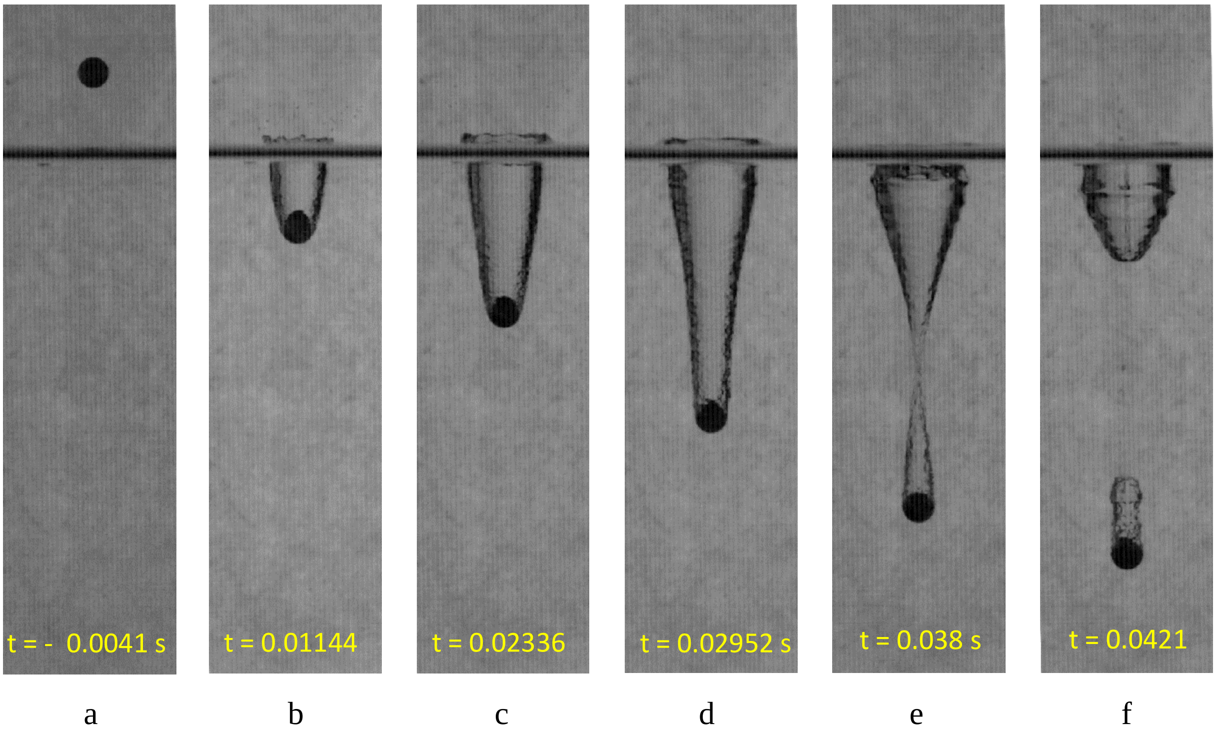


Fig 1: The total phenomenon (impact, cavity formation and pinch-off) taken at ***Fr*** = 164.64 and at ***Ja*** = 0.3701228783. The time of impact is considered as t = 0 s.

The major processes occurring during this phenomenon are discussed as follows -

a. Impact of steel sphere into water

When a steel sphere at normal temperature strikes the surface of water the kinetic energy of the sphere is partially transferred to water and it overcomes the surface tension of water and travels through it. It experiences the gravity force and the buoyancy of by the liquid. But when the sphere is heated the energy is in form of kinetic as well as heat. So the total energy transferred is more compare to cold one so, it is easier to overcome the surface tension of water for hot sphere than the cold sphere.

b. Cavity formation

If the impacting object is able to penetrate water or any liquid by overcoming the surface force of the liquid, the object can create cavity. As the object has some impact velocity, it first deform the surface so some amount of air gets into the deformed part due to vacuum pressure. This triggers the formation of cavity.

c. Cavity pinch-off

The term "pinch-off" in fluid dynamics describes phenomena where a fluid-filled cavity or bubble separates from a continuous flow or a parent cavity. It happens when the cavity's neck gets so small that fluid can no longer pass through it, causing the cavity to split into two separate entities. Pinch-off often happens when a fluid is stretched or lengthened, which causes a cavity or bubble to form. This may occur in a variety of situations, including the disintegration of liquid jets, the creation of droplets, and the pinch-off of bubbles in multiphase flows.

Fluid dynamics play a complex role in the pinch-off process, balancing viscous forces, surface tension, and inertial effects, among other factors. The neck of the hollow gets thinner as the fluid is stretched until it reaches a critical point where surface tension forces take control and cause the pinch-off to happen. The precise geometry and dynamics of the pinch-off depend on a number of variables, including the flow rate, fluid characteristics, and system architecture.

In fluid dynamics research, pinch-off events are frequently investigated experimentally and computationally because they are essential for comprehending phenomena including droplet formation, bubble dynamics, and the behaviour of liquid jets. These techniques have uses in a variety of industries, including micro fluidics, inkjet printing, biomedical engineering, and industrial operations.

d. Cavity pinch-off depth

At a certain depth from the surface of water the cavity breaks due to the hydrostatic pressure of the water, that depth is called the pinch-off depth.

e. Cavity pinch-off time

The time required of the cavity pinch-off or cavity break up after impact of the object to the surface is the pinch-off time.

f. Boiling

The boiling part is introduced to the impact phenomena when the dropped sphere is heated much above the boiling temperature of water. Film boiling, also known as the Leidenfrost effect, occurs when a liquid comes into contact with a surface significantly hotter than its boiling point, creating a vapour layer that insulates the liquid from direct contact with the hot surface. This phenomenon can be observed in various situations, including the impact of a hot sphere in a water pool. When a heated sphere is dropped into a pool of cooler water, the instantaneous contact between the hot sphere's surface and the water prompts fast vaporisation of the water close to the sphere's surface. The sphere is surrounded by a layer of this vapour, preventing any more direct contact between it and the liquid. As an insulator, the vapour layer slows the heat transfer from the sphere to the water.

The water vapour layer may thicken while the heated sphere keeps heating it, creating a stable film boiling regime. In this regime, there is little to no direct contact between the sphere and the liquid water; it appears to hover or float on the vapour layer. The vapour layer lessens the liquid's cooling impact, which enables the sphere to maintain a reasonably high temperature. The initial temperature difference between the sphere and the water, the size and shape of the sphere, and the characteristics of the liquid are only a few of the variables that affect how stable the film boiling regime is. The film boiling regime can continue if the heat transfer from the sphere to the Vapour layer is greater than the heat transfer from the Vapour layer to the surrounding liquid.

However, if the heat transfer from the sphere decreases or the vapour layer becomes unstable, the film boiling regime may transition to a more violent form of boiling known as nucleate boiling. In nucleate boiling, small bubbles form directly on the hot surface of the sphere, causing rapid Vaporization and potentially leading to a more vigorous interaction between the sphere and the water. This happens when the sphere further stays inside the water pool.

Chapter 2

LITERATURE REVIEW

The impact of a hot solid sphere into a water pool creates such beautiful phenomena. Splash and cavity formation are the most interesting part for the research purpose. There are lots of researches done on this field.

The first experiment was conducted by Worthington and Cole [1]. They captured images of the splashes produced by impact of: (i) liquid drop to solid surface; (ii) Liquid drop to liquid surface and (iii) Solid sphere to liquid surface, using a Leyden-jar that generates spark for photography.

Richardson [2] performed experimental study on the impact of a solid sphere on liquid to study (i) form and splash of cavity and (ii) to measure the force of impact. The major applications of the experiments are in navy, aeronautics and military, landing of seaplanes, sphereistic projectile impact into water

To investigate the creation and collapse of transitory cavities at high Reynolds numbers and high Weber numbers, Duclaux et al. [3] conducted a number of experiments. To accomplish their goals, they used cylinders and spheres. They recorded the entire experimental phenomenon with a high-speed video camera.

Li et al. [4] created an experimental facility for molten fuel coolant interactions (MFCI). A high-speed camera is used to record the path of a molten metal droplet as it descends into coolant and produces transient moving velocity-time curves for the droplets. The impact of the droplets' starting temperature and the coolant temperature on their mobility in coolants is the focus of the study. And they find that the velocity with which the droplets are falling increases with the increase of initial droplet temperature as well as the coolant temperature.

According to research by Truscott and Techet [5], relative surface velocity can have dynamic effects that are similar to those of static surface conditions. When cavity-forming spheres rotate transversely, a wedge-shaped region of fluid forms across the cavity from the side with the lowest relative velocity to the side with the highest relative velocity, essentially dividing the cavity into two halves. When the critical relative velocity is surpassed on just one side of the sphere, the wedge formation and asymmetric cavity can occur for both hydrophobic and hydrophilic spheres. Furthermore, by coating the spheres with a hydrophobic and hydrophilic coating alternately, similar effects can be reproduced without rotating the spheres. This straightforward yet elegant discovery has applicability to numerous naval hydrodynamics issues, and it should be taken into account whenever cavity shape or trajectory play a significant role in engineering applications.

In their study, Bergmann et al. [6] looked into the purely gravitationally caused collapse of a surface cavity produced by the carefully timed collision of a disc with water. They discover excellent agreement for the dynamics of the interface and the flow surrounding the cavity between measurements and boundary integral simulations.

During the experimental study Biance et al. [7] found that two regimes at different Weber numbers when a low viscous liquid drop impacts a hot solid surface. One is at low high impact velocity which is low elastic and another is at low impact velocity which is quasi-static.

According to a recent study by Vakarelski et al. [8], when a sphere is heated to a temperature beyond the Leidenfrost temperature of the liquid and then released below the free surface, the drag force acting on it as it descends through a liquid can be reduced by up to 85%. A vapour layer of the liquid coolant surrounds the sphere when it is heated above the liquid's film boiling point, maintaining the non-contact situation between the sphere and liquid. The liquid layer lessens skin friction and drag force.

The pressure decrease before to surface closure is an order of magnitude more than was previously believed, according to the results of Abelson's [9] experimental investigation. The pressure drop in the cavity dropped along with the entry angle (from the horizontal), at first very slowly and later more quickly. The cavity pressure, for instance, was approximately the same for vertical and 60° entries but significantly different for 45° entries. Over the range of velocities examined, it was discovered that the minimum cavity pressure decreased linearly with increasing entry speed. The minimal entry velocity necessary to cause a drop in cavity pressure grew when the entry angle was reduced. When genuine cavity volume rather than outline volume was taken into account, the pressure-volume correlation was improved.

The emergence of hydrodynamic voids behind a number of axisymmetric head forms was observed by Brennen [10]. The transition of the interfacial or separated boundary layer on the cavity surface was one of the phenomena examined. Using high-speed photography, the initial stage of this process, the spatial expansion of instability waves, could be identified. An investigation of theoretical instability is used for comparison.

In order to calculate the drag coefficient and heat transfer coefficient, Zvirin et al. [11] carried out an experimental investigation. The spheres were made of copper coated by thin nickel layer, heated by electrical glo-heater above the film boiling temperature of water and dropped it into a water tank. The water temperature was measured by a copper TC. To track the temperature of the sphere chromel-alumel TC was mounted at the centre of the sphere. The boiling nature of the sphere's surface was investigated too. They discover that the switch to nucleate boiling takes place when the initial spherical temperature is above 450^{o}C and the film collapses.

A technique for simulating cavity formation and collapse brought about by the high-speed impact and penetration of a hard projectile into water was presented by Lee et al [12]. According to the method, high-speed water entry is distinguished by a cavity that closes deeply before closing at the surface. Recent high-speed water-entry experimental data, findings from computational studies utilising a hydro code, and knowledge of the underlying physics of the mechanisms governing surface closure all point to this order in the physical events of the generated cavity dynamics. The analytical model gives precise estimates for variables that are crucial in characterising the cavity dynamics and sheds light on magnitudes and trends. It specifies that the energy transfer for cavity production is equivalent to the energy lost by velocity-dependent drag on the projectile. For a given projectile size, it is discovered that, while the position of deep closure has a modest dependence on impact velocity, the time of deep closure is largely constant and independent of impact velocity. The analytical answers are confirmed by comparing these results with experimental results from the literature and with results from numerical simulations.

When investigating the cavity ripples experimentally, a rapidly moving solid item entering the free surface of a liquid (water or ethanol) caused a well-defined rippling of the air cavity, which was experimentally observed by Grumstrup et al. [13]. They noticed that the rippling began simultaneously with the acoustic emission, right after the pinch-off (deep seal) of the cavity. The Minnaert frequency for bubble volume oscillations roughly matches to this acoustic resonance. We provide an irrotational model that describes the ripples as the surface of the moving object's surface spatially rectifying these volume oscillations.

Aristoff and Bush [14] reported the findings of an inquiry that used experimental and theoretical data to examine how hydrophobic spheres often interact with water surfaces at low Bond numbers. Characterising the design of the resulting air cavity in the low Bond is given special consideration. Numerical limit, when surface tension dominates over gravity as the primary force driving cavity collapse. They provided a theoretical model that describes how the splash curtain evolves when it forms at a high Weber number and connect it to the underlying cavity dynamics.

Gekle at al. [15] have demonstrated that the dynamics of the cavity are strongly and persistently affected by the capillary waves produced when a submerged object passes the water surface. Right up until the very last moment of the cavity collapse, its influence can still be seen appearing in distinctly different closure depth regimes as a function of sinking velocity.

A drop of water will bounce off a superhydrophobic solid surface like an elastic sphere when it encounters it. Lee and Kim [16]. demonstrated in their study that a tiny super hydophobic solid sphere can bounce off the free surface when it contacts with water in the same way that it does when it impacts with an elastic membrane. Through the analytical solution of a potential flow whose free boundary is established by the Young-Laplace equation, they were able to compute the motion of a sinking sphere. They created simple scaling laws that are shown to agree well with experimentally discovered boundaries between the various impact behaviours in a regime map based on dimensionless parameters (Weber number, Bond number, and density ratio). The goal was to determine the conditions under which the solid sphere should sink, bounce off, or oscillate upon impact with water.

Marston et al. [17] reported their experimental observations of cavity creation and eventual collapse when a heated sphere collides with a liquid pool. They notice an inverted Leidenfrost effect, where the sphere is encircled by a vapour layer that precludes direct contact with the liquid, when the sphere temperature is significantly higher than the boiling point of the liquid. This results in exceptionally smooth hollow walls and the best non-wetting situation possible for sphere penetration through a free surface. But occasionally, at initial entry, the liquid makes contact with the sphere at the equator, resulting in the construction of a dual cavity structure. They described the specifics of the contact line pinning, which initially takes the form of a sawtooth pattern, for cold spherical impacts where a contact line is visible. On the cavity interface for cold spheres, they have also seen surface waves. They compared their experimental findings to earlier research on cavity dynamics, focusing on how hydrophobicity affected the sphere's entry.

Gekle et al. [18] have carefully examined the mechanism underlying the development of fast Worthington jets following the impact of solid objects on a liquid surface. They demonstrated that the thin layer straddling the surface of the impact cavity is where the liquid that forms the jet begins. However, their most important discovery is the crucial significance of the radial energy concentrating throughout the whole wall of this cavity.

In their experimental investigation on the entry of a spinning sphere into water, Truscott and Techet [19], found that a higher spinning rate causes a more curved trajectory path of the sphere inside water, but that as the mass increases, the influence of spinning becomes less significant. Froude number has a greater impact on pinch-off than spin. Overall, the introduction of spin results in a unique modification rather than destruction of the essential properties of water entry. Splash crown and subsurface air cavity do form and collapse in stages that are identical, but in the presence of spin, a new fluid wedge forms that can split the cavity in half.

The dynamics of the air cavity produced by a three-dimensional body's vertical water entrance was studied theoretically, computationally, and empirically by Yan et al. [20]. Inertia and gravity effects are relevant for relatively low Froude numbers, where this research focuses on how the air cavity behind the item forms and changes. The outcomes of emphasise how crucial air cavity dynamics are for bluff body water penetration. Before and after the cavity is closed, the body behaves very differently, and the cavity closure parameters have a considerable impact on this. Particularly in the low Froude number regime, the total cavity height and the depth of cavity closure both rise linearly with the Froude number regardless of body form. This research offers the groundwork for comprehending more complex geometries in more broad water impact/entry problems, such as animal sprinting on water surface and ship bow collision.

In an experimental study, Kubota and Mochizuki [21] looked at how the geometry of a solid body's head affected the creation of splashes. A hemisphere, cone, and circular cylinder were the three head forms that were put to the test. All three head shapes have a hemisphere as their tail shape. Using a high-speed CMOS camera, they acquired pictures of the splash formation. They discovered that following occurrences are influenced by a film flow created early on when a body contacts the water's surface up until the splash sequence is finished. Utilising the momentum conservation concept, they provided an explanation for the development of the film flow. The main splash, known as the film flow, is caused by water that the head has displaced. The separation of the film flow and secondary splash are both influenced by the meridian line that runs from the head to the tail of the body. The form of the head also affects the air cavity created as the body submerges into the water. The air cavity, which has been severed from the body, reacts to create the tertiary splash. They discovered that the tertiary splash's expansion is restricted by the secondary dome type splash. Therefore, they draw the conclusion that the head shape influences all splash events.

High-speed video was utilised in an experimental investigation by Shepard et al. [22] to analyse the impact velocity and sphere density impacts on the forces acting on a sphere during the initial impact, cavity creation, and cavity pinch-off phases of water entry. According to experimental findings, decreasing impact velocity causes average force coefficients to increase. Increasing impact velocity or sphere density, on the other hand, causes lower force coefficients, albeit it is demonstrated that this trend flattens out over time. The sort of cavity that forms has an impact on the net hydrodynamic force, according to a comparison of impact forces for spheres with comparable densities and impact velocities. It has been demonstrated that deep-sealed cavities receive less force upon water ingress than quasi-static seal cavities.

The study by Schwalbach et al. [23] examined the effects of surface coating, spherical density, impact velocity, cavity development, and after-impact acceleration. The range of the experiments included a ten-fold variation in sphere density and a nearly three-fold variation in sphere velocity. The cavity pinch-off depth and pinch-off time rise with increasing impact velocity and decrease with decreasing sphere density. It has been demonstrated that increasing spherical density while maintaining a constant impact velocity causes the cavity pinch-off depth and time to rise. The pinch-off depth/Weber number association was found to hold for both deep-seal and quasi-static cavities when the cavity behaviour was recast in dimensionless formats using a Weber number that included the sphere density. Further research revealed that regardless of how spheres were treated with a hydrophobic coating for the conditions investigated, there was a striking resemblance in the behaviour of the pinch-off time with Weber number (based on liquid density). All sphere mass ratio values and all impact velocities were covered by the similar behaviours. All impact velocities and sphere mass ratios were then used to categorise the deceleration behaviours. All of the investigated cases shared a lot in common.

Using a combination of experiments, simulations, and theoretical analysis, Ding et al. [24] explored the cavity creation after the impact of spheres and cylinders into a liquid pool with a focus on contact-line pinning and its relationship with subsequent cavity evolution. A Navier-Stokes diffuse interface solution that supports shifting contact lines simulates the flows. By altering the position and slope of the interface connecting the pinned meniscus to the interface region of radial expansion, the local flow near the pinned contact-line was discovered to have an impact on the global cavity dynamics. The radial growth of the cavity following the pinning of the contact-line was successfully modelled theoretically using the Rayleigh-Besant issue. It was discovered that the evolution of perturbations on a hollow jet and the vertical propagation of ripples on the cavity wall had a similar dispersion relation.

The disc, with a shape that takes advantage of the geometric effects from every angle, requires the slowest impact velocity among all the blunt objects taken into consideration. This is because the disk's shape exploits the geometric effects from every angle and can cause forced flow separation and an effective contact-angle hysteresis at the edges. As a result, a streamlined object finds it more difficult to create an air cavity than an irregular object.

Super hydrophobic paint was created by Hwang et al. [25] and its potential for aquatic use was identified. Testing for buoyancy demonstrated that the super hydrophobic coating's reduction of surface energy makes it possible for glass to be supported by the surface tension of water, and testing for sailing demonstrated that the low surface energy decreased water molecules' adhesion to the surface of the boat, reducing the water drag force. Additionally, it is challenging to apply traditional super hydrophobic coating techniques for use in the real world on curved vehicles with a huge surface area, such as chemical vapour deposition, plasma etching, and sol-gel process. However, the robust super hydrophobic surface can be simply constructed since the paint is integrated with the adhesive, and the super hydrophobic paint that we have developed can be easily applied to surfaces via painting and spraying regardless of the size and structure of the aquatic vehicle.

Kim et al.[26] used high-speed visualisation and real-time analysis by recording audio of the experiment to examine the hydrodynamics of the water entrance problem using aluminium spheres that varied in surface wettability. According to the wettability of the surface and the impact velocity of the sphere, they saw three different forms of water entry: no cavity, air entrainment, and substantial cavity creation. The interval between cavity development and no cavity formation was thought to include the air entrainment type of water entry event, which often occurs at hydrophobic conditions. They observed that the climbing up velocity reduces with increasing hydrophobicity by direct measurement of the climbing up velocity. They concluded that significant acoustic pressure waves might be produced by air entrainment (or cavity creation) during the submersion of hydrophobic spheres.

In their research Raja Sekar et al.[27] used the impact and penetration of a solid sphere into the water as well as its effect on the solid sphere's deceleration into water to illustrate the evolution of air entrained cavity and its closing. Designing underwater machinery, cluster bombs, submarines, and torpedoes requires an understanding of the physics of water entering solid things. The drag experienced by the solid sphere is mostly caused by pinning of the liquid front at the three-phase contact point; however, pinning of the three-phase contact line in the micro-asperities of the rough surface results in an air cavity in the majority of the liquid. At the same time, the pinning effect is minuscule when the solid sphere has smooth solid surfaces and no air cavity is formed. Behind the rough solid surfaces where they enter the water, a hollow cavity has developed. Additionally, the rough sphere's velocity within the water column is increased by the larger air cavity associated with the pinning effect at the three phase contact line. The small layer of air that separates the water from the solid surface and causes less drag is primarily responsible for the rough sphere's rise in speed.

The above researches were done for the cavity nature and to study the cavity dynamics for the impact mainly, so in this study we consider impact phenomena and as well as the boiling phenomena for the cavity formation.

2.1 RESEARCH GAP

Various researches are done on solid (both cold and heated) impact into liquid previously but no such experimental of numerical investigation was done previously finding the combined effect of ***Fr*** and ***Ja*** on such impact phenomena and pinch-off parameters.

2.2 OBJECTIVE

We performed experiments to address the impact dynamics of a hot solid sphere (steel) on a liquid (water) pool. The cavity formation due to such an impact is studied both experimentally and analytically.

In this study we experimentally captured the formation and pinch-off dynamics of the cavity formed due to high impact speed of the hot solid sphere and analysed the heat transfer characteristics.

This study aims to unravel the effects of Froude number and Jakob number on the pinch-off parameters like pinch-off depth and pinch-off time. Subsequently, this can be used to study the regimes of cavity formation.

To study the cooling nature of the hot sphere some experimental investigation are done.

Chapter 3

METHODOLOGY

This section includes details of the set up and the instruments and accessories used for the experiment. This also includes the procedure of the experiment in detail.

3.1 Set-up for experimental study

The aim this study is to study the formation of cavity due the impact of heated metal sphere into a coolant. The velocity is controlled by changing the drop height of the sphere above the surface of the liquid coolant. The phenomenon is captured by a high speed camera. During the experiment the steel sphere temperature is maintained some amount above the impact temperature as there is a time gap between when the sphere is taken out from furnace to when it contacts the coolant during impact. The camera is operated by photron fast cam viewer software.

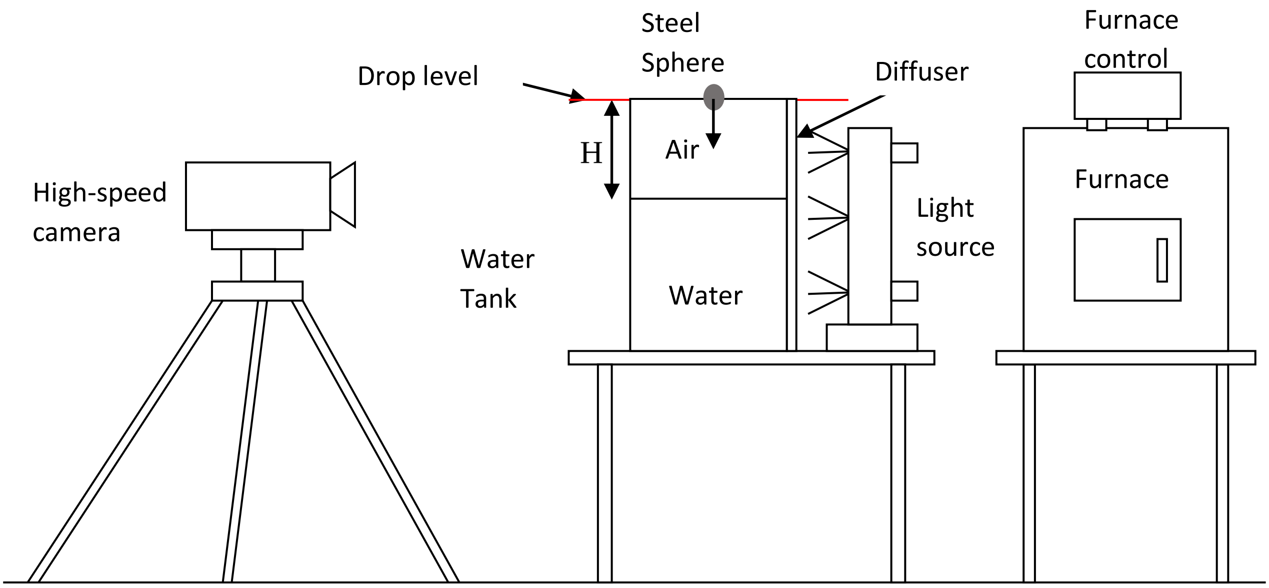


Fig 2: Schematic of the experimental set up

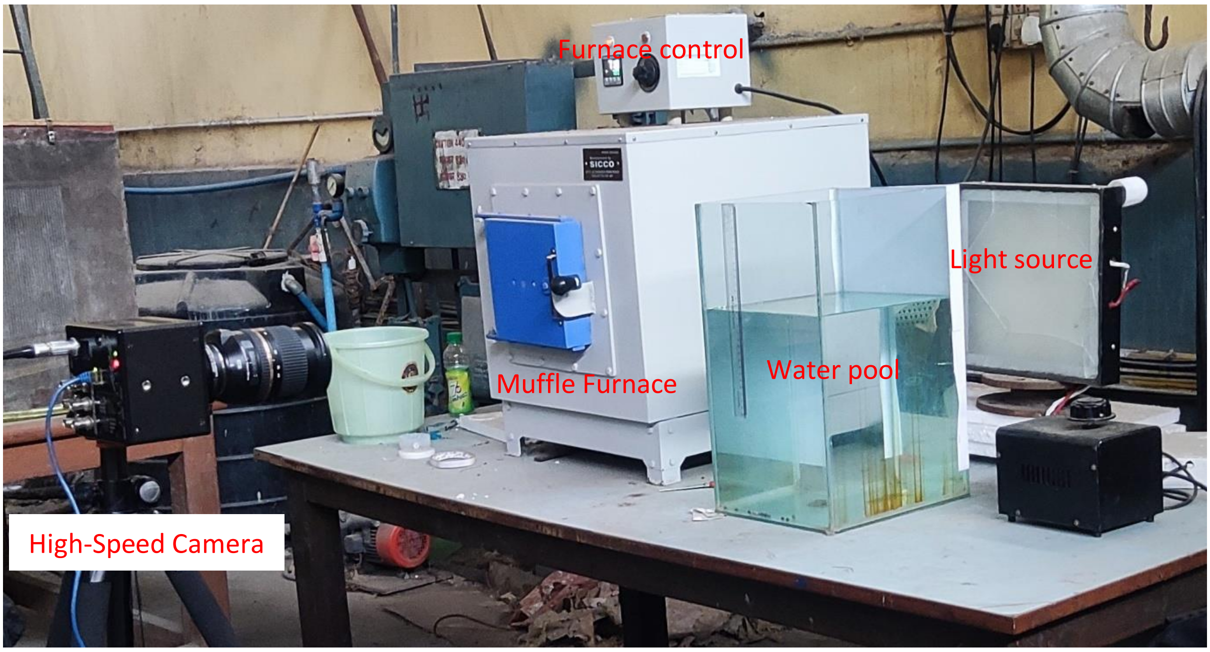


Fig 3: The experimental setup used in this present study

3.2. Description of the experimental apparatus

The sphere used for the experiment is made of high carbon steel. The diameter of the sphere is 6.35 mm and for every experiment the diameters of the used spheres were same. The density of the sphere material is ρ_s= 8450 kg.m^{-3}. The specific heat capacity of the sphere material C_p= 420 kJ/kgK.

Deionised water is used as coolant in this experiment. The density of water is taken ρ_w= 1000 kg.m^{-3}. Boiling temperature of water at the ambient conditions is taken 100^{o}C. The latent heat for Vaporization of water h_{fg} is taken 540 kJ/kg.

The tank/container used in this experiment is made of glass with dimension of 0.24m length, 0.28m width and 0.46m height. As the tank has enough width, height and length so, the wall effects can be neglected.

The furnace used for heating the spheres is electrically operated muffle furnace. A muffle furnace is a kind of furnace or oven used in scientific settings for high-temperature tasks like sample preparation, heat treatment, and material testing. With temperatures typically ranging from several hundred °C up to about 1200 °C or greater, it is intended to create regulated heating settings. A muffle, which is a distinct chamber or compartment within the furnace, is its primary characteristic. The muffle is used to confine the sample or the substance being heated and is often composed of refractory materials like metal or ceramic. The muffle's job is to shield the sample from direct contact with the heating components so that heating is more evenly distributed and contamination is reduced. Applications for muffle furnaces in science and industry include materials research, metallography, ashing, ceramics, and medicines. To enable precise and repeatable heating cycles, they frequently come with precise temperature controls, timers, and programmable features. In this study it is used to provide heat to the spheres.

The temperature of the furnace can be set using a digital display controller. The steels spheres are taken into a porcelain pot and then put inside the muffle furnace. The temperature of the sphere taken at a range from 200ºC to 700ºC with an interval of 50ºC. Electrical heater is placed inside the furnace and further the sphere is heated by radiation.

The *Photron FASTCAM Mini UX100* high-speed camera is used to record the event of impact, cavity formation and pinch-off phenomena. The camera can capture in a maximum frame rate of 2 lakh fps. Tamron SP 24-70mm F/2.8 Di VC USD model:A007N 70 mm lens is used and the video was captured at 12500 fps and at a resolution of 1280 x 240.The video is taken using a software named Photron FASTCAM viewer (PFV).

The light source used in this experiment is LED light with regulatable intensity. A variac is to regulate the intensity and a device is fitted to transform the AC current to DC current.

3.3. Procedure

The steels spheres are taken into a porcelain pot and then put inside the muffle furnace .The spheres are heated from 200º C to 700º C with a interval of 50º C. Taking the delay time (furnace out to drop into water pool time) the furnace exit temperatures are calculated for each set temperatures. Changing the water level inside the tank drop velocity is varied and it is calculated using the relation $V_0 = \sqrt{2gH}$, where H is the drop height above the water surface. The height is varied from 5 cm to 26 cm (5 cm ≤ H ≤ 26 cm). The drop location is maintained at a fixed position but the drop height is changed by changing the height of water by pouring water into the tank.

The impact, cavity formation due to impact and the cavity collapse or pinch-off phenomena is captured using high-speed camera, which is operated by PFV software at 12500 fps frame rate. The video is then converted into images using a MATLAB code of image processing.

Then from the image the pinch-off depth, cavity length, velocity of the sphere tip can be calculated. From the images the instabilities, cavity deformation, cavity ripples and also the cavity nature can be studied.

The experiments are conducted by controlling some parameters like the temperature of the sphere and the effective impact velocity of the sphere, which is changed by changing the height of release of the sphere above the water surface. Combination of some temperature and height are taken for the experiment that is given in a table below and the non-dimensional number combinations are given also.

Table 1: The table below contains combination of temperature (corresponding ***Ja***) and height of drop (corresponding ***Fr***) for the experimental study

Sl. No.	**Sphere temperature (^oC)**	***Ja***	**Drop height above water surface (cm)**	***Fr***
1	200	0.185061339		
2	250	0.2776		
3	300	0.370122878		
4	350	0.462653348		
5	400	0.555184		
6	450	0.647714687	5 – 26	32.1 – 164.46
7	500	0.740245357		
8	550	0.832776026		
9	600	0.9253067		
10	650	1.017837365		
11	700	1.110368485		

Chapter 4

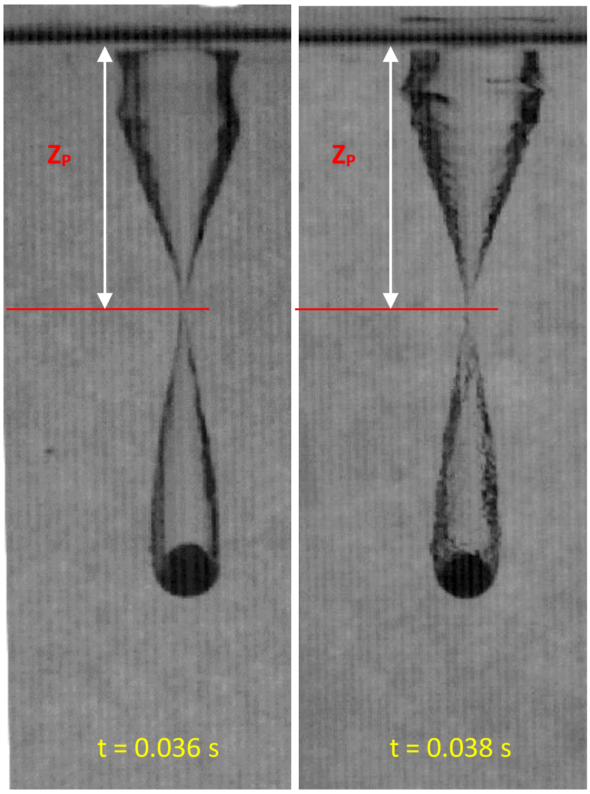
RESULTS AND DISCUSSION

The experimental results reveal that the cavity formation process is highly dependent on the impact velocity of the solid sphere, steel sphere temperature and temperature of the water in the pool. Depending on these parameters the size and shape of the cavities also varies. The cavity formation phenomena have two stages - in the first stage the cavity grows continuously and in the second stage the cavity collapses into two cavities. The experiment and analysis are carried out to study the effects of some non dimensional numbers ***Fr*** and ***Ja*** on the pinch-off phenomena. For a single ***Fr*** the experiment is repeated for different temperatures (***Ja***). It is observed that for a particular ***Fr*** in a particular range of ***Ja*** cavity is formed and the pinch-off is taking place. When the hot steel sphere comes contact with the water due to high velocity it overcomes the cohesive force of the water molecule and creates the cavity. After a certain value of ***Ja*** cavity formation stops and behalf of cavity formation nucleate boiling is observed surrounding the steel sphere. When the ΔT_{sat} is in the nucleate boiling regime only nucleate boiling is observed. Further increase of ΔT_{sat} when the temperature of the steel sphere is much above the Leidenfrost temperature of the water a vapour film is generated surrounding the lower hemispherical part of the steel sphere. That vapour layer keeps the steel sphere surface no wetted but after certain time the vapour bubble condenses and the sphere surface comes directly contact with the water. This follows the inverse Leidenfrost effect. When the sphere is moving inside water there is a relative velocity between the sphere and the water inside the pool. So Kelvin-Helmholtz instability is observed this is an important reason for the pinch off of the cavity. Also, when the sphere moves with extending the cavity air and vapour entrapped inside the cavity so low pressure is formed. Pressure outside the cavity wall is high because of the water and the effective pressure acts at a point called centre of pressure and so the cavity pinches-off at the centre of pressure of the cavity.

4.1 Analysis of cavity formation and collapsion process

When a hot steel sphere is dropped into a water pool due to impact and sudden temperature change variety of phenomena can be observed. Cavity formation is most important among them .The process is analysed in some stages.

The depth from the free surface of the water at which the cavity formed due to impact of hot solid steel sphere is collapsed and breaks into two cavities (dual cavity) is called the pinch-off depth and the time needed for the pinch-off of the cavity after impact is called the pinch-off time. The pinch-off depth (Z_P) is shown in Fig 4.

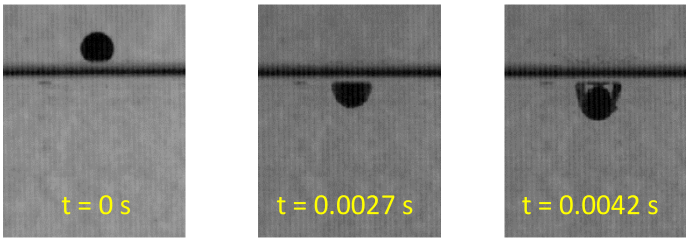


a b

Fig 4: Cavity pinch-off depth(Z_P)

4.1.1. Initial contact of hot steel sphere and water

When a hot steel sphere comes in contact with water due to high temperature difference some amount of water get converted into vapour (when superheat is more enough). And this vapour layer keeps the sphere surface dry and creates a hydrophobic scenario. Fig 5 shows the initial contact.



a b c

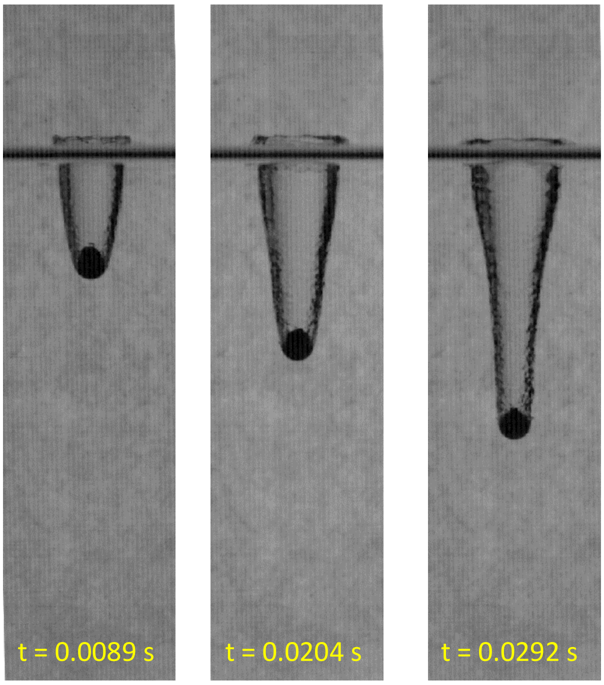
Fig.5: Initial contact of hot steel sphere into water (taken at ***Fr*** = 126 and ***Ja*** = 0.2776).

4.1.2. Vapour bubble formation

As the sphere has velocity downward at the same time it feels the pressure of the water (mainly buoyancy) the thin vapour layer gets compressed between sphere surface and water and collapses. This causes formation of bubble, which further may grow due to the heat flux released from the sphere.

4.1.3 Cavity formation

As the sphere has high velocity and also heated, it breaks the surface tension of the water and get into the liquid. For this air is entrapped (some vapour also) from the opening and a cavity forms. The cavity is formed not for every superheat. For a certain range of superheat there is no formation of cavity. The cavity formation shown in Fig 6 below.

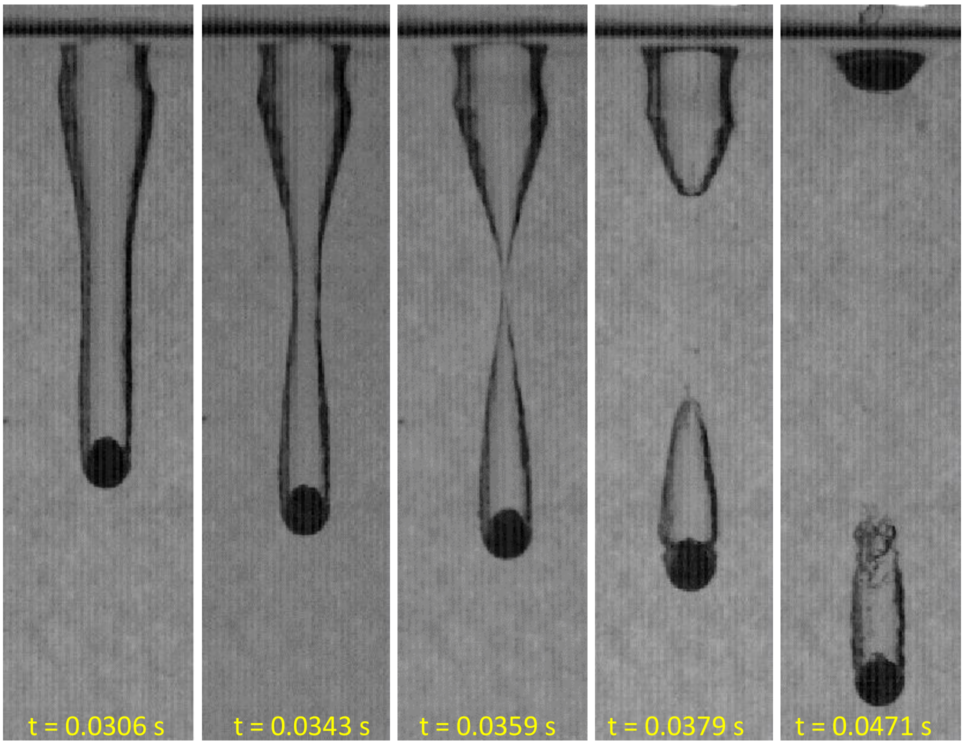


a b c

Fig 6: Cavity formation (taken at ***Fr*** = 126 and ***Ja*** = 0.2776)

4.1.4. Cavity collapse

As the sphere enters with some velocity and air gets entrapped the pressure inside the cavity is much less than the pressure outside the cavity because of water outside. So water pushes the cavity inward and as a result the cavity pinches off. Due to collapse of the cavity a shock wave is formed creating instability at the newly formed dual cavity. And so the tail part of the mother cavity attached with the sphere further breaks into smaller cavities. If the cavity contains some amount of vapour then its volume observed to be shrinking. The phenomena are shown in Fig 7.

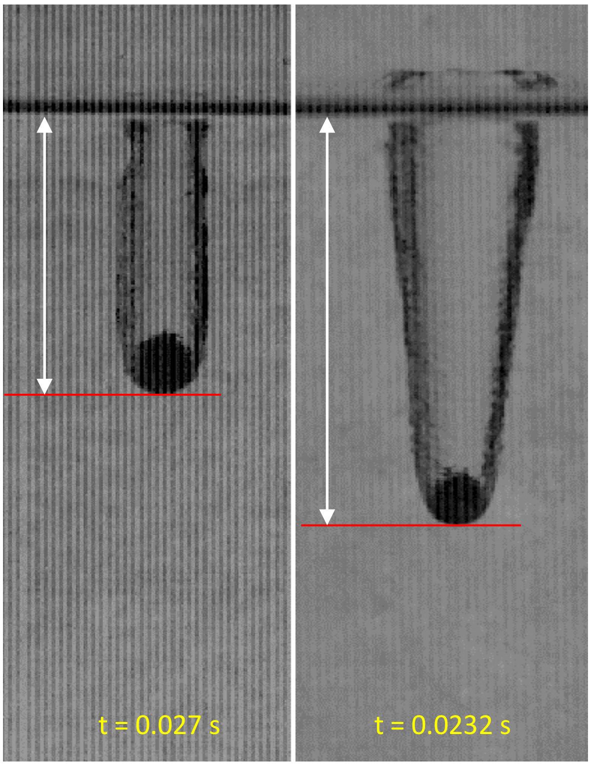


a b c d e

Fig 7: Cavity collapse (taken at ***Fr*** = 126 and ***Ja*** = 0.2776)

4.2 Effects of impact velocity on cavity formation

Impact velocity of hot steel sphere into water have a great role on cavity formation. Normally, for greater impact velocity large cavity is formed due to high energy involved in the impact. The effects can be analysed in such ways. Higher impact velocity can create shock waves, which can damage the structure of the cavity. Fig 8 shows the effect of impact velocity on cavity formation.



a b

Fig 8: Effect of impact velocity on cavity formation.

The figures above are taken at ***Ja*** = 0.37 and images are captured just before deformation of the cavity. In Fig a the impact velocity of the sphere was 1 m/s (***Fr*** = 32.1061) and Fig b impact velocity of the sphere was 2.263 m/s (***Fr*** = 164.46)

4.2.1. Cavity shape and size

When the impact velocity is very high it creates turbulence inside the water due to higher impact energy (heat + kinetic). This causes deformation of the cavity and collapse of cavity in such way which can't be predicted. Fig 9 shows the cavity shape and size change with chance of impact velocity.

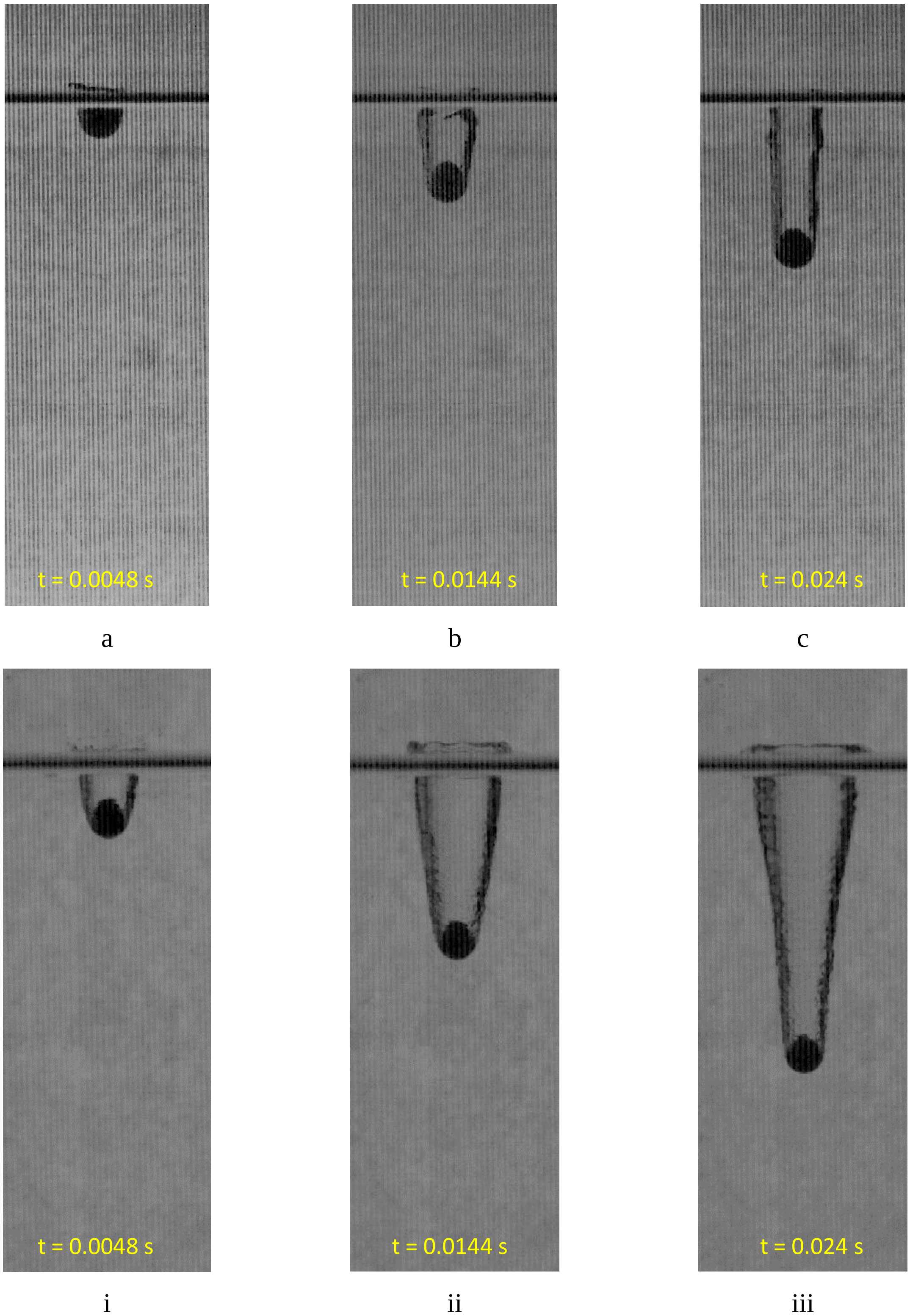


Fig 9: Effect of impact velocity on cavity shape and size (taken at ***Ja*** = 0.2776)
a, b, c are taken for ***Fr*** = 32.1016 and i, ii, iii are for ***Fr*** = 164.49

4.2.2. Energy transfer

The impact velocity of the hot sphere may affect the amount of energy transfer to the water during the impact. This can be important applications where the energy transfer is such an important factor, like underwater machinery. For a particular temperature if a liquid with higher surface tension is used then to break the surface tension higher velocity of the sphere should be required.

4.2.3 Effects of $\boldsymbol{Fr}$ on pinch-off time

The Froude number is a dimensionless parameter that is used to describe how fluid flows behave, particularly in regard to gravity's effects. It can be summed up as the proportion of gravitational forces to inertial forces operating on a fluid element. The Froude number is one of many variables that affect the pinch-off time of a cavity created by the impact of a hot steel sphere. The nature of the flow and the particular circumstances of the experiment or system under study determine the precise impact of the Froude number on the pinch-off time.

High Froude number**:** When the Froude number is large, gravitational forces are subordinated in favour of inertial forces. The hot steel sphere's interaction with the fluid's surface in this instance will result in more energising and vigorous flow patterns. The pinch-off period might be substantially shorter, and the resulting cavity creation could happen quickly.

Low Froude number**:** In contrast, a low Froude number indicates that gravitational forces are more powerful than inertial forces. In such cases, gravity exerts a stronger gravitational pull on the flow, and the hot steel sphere's impact may result in less frantic and slower flow patterns. This could result in a longer pinch-off time and a longer cavity creation process.

The non dimensional pinch-off time is expressed as $t^* = \ t \times \frac{V_0}{D_0}$.

The variation of non dimensional pinch-off time with $\boldsymbol{Fr}$ at different $\boldsymbol{Ja}$ is shown in Fig 10 below. Here the pinch-off time at the middle for each $\boldsymbol{Ja}$ is taken zero as there is no cavity formation.

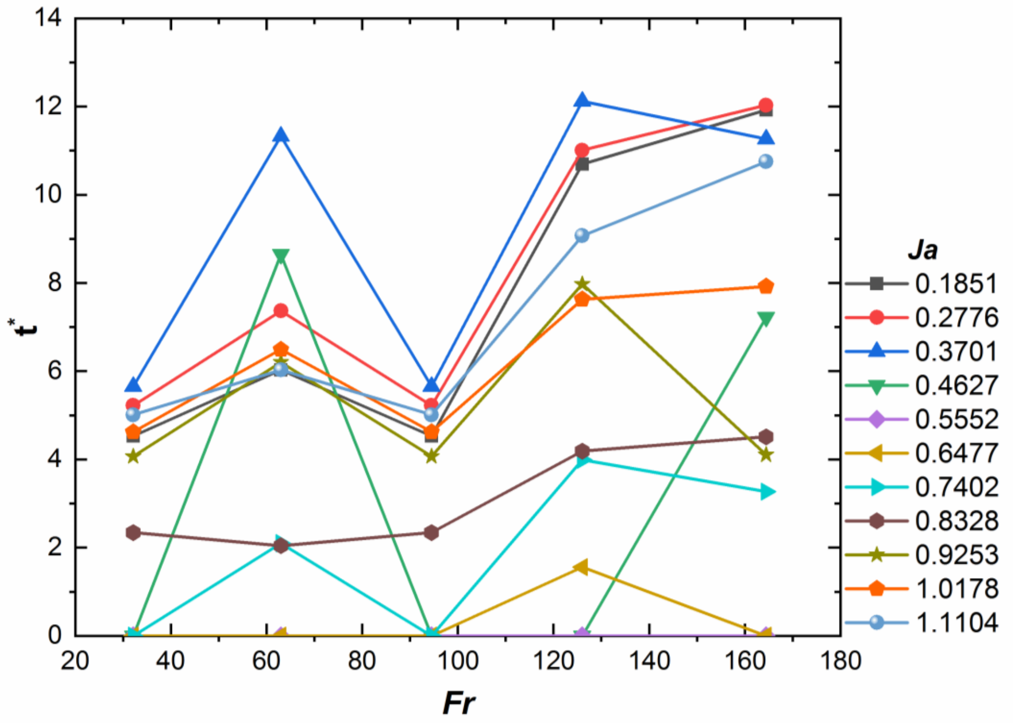


Fig 10: Effects of ***Fr*** on non dimensional pinch-off time

4.2.4 Effects of ***Fr*** on pinch-off depth

Fr is expressed as $= V_0/gR_0$, in this experiment all the steel spheres are of same R_0 so, by changing the V_0 ***Fr*** is changes and the V_0 is changed by changing the H. In this experiment it is observed that at different ***Ja*** the effect of ***Fr*** on the pinch-off depth is different like at ***Ja*** = 0.2776 the pinch-off depth increases as the ***Fr*** increases but for ***Ja*** = 0.3701228783 first pinch-off depth decreases with increase of ***Fr*** then increases then again slight decrease. But for higher ***Ja*** like ***Ja*** = 0.8327760262, with the increase of ***Fr*** the pinch-off depth first increases then decreases the again increases. The non dimensional pinch-off depth is expressed as $Z^* = \frac{Z}{D_0}$.

The comparison is shown by a graph in Fig 11.

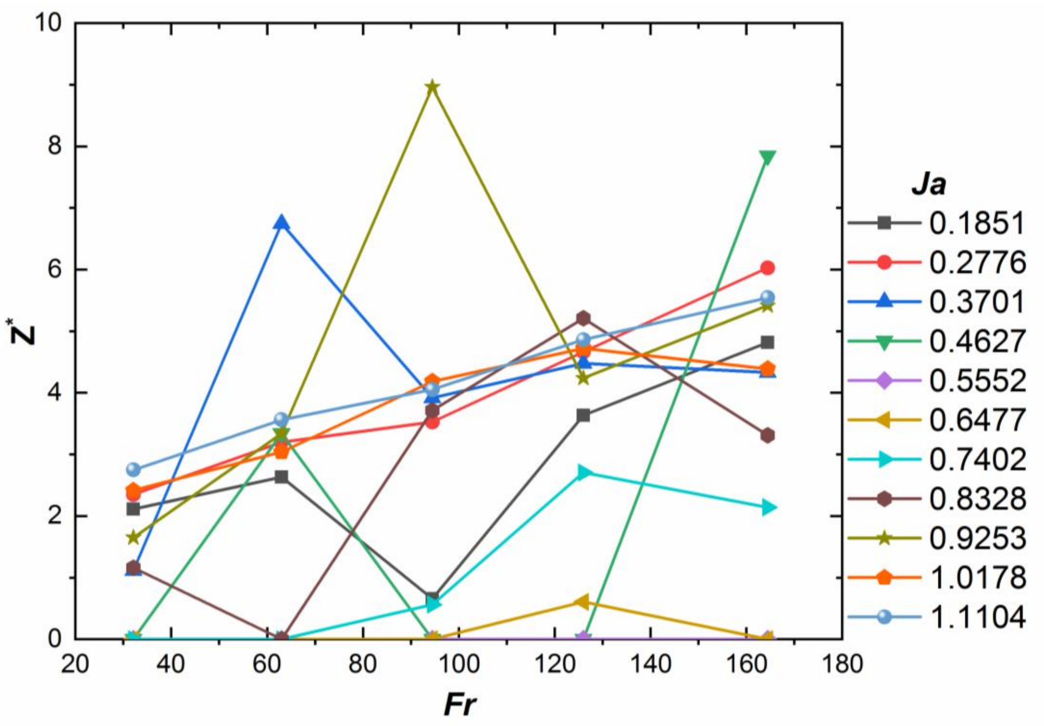


Fig 11: Effects of ***Fr*** on non dimensional pinch-off depth

4.3 Effects of steel sphere temperature on cavity formation

The temperature of the hot steel sphere is an important factor having enough effect on cavity formation during water entry of the sphere. When a hot steel sphere impacts a water pool, the temperature of the sphere can have several effects on the formation of cavities inside the water. The key factor is the temperature differential between the hot steel sphere and the water. Higher the steel sphere temperature formation of vapour is high and that leads to more intense cavity formation.

4.3.1. Vapour layer formation

When hot steel sphere dropped into water it creates a vapour layer surrounding the sphere. If the sphere temperature is much higher, the vapour layer thickness also gets high due to formation of more vapour. It can affect the initial impact velocity.

4.3.2 Cooling effect

Heat is transferred from a heated steel sphere into a pool of water when it comes into contact with the water. The steel sphere cools down quickly as a result of this heat transfer, and the water nearby becomes hotter as a result. Compared to the situation of a significantly hotter sphere, the cooling action can lessen the level of cavitations formation.

4.3.3. Formation of bubble

Due to the heat transfer from the sphere to the water bubbles are formed at the surface of the sphere. More the temperature of the sphere leads more formation of the Vapour bubble. There are three types of bubbles can be formed, 1.Air bubble; 2.Air-Vapour bubble and 3.Vapour bubble.

1.As the sphere enters into water with velocity so some amount of air entrapped with the sphere and forms air cavity and further it breaks up into small bubbles and comes up to the surface due to buoyancy.

2. When a heated sphere (above boiling temperature of water) impacts water some amount of air gets entrapped and some amount of water gets Vaporized due to heat transfer and the Vapour air mixture forms cavity. Further the cavity collapses and forms bubbles of air and Vapour mixture.

3. Sometimes the sphere is heated at a certain range of temperature in which when it impacts water it doesn't create any air entrapment but nucleate boiling and bubble formation is observed at the surface of the sphere. These bubbles are Vapour bubbles.

4.3.4. Cavity shape and size

The effect of the temperature of the impacting steel sphere is very important in the present study. The initial water temperature is maintained at room temperature, as the sphere temperature is higher the heat flux from the sphere surface to the water is higher due to high temperature difference between the sphere and the water. Higher temperature of the sphere creates more turbulence in the water. So at high temperature of the sphere the cavity may have more irregular shape. All figures (Fig 12) are images taken at a drop height of 15 cm but Fig a, b, c shows the size and shape of cavity at 300^{o}C but Fig i, ii, iii shows the shape and size of cavity at 550^{o}C.

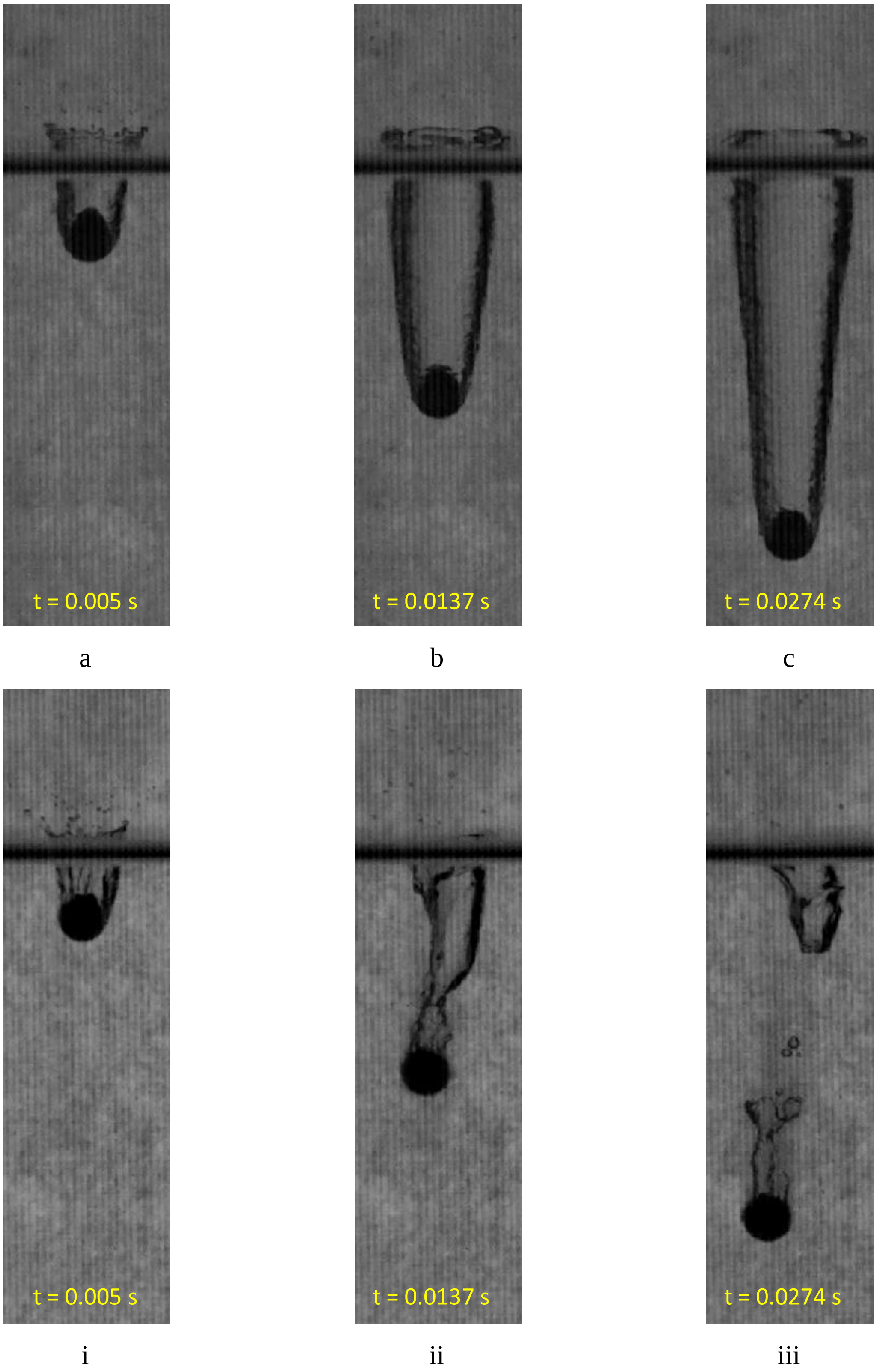


Fig 12: Effect of steel sphere temperature on cavity shape and size

4.3.5. Surface effects:

The temperature of the steel sphere can also affect the surface tension and wettability of the sphere's material. These surface properties can influence the behaviour of the water pool upon impact. For example, if the sphere's surface is hydrophobic (repels water), it may experience different interaction dynamics with the water pool compared to a sphere with a hydrophilic (water-attracting) surface.

4.3.6 Effects of ***Ja*** on pinch-off time

The Jakob number is a dimensionless parameter used in heat transfer analysis, particularly in convective heat transfer. It represents the ratio of the convective heat transfer rate to the conductive heat transfer rate. In the context of your question, the Jakob number is related to the heat transfer occurring during the impact of a hot steel sphere into a water pool. Convective heat transfer occurs when the hot steel sphere strikes the water pool, heating the surrounding water. The temperature difference between the sphere and the water, the way the water flows, and the fluid's thermal properties are all factors that affect the convective heat transfer rate. ***Ja*** is expressed as $= Cp\Delta T/hfg$, in this experiment all the used spheres are made of steel and it can be assumed that all the spheres are having same C_p . as the fluid used is water so the hfg is also constant here. Only changing the super heat ΔT, ***Ja*** is changed. For each value of ***Fr***, in a range of ***Ja*** only nucleate boiling is observed. Other than that range of ***Ja*** cavity formation and pinch-off phenomena is observed. For a particular ***Fr*** as ***Ja*** is increased first pinch-off depth increases then cavity formation stops and only nucleate boiling starts again increase in ***Ja*** cavity formation observed and pinch-off depth increases with ***Ja***. The variation of non-dimensional pinch-off depth with ***Ja*** is shown by a graph in Fig 13.

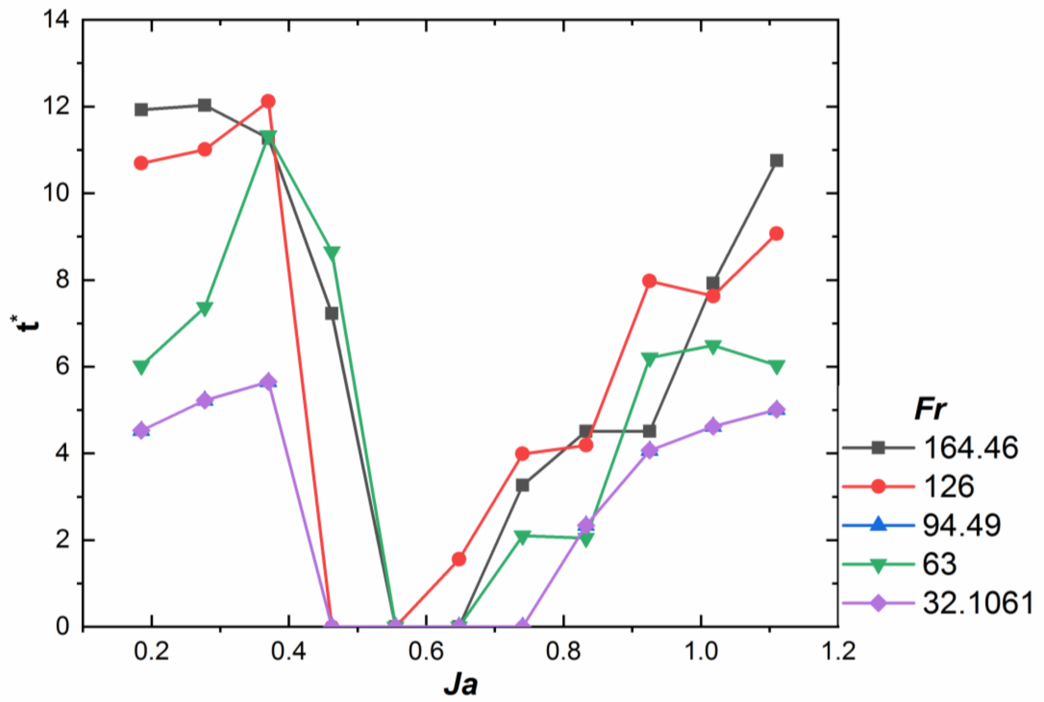


Fig 13: Effects of ***Ja*** on non dimensional pinch off time

4.3.7 Effects of ***Ja*** on pinch-off depth

The greater the Jakob number, the faster the convective heat transfer rate is compared to the conductive heat transfer. This suggests that convection, as opposed to conduction, is transferring more heat from the hot steel sphere to the water pool. In turn, this causes the water to rapidly boil up close to the impact site, which alters how the cavity behaves. In general, higher Jakob numbers result in faster energy transfers and more ferocious fluid action. This can lead to a deeper pinch-off depth for the impact cavity. The water at the impact site is heated and brought to a boil as a result of the increased convective heat transfer, which intensifies bubble production and expansion. Before it finally collapses, the cavity grows as a result of these activities. Fig 14 shows the variation of pinch-off depth with ***Ja***.

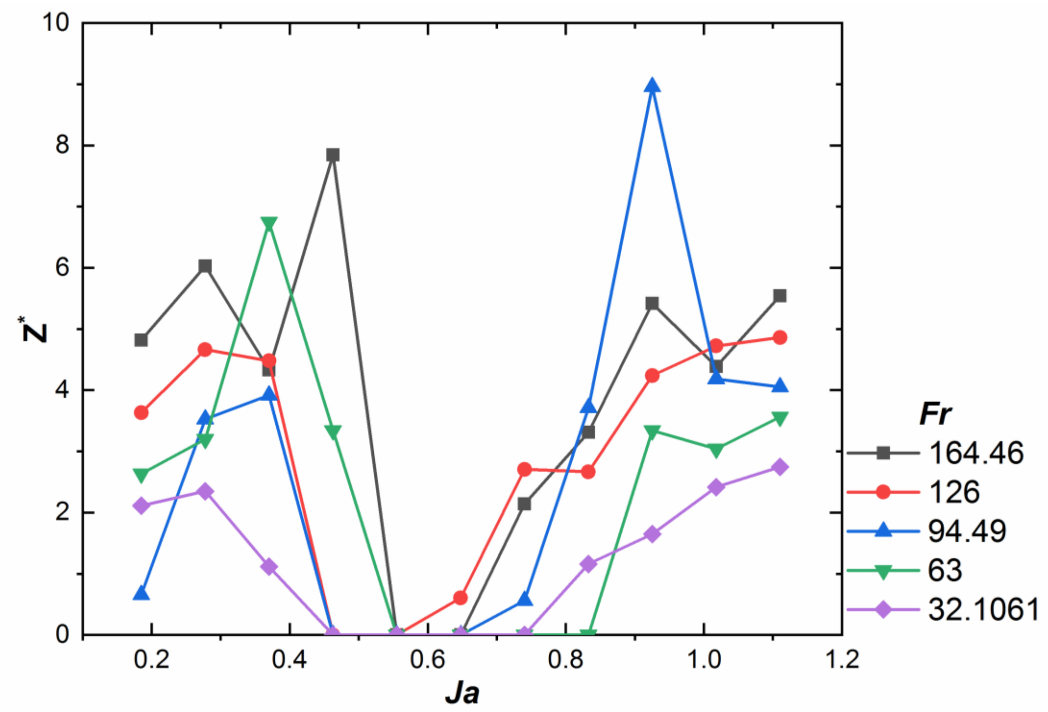
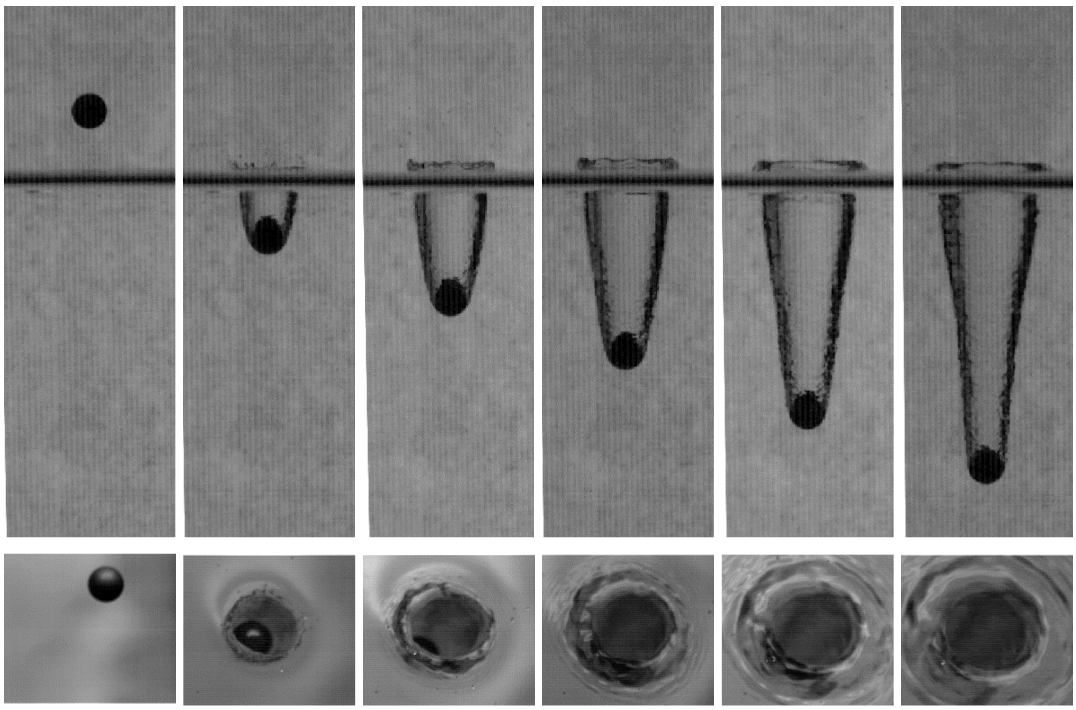


Fig 14: Effects of ***Ja*** on non dimensional pinch-off depth

To study the cavity mouth behaviours (opening and closing) some images are taken at 15cm drop height and three different temperatures of three regimes. The first set of images are taken at T = 250^{o}C, where we observed formation of cavity with a open mouth, in the second regime at T= 400^{o}C, where there is no such cavity formation occurs so the entry of the sphere opens and immediately closes when the sphere gets just into water and in the third regime at T= 650^{o}C, re-occurrence of the cavity is observed. Some snaps of the experiment at 15 cm drop height and three different temperatures 250°C, 400°C and 650°C are given below in Fig 15. The side views and corresponding top views of the total phenomena at different times are shown in the snaps.

T = 250°C drop height 15 cm



t=-0.0048 s t= 0.0048 s t=0.0096 s t=0.0144 s t=0.0192 s t=0.0240 s

Fig 15 : Combination of images from side view and top view at same instances at 250°C and 15 cm drop height

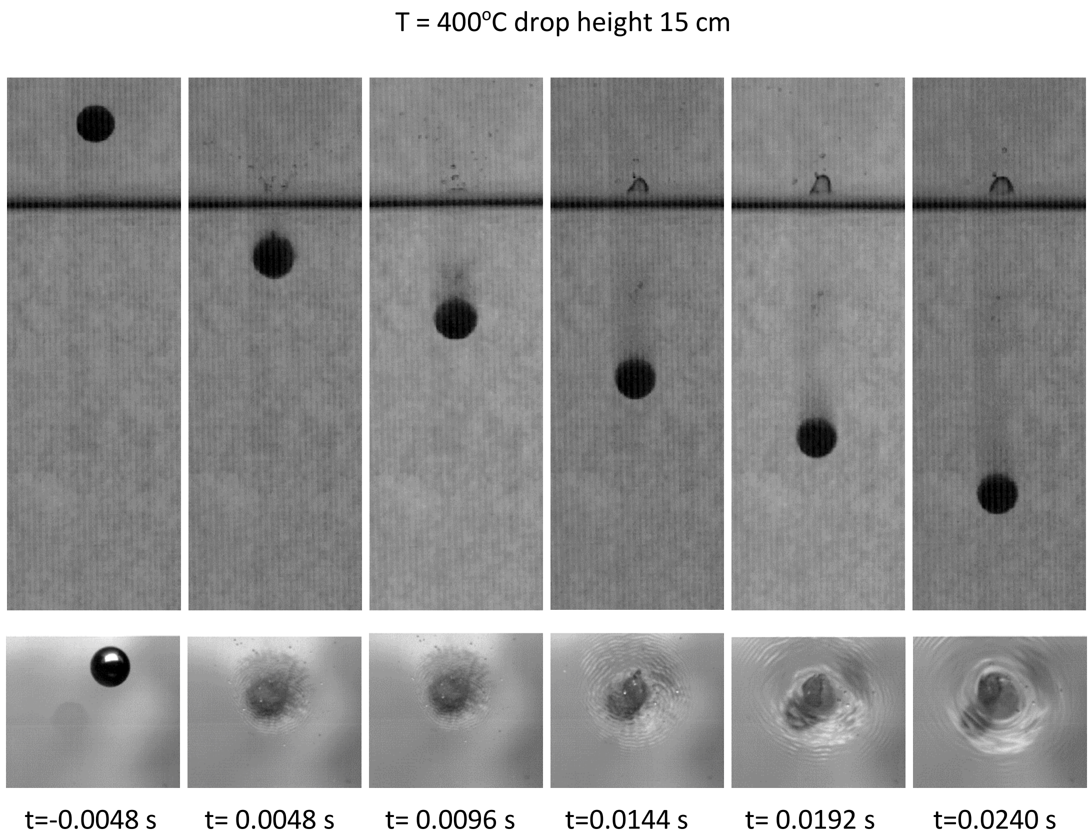


Fig 16 : Combination of images from side view and top view at same instances at 400°C and 15 cm drop height

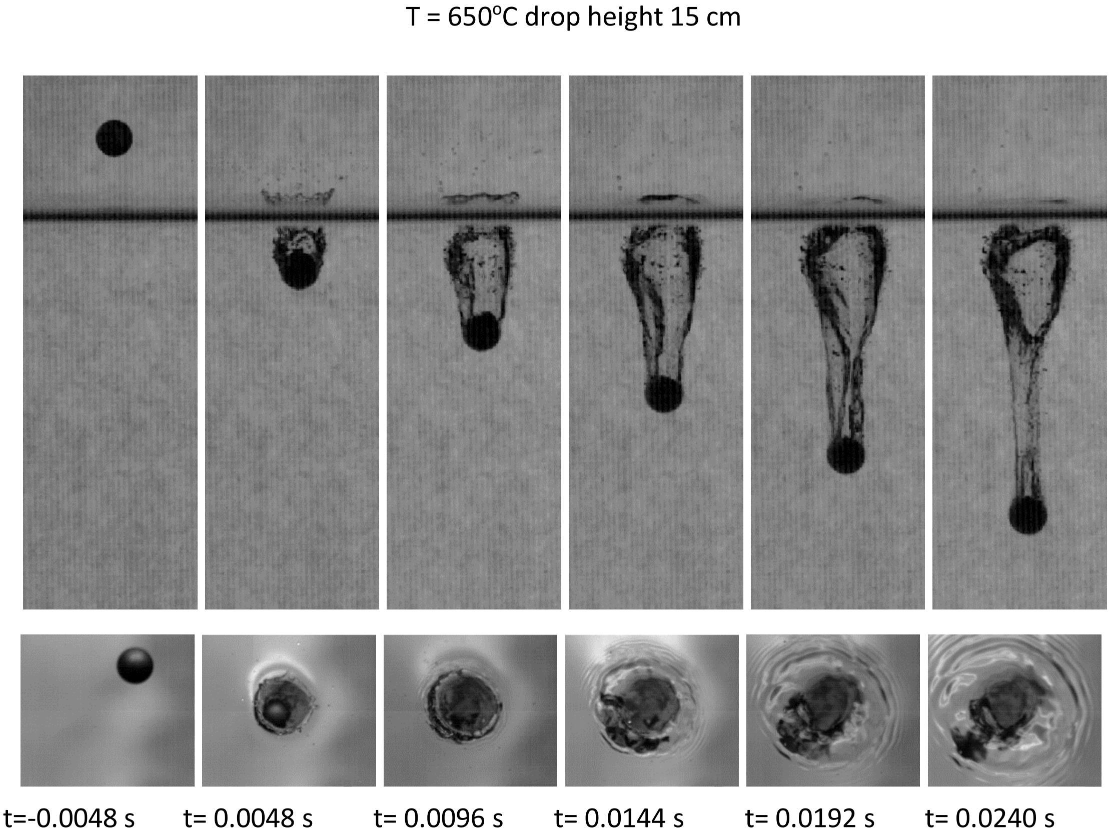


Fig 17: Combination of images from side view and top view at same instances at 650°C and 15 cm drop height

4.4 Validation of correlation used to measure temperature

The temperature of the small spheres cannot be tracked using thermocouple as the sphere is in motion. So to find the temperature drop a correlation can be used. To validate the correlation and to study the heat transfer phenomena a 50.8 mm diameter sphere of SS304 is used. Two thermocouples are used to measure the temperature of the sphere, one is mounted at the centre to get the centre temperature and another is attached to the surface passing through the centre. The temperature sensors are controlled by an arduino and data stored using software named coolterm.

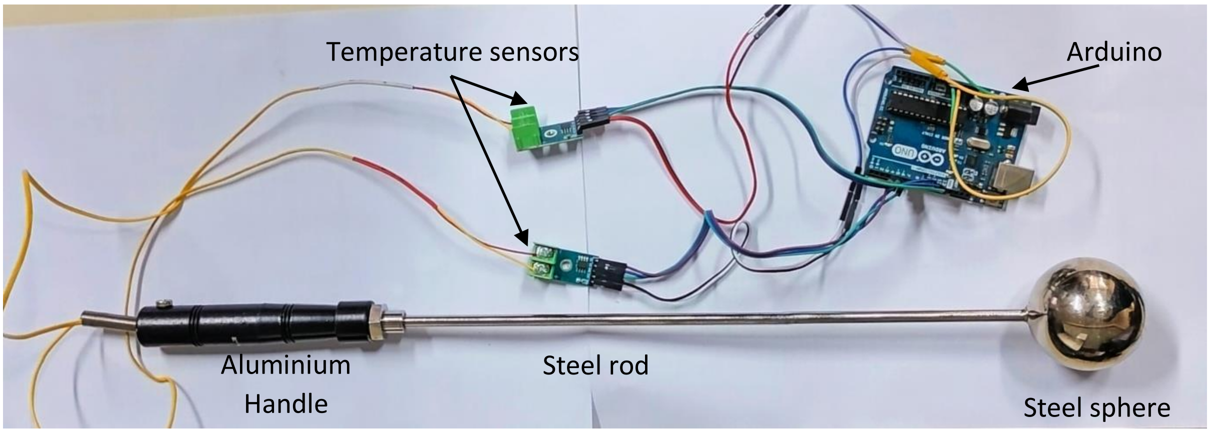


Fig 18: Experimental set up for temperature measurement validation experiment

In the first test we used a muffle furnace to heat the sphere up to a centre temperature of 100°C and surface temperature of 102°C and then it is kept into air for cooling naturally. The natural convectional cooling curve of the sphere in air is shown by a figure below in Fig 17.

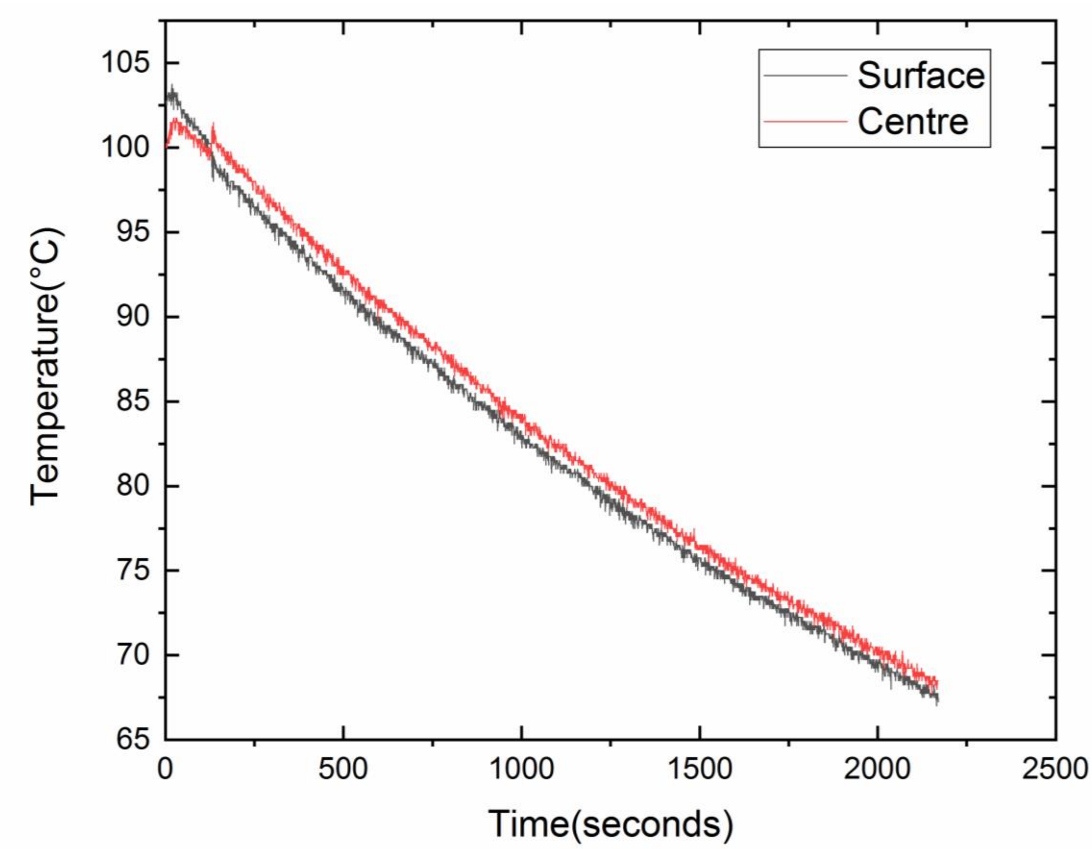


Fig 19: Variation of centre and surface temperature of a solid steel sphere with time during cooling in air.

To validate the experimental results, the convective heat transfer coefficient is calculated at mean film temperature using a correlation for natural convection around solid sphere which was proposed by Churchill. All the properties of air are taken at mean film temperature. From the correlation the expression for the Nusselt number is,

$$\overline{Nu}_D = 2 + \frac{0.589Ra_D^{\frac{1}{4}}}{\left[1 + \left(\frac{0.469}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}}$$

Where $\overline{Nu}_D$ is the average Nusselt number Ra_D is the Rayleigh number and Pr is the Prandtl number calculated over diameter of the solid sphere. The expressions for Rayleigh and Prandtl number are given below,

$$Ra_D = \frac{g\beta\Delta T D^3}{\nu\alpha}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha}$$

Where g is the gravitational acceleration, β is coefficient of thermal expansion of the fluid, ΔT is temperature difference, D is diameter, ν is kinematic viscosity and α is thermal diffusivity of the fluid.

The heat transfer coefficient calculated from the Churchill's correlation is further used to calculate the theoretical temperature fall with time for the sphere taking uniform temperature distribution in the sphere i.e. the temperature of each section of sphere is taken to be in same temperature as the temperature difference between surface and centre is very low. The relation used to calculate the temperatures with time instant is,

$$\frac{T_t - T_\infty}{T_0 - T_\infty} = e^{-\frac{hAt}{\rho CV}}$$

Where T_t is temperature of the sphere after t seconds, $T_0$is the initial sphere temperature, $T_\infty$is the ambient temperature, h is heat transfer coefficient calculated from Churchill's correlation, A is area of the sphere, ρ is density of sphere material, C is heat capacity of the sphere material and V is the volume of the sphere.

To compare the theoretical and experimental temperature variation with time, a graph is shown below in Fig 18.

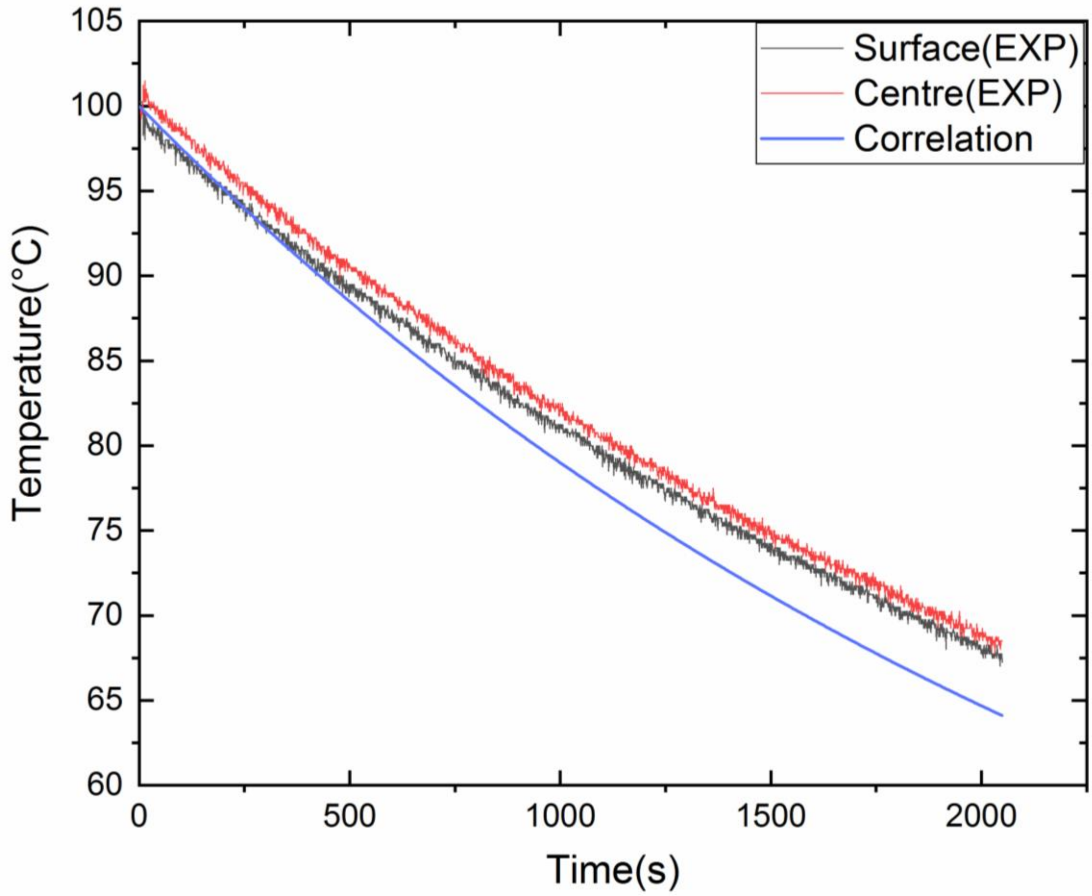


Fig 20: Temperature variation curve.

Chapter 5

CONCLUSION

In this study several experiments are done and some parameters like impact velocities and sphere temperatures at the time of impact are controlled and it is observed that the cavity formation depends upon a combination of ***Fr*** and ***Ja*** or impact velocity and sphere temperature at the time of impact. From all the results of the performed experiments some conclusion can be drawn are those are following,

1. The formation of cavity due to impact of hot solid sphere into liquid depends on both the sphere temperature (***Ja)*** and impact velocity (***Fr)*** of the sphere at liquid surface.
2. For a particular ***Fr***, with increase in ***Ja*** three regimes of cavity formation are observed. In the first regime for low ***Ja*** cavity formation is observed. As ***Ja*** is increased beyond a certain limit there is no such cavity formation in the middle or second regime then again after a certain value of ***Ja*** reoccurrence of cavity formation is observed and this is the third regime.
3. For a particular ***Ja*** with increase in ***Fr*** the pinch-off depth of the cavity first increases, then decreases then again observed to be increased.
4. With increase in both impact velocity (***Fr***) and sphere temperature (***Ja***) the shape of cavity deforms.
5. At very high temperature there is formation of oxide and that affects the cavity shape and size.

REFRENCES

[1] Worthington, A. M., & Cole, R. S. (1897). V. Impact with a liquid surface, studied by the aid of instantaneous photography. Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character, (189), 137-148.

[2] Richardson, E. G. (1948). The impact of a solid on a liquid surface. Proceedings of the Physical Society, 61(4), 352.

[3] Duclaux, V., Caillé, F., Duez, C., Ybert, C., Bocquet, L., & Clanet, C. (2007). Dynamics of transient cavities. Journal of Fluid Mechanics, 591, 1-19.

[4] Li, L., Li, H., & Chen, T. (2008). Experimental investigation on the moving characteristics of molten metal droplets impacting coolant. Experimental thermal and fluid science, 32(4), 962-972.

[5] Truscott, T. T., & Techet, A. H. (2009). A spin on cavity formation during water entry of hydrophobic and hydrophilic spheres. Physics of Fluids, 21(12).

[6] Bergmann, R., Van Der Meer, D., Gekle, S., Van Der Bos, A., & Lohse, D. (2009). Controlled impact of a disk on a water surface: cavity dynamics. Journal of Fluid Mechanics, 633, 381-409.

[7] Biance, A. L., Chevy, F., Clanet, C., Lagubeau, G., & Quéré, D. (2006). On the elasticity of an inertial liquid shock. Journal of Fluid Mechanics, 554, 47-66.

[8] Vakarelski, I. U., Marston, J. O., Chan, D. Y., & Thoroddsen, S. T. (2011). Drag reduction by Leidenfrost Vapour layers. Physical Review Letters, 106(21), 214501.

[9] Abelson, H. I. (1970). Pressure measurements in the water-entry cavity. Journal of Fluid Mechanics, 44(1), 129-144.

[10] Brennen, C. (1970). Cavity surface wave patterns and general appearance. Journal of Fluid Mechanics, 44(1), 33-49.

[11] Zvirin, Y., R HEWITT, G., & Kenning, D. B. R. (1990). Boiling on free-falling spheres: drag and heat transfer coefficients. Experimental Heat Transfer, 3(3), 185-214.

[12] Lee, M., Longoria, R. G., & Wilson, D. E. (1997). Cavity dynamics in high-speed water entry. Physics of Fluids, 9(3), 540-550.

[13] Grumstrup, T., Keller, J. B., & Belmonte, A. (2007). Cavity ripples observed during the impact of solid objects into liquids. Physical review letters, 99(11), 114502.

[14] Aristoff, J. M., & Bush, J. W. (2009). Water entry of small hydrophobic spheres. Journal of Fluid Mechanics, 619, 45-78.

[15] Gekle, S., van der Bos, A., Bergmann, R., van der Meer, D., & Lohse, D. (2008). Noncontinuous Froude number scaling for the closure depth of a cylindrical cavity. Physical review letters, 100(8), 084502.

[16] Lee, D. G., & Kim, H. Y. (2008). Impact of a superhydrophobic sphere onto water. Langmuir, 24(1), 142-145.

[17] Marston, J. O., & Thoroddsen, S. T. (2008). Apex jets from impacting drops. Journal of Fluid Mechanics, 614, 293-302.

[18] Gekle, S., Gordillo, J. M., van der Meer, D., & Lohse, D. (2009). High-speed jet formation after solid object impact. Physical review letters, 102(3), 034502.

[19] Truscott, T. T., & Techet, A. H. (2009). Water entry of spinning spheres. Journal of Fluid Mechanics, 625, 135-165.

[20] Yan, H., Liu, Y., Kominiarczuk, J., & Yue, D. K. (2009). Cavity dynamics in water entry at low Froude numbers. Journal of Fluid Mechanics, 641, 441-461.

[21] Kubota, Y., & Mochizuki, O. (2011). Influence of head shape of solid body plunging into water on splash formation. Journal of visualization, 14, 111-119.

[22] Shepard, T., Abraham, J., Schwalbach, D., Kane, S., Siglin, D., & Harrington, T. (2014). Velocity and density effect on impact force during water entry of sphere. J. Geophys. Remote Sens, 3(129), 2169-0049.

[23] Schwalbach, D. S., Shepard, T., Kane, S., Siglin, D., Harrington, T., & Abraham, J. P. (2014). Effect of impact velocity and mass ratio during vertical sphere water entry. Dev. Appl. Oceanic Eng, 3, 55-62.

[24] Ding, H., Chen, B. Q., Liu, H. R., Zhang, C. Y., Gao, P., & Lu, X. Y. (2015). On the contact-line pinning in cavity formation during solid–liquid impact. Journal of Fluid Mechanics, 783, 504-525.

[25] Hwang, G. B., Patir, A., Page, K., Lu, Y., Allan, E., & Parkin, I. P. (2017). Buoyancy increase and drag-reduction through a simple superhydrophobic coating. Nanoscale, 9(22), 7588-7594.

[26] Kim, S., Kim, D., & Kim, H. (2020). Effect of wettability on the water entry problem of aluminum spheres. Journal of Mechanical Science and Technology, 34, 1257-1263.

[27] Sekar, K. R., Kannan, R., Elanchezhian, T., Sangeetha, B., & Gokul, J. (2021). Effect of surface roughness on the motion of a sphere through the water column. Materials Today: Proceedings, 45, 3296-3301.