# AN EXPERIMENTAL STUDY ON VOID GENERATION AROUND HOT METAL PARTCLE QUENCHED INTO WATER POOL

**Louis Manickam, Sachin Thakre, Weimin Ma**

Division of Nuclear Power Safety, Royal Institute of Technology (KTH)
AlbaNova University Center, Roslagstullsbacken 21, 106 91 Stockholm, Sweden
louis@safety.sci.kth.se, thakre@safety.sci.kth.se, ma@safety.sci.kth.se

## ABSTRACT

Motivated to understand the void formation in fuel coolant interactions during a postulated severe accident of light water reactors, an experimental study was carried out to characterize void generation and evolution from stainless steel spheres quenched into a subcooled water pool. The major experimental parameters ranged from variations in water subcooling as well as the initial temperature and the diameter of the spheres which were kept still or falling in the water pool. The experimental results show that under the stagnant condition, axisymmetric vapor waves develop at the stagnation point which travels through the droplet's rear periphery and subsequently detaches into almost equal size bubbles at regular intervals in the stable film boiling regime, but a sharp decrease in the bubble detachment frequency was observed due to a transition in boiling regime. The effect of the water subcooling on the detached vapor volume is significant. The number of bubbles detached from the sphere periphery drastically reduces at high subcooling conditions. Under the falling condition, the temperature and diameter of the sphere as well as water subcooling significantly affect the dynamics of the bubbles entrained to the sphere's periphery.

**KEYWORDS**
Fuel-coolant interactions, film boiling, void, non-condensable gases, vapor film stability, high-speed visualization.

## 1. INTRODUCTION

A typical severe accident scenario in a light water reactor can involve relatively high temperature molten materials (corium) pouring into a subcooled water pool. Upon interaction with subcooled water the melt stream breaks-up into fragments of various sizes forming a mixture of fragments, vapor and water. The fragments in molten state are enshrouded by a vapor film. The vapor film drastically reduces heat transfer between the molten fragments and water. On collapse of this vapor film, typically due to transition in boiling regimes or by some external forcing, direct contact between the fragment and water occurs. As a result, the surrounding water layer boils rapidly and explosively producing a shock wave which travels through the entire mixture thereafter rapidly expanding against the constraints of surrounding structures. These conditions commonly referred to as steam explosions can pose a catastrophic hazard by releasing radioactive material into the environment. State-of-art review on experimental and analytical studies on steam explosion is provided by [1, 2, 3]. The review of experimental and theoretical works have shown that the void build-up namely the amount of vapor produced by the molten fragments in the water pool and the solidification trends exhibited by the quenching droplets are the major limiting factors for an energetic steam explosion to occur [3].

As important as the evaluation of heat transfer characteristics between the molten fragments and water, the void produced from the molten fragments and subsequent overall void build-up in a water pool is equally important in steam explosion risk analysis. Experimental and analytical studies on the overall heat transfer characteristics between molten fragments and water are overwhelming [4, 5, 6, 7]. Attempts were made in relatively large-scale steam explosion experiments to measure the overall void build-up in the water pool during quenching of molten corium before a steam explosion is triggered and assess the impact of void build-up on steam explosion energetics with sufficient accuracy. However, the complexities involved with such multi-faceted phenomena have hindered progress in firm assessment on the effects of void build-up on steam explosion [3]. A specific study on void production from a molten fragment is still at its primitive stages.

Motivated to understanding void produced from a molten fragment quenched into a water pool, an experimental study has been carried out in the present paper. The scope of the work is mainly focused on understanding the void produced from a hot particle which is either stagnant or falling into a water pool. The data can help reduce uncertainties in understanding void production and boiling transition around the droplets formed during a fuel coolant interaction (FCI).

## 2. EXPERIMENTAL CONDITIONS AND PROCEDURE

A set of experiments have been performed by pre–heating a steel sphere and discharging it into water pool. The major experimental parameters are diameter and initial temperature of the sphere and water subcooling. The experiments were performed under two conditions:- i) the sphere is stagnant in the pool and ii) the sphere is falling into the pool. For the stagnant condition, a thin thermocouple wire was attached to the sphere which was heated in the induction furnace, and then immersed and in held still in the water pool. For falling condition sphere was heated and subjected to free fall into the water pool. The void generated from the sphere was characterized by high speed visualization (photography). Table I, presents the overall test conditions of the experiments performed in the scope of this paper.

**Table I. Overall Experimental Conditions**

| Conditions | Diameter of the sphere (mm) | Initial sphere temperature (°C) | Water temperature (°C) |
|---|---|---|---|
| **Stagnant** | *10,20* | *1000* | *30,60* |
| **Falling** | *5,10* | *500,1000* | *30,60,90* |

### 2.1. Facility Description

The experimental arrangement mainly consists of a melt generation system, test section (water pool), high speed visualization system and data acquisition system. Fig. 1, shows the schematic of the experimental facility. The melt generation system consists of an induction furnace *(260 V, 40 A)*. The test section is a rectangular plexi-glass tank *(500×75 mm)*. K type thermocouples are placed at the top and bottom of the test section to measure the temperature of water considering stratification. At the centre of the bottom of the test section is a narrow hole with a rubber guide tube for collection of the particles. The visualization system consists of a high speed videography system. The high speed videography system is a CMOS digital camera (Redlake HG50LE), with imaging up to 200000 fps.

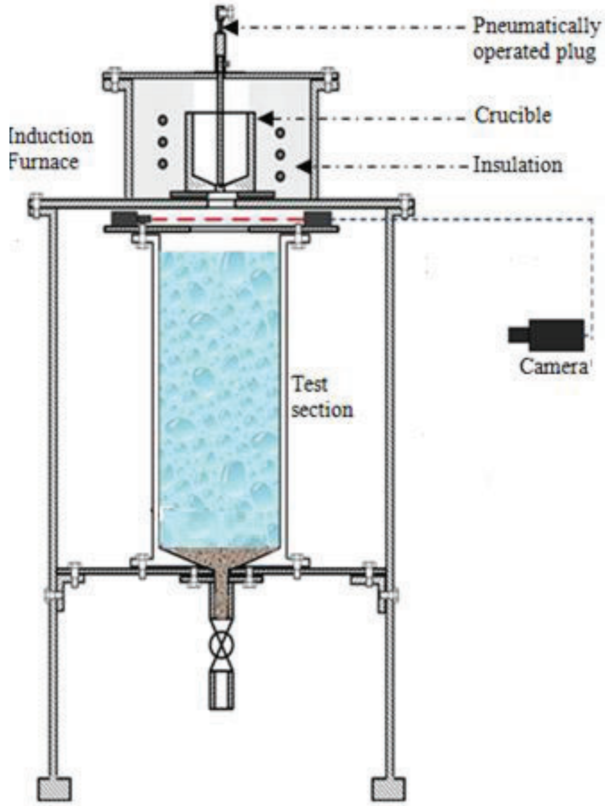


**Figure 1. Schematic of the Experimental Facility.**

## 3. EXPERIMENTAL CONDITIONS AND PROCEDURE

### 3.1. Stagnant Conditions

Similar to most other relevant studies on boiling around a sphere, the present study also uses the technique of mounting a thermocouple from a pre-made cavity on the sphere thereby heating it to a desired temperature and immersing it into a water pool. Fig. 2a represents typical time sequence snapshots of a 10 mm stainless steel sphere pre-heated to ~1000°C quenched into water pool at ~60°C. Fig.2a represents the initial stages of the interaction showing stable film boiling around the immersed sphere. As the images reveal the vapor film surrounding the sphere varies in thickness owing to the axisymmetric waves which start to develop at the spheres lower periphery. The developed wave passes upward around the sphere and accumulates at the upper periphery of the sphere (t= 0.018 s). A bubble begins to detach thereby from the upper periphery soon after a preceding axisymmetric wave also reaches the upper periphery (t= 0.142 s). The frequency of bubble detachment from the droplet upper periphery is almost constant (average dominant bubble detachment frequency ≈ 0.035 s) in the stable film boiling region, see Fig. 2b. The formation of axisymmetric waves from the stagnation point diminishes and solid-liquid contact at localized regions is observed. A combination of both film boiling and nucleate boiling co-existing at localized locations is observed. The time taken for each bubble detachment in this transition region is observed to increase. Eventually, fully developed nucleate boiling is observed resulting in detachment of discrete bubbles from random sites of the sphere.

In multi-phase flow, bubble volume is a very useful parameter in obtaining the amount of void formed at the droplet/particle rear surface. The parameter can help attain useful information on the void build-up in a FCI. In the present work the bubble volume is estimated geometrically from the acquired high speed video images. Full bubbles, soon after undergoing detachment and while in rising movement at a similar level are considered as an ellipsoid (appear as an ellipsoid from most of the experiments pictures). It is instructive to note that the bubble distorts while in rising motion. However it is considered in the present work that the horizontal forces acting on the bubble are equal when the bubble is at a specific distance from the droplet/particle. By detecting the edges of the bubble in the high speed images the major semi-axis (a) and the minor semi axis (b, b=c) is determined. Thus the volume of the ellipsoid/bubble is estimated ($V = \frac{4}{3}\pi abc$). Fig. 2c is a representation of the measured volume of the bubble over time. After stable film boiling regime, the volume of detatched bubbles decreases drastically until the sphere is completely cooled.

A number of models have been developed to theoretically depict the vapor film thickness surrounding the sphere [4, 5, 6, 7]. The predictions include an assumption of constant thickness across the sphere periphery. The thickness of the vapor film varies over the entire periphery. At stable film boiling regime, formation of axisymmetric waves from the droplet stagnation point travels through the droplet periphery that the thickness of the vapor film is not constant but oscillates in periodic intervals. In the present work, the thickness of the vapor film soon after each bubble detachment is estimated by detecting the edges of the lateral periphery in the high speed images. The average thickness of the vapor film enshrouding a 10 mm stainless steel sphere pre-heated to ~1000°C and quenched into water pool at ~60°C is measured to be ~0.20935 mm.

Fig. 3 is a representation of the comparison of measured volume of the bubble over time with a varied water temperature. A significant decrease in the number of bubbles detaching from the immersed sphere can be noticed. The time frequency for bubble detachment increases drastically. The observations point out the significantly higher amount of energy transferred to cause evaporation at high subcooling conditions. However it can be observed that the bubble detachment frequency ≈ 0.51 s is also uniform in high subcooling conditions similar to that of low subcooling conditions. The frequency of bubble detachment from a pre-heated sphere at ~60°C water temperature is ~15 times greater than that of conditions at ~30°C water temperature. A linear decrease in the detached bubble volume as a function of time can also be noted.

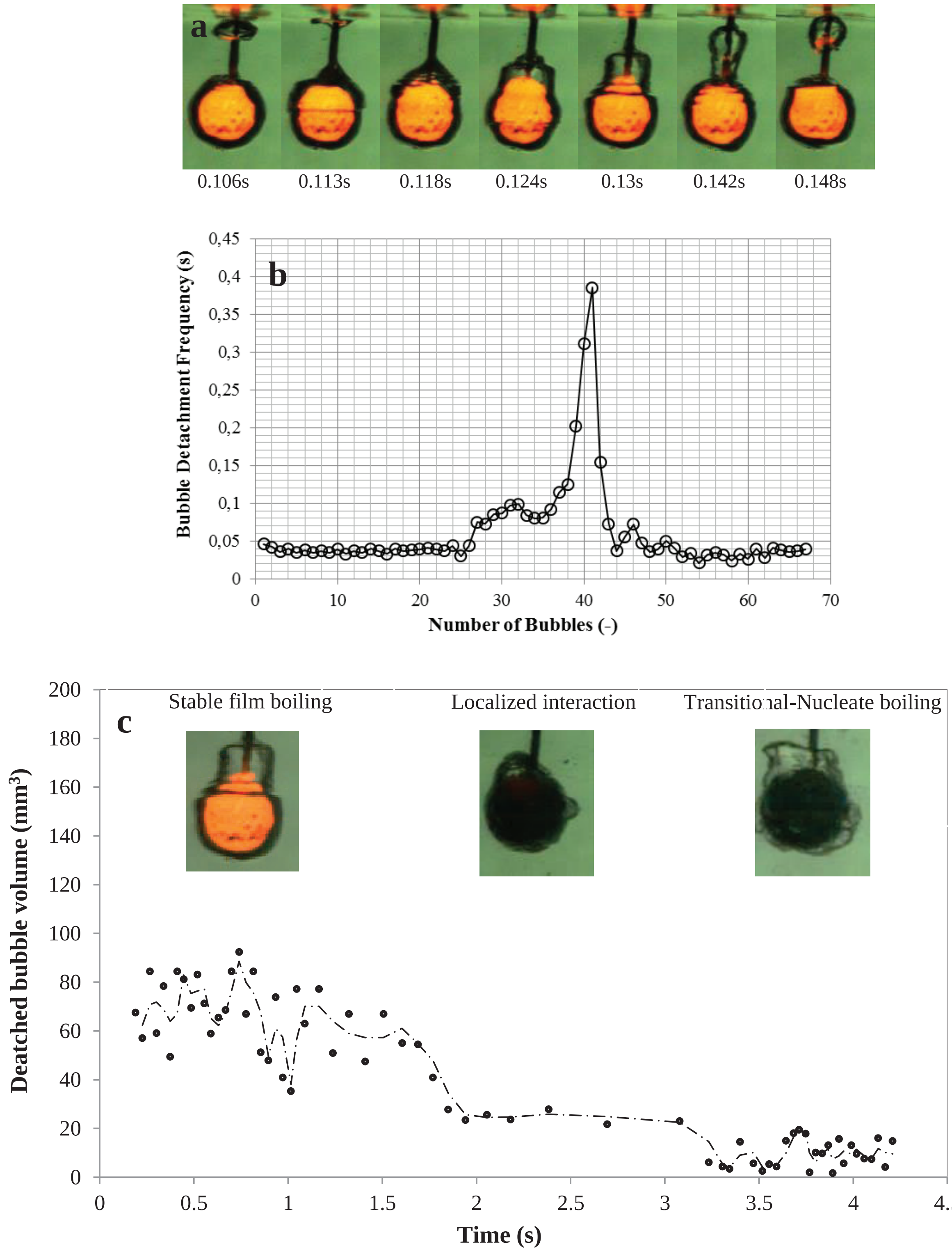


**Figure 2. a) Time sequence snapshots of pre-heated stainless steel sphere undergoing film boiling in water b) time frequency for bubble detachment from the sphere and c) measured volume of bubble after detachment as a function of time ( $T_{sphere\ int}$ ≈1000°C, $T_{water}$ ≈ 60°C).**

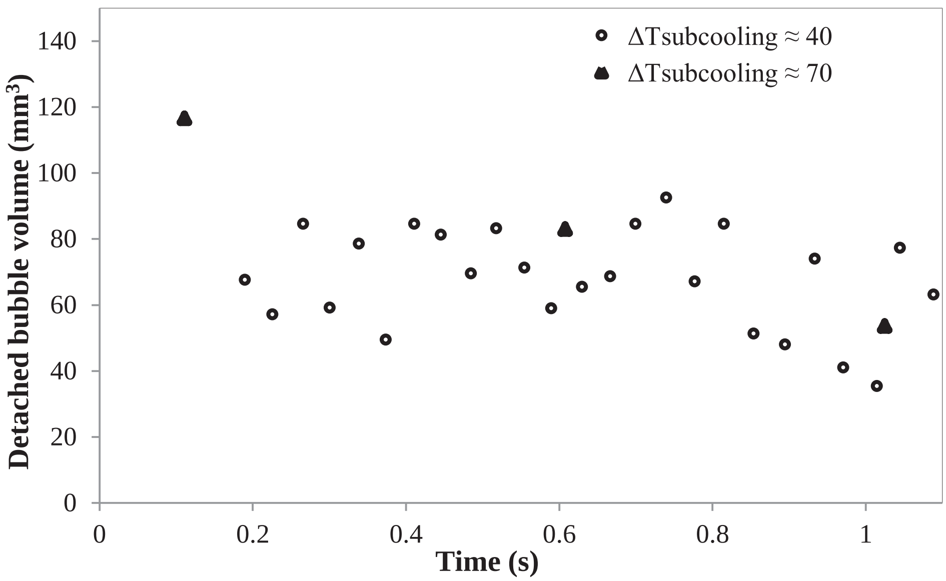


**Figure 3. Measured volume of bubble after detachment as a function of water subcooling during film boiling regime.**

## 3.2. Falling Conditions

The dynamics of a pre-heated sphere quenched into a subcooled water pool are represented in fig. 4 as time sequence snapshots. For convenience and ease of comparison between data, the time at which the sphere first contacts the water surface is taken as t=0. The snapshots reveal significant accumulation of gases dragged during free fall on the rear periphery of the spherical material. It is thus instructive to note that a significant portion of the void described in this study can be attributed to the accumulated non-condensable gases. Hence the bubble described in this study can be considered as the net mass of non-condensable gases and the evaporated mass. Dynamics of the gases enshrouding a molten droplet falling in water is a key parameter since it dictates the intensity of destabilization or collapse if a steam explosion is to be triggered. The effect of vapor film characteristics on steam explosion has been studied by a number of researchers [8, 9, 10, 11]. It is suggested that the presence of such dragged gases can suppress the intensity of a steam explosion.

Fig. 5a presents the effect of water subcooling on the evolution of void along the periphery of a pre-heated sphere over time. A significant influence of water subcooling on the overall dynamics of the void evolution is apparent. At approximately t=0.035 s after penetration into water a fully developed gas trail along with the sphere emerges. The peaks and valleys in the graphic denote the growth of the bubble over time and detachment of smaller sized bubbles from the rear periphery. The peaks can be attributed to the addition of vapor to the total net void enshrouding sphere.

For conditions at $\Delta T_{subcooling} \approx 14$ i.e. low subcooling, the bubble trace evolves for a longer time without significant reduction in the equivalent bubble volume. The equivalent volume of the bubble increases over time. At high subcooling ($\Delta T_{subcooling} \approx 70$) conditions the equivalent bubble volume reduces drastically that a significant portion of the bubble is already detatched already at t=0.06 s i.e. the time at which the elliptical shaped void from the droplet rear periphery has already detached. However, not to say that the vapor film surrounding the droplet has entirely collapsed which can be observed by the evolution of the bubble after t=0.06 s presented in fig. 5a. On an average the net bubble volume at high subcooling conditions is lesser than that for low subcooling conditions. The observations can be rationalized considering the lesser amount of energy utilized from the sphere to evaporate water at low subcooling conditions. The change in bubble volume is more pronounced for high subcooling conditions between short time intervals. A significant reduction and increase can be noted at very short time span compared to that of the low subcooling conditions.

In general, the profile of void entraining the sphere is significant over a longer period of time for low subcooling cases that conditions for direct solid-coolant contact is reduced drastically. A similar characteristic described above can be noted in fig. 5b, for similar experimental conditions but with an increased diameter of the sphere. The effect of sphere diameter on the bubble evolution is significant as expected. For 10 mm spheres, the equivalent bubble diameter can be noted to increase by four times compared to the tests with 5 mm spheres. Fig. 6 presents the influence of sphere surface temperature on the dynamics of void entraining the sphere peripheries. The effect is apparent. A drastically reduced equivalent bubble volume is observed and the same goes to bubble detachment time interval. It can also be noted that for similar test conditions irrespective of subcooling the time taken for the sphere to emerge from the water level into a fully formed sphere enshrouded by a bubble is similar whereas the conditions differ for variation in sphere surface temperature, see fig. 6.

0.015s 0.06s 0.095s 0.122s

**Figure 4. Time sequence snapshots of a pre-heated stainless steel sphere of diameter 10 at 1006°C quenched into a water pool at 89°C.**

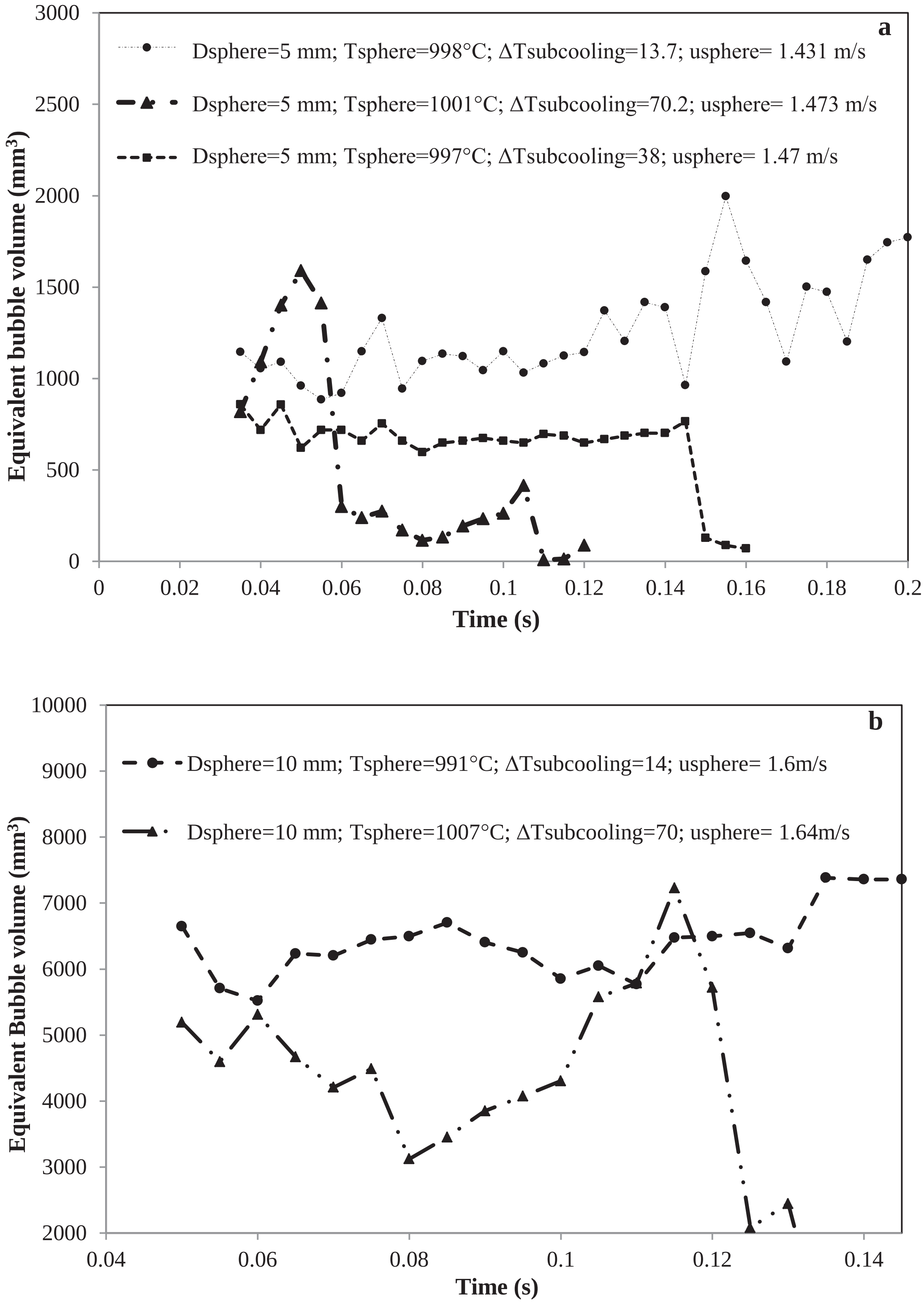


**Figure 5. Effect of subcooling on the volume of the bubble trailing along the sphere periphery for sphere diameter a) 5 mm and b) 10mm.**

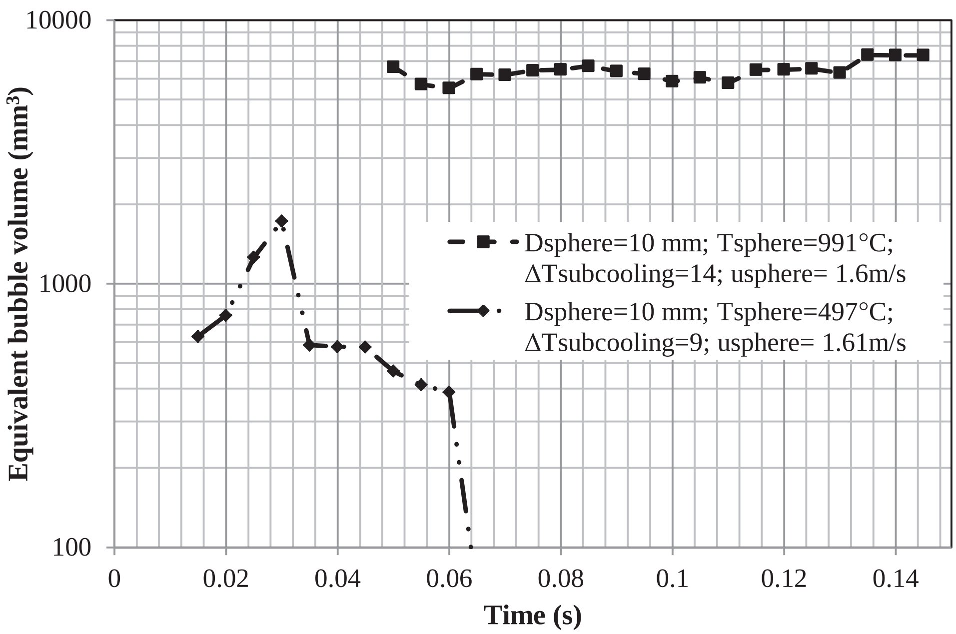


**Figure 6. Effect of sphere surface temperature on the volume of the bubble trailing along the sphere periphery.**

## 4. CONCLUSIONS

An experimental study has been performed to characterize void around a hot metallic particle quenched into a water pool at stagnant and falling conditions. The influential parameters which were investigated are the diameter and initial temperature of the particle as well as, water subcooling of the pool. The experimental results presented here specifically focused on the void formation and evolution. Based on the experimental findings the following points can be summarized,

Under stagnant conditions,

- Axisymmetric vapor waves develop at the stagnation point and travel through the droplet rear periphery and subsequently detach into almost equal size bubbles at regular intervals while in stable film boiling regime.
- A transition in boiling is observed and followed by a sharp decrease in the bubble detachment frequency.
- The effect of water subcooling on the detached bubble volume is significant. The frequency for bubble detachment at low subcooling conditions is ~15 times greater than that for the high subcooling conditions.

Under falling conditions,

- The temperature and diameter of the sphere as well as water subcooling significantly affect the dynamics of the bubbles entrained to the sphere's periphery.
- At low subcooling, the bubble evolves for a longer time with constantly increasing volume prior to its detachment from the sphere. At high subcooling a pronounced change in bubble volume is noted with a shorter time span of the detached bubble.
- The initial bubble volume, i.e.the net contribution of non-condensable gases and vapor is significantly less for a decreased sphere surface temperature.

## NOMENCLATURE

| | |
|---|---|
| *D* | diameter (m) |
| *T* | Temperature (°C) |
| *fps* | frames per second |
| *t* | time (s) |
| *u* | velocity (m/s) |

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