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Influence of fluids properties and droplet impinging height on Leidenfrost phenomena over a plain silicon surface

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Summary

The need for high heat flux removal has been triggered by the development of new technologies ranging from computers, data centers, medical applications, electric cars, radars, satellite, and lasers, to mention some applications. Today it is recognized that manufacturability is not the limiting factor with regards to the small size of the devices and that major challenge is the power dissipation problem.

Spray cooling has been shown as a possible solution for cooling of high heat fluxes systems. However, the Leidenfrost phenomena pose a limitation to the use of liquid to cool down hot surfaces as it prevents the dissipation of heat. This effect consists of the development of a vapor layer that makes the impinging cooling fluid bounce away when impacting the hot surface, becoming heat dissipation ineffective. This regime is named film boiling.

The primary objective of this work is to experimentally determine the different boiling regimes and Leidenfrost point for deionized water and various dielectric fluids evaluating the influence of fluids properties and the dependence of droplet impact height over a heated plain silicon surface. Furthermore, designing and fabrication of a test section for studying impacting droplets over a plain silicon surface have been completed.

Final results show and discuss the different droplet deposition heights evaporation curves for deionized water and FC-72, boiling regimes along the deionized water and FC-72 experimental curve, Weber map showing different boiling regions and a comparison between deionized water and FC-72 performance.

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1 Introduction

1.1 Background and Motivation

The need for high heat flux removal has been triggered by the development of new technologies ranging from computers, data centers, medical applications, electric cars, radars, satellite, and lasers, to mention some applications. Today it is recognized that manufacturability is not the limiting factor with regards to the small size of the devices and that major challenge is the power dissipation problem, i.e. how to remove the heat from a confined space.

Nowadays power densities to be dissipated are beyond air cooling limits. [comparison FC-72] Liquids present higher specific heat capacity and thermal conductivity than air, making liquid cooling becomes necessary. There are many different mechanisms of liquid cooling depending on their applications.

In particular, spray cooling [1] has been shown as a possible solution for cooling of high heat fluxes systems such as of diode array, large radar and laser transmitters because it allows a low superheat, no temperature overshoot, no contact thermal resistance, and less flow rate demand. However, the Leidenfrost phenomena pose a limitation to the use of liquid to cool down hot surfaces as it prevents the dissipation of heat. This effect consists of the development of a vapor layer that makes the impinging cooling fluid bounce away when impacting the hot surface, becoming heat dissipation ineffective. This regime is named film boiling.

As the rate of heat transfer in the film boiling is significantly reduced due to the poor thermal conductivity of the vapor layer, this regime should be avoided for applications that require high heat transfer rates. Methods to increase the Leidenfrost point, or delay the onset of the film boiling regime, are therefore of great interest for such applications. [1]

Since Leidenfrost phenomena was first described by Johann Gottlob Leidenfrost in 1756, various aspects have been investigated, such as the effect of droplet size, velocity, fluid physical properties [2][3], and surface roughness, the transition between different boiling regimes, the surface temperature change and heat transfer during impact, the residence time of the impacting droplet, the spreading factor [4-11] and others.

Regarding literature and previous studies, not good references can be found. There are not sufficient studies explaining how these factors can affect or how they could be used to control the Leidenfrost point.

In summary, controlling the Leidenfrost point allows reaching the optimal heat dissipation regime in a better manner, making possible heat transfer more efficient. It has become fundamental in the high heat flux removal, where spray cooling plays an important role. The lack of information in the current literature makes necessary the development of a systematic study about how Leidenfrost point behaves.

1.2 Main objective of the thesis

The primary objective of this work is to experimentally determine the different boiling regimes and Leidenfrost point for deionized water and FC-72 evaluating the influence of fluids properties and the dependence of droplet impact height over a heated plain silicon surface. The study will be accomplished by determining the evaporation curve of both liquids.

The following main tasks are to consider:

- Literature review on previous Leidenfrost works and studies over plain silicon and other plain and structured surfaces. Different Leidenfrost points for water over different material surfaces are reported.
- Design and fabricate a test facility for studying impacting droplet behavior and evaporation time.
- Identify deionized water and FC-72 Leidenfrost points on a plain silicon surface at different droplet impinging height.
- Determine droplet boiling regimes for deionized water and FC-72 at various droplet impinging height.
- Estimate the pool boiling curve for water and FC-72

1.3 Scope of the thesis

This work focuses on the determination of the different boiling regimes and LFP of deionized water and FC-72 over a heated plain silicon surface. The influence of fluid properties and impinging droplet height will be studied. This will be achieved by representing and analyzing the evaporation curve of both fluids. A Weber map showing the different boiling regimes is developed for both fluids.

1.4 Structure of the thesis

Chapter 2 clarifies fundamental concepts and definitions used in the field and reviews previous results in the research area “Leidenfrost Phenomenon.”

Chapter 3 defines the study method, working fluids and materials used and describes facility setup for droplet regimes visualization.

Chapter 4 presents and discuss final results achieved.

Chapter 5 presents concluding remarks and offers a track for further work.

2 Theory and Literature Review

This section presents a review of the basic notions needed to obtain a good understanding of the work.

2.1 Boiling regimes and droplet behavior

2.1.1 Pool boiling curve

The most important concept in the field of boiling was developed by S. Nukiama in 1934. Nukiama described different boiling regimes regarding fluid behavior and heat transfer efficiency. [12]

The standard pool boiling curve is a plot of heat flux, q'', versus excess temperature, $\Delta T = Tw - Tsat$. As the value of the excess temperature increases, the curve traverses four different regimes:

- Natural or free convection
- Nucleate boiling
- Transition boiling
- Film boiling

Different experimental methods may be used to define the pool boiling curve; nevertheless, constant temperature control and constant heat flux control are the two most commonly cited.

A typical boiling curve for saturated pool boiling of water at atmospheric pressure for a temperature-controlled environment is shown in Fig. 2.1.

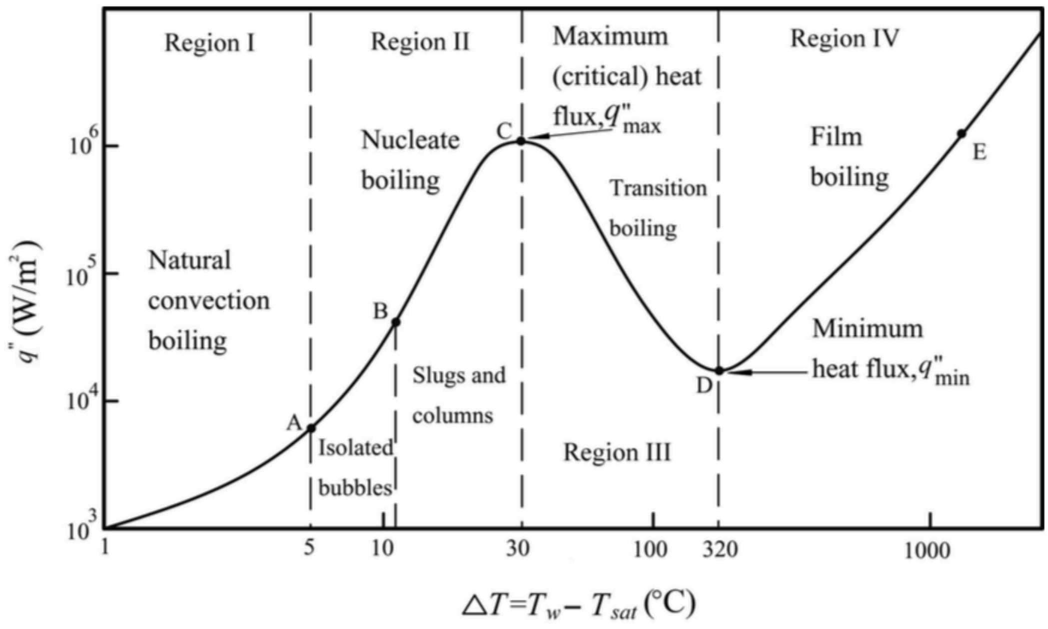

Figure 2.1 - ***Boiling curve for saturated pool boiling of water at atmospheric pressure for a temperature-controlled environment [13]***

The theoretical curve is divided into four regions defining the different boiling behaviors.

a. Region I

When the excess temperature ΔT is less than 5 °C, there are not bubbles formation. Instead, heat is transferred from the solid surface to the bulk liquid via natural convection. Heat transfer coefficients in this regime can be calculated using the semi-empirical correlations for natural convection.

b. Region II

When the excess temperature increases beyond 5 °C, the system enters the nucleate boiling regime – point A on Fig. 2.1. Vapour bubbles are generated at certain preferred locations on the hot surface called nucleation sites; these are often microscopic cavities or cracks on the solid surface. As the excess temperature increases beyond point B in Fig. 2.1, additional nucleation sites become active and more bubbles are generated. The higher density of bubbles leads to their interaction with each other.

Bubbles from separate sites now merge to form columns and slugs of vapor, hence decreasing the overall contact area between the hot surface and the saturated liquid.

Consequently, the slope of the boiling curve begins to fall and the heat flux eventually reaches a maximum value, $q''max$, referred to as the critical heat flux. The critical heat flux (CHF) results in the maximum heat flux and minimum droplet evaporation time.

c. Region III:

As the temperature increases beyond the critical heat flux point, the rate of bubble generation exceeds the rate of bubble detachment from the heated surface. Bubbles from an increasing number of sites merge to form continuous vapor films over portions of the surface, further decreasing the contact area between the heated surface and the saturated liquid. These vapor films are not stable; however, they can detach from the surface, leading to restoration of contact with the liquid and resumption of nucleate boiling.

Under these unstable conditions, the surface temperature may fluctuate rapidly, so the excess temperature shown on the ΔT-axis of Fig 2.1 between points C and D should be regarded as an average value.

Since the boiling in this regime combines unstable film with partial-nucleate boiling types, it is referred to as the region of transition boiling.

d. Region IV

When the excess temperature becomes high enough to sustain a stable vapor film, the heat flux reaches its minimum value, $q''min$. This point, known as the Leidenfrost temperature, marks the upper-temperature limit of the transition boiling regime. The Leidenfrost point (LFP) results in the minimum heat flux and maximum droplet evaporation time.

At temperatures above the Leidenfrost temperature, the bulk liquid and the heating surface are completely separated by a stable vapor film, so boiling in this regime is known as film boiling. The phase change in film boiling occurs at a liquid-vapour interface, instead of directly on the surface, as in the case of nucleate boiling.

Pool boiling continues in this regime until the surface temperature reaches the maximum allowable temperature of the heating surface (1687 K for silicon, for instance). Beyond that point, the heating surface can melt in a potentially catastrophic failure [13]. The boiling curve is important for understanding the evaporation of droplet in contact with a hot surface describes in the next section.

2.1.2 Evaporation curve

A common technique used for determining the Leidenfrost temperature requires measuring evaporation times of liquid sessile droplets of a given initial volume over a range of surface temperatures to produce a droplet evaporation curve as shown in Fig. 2.2(b). The curve displays droplet evaporation lifetime versus surface temperature and exhibits the four distinct heat transfer regimes also shown on the traditional pool boiling curve of Fig. 2.2(a). In the single-phase regime, characterized by long evaporation times, heat from the surface is conducted through the liquid film and is dissipated by evaporation at the liquid-gas interface [14].

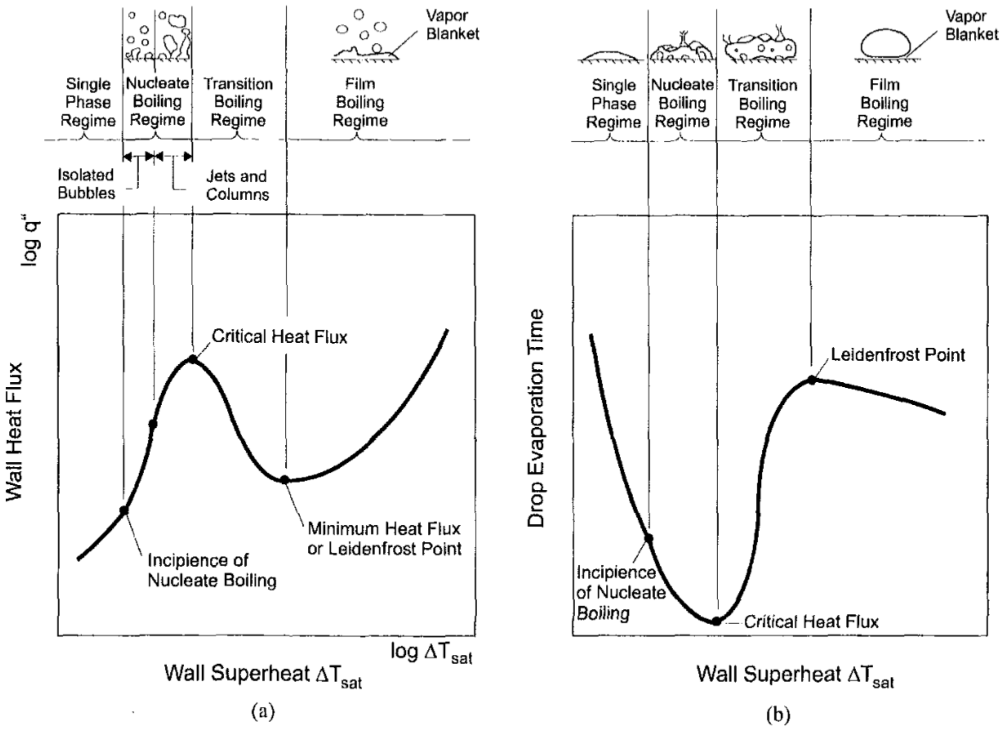

Figure 2.2 – ***(a) Traditional pool boiling curve. (b) Droplet evaporation curve***

2.2 Leidenfrost Phenomenon

When a drop impinges gently on a surface heated well above the liquid's boiling temperature, the liquid may evaporate so fast that the drop floats on its vapor. The vapor layer then acts as a thermally insulating film causing the drop to evaporate much more slowly than if it remained in contact with the surface. This phenomenon is known as the Leidenfrost effect. The Leidenfrost Point is identified to the onset of the film boiling and results in the minimum heat flux and maximum droplet evaporation time.

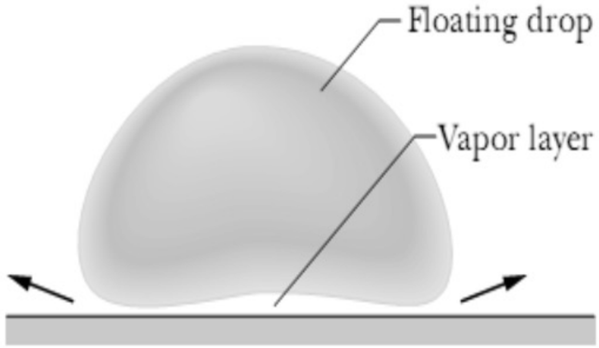

Figure 2.3 – ***Leidenfrost drop in cross section***

Since it was first reported in 1756, by Johann Gottlob Leidenfrost, various aspects of the Leidenfrost effect have been studied, most importantly the determination of the Leidenfrost temperature for different liquids and surfaces [15, 16].

In this work, the Leidefrost point is defined as the surface tested sample temperature, at which the droplet evaporation time is greatest, and will be referred as LFP.

2.2.1 Static and dynamic Leidenfrost point

In general, measurements of the Leidenfrost temperature were performed with zero or at most small incident velocity because of the characteristic time scale of the impact, of an order of several milliseconds, is negligible compared to the drop’s total evaporation time.

In other words, the Leidenfrost temperature is assumed not to be affected by the impact dynamics and is commonly considered as the lowest boundary of the film boiling regime [17–20]. Hence to be referred herein as the static Leidenfrost temperature.

However, in most realistic situations where the impact velocity is not negligible, the Leidenfrost temperature should be regarded as a dynamic quantity [21, 22]. One can define the dynamic Leidenfrost temperature as the minimum temperature of the surface at which the developing vapor layer causes an impinging droplet to bounce.

As compared to the static case, there have been very few studies that focus on the dependence of dynamic LFP on impact conditions.

2.2.2 Influential parameters

Previous research work carried out so far have determined that LFP may depend on the following parameters: Size of the liquid mass, the method of liquid deposition, liquid subcooling, solid thermal properties, surface conditions and pressure.

The following table summarizes how different authors define the influence of these parameters on LFP.

Table 2.1 – ***Leidenfrost point influential parameters literature review [14]***

Parameter	Observations/References
Size of liquid mass	• LFP independent of liquid mass size (Goltfried et al. 1966 and Patel and Bell, 1966) • LFP increased with droplet volume (Nishio and Hirata, 1978)
Method of liquid deposition	• LFP differed between steady state drop size technique using a pipet and the transient sessile drop technique (Godleski and Bell, 1966) • LFP increased with droplet velocity (Patel and Bell, 1966, Yao and Cai, 1988; Klinzing et al., 1993; and Labeish, 1994) • LFP did not differ between sessile and impinging drop (u_0 < 5 m/s) (Bell, 1957 and Nisihio and Hirata, 1978)
Liquid subcooling	• Liquid subcooling had little effect on LFP for water on polished aluminum brass, and stainless steel, but did cause an increased LFP on Pyrex (Baumeister et al., 1970) • Subcooling increased drop lifetime but did not influence the LFP (Hiroyasu et al. 1974) • Subcooling raised the LFP for wate rand other fluids at high pressures where both sensible and latent heat exchange are significant (Emmerson and Snock, 1978)
Solid thermal properties	• LFP increases as solid thermal capacitance decreases (Patel and Bell, 1966; Baumeister et al., 1970; and Nishio and Harata, 1978). • Baumeister and Simon (1973) developed a LFP correlation accounts for solid thermal properties • LFP independent for solid thermal diffusivity (Bell, 1967 and Emmerson, 1975).
Surface conditions	• Gotfried et al. (1996) estimated the vapor layer beneath a film boiling sessile water drop was on the order of 10 μm, which is on the same length scale as surface aspirates on machine finished surfaces (Bernardin, 1993). Thus. Rough surfaces in comparison to polished surfaces would be expected to require a higher LFP to support a thicker vapor layer to avoid liquid-solid contact for a sessile drop (Bradfield, 1996). • LFP increased as a surface roughness and fouling increased (Baumeister et al. 1970; Baumeister and Simon, 1973; and Nishio and Hirata, 1978) In contrast, Bell (1967) claimed that surface oxide films had a negligible effect on the LFP for droplets • LFP increased with increasing surface porosity (Avedisian and Koplik, 1987). • LFP decreased with increased advancing contact angle in pool boiling (Kovalev, 1996; Unal et al., 1992; and Labesih, 1994 and Ramilison and Lienhard, 1987)

Pressure	• LFP increased with pressure for various fluids (Nikolayev et al. 1974; Hiroyasu et al. 1974; and Emmerson, 1975; Emmerson and Snoek, 1978). • ($T_{leid} - T_{sat}$) found to remain constant for various pressures (Hiroyasu et al. Emmerson, Nishio and Hirata, 1978; and Testa and Nicotra,1986). • Rhodes and Bell 819879 observed ($T_{leid} - T_{sat}$) for Feon-114 to be constant over a reduced pressure range of 0.125 to 0.350 and found it to decrease with increasing pressure above this range. Klimenko and Snytin (1990) reported similar findings for four inorganic fluids.

This work will be focused on how the Liquid Deposition Method influence on LFP. It is important to state that the rest of the influential parameters are not modified during the experimental procedure.

2.3 Weber number and droplets fundamentals

2.3.1 Weber number

The Weber number (We) is a dimensionless number that represents the ratio of the fluid inertia force and the fluid surface tension. It is often useful in analyzing fluid flows where there is an interface between two different fluids, especially for multiphase flows with curved surfaces. The quantity is useful in analyzing thin film flows and the formation of droplets and bubbles.

For a droplet with density ρ, velocity before impact v^2, characteristic length l (e.g. initial droplet diameter) and surface tension σ the Weber number is,

$$We = \frac{\rho v^2 l}{\sigma}$$

We number is also an important parameter when comparing contact angle (CA) measurements and evaporation lifetime of a droplet on a heated surface due to their dependence on the inertia force.

Different Weber number is considered in this work. A Weber map is defined for the studied fluids. Due to the difficulty that represents the measurement of the droplet falling speed, the different Weber numbers have been estimated by substituting $2gH$ for v^2 in the definition,

$$We = \frac{2\rho g H l}{\sigma}$$

where g corresponds to the gravity and H to the height from the droplet is thrown out [13].

2.3.2 Surface Wettability

Wetting is the ability of a liquid to maintain contact with a solid surface. Wettability is the degree of wetting, and it is determined by a force balance between adhesive and cohesive forces. Adhesive forces between a liquid and solid cause a liquid drop to spread across the surface. Cohesive forces within the liquid cause the drop to ball up and avoid contact with the surface. A substrate surface can have the properties of complete wetting or non-wetting and everything in between. If a liquid is brought in contact with a substrate and the liquid spontaneously make a film on the substrate, then the substrate is complete or total wetting.

2.3.3 Contact Angle

The Contact Angle (*CA*) is the angle formed by a liquid and the three-phase boundary where the liquid-vapour interface meets the solid-liquid interface. The contact angle is determined by the result of adhesive and cohesive forces. The contact angle provides an inverse measure of wettability.

A contact angle less than 90º usually indicates that wetting of the surface is very favorable, spreading over the surface. Contact angles greater than 90º means that wetting of the surface is unfavorable, forming a compact liquid droplet.

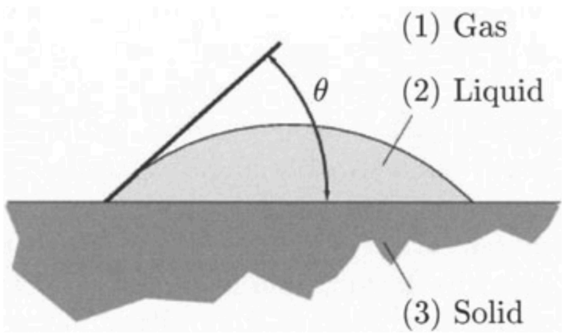

Figure 2.4 - ***Liquid droplet on a solid surface with contact angle. For $\theta \rightarrow 0^o$ complete wetting of the solid occurs, whereas for $\theta \rightarrow 180^o$ the contact between the two phases and liquid would disappear [24]***

2.4 Previous results

While the interaction between liquid sprays and hot solid objects occurs in a wide variety of industrial, domestic and environmental applications, our understanding of the mechanisms involved in the process is far from complete. Indeed, current methods of estimating the heat transfer and fluid dynamics of sprays impacting hot surfaces are mostly empirically derived. Of fundamental importance to such processes is the hydrodynamic and thermodynamic behavior of individual droplets which impact a solid surface.

In 1756 Johann Gottlob Leidenfrost published *A Tract About Some Qualities of Common Water* where the film boiling regime was first described as the Leidenfrost phenomena. The Leidenfrost experiment consisted in throwing water droplets on a heated frying pan. Around 200ºC Leidenfrost observed water droplets “dancing” on the pan due water evaporates so quickly that a thin vapor layer formed between the heated surface and the droplet, leading to a longer droplet lifetime.

Since this first statement made by Leidenfrost, increasing development of technology, instrumentation, and computational tools, next to the desire of explaining how LFP behaves have made that a great quantity of studies has appeared in the literature. A brief review must suffice here.

The droplet evaporation process after impinging on a solid wall near Leidenfrost point was theoretically analyzed by Heng and Zhou [25]. A correlation for predicting evaporation lifetime was obtained based on the theoretical analysis and experimental results.

Gottfried [26] have presented evaporation time data for a small droplet of five ordinary liquids and have proposed an analytical model which is in fair agreement with the data. The model postulates that heat is transferred to the droplet by conduction from the plate below the drop through the supporting vapour film and by radiation from the plate; mass is removed by diffusion from the outer surface and by bulb evaporation from the lower surface; the drop is supported by the excess pressure above atmospheric in the flowing vapour film under the droplet. Gottfried reported a LFP for water on a stainless steel surface of 285ºC. Impinged droplets diameter were between 3.7 and 4.3 mm and liquid subcooling temperature 25ºC.

Baumeister [27] analyzed the evaporation rate of larger masses, especially those smaller than the critical size for bubble break-through and obtained good agreement between theory and experiment. Droplets impinged on stainless steel, brass, aluminum, Pyrex, and gold. Different LFPs for water were reported depending on the characteristic of the materials where the droplets were impinged (see table xx).

Patel and Bell [28] obtained evaporation rate data for masses up to 10 ml; they also studied bubble dynamics in the 10 ml masses photographically and found that the results were consistent with the submerged surface film boiling studies of Hosler and Westwater [29] and with the prediction of Taylor instability theory. Water LFP on a stainless steel surface was predicted to be 305ºC, considerably higher than the one reported by Gottfried.

Tamura and Tanasawa [30] define water LFP for a stainless steel surface at 302ºC. They studied the total evaporation time of a liquid drop on a hot surface at a temperature up to 900ºC. Ten liquids were used including the pure substances ethanol, benzene and water and the mixtures gasoline, kerosene and heavy oil. Their apparatus consisted of a 16 cm diameter stainless steel plate with a concave surface. Small droplets were placed on the plate, and the evaporation process observed and photographed. Plate temperatures are starting about 50ºC below the liquid boiling point and ranging beyond the point where the combustible liquid ignited resulted in evaporation curves that covered all regions of boiling.

Michiyoshi and Makino [31] investigated the heat transfer characteristics for evaporation of droplet of pure water placed on smooth surfaces of copper, brass, carbon steel and stainless steel at a temperature ranging from 80-450°C. They correlated the heat transfer with temperature.

Kim et al. [32] and Auliano et al. [33] reported water LFP for plain silicon in two recent studies. In Kim et al. experiment water droplets impinged from a height of 1.5 mm over the surface. For plain silicon oxide, water LFP achieved was at a surface temperature of 275ºC. Auliano et al. article reported a LFP for water on plain silicon at 269ºC. A droplet evaporation curve is represented where droplets were released on a plain silicon surface from 7 mm height. Droplet volume was about 20 µl and initial droplet diameter, D_0, of around 3 mm.

Tabla 2.1 – ***LFPs review for different materials***

Reference	LFP (ºC)	Surface Material	Notes
Baszkowska and Zakrzewka (1930)	157	Silver	
Borishansky and Kutadeiadze (1953)	310 255	Graphite	T_f=20ºC T_f=85ºC
Borishansky (1953)	222 194 250 237	Brass Brass Copper Copper	T_f=19ºC T_f=89ºC T_f=20ºC T_f=85ºC D_0 = 4.5 mm
Tamura and Tamasawa (1962)	302	Stainless steel	
Gottfried (1962)	285	Stainless steel	T_f=25ºC 3.7 < D_0 < 4.3 mm
Betta (1963)	245	Not given	4.6 < D_0
Lee (1965)	280	Not given	7.8 < D_0
Godleski and Bell (1966)	320	Stainless steel	LFP = 264ºC for ext. liquid masses and 161ºC for transient technique
Gottfried et al. (1966)	280	Stainless steel	
Kutateladze and Borishanski (1966)	250	Not given	
Patel and Bell (1996)	305	Stainless steel	0.05 < V< 10 ml
Baumeister et al. (1970)	515 305, 325 230, 235 > 200 235 155 265 < 184	Pyrex Stainless steel Brass Brass fresh polish Aluminium Alum. Fresh pol. Aluminium Gold fresh pol.	D_0 = 0.39 mm D_0 = 0.39 & 2.25 mm D_0 = 0.39 & 2.25 mm D_0 = 2.25 mm D_0 = 0.39 & 2.25 mm D_0 = 0.39 mm D_0 = 2.25 mm D_0 = 2.25 mm
Emmerson (1975)	282 316 284	Stainless steel Monel Brass	LFP also given for pressures of 210, 315, 420 and 525 kPa
Xiond and Yuen (1991)	280 - 310	Stainless steel	
Kim et al.	275 ± 5 264 ± 5	Silicon (SiO_2) Gold (Au)	Impinging height 1.5 mm
Auliano et al.	269	Plain silicon	Impinging height 7 mm

Considering all these studies in Leidenfrost phenomena filed and despite significant advances in experimental, theoretical and computational research in understanding of droplet boiling behaviour from the moment of impact, there are many inconsistencies concerning some of the most important aspects related to the boiling regimes and consequent heat transfer, especially regarding critical heat flux, transition boiling, and Leidenfrost point.

To explain this knowledge gap about Leidenfrost phenomenon and boiling regimes for water and dielectric fluids, several experiments have been carried out focusing on different aspects of the phenomenon. This thesis helps to have a better understanding of these Leidenfrost phenomenon aspects.

3 Experimental setup and procedure

3.1 Introduction

A sessile drop facility was built to study the droplet evaporation characteristics on a heated surface. In particular, the liquid-solid interface temperature corresponding to the Leidenfrost point is determined from droplet evaporation curve for a plain silicon of different liquids. The different fluids boiling regimes are also determined.

3.2 Droplet evaporation method

The representation of the droplet evaporation curve is the selected method to determine the LFP.

This method consists of a droplet being placed on a hot surface while the evaporation time is recorded and plotted as a function of the surface temperature.

To perform the experiment steady-state conditions are achieved (surface temperature oscillations lower than 5ºC). For every steady-state case, at least five droplets impinged on the sample.

During nucleate boiling, droplet evaporation time is recorded with the high-speed camera (125-500 fps) due the short droplet lifetime during this regime. For the film boiling regime, a stopwatch is used as the droplet starts hovering over the sample and the droplet lifetime becomes longer. A stainless steel ring is used to maintain the droplet on the wafer surface during film boiling regime.

A droplet of the tested fluid spreads on the surface, and at the same time vigorously boils, ejecting smaller drops. Once reached the critical point, it floats on the surface without experiencing significant phase change known as the Leidenfrost effect.

3.3 Facility Setup

The purpose of this facility is related to the necessity boiling heat transfer on different materials and processed surfaces with the possibility of performing visual experiments. The facility designed presents the capacity of changing experimental condition such as droplet volume and heat provided to the test section.

3.3.1 Schematic diagram of experimental setup

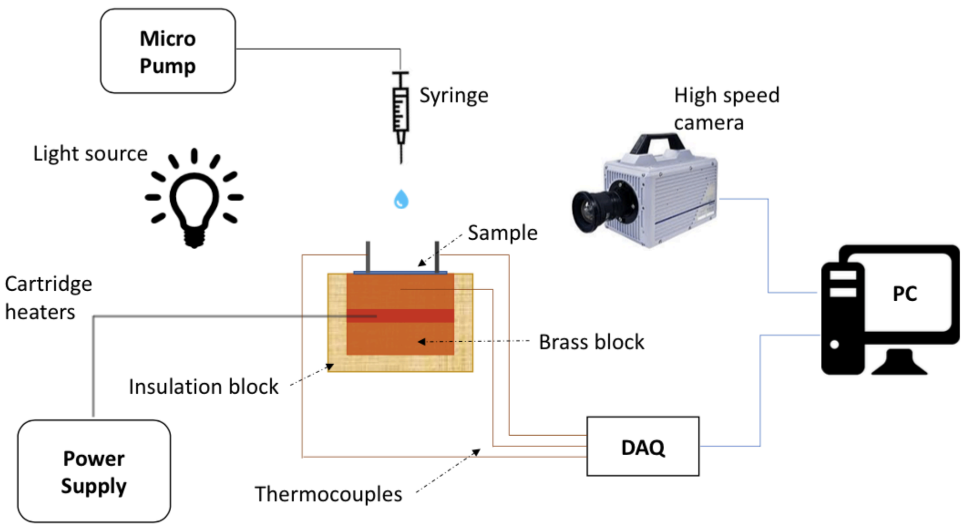

Figure 3.1 - ***Schematic of the apparatus developed to measure droplet evaporation time***

The overall system is placed on a stage that allows the level adjustment. The test section is composed of a power supply with cartridge heaters used to heat a brass block that contains the processed sample (silicon wafer). A syringe pump is used to impinge droplets on the sample, and a high-speed camera is utilized for the visualization of the dynamics and record the evaporation time. The entire system is located under a suction duct.

Figure 3.2 - ***Sessile drop experimental apparatus***

3.3.2 Facility main components

3.3.2.1 Power supply, cartridge heaters, and brass block

Four high-temperature cartridge heaters connected in parallel to a power supply (Sorensen AMETEK 100-15 DC) are inserted into a brass block, covered by a 10 mm thick isolation material and used as heat source.

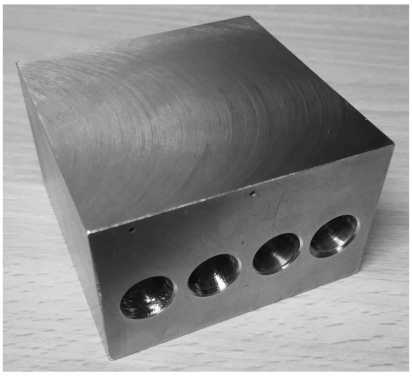

Figure 3.3 - ***Brass block for studying impacting droplets over a plain silicon surface***

Three K-type thermocouples (calibrated prior to the experiment) are placed. Two on opposite sides of the surface and a third one inside the brass block. Both surface thermocouples are held by two screws making their points contact the wafer surface. Ensuring a good contact between thermocouples and the tested sample and reducing the interfacial thermal contact resistance between the heating block and the sample.

The thermally conductive paste is used to improve temperature measurement by thermocouples (to improve thermocouples accuracy).

Surface and inside block temperatures were recorded by using LABVIEW with an acquisition rate of 2 Hz.

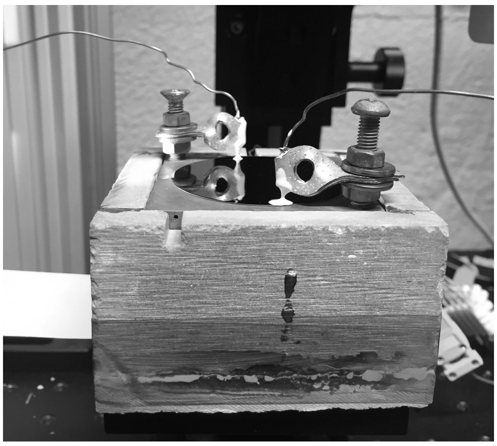

Figure 3.4 – ***Surface thermocouples placed on a plain silicon wafer***

3.3.2.2 *Syringe pump*

A micro-syringe pump above the center of the heated test surface is used to dispense droplets of deionized water and FC-72 with a small flow rate 0.1 mL/min in the case of water and 0.05 mL/min in FC-72 case. The droplet detachment from the needle due only to the gravitational force keeps the droplet size uniform (20 µl for water/ 3 µl for FC-72).

The syringe needle used is 0.8 mm in diameter and 22 mm in length, it is kept the same syringe for every experiment in order to keep the same conditions of the experiments, and enable the comparison and discussion of the results.

Droplets are impingement from different heights. The micro-syringe pump is placed on a long travel linear translation stage. This allows to change the position of the droplet impingement and to keep the syringe away from the hot source surface, particularly at the high temperature, avoiding fluid warming.

Figure 3.5 – ***Micro-syringe pump operating panel***

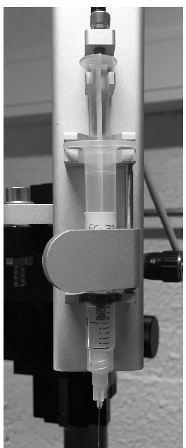

Figure 3.6 – ***Syringe placed on micro pump***

3.3.2.3 Ring

A stainless steel ring avoids the droplet from rolling off the test area during the film boiling regime.

Figure 3.7 – ***Stainless steel ring used during film boiling regime***

3.3.2.4 High-speed camera

A high-speed digital camera is used to visualize liquid droplet behavior, droplet lifetime recording and computing Weber number. Videos are recorded at 125, 500 and 10000 frames per seconds.

Figure 3.8 – ***High-speed digital camera: PHOTRON FASTCAM SA3***

3.3.2.5 Data acquisition

A data acquisition (DAQ) unit provide by national instruments is used. Thermocouples are connected to the DAQ, and the recorded data is sent to the facility working computer where data is processed by the designed LABVIEW file.

3.3.3 Material

3.3.3.1 Silicon Wafer

The facility is constructed and designed to use NTNU Nano lab Silicon wafers. Silicon is not expensive and presents excellent properties making it suitable for many different applications. This particular type of wafer is selected due it is used in a significant part of previous works, making easier the comparison with existing data and enable future testing of micro and nanostructured samples previously fabricated.

Table 3.1 shows plain silicon wafer characteristics.

Table 3.1 – *Silicon wafer characteristics*

Supplier	University Wafer
Diameter	2'' or 5.1 mm
Polish	SSP
Dopant	B
Fabrication Method	Czochralski (CZ)
Thickness	250-300 μm
Orientation	100
Type	P
Resistivity	0-100
Test	Test

3.3.4 Fluids

The working fluids are appointed to be deionized water, FC-72 and HFE 7000.

3.3.4.1 Deionized Water

Water is used in many different cooling applications as computer components, industrial facilities, internal combustion engines, etc. Moreover, water is the most common and cheapest fluid all over the world, its properties are well-known and present a great availability making it suitable to examine the influence of Weber number on LFP.

Deionized water is used to avoid the interaction of mineral ions, contained by the regular water, with the plain silicon wafer.

However, water cooling in electric and electronic devices can be hazardous due the electrical conductivity properties of normal water, becoming necessary the study of non-conductors fluids, dielectric fluids.

3.3.4.2 Dielectric fluids: FC-72 and HFE 7000

As mention above, electric and electronic devices need to meet safety and reliability requirements, for this reason, dielectric fluids, instead of water, are tipically used. In the case of coolant leakage, their dielectricity property protects circuits from being short and electrical discharge, not damaging the equipment.

However, due to their low thermal conductivities and small latent heat, boiling heat transfer rates on dielectric fluids are usually significantly lower than water under similar working conditions. For instance, the thermal conductivity of hydrofluoroether (HFE 7000) is 0.0075 W/m·K which is only 13% of the thermal conductivity of water, 0.58 W/m·K, at 25ºC. Furthermore, HFE 7000 latent heat of vaporization at the boiling point is 142 kJ/kg, only 6.3% of water latent heat of vaporization at the same point [34]. In addition, the low-surface-tension coolant tends to be blown away from the heating walls by vapor flow instead of forming a favourable thin liquid film on the walls for better heat transfer performance. As a result, these efficient heat transfer mechanisms including thin-film evaporation, convective boiling and nucleate boiling are deteriorated.

3.4 Validation

In this section, the different tests carried out in order to prove the validation of the facility is described.

3.4.1 Facility improvements

Here below various improvements achieved while building and designing the facility setup are commented.

a. Evaporation curve plotting

Initially the evaporation curve was represented with a standard plot, where the differentiation between points with short droplet lifetime was difficult. Figure 3.9 shows the original plot.

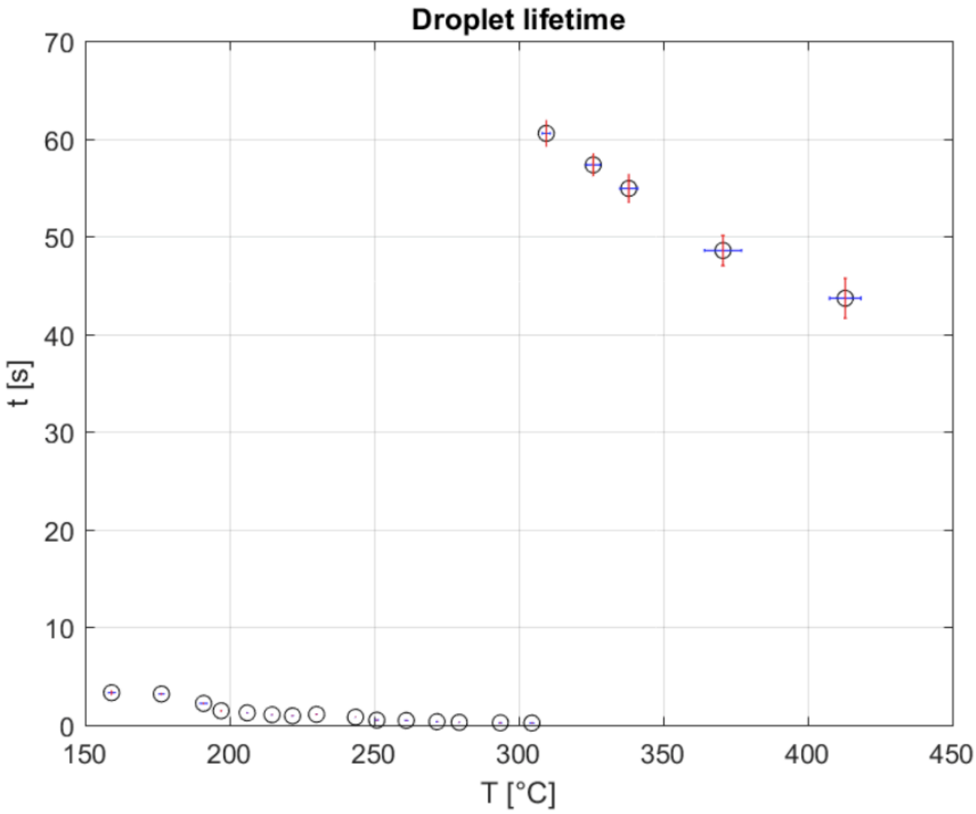

Figure 3.9 – ***Original MatLab deionized water evaporation curve plotting***

MatLab code was modified with the purpose of representing the evaporation curve in a log log plot. Figure 3.10 shows the log log plot, where the different boiling regimes can be appreciated more accurately.

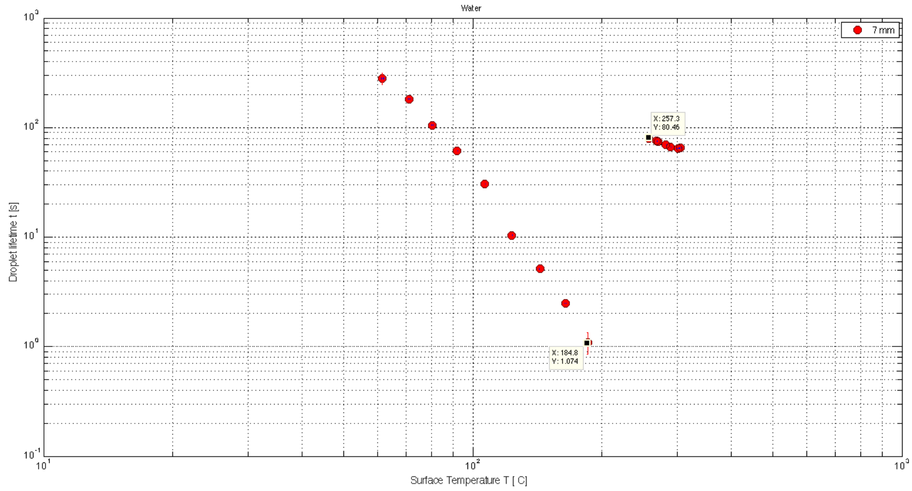

Figure 3.10 – ***Loglog MatLab deionized water evaporation curve plotting***

b. Thermally conductive paste

OT-201 OMEGATHERM thermally conductive paste is used to improve thermocouples measurement on the silicon surface. It is a very high thermally conductive filled silicone paste, which provides an excellent means of conducting heat and expanding the heat path area from the surface to thermocouples, thus increasing the speed of response and improving accuracy. It is rated for continuous use from -40ºC to 200°C. During experiments temperature range exceed. Previous work assures that thermally conductive paste is safe working outside the temperature range. It could be observed that paste performance decrease while not operating in the temperature range.

Figure 3.11 – ***Omegatherm thermally conductive paste***

In order to validate thermally conductive paste, a test comparing thermocouples performance with and without paste was carried out.

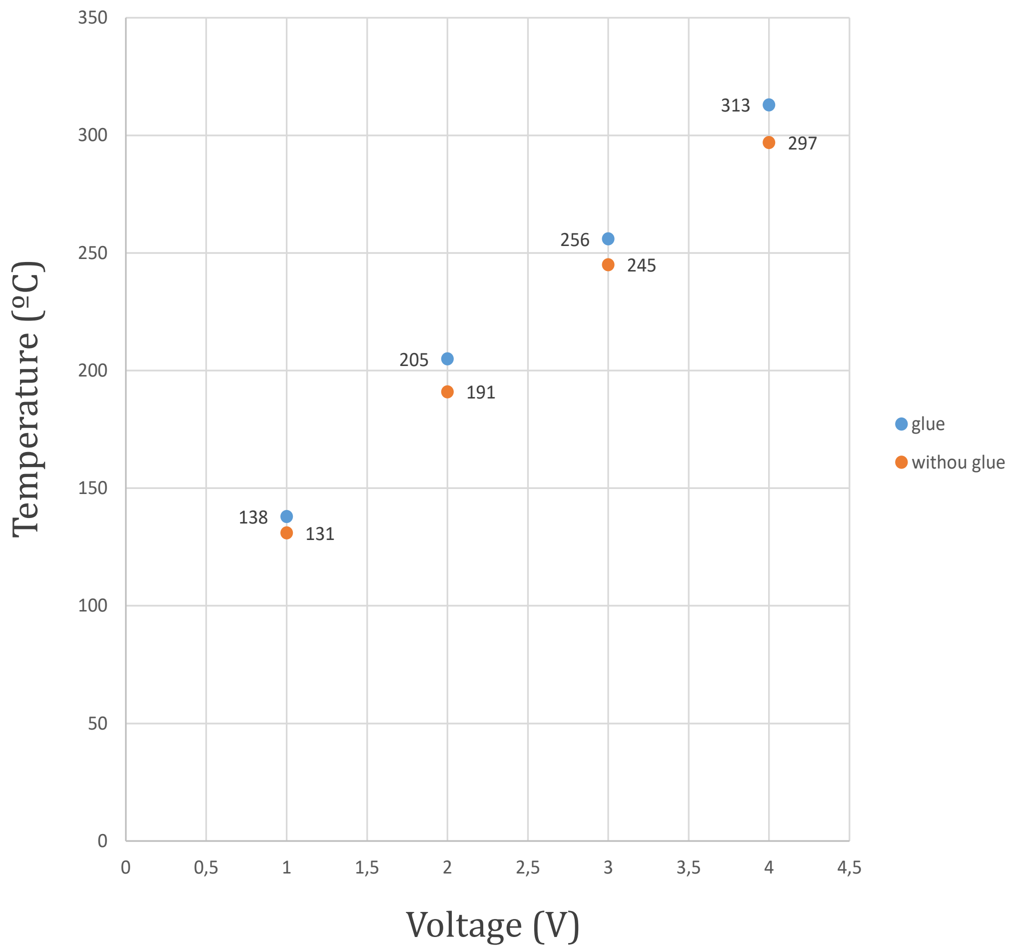

Figure 3.12 – ***Correlation among temperature measurement with or without paste***

Figure 3.12 shows the correlation between temperatures measured with thermally conductive paste and temperatures measured without paste. When using thermally conductive paste on surface thermocouples voltage always corresponded to the same surface and inside block temperature. Temperature oscillation is achieved to be stable around ± 2.5ºC.

c. Thermocouples

The tested area is monitored by three thermocouples, two on the surface and one inside the brass block.

Surface thermocouples were initially placed horizontally pressed by a screw. This way of placement strongly depended on the pressure applied to the thermocouple. To avoid this dependency, a mechanism to place surface thermocouples vertically was designed.

Figure 3.13 – ***Surface thermocouples designed mechanism***

Figure 3.13 shows designed mechanism to place thermocouples vertically where their points are in the tested sample, enabling more precise temperature measurement.

A third thermocouple, placed inside the brass block, is used as a reference.

A correlation between surface and inside block temperatures was conducted in order to ensure the correct operation of the facility.

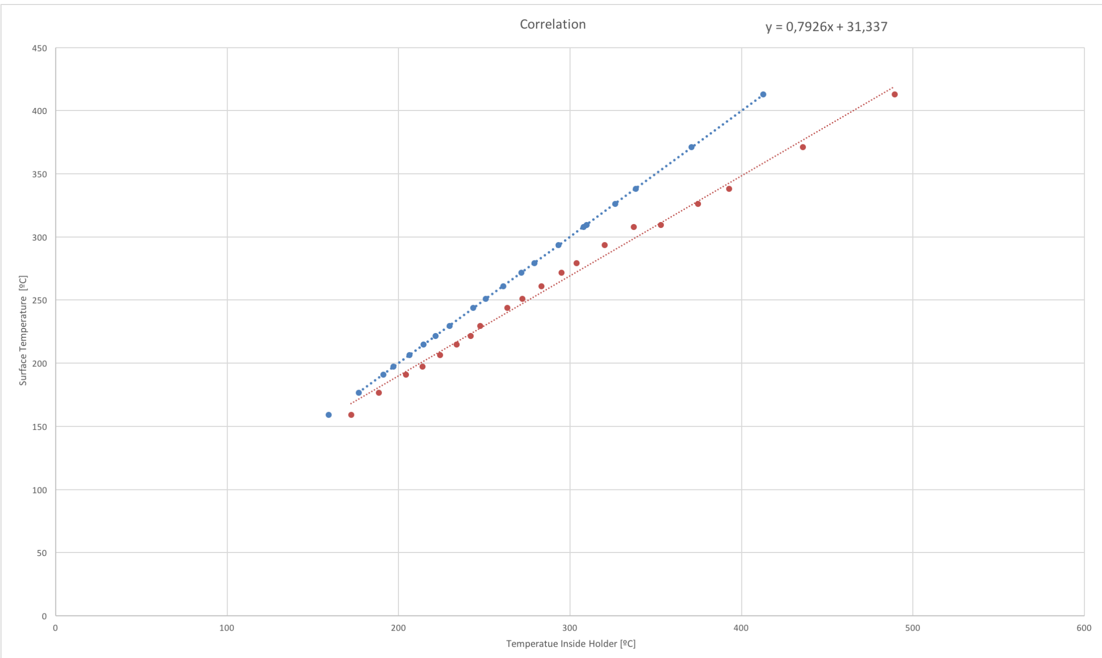

Figure 3.14 – ***Surface and inside brass block temperatures correlation***

Figure 3.14 shows the correlation between inside the block and surface temperature. Notice the greater difference among them when rising temperature. This difference has also been reported by other authors in the reviewed literature.

3.4.2 Facility reproducibility and repeatability

In the present work, the reproducibility and repeatability of the results have been proved by the reproduction of different experiments by various users in different days, obtaining consistent results. The droplet size is very accurate. Figure 3.15 shows that all experiments results follow the same trend regardless user, day, ambient condition, etc.

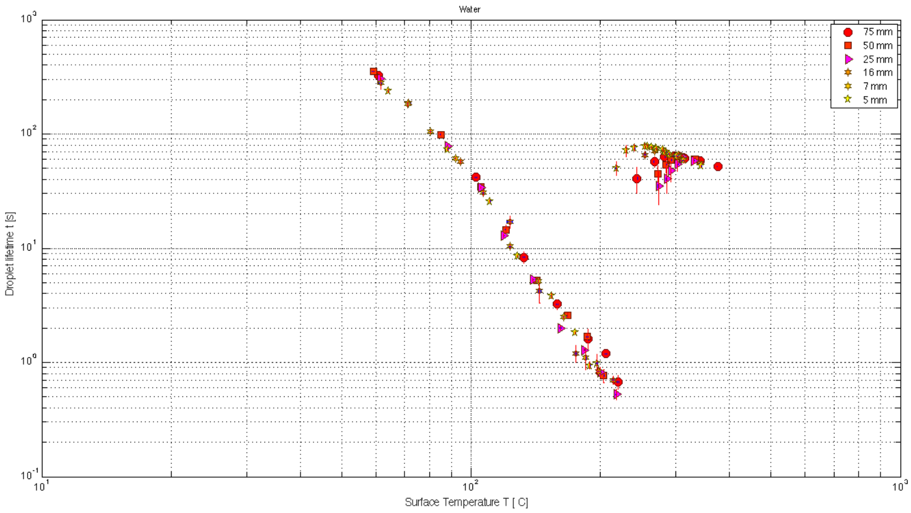

Figure 3.15 – ***All experiments deionized water evaporation curve***

Results consistency shows that facility and conducted experiments reliability are proved.

3.4.3 Calibrations

3.4.3.1 Contact angle measurements

Contact angles of each working fluid are measured with the objective of testing the wettability of these fluids on plain silicon.

The contact angle for deionized water on an original plain silicon wafer is around 75°.

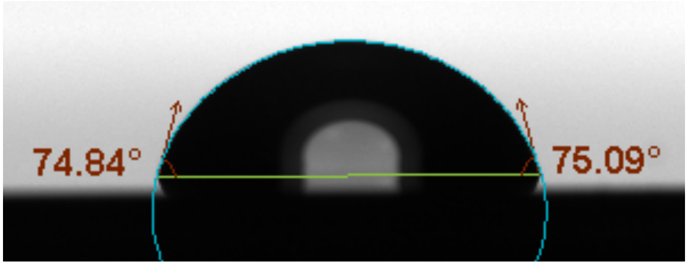

Figure 3.16 – ***Deionized water contact angle on a plain silicon surface***

The contact angle for FC-72 on an original plain silicon wafer is around 12°.

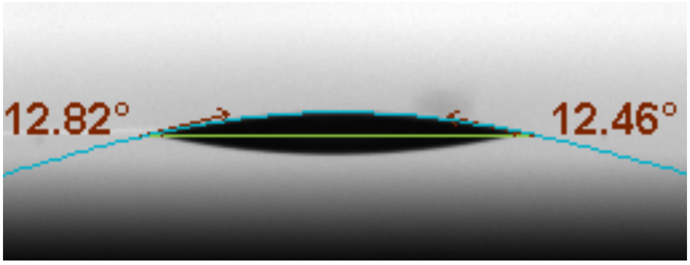

Figure 3.17 – ***FC-72 contact angle on a plain silicon surface***

The contact angle for HFE 7000 on an original plain silicon wafer is around 15°.

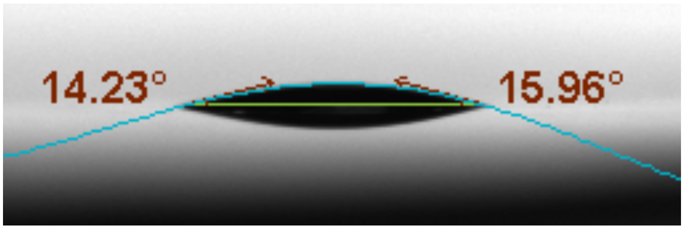

Figure 3.18 – ***HFE 7000 contact angle on a plain silicon surface***

Contact angles are measured using OneAttension Version 2.9 software. The reports generated by the software can be found in C Contact Angle reports.

In the case of FC-72 and HFE 7000, with significant low boiling points, 56.6ºC and 34ºC respectively, contact angle measures are not accurate due droplets were reducing their volume while the software was recording contact angles. A box mechanism allowing the consecution of pressurized conditions should be used in future experiments with low boiling point fluids.

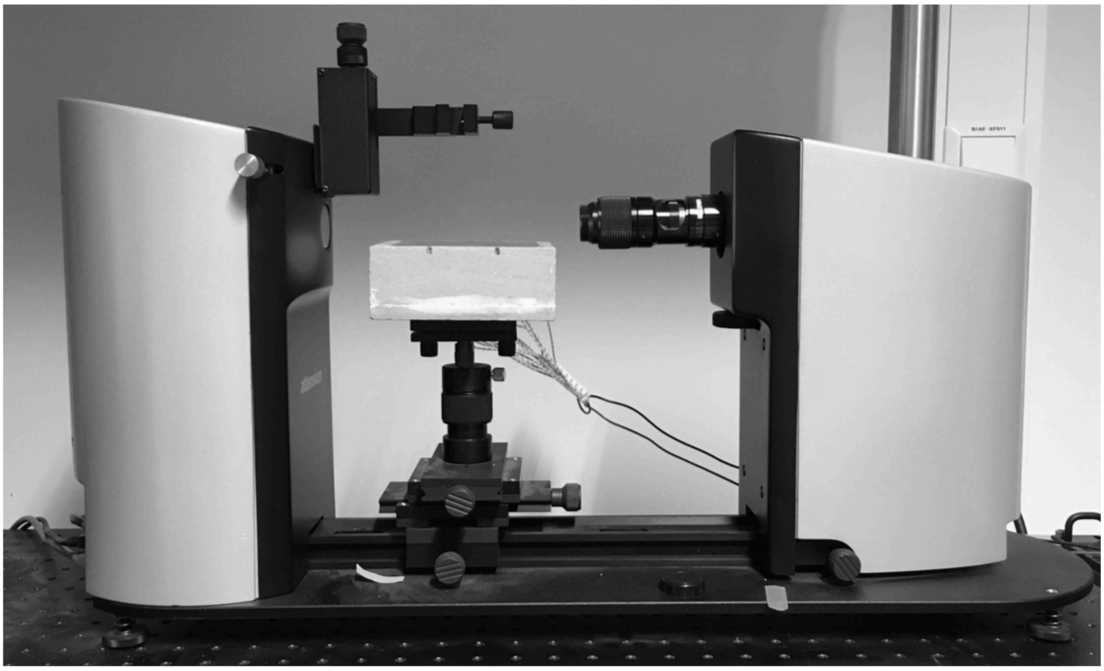

Figure 3.19 – ***Contact angle measurement apparatus***

3.4.3.2 Thermocouples calibration

In order to achieve accurate readings from thermocouples, it is essential to calibrate the device accordingly. Thermocouples are calibrated to measure temperatures between 33ºC and 700ºC.

3.4.3.3 Camera calibration

For each recorded video a frame where syringe needle appears is saved, so knowing the real needle diameter, tested liquid droplet diameter can be calculated.

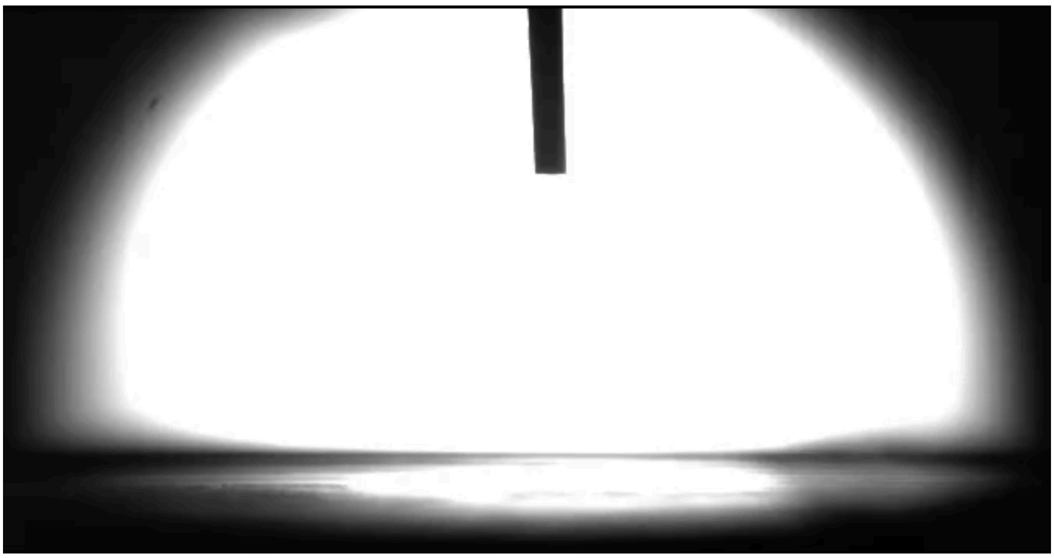

Figure 3.20 – ***Camera calibration frame***

3.4.4 Uncertainty analysis

After the validation tests to reduce experiment uncertainties, the major uncertainties left are related to:

a. Thermocouple calibration accuracy and precision resolution;
b. Uniformity of the temperature distribution over the sample;
c. Droplet lifetime during the transition boiling;
d. Subcooling temperature: Syringe fluid temperature;
e. Droplet keeping ring;

The maximum error in the temperature is the other of 30% while for the time is about 10 seconds for the longest droplets lifetime and 0.05 seconds for the shortest droplets lifetime.

4 Results and Discussions

4.1 Introduction to the results

Heat transfer performance of deionized water and FC-72 in droplet impingement boiling scenarios are discussed in this section. The section begins with a presentation of the different evaporation curves experimentally obtained, where the LFP and CHF are determined for each case and is followed by a classification of the different boiling regimes. A comparison of how different droplet impingement height influence on both fluids boiling regimes and consequently on LFP is also discussed.

4.2 Evaporation curves for deionized water and FC-72

The experimental evaporation curves for deionized water and FC-72 are shown in the following sections. Evaporation curves are given in terms of droplet lifetime versus silicon surface temperature. Different droplet impinging heights evaporation curves are plotted for both fluids. Critical heat flux (CHF) and Leidenfrost point (LFP) are given for each case. All evaporation curves are plotted in log log scale.

It is important to know that all experiments were developed on plain silicon wafers describe in section 3.3.3.1.

4.2.1 Evaporation curves water

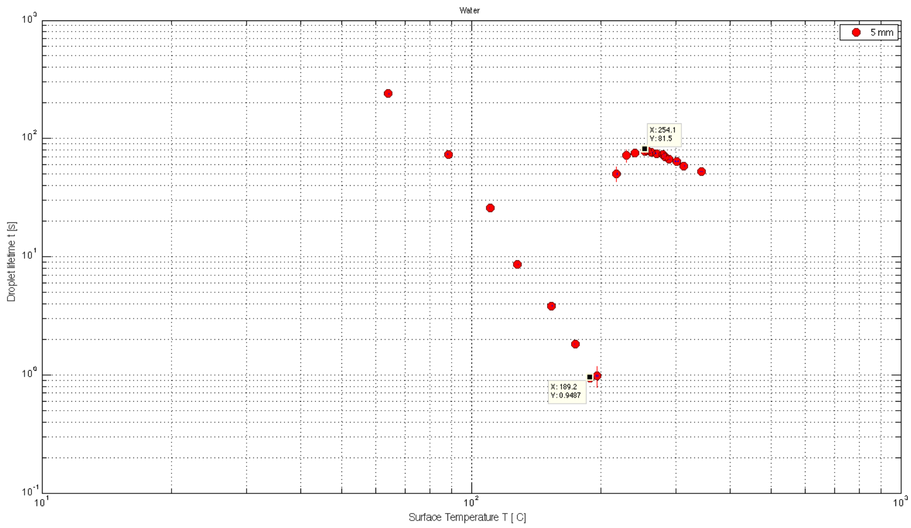

Figure 4.1 – *Deionized water evaporation curve for 5 mm: LFP = 254.1ºC; CHF = 189.2ºC*

Figure 4.1 shows the evaporation curve for a droplet of deionized water released from a height of 5 mm on a plain silicon surface. The droplet takes maximum time to evaporate completely (LFP) at a temperature of 254.1°C and this evaporation time is 81.5 seconds. The droplet takes minimum time to evaporate completely (CHF) at a temperature of 189.2°C and the evaporation time is around 0.9487 seconds.

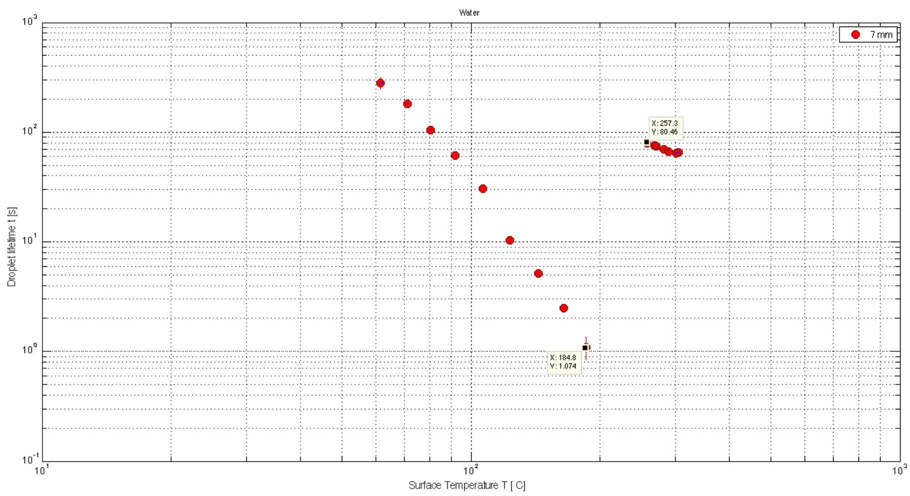

Figure 4.2 - *Deionized water evaporation curve for 7 mm: LFP = 257.3ºC; CHF = 184.8ºC*

Drop evaporation time curve of deionized water (Fig. 4.2) on plain silicon, released from 7mm, shows that the droplet takes maximum time to evaporate completely at a temperature about 257.3°C and corresponding time is around 80.46 seconds. The droplet takes minimum time to evaporate completely (CHF) at a temperature about 184.4°C and the evaporation time is around 1.074 seconds.

For droplets released from 5 mm and 7 mm, it can be observed that fluid impact dynamics are not influencing on the displacing of LFP. At small droplet incident velocity, the characteristic time scale of the impact, of the order of several milliseconds, is insignificant compared to the droplets lifetime. Comparing LFP and CHF temperatures, it can be observed that both cases are in a narrow range.

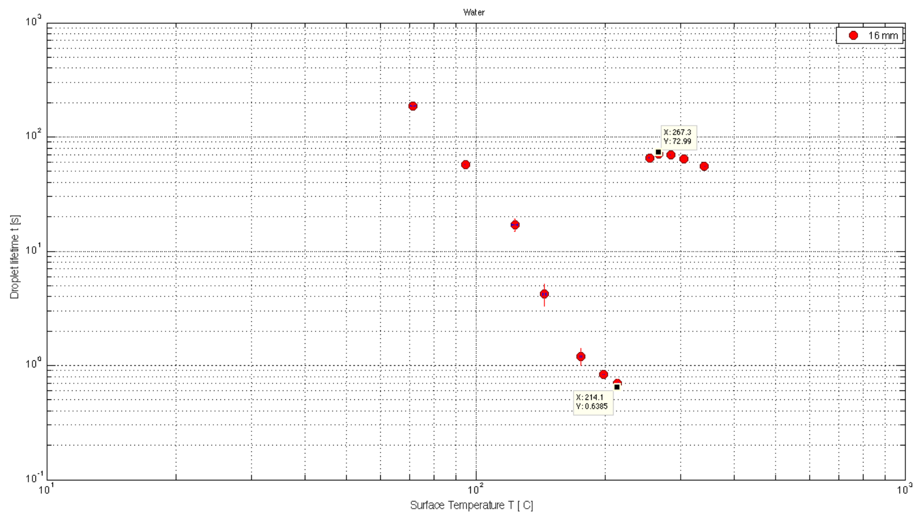

Figure 4.3 - ***Deionized water evaporation curve for 16 mm: LFP = 267.3ºC; CHF = 214.1ºC***

Figure 4.3 shows the evaporation drop time of deionized water on a plain silicon surface impinged from 16 mm. Maximum droplet lifetime, 72.99 seconds, is at a temperature about 267.3ºC, while minimum droplet lifetime is at a temperature of 214.1ºC. From this height droplet dynamics become more important. The influence of the impact droplet dynamics can be notified by the shift on the LFP temperature (About 10ºC delayed respect previous cases) but especially in the CHF delay, almost 30ºC. When droplets, released from such a high height, impact the heated surface, they rebound avoiding the contact during a small fraction of the time.

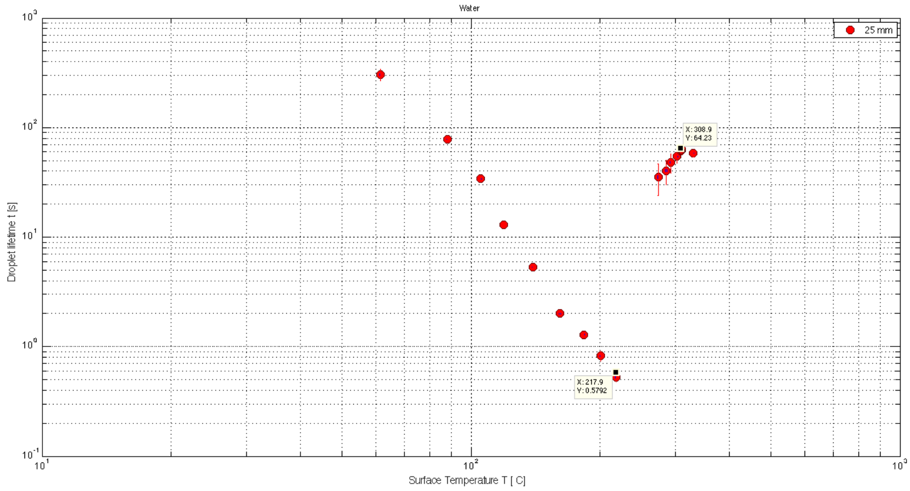

Figure 4.4 - ***Deionized water evaporation curve for 25 mm: LFP = 308.9ºC; CHF = 217.9ºC***

Regarding Fig. 4.4 can be observed that the LFP temperature for a droplet of deionized water released from a height of 25 mm on a plain silicon surface is 308.9ºC. This means an increase of almost 30ºC on LFP temperature compared to 16 mm LFP. As explained before, this increase on LFP could be based on the greater effect of impact dynamics caused by realiszing the studied droplet from a height 10 mm higher than in the previous case.

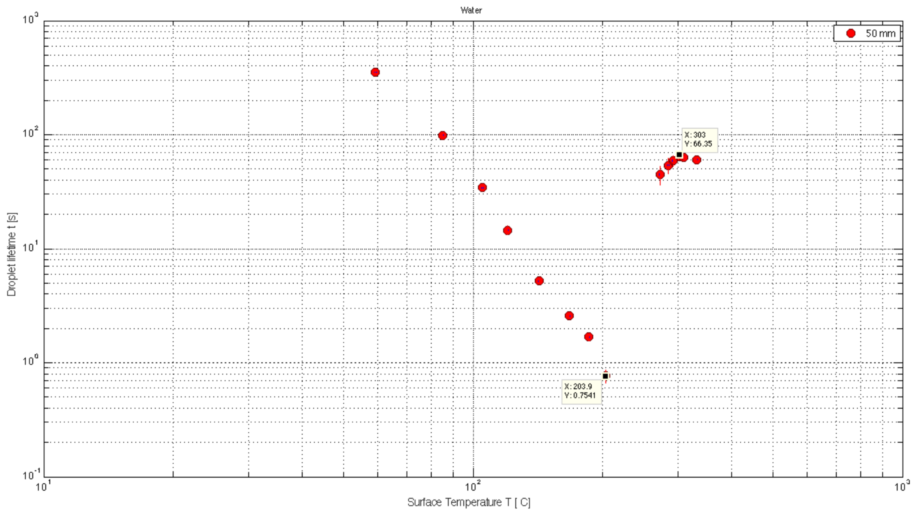

Figure 4.5 - ***Deionized water evaporation curve for 50 mm: LFP = 303ºC; CHF = 203.9ºC***

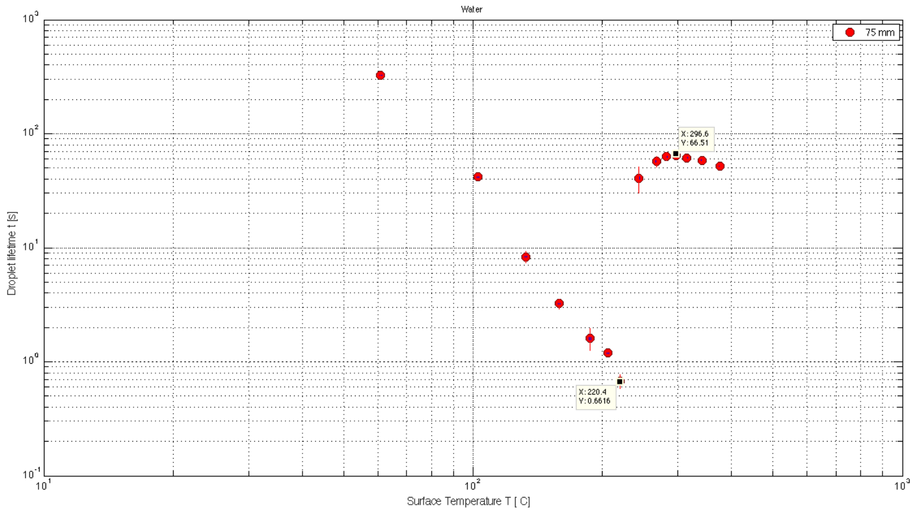

Figure 4.6 - ***Deionized water evaporation curve for 75 mm: LFP = 296.6ºC; CHF = 220.4ºC***

Figures 4.5 and 4.6 show the evaporation curve for 50 mm and 75 mm droplet impinging heights respectively. Maximum droplet lifetimes, 66.35 seconds for 50 mm and 66.51 seconds for 75 mm, are at a temperature around 300ºC in both cases. Also, the maximum droplet lifetime for all three cases is about 65 seconds. However, there is a switch of almost 17 ºC for the minimum droplet lifetime, around half a second on the three cases. This temperature difference can be due to the difficulties to identify when nucleate boiling regime finish and transition boiling starts.

It is important to notice that for 25 mm, 50 mm and 75 mm there is not a significant change in LFP, what suggest that droplet impact dynamics present a limit on influencing LFP displacement.

In summary, in deionized water case, it can be reported that impingement droplets height highly influence on LFP but exists a limit. There is a small shift on the LFP, from droplets releasing heights of 5 mm and 7 mm. As the height is increasing the LFP is delaying in temperature, for a droplet impinged from 16 mm the LDF point is 267.5ºC, 10ºC more than from 5 mm and 7 mm, while for droplets impinged from 25 mm, 50 mm and 75 mm, LFP temperature is stable around 300ºC and droplets maximum lifetime is about 65 seconds. For the CHF temperature can also be observed a delay when increasing the droplets impinging height, even so, the complexity to establish when transition boiling regime starts.

4.2.2 Deionized water boiling regimes

Five different boiling regimes have been identified during deionized water droplet evaporation experiments. These regimes are natural or free convection, nucleate boiling with isolated bubbles, nucleate boiling with slugs and columns, transition boiling and film boiling.

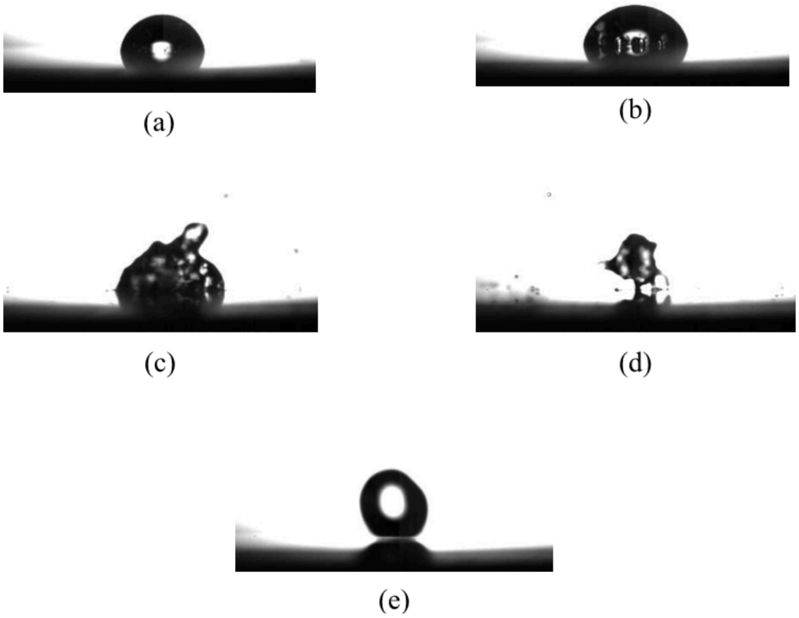

Figure 4.7 – ***Deionized water boiling regimes: (a) Natural or free convection, (b) Nucleate boiling isolated bubbles, (c) Nucleate boiling slugs and columns, (d) Transition boiling and (e)Film boiling***

Figure 4.8 displays droplet evaporation lifetime versus surface temperature and exhibits the five distinct heat transfer regimes. Droplet impinging height: 16 mm.

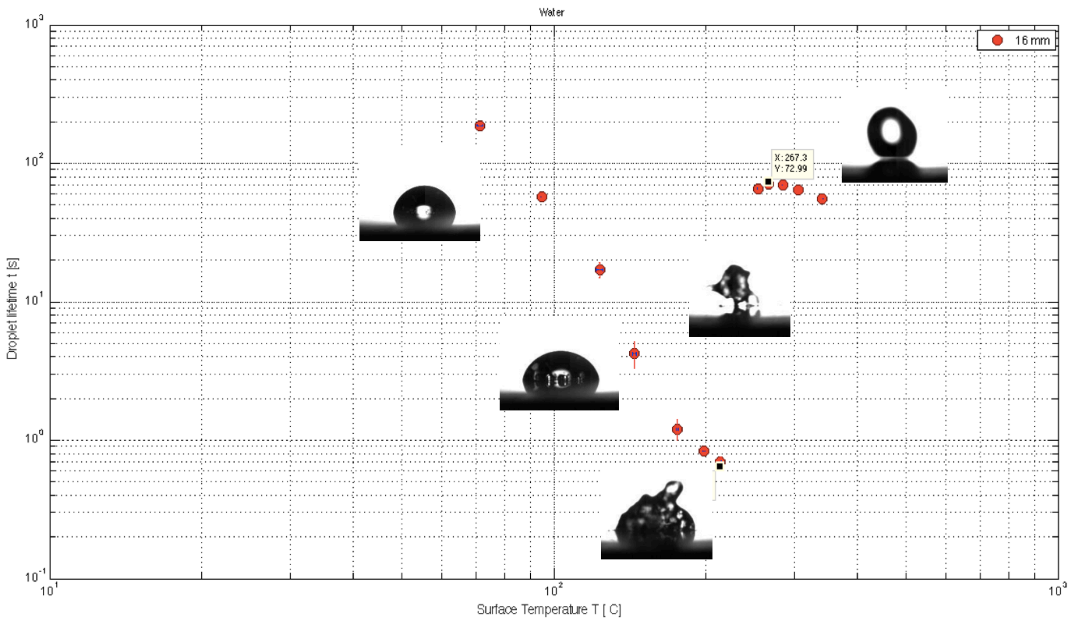

Figure 4.8 – ***Boiling regimes along 16 mm droplet impinging height deionized water evaporation curve***

In the 16 mm case, recognised regimes temperature range are: natural or free convection boiling, from ambient temperature to 94ºC; nucleate boiling: isolated bubbles from 94 to 124ºC; nucleate boiling: slugs and columns, from 124 to 214ºC; transition boiling, from 214 to 267ºC; and finally, film boiling, from 267ºC. During transition boiling regime part of the droplet boils and another part levitates. Notice the difficulty that requires the representation of any point in the transition boiling regime.

4.2.3 Evaporation curve FC-72 results

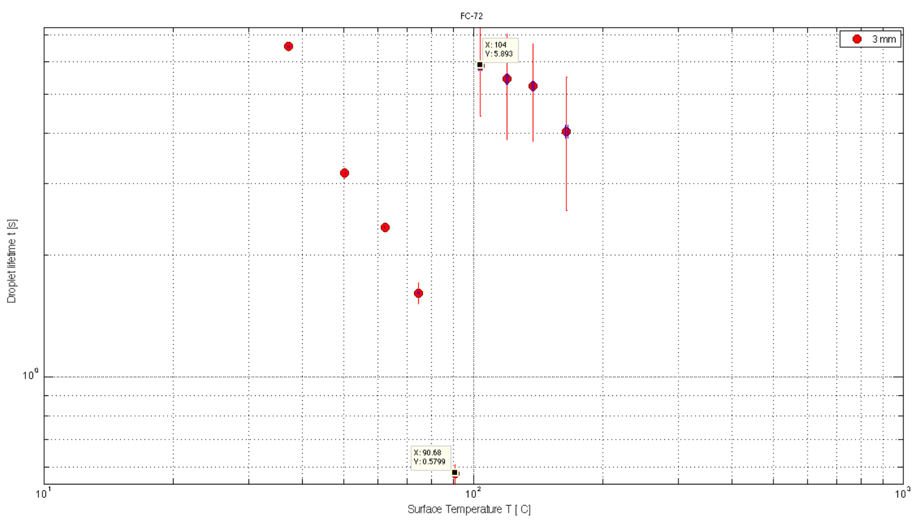

Figure 4.9 – ***FC-72 evaporation curve for 3 mm: LFP = 104ºC; CHF = 90.68ºC***

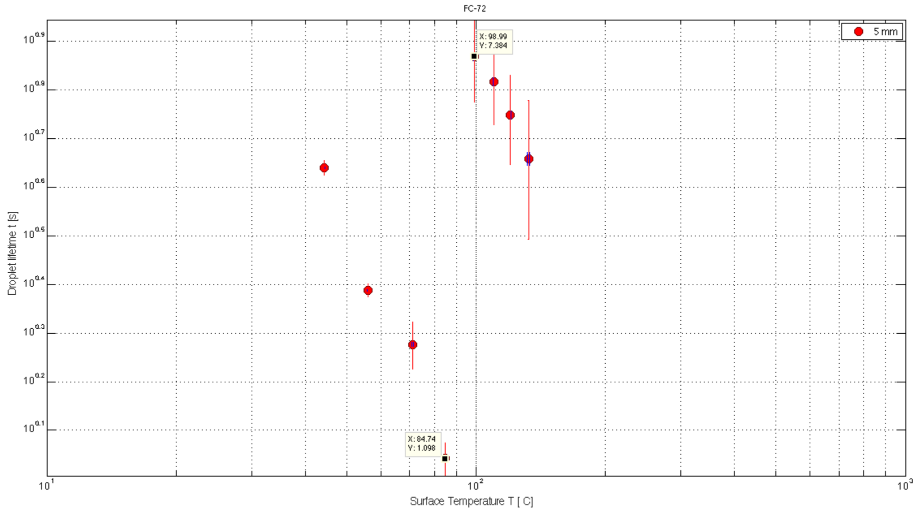

Figure 4.10 - ***FC-72 evaporation curve for 5 mm: LFP = 98.99ºC; CHF = 84.74ºC***

Figure 4.9 and figure 4.10 show the evaporation curves for droplets of FC-72, released from a height of 3 mm and 5 mm respectively. In 3mm case, droplets take maximum time to evaporate completely at a temperature of 104°C and their lifetime is about 5.893 seconds. The CHF temperature for this case is 90.68ºC and droplet lifetime is 0.579 seconds. In 5 mm case, droplets take maximum evaporation time at a temperature of 98.99ºC and their lifetime is 7.384 seconds. For this case, the CHF temperature is 84.74ºC and droplet evaporation time is 1.098 seconds.

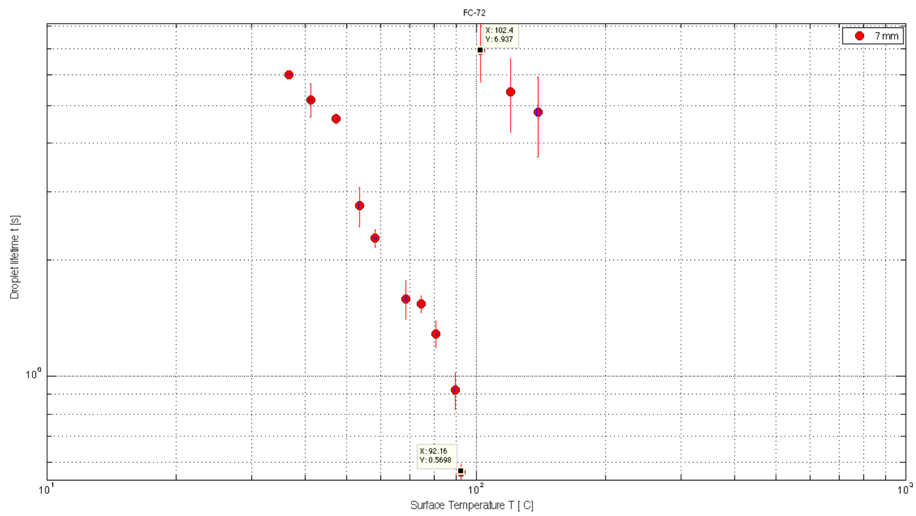

Figure 4.11 - ***FC-72 evaporation curve for 7 mm: LFP = 102.4ºC; CHF = 92.15ºC***

Drop evaporation time curve for FC-72 on plain silicon, droplet released from 7mm, shows that the droplet takes maximum time to evaporate completely at a temperature about 98.99°C and equal evaporation time is around 7.384 seconds. The droplet takes minimum time to evaporate completely (CHF) at a temperature about 84.74°C and the evaporation time is around 1.098 seconds.

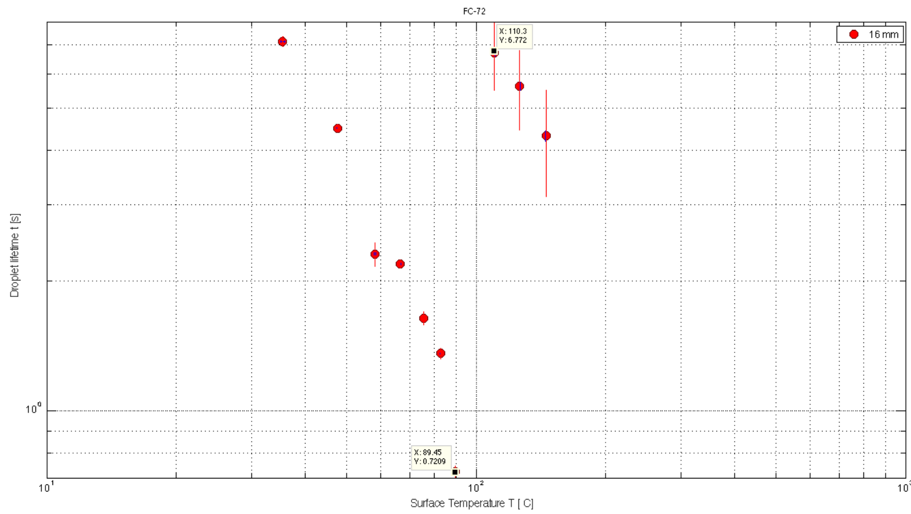

Figure 4.12 - ***FC-72 evaporation curve for 16 mm: LFP = 110.3ºC; CHF = 89.45ºC***

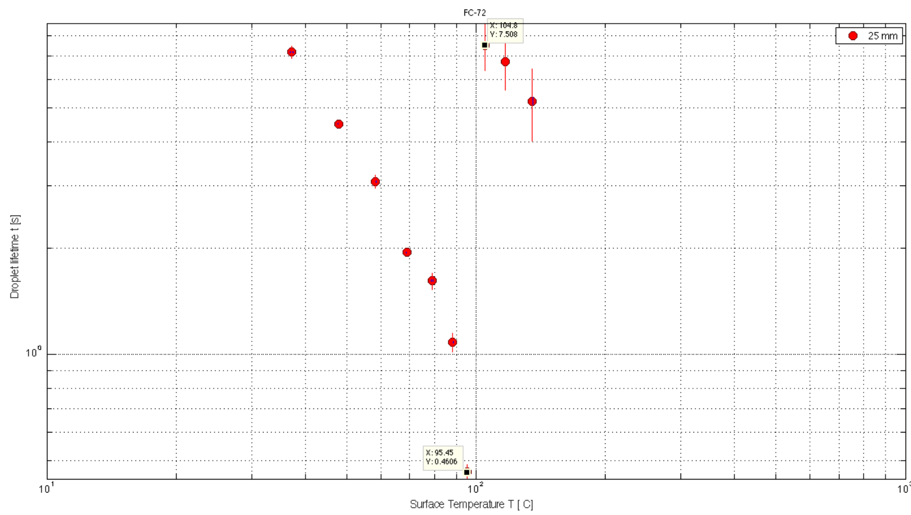

Figure 4.13 - ***FC-72 evaporation curve for 25 mm: LFP = 104.8ºC; CHF = 95.45ºC***

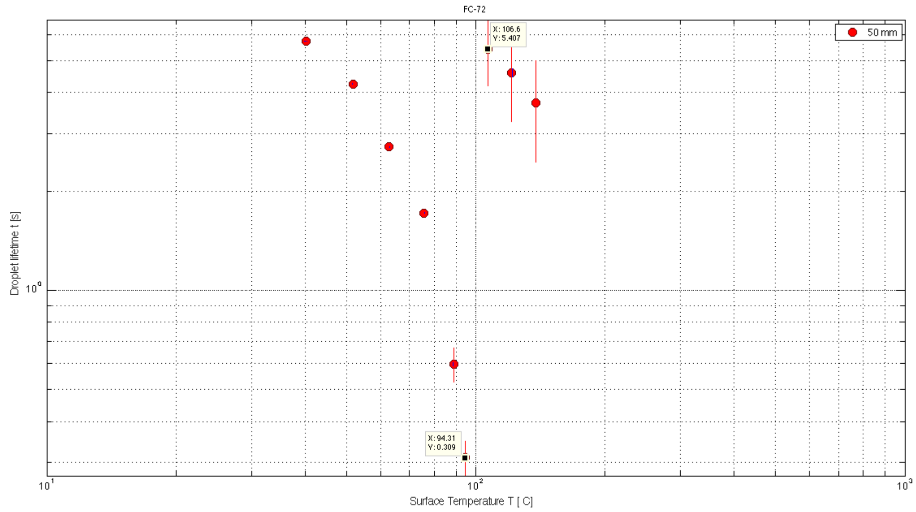

Figure 4.14 - ***FC-72 evaporation curve for 50 mm: LFP = 106.6ºC; CHF = 94.31ºC***

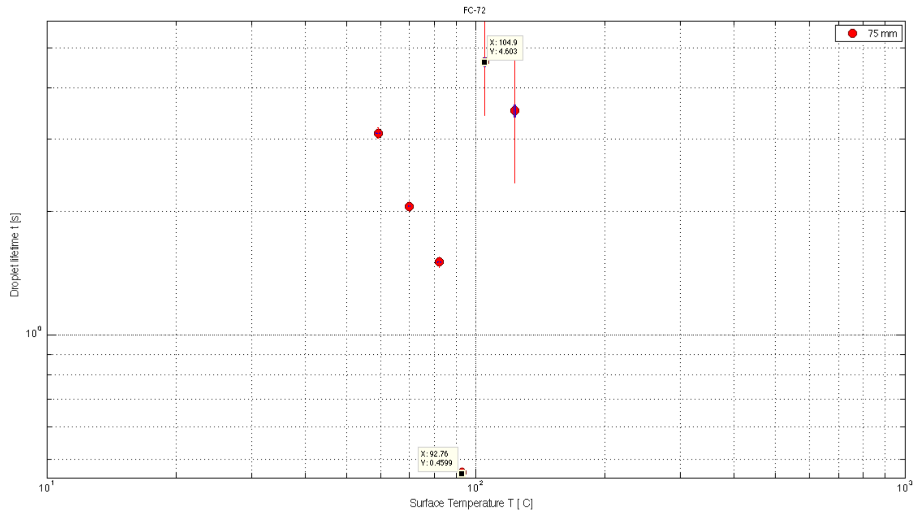

Figure 4.15 - ***FC-72 evaporation curve for 75 mm: LFP = 104.9ºC; CHF = 92.76ºC***

Figures 4.12, 4.13, 4.14, and 4.15 correspond to the evaporation curves for FC-72 droplets impinged from 16 mm, 25 mm, 50 mm and 75mm. Maximum droplet lifetimes are considerably stable, around 5 seconds for all cases, at a mean temperature of 105ºC.

Comparing to the deionized water case, droplet dynamics influence can be considered negligible for every FC-72 droplet impinging height. There is not increase observed on LFP temperature while rising droplet impinging height for this fluid.

Notice about the dispersion of droplet lifetime data during film boiling regime for FC-72. As a result of fluid properties and droplet behavior on the heated silicon surface, the points measured during this regime were considerably challenging for the experiment consecution.

In short, FC-72 evaporation curves showed that LFP for this fluid was around 105ºC independently of the impinging droplet height. Maximum droplet evaporation time varies from 7.304 to 4.603 seconds. During film boiling regime, droplet lifetime was measured by using a stopwatch. Human reaction time when manually operating a stopwatch should be considered.

4.2.4 FC-72 boiling regimes

In FC-72 case, four different boiling regimes have been identified during droplet evaporation experiments. These regimes are natural or free convection, nucleate boiling with slugs and columns, transition boiling and film boiling. However, only three could be recorded. FC-72 evaporation curve presents a significantly narrow transition boiling regime, what makes difficult to determine a point during this region.

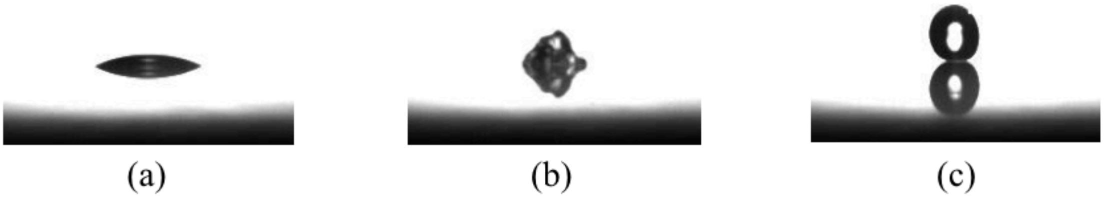

Figure 4.16 – ***FC-72 boiling regimes: (a) Natural or free convection, (b) Nucleate boiling and (c) Transition boiling***

Figure 4.17 displays FC-72 droplet evaporation lifetime versus surface temperature and exhibits the three distinct heat transfer regimes. Droplet impinging height: 25 mm.

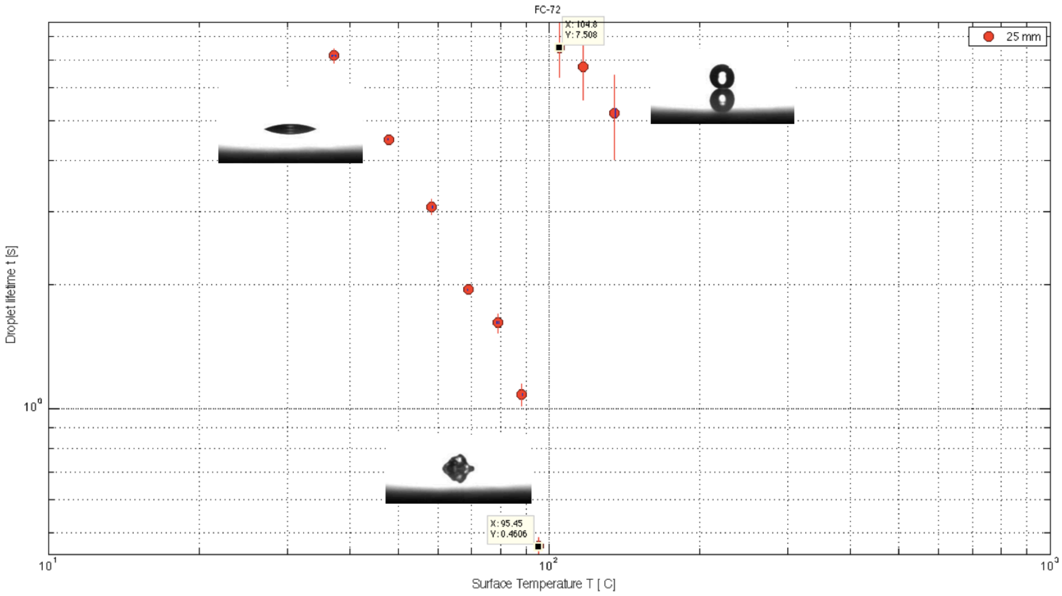

Figure 4.17 – ***Boiling regimes along 25 mm droplet impinging height FC-72 evaporation curve***

In the FC-72 case, 25 mm curve has been selected. Recogniszed regimes temperature range are natural or free convection boiling, from ambient temperature to 69ºC; nucleate boiling: slugs and columns, from 69 to 105ºC; and film boiling, from 105ºC. Transition boiling region should be range between the critical heat flux temperature and the LFP, from 95.4 to 104.5ºC in this case.

4.3 Weber map regimes

To obtain a better understanding and explain boiling regimes along droplet evaporation curve, a weber map has been developed and discussed for both fluids.

As reported in previous theory fundamentals, Weber number is given by the expression:

$$We = \frac{\rho v^2 l}{\sigma}$$

Where ρ is the density, v^2 is the velocity before impact, l the characteristic length (e.g. initial droplet diameter, D_0) and σ the surface tension. The velocity before impact v^2 has been estimated by substituting $2gH$ on v^2.

Table 4.1 summarizes deionized water and FC-72 binding properties to calculate Weber number.

Table 4.1 – ***Deionized water and FC-72 properties at atmospheric pressure.***

	Deionized water	**FC-72**
ρ [kg/m^3]	984.5	1594
σ [N/m]	0.0667	0.008024
l [m]	0.00155	0.003285

The selected value of g was 9.8 m/s^2, while height H was considered different for each experiment in order to modify Weber number.

The influence of Weber number on height is shown in figure 4.18 for both fluids. In the plot can be deduced that FC-72 droplet impinging height has a greater impact on Weber number for FC-72 than for water.

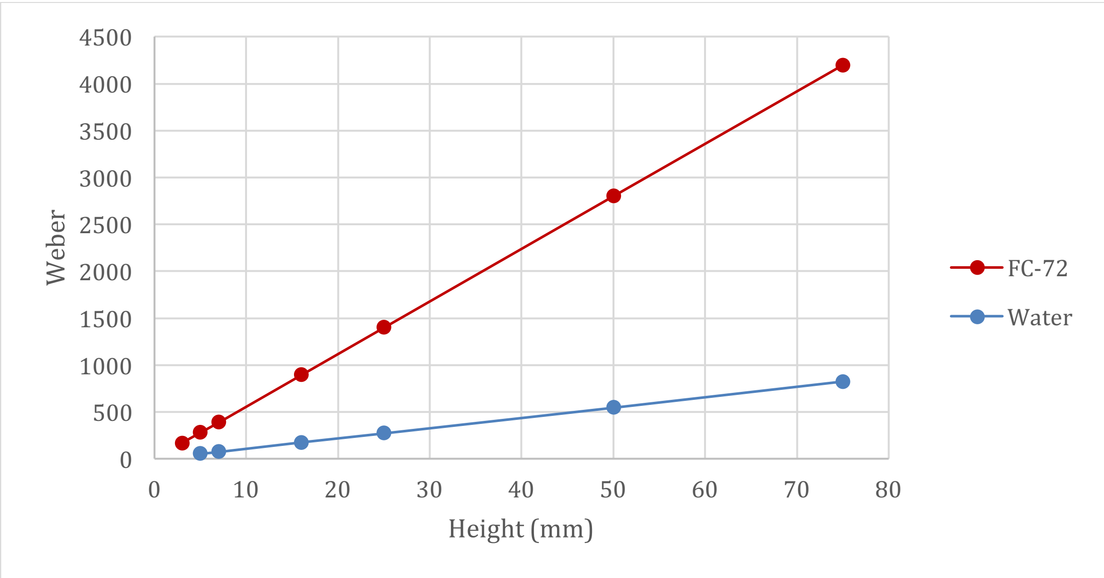

Figure 4.18 – ***Weber number vs. height for deionized water and FC-72***

4.3.1 Water weber map

A Weber map showing experimental boiling regimes is represented for deionized water. As mention in 4.2.2 five regions are identified for deionized water: natural or free convection, nucleate boiling with isolated bubbles, nucleate boiling with slugs and columns, transition boiling and film boiling.

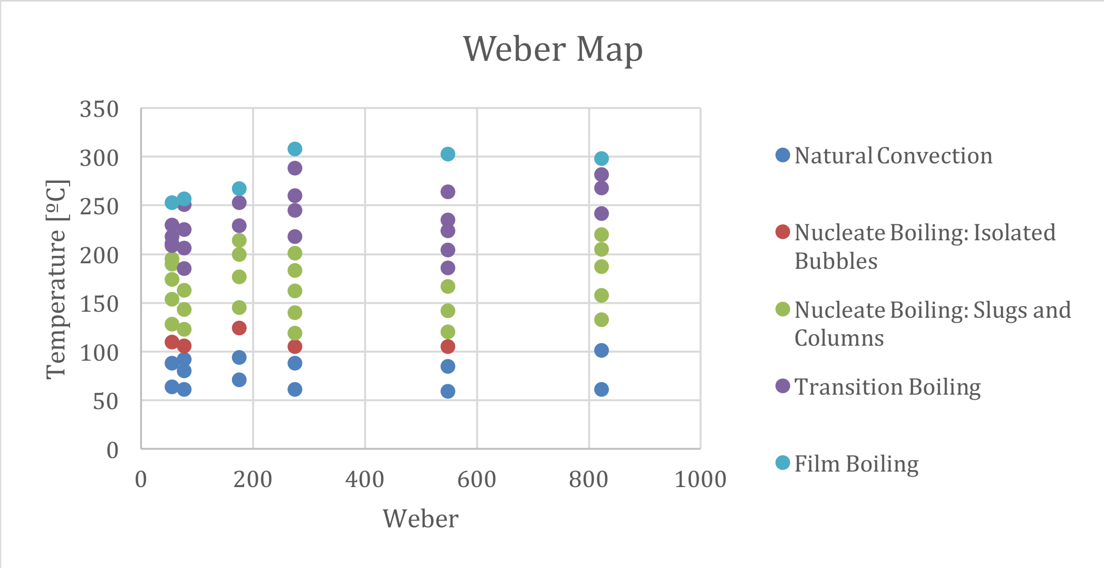

Figure 4.19 – ***Deionized water weber map showing different boiling regimes for all experimental cases***

Figure 4.19 displays the distribution of the different boiling regimes in relation to the Weber number. The most challenging region is transition boiling. For deionized water case can be shown that film boiling regime onset is stabilized from Weber numbers greater than 200.

4.3.2 Demonstration of water boiling regimes on Weber map

Figure 4.20 demonstrates deionized water Weber map where boiling regions are shown. The figure shows water boiling regimes evolution along the time.

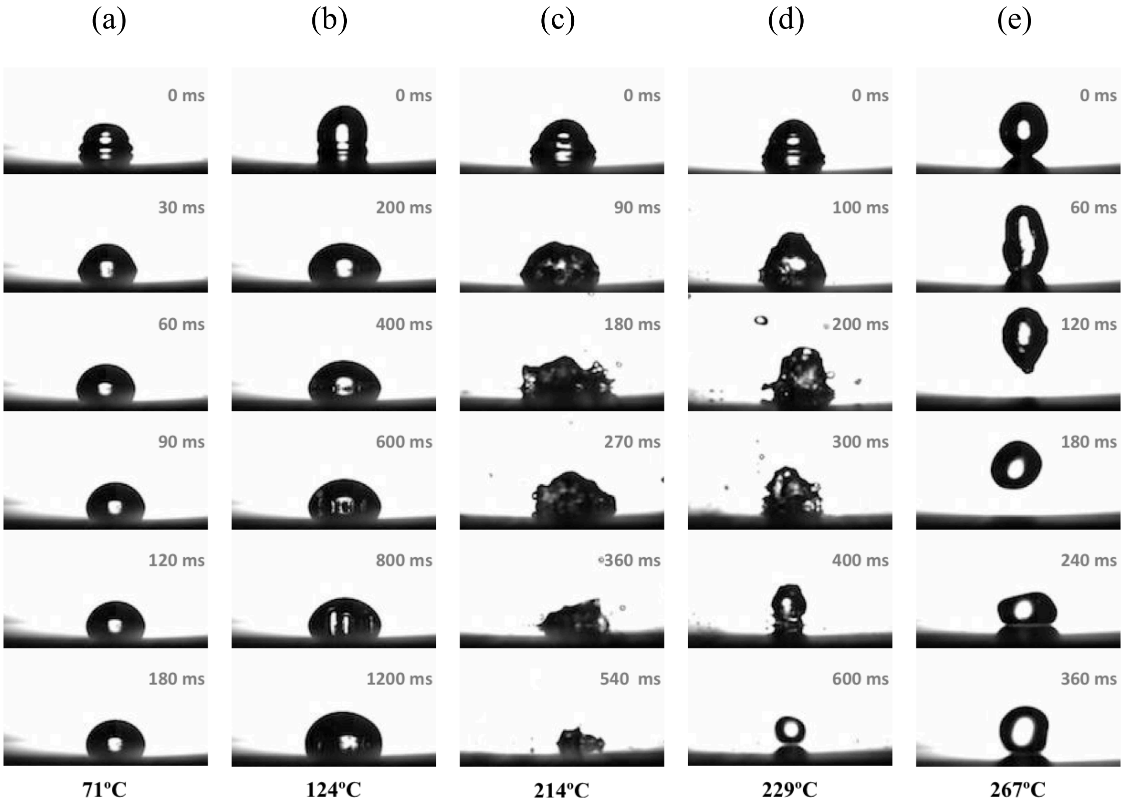

Figure 4.20 – ***Deionized water regimes demonstration for 16 mm evaporation curve: (a) natural convection, (b) nucleate boiling: isolated bubbles, (c) nucleate boiling: slugs and columns, (d) transition boiling and (e) film boiling***

4.3.3 FC-72 weber map

A Weber map showing experimental boiling regimes is represented for FC-72. Four regions are identified for FC-72: natural or free convection, nucleate boiling with slugs and columns, transition boiling and film boiling.

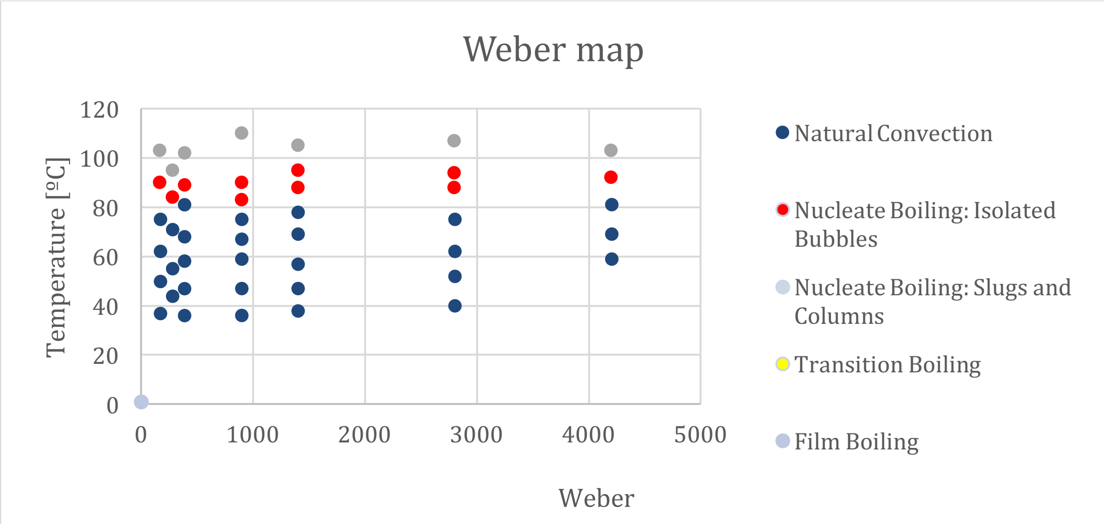

Figure 4.21 – ***FC-72 weber map showing different boiling regimes for all experimental cases***

In figure 4.20 can be appreciated that all regimes are in the same range of temperatures regardless Weber number. In comparison with water, FC-72 weber map shows a very compressed nucleate boiling region. In this regime, bubbles formation can be observed. Due to the small difference between the CHF and the LFP, transition boiling could not be represented. It should be placed between nucleate boiling and film boiling regimes.

4.3.4 Demonstration of FC-72 boiling regimes on Weber map

Figure 4.22 demonstrates FC-72 Weber map where boiling regions are shown. The figure shows FC-72 identified boiling regimes evolution along the time.

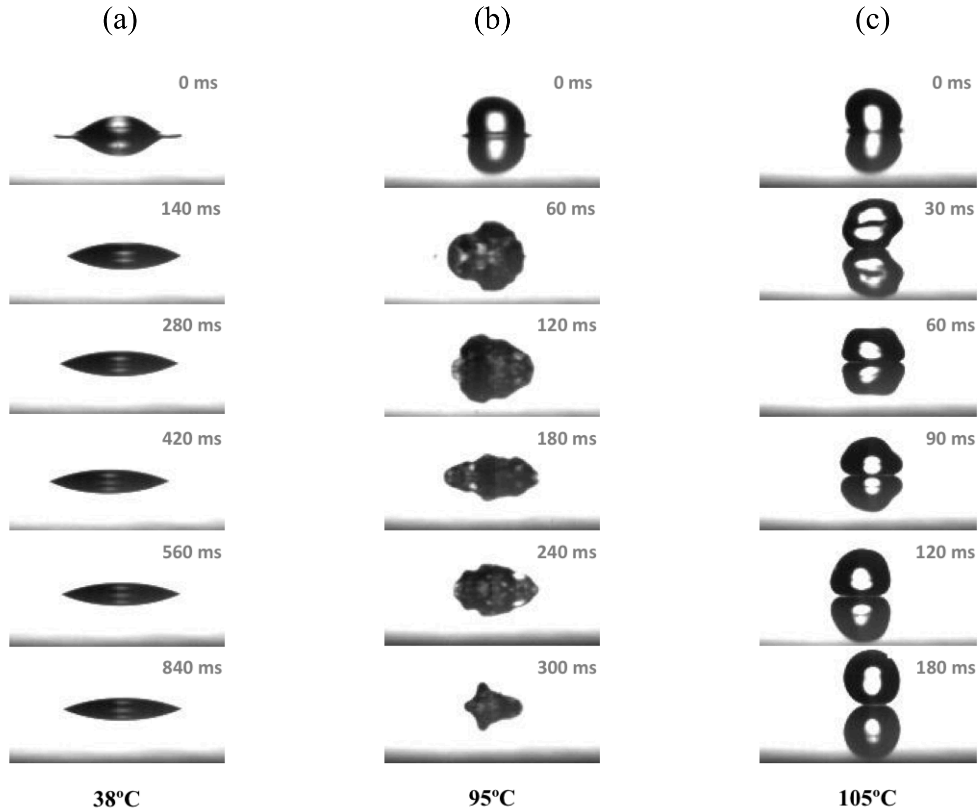

Figure 4.22 – ***FC-72 regimes demonstration for 25 mm evaporation curve: (a) natural convection, (b) nucleate boiling: isolated bubbles, (c) nucleate boiling: slugs and columns, (d) transition boiling and (e) film boiling***

4.4 Fluids comparison

4.4.1 Water all cases

In figure 4.23 boiling regimes along all heights deionized water experiments are represented. As stated above, natural convection, nucleate boiling, transition boiling and film boiling regimes are identified. The curve shows a smooth difference on the trend on the onset of nucleate boiling. Transition boiling and film boiling are perfectly identifiable.

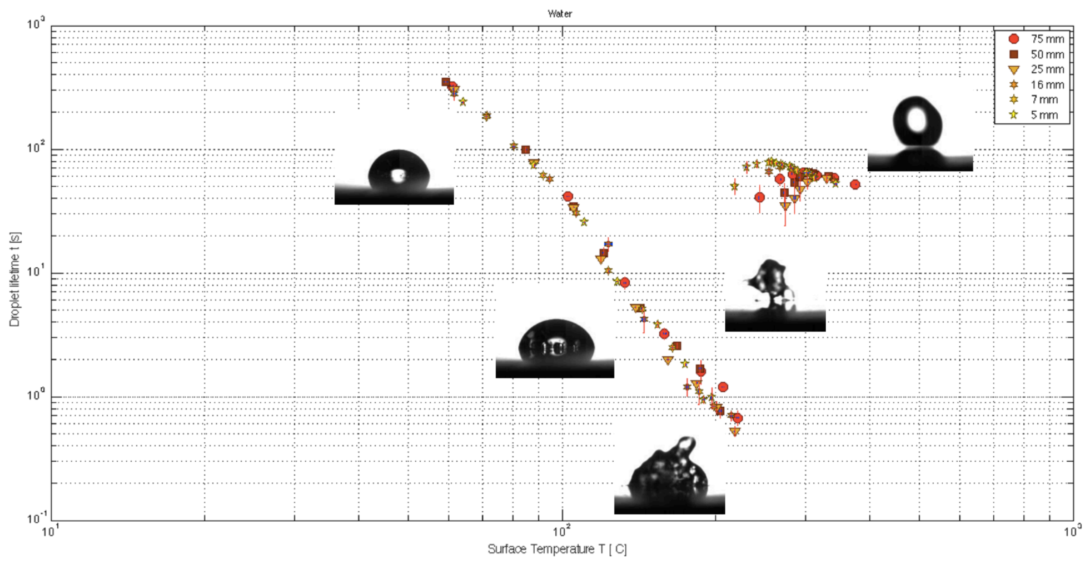

Figure 4.23 – ***Boiling regimes along all deionized water experimental evaporation curves***

4.4.2 FC-72 all cases

Figure 4.24 shows FC-72 boiling regimes along all tested heights, evaporation curves.

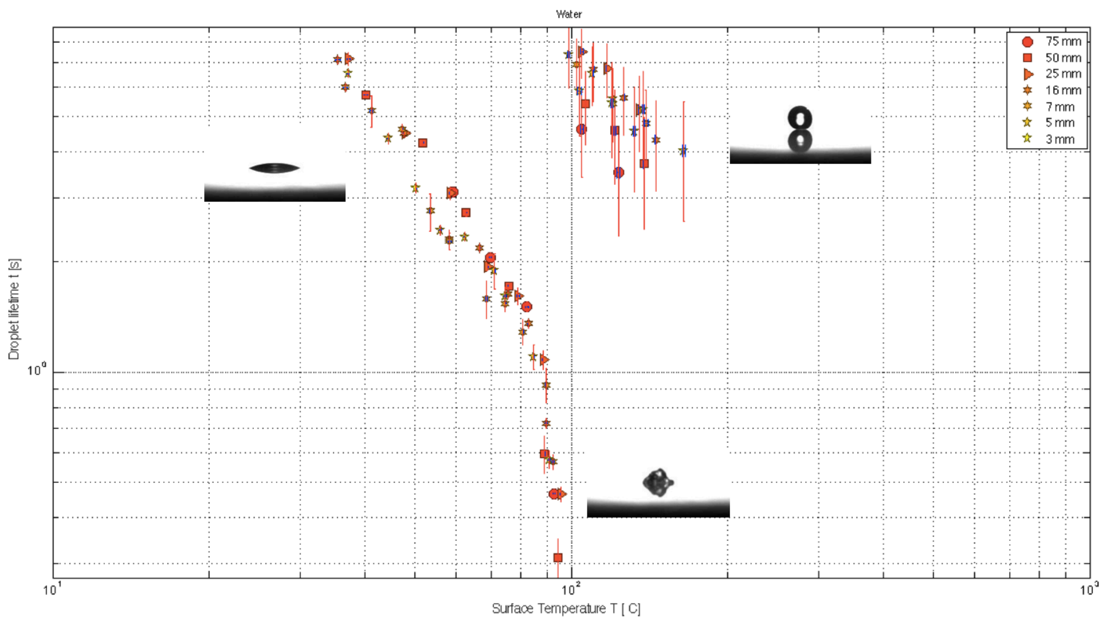

Figure 4.24 – Boiling regimes along all FC-72 experimental evaporation curves

Natural or free convection, nucleate boiling, and film boiling trends can be observed. Notice about the switch on the curve slope between natural convection and nucleate boiling regimes, where quicker droplet lifetimes make the slope almost vertical. This shows the high heat dissipation efficiency during this region. For FC-72 nucleate boiling region, only slugs and columns behavior can be identified.

Comparing deionized water and FC-72 transition boiling range, one can note that for water transition is more progressive than for FC-72, where it suddenly changes, from nucleate boiling to film boiling.

4.4.3 Deionized water vs. FC-72

FC-72 is a dielectric fluid, and it possesses some disadvantages versus water. On the one hand, dielectric fluids evaporation enthalpy is around 150 kJ/kg, lower than water evaporation enthalpy, around 2600 kJ/kg, making water significantly more suitable for heat dissipation.

On the other hand, it has some advantages. While to evaporate water below 100ºC pressure higher than atmospheric is needed to achieve the evaporation, at atmospheric pressure FC-72 can be evaporated at temperatures around 60ºC. FC-72 is an electric isolator; this is an desirable property for cooling in the field of electric devices, especially when cooling fluid is in direct contact with electrical circuits and electronic components, even though FC-72 presents worse thermo-physical properties in comparison with water.

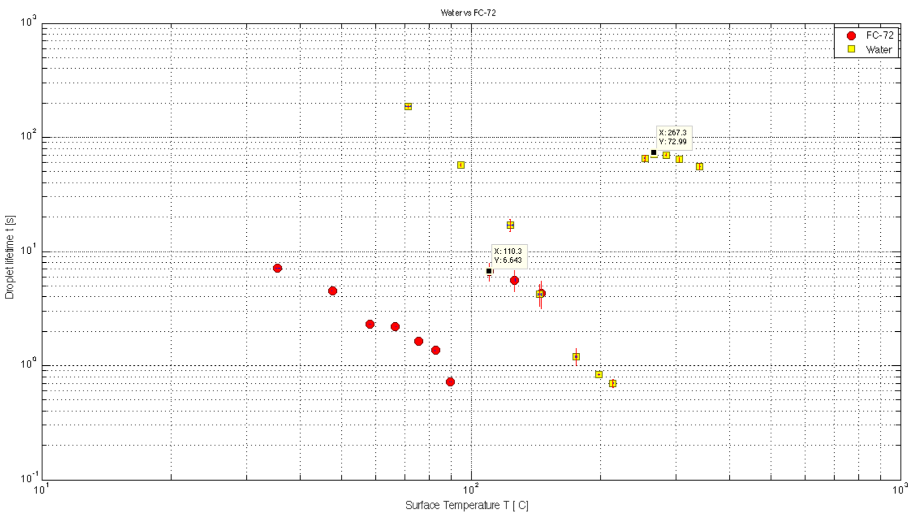

Figure 4.25 – ***Comparison between deionized water and FC-72 16 mm droplet impinging height evaporation curves***

Figure 4.25 shows the evaporation curves for deionized water and FC-72 at atmospheric pressure, for a droplet impinging height of 16 mm. It is used the same needle diameter for both experiments. Deionized droplet diameter is 3.285 mm, and FC-72 droplet diameter is 1.55 mm.

4.4.4 FC-72 different droplet volumes

For FC-72 experiments, needle diameter is changed to observe how droplet size alter fluid evaporation curve. The needle diameter causes different droplet diameters due to the properties of the different fluids.

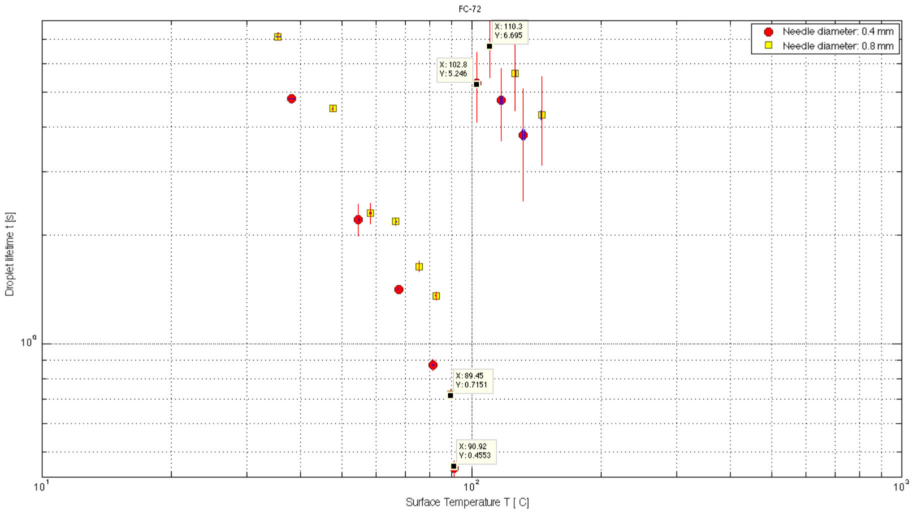

Figure 4.26 – ***FC-72 16 mm height droplet evaporation curve for 0.8 mm and 0.4 mm needle diameters***

Two needle diameters are used; 0.4 mm needle diameter, producing 0.944 mm droplets diameter and 0.8 mm needle diameter, producing 1.55 mm droplets diameter. Both needles length is 22 mm.

Figure 4.26 displays both needles FC-72 evaporation curves for an impinging droplet height of 16 mm. Regarding both curves, it can be observed that there is a small difference between CHFs, around 1.5ºC, while LFPs present greater difference, almost 8ºC. For FC-72 film boiling region recorded points present a significant uncertainty, due to the difficulties of measuring droplet lifetime during this regime. This could explain why there is such a difference between LFPs while CHFs, where measures are more accurate, present the same temperature.

Considering Fig. 4.26 droplet size should not mean a major change on droplet evaporation curve.

4.5 Weber vs. LFP: Water and FC-72

Figure 4.27 displays the correlation between LFP and Weber number for deionized water and FC-72 experiments. As seen in sections 4.2.1, deionized water case presents a growing trend on LFP as Weber number is increased, due the increasing influence of droplet impact dynamics, and then is stabilized for Weber numbers greater than 275. However, FC-72 presents a straight trend around the same LFP temperature along with all tested Weber numbers.

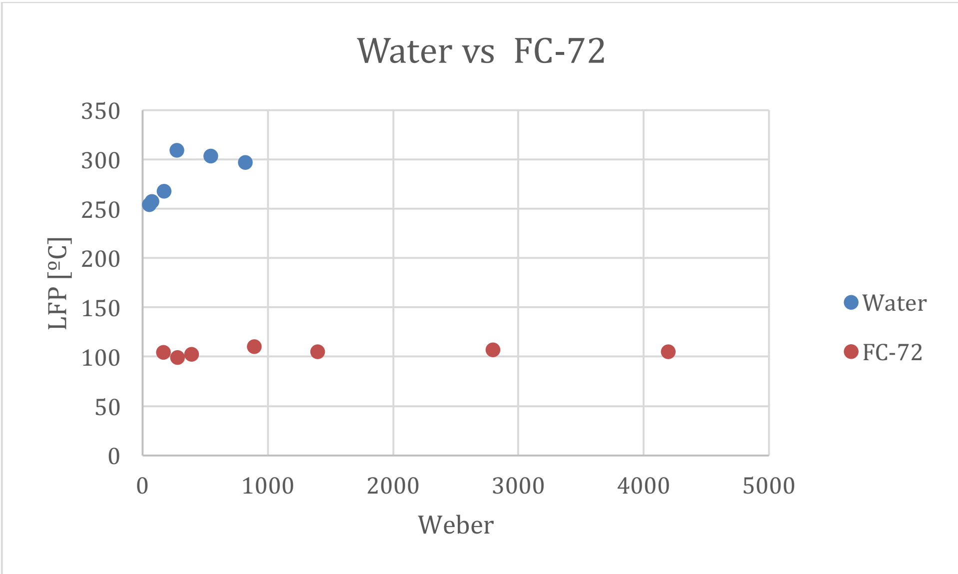

Figure 4.27 – ***Weber vs. LFP comparison between deionized water and FC-72***

Note the great difference on LFPs between deionized water and FC-72 for the same weber number. Tested fluids present different properties influencing LFP, especially the big difference between fluids saturation temperature at atmospheric pressure. A better comparison can be accomplished by modifying pressure conditions in order to have the same saturation temperature for both fluids.

4.6 Pool boiling curves

As stated in section 2.1.2 traditional pool boiling curve can be plotted as the inverse of the evaporation curve. Figures 4.28 and 4.29 shows deionized water and FC-72 inverse evaporation curves respectively.

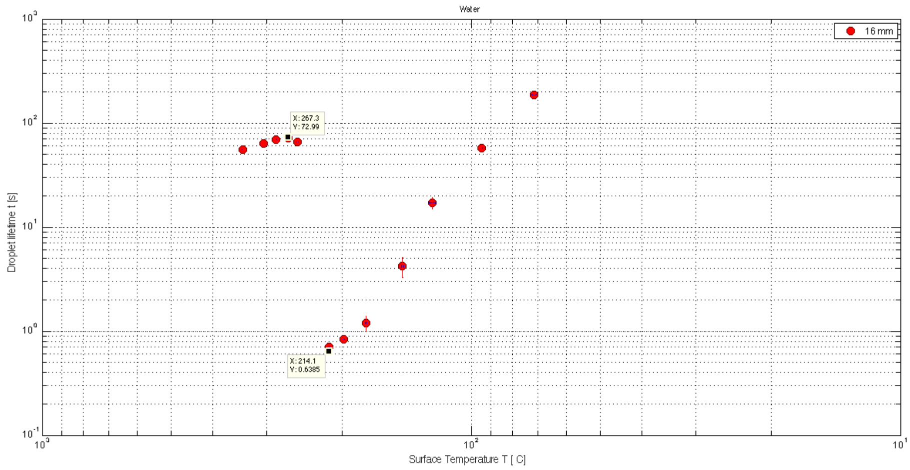

Figure 4.28 – 16 mm droplet impinging height deionized water inverse evaporation curve

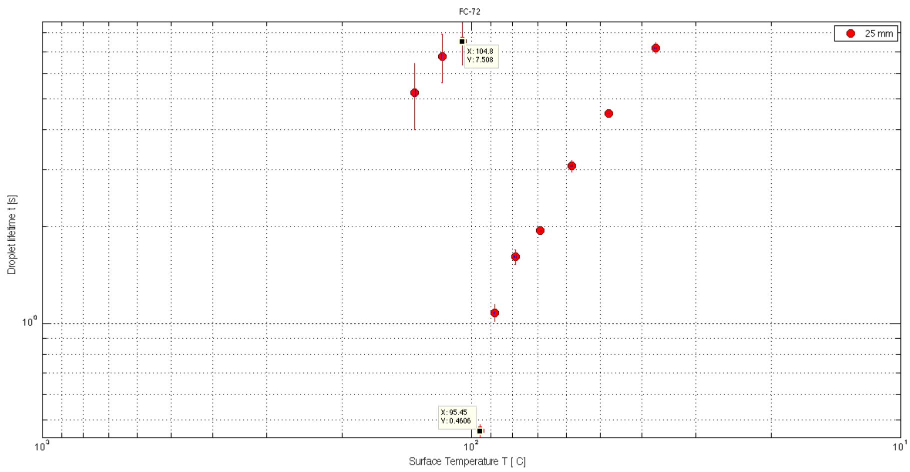

Figure 4.29 – 25 mm droplet impinging height FC-72 inverse evaporation curve

The inverse evaporation curve presents the same shape as the pool boiling curve, where the same boiling regimes can be identified.

To calculate the pool boiling heat flux q'', it needs the droplet lifetime; droplet volume, that depends on the drop diameter that changes along the droplet lifetime; evaporation enthalpy of both fluids; fluid density and heat transfer contact area, that also change along droplet lifetime.

4.7 Unsuccessful HFE 7000

HFE 7000 evaporation curve experiment was unsuccessfully conducted. There were a series of inconvenient that made impossible to perform HFE 7000 evaporation curve with the actual facility conditions.

Firstly, a 0.4 mm diameter needle was used. However, due to the low surface tension value HFE 7000 possess, it was tough to keep the fluid inside the syringe.

Secondly, even with the silicon wafer surface perfectly aligned, it was really challenging to keep fluid droplet on the tested surface. It moved all around the wafer drawing paths on it. Figure 4.25 shows how HFE 7000 droplet spot the plain silicon surface.

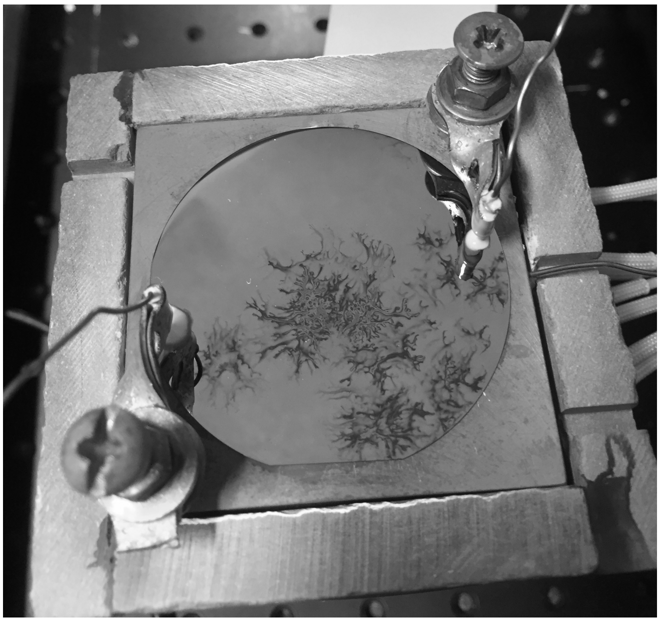

Figure 4.30 – ***HFE 7000 droplet spot on the plain silicon surface***

Finally, HFE 7000 boiling point, at atmospheric pressure, is around 34ºC. Facility monitoring thermocouples are designed and calibrated to measure temperatures from +33 to +700ºC.

5 Conclusions

5.1 Summary

The main objective of this master thesis is provided guidelines on Leidenfrost effect, report a reference droplet evaporation curve, define the different boiling regimes and determine how fluids properties and droplet deposition method can induce a switch on LFP. A review of previous results and theory fundamentals is also provided.

To enable the visualization and identification of the different boiling regimes for both fluids, the design and construction of an experimental facility have been conducted. Computational tools have been used to plot and then analyzee experimental results.

In order to study how fluids properties influence on LFP deionized water, FC-72 and HFE 7000 have been tested. Furthermore, to study how deposition method influence on boiling regimes and consequently on LFP, both fluids droplets were impinged from several heights modifying droplets impact dynamics.

Final results show the different droplet deposition heights evaporation curves for deionized water and FC-72, boiling regimes along the deionized water and FC-72 experimental curve, weber map showing different boiling regions and a comparison between deionized water and FC-72 performance. Unsuccessful HFE 7000 experiments are also explained.

5.2 Direction for further work

Previous studies have determined that LFP may depend on the following parameters: Size of the liquid mass, the method of liquid deposition, liquid subcooling, solid thermal properties, surface conditions and pressure. This work is focused on how liquid deposition method, droplet size, and fluid properties influence on LFP. However, a more detailed study of the rest of the influential parameters should be conducted.

Nowadays, development of micro and nanotechnology have encouraged numerous reports to be focused on how modifying surface conditions could affect on LFP and boiling regimes. The facility designed for this work could be suitable for the testing of enhanced surfaces.

Another significant parameter mention above is the working pressure. This pressure could be modified in order to achieve same saturation temperature allowing a better comparison between fluids.

Results show the difficulties of measuring droplets lifetime during transition boiling regime. A mechanism or a method should be developed to improve measurements along this boiling regime.

A wide range of fluids are currently used as refrigerants but not all fully satisfy spray cooling requirements, as proved on the unsuccessful HFE 7000 test. Different fluids testing could help to define more suitable fluids for spray cooling.

Monitoring subcooling temperature and controlling sample surface temperature uniformity could improve experiments performance.

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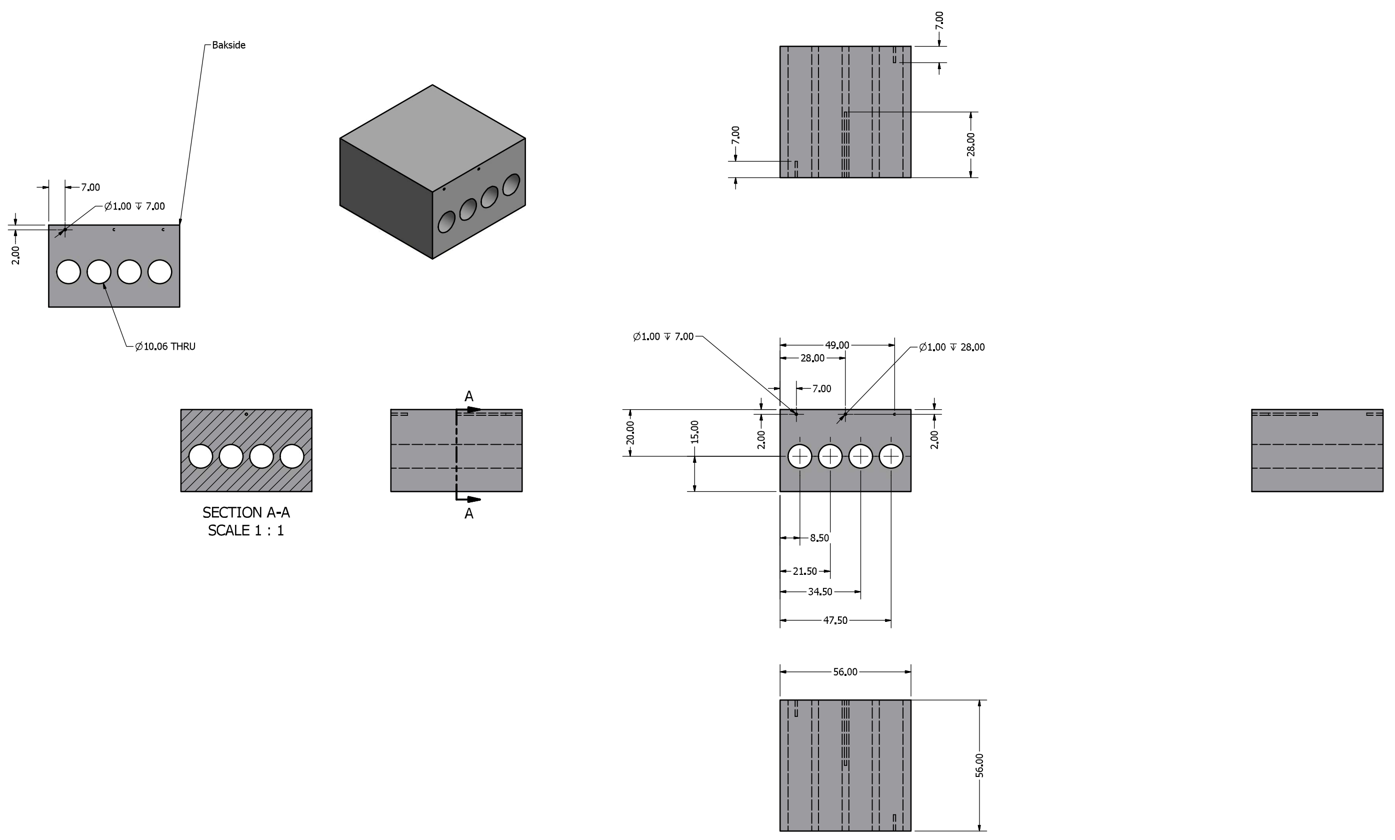
A Drawings



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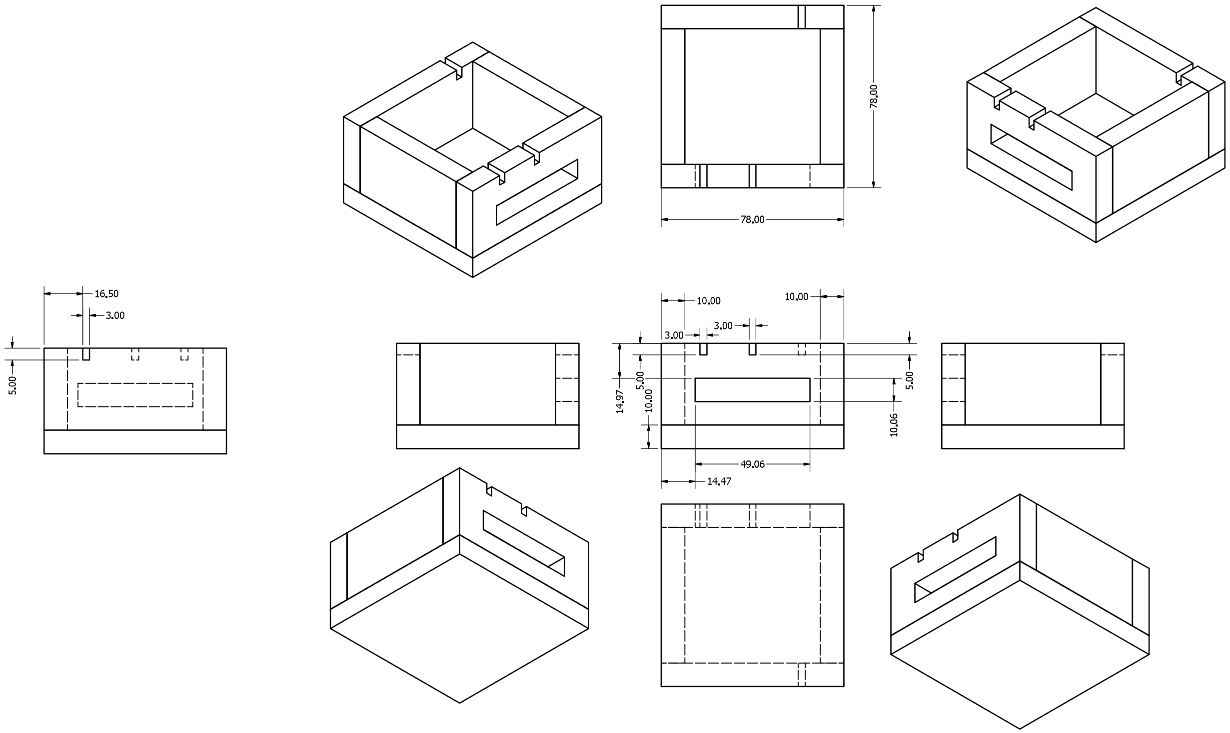

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B Datasheets

FASTCAM SA3

HIGH-G HIGH SPEED VIDEO SYSTEM

A rugged, megapixel High-Speed imaging system for General Application and Automotive Safety Test recording

2,000fps operation at 1024 x 1024 pixels

Designed referring to SAE-J211 to provide ruggedness and reliability, the Photron FASTCAM SA3 offers high performance recording for a broad range of applications in research and development and automotive safety testing.

Like the award winning FASTCAM MH4 multi-head camera system the FASTCAM SA3 ensures system stability under High-G conditions and long term system reliability.

The FASTCAM SA3 offers remote control through user selectable camera controls on rear panel, Gigabit Ethernet communications or through optional RS422 keypad with built-in 5" LCD display.

The FASTCAM SA3 provides exceptional light sensitivity, image quality and color fidelity through genuine 12-bit ADC, with extra record time provided by selecting 8-bit record mode.

Two FASTCAM SA3 models are available, Model 60K and Model 120K. Both systems offer higher frame rates at reduced image resolution and two microsecond global shutter.

Benefits

- Performance:

  FASTCAM SA3 Model 60K
  1024 x 1024 pixel resolution at frame rates up to 1,000 fps, and at reduced resolution up to 60,000 fps

  FASTCAM SA3 Model 120K
  1024 x 1024 pixel resolution at frame rates up to 2,000 fps, and at reduced resolution up to 120,000 fps

- User selectable Variable Framerate / Resolution
- Suitable for operation in HiG environments. Operation tested to 100G, 10ms, 6 axis
- 17μm pixel size to ensure high light sensitivity for demanding frame rate or low light applications
- 2μs global shutter selectable independent of frame rate.
- Composite video output for real time monitoring during set up, recording and playback
- Optional remote keypad control with integrated viewfinder
- 2GB, 4GB or 8GB memory options
- 8-bit recording mode increases record duration by 50%
- High performance Gigabit Ethernet interface
- Optional battery backup to protect data in the event of unexpected power loss (Pictured below)

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FASTCAM SA3

HIGH SPEED VIDEO SYSTEM

TARGET APPLICATIONS:
- Onboard vehicle impact testing
- Military test ranges where a sealed unit is beneficial
- Particle Image Velocimetry (PIV)
- Digital Image Correlation (DIC)
- Biomechanics

Specifications: Frame Rate / Resolution Table

FRAME RATE (fps)	MAXIMUM RESOLUTION				RECORD DURATION (12-BIT)														
					TIME (Sec.)						FRAMES								
	Model 60K		Model 120K		Model 60K			Model 120K			Model 60K			Model 120K					
	Horizontal	Vertical	Horizontal	Vertical	2GB	4GB	8GB	2GB	4GB	8GB	2GB	4GB	8GB	2GB	4GB	8GB			
1,000	1,024	1,024	1,024	1,024	1.36	2.72	5.45	1.36	2.72	5.45	1,361	2,726	5,457	1,361	2,726	5,457			
1,500	896	736	1,024	1,024	1.44	2.89	5.78	0.90	1.81	3.63	2,164	4,335	8,677	1,361	2,726	5,457			
2,000	768	608	1,024	1,024	1.52	3.06	6.12	0.68	1.36	2.72	3,057	6,123	12,255	1,361	2,726	5,457			
2,500	640	544	896	896	1.64	3.28	6.57	0.71	1.42	2.85	4,100	8,212	16,436	1,778	3,561	7,127			
3,000	512	512	896	736	1.81	3.63	7.27	0.72	1.44	2.89	5,445	10,906	21,829	2,164	4,335	8,677			
5,000	384	352	640	544	2.11	4.23	8.46	0.82	1.64	3.28	10,560	21,152	42,335	4,100	8,212	16,436			
6,000	384	288	512	512	2.15	4.30	8.62	0.90	1.81	3.63	12,907	25,852	51,743	5,445	10,906	21,829			
7,500	384	224	512	416	2.21	4.43	8.87	0.89	1.78	3.58	16,595	33,239	66,527	6,701	13,423	26,866			
10,000	256	192	384	352	2.90	5.81	11.64	1.05	2.11	4.23	29,041	58,168	116,423	10,560	21,152	42,335			
15,000	256	112	384	224	3.31	6.64	13.30	1.10	2.21	4.43	49,785	99,718	199,582	16,595	33,239	66,527			
20,000	256	80	256	192	3.48	6.98	13.97	1.45	2.90	5.82	69,700	139,605	279,415	29,041	58,168	116,423			
25,000	256	64	256	144	3.48	6.98	13.97	1.54	3.10	6.20	87,125	174,506	349,269	38,722	77,558	155,230			
30,000	256	48	256	112	3.87	7.75	15.52	1.65	3.32	6.65	116,167	232,675	465,692	49,785	99,718	199,582			
50,000	384	16	256	64	4.64	9.30	18.62	1.74	3.49	6.98	232,334	465,351	931,384	87,125	174,506	349,269			
60,000	128	16	256	48	11.61	23.26	46.56	1.93	3.87	7.76	697,002	1,396,053	2,794,154	116,167	232,675	465,692			
75,000	-	-	256	32	-	-	-	2.32	4.65	9.31	-	-	-	174,250	349,013	698,538			
100,000	-	-	384	16	-	-	-	2.32	4.65	9.31	-	-	-	232,334	465,351	931,384			
120,000	-	-	128	16	-	-	-	5.80	11.63	23.28	-	-	-	697,002	1,396,053	2,794,154			

Sensor 12-bit ADC (Bayer system color, single sensor) with 17µm pixel size

Shutter Global electronic shutter from 16.7ms to 2µs independent of frame rate

Lens Mount Interchangeable F-mount and C-mount using supplied adapters (Optional High-G block mount available)

Extended Dynamic Range Selectable in twenty steps (0 to 95% in 5% increments) to prevent pixel over-exposure

Memory 2GB (standard), 4GB (optional) and 8GB (optional)

Video Outputs NTSC/PAL composite VBS (BNC). Ability to zoom, pan and scroll within image via keypad (option). Live video during recording

Camera Control Through optional keypad with integrated viewfinder and Gigabit Ethernet or RS-422

User Preset Switch User selectable camera function control mounted on the camera's rear panel

Low Light Mode Low light mode for simple camera adjustment when working in low ambient light, high frame rate or short exposure modes

Triggering Selectable positive or negative TTL 5Vp-p or switch closure

Trigger Delay Programmable delay on selected input and output triggers, 100ns resolution

Timing Internal clock or external source

IRIG Time Code IRIG/GPS timing is recorded in real time on every frame

Event Markers Ten user entered event markers mark specific events within the image sequence in real time. Immediately accessible through software

Variable Framerate/ Resolution User selectable Variable Framerate/Resolution function adjustable in 128 x 16 pixel steps

Selectable Recording Bit Depth User selectable 12-bit (high-dynamic range) or 8-bit (50% frame increase) recording mode

Trigger Modes Start, End, Center, Manual, Random, Random Reset

Saved Image Formats JPEG, AVI, TIFF, BMP, RAW, PNG, MOV, and FTIF. Images can be saved with or without image or comment data

Data Display Frame Rate, Shutter Speed, Trigger Mode, Date or Time, Status (Playback/Record), Real Time, Frame Count, Resolution and LUT

Partitioning Up to 8 memory partitions may be set by the user

High-G Tested to 100G, 10ms, six-axis

Operating Temperature 0-40 degrees C (32-104 degree F)

Mounting 1 x 1/4-20 UNC, 6 x M5 on all four sides

Dimensions 120mm (4.72″)H x 120mm (4.72″)W x 215.8mm (8.50″)D *excluding protrusions

Weight 9.48 lbs (4.3kg)

Power Requirements 100V-240V AC ~ 1.5A, 50-60Hz optional DC operation 22-32VDC, 60VA

Specifications subject to change without notice

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OT-201

OMEGATHERM® Thermally Conductive Silicone Paste

INSTRUCTION SHEET

M0066/1104

Introduction

OMEGATHERM® 201 is a thermally conductive, “Heat Sink” silicone grease. It has a very high thermal conductivity coupled with high insulation resistance and high dielectric strength. The term heat sink compound or thermal joint compound is used to describe this type of material. It does not harden on long exposure to elevated temperatures, but retains its past-like consistency. It is rated for continuous use between -40°F and +392°F (40°C and 200°C).

OMEGATHERM® is available in four quantity sizes, from a ½ oz. jar to a 2 lb. can, as outlined below.

OMEGATHERM® 201 Part Numbers and Sizes	
OT-201-½ one ½ oz. jar	**OT-201-2** one 2 oz. jar
OT-201-16 one 16 oz. can	**OT-201-32** one 32 oz. can

OMEGATHERM 201 provides an excellent means of conducting heat and expanding the heat-path area from a surface to a temperature measurement sensor, thus increasing the speed of response and improving accuracy.

OMEGATHERM 201 improves the heat transfer between a solid state relay and its finned heat dissipating heat sink. Apply a thin layer of “201” thermal compound to the bottom of the solid state relay (SSR), then securely mount the SSR on the finned heat sink with the supplied screws.

Instructions for Use

Although OMEGATHERM 201 does not normally settle in its container, storage for long periods of time at elevated temperature may result in a slight separation of the conductive fillers from the silicone oil. If this condition is seen to exist, the fillers may be easily mixed by hand or mechanical mixing.

OMEGATHERM 201 may be dispensed through a nozzle using any appropriate hand operated or automatic equipment. For some applications, it will be convenient to apply thin films with a stiff brush.

To CLEAN OT-201 from surfaces, use a solvent containing Alcohol, MEK, or Xylene. Repeated use is required to completely clean silicon grease from surface.

Applications

A. Surface Measurement Probes-dab a small amount on the surface and push the thermocouple into this area.

B. Temporary Temperature Monitoring of Surfaces and Bodies-For applications to 392°F (200°C). OT-201 works well with insulated wire thermocouples. Simply dab this paste on the surface or into a cavity, put the sensor in the paste, and tape to hold.

C. Thermocouple Wells (to 200°C)-improve the response time of your thermowell assemblies. Simply put enough OMEGATHERM 201 into the bottom of the wells to cover the active length of the sensor. This application holds for vertical wells or those canted down.

D. NOT FOR USE IN A VACUUM. OT-201 will outgas if used in a vacuum.

Hygiene

MAY CAUSE IRRITATION.

1. Avoid contact with skin and eyes.
2. Wash thoroughly after handling.

First Aid

1. In case of contact, wash skin thoroughly with soap and water.
2. For eyes, flush with water for 15 minutes and consult physician immediately.

FOR INDUSTRIAL USE ONLY.

Typical Properties

Color:	Off-white
Temperature Range of Use:	-40° to +392°F (40° to +200°C)
Consistency:	Thick, smooth paste
Volume Resistivity:	10^{14} ohm-cm
Dielectric Strength:	500 volts/mil (19.7 kv/mm)
Thermal Conductivity:	16 (BTU) (in)/(hr) (ft^2) (°F) 0.0055 (cal)/(cm)/(sec) (cm^2) (°C)
Specific Gravity:	2.53 g/cc
Weight Loss:	0.2% (24 hours/100°C
Shelf life:	1 Year (Storage at 35°F or below will approximately double the shelf life).
Solvents:	Alcohol or MEK or Xylene Solvents

This information is not a warranty and assumes no legal responsibility. Actual suitability for a particular purpose is to be determined by the user.

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U.S.A. and Canada: Sales Service: 1-800-826-6342 / 1-800-TC-OMEGA®
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It is the policy of OMEGA Engineering, Inc. to comply with all worldwide safety and EMC/EMI regulations that apply. OMEGA is constantly pursuing certification of its products to the European New Approach Directives. OMEGA will add the CE mark to every appropriate device upon certification.

The information contained in this document is believed to be correct, but OMEGA accepts no liability for any errors it contains, and reserves the right to alter specifications without notice.
WARNING: These products are not designed for use in, and should not be used for, human applications.

MADE IN USA

WARRANTY/DISCLAIMER

OMEGA ENGINEERING, INC. warrants this unit to be free of defects in materials and workmanship for a period of **13 months** from date of purchase. OMEGA's WARRANTY adds an additional one (1) month grace period to the normal **one (1) year product warranty** to cover handling and shipping time. This ensures that OMEGA's customers receive maximum coverage on each product.

If the unit malfunctions, it must be returned to the factory for evaluation. OMEGA's Customer Service Department will issue an Authorized Return (AR) number immediately upon phone or written request. Upon examination by OMEGA, if the unit is found to be defective, it will be repaired or replaced at no charge. OMEGA's WARRANTY does not apply to defects resulting from any action of the purchaser, including but not limited to mishandling, improper interfacing, operation outside of design limits, improper repair, or unauthorized modification. This WARRANTY is VOID if the unit shows evidence of having been tampered with or shows evidence of having been damaged as a result of excessive corrosion; or current, heat, moisture or vibration; improper specification; misapplication; misuse or other operating conditions outside of OMEGA's control. Components in which wear is not warranted, include but are not limited to contact points, fuses, and triacs.

OMEGA is pleased to offer suggestions on the use of its various products. However, OMEGA neither assumes responsibility for any omissions or errors nor assumes liability for any damages that result from the use of its products in accordance with information provided by OMEGA, either verbal or written. OMEGA warrants only that the parts manufactured by the company will be as specified and free of defects. OMEGA MAKES NO OTHER WARRANTIES OR REPRESENTATIONS OF ANY KIND WHATSOEVER, EXPRESSED OR IMPLIED, EXCEPT THAT OF TITLE, AND ALL IMPLIED WARRANTIES INCLUDING ANY WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE HEREBY DISCLAIMED. LIMITATION OF LIABILITY: The remedies of purchaser set forth herein are exclusive, and the total liability of OMEGA with respect to this order, whether based on contract, warranty, negligence, indemnification, strict liability or otherwise, shall not exceed the purchase price of the component upon which liability is based. In no event shall OMEGA be liable for consequential, incidental or special damages.

CONDITIONS: Equipment sold by OMEGA is not intended to be used, nor shall it be used: (1) as a "Basic Component" under 10 CFR 21 (NRC), used in or with any nuclear installation or activity; or (2) in medical applications or used on humans. Should any Product(s) be used in or with any nuclear installation or activity, medical application, used on humans, or misused in any way, OMEGA assumes no responsibility as set forth in our basic WARRANTY/DISCLAIMER language, and, additionally, purchaser will indemnify OMEGA and hold OMEGA harmless from any liability or damage whatsoever arising out of the use of the Product(s) in such a manner.

RETURN REQUESTS / INQUIRIES

Direct all warranty and repair requests/inquiries to the OMEGA Customer Service Department. BEFORE RETURNING ANY PRODUCT(S) TO OMEGA, PURCHASER MUST OBTAIN AN AUTHORIZED RETURN (AR) NUMBER FROM OMEGA'S CUSTOMER SERVICE DEPARTMENT (IN ORDER TO AVOID PROCESSING DELAYS). The assigned AR number should then be marked on the outside of the return package and on any correspondence.

The purchaser is responsible for shipping charges, freight, insurance and proper packaging to prevent breakage in transit.

FOR **WARRANTY** RETURNS, please have the following information available BEFORE contacting OMEGA:
1. Purchase Order number under which the product was PURCHASED,
2. Model and serial number of the product under warranty, and
3. Repair instructions and/or specific problems relative to the product.

FOR **NON-WARRANTY** REPAIRS, consult OMEGA for current repair charges. Have the following information available BEFORE contacting OMEGA:
1. Purchase Order number to cover the COST of the repair,
2. Model and serial number of the product, and
3. Repair instructions and/or specific problems relative to the product.

OMEGA's policy is to make running changes, not model changes, whenever an improvement is possible. This affords our customers the latest in technology and engineering.

M0066/1104

Safety Data Sheet

Document Group:	10-3789-4	**Version Number:**	33.00
Issue Date:	12/01/16	**Supercedes Date:**	08/05/15

SECTION 1: Identification

1.1. Product identifier
3M™ Fluorinert™ Electronic Liquid FC-72

Product Identification Numbers

ID Number	UPC	ID Number	UPC
98-0211-0216-9	00-51135-09194-4	98-0211-0217-7	00-51135-09195-1
98-0211-0267-2	00-51135-09209-5	98-0212-4823-6	00-51138-99198-2
98-0212-4842-6	0-00-51138-99222-4	ZF-0002-0321-4	
ZF-0002-0354-5		ZF-0002-0802-3	
ZF-0002-1162-1		ZF-0002-1872-5	

1.2. Recommended use and restrictions on use

Recommended use
For Industrial Use Only. Not Intended for Use as a Medical Device or Drug., Testing Fluid or Heat Transfer Fluid for Electronics.
Restrictions on use
Fluorinert™ Electronic Liquids are used in a wide variety of applications, including but not limited to precision cleaning of medical devices and as lubricant deposition solvents for medical devices. When the product is used for applications where the finished device is implanted into the human body, no residual Fluorinert solvent may remain on the parts. It is highly recommended that the supporting test results and protocol be cited during FDA registration.

3M Electronics Markets Materials Division (EMMD) will not knowingly sample, support, or sell its products for incorporation in medical and pharmaceutical products and applications in which the 3M product will be temporarily or permanently implanted into humans or animals. The customer is responsible for evaluating and determining that a 3M EMMD product is suitable and appropriate for its particular use and intended application. The conditions of evaluation, selection, and use of a 3M product can vary widely and affect the use and intended application of a 3M product. Because many of these conditions are uniquely within the user’s knowledge and control, it is essential that the user evaluate and determine whether the 3M product is suitable and appropriate for a particular use and intended application, and complies with all local applicable laws, regulations, standards, and guidance.

1.3. Supplier’s details

MANUFACTURER:	3M
DIVISION:	Electronics Materials Solutions Division
ADDRESS:	3M Center, St. Paul, MN 55144-1000, USA
Telephone:	1-888-3M HELPS (1-888-364-3577)

1.4. Emergency telephone number
1-800-364-3577 or (651) 737-6501 (24 hours)

SECTION 2: Hazard identification

2.1. Hazard classification
Not classified as hazardous according to OSHA Hazard Communication Standard, 29 CFR 1910.1200.

2.2. Label elements
Signal word
Not applicable.

Symbols
Not applicable.

Pictograms
Not applicable.

2.3. Hazards not otherwise classified
None.

SECTION 3: Composition/information on ingredients

Ingredient	C.A.S. No.	% by Wt
PERFLUORO COMPOUNDS, C5-18	86508-42-1	100 (typically 100)

SECTION 4: First aid measures

4.1. Description of first aid measures

Inhalation:
Remove person to fresh air. If signs/symptoms develop, get medical attention.

Skin Contact:
Wash with soap and water. If signs/symptoms develop, get medical attention.

Eye Contact:
Flush with large amounts of water. Remove contact lenses if easy to do. Continue rinsing. If signs/symptoms persist, get medical attention.

If Swallowed:
No need for first aid is anticipated.

4.2. Most important symptoms and effects, both acute and delayed
See Section 11.1. Information on toxicological effects.

4.3. Indication of any immediate medical attention and special treatment required
Not applicable

SECTION 5: Fire-fighting measures

5.1. Suitable extinguishing media
Non-combustible. Use a fire fighting agent suitable for surrounding fire.

5.2. Special hazards arising from the substance or mixture
Exposure to extreme heat can give rise to thermal decomposition.

Hazardous Decomposition or By-Products

Substance	Condition
Carbon monoxide	During Combustion
Carbon dioxide	During Combustion

5.3. Special protective actions for fire-fighters
When fire fighting conditions are severe and total thermal decomposition of the product is possible, wear full protective clothing, including helmet, self-contained, positive pressure or pressure demand breathing apparatus, bunker coat and pants, bands around arms, waist and legs, face mask, and protective covering for exposed areas of the head.

SECTION 6: Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures
Ventilate the area with fresh air. For large spill, or spills in confined spaces, provide mechanical ventilation to disperse or exhaust vapors, in accordance with good industrial hygiene practice. Observe precautions from other sections.

6.2. Environmental precautions
Avoid release to the environment. For larger spills, cover drains and build dikes to prevent entry into sewer systems or bodies of water.

6.3. Methods and material for containment and cleaning up
Contain spill. Working from around the edges of the spill inward, cover with bentonite, vermiculite, or commercially available inorganic absorbent material. Mix in sufficient absorbent until it appears dry. Collect as much of the spilled material as possible. Place in a closed container approved for transportation by appropriate authorities. Clean up residue with an appropriate solvent selected by a qualified and authorized person. Ventilate the area with fresh air. Read and follow safety precautions on the solvent label and SDS. Seal the container. Dispose of collected material as soon as possible.

SECTION 7: Handling and storage

7.1. Precautions for safe handling
Do not breathe thermal decomposition products. Avoid skin contact with hot material. Store work clothes separately from other clothing, food and tobacco products. Keep away from reactive metals (eg. Aluminum, zinc etc.) to avoid the formation of hydrogen gas that could create an explosion hazard. No smoking: Smoking while using this product can result in contamination of the tobacco and/or smoke and lead to the formation of hazardous decomposition products.

7.2. Conditions for safe storage including any incompatibilities
Store away from heat.

SECTION 8: Exposure controls/personal protection

8.1. Control parameters

Occupational exposure limits
No occupational exposure limit values exist for any of the components listed in Section 3 of this SDS.

8.2. Exposure controls

8.2.1. Engineering controls
Provide appropriate local exhaust when product is heated.

8.2.2. Personal protective equipment (PPE)

Eye/face protection
None required.

Skin/hand protection
No chemical protective gloves are required.

Respiratory protection

Use a positive pressure supplied-air respirator if there is a potential for over exposure from an uncontrolled release, exposure levels are not known, or under any other circumstances where air-purifying respirators may not provide adequate protection.

Thermal hazards
Wear heat insulating gloves when handling hot material to prevent thermal burns.

SECTION 9: Physical and chemical properties

9.1. Information on basic physical and chemical properties

General Physical Form:	Liquid
Specific Physical Form:	Liquid
Odor, Color, Grade:	Colorless, odorless liquid.
Odor threshold	*No Data Available*
pH	*Not Applicable*
Melting point	*Not Applicable*
Boiling Point	50 - 60 ºC
Flash Point	No flash point
Evaporation rate	> 1 [*Ref Std:* BUOAC=1]
Flammability (solid, gas)	Not Applicable
Flammable Limits(LEL)	None detected
Flammable Limits(UEL)	None detected
Vapor Pressure	232 mmHg [@ 20 ºC]
Vapor Density	Approximately 11.7 [@ 20 ºC] [*Ref Std:* AIR=1]
Density	1.7 g/ml
Specific Gravity	1.7 [*Ref Std:* WATER=1]
Solubility in Water	Nil
Solubility- non-water	*No Data Available*
Partition coefficient: n-octanol/ water	*No Data Available*
Autoignition temperature	*No Data Available*
Decomposition temperature	*Not Applicable*
Viscosity	0.4 centistoke [@ 20 ºC]
Molecular weight	*No Data Available*
Volatile Organic Compounds	[*Details:* Exempt]
Percent volatile	100 %
VOC Less H2O & Exempt Solvents	[*Details:* Exempt]

SECTION 10: Stability and reactivity

10.1. Reactivity
This material may be reactive with certain agents under certain conditions - see the remaining headings in this section.

10.2. Chemical stability
Stable.

10.3. Possibility of hazardous reactions
Hazardous polymerization will not occur.

10.4. Conditions to avoid
Heat

10.5. Incompatible materials
Finely divided active metals
Alkali and alkaline earth metals

10.6. Hazardous decomposition products

Substance	Condition
Hydrogen Fluoride	At Elevated Temperatures - greater than 200 ºC
Perfluoroisobutylene (PFIB)	At Elevated Temperatures - greater than 200 ºC

Refer to section 5.2 for hazardous decomposition products during combustion.

If the product is exposed to extreme condition of heat from misuse or equipment failure, toxic decomposition products that include hydrogen fluoride and perfluoroisobutylene can occur.

SECTION 11: Toxicological information

The information below may not be consistent with the material classification in Section 2 if specific ingredient classifications are mandated by a competent authority. In addition, toxicological data on ingredients may not be reflected in the material classification and/or the signs and symptoms of exposure, because an ingredient may be present below the threshold for labeling, an ingredient may not be available for exposure, or the data may not be relevant to the material as a whole.

11.1. Information on Toxicological effects

Signs and Symptoms of Exposure

Based on test data and/or information on the components, this material may produce the following health effects:

Inhalation:
Vapors from heated material may cause irritation of the respiratory system. Signs/symptoms may include cough, sneezing, nasal discharge, headache, hoarseness, and nose and throat pain.

Skin Contact:
Contact with the skin during product use is not expected to result in significant irritation.

Eye Contact:
Contact with the eyes during product use is not expected to result in significant irritation.

Ingestion:
No known health effects.

Toxicological Data
If a component is disclosed in section 3 but does not appear in a table below, either no data are available for that endpoint or the data are not sufficient for classification.

Acute Toxicity

Name	Route	Species	Value
PERFLUORO COMPOUNDS, C5-18	Dermal		LD50 estimated to be > 5,000 mg/kg
PERFLUORO COMPOUNDS, C5-18	Inhalation-Vapor (4 hours)	Rat	LC50 > 41 mg/l
PERFLUORO COMPOUNDS, C5-18	Ingestion	Rat	LD50 > 5,000 mg/kg

ATE = acute toxicity estimate

Skin Corrosion/Irritation

Name	Species	Value
PERFLUORO COMPOUNDS, C5-18	Rabbit	No significant irritation

Serious Eye Damage/Irritation

Name	Species	Value
PERFLUORO COMPOUNDS, C5-18	Rabbit	No significant irritation

Skin Sensitization
For the component/components, either no data are currently available or the data are not sufficient for classification.

Respiratory Sensitization
For the component/components, either no data are currently available or the data are not sufficient for classification.

Germ Cell Mutagenicity

Name	Route	Value
PERFLUORO COMPOUNDS, C5-18	In Vitro	Not mutagenic

Carcinogenicity
For the component/components, either no data are currently available or the data are not sufficient for classification.

Reproductive Toxicity

Reproductive and/or Developmental Effects
For the component/components, either no data are currently available or the data are not sufficient for classification.

Target Organ(s)

Specific Target Organ Toxicity - single exposure
For the component/components, either no data are currently available or the data are not sufficient for classification.

Specific Target Organ Toxicity - repeated exposure

Name	Route	Target Organ(s)	Value	Species	Test Result	Exposure Duration
PERFLUORO COMPOUNDS, C5-18	Inhalation	heart | endocrine system | bone, teeth, nails, and/or hair | hematopoietic system | liver | immune system | nervous system | eyes | kidney and/or bladder | respiratory system	All data are negative	Rat	NOAEL 49,821 ppm	13 weeks
PERFLUORO COMPOUNDS, C5-18	Ingestion	heart | endocrine system | hematopoietic system | liver | nervous system |	All data are negative	Rat	NOAEL 2,000 mg/kg/day	28 days

		kidney and/or bladder | respiratory system				

Aspiration Hazard
For the component/components, either no data are currently available or the data are not sufficient for classification.

Please contact the address or phone number listed on the first page of the SDS for additional toxicological information on this material and/or its components.

SECTION 12: Ecological information

Ecotoxicological information

Please contact the address or phone number listed on the first page of the SDS for additional ecotoxicological information on this material and/or its components.

Chemical fate information

Please contact the address or phone number listed on the first page of the SDS for additional chemical fate information on this material and/or its components.

SECTION 13: Disposal considerations

13.1. Disposal methods
Dispose of contents/ container in accordance with the local/regional/national/international regulations.

Dispose of waste product in a permitted industrial waste facility. Combustion products will include HF. Facility must be capable of handling halogenated materials.
Empty and clean product containers may be disposed as non-hazardous waste. Consult your specific regulations and service providers to determine available options and requirements.

EPA Hazardous Waste Number (RCRA): Not regulated

SECTION 14: Transport Information

For Transport Information, please visit http://3M.com/Transportinfo or call 1-800-364-3577 or 651-737-6501.

SECTION 15: Regulatory information

15.1. US Federal Regulations
Contact 3M for more information.

311/312 Hazard Categories:

Fire Hazard - No Pressure Hazard - No Reactivity Hazard - No Immediate Hazard - No Delayed Hazard - No

15.2. State Regulations
Contact 3M for more information.

15.3. Chemical Inventories
The components of this material are in compliance with the provisions of Australia National Industrial Chemical Notification and Assessment Scheme (NICNAS). Certain restrictions may apply. Contact the selling division for additional information.

The components of this product are in compliance with the new substance notification requirements of CEPA.

The components of this material are in compliance with the China "Measures on Environmental Management of New Chemical Substance". Certain restrictions may apply. Contact the selling division for additional information.

The components of this material are in compliance with the provisions of the Korean Toxic Chemical Control Law. Certain restrictions may apply. Contact the selling division for additional information.

The components of this material are in compliance with the provisions of Japan Chemical Substance Control Law. Certain restrictions may apply. Contact the selling division for additional information.

The components of this material are in compliance with the provisions of Philippines RA 6969 requirements. Certain restrictions may apply. Contact the selling division for additional information.

The components of this product are in compliance with the chemical notification requirements of TSCA.

Contact 3M for more information.

15.4. International Regulations

Contact 3M for more information.

This SDS has been prepared to meet the U.S. OSHA Hazard Communication Standard, 29 CFR 1910.1200.

SECTION 16: Other information

NFPA Hazard Classification

Health: 3 **Flammability:** 0 **Instability:** 0 **Special Hazards:** None

National Fire Protection Association (NFPA) hazard ratings are designed for use by emergency response personnel to address the hazards that are presented by short-term, acute exposure to a material under conditions of fire, spill, or similar emergencies. Hazard ratings are primarily based on the inherent physical and toxic properties of the material but also include the toxic properties of combustion or decomposition products that are known to be generated in significant quantities.

HMIS Hazard Classification

Health: 0 **Flammability:** 0 **Physical Hazard:** 0 **Personal Protection:** X - See PPE section.

Hazardous Material Identification System (HMIS® IV) hazard ratings are designed to inform employees of chemical hazards in the workplace. These ratings are based on the inherent properties of the material under expected conditions of normal use and are not intended for use in emergency situations. HMIS® IV ratings are to be used with a fully implemented HMIS® IV program. HMIS® is a registered mark of the American Coatings Association (ACA).

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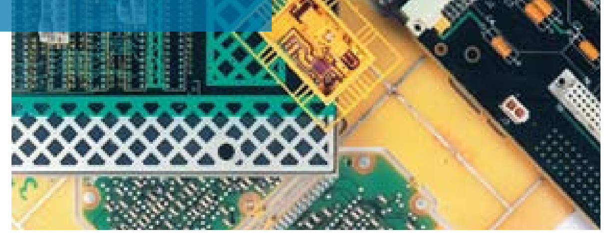
3M™ Thermal Management Fluids

Safe Sustainable Cooling Performance

Dielectric heat transfer solutions for the electronics industry

3M



Reliable performance.
Environmentally sustainable options.

Thermal management issues are becoming increasingly important to electronics and semiconductor manufacturers. New designs put more demands on the dielectric fluids used to maintain proper temperatures. Environmental issues have become a critical factor in fab/plant operating decisions. And system maintenance is always an issue. In short, selection of a heat transfer fluid for your semiconductor processing and electronics equipment can no longer be an afterthought. Long-term, high-performance solutions are needed.

Whether for single-phase or two-phase systems, 3M has a broad range of thermal management fluids and technical support you need to make the right choice for your particular needs. Customers have used 3M products in many applications, including thermal test and immersion cooling of electronics. 3M experts are available to help you choose the right thermal management fluid to improve reliability, address environmental concerns, and lower your overall operating costs.

Cool Solutions for Today's Electronics

3M™ Thermal Management Fluids Properties

3M™ Novec™ Engineered Fluids

	Unit	Novec 7000	Novec 7100	Novec 7200	Novec 7300	Novec 7500	Novec 7600
Boiling Point	°C	34	61	76	98	128	131
Pour Point	°C	-122	-135	-138	-38	-100	-98
Molecular Weight	g/mol	200	250	264	350	414	346
Critical Temperature	°C	165	195	210	243	261	260
Critical Pressure	MPa	2.48	2.23	2.01	1.88	1.55	1.67
Vapor Pressure	kPa	65	27	16	5.9	2.1	0.96
Heat of Vaporization	kJ/kg	142	112	119	102	89	116
Liquid Density	kg/m^3	1400	1510	1420	1660	1614	1540
Coefficient of Expansion	K^{-1}	0.0022	0.0018	0.0016	0.0013	0.0013	0.0011
Kinematic Viscosity	cSt	0.32	0.38	0.41	0.71	0.77	1.1
Absolute Viscosity	cP	0.45	0.58	0.58	1.18	1.24	1.65
Specific Heat	J/kg-K	1300	1183	1220	1140	1128	1319
Thermal Conductivity	W/m-K	0.075	0.069	0.068	0.063	0.065	0.071
Surface Tension	mN/m	12.4	13.6	13.6	15.0	16.2	17.7
Solubility of Water in Fluid	ppm by weight	~60	95	92	67	45	410
Solubility of Fluid in Water	ppm by weight	<50	12	<20	<1	<3	<10
Dielectric Strength, 0.1" gap	kV	~40	~40	~40	~40	~40	~40
Dielectric Constant @ 1kHz	–	7.4	7.4	7.3	6.1	5.8	6.4
Volume Resistivity	Ohm-cm	10^8	10^8	10^8	10^{11}	10^8	10^{10}
Global Warming Potential	GWP	420	297	59	210	100	700

For test methods and variability, contact 3M Technical Service

3M™ Fluorinert™ Electronic Liquids

	Unit	FC-3284	FC-72	FC-84	FC-770	FC-3283	FC-40	FC-43
Boiling Point	°C	50	56	80	95	128	155	174
Pour Point	°C	-73	-90	-95	-127	-50	-57	-50
Molecular Weight	g/mol	299	338	388	399	521	650	670
Critical Temperature	°C	161	176	202	238	235	270	294
Critical Pressure	MPa	1.94	1.83	1.75	2.47	1.22	1.18	1.13
Vapor Pressure	kPa	35	30	11	6.6	1.4	0.43	0.19
Heat of Vaporization	kJ/kg	105	88	90	86	78	68	70
Liquid Density	kg/m^3	1710	1680	1730	1793	1820	1850	1860
Coefficient of Expansion	K^{-1}	0.0016	0.0016	0.0015	0.0015	0.0014	0.0012	0.0012
Kinematic Viscosity	cSt	0.42	0.38	0.53	0.79	0.75	1.8	2.5
Absolute Viscosity	cP	0.71	0.64	0.91	1.4	1.4	3.4	4.7
Specific Heat	J/kg-K	1100	1100	1100	1038	1100	1100	1100
Thermal Conductivity	W/m-K	0.062	0.057	0.060	0.063	0.066	0.065	0.065
Surface Tension	mN/m	13	10	12	15	15	16	16
Solubility of Water in Fluid	ppm by weight	14	10	11	14	7	<7	7
Solubility of Fluid in Water	ppm by weight	<5	<5	<5	<5	<5	<5	<5
Dielectric Strength, 0.1" gap	kV	>40	>40	>40	>40	>40	>40	>40
Dielectric Constant @ 1kHz	–	1.9	1.8	1.8	1.9	1.9	1.9	1.9
Volume Resistivity	Ohm-cm	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}

For test methods and variability, contact 3M Technical Service

For discussion on GWP, refer to additional content in this brochure.

3M™ Novec™ 649 Engineered Fluid

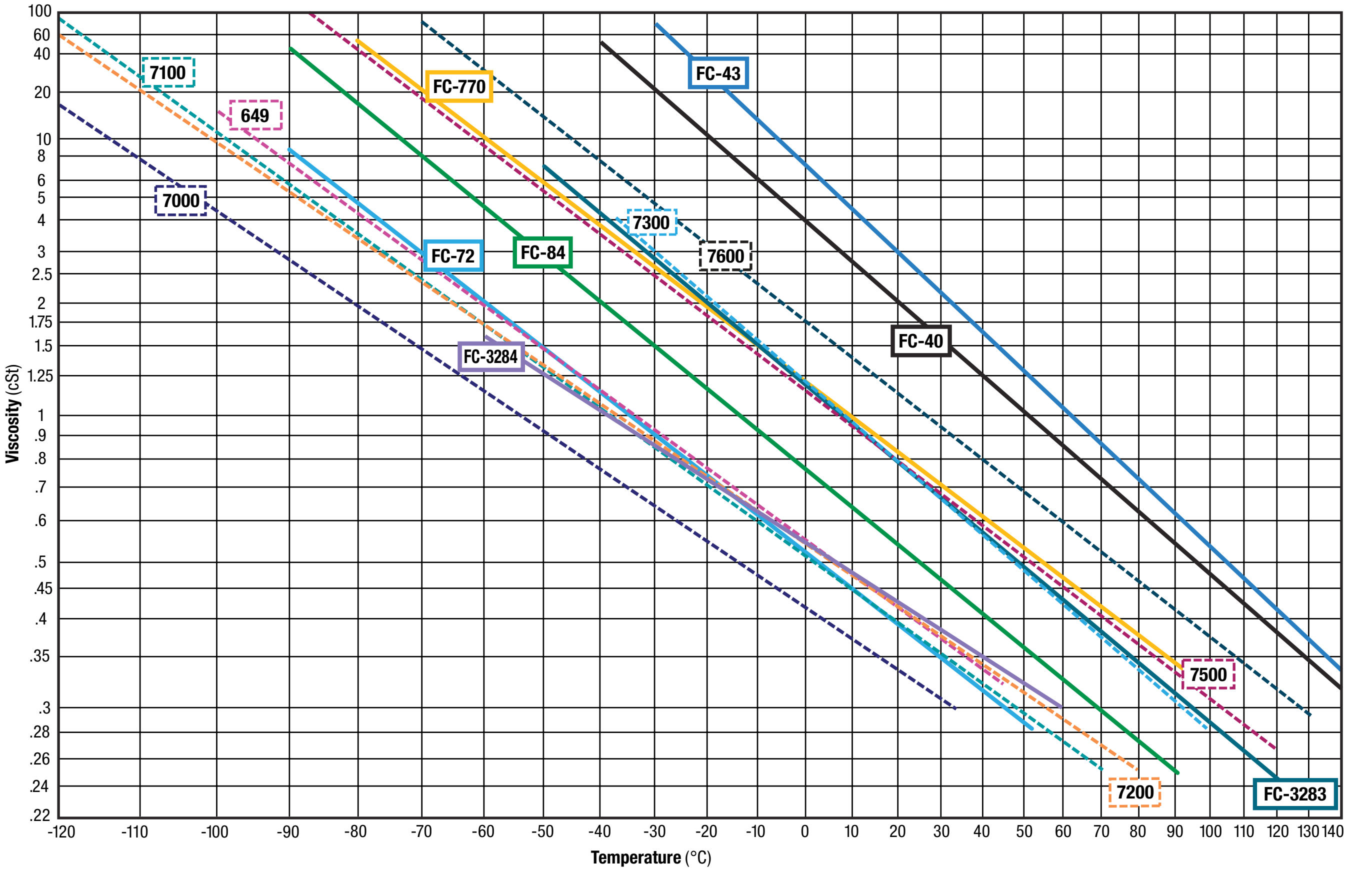
	Unit	Novec 649
Boiling Point	°C	49
Pour Point	°C	-108
Molecular Weight	g/mol	316
Critical Temperature	°C	169
Critical Pressure	MPa	1.88
Vapor Pressure	kPa	40
Heat of Vaporization	kJ/kg	88
Liquid Density	kg/m^3	1600
Coefficient of Expansion	K^{-1}	0.0018
Kinematic Viscosity	cSt	0.40
Absolute Viscosity	cP	0.64
Specific Heat	J/kg-K	1103
Thermal Conductivity	W/m-K	0.059
Surface Tension	mN/m	10.8
Solubility of Water in Fluid	ppm by wt	20
Dielectric Strength, 0.1" gap	kV	>40
Dielectric Constant @ 1kHz	–	1.8
Volume Resistivity	Ohm-cm	10^{12}
Global Warming Potential	GWP	1

Novec 649 fluid is an advanced heat transfer fluid with the lowest Global Warming Potential (GWP) in the Novec family. It belongs to a new class of fluoroketone fluids which are being explored for their use in thermal management applications such as direct and indirect heat transfer systems and Organic Rankine Cycle (ORC) systems.

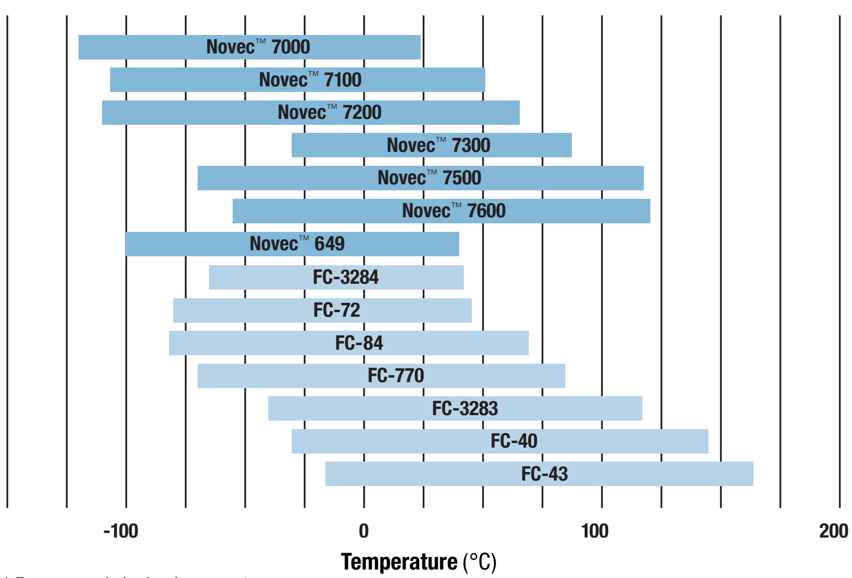
3M heat transfer fluids, sold under the 3M™ Novec™ Engineered Fluids and 3M™ Fluorinert™ Electronic Liquids brands, are available in a wide range of boiling points (34°C up to 175°C) and freezing points (-38°C down to -138°C), to meet your specific requirements.

3M™ Thermal Management Fluids Kinematic Viscosity

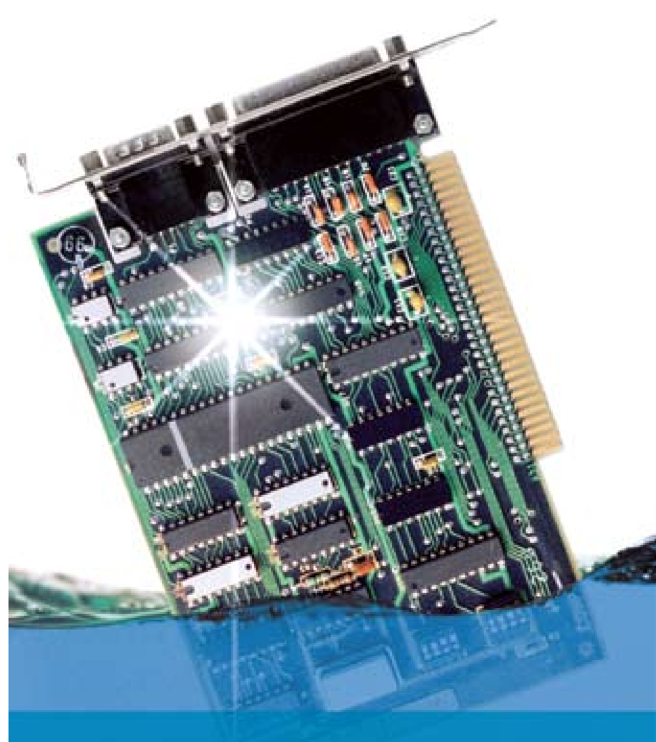
Viscosity vs. Temperature



Recommended Operating Temperature Range*



* For pumped single phase systems.



3M™ Novec™ Engineered Fluids

3M™ Novec™ Engineered Fluids are a family of low-Global Warming materials designed to deliver on the Novec promise of safe, sustainable chemistry.

Performance

Novec Engineered Fluids have excellent properties for heat transfer applications:

- Excellent dielectric properties
- Wide range of boiling points
- Good materials compatibility

These fluids require little maintenance and offer dependable performance. They have high resistivity and will not damage electronic equipment or integrated circuits in the event of a leak or other failure.

Environmental profile

Novec Engineered Fluids also offer favorable environmental and worker safety properties:

- Low toxicity
- Nonflammability
- Low Global Warming Potential (GWP)
- Zero Ozone Depletion Potential (ODP)

The chemical inertness and non-corrosivity of Novec Engineered Fluids make them safe for workers to handle, while the environmental properties mean they can be used both now and in the future while leaving behind a smaller footprint on the world.

The next generation of heat transfer fluids

The favorable environmental, health and safety properties of Novec fluids have made them a long-term, sustainable solution. Novec fluids have been recognized by a number of industry and regulatory bodies around the world, including 3M™ Novec™ Engineered Fluids 7100 and 7200 being approved for "use without restriction" under the U.S. EPA's Significant New Alternatives Policy (SNAP).

Novec fluids are already widely used as heat transfer fluids in the semiconductor industry, where they are used for temperature control of manufacturing equipment while reducing a facility's greenhouse gas emissions. They have also been used in direct contact dielectric test applications.

Safe
Reliable
Sustainable
Chemistries

3M™ Fluorinert™ Electronic Liquids

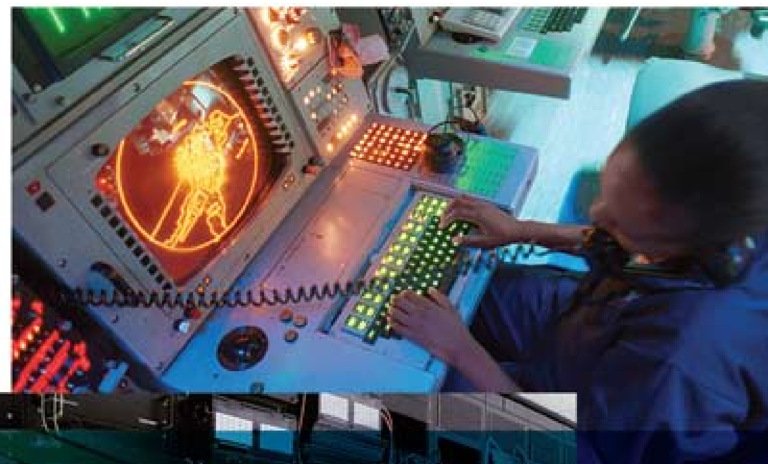
3M™ Fluorinert™ Electronic Liquids are part of a family of fully-fluorinated compounds known as perfluorocarbons, or PFCs. Fluorinert liquids are premier heat transfer fluids, and have long been used as heat transfer media for extreme cooling applications.

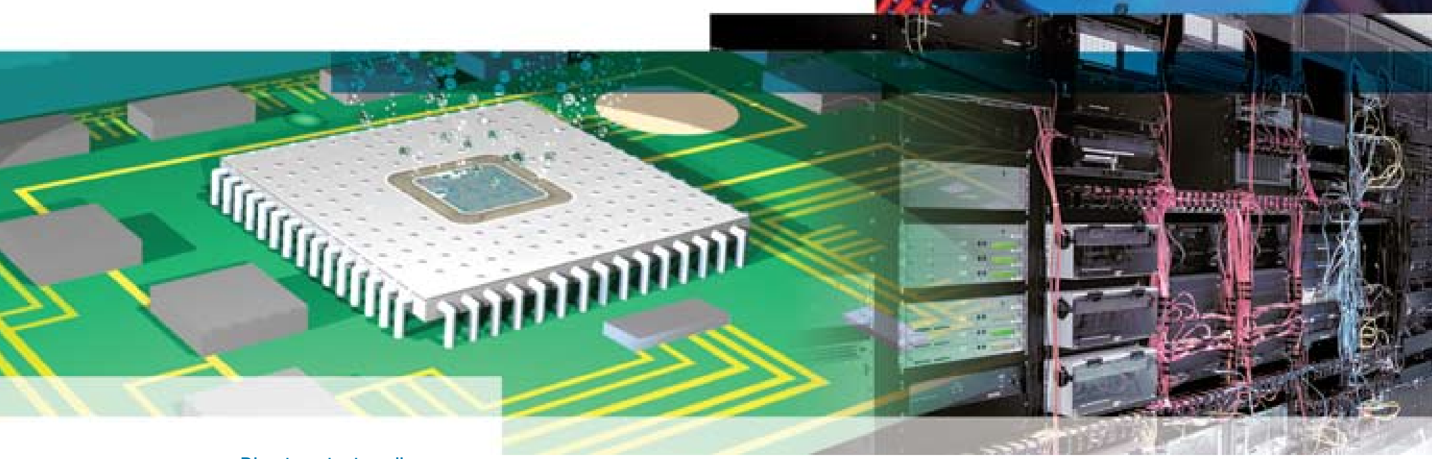
Originally used for direct contact cooling due to their stability, Fluorinert liquids are also used in a variety of semiconductor operations such as automated testing, etching, deposition, photolithography and more. Fluorinert liquids offer:

- Excellent dielectric properties
- Wide range of boiling points
- Good materials compatibility
- Low toxicity
- Nonflammability
- Zero Ozone Depletion Potential (ODP)

In addition, you have the assurance that comes from dealing with 3M, a company with over 40 years of experience addressing industrial-strength cooling needs.

While they are non-ozone depleting, high-performance Fluorinert liquids do have high global warming potentials (GWP) and long atmospheric lifetimes. Because emission of materials with these properties could have a significant impact on the environment, users must take care to carefully manage and minimize emissions. 3M recommends that users of Fluorinert liquids limit emissions by employing good conservation practices, and by implementing recovery, recycling and/or proper disposal procedures.





Direct contact cooling with 3M™ Fluorinert™ Electronic Liquids helped enable the development of dense electronics, such as supercomputers and power converters.

Material Compatibility

3M™ Novec™ Engineered Fluids and 3M™ Fluorinert™ Electronic Liquids are compatible with a wide variety of materials used in heat transfer equipment. As with any design, selection of these materials is very important. A 3M specialist in this area can help you make the proper choice.

Polymers

Most of the materials commonly considered "hard" plastics will perform well with both Novec fluids and Fluorinert liquids.

Elastomers

Elastomers should be limited to those that are not heavily plasticized. 3M engineers can assist you with recommendations and testing on specific compounds.

More
Options
More
Answers

The hidden benefit: 3M experience

The use of fluorochemicals in heat transfer systems is a science that 3M has studied like no other company. Bringing this extensive knowledge to bear on your heat transfer equipment is a major part of our Thermal Management program ... and a major benefit of purchasing 3M™ Novec™ Engineered Fluids or 3M™ Fluorinert™ Electronic Liquids.

Here are just some of the services that 3M can provide to help you utilize these innovative fluids in your heat transfer equipment:

Heat Transfer Seminar/Design Assistance

Given free of charge at qualifying customer sites, this seminar teaches appropriate design procedures by discussing material compatibility, sources of leakage, pumping, component selection, environmental issues and more. The content of these seminars can be tailored to the specific interests of the audience. 3M has conducted seminars at numerous customer locations.

Compatibility Testing

3M engineers can evaluate parts with advanced testing methods to help you determine if a component or material is suitable in your design.

On-Site Consultations

Working side-by-side with equipment designers and end users, 3M engineers frequently help customers tighten-up equipment and optimize system performance.

Analytical Services

3M has state-of-the-art analytical resources which are used to help answer customer questions.

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3M™ Novec™ 7000 Engineered Fluid

Introduction

3M™ Novec™ 7000 Engineered Fluid, 1-methoxyheptafluoropropane, is a non-flammable, low global warming potential (GWP) heat transfer fluid capable of reaching -120°C. It is also useful as a direct expansion refrigerant.

For information on other applications, contact your 3M representative or 3M authorized distributor.

Applications

- Semiconductor
  - Ion implanters
  - Dry etchers
  - CVD/PVD tools
  - Electronic Automated Test Equipment (ATE)
- Industrial/Pharmaceutical
  - Chemical reactors
  - Freeze dryers
  - VOC capture
- Fuel cells
- Electronic Cooling
  - Supercomputers
  - Sensitive military electronics
  - High voltage transformers
- Electronics
  - Reliability testing
  - Temperature calibration
- Autocascade refrigeration
  - HCFC-123 replacement
- Medical Lab
  - Histobath working fluid

Benefits

- Low GWP (530, 100-year ITH)
- Excellent dielectric properties
  - In event of leakage or other failure, will not damage electronic equipment
- Zero ozone depletion potential (ODP)
- Good materials compatibility
- Low toxicity
- Non-flammable
- Non-corrosive
- Good thermal stability
- Useful at extreme low temperatures
  - Viscosity is less than 20 cSt at -120°C

Material Description

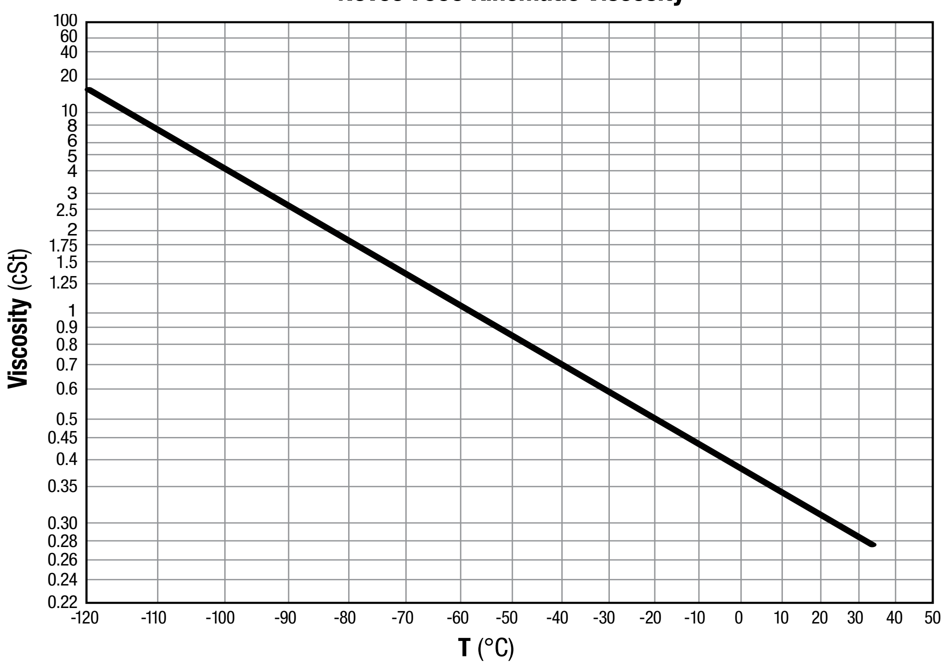
Ingredients	Novec™ 7000 Engineered Fluid
1-methoxyheptafluoropropane ($C_3F_7OCH_3$)	99.5% by weight
Appearance	Clear, colorless
Non-volatile residue (NVR)	25.0 ppm maximum

Typical Physical Properties

Not for specification purposes. All values @ 25°C unless otherwise specified.

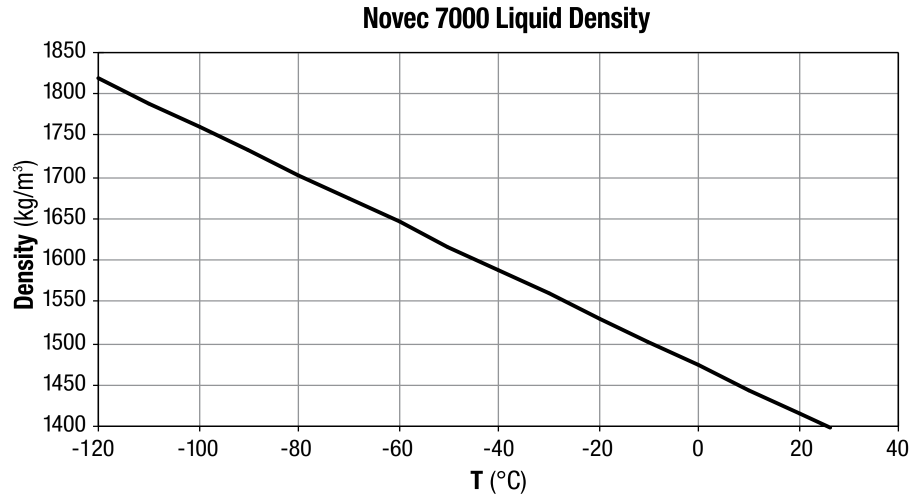
Properties	3M™ Novec™ 7000 Engineered Fluid
Molecular Weight (g/mol)	200
Boiling Point @ 1 atmosphere (°C)	34
Freeze Point (°C)	-122.5
Liquid Density (kg/m^3)	1400
Kinematic Viscosity (cSt)	0.32
Kinematic Viscosity @ -80°C (cSt)	2.0
Kinematic Viscosity @ -120°C (cSt)	17
Coefficient of Expansion	0.00219 K^{-1}
Critical Density (kg/m^3)	553
Critical Pressure (MPa)	2.48
Critical Temperature (°C)	165°C
Dielectric Constant	7.4
Dielectric Strength (kV)	~40
Flash Point	None
Latent Heat of Vaporization (kJ/kg)	142
Solubility of water in fluid (ppmw)	~60
Solubility of air in fluid (vol %)	~35
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	1300
Surface Tension (dynes/cm)	12.4
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.075
Vapor Pressure (kPa)	64.6
Volume Resistivity (ohm-cm)	108

Novec 7000 Kinematic Viscosity

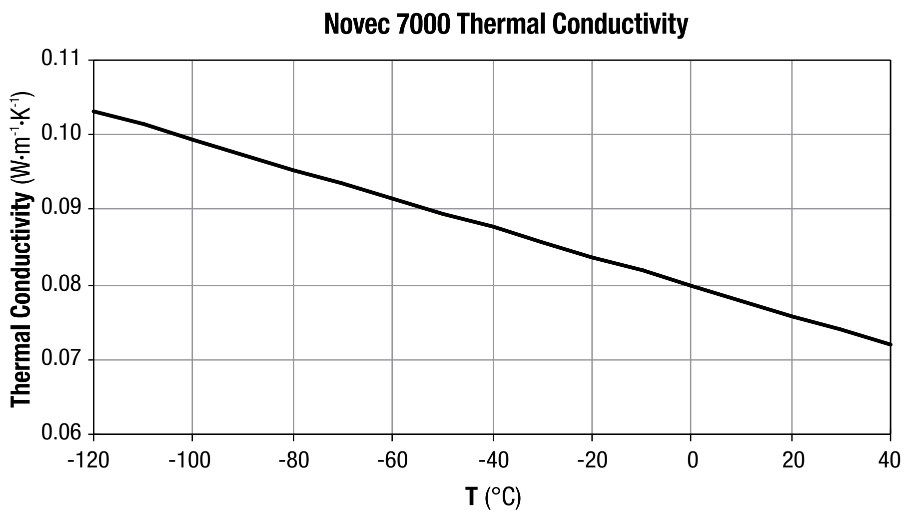


Typical Physical Properties (continued)

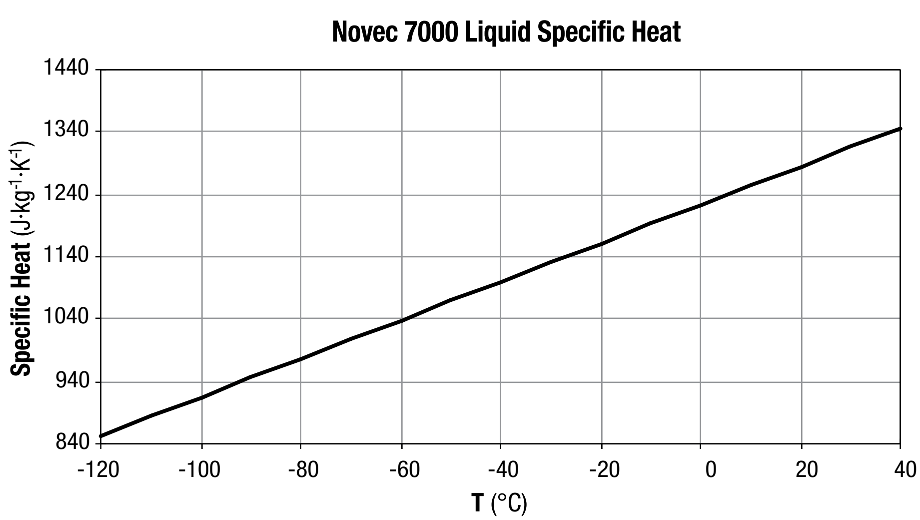
Not for specification purposes. All values @ 25°C unless otherwise specified.



Liquid Density [kg/m^3] = 1472.6 - 2.880·T(°C)



Thermal Conductivity [W·m^{-1}·K^{-1}] = 0.0798 - 0.000196·T(°C)



Liquid Specific Heat [J·kg^{-1}·K^{-1}] = 1223.2 + 3.0803·T (°C)

Novec 7000 Vapor Pressure

$$\ln(P[Pa]) = -3548.6/T[K] + 22.978$$
$$-30°C < T < T_c$$

Toxicity Profile

Not for specification purposes. All values @ 25°C unless otherwise specified.

The toxicological testing completed on 3M™ Novec™ 7000 Engineered Fluid indicates low acute and sub-acute toxicity. A 28-day inhalation study conducted at 1000, 10,000 and 30,000 ppm helped establish an exposure guideline of 250 ppmv for an average 8 hour work day. The No Adverse Effect Level (NOAEL) in this study was 1000 ppm. This data suggests there is a large margin of safety for use of this fluid in relatively non-emissive heat transfer systems.

Toxicological Test Results

Properties	Novec™ 7000 Engineered Fluid
Acute Lethal Concentration (ppmv)	>30,000
8 hr Exposure Guideline (ppmv)	250
Skin Irritation	Negative[1]
Mutagenicity	Negative[1]
Ecotoxicity (water solubility < 2.5 ppb)	Very low aquatic toxicity
Acute Oral Toxicity	LD50 > 2000 mg/kg[1]
28-day Inhalation	NOAEL=1000 ppm

[1] A. Sekiya and S. Misaki, "*The potential of hydrofluoroethers to replace CFCs, HCFCs and PFCs*" J. of Fluorine Chemistry, 101, 2000, pp. 215-221.

Environmental Properties

Properties	Novec™ 7000 Engineered Fluid
Ozone Depletion Potential[1] (ODP)	0.0
Global Warming Potential[2] (GWP)	530
Atmospheric Lifetime (years)	4.9

[1] CFC-11 = 1.0
[2] GWP 100-year integrated time horizon (ITH). IPCC 2013.

Environmental, Health and Safety

Before using this product, please read the current product Safety Data Sheet (available through your 3M sales or technical service representative) and the precautionary statement on the product package. Follow all applicable precautions and directions.

3M™ Novec™ 7000 Engineered Fluid is non-flammable. The fluid is resistant to thermal breakdown and hydrolysis during storage and use. Recommended handling procedures are provided in the Safety Data Sheet, which is available from your local 3M representative upon request.

Materials Compatibility

Novec 7000 fluid is compatible with most metals and hard polymers such as:

Metals	Plastics
Stainless Steel	Polypropylene
Brass	Polyethylene
Copper	Nylon
Aluminum	Polyacetyl
	PEEK
	PTFE

Elastomeric materials should be limited to those compounds that contain the least amount of extractible plasticizer. 3M engineers can suggest appropriate compounds or assist with test procedures.

Heater Selection

The critical heat flux of Novec 7000 fluid is 18 W/cm^2 when boiling from a horizontal 0.5 mm diameter platinum wire in a quiescent pool of saturated fluid. The maximum heat flux obtainable in forced convection applications will be significantly higher, but depends strongly upon the geometry and flow conditions. A safety interlock between the pump and heater is strongly recommended in applications with heat fluxes exceeding 15 W/cm^2.

Regulatory Status

Novec 7000 fluid is available for commercial sale in the United States, China, Malaysia, Singapore and Taiwan and is currently under review by regulatory agencies in Europe, Japan, the Philippines and Korea.

Contact your local 3M representative for an update on the regulatory status of Novec 7000 fluid.

Recycle and Disposal Options

Used Fluid Return Program

3M offers a program for free pickup and return of used 3M specialty fluids in the U.S. A pre-negotiated handling agreement between users and our authorized service provider offers users broad protection against future liability for used 3M product. The fluid return program is covered by independent third-party financial and environmental audits of treatment, storage and disposal facilities. Necessary documentation is provided. A minimum of 30 gallons of used 3M specialty fluid is required for participation in this free program.

For additional information on the 3M Used Fluid Return Program, contact your local 3M representative or call 3M Customer Service at 800.810.8513.

Resources

3M™ Novec™ Engineered Fluids are supported by global sales, technical and customer service resources, with technical service laboratories in the U.S., Europe, Japan, Latin America and Southeast Asia. Users benefit from 3M's broad technology base and continuing attention to product development, performance, safety and environmental issues. For additional technical information on 3M™ Novec™ 7000 Engineered Fluid in the United States or for the name of a local authorized distributor, call 3M Electronics Materials Solutions Division: **800 810 8513.**

The 3M™ Novec™ Brand Family

The Novec brand is the hallmark for a variety of proprietary 3M products. Although each has its own unique formula and performance properties, all Novec products are designed in common to address the need for safe, effective, sustainable solutions in industry-specific applications. These include precision and electronics cleaning, heat transfer, fire protection, protective coatings, immersion cooling, advanced insulation media replacement solutions and several specialty chemical applications.

3M™ Novec™ Engineered Fluids • 3M™ Novec™ Aerosol Cleaners • 3M™ Novec™ 1230 Fire Protection Fluid • 3M™ Novec™ Electronic Grade Coatings • 3M™ Novec™ Electronic Surfactants • 3M™ Novec™ Dielectric Fluids

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C Contact Angle reports

OneAttension experiment report

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Sun Jun 11 18:34:33 CEST 2017

Experiment info

Name	
Type	Contact angle
Date	11.jun.2017 18:28

Solid

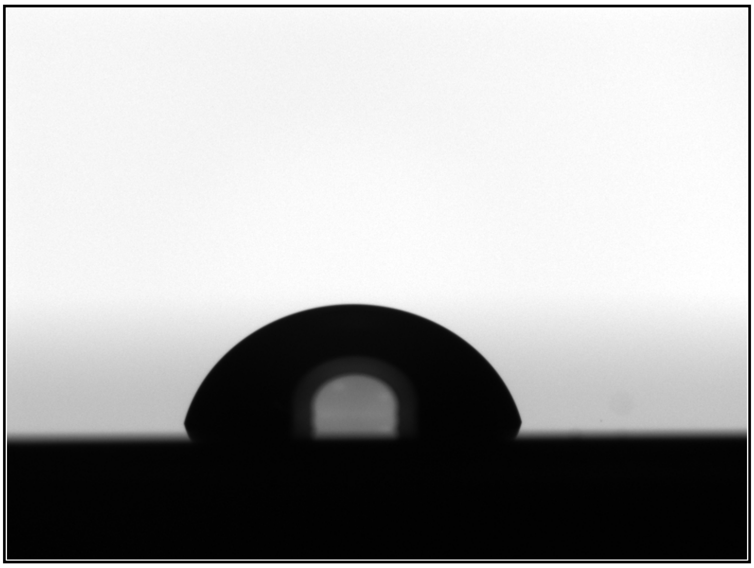
Name	
tot [mN/m]	
d [mN/m]	
+ [mN/m]	
- [mN/m]	
[g/cm³]	

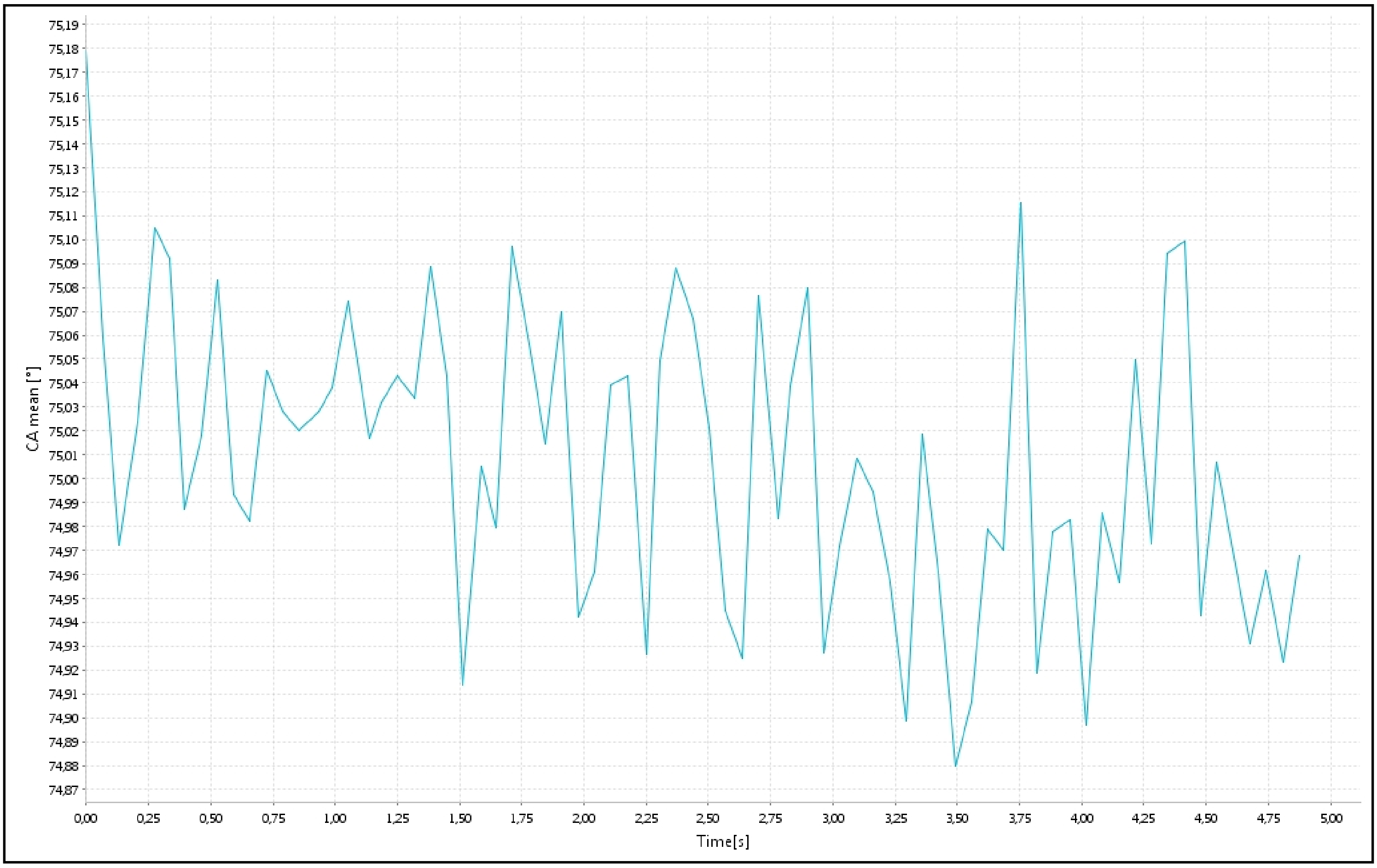
Heavy phase

Name	Water
tot [mN/m]	72.800
d [mN/m]	21.800
+ [mN/m]	25.500
- [mN/m]	25.500
[g/cm³]	0.9980
[mPa.s]	1.002
Temperature [°C]	20.000
Molecular weight [g/mol]	18.010

Light phase

Name	Air
tot [mN/m]	
d [mN/m]	
+ [mN/m]	
- [mN/m]	
[g/cm³]	0.0012
[mPa.s]	
Temperature [°C]	20.000
Molecular weight [g/mol]	0.029





Detailed results

Time [s]	CA left [°]	CA right [°]	CA mean [°]	Volume [l]	Baseline [mm]
0.00	75.03	75.33	75.18	15.97	4.57
0.07	75.05	75.07	75.06	15.90	4.57
0.13	75.09	74.86	74.97	15.88	4.57
0.21	75.10	74.95	75.02	15.91	4.57
0.27	75.05	75.16	75.10	15.93	4.57
0.33	74.98	75.20	75.09	15.94	4.57
0.40	74.87	75.10	74.99	15.89	4.57
0.46	74.95	75.09	75.02	15.90	4.57
0.53	75.02	75.15	75.08	15.92	4.57
0.59	74.94	75.05	74.99	15.87	4.57
0.66	74.99	74.98	74.98	15.87	4.57
0.72	74.91	75.18	75.05	15.90	4.57
0.79	75.01	75.05	75.03	15.90	4.57
0.86	74.88	75.16	75.02	15.90	4.57
0.94	75.03	75.02	75.03	15.89	4.57
0.99	74.90	75.17	75.04	15.92	4.57
1.05	75.11	75.04	75.07	15.93	4.57
1.14	75.11	74.93	75.02	15.88	4.57
1.19	75.02	75.05	75.03	15.89	4.57
1.25	75.05	75.03	75.04	15.90	4.57
1.32	74.88	75.19	75.03	15.91	4.57
1.38	74.79	75.38	75.09	15.94	4.57
1.45	74.87	75.22	75.04	15.91	4.57
1.51	74.81	75.02	74.91	15.86	4.57
1.59	75.04	74.97	75.01	15.88	4.57
1.65	74.96	75.00	74.98	15.86	4.57
1.71	74.97	75.22	75.10	15.93	4.57
1.78	74.99	75.13	75.06	15.90	4.57
1.84	74.96	75.07	75.01	15.90	4.57
1.91	75.13	75.01	75.07	15.93	4.57
1.98	74.94	74.94	74.94	15.86	4.57
2.04	74.85	75.07	74.96	15.86	4.57
2.11	75.07	75.00	75.04	15.89	4.57
2.18	74.92	75.17	75.04	15.92	4.57
2.25	74.82	75.03	74.93	15.86	4.57
2.31	74.90	75.20	75.05	15.90	4.57

2.37	75.03	75.15	75.09	15.94	4.57
2.44	74.92	75.21	75.07	15.91	4.57
2.50	74.97	75.08	75.02	15.91	4.57
2.57	74.80	75.09	74.94	15.86	4.57
2.63	74.90	74.95	74.93	15.84	4.57
2.70	74.95	75.21	75.08	15.93	4.57
2.78	75.02	74.94	74.98	15.89	4.57
2.83	74.95	75.12	75.04	15.88	4.57
2.90	75.10	75.06	75.08	15.91	4.57
2.96	74.83	75.03	74.93	15.85	4.57
3.03	74.89	75.06	74.97	15.86	4.57
3.10	74.89	75.13	75.01	15.88	4.57
3.16	74.92	75.07	74.99	15.89	4.57
3.23	74.84	75.07	74.96	15.86	4.57
3.29	74.89	74.90	74.90	15.86	4.57
3.36	74.99	75.04	75.02	15.89	4.57
3.42	74.90	75.02	74.96	15.86	4.57
3.49	74.87	74.89	74.88	15.84	4.57
3.56	74.84	74.97	74.91	15.85	4.57
3.62	74.94	75.02	74.98	15.87	4.57
3.69	74.92	75.02	74.97	15.87	4.57
3.75	75.06	75.17	75.12	15.93	4.57
3.82	74.84	74.99	74.92	15.85	4.57
3.89	74.90	75.06	74.98	15.85	4.57
3.95	74.99	74.98	74.98	15.88	4.57
4.02	74.77	75.02	74.90	15.84	4.57
4.08	74.91	75.06	74.99	15.88	4.57
4.15	74.94	74.97	74.96	15.86	4.57
4.21	74.96	75.14	75.05	15.93	4.57
4.28	74.87	75.08	74.97	15.88	4.57
4.35	75.03	75.15	75.09	15.94	4.57
4.41	75.05	75.15	75.10	15.94	4.57
4.48	74.90	74.98	74.94	15.86	4.57
4.54	74.95	75.06	75.01	15.88	4.57
4.61	74.94	75.00	74.97	15.88	4.57
4.68	74.86	75.00	74.93	15.85	4.57
4.74	74.95	74.97	74.96	15.86	4.57
4.81	74.77	75.07	74.92	15.87	4.57
4.87	74.84	75.09	74.97	15.87	4.57

OneAttension experiment report

Generated with OneAttension Version 2.9 (r5612)
Tue May 30 12:12:27 CEST 2017

Experiment info

Name	FC72
Type	Contact angle
Date	30.mai.2017 12:09

Solid

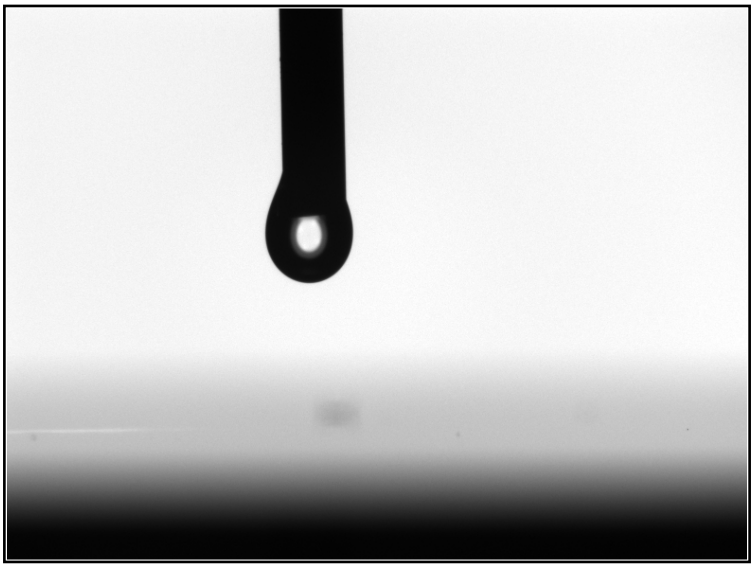
Name	
tot [mN/m]	
d [mN/m]	
+ [mN/m]	
- [mN/m]	
[g/cm^3]	

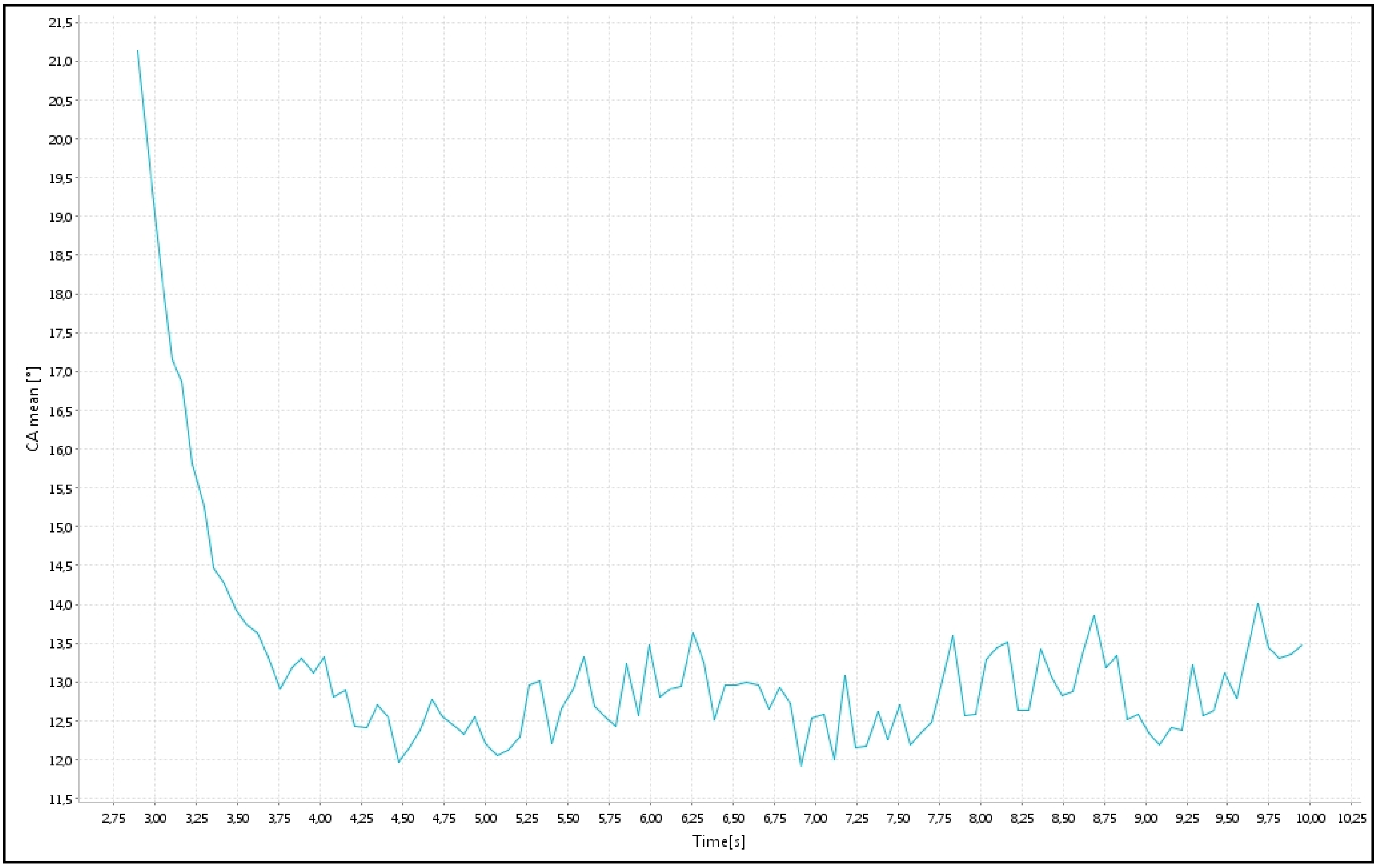
Heavy phase

Name	FC72
tot [mN/m]	10.000
d [mN/m]	
+ [mN/m]	
- [mN/m]	
[g/cm^3]	1.6800
[mPa.s]	0.380
Temperature [°C]	25.000
Molecular weight [g/mol]	338.000

Light phase

Name	Air
tot [mN/m]	
d [mN/m]	
+ [mN/m]	
- [mN/m]	
[g/cm^3]	0.0012
[mPa.s]	
Temperature [°C]	20.000
Molecular weight [g/mol]	0.029





Detailed results

Time [s]	CA left [°]	CA right [°]	CA mean [°]	Volume [l]	Baseline [mm]
0.00					
0.07					
0.13					
0.20					
0.26					
0.33					
0.39					
0.46					
0.53					
0.59					
0.66					
0.72					
0.79					
0.86					
0.92					
0.99					
1.05					
1.12					
1.19					
1.25					
1.32					
1.38					
1.45					
1.51					
1.58					
1.65					
1.71					
1.78					
1.84					
1.91					
1.98					
2.04					
2.11					
2.17					
2.24					
2.30					

2.37					
2.44					
2.50					
2.57					
2.63					
2.70					
2.77					
2.83					
2.90	21.18	21.07	21.13	1.16	3.23
2.98	19.18	19.82	19.50	1.12	3.24
3.04	18.12	18.37	18.25	1.46	3.50
3.11	17.18	17.12	17.15	1.15	3.39
3.16	17.11	16.65	16.88	1.36	3.49
3.23	16.03	15.60	15.82	1.33	3.48
3.30	15.72	14.79	15.26	1.43	3.57
3.36	14.83	14.12	14.47	1.23	3.41
3.42	14.34	14.20	14.27	1.20	3.58
3.49	14.32	13.52	13.92	1.15	3.53
3.56	14.10	13.38	13.74	1.24	3.65
3.62	13.93	13.35	13.64	1.21	3.64
3.69	13.77	12.88	13.32	1.20	3.64
3.76	13.04	12.79	12.91	1.14	3.61
3.83	13.78	12.59	13.19	1.16	3.59
3.89	13.75	12.87	13.31	1.17	3.60
3.96	13.20	13.04	13.12	1.12	3.61
4.02	13.72	12.92	13.32	1.17	3.60
4.08	12.94	12.69	12.81	1.08	3.56
4.15	13.13	12.64	12.89	1.17	3.65
4.21	12.96	11.91	12.44	0.93	3.44
4.28	12.71	12.11	12.41	1.00	3.48
4.35	13.26	12.14	12.70	1.03	3.51
4.41	13.10	11.99	12.54	0.97	3.46
4.48	12.52	11.42	11.97	0.90	3.41
4.54	12.81	11.52	12.16	1.03	3.56
4.61	13.04	11.74	12.39	0.99	3.49
4.68	13.90	11.63	12.77	1.15	3.46
4.74	13.56	11.54	12.55	1.00	3.44
4.81	11.74	13.16	12.45	0.93	3.46
4.87	12.60	12.06	12.33	0.80	3.27
4.94	13.03	12.08	12.56	1.00	3.42
5.00	12.13	12.29	12.21	0.92	3.42
5.07	11.56	12.54	12.05	0.91	3.44
5.14	12.10	12.16	12.13	0.77	3.26
5.21	12.51	12.06	12.29	0.75	3.22
5.27	13.03	12.90	12.96	0.77	3.22
5.33	12.97	13.07	13.02	1.02	3.50
5.40	12.22	12.19	12.20	0.76	3.24
5.47	12.86	12.44	12.65	0.76	3.18
5.53	12.55	13.28	12.91	0.88	3.34
5.60	13.33	13.32	13.33	0.85	3.27
5.66	12.67	12.72	12.69	0.67	3.10
5.74	12.59	12.47	12.53	0.66	3.08
5.79	12.42	12.43	12.42	0.65	3.08
5.86	13.15	13.31	13.23	0.77	3.19
5.93	12.50	12.63	12.57	0.64	3.05
5.99	13.73	13.24	13.48	0.78	3.15
6.06	13.07	12.55	12.81	0.64	2.99
6.12	12.62	13.19	12.90	0.73	3.15
6.19	13.02	12.86	12.94	0.66	3.04
6.26	13.76	13.51	13.64	0.71	3.09
6.32	13.29	13.22	13.26	0.76	3.18
6.39	12.28	12.75	12.52	0.72	3.15
6.45	13.19	12.72	12.96	0.69	3.09
6.52	13.06	12.86	12.96	0.82	3.24
6.59	12.98	13.02	13.00	0.81	3.24
6.66	12.58	13.36	12.97	0.81	3.23
6.72	12.59	12.71	12.65	0.80	3.23
6.78	13.06	12.79	12.92	0.66	3.04
6.85	12.86	12.58	12.72	0.64	3.02
6.91	11.90	11.92	11.91	0.49	2.83
6.98	12.41	12.67	12.54	0.63	3.00
7.05	12.82	12.35	12.58	0.61	2.97

7.11	11.92	12.08	12.00	0.46	2.74
7.18	12.77	13.38	13.08	0.65	3.01
7.24	12.44	11.88	12.16	0.53	2.85
7.31	12.62	11.71	12.16	0.54	2.87
7.38	13.15	12.07	12.61	0.58	2.91
7.44	12.47	12.06	12.27	0.53	2.84
7.51	13.01	12.41	12.71	0.49	2.76
7.57	12.60	11.77	12.18	0.45	2.68
7.64	12.83	11.86	12.34	0.54	2.88
7.70	12.72	12.25	12.48	0.42	2.65
7.77	13.08	12.95	13.01	0.48	2.74
7.84	13.35	13.85	13.60	0.59	2.89
7.90	12.63	12.52	12.57	0.50	2.77
7.97	13.23	11.94	12.59	0.46	2.70
8.03	13.93	12.64	13.29	0.50	2.72
8.10	13.89	13.00	13.44	0.51	2.72
8.17	13.75	13.26	13.51	0.47	2.70
8.23	12.48	12.81	12.64	0.38	2.55
8.30	12.53	12.74	12.64	0.36	2.51
8.36	13.34	13.51	13.42	0.45	2.62
8.43	13.25	12.90	13.07	0.36	2.46
8.50	13.21	12.45	12.83	0.35	2.44
8.56	13.16	12.58	12.87	0.34	2.43
8.63	13.48	13.33	13.41	0.33	2.39
8.69	13.94	13.76	13.85	0.35	2.41
8.76	13.21	13.15	13.18	0.29	2.31
8.82	12.90	13.79	13.34	0.40	2.53
8.89	11.94	13.08	12.51	0.40	2.57
8.96	12.92	12.24	12.58	0.32	2.38
9.02	12.18	12.51	12.34	0.31	2.39
9.09	12.04	12.36	12.20	0.33	2.41
9.15	12.01	12.82	12.41	0.32	2.40
9.22	12.37	12.40	12.39	0.28	2.30
9.29	13.10	13.35	13.22	0.29	2.28
9.35	12.45	12.70	12.58	0.29	2.30
9.42	12.50	12.77	12.63	0.28	2.27
9.48	12.91	13.31	13.11	0.26	2.21
9.55	12.85	12.75	12.80	0.26	2.20
9.61	13.44	13.36	13.40	0.27	2.23
9.68	13.86	14.17	14.02	0.32	2.30
9.75	13.28	13.59	13.44	0.24	2.16
9.81	12.92	13.70	13.31	0.23	2.12
9.88	13.04	13.68	13.36	0.25	2.16
9.95	12.94	14.01	13.48	0.29	2.25