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DROPLET VAPORIZATION OF ETHANOL, N-HEPTANE, AND ISO-OCTANE ON HEATED SURFACES OF DIFFERENT METALS

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Abstract. A study of droplet evaporation in two heating surfaces was conducted. Ethanol, n-heptane, and iso-octane were used as test fluids while heated surfaces tested were copper and aluminum. The motivation to perform this work consists of a better understanding of how the evaporation process occurs in different surface materials. The test fluids were released onto the heated surfaces through individual drops, and the evaporation process was filmed by a digital camera. The observations were used to construct curves relating droplet lifetime with the wall temperature and determine the effects of the heating surface material at the Nukiyama and Leidenfrost Point. The experimental results were compared with the data found in the literature.

Keywords: Vaporization, Heated Surfaces, Nukiyama Point, Leidenfrost Point.

1. INTRODUCTION

The boiling heat transfer process and the phase change phenomenon during the drop-surface interaction play a significant role in a series of applications and techniques. Generally the interest of this kind of study is related to refrigeration processes by spraying due to the difficulty of obtaining high removal rates heat removal in confined spaces that comprise electronics packaging, medical equipment and small devices (Rein, 2002). The importance of this theme has attracted the attention of many researchers over the years who seek a better understanding of the physical aspects during the droplet impingement process. The technological advance has facilitated studies in this area of research due to the emergence of modern cameras.

Most applications of the droplet impact on solid surfaces involve high temperatures. For example, Stanglmaier *et al.* (2002) reported that the impact of liquid fuel on the combustion chamber surfaces can result in the emission of HC in direct injection SI engines. Segawa *et al.* (2009) affirms that momentum, heat and mass transfer process associated with fuel spraying onto the heated surface plays an important role in the formation of blends, ignition, combustion and at formation of pollutants harmful into the environment within the combustion chamber. The same authors point that the evaporation process of fuel droplets on a heated surface is only one of the key factors involved in this context. Nuclear reactors, power plants, electronics packaging, and applications using atomized liquids such spray cooling, and spray painting are others applications of the droplet impact onto hot surface (Peyghambarzadeh *et al.*, 2009; Kim, 2015).

The boiling phenomenon during the droplet impact on a heated surface occurs when the surface temperature is higher than the saturation temperature, implying the nucleation of small vapor bubbles at the solid-liquid interface during spreading the droplet at the surface (Khavari *et al.*, 2015). According to Liang and Mudawar (2017), the wall temperature plays an important role in the investigation of droplet impingement on heated surfaces, significantly influencing in the impact dynamics and heat transfer efficiency. The boiling phenomenon is usually represented by the well-known boiling curve, given in (Fig. 1b), which relates the heat flux to the wall superheat (the difference between the surface temperature and the fluid saturation temperature).

Through the graph, four distinct evaporation regimes can be identified: film evaporation, nucleate boiling, transition boiling, and film boiling. In addition, it is possible to identify critical points such as the critical heat flux (CHF) or the Nukiyama point which is the peak heat flux in nucleate boiling regime, and minimum heat flux (MHF) or the Leidenfrost point, which indicates the lowest possible heat flux in the film boiling regime. These points can also be found on the graph that relate the total evaporation of droplets (lifetime), with the temperature of the heating surface (Fig. 1b). At the Nukiyama temperature (T_N) the total drop evaporation time corresponds to the minimum, meanwhile at Leidenfrost's temperature, the total evaporation time of a drop reaches a maximum due to the emergence of a layer of steam that is

instantly produced and causes the drop to levitate on a cushion of its own vapor (Leidenfrost effect). This same vapor also provides thermal insulation of the surface (Rein, 2002; Geraldi *et al.*, 2016). Its degree of complexity depends on several parameters such as surface effect, pressure, subcooling, among others.

These critical temperatures are considered design variables, therefore, is necessary to characterize and investigate the parameters that can affect Nukiyama and Leidenfrost temperatures. For example: according to the work of Fardad and Ladommatos (1999), it is expected that heating surface material will have an influence on the total evaporation time of droplets in temperatures below the boiling point and above the Leidenfrost temperature. They explain that the evaporation of n-heptane in the subcooling regions (below 70°C) occurs because n-heptane wetting the surface of different materials in different manners, causing variations in the area of droplet spreading on the surface, affecting the rate of heat transfer. It should also be noted that similar behaviour was observed for iso-octane. These authors report that the surface roughness influences the evaporation rate of the droplet. The greater roughness increases the contact area of the droplet with the surface, and the irregularities in the test section penetrate the region below the droplet, thus improving the rate heat transfer rate. For Bernardin and Mudawar (1999), the higher value of the Leidenfrost point (LFP) for the copper surface can be explained as the result of the inherent surface roughness of generating a large oxide layer on the test surface during heating. Misyura (2016) in their experiment of the distilled water droplet evaporation at distinct surface materials observed different behaviors that fluid evaporation in the transition boiling region. He explains that distilled water cools the heated surface at different degrees for each material. The same author affirms that the lower thermal diffusivity also makes the residence time of a droplet on the wall longer in the transient crisis regime.

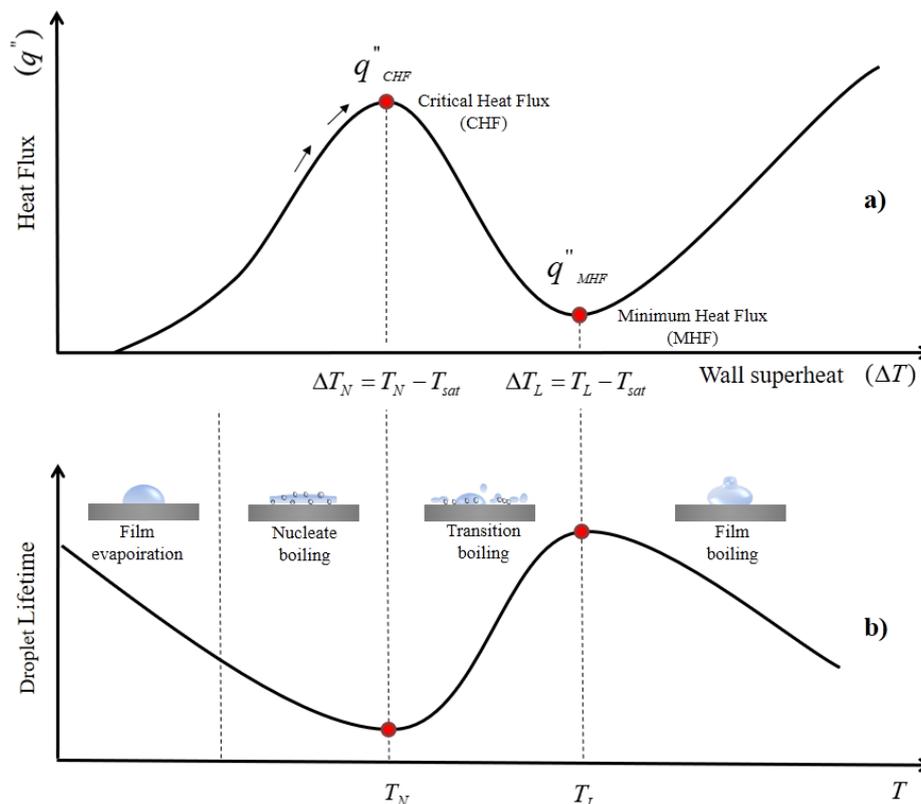


Figure 1. Typical boiling and lifetime curve with the critical points.

The objective of the present work was to obtain the ethanol, n-heptane, and iso-octane droplet lifetime curves in function of the wall temperature from the analysis of droplet evaporation at different surfaces and to evaluate the influence of the surface material on the Nukiyama and Leidenfrost points.

2. MATERIALS AND METHODS

To perform the tests, a droplet evaporation bench was designed and constructed to ensure repeatability in the tests and minimizing the factors that could influence the experiments. For a better visualization of the experimental apparatus, a schematic drawing of the experimental bench was made, showing its main components (Fig. 2a). This bench is the same used in the work of (Reis *et al.*, 2017).

The experimental apparatus was developed to measure the vaporization times of individual fuel drops deposited on a heated surface, and it comprises the droplet generation section (2) responsible for forming and releasing the droplet, data

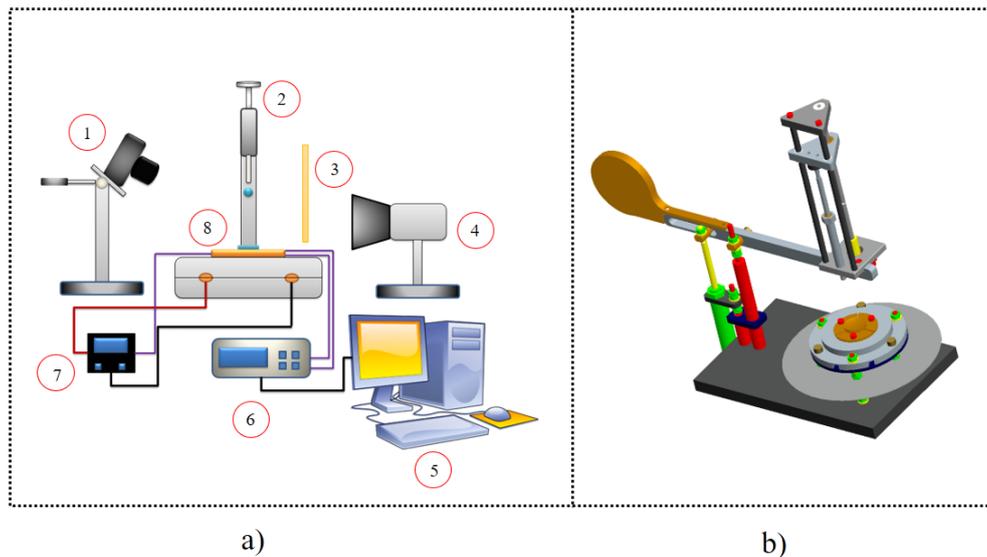


Figure 2. Schematic of experimental apparatus with its main components (a) and test bench in CAD (b).

acquisition system (6), PID controller temperature (7), lighting system and diffuser (3-4), heated test section (8), digital camera (1) and computer (5). Two test sections were used with different materials: copper and aluminum. These materials were tested with the objective of evaluating the influence of the surface material on the evaporation of hydrocarbon droplets.

The test consisted of dropping a small volume of the test fluid onto a heated surface above the boiling point of this fluid and measuring the lifetime (evaporation time) of the droplet (Biance *et al.*, 2003), this method is similar to that described in several references (Misyura, 2016; Stanglmaier *et al.*, 2002; Fardad and Ladommatos, 1999). A stainless steel syringe and a medical needle were used to release the droplet onto hot surface. The circular copper and aluminum section with an average roughness of $0.63 \mu\text{m}$ and $0.48 \mu\text{m}$, respectively (measured by a rugosimeter model SJ-210), has its temperature controlled by an electrical resistance connected to a controller. The test section has a concave shape to prevent the droplet from leaving the surface and contains three channels for the coupling of three K-type thermocouples. Two of these thermocouples were used to measure the surface temperature through a data acquisition system. It is important to highlight that the experiments were carried out at ambient pressure and temperature of Campinas (0.928 atm and 25°C). The procedure is then repeated with various surface temperatures, always with droplets with the same volume, and the boiling process was filmed by a digital camera at 60 frames per second. The captured videos were used to measure the lifetime of the droplet. In this work, the droplets lifetime was estimated from the point where it leaves the needle until it evaporates completely on the surface.

The fluids used for the tests were: ethanol, n-heptane, and iso-octane. Table 1 shows the measured volume and diameter of droplets generated by the syringe for each test fluid. It is important to note that all the tests were performed with the same needle. The properties necessary to calculate the volume of each droplet were taken from Poling *et al.* (2001) and Yaws (2008). Table 2 lists the thermal physical properties of the wall materials used in the tests.

Table 1. Measured average volume and diameter of droplets to the ethanol, n-heptane, and iso-octane.

Fuels	V_0 (μL)	d_0 (mm)
Ethanol	6.88	2.3
n-Heptane	7.13	2.4
iso-Octane	5.01	2.0

Table 2. Thermal and physical properties of the wall material used in the tests at 127°C (Misyura, 2016).

Thermophysical properties	Cooper	Aluminum
Thermal conductivity ($W/(m \cdot K)$)	392	239
Density (kg/m^3)	8870	2675
Heat capacity ($J/(kg \cdot K)$)	389	951
Thermal difusivity (m^2/s)	$111 \cdot 10^{-6}$	$94 \cdot 10^{-6}$

3. RESULTS AND DISCUSSIONS

This section shows the results obtained from the evaporation of the hydrocarbons with the copper and aluminum test sections. The results obtained experimentally in this research were compared to the data found in the literature.

For the present work, the Nukiyama and Leidenfrost temperature for copper surface with ethanol, n-heptane and iso-octane corresponds to $T_N = 119 \pm 1^\circ\text{C}$ and $T_L = 200 \pm 3^\circ\text{C}$, $T_N = 125 \pm 3^\circ\text{C}$ and $T_L = 180 \pm 5^\circ\text{C}$, $T_N = 119 \pm 1^\circ\text{C}$ and $T_L = 175 \pm 5^\circ\text{C}$, respectively. The temperatures at the Nukiyama and Leidenfrost point for the aluminum surface using the same test fluids cited above are: $T_N = 108 \pm 3^\circ\text{C}$ and $T_L = 160 \pm 5^\circ\text{C}$ with ethanol, $T_N = 122 \pm 1^\circ\text{C}$ and $T_L = 175 \pm 5^\circ\text{C}$ with n-heptane, and $T_N = 122 \pm 2^\circ\text{C}$ and $T_L = 180 \pm 15^\circ\text{C}$. The results found experimentally with the copper and aluminum test sections are summarized in Tab. 3.

Mills and Sharrock (1986), present Nukiyama and Leidenfrost temperature on a copper surface for ethanol with the following values: $T_N = 126 \pm 4^\circ\text{C}$ and $T_L = 140 \pm 3^\circ\text{C}$. Fardad and Ladommatos (1999) in their paper, found for n-heptane the Nukiyama temperature around 150°C and Leidenfrost 210°C for a polished aluminum surface. Stanglmaier *et al.* (2002), found these temperatures in the value of 122°C and 190°C for iso-octane using an aluminum surface, while, Baumeister *et al.* (1970) found the Leidenfrost temperature around 157°C using aluminum as the test section. The results obtained with the present research can be compared with the data in the literature through the table Tab. 4.

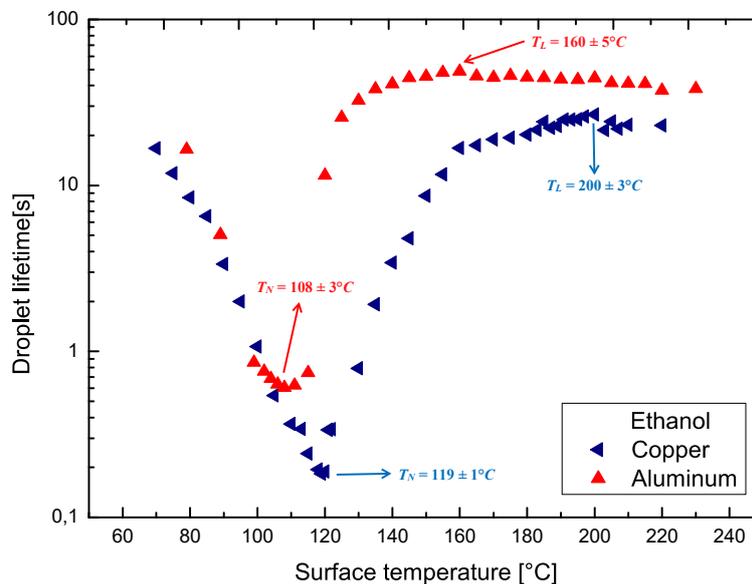


Figure 3. Results of the droplet lifetime with the surface temperature for ethanol.

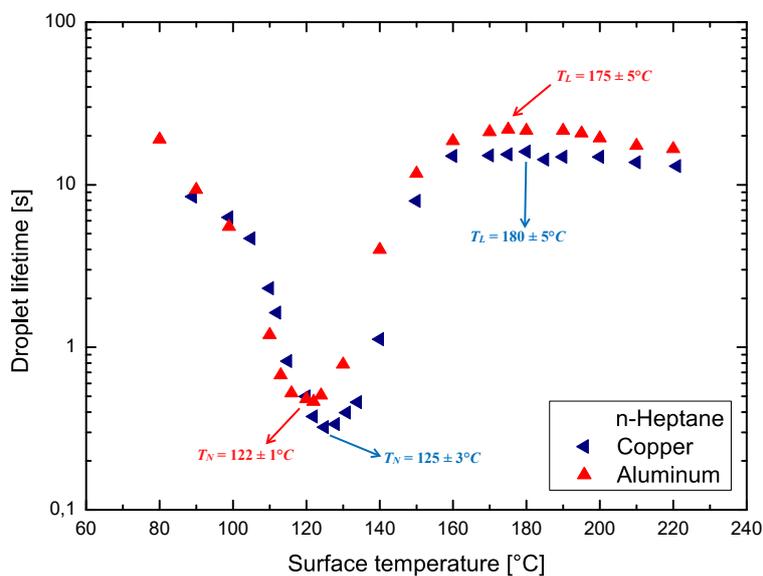


Figure 4. Results of the droplet lifetime with the surface temperature for n-heptane.

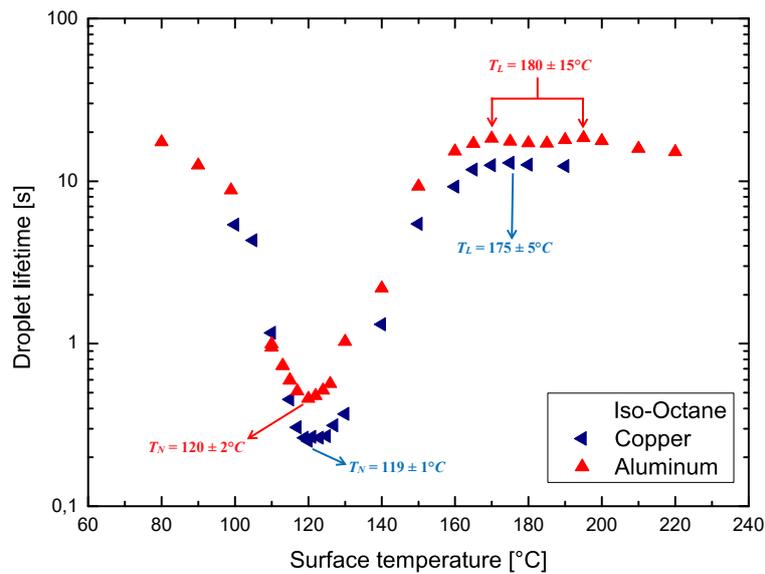


Figure 5. Results of the droplet lifetime with the surface temperature for iso-octane.

Table 3. Values obtained from T_N , T_L through the tests for copper and aluminum surface.

Fuels	Copper		Aluminum	
	T_N (°C)	T_L (°C)	T_N (°C)	T_L (°C)
Ethanol	119 ± 1	200 ± 3	108 ± 3	160 ± 5
n-Heptane	125 ± 3	180 ± 5	122 ± 1	175 ± 5
Iso-Octane	119 ± 1	175 ± 5	120 ± 2	180 ± 15

Table 4. Comparison of experimentally obtained values of Nukiyama and Leidenfrost temperatures with data in the literature.

Reference	Fuels	T_N (°C)	T_L (°C)	Surface Material
Present paper	Ethanol	119 ± 1	200 ± 3	Copper
(Mills and Sharrock, 1986)	Ethanol	126 ± 4	140 ± 3	Copper
Present paper	Ethanol	108 ± 3	160 ± 5	Aluminum
(Baumeister <i>et al.</i> , 1970)	Ethanol	—	157	Aluminum
Present paper	n-Heptane	122 ± 1	175 ± 5	Aluminum
(Fardad and Ladommatos, 1999)	n-Heptane	150	210	Aluminum
Present paper	Iso-Octane	120 ± 2	180 ± 15	Aluminum
(Stanglmaier <i>et al.</i> , 2002)	Iso-Octane	122 ± 2	190	Aluminum

As expected, the heating surface material had some influence on the evaporation of the fuels tested in the present process mainly in the transition region and Leidenfrost point. As can be observed in the Table. 3, the Nukiyama temperature with ethanol in the aluminum surface was much smaller the temperature found by using the copper section. In the case of n-heptane, the Nukiyama temperature found in both materials have close values. This was also noted with iso-octane.

The Leidenfrost temperature with ethanol in copper surface has a value higher compared to the results obtained with the aluminum disk. The higher Leidenfrost temperature in copper section for the ethanol can be explained by the appearance of an oxide layer formed on the surface of the copper during its heating (see section 1). For hydrocarbons, the Leidenfrost point for both fluids does not vary much with heating wall material.

It is also possible to note that the evaporation time for all fluids is higher in the aluminum test section than in the copper section. The heat transfer rate is higher in the copper disk. One possible explanation for these results in the greater roughness present on the copper surface, which may have penetrated through the droplet surface and initiated its internal heating.

4. CONCLUSIONS

The evaporation of small droplets on heated surfaces in two different materials was investigated. The curves relating the droplet lifetime as a function of the wall temperature for ethanol, n-heptane, and iso-octane were obtained. Through this work it was possible to conclude that the Nukiyama and Leidenfrost points and even the transition boiling region can be influenced by the type of material of the heating surface. This influence is more significant in the Leidenfrost region as seen in the results presented in the previous section. For future work, more investigations will be carried out about the effect of wall material type, surface roughness, and oxidation.

5. ACKNOWLEDGEMENTS

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