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Determination of Nukiyama and Leidenfrost Temperatures for Hydrocarbons using the Droplet Evaporation Method

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Abstract. *Boiling usually an efficient mechanism of heat exchange, presenting high heat transfer coefficients. The study of this phenomenon is based on experiments of great complexity, making it difficult to identify relevant parameters for practical applications, such as the Nukiyama and Leidenfrost temperatures. The objective of this research was to obtain the temperatures of Nukiyama and Leidenfrost, from the droplet evaporation of different fluids on a heated surface, measuring the lifetime of the droplet through a digital camera. The fluids tested were: ethanol, iso-octane, n-heptane and a mixture of 11,1% ethanol and 88,9% n-heptane respectively. The results were compared with data in the literature. Despite the difficulty of comparing the results found for mixtures with the correlations and experimental data from other authors, the method showed to be effective for the determination of these critical temperatures.*

Keywords: *Droplets Evaporation, Hydrocarbons, Leidenfrost Point, Nukiyama Point.*

1. INTRODUCTION

Boiling is a physical phenomenon of great relevance in the areas of science and engineering. The boiling and evaporation of droplets have been utilized extensively in industry because it is one of the most efficient modes of heat transfer, particularly in high-energy-density systems such as nuclear reactors, power plants, electronics packaging, and applications using atomized liquids such as fuel spray, spray cooling, and spray painting (Peyghambarzadeh *et al.*, 2009; Kim, 2015).

Its degree of complexity depends on several parameters such as surface effect, pressure, subcooling, among others. The boiling phenomenon is usually represented by the well-known boiling curve, given in (Fig. 1a), which relates the heat flux to the wall superheat (the difference between the surface temperature and the fluid saturation temperature). Through the graph, it is possible to identify key-points such as the critical heat flux (CHF) or the Nukiyama point wich 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 regime of film boiling. At the Nukiyama temperature (T_N) the total evaporation time of a drop is at its 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 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).

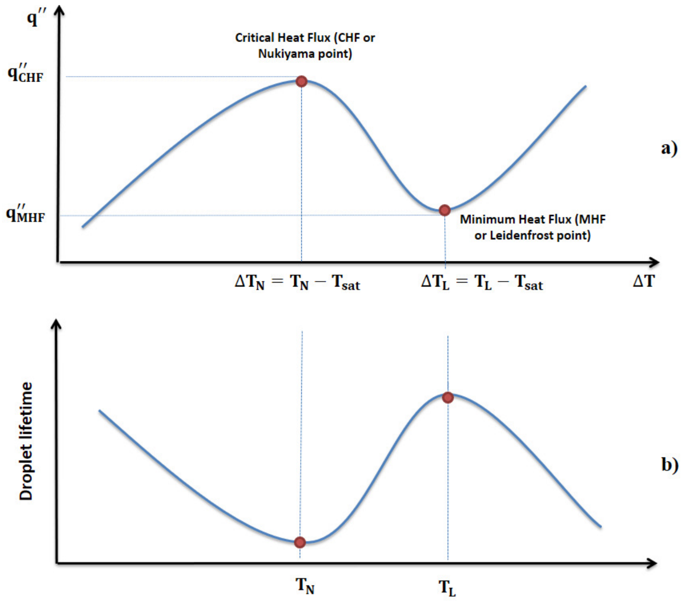


Figure 1. Typical boiling and lifetime curve with the critical points

A simple technique used for obtaining such critical temperatures is the droplet evaporation method, This technique requires measuring evaporation times (lifetime) of liquid sessile droplets with a given initial volume over a range of surface temperatures to produce a droplet evaporation curve (Bernardin and Mudawar, 1999). Another method to estimate these temperatures is the use of Eq. (1) found in the work of Habchi (2010). The author estimated at Leidenfrost temperatures (T_L) through the metastable liquid model (Spiegler *et al.*, 1963) and Nukiyama through the Eq. (2), where T_b is the boiling temperature and T_c is the critical temperature of the fluid.

$$T_L = \frac{27}{32} T_c \tag{1}$$

$$T_N = \frac{T_b + T_L}{2} \tag{2}$$

The process of the droplet evaporation for single-component liquids has seen studied along the years, however, experimental data are insufficient for the achievement of the physicals patterns on evaporation of mixture and solution droplets on surfaces with different shapes and orientations (Nakoryakov *et al.*, 2013).

The objective of the present work was to obtain the Nukiyama and Leidenfrost temperatures for hydrocarbons from the analysis of droplet evaporation on a copper heated surface.

2. EXPERIMENTAL PROCEDURE

To perform this work, an experimental droplet evaporation bed was built and instrumented with the aim of automating the tests (Fig 2).

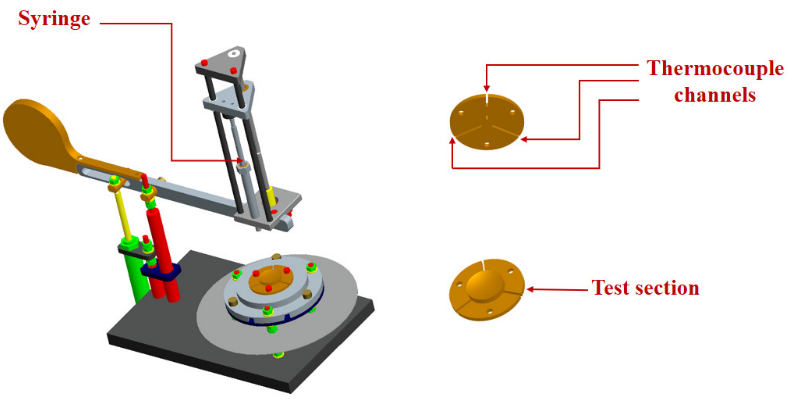
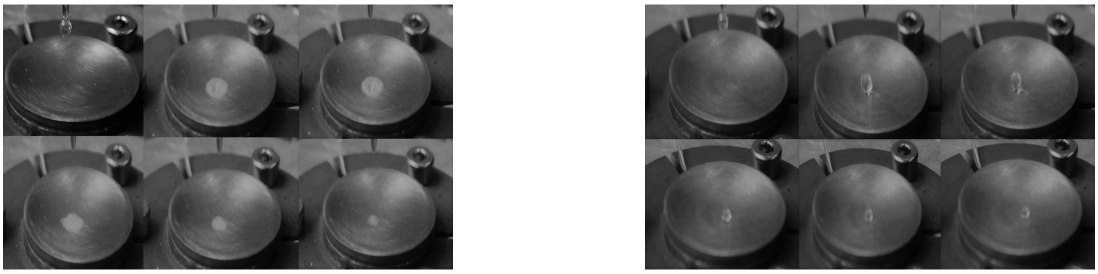


Figure 2. Schematic of experimental setup

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 by (Misyura, 2016; Stanglmaier *et al.*, 2002; Fardad and Ladommatos, 1999). A stainless steel syringe and a medical needle used to release the droplet onto hot surface. The circular copper section with an average roughness of 0.63 μm (measured by a rugosimeter model SJ-210) has its temperature increased 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 standard pressure and temperature (1 atm pressure and 25°C temperature). 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 mostly single-component: ethanol, iso-octane and n-heptane. However, a binary mixture was also tested, made up of 11,1% ethanol and 88,9% n-heptane (molar fraction).

3. RESULTS AND DISCUSSION

Figure 3 presents some frames taken from the video used to measure the droplet lifetime close to Nukiyama and Leidenfrost temperatures. Forward, curves showing the lifetime of the fluids used in the tests will be presented.



(*a*) (*b*)

Figure 3. Frames taken from the test with n-heptane: (a) at 125°C; (b) 180°C

Initially, the needle warm-up was investigated as a function of time. The test consisted of keeping the needle at a distance of 10.7 mm from the test section with a temperature set at 250°C during 5 minutes. This distance corresponds to the height at which the needle is held in relation to the heated surface for the launch of the droplet. As observed (Fig. 4), from 7 seconds its temperature increased by 1°C. It was important to evaluate this parameter because the droplet launch on the surface had a duration of approximately 5 seconds, thereafter, the needle is immediately spaced far from the surface. This proves that the fluid contained in the syringe does not suffer much influence from the radiation emitted by the copper dish during the experiments.

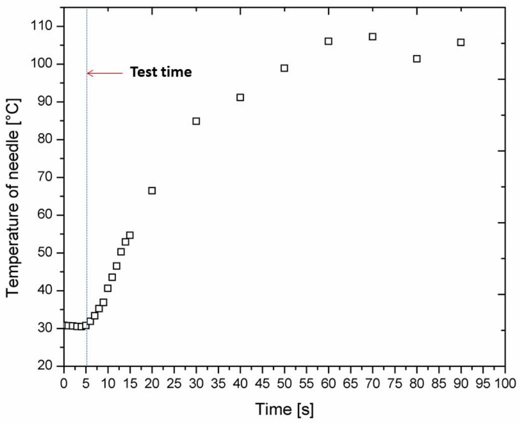


Figure 4. Needle temperature variation with time (test section at 250°C)

Figure 5 shows the lifetime for evaporation of ethanol droplet with the volume initial of the 6.88 μL. The test started at 70°C where the drop took 16,7 seconds for total evaporation (region of liquid film evaporation). The Nukiyama temperature for this fuel was 119 $\pm$ 1°C, and Leidenfrost temperature correspond to 200 $\pm$ 3°C. These results show good agreement with the temperatures found by (Oliveira *et al.*, 2015) where T_N = 122 $\pm$ 2°C and T_L = 190 $\pm$ 5°C and (Habchi, 2010) with T_N = 119,25°C. The result obtained for the Leidenfrost temperature is close to the value cited in (Aplinc, 2012), which is around 200°C, but differs with the temperature found by other authors (140°C, 158°C) and 160,5°C), by (Mills and Sharrock, 1986; Wang *et al.*, 2000; Spiegler *et al.*, 1963), respectively.

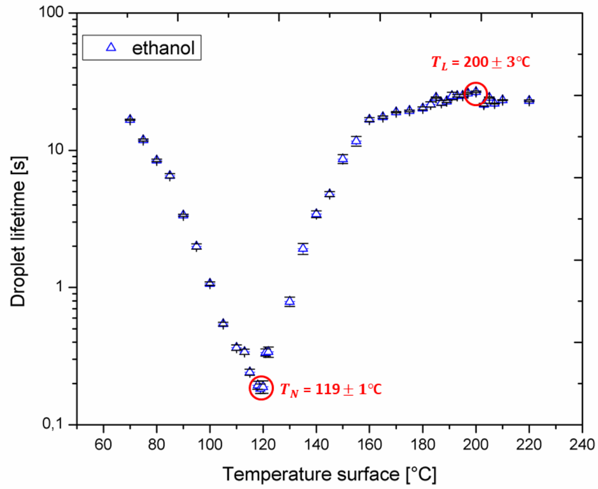


Figure 5. Results of the droplet lifetime with the surface temperature for ethanol

For iso-octane (Fig. 6), the Nukiyama and Leidenfrost temperature were determined in T_N = 119 $\pm$ 1°C and T_L = 175 $\pm$ 5°C. Nukiyama temperature found experimentally differs from the temperature calculated by Eq. (2) (T_N = 142°C) but T_L is close to the temperature caculated by the Spiegler *et al.* (1963) model (T_L = 186°C).

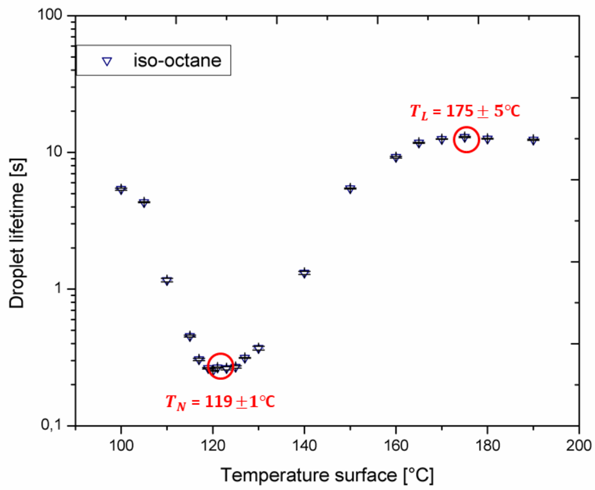


Figure 6. Results of the droplet lifetime with the surface temperature for iso-octane

Figure 7 shows the lifetime for evaporation of n-heptane droplet with the volume initial of the 7.13 μL. The Nukiyama temperature for this hydrocarbon corresponds to 125 $\pm$ 3°C, and Leidenfrost temperature corresponds to 180 $\pm$ 5°C. T_L found by the Spiegler *et al.* (1963) model (T_L = 182,6°C), is in agreement with the experimental value.

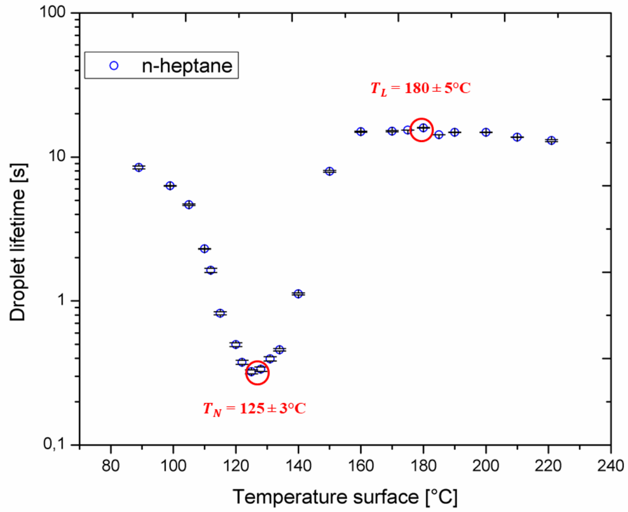


Figure 7. Results of the droplet lifetime with the surface temperature for n-heptane

For the mixture of 11.1% ethanol and 88.9% n-heptane (Fig. 8), the experimental values observed were, T_N = 118 $\pm$ 1°C and T_L = 180 $\pm$ 5°C.

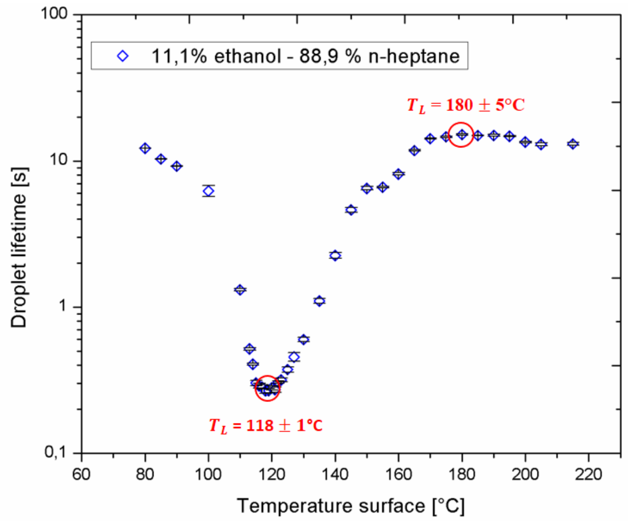


Figure 8. Results of the droplet lifetime with the surface temperature for mixing ethanol and n-heptane

An important detail and worth mentioning is the fact that all the tests were made with the same needle but the initial droplet volume (V_0) of each fuel was different. It is believed that this is a consequence of the property difference for each fluid. The properties necessary to calculate the volume of each droplet can be found in Poling *et al.* (2001) and Yaws (2008). Shortly afterward, the results obtained through the tests and correlations are summarized in Tab. 1:

Table 1. Values obtained from T_N, T_L, and V_0 through the tests and correlations

Fuels	T_N(°C)	T_L(°C)	T_N(°C) by Eq. (2)	T_L(°C) by Eq. (1)	V_0(μL)
ethanol	119 $\pm$ 1	200 $\pm$ 3	119,25	160,5	6.88
iso-octane	119 $\pm$ 1	175 $\pm$ 5	142	186	5.01
n-heptane	125 $\pm$ 3	180 $\pm$ 5	140	182,6	7.13
(11,1%)ethanol / (88,9%)n-heptane	118 $\pm$ 1	180 $\pm$ 5	—	—	6.53

4. CONCLUSION

Through the obtained results, it was possible to evaluate and compare the Nukiyama and Leidenfrost temperatures of the fluids with correlations and experimental data of other literature. Some important aspects were taken into account as the investigation of the influence of the radiation emitted by the test section and it was concluded that the radiation influences very little on the temperature of the needle during the stay of the needle near the test section to release the droplet. Another important point was the difficulty of comparing the results of mixtures with correlations. it is expected in future work to compare these results with other works and correlations existing in the literature. The droplet evaporation method, besides being simple, proved to be efficient to find the Nukiyama and Leidenfrost temperatures for single component.

5. ACKNOWLEDGEMENTS

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