

## EXPERIMENTAL STUDY ON THE EFFECT OF THE LIQUID/SURFACE THERMAL PROPERTIES ON DROPLET IMPACT

by

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*Droplet impact on hot surfaces is widely encountered in industry and engineering applications. In the present paper we investigate the effect of the combination of the droplet liquid type and the solid surface type and their effect on droplet impact dynamics. We test three surfaces, copper 110, aluminum 1199, and stainless steel 304, and two liquids, water and ethanol. These surfaces and liquids are characterized by high and low thermophysical properties. The three surfaces are tested with water to investigate the effect of the surface on the droplet dynamics. After that, we test both liquids with aluminum. Our findings showed that the Leidenfrost temperature does not always correlate with the surface thermal properties as reported in the literature. Some surfaces can undergo changes because of the heating and this reduces their initial thermal properties. For this reason, such surfaces are capable to show two Leidenfrost temperatures because of the thermophysical properties reduction during heating. Our findings also revealed that the Leidenfrost temperature of liquids with low thermophysical properties including surface tension, evaporation latent heat and density show trivial effect by the droplet impact velocity; i.e. the Leidenfrost temperature show trivial increase by increasing the droplet impact velocity. Liquids with high thermophysical properties show significant Leidenfrost temperature increase by increasing the impacting velocity.*

*Key words: droplet impact, Leidenfrost temperature, thermophysical properties, phase diagram, surface oxidation*

### Introduction

Heat spray cooling which totally relies on the impact of a bunch of droplets has attracted much attention as a promising technology for high heat flux cooling [1]. In previous experiments, spray cooling showed the highest heat flux compared to other cooling technologies such as pool boiling and jet impingement [2]. Heat spray cooling is often utilized for high temperature quenching of metals [3] and the cooling of the superheated steam [4]. Recent studies have also focused on the heat spray cooling for electronic cooling purposes [5-7]. Heat spray cooling can cover a wide range of surface temperatures from cryogenic [8], medium [9] to very high surface temperatures [3]. Although heat spray cooling technique encompasses the injection of droplets in the form of spray of very small droplets and not a single droplet, insight into the interaction of one droplet with a hot surface is essential and can build fundamental understanding for spray cooling [10].

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Droplet impact on hot surfaces is a complicated phenomenon due to the fast droplet interaction with the hot surface. The recently developed high speed imaging and other visualization techniques have allowed to make important progress and droplet impact dynamics can now be visualized with high quality [11]. Thanks to these developed techniques, the behavior of droplet impacting a hot surface can be classified according to the final droplet dynamics which in turn can be assigned to one of the regimes in the spray cooling curve [12]. In general, the final fate of droplet impacting a hot surface can be in contact state or non-contact state (film boiling). The temperature at which the droplet changes from contact to non-contact state is called the Leidenfrost temperature. At this temperature, *i.e.* the Leidenfrost temperature,  $T_L$ , the droplet is levitated upon its own vapor and the heat transfer is significantly reduced due to the poorly thermal properties of the vapor [13]. Hence, it is of high interest for spray cooling to understand the mechanism by which the Leidenfrost phenomenon is driven [14, 15]. The influencing properties on the Leidenfrost temperature are in most cases related to the solid surface and to the liquid as well [16, 17].

Previous investigations have tested droplet impact in order to understand the effect of each single parameter separately such as the liquid type [18, 19], droplet impact velocity and impact angle [20] and the wall type [16]. The previous parameters were investigated separately in different studies with different working conditions like surfaces and liquids with different thermal and physical properties [21, 22]. This led to significant differences in the droplet/wall results based on the proposed working conditions in each study. For instance, the transition to dry impact *i.e.* Leidenfrost state, was reported to occur at various temperatures for different working conditions [23]. The Leidenfrost temperature was reported to increase by increasing the droplet impact velocity or Weber number [21, 24] and it was also reported to happen at constant temperature with increasing the impact velocity [22, 25]. However, the Weber number which is widely used to describe the final droplet impact dynamics [21, 24, 26] was reported to not be relevant to describe the droplet impact dynamics on hot surfaces [27].

The solid surface can be characterized by various thermophysical properties. The droplet liquid is also characterized by its thermophysical properties such as the surface tension, the viscosity and the contact angle on the surface which defines its wettability. Each of these parameters has its particular effect on the physics behind the droplet impact, spreading, retraction, deposition, rebound and/or breakup and the resultant heat transfer from the hot surface. For this reason, the present study investigates experimentally the effect of the wall and the droplet liquid properties on droplet impact dynamics. The key parameters to investigate are the thermophysical properties of the wall and the liquid as well. Also, how these thermophysical properties influence the transition from droplet contact state to non-contact state.

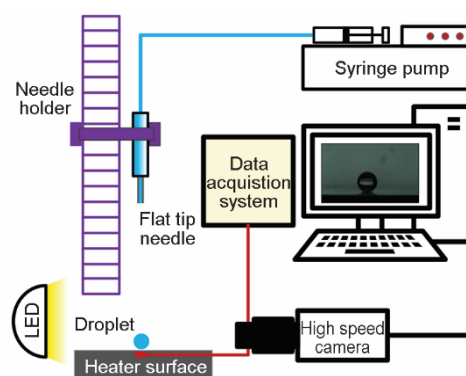
### Experimental set-up and methodology

Figure 1 shows the experimental set-up utilized in our experiments. It consists on a liquid delivery system including a syringe pump, tubes and a flat tip needle. A heater block includes the surface substrates and the heater cartridges. In addition to a high-speed camera connected with a computer for images recording.

Experiments were performed by releasing liquid droplets at very small rates of 0.1 mL per minute (syringe pump 11 Elite Harvard apparatus). Two different liquids were used in the present study, deionized water and ethanol. Ethanol is hydrophilic on large metal types while water is hydrophobic, ethanol also has low thermal conductivity and specific heat while water has higher thermal properties. The thermophysical properties of each of the liquids is shown in tab. 1. Two flat tip needles were used for each liquid, gauge 18 for ethanol

and gauge 26 for water (having an inner diameter 0.86 mm and 0.24 mm, respectively), giving same droplet size of 2.7 mm for each of the liquids. The droplets were released at increasing heights so as to increase the droplets impact velocity, their Weber number and therefore, their inertial forces.

Three different surfaces were examined; copper 110, aluminum 1199, and stainless steel 304. The thermal properties of these surfaces show high (copper 110), medium (aluminum 1199), and low (stainless steel 304) thermal properties. The three surfaces were mirror polished and had a roughness of less than  $0.1 \mu\text{m}$  (Bio-FastScan AFM). The thermophysical properties of the surfaces are shown in tab. 2. To provide a uniform surface temperature, six heater cartridges with 48 W each were uniformly inserted at the mid-thickness of each surface. The surface temperature was measured and controlled via K-type thermocouple within a temperature difference of  $\pm 1 \text{ }^\circ\text{C}$  (Keysight 34970A LXI). Diffused LED light was used as a light source. Each impact in our experiments was captured using a high-speed camera adjusted at 2000 fps with  $1024 \times 1024$  pixel resolution (IDT NXA7-S1).



**Figure 1. Sketch of the experimental set-up; the experimental set-up has a heater part which is the surfaces tested and the heater cartridges, liquid delivery part has syringe pump and flat tip needles, and the high-speed camera**

**Table 1. Relevant thermophysical properties of the deionized water and ethanol**

Property	Deionized water	Ethanol
Thermal conductivity, $k$ , [ $\text{Wm}^{-1}\text{K}^{-1}$ ]	0.6071	0.167
Specific heat capacity, $C_p$ , [ $\text{Jkg}^{-1}\text{K}^{-1}$ ]	4181	2597
Material density, $\rho$ , [ $\text{kgm}^{-3}$ ]	997.1	785.3
Surface tension, $\sigma$ , [ $\text{mNm}^{-1}$ ]	72	21.97
Dynamic viscosity, $\mu$ , [ $\text{mPa}\cdot\text{s}$ ]	0.8941	1.0903
Boiling point, $T_b$ , [ $^\circ\text{C}$ ]	100	78
Evaporation latent heat, $L$ , [ $\text{kJkg}^{-1}$ ]	2260	853

**Table 2. Relevant thermophysical properties of the examined surfaces**

Property	Copper 110	Aluminum 1199	Stainless steel 304
Thermal conductivity, $k$ , [ $\text{Wm}^{-1}\text{K}^{-1}$ ]	390	226	14
Specific heat capacity, $C_p$ , [ $\text{Jkg}^{-1}\text{K}^{-1}$ ]	385	921	502
Material density, $\rho$ , [ $\text{kgm}^{-3}$ ]	8910	2698	7920
Thermal diffusivity, $\alpha$ , [ $\text{mm}^2\text{s}^{-1}$ ]	116	91	3.6
Thermal effusivity, $e$ , [ $\text{Ws}^{0.5}\text{m}^{-2}\text{K}^{-1}$ ]	36983	23688	7631

For each test, the heater was first heated up to the desired temperature and kept constant for a short time for temperature measurements certainty. Then, the syringe pump was turned on to release the droplet. The high speed camera was turned on simultaneously to capture the droplet impact on the hot surface. For each surface temperature and each needle height corresponding to a specific droplet velocity, the experiment was repeated several times for certainty purposes. To investigate the surface thermal properties, only water was used for the three surfaces (copper 110, aluminum 1199, and stainless steel 304). To investigate the effect of the liquid properties, only aluminum surface was used for deionized water and ethanol.

## Results and discussion

### *Droplet impact dynamics*

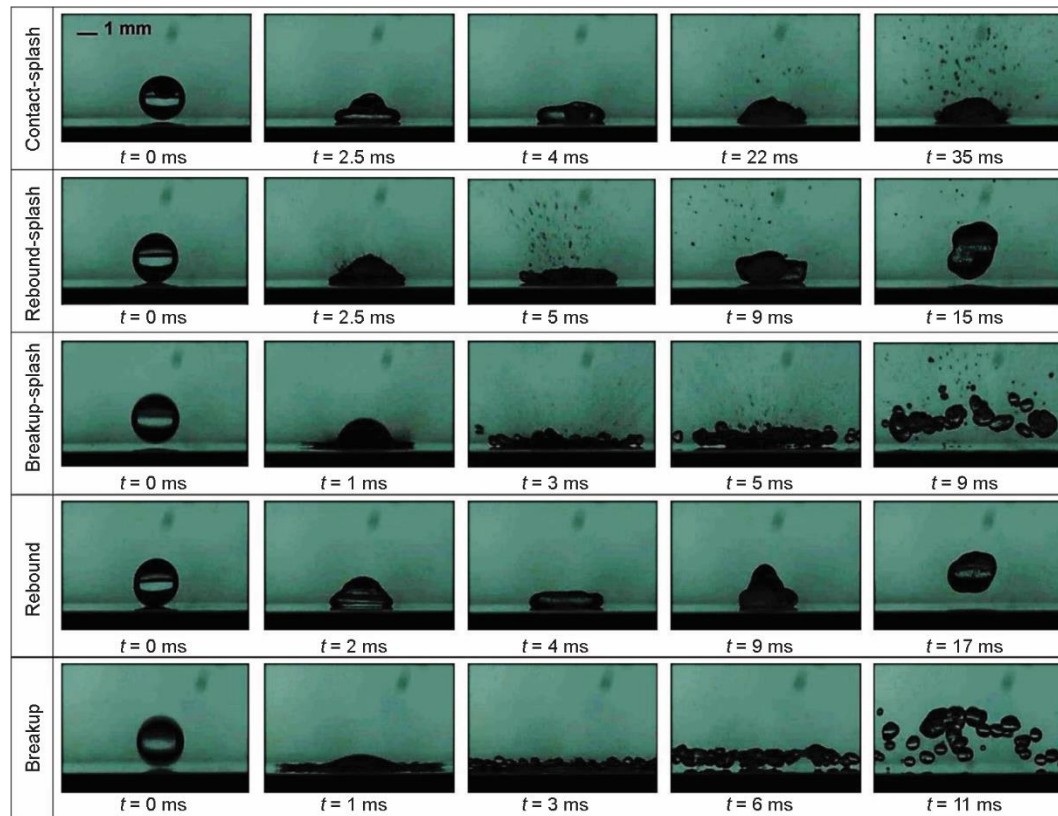
Figure 2 shows snapshots of droplet impact dynamics for different regimes observed during our experiments. In general, five main regimes were observed. Splash (*i.e.* secondary atomization) was observed in three of these regimes, these regimes are contact-splash, rebound-splash and breakup-splash. Two regimes happened with no splash which are rebound and breakup. Absence of splash means that the impacting droplet did not make contact with the hot surface. The splash is the result of the bubbles burst on the free surface of the droplet [21]. Each regime dynamic is a result of droplet impact velocity at a specific surface temperature. In what follows, each regime will be briefly explained.

At surface temperatures below or close to the boiling temperature of the liquid (deionized water/ethanol), the droplet simply deposits on the surface and no splash is observed, and the temperature of the droplet simply increases by convection. The droplet spreading increases by increasing the droplet impact velocity and therefore, its Weber number. Weber number is the competition between the droplet inertial forces and its surface force. Further increasing the surface temperature, the droplet starts to show some disturbances or dancing-like on its surfaces, this corresponds to creation of bubbles at the droplet-surface interface. These tiny bubbles collapse before they reach the free droplet surface, this regime corresponds to the liquid entertainment in the boiling curve. Increasing more the surface temperature, the droplet starts to show splash as a result of bubbles burst. The splash intensifies by increasing the surface temperature. This regime corresponds to the first regime shown in fig. 2, contact-splash and to the nucleate boiling regime in the boiling curve as shown in fig. 3.

At temperatures below the corresponding Leidenfrost temperature of the liquid and at low impact velocities, rebound-splash regime is observed, fig. 2. The droplet impacts the hot solid surface, spreads and retracts and finally bounces back as a whole with few splashes during spreading and/or retraction. The retraction and the rebound are a result of the strong surface forces while the inertial forces are feeble at low impact velocity. The splash in this regime is caused by the very short and intermittent contact between the droplet and the surface resulting in tiny satellite droplets.

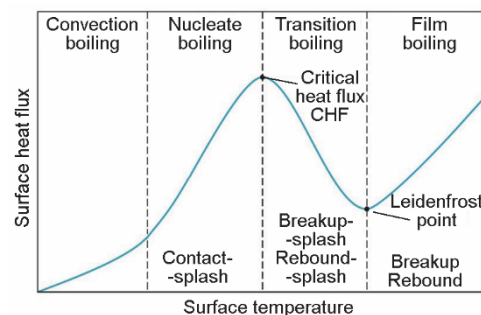
At temperatures below the corresponding Leidenfrost temperature but with a relatively high impact velocity, breakup-splash regime is observed, fig. 2. In this regime the droplet impacts the hot surface and during the spreading, short and intermittent contact happens between the surface and the droplet resulting in satellite droplets, same as rebound-splash regime. Because of the high inertial forces due to the high impact velocity which overcome the surface forces responsible for droplet retraction, the droplet breaks up into smaller droplets, different in size and shape than the satellite droplets caused by bubbles burst, hence, breakup with splash. The two aforementioned regimes correspond to impact with intermittent contact

between the droplet and the surface resulting in a splash. These regimes are shown in fig. 3, they both correspond to transient boiling regime in the boiling curve.



**Figure 2.** Snapshot sequences of droplet impact dynamics on the hot surfaces; droplet impact regime sequences at relevant times for each regime; three regimes are related to droplet-surface contact state where the splash was ejected due to the bubbles burst; these three regimes are contact-splash, rebound-splash and breakup-splash; two regimes happened with no splash meaning that the droplet did not make any contact with the surface, these regimes are breakup and rebound

At temperatures higher than the Leidenfrost temperature and low impact velocity, the droplet rebounds as a whole with no splash; rebound regime, fig. 2. The droplet impacts and spreads by inertial forces, at the end of the inertial forces which are weak at these velocities, it retracts back by the surface force and then bounces off the surface. Due to the high surface temperature, the droplet generates enough vapor with high pressure that levitates the droplet on its own vapor. This vapor cushion plays a role of a lubrication layer which facilitates the droplet retraction and bouncing off.



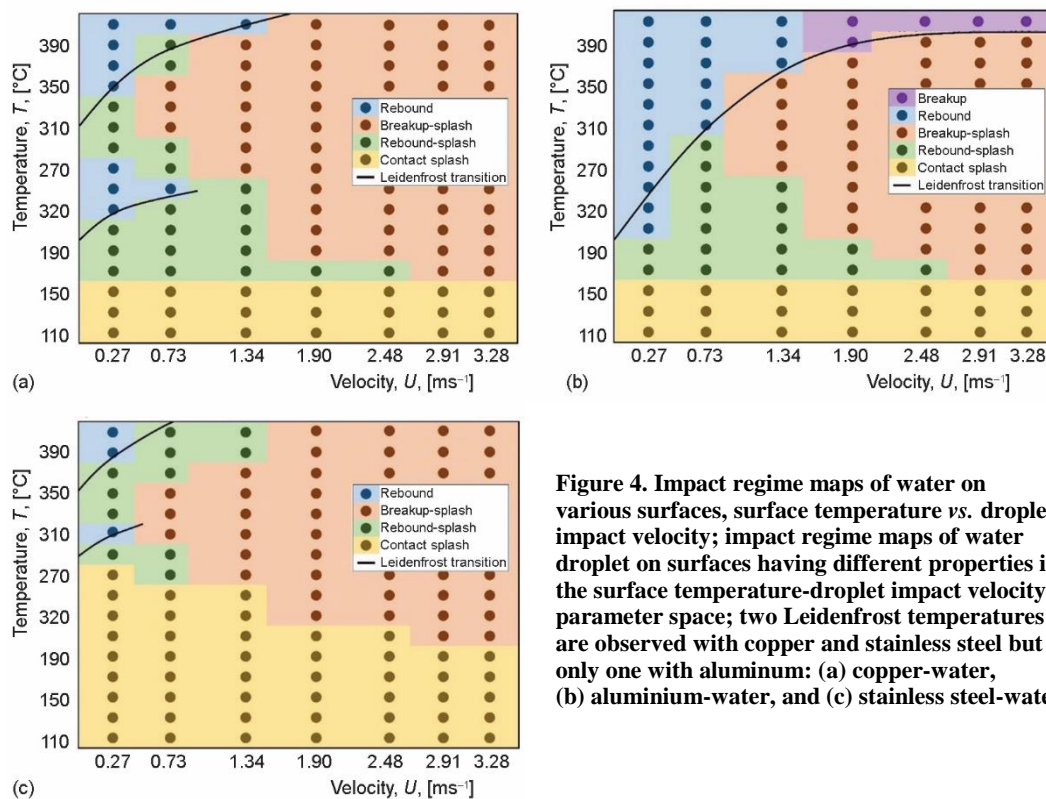
**Figure 3.** Corresponding boiling curve to the different droplet impact dynamics

At higher velocities above the Leidenfrost temperature, the droplet breaks up into smaller droplets because of the strong inertial forces overcoming the surface force. No splash is observed in this regime because the vapor generation is always intense making high pressure beneath the spreading droplet which lead to levitate the droplet on its vapor cushion. This vapor cushion plays always the role of a lubrication layer and hindering the spreading droplet to make any contact with the hot surface. This regime is as mentioned previously is breakup regime, fig. 2.

The two aforementioned regimes, rebound and breakup correspond to film boiling regime in the boiling curve as shown in fig. 3. This classification where splashing corresponds to surface-droplet contact and its absence corresponds to film boiling or Leidenfrost state was previously adopted [21].

#### Effect of surface thermal properties on droplet impact

Figure 4 shows the droplet impact regime maps of deionized water on surfaces having different thermophysical properties, copper 110 with water, aluminum 1199 with water, and stainless steel 304 with water. The relevant thermophysical properties of these solid surfaces are shown in tab. 2. Based on the thermal properties of these surfaces, it is expected that transition to the Leidenfrost state occurs at different temperatures. *i.e.* surfaces with higher thermal properties are expected to show Leidenfrost temperature,  $T_L$ , lower than surfaces having low thermal properties [28, 29]. The reason of such expected behavior is that the vapor generation is more



**Figure 4. Impact regime maps of water on various surfaces, surface temperature vs. droplet impact velocity; impact regime maps of water droplet on surfaces having different properties in the surface temperature-droplet impact velocity parameter space; two Leidenfrost temperatures are observed with copper and stainless steel but only one with aluminum: (a) copper-water, (b) aluminium-water, and (c) stainless steel-water**

intense with surfaces having high thermal properties resulting in high vapor pressure to levitate the droplet at moderate surface superheats. The Leidenfrost temperature of surfaces with low thermal properties is expected to occur at higher surface superheats.

However, our results do not show such trend despite they are in good agreement with previous studies regarding the Leidenfrost temperature. To provide clear comparison, low droplet impact velocity or the case of static Leidenfrost temperature will be discussed (impact velocity 0.27 m/s). The Leidenfrost temperature was observed at 230 °C with copper, at 210 °C with aluminum, and at 310 °C with stainless steel, these values are also reported in [23]. We here observe that the static Leidenfrost temperatures of these surfaces do not correlate with their thermal properties. Copper was expected to show the smallest Leidenfrost temperature followed by aluminum and then stainless steel. On the other hand, we also notice from the regime maps of copper and stainless steel that two Leidenfrost temperatures appear at low velocity, at 230 °C and 350 °C with copper and at 310 °C and 390 °C with stainless steel. We stress here that only the first static Leidenfrost temperatures resulting in a complete rebound of the two surfaces are in good agreement with the previous ones mentioned in the literature. After the complete rebound of the first Leidenfrost temperature, rebound with splash regime appears again at 290 °C with copper and at 330 °C with stainless steel. This brings back the effect of the thermal properties of these two surfaces on the Leidenfrost temperature.

On the other side, we also need to consider the effect of the high temperature and the water and their relative effect the surfaces by changing their surface thermophysical properties. The surface structure change can alter the thermal properties and therefore change the resulting droplet impact dynamics. It was mentioned in the literature that an oxide layer can grow on stainless steel at 300 °C [30]. At the beginning, this layer can be very thin and has neglect effect to be able to affect the thermal properties of the surface, hence, a Leidenfrost temperature of 310 °C, consistent with previous studies. By further increasing the surface temperature, this oxide layer gets thicker and now it has the ability to affect the surface thermal properties and reduce them, hence, bringing back the preceding regime which is rebound-splash. Further increasing the surface temperature, the complete rebound appears again at 390 °C, this temperature corresponds to the Leidenfrost temperature of stainless steel covered with an oxide layer having lower thermal properties than clean stainless-steel surface. In regard to the case of copper, it was also mentioned that an oxide layer can grow at temperatures between 200 °C and 300 °C [31]. This layer has a minor effect at the beginning when it is thin and the first Leidenfrost temperature occurs at 230 °C, consistent with the previous studies. This layer gets thicker by increasing the surface temperature. This reduces the thermal properties of the copper and the oxide layer has now a major effect at 290 °C by bringing back the preceding regime which is rebound-splash. Further increasing the surface temperature until 350 °C, the rebound regime appears again, this temperature corresponds to the Leidenfrost state on a copper surface covered with its oxide.

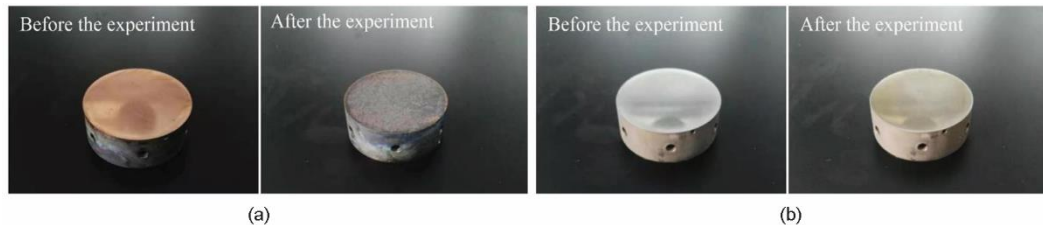
We emphasize here that the appearance of two static Leidenfrost temperatures was surprising at the beginning. After that we noticed that the color of copper and stainless-steel surfaces changes after each set of experiments and this led us to check their oxidation properties at high temperatures (the two surfaces were cleaned from their oxide layer after each set of experiments). The oxide layer on copper and stainless steel observed after the experiment is shown in fig. 5. In the case of the aluminum surface, only one static Leidenfrost temperature is noticed which is logic and its color remained intact during all experiments.

In the case of the transition to rebound-splash and breakup-splash (transition boiling regimes), aluminum and copper show constant transition temperature from contact-splash to



rebound-splash and breakup-splash regimes at 170 °C, figs. 4(a) and 4(b). It was also expected that the transition to these regimes occurs with copper at lower surface superheats than aluminum because of its higher thermal properties. But as we explained earlier, the oxide layer on the copper surface altered and decreased its thermal properties making the transition temperature to these regimes same as aluminum.

In contrast to the previous two surfaces where the transition from contact-splash to the next regimes happened at constant temperature, stainless steel surface shows decreasing transition temperature from contact-splash to rebound-splash and breakup-splash. It decreases from 290 °C at 0.27 m/s droplet impact velocity to 210 °C at 3.28 m/s. This decrement is due to the very low thermal properties of stainless steel as shown in tab. 2. Transition to transition boiling regimes (rebound-splash and breakup-splash) with decreasing surface superheats at increasing droplet impact velocity was also reported previously when using surfaces with low thermal properties (such as sapphire and glass) [17, 32]. At the moment of the impact, the droplet needs time to heat up to the temperature that will take it to the next regime because the thermal diffusivity,  $\alpha$ , of stainless steel is low. The surface thermal diffusivity,  $\alpha$ , has major effect in characterizing the resultant impact dynamic features in the case of droplet-surface contact [33]. In this case of low thermophysical properties, the droplet impact velocity has the primary effect to take over the regime transition with such weak thermal surface properties because the heating effect takes longer time. However, with surfaces having high thermal properties, the thermal effect takes over the regime transition as shown in the case of copper and aluminum.



**Figure 5. Oxide layer on (a) copper 110 and (b) stainless steel 304; oxide layer has been observed on (a) copper 110 and (b) stainless steel 304; copper surface color changed to gray while stainless steel changed to yellow-like after the experiment.**

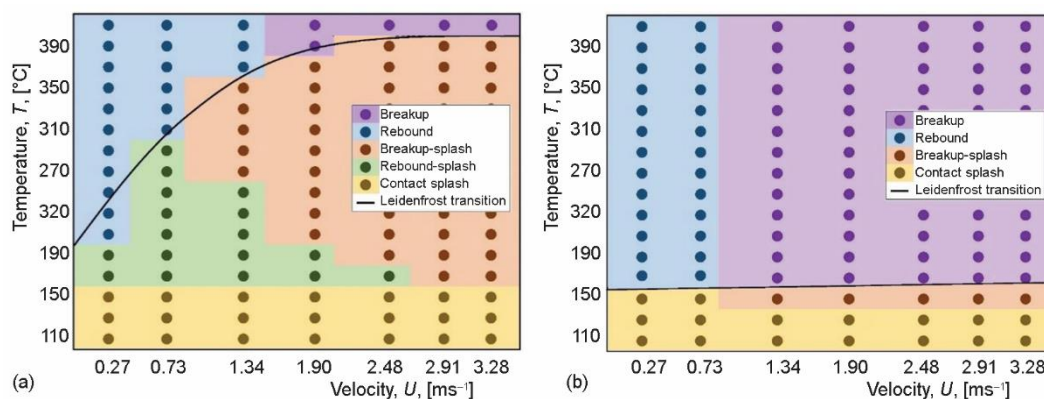
#### *Effect of liquid thermal properties on droplet impact*

Because copper and stainless-steel showed oxidation on their surfaces which altered their properties during heating, only aluminum surface was utilized to investigate the effect of the droplet liquid. Figure 6 shows the effect of the droplet liquid type on the impact regime maps, *i.e.* regime dynamics and transition temperatures. The two maps: aluminum with water and aluminum with ethanol exhibit substantial differences. Water droplet impact on the hot surface encompasses the five regimes discussed in the section droplet impact dynamics and rebound-splash regime is widely observed in this regime map, fig. 6(a). However, rebound-splash regime is hardly observed with ethanol droplets. The reason for this difference in this regime is due to the fact that the surface tension responsible for the droplet retraction and eventual rebound at moderate droplet velocity is low as compared with water as mentioned in the tab. 1, water has 72 mN/m and ethanol has 21.97 mN/m surface tension. Consistent with the previous explanation regarding the retraction and rebound of water.



To provide a clear comparison regarding the lowest Leidenfrost temperature of both liquids, the Leidenfrost temperature with low velocities are to be compared. The water droplet has a Leidenfrost temperature at 210 °C while with ethanol droplets it occurs at about 150 °C. This difference can be expected because the boiling point of water 100 °C and is much higher than that of ethanol 78 °C. Hence, transition to the Leidenfrost state with ethanol at lower temperature than water.

In addition to the difference of the Leidenfrost transition temperature for each liquid, transition to the Leidenfrost state occurs in different manners for each liquid. Dry impacts occur at constant to very small temperature increments by increasing the droplet impact velocity with ethanol. The impacting velocity has trivial effect on the dynamic Leidenfrost temperature, consistent with previous study on ethanol droplets [22, 25]. However, water droplets showed significant Leidenfrost temperature increase by increasing the droplet impact velocity, consistent with previous studies using water droplets [21, 24]. In the Leidenfrost state, the droplet is levitated on its own vapor generated at the moment of the impact and during spreading. This vapor generates sufficient pressure to levitate the droplet, which in turn can be opposed by two possible pressures. One is the capillary pressure between the droplet liquid and the surface, the other one is the dynamic pressure at the moment of the impact. Capillary pressure can have an effect when using textured surfaces [14]. In our experiments, we used smooth surfaces and the capillary pressure cannot have great effect on the droplet dynamics. Therefore, the increased dynamic Leidenfrost temperature is explained by the effect of increasing dynamic pressure overcoming the vapor pressure by increasing the droplet impact velocity [24].



**Figure 6. Impact regime maps of water and ethanol droplets on aluminum surface; water and ethanol droplet impact regime maps on aluminum surface; the Leidenfrost temperature significantly increases by increasing the droplet impact velocity with water, but it occurs at very trivial temperature increase with ethanol: (a) aluminium-water and (b), aluminium-ethanol**

In droplet impact studies, the regime maps are mostly drawn in the surface temperature-Weber number parameter space. Recent study has suggested that Weber number is not relevant to describe the droplet impact dynamics and proposed other dimensionless parameters such as dimensionless heat flux and time [27]. In fact, the Weber number which is the competition between the inertial forces and the surface force does not take into account the effect of droplet liquid heating and evaporation. During regimes of impacts with droplet-surface contact, the thermophysical properties has to be considered. These properties can be the specific heat capacity,  $C_p$ , dynamic viscosity,  $\mu$ , and latent heat of evaporation,  $L$ . All these parameters have not been taken into consideration while Weber number considers only the sur-

face tension force and ignores the effect of the other properties. The droplet spreading can be very important because it also reflects the physical properties of the liquid. Figure 7 shows a sketch of the spreading magnitude of water and ethanol droplets at their maximum spreading in the Leidenfrost state regime at 270 °C and 0.27 m/s impact velocity. Ethanol droplet shows larger spreading than water droplet. The spreading of a droplet can be related to two physical properties which are the dynamic viscosity and the surface tension. While the dynamic viscosity is the interaction of the molecules situated in the same liquid, the surface tension is the interaction of the molecules of the liquid with the adjacent material, fluid or solid. In the case of dry impacts, the adjacent material is the vapor of the droplet. Furthermore, the dynamic viscosities of both liquids are close to each other, 0.8941 mPas for water and 1.0903 mPas for ethanol. Hence, the viscosity can have secondary effect on the droplet spreading during impacts [34]. On the other hand, we observe large difference in the surface tension between the water and ethanol, 72 mN/m for water and 21.97 mN/m for ethanol. Hence, the surface tension has the main effect for the maximum spreading of the impacting droplet. Next, we must consider that more spreading yields thinner lamella as sketched in fig. 7 and large spreading allows for larger heat transfer from the hot surface to the droplet because of the large area covered. Additionally, we also observe that the latent heat of vaporization of ethanol is much lower than water, 853 kJ/kg for ethanol and 2260 kJ/kg for water. This means that the ethanol droplet is able to quickly create a vapor cushion. The previous larger spreading of ethanol is also related to the fast vapor generation and its magnitude resulting in larger spreading dragged by more evaporation with ethanol than with water [35].



**Figure 7. Sketch of the spreading of water and ethanol droplets; measurement of the spreading of ethanol and water droplets in the Leidenfrost state at the same surface aluminum temperature 270 °C; both droplets have the same initial diameter 2.7 mm and the impacting velocity is low 0.27 m/s; ethanol droplet spreads more than water droplet; the sketch is not to scale: (a) spreading of water droplet and (b) spreading of ethanol droplet**

The previous process of fast evaporation (because of low evaporation latent heat,  $L$ ) and larger spreading (because of low surface tension and large spreading induced by strong vapor flow beneath the droplet) explains the reason why the dynamic Leidenfrost temperature shows trivial increase by increasing the droplet impact velocity with ethanol droplets. In regard to the case of water droplets, in addition to the mentioned thermophysical properties responsible for fast ethanol droplet evaporation which are high in the case of water (high  $L$ ), the density of water is also larger than that of ethanol. This means that in addition to the slow evaporation (because of the high  $L$  of water) which creates the levitating pressure beneath the droplet, it has higher dynamic pressure at the moment of the impact at the same droplet size as ethanol induced by large inertia (large density of water increases the water droplet impact inertia). This causes intermittent contact at the droplet-surface interface during spreading and/or retraction, hence, increasing the dynamic Leidenfrost temperature at increasing droplet impact velocity.

## Conclusions

The influence of the surface and liquid type on droplet impact dynamics was investigated. To study the effect of the surface properties, substrates made of copper, aluminum

and stainless steel were tested with deionized water. To study the effect of the liquid properties, water and ethanol were tested with aluminum. The surfaces were heated from temperatures close to the boiling point of the liquid till 400 °C.

Results showed that Leidenfrost temperature occurred at different temperatures according to each surface but did not correlate with the surfaces thermal properties. The surface properties could change during heating and this affects the initial surface properties. Moreover, two Leidenfrost temperatures were observed for copper and stainless steel surfaces. The first Leidenfrost temperature for each of these surfaces was consistent with previous studies; the second Leidenfrost temperature of these two surfaces corresponds to the low thermal properties of their oxide layer which was grown because of heating.

Ethanol showed lower Leidenfrost temperature than water because of its lower boiling point than water. Ethanol showed very trivial increase in the dynamic Leidenfrost temperature while water showed significant increase by increasing the impact velocity. This was due to the low properties of ethanol including surface tension, evaporation latent heat and density. Such low values of these properties promote spreading and evaporation leading to reduce to effect of the droplet impact velocity on the Leidenfrost temperature. Water has high surface tension and high latent heat of evaporation which are responsible to delay the evaporation, in addition to its high density which increases the dynamic pressure. Hence, eventual intermittent contact at higher impact velocity and the Leidenfrost temperature is significantly delayed by increasing the droplet impact velocity.

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