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Interaction of Cooling Lubricant Droplets with Hot Metal Surfaces

Kaissar Nabbout[1,*], Martin Sommerfeld[1], Eckart Uhlmann[2,3], Enrico Barth[2], Jörg Kuhnert[4]
[1]Otto-von-Guericke-University Magdeburg, Institute of Process Engineering
Universitätsplatz 2, 39106 Magdeburg, Germany
[2]Technische Universität Berlin, Institute for Machine Tools and Factory Management (IWF)
Pascalstr. 8-9, 10587 Berlin, Germany
[3]Fraunhofer Institute for Production Systems and Design Technology (IPK)
Pascalstr. 8-9, 10587 Berlin, Germany
[4]Fraunhofer Institute for Industrial Mathematics (ITWM)
Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany
*** Corresponding author:** kaissar.deoliveira@ovgu.de

Abstract - Several parameters have influence on the outcome of a single droplet impacting a hot surface. Droplet size, droplet impact velocity, droplet impact angle, surface roughness and temperature of the substrate are the most frequently used parameters to analyse the different hydrodynamic outcomes of droplet impacts. The main aim of this study is to experimentally analyse the impact of droplets, made of a mixture of water and mineral oil Adrana AY 401 from Houghton Deutschland GmbH, onto a hot surface of an Inconel 718 plate. Different concentrations of oil-in-water emulsions and two surface roughness were investigated and compared to results obtained for pure water droplets. The droplets (2.4 mm for water and 1.9 mm for emulsions) were generated by a high precision syringe connected to a moving system and a stepper motor, which is controlled by Arduino, an open-source electronic platform based on easy-to-use hardware and software. The Inconel 718 plate is heated by electromagnetic induction and has its rear face temperature measured by means of an infrared camera. The impacts of the droplets were recorded by a high-speed camera. Maps of impact outcomes of droplets were constructed by relating the substrate temperature, up to 500°C, to the dimensionless number K, which is a combination of the Weber number (We) and the Reynolds number (Re). Different values of K were obtained for the same liquid by adjusting the needle height and, consequently, the impact velocity, which was measured by high-speed imaging analysis. In the temperature range studied here, Leidenfrost effect is due to occur. Static and dynamic Leidenfrost temperatures were identified with help of a droplet lifetime graph and an impact regime map, respectively.

***Keywords*:** Droplet lifetime, droplet impact, hot surfaces, evaporation curve, impact regimes map

1. Introduction

Cooling lubricants are widely used in metal cutting processes to reduce tool wear or improve workpiece quality. Their main acting mechanisms are the dissipation of heat and the reduction of friction. However, the impact of cooling lubricants depends on various process parameters such as the cutting speed or cooling lubricant strategy itself [1]. Under certain flow conditions, high process temperatures lead to the evaporation of the cooling lubricant around the chip surface [2]. An isolating damper barrier due to the Leidenfrost effect and a reduced cooling action could follow.

Since the pioneer work of J. G. Leidenfrost in 1756 who first identified what is today called Leidenfrost effect, a lot of effort has been put in studying the interaction between liquids and hot substrates. More specifically for the interaction between liquid droplets and hot surfaces, different parameters proved to have great influence on the thermo-fluid dynamics of such problems, although no final model was developed yet due to the difficulty in combining the influence of all these parameters, that are frequently studied separately. The Leidenfrost effect is characterised by the formation of a thin vapor layer between the liquid and the hot substrate, avoiding the contact between both phases. The thickness of the vapor layer has been experimentally studied and was found to be proportional to the droplet size for sessile droplets [3][4][5].In the case of droplets impacting on hot surfaces at different temperatures, Kim et al. [6] concluded that higher the surface temperature, thicker the vapor layer.

With help of the droplet evaporation method, which consists in measuring the lifetime of a single droplet deposited, with zero or almost zero velocity, on a substrate at different temperatures, it is possible to obtain the static Leidenfrost temperature (T_L) and the critical heat flux temperature, also known as Nukiyama temperature (T_N) [7]. These temperatures are very important, because they mark, together with the nucleate boiling temperature (T_B), the limits between the evaporation regimes: film evaporation, nucleate boiling, transition boiling, and film boiling. As can be seen in Fig. 1, adapted from [8], T_L delimits the change from "transition boiling" to "film boiling", being identified by the longest droplet lifetime in this region. On the other hand, T_N is identified by the shortest lifetime and represents the change from "nucleate boiling" to "transition boiling". For temperatures slightly higher than the saturation temperature, bubbles start to form at nucleation sites, defining T_B.

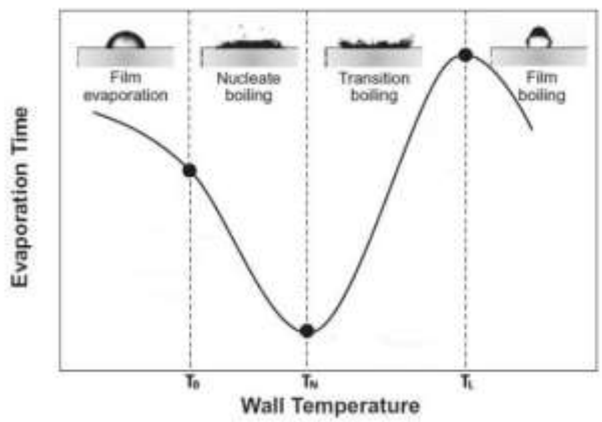

Fig. 1: Representation of a lifetime curve with the critical temperature points (adapted from [8]).

The effect of substrate material, its thickness and surface roughness were found to have great influence on T_L and T_N [9]. Smoother surfaces led to lower T_L and general higher droplet lifetime, although T_N did not show significant changes. For impinging drops, surface roughness seems to play a different role, i.e., rougher surfaces have lower dynamic Leidenfrost temperature ($T_{L,d}$) [10][11]. $T_{L,d}$ is defined as the temperature which an impinging droplet rebound without touching the hot surface (dry rebound) [12] and can be seen in a impact regime map, which will be shown and discussed later in the results. Due to droplet *momentum*, $T_{L,d}$ is found to be greater than T_L and is commonly represented as function of Weber number (We):

$$We = \frac{\rho v^2 d}{\sigma}. \tag{1}$$

The parameters ρ, v, d and σ stand for the droplet density, impacting velocity, diameter and surface tension, respectively. In the present study, the K number [13] was preferred since it also takes the fluid's dynamic viscosity (μ) into consideration. It is obtained by combining the well-known Reynolds number (Re) with the above mentioned Weber number:

$$K = We^{0.5} Re^{0.25}, \tag{2}$$

$$\mathrm{Re} = \frac{\rho v d}{\mu}. \tag{3}$$

Droplets impacting non heated surfaces have been widely studied [14][15][16][17] and the regimes identified are commonly named: deposition, rebound, splash and breakup. Small variations on the nomenclature can be found to describe specific behaviours [18], but nothing drastically different. Heated surfaces, on the other hand, increase significantly the complexity of the phenomenon and make the classification of some regimes challenging due to the combined thermo-fluid dynamic behaviour. For that reason, numerous different classifications have been used to classify the same problem [5][19][20].

2. Experimental setup and procedure

A simplified scheme of the experimental setup used is depicted in Fig. 2. The droplets were generated by a high precision syringe, which was connected to two moving systems, one responsible for controlling the droplet generation and the other for controlling the droplet impact velocity through height adjustment of the needle. Both systems were connected to stepper motors controlled by an Arduino board, which send signals to the stepper motors for moving speed and distance. The droplets were recorded by a high-speed camera Photron FASTCAM SA4 that was connected to a computer. A Nikon 200mm f/4 AF-D Macro lens made it possible to capture the droplet with good resolution and long working distance (26 cm), avoiding damage to the equipment due to the electromagnetic field and the heat. The backlight was generated by a single Cree XHP50 SMD-LED. An Inducta IH-25 induction heating system is used to heat the 140 mm diameter plates made of Inconel 718. The rear surface was covered with a LabIR® thermographic spray paint and its temperature recorded by an Infratec PIR uc 605 infrared camera.

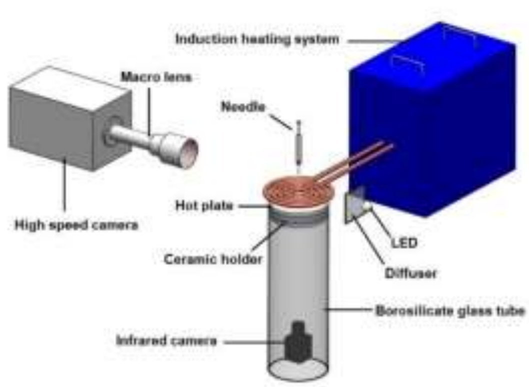

Fig. 2: Experimental setup used to obtain the droplet evaporation curve and droplet impact regime map.

Since all the measurements were done with the temperature field provided by the infrared camera for the rear surface, a correction for the temperature of the impinging surface was done in two steps with help of a Optris CS LT15 pyrometer, which was used as reference. In the first step, pyrometer and camera were positioned to record the temperature of the same face, what gives the temperature difference between the devices ($\Delta T_{devices,1}$). In the second step, the camera was put in the working position to measure the rear surface and the pyrometer on the opposite side to measure the impinging surface and another temperature difference is obtained ($\Delta T_{devices,2}$). By summing up them, the temperature difference for the different faces is obtained (ΔT_{faces}) and it is now possible to know the impinging surface temperature by knowing the rear surface.

Table 1: Properties for water, 8% and 20% emulsions, and oil Adrana AY 401 at 30°C.

Liquid	**Density** **Kg/m³**	**Surface tension** **mN/m**	**Dynamic Viscosity** **mPa.s**
Water	995.4	70.8	0.7060
Emulsion 8%	993.5	32.9	0.9608
Emulsion 20%	992.3	32.7	1.5760
Adrana AY 401	962.2	27.8	68.0842

Three different liquids were analysed in the present work: water and two emulsions made of a mixture of water and mineral oil Adrana AY 401 from Houghton Deutschland GmbH with 8% and 20% oil concentration, defined by volume. After putting oil and water together, the mixture is handshake for 10 minutes and the resulting emulsion has a stable approximately two weeks, before a thin layer of oil forms on the top. Due to the good miscibility of the oil, no surfactant stabilizer is needed. The properties of the liquids used are summarised in Table 1. The equipment used to measure the properties can be found in a previous work [2].

3. Results and discussion

In order to obtain the droplet evaporation curve, the needle is moved from an initial position of 80 mm to a final position of 3 mm (measured from the heated plate). At the final position, the droplet is released and touch the plate with low impact velocity, here considered to be zero. After releasing the droplet, the needle moves back to the initial position. This process is repeated three times for each temperature measured and the mean values are used for the droplet lifetime. This procedure is necessary to avoid the heating of the needle and, consequently, of the droplet. For a distance of 10.7 mm and a plate temperature of 250°C, the needle starts to heat after approximately 6 seconds [21].

The results for the droplet lifetime can be seen in Fig. 3. Since droplets generation is dictated by gravity force, their size is mainly affected by the surface tension, therefore water droplets are bigger due to their higher surface tension with a mean diameter of 2.4 mm and emulsion droplets have a mean diameter of 1.9 mm. The oil concentration seems to influence the Leidenfrost temperature in a way that droplets with lower content of oil present a higher static Leidenfrost temperature up to the limit of pure water, or 0% oil concentration, which has T_L equals to approximately 300°C, while the emulsions with 8% and 20% concentration have T_L equals to approximately 260°C and 240°C, respectively. The same trend was found by adding surfactants to water drops [22]. It was also observed a higher T_N of approximately 240°C for water when compared to both emulsions, which were around 200°C. It is important to mention here that the emulsion with 20% concentration presented noticeable oil residuals on the surface for temperatures lower than 200°C and these residuals were not taken into account for the droplet lifetime. The same did not happen to the 8% emulsion. Also, the presence of oil in the emulsions promoted foaming in the liquid during the nucleate boiling regime.

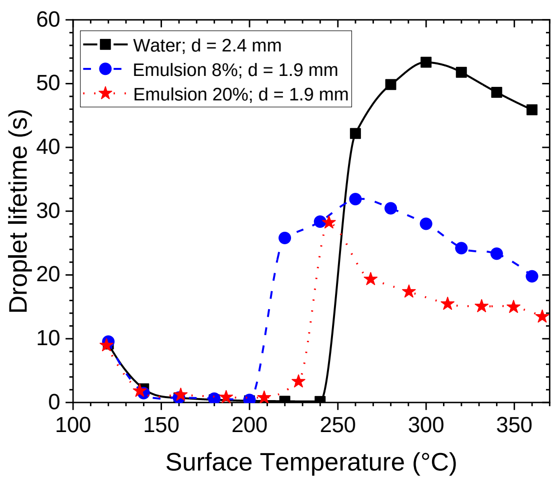

Fig. 3: Measurements for the droplet lifetime for surface temperatures higher than the boiling point of water.

For temperatures higher than T_L, droplets of water present a different behaviour at the end of the lifetime when compared to the emulsion droplets. Water droplets shrink until they are completely evaporated, while the emulsion droplets usually presented two different ends: either they explode (presenting abrupt expansion and contraction moments before the explosion) or they are ejected from the surface due to vapor explosions. For the transition temperatures, i.e., between T_N and

T_L, the droplet presents a combined behaviour between contact and noncontact, with ejection of small droplets (atomization) being responsible for the intermediate lifetime.

As mentioned before, the droplet lifetime method is a straightforward tool used to identify T_N and T_L. Although several several parameters can affect this curve, the droplet diameter is not one of them [9][23]. For the dynamic Leidenfrost Temperature, on the other hand, the droplet size has direct effect on it, once the diameter is one of the most important parameters for the droplet dynamics (Re and We). $T_{L,d}$ can be identified with help of the impact regime map, being the region between rebound with atomization and dry rebound [12]. In the present work, seven different outcomes (deposition with atomization, rebound with atomization, dry rebound, breakup with atomization, dry breakup, transition and transition breakup) were identified for millimetric droplets of water and oil-in-water emulsions impacting onto a heated surface with temperatures between approximately 180°C and 500°C. The term “dry” in “dry rebound” and “dry breakup” means that the droplet did not touch the substrate due to the Leidenfrost effect.

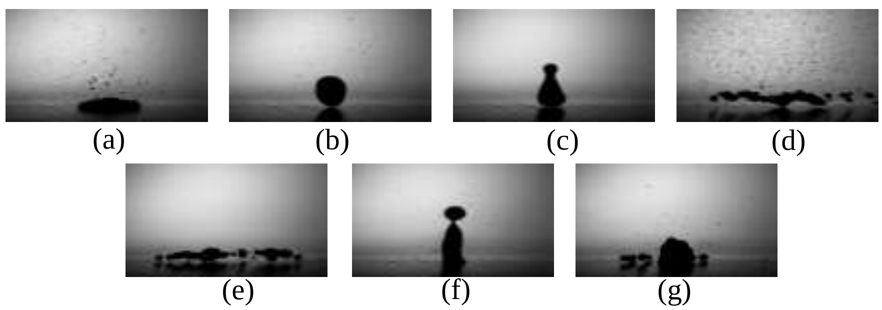

Fig. 4: Different outcomes for a 8% emulsion droplet impacting onto an Inconel 718 plate for different temperatures and We: (a) deposition with atomization, (b) rebound with atomization, (c) dry rebound, (d) breakup with atomization, (e) dry breakup, (f) transition and (g) transition breakup.

The nomenclature used in this work is based in the one proposed by [24], with addition of two outcomes: transition and transition breakup. These outcomes were added because they do not fit well in just one of the other outcomes, but instead they present combined behaviour from the regions they are dividing, which can result in significant changes in studies involving, for example, heat transfer. This different behaviour can be easily noticed comparing transition breakup, Fig. 4(g), with dry breakup, Fig. 4(e), and breakup with atomization, Fig. 4(d). For breakup (with or without atomization), the droplet impacts the hot substrate and then is divided into smaller droplets which will no longer interact with the plate, either because they were expelled far away from the impacting region due to inertia or because their inertia is not enough to promote contact with the hot substrate, so Leidenfrost phenomenon can be observed. On the other hand, for transition breakup the droplet impinges on the hot substrate and breakup due to the inertia and thermal effects, but a considerable amount of liquid is still in contact with the hot substrate around the impact region, which promotes intense boiling and atomization.

The above-mentioned impact regimes are organized in a map as function of surface temperature and K number, as shown Fig. 5. The results on the left are for the plate 1 (Ra=1.47µm and Rz=9.62 µm) and on the right for the plate 2 (Ra=5.3µm and Rz=28.7 µm). The surface roughness was measured with the device Hommel-Tamic W5 from Hommel GmbH. It was not detected significant difference for the $T_{L,d}$ (transition between rebound with atomization to dry rebound) for both surface roughness in the temperature and K range analysed, although [10] suggest that rougher surfaces yields to a lower $T_{L,d}$ and [11] confirm this trend only for structured surfaces. Surface roughness seems to have a bigger influence on the change from dry rebound to dry breakup for both emulsions. The smoother surface has a $60<K_c<70$ while $50<K_c<60$ for the rougher surface, which is in good agreement with $K_c=57.7$ found by Mundo et al. [13]. The same analyses are not possible for water droplets, because there were almost no Leidenfrost regimes for temperatures up to 500°C. Such a result makes one wonder on the importance of thermal properties and roughness of the substrate for having dry regimes, since [24] found $300°C<T_{L,d}<350°C$ for water droplets impinging onto polished aluminium in the range here studied ($20<We<120$). Different values were also found by [5] for water impacting onto heated silicon wafers. It is important to highlight how difficult is to determine with precision $T_{L,d}$ since in this transition area there is a certain probability to observe the formation of atomisation [25].

It was also noted that the size and quantity of droplets created in the "breakup with atomization" regime are strongly related to the substrate temperature. Substrate temperatures close to change in regime areas, from "transition with breakup" to "breakup with atomization" and from "breakup to atomization" to "dry breakup", produce fewer secondary droplets than intermediate temperatures, as depicted in Fig. 6. Those regimes involving atomization are subject of ongoing research, since the most common non dimensional numbers used for impact maps (We and K) seems to be

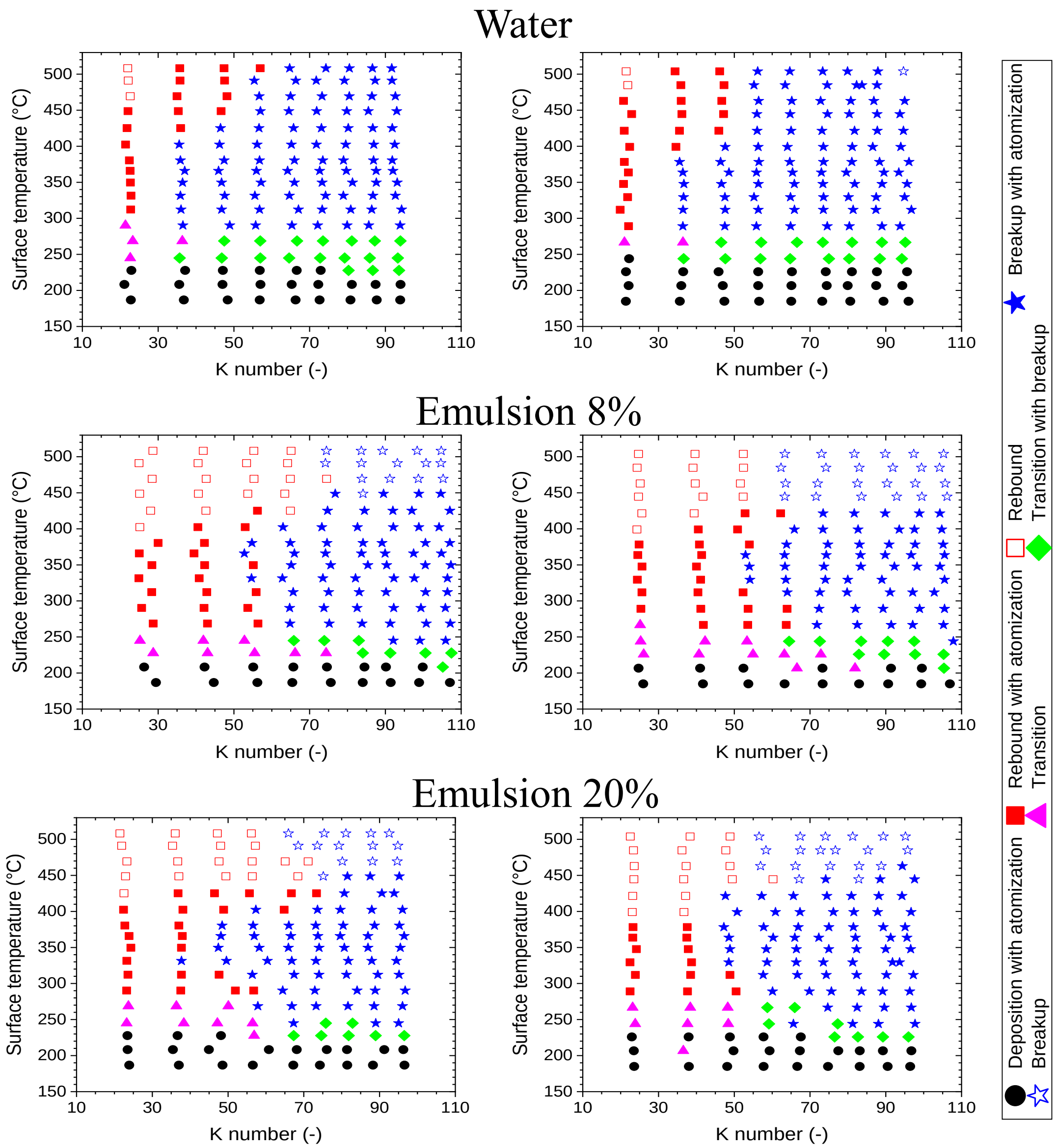

Fig. 5: Impact regime maps for droplets of water and oil-in-water emulsions impacting onto a heated Inconel 718 plate. Two plates with different roughness were used: on the left side are the results for the plate 1 (Ra=1.47µm and Rz=9.62 µm) and on the right side are the results for the plate 2 (Ra=5.3µm and Rz=28.7 µm).

inappropriate to describe them, as proposed by [26]. In their work, a new regime map is proposed having as coordinates dimensionless contact time and dimensionless heat flux.

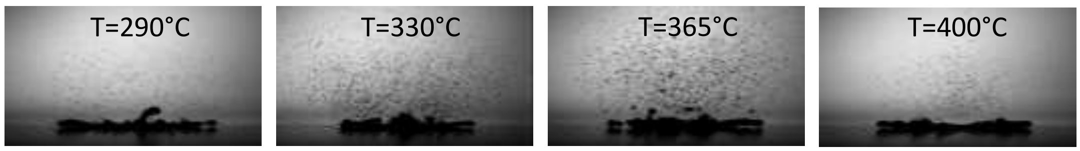

Fig. 6: Emulsion droplet (8% concentration) in the "breakup with atomization" regime impacting the substrate at different surface temperatures with the same velocity. It is noticeable that intermediate temperatures generate more secondary droplets.

The regimes here called "transition" and "transition with breakup" are very hard to characterize due to their combined behaviour, although it is noticeable that they occur in the same temperature interval that was identified for the transition zone in the droplet evaporation curve.

4. Conclusion

Impact of droplets made of water and oil-in-water emulsion with 8% and 20% concentration were experimentally studied with help of high-speed imaging analysis. Seven different impact regimes were identified and put together in a map as function of surface temperature and K number. The results presented here are a quantitative contribution to the behaviour of droplets made of two liquids and can be used to represent problems with similar characteristics, although care must be taken, since the outcome can be very sensitive to numerous parameters, mainly surface properties, as shown comparing the results obtained for water in the present work with those from the literature.

Also, a droplet evaporation curve was used to estimate T_N and T_L and, consequently, transition and boiling regimes. The transition regime for impacting and sessile droplets were shown to be related. The atomisation in the "breakup with atomisation" regime was brief and qualitatively discussed, showing its dependence on the substrate temperature. The results for both emulsions studied were significantly different from those for pure water, which shows how even a small concentration of oil can have huge impact in the outcome results.

In the future, the observed differences in evaporation and impact regimes will be connected to resulting heat fluxes. In combination with cutting simulations, this will contribute to further understanding of the evaporation and cooling action of cooling lubricants during chip formation.

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