Thermal infrared mapping of the Leidenfrost drop evaporation

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Abstract. The paper presents an author complementary study on the Leidenfrost drop evaporation. The research was conducted under ambient conditions and in the film boiling regime. Large water drops were placed on the copper substrate of the constant temperature $T_w$ ranging from 297.6 to 404°C. The initial single drop diameter and its mass was $D_0 \approx 1$cm and $m_0 \approx 1$g respectively. One of the obtained results, for each $T_w$ are the drop thermal images versus time. They were used to calculate an average temperature over the drop upper surface ($T_d$). For an exemplary heating surface temperature of $T_w = 297.6$°C the average drop temperature is approximately 11°C lower than the saturation one and equals $T_d = 88.95$°C. This value is estimated for the first 200s of evaporation and with time step size $\Delta t = 0.5$s. The drop upper surface temperature is highly variable and indicates strong convection inside it. This is due to the complex nature of heat and mass transfer. The maximum standard deviation from $T_d = 88.95$°C is $SD = 1.21$.

1. Introduction
Nowadays, a fast rate of new technologies is observed in any industrial branch, especially in material engineering [1] and heat engines of various purposes [2]. The water drop evaporation on a hot surface is of a great importance in many manufacturing processes associated with heat treatment e.g. in hardening [3,4], tempering, evaporative cooling [5, 6], electronics cooling [7], lasers [8], fuel engineering [9], and so on.
During liquid drop evaporation on the surface of very high temperature i.e. above the Leidenfrost point, highly intensive vapor production is observed. It causes lifting forces [10] that enable the drop to float. In this instance surface wetting is negligible [11]. Additionally, the drop takes spherical shape and minimizes its surface energy. Further overheating, above the value relating to the Leidenfrost point, results in increase of dissipating heat flux. Then the drop lifetime decreases.
In some cases, various additives into the liquid base are desired and searched for. Some of them change the wetting conditions [12] and lead to a more intense heat transfer between the drop and the surface [13], while others suppress it [14]. And thus, for example during electronics cooling or in firefighting it is important to increase the amount of discharged heat which involves the Leidenfrost state suppression. In [15] such a suppression is obtained by the electric field in the vapor layer, beneath the liquid drop. The electrical charge results in the reduction of the vapor cushion height.

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In the literature review various models of the Leidenfrost drop shape are described. These of higher mass and volume are most often presented in the form of a disc ($R_d \sim 1\text{cm}$) and the smaller ones ($R_d \sim 1\text{mm}$) in the spherical forms [16-18]. One of the latest papers [19] examines water droplets evaporation on a copper surface of 400°C. The initial droplet volumes are $V_0 = 1$, 2 and 3 ml. For this purpose, an individual test stand was set. One of the most important components was a system for image recording and processing. In such a way the phenomenon of liquid evaporation was able to be recorded.

It has been noticed that a single droplet changes its shape, vibrates and simultaneously rotates around its own axis. Depending on the initial droplet volume and during its entire lifetime, several basic shapes are distinguished and classified as follows: tri-lobed and circular shapes for $V_0 = 1$ ml, ellipse, circular, six- and tri-lobed, and again ellipse or circular shapes for $V_0 = 2$ ml as well as puddle formation, tri-lobed, star, four- and six-lobed, ellipse and again four-lobed shapes for the highest volume i.e. for $V_0 = 3$ ml.

The study of similar droplet's states during evaporation on the surface under film boiling regime i.e. above the Leidenfrost point can also be found in [20, 21]. In [19] it is delineated that the droplet's evaporation has an exponential nature. This allows deriving a relationship formula of the droplet upper surface area and its lifetime which was also noted earlier in [21]. The authors of [19] highlight a need of further study on the mechanism of Leidenfrost droplet evaporation in order to better understand the phenomenon.

The intense convection movements inside the droplet depend on its shape and heat transfer conditions. The phenomenon can be observed by the use of thermography [20, 22-24], other optical equipment and CCD camera or by means of a numerical study [4, 25, 26].

In [27] the visualization of the vapor flow inside the droplet during its evaporation is performed with the Ray-Tracing method. Presented simulations suggest that convection movements inside the droplet are distributed symmetrically and therefore the problem is an axisymmetric one. Similar conclusions can also be found in [28].

On the basis of thermal images, in [29] a physical approach of the liquid droplets evaporation is presented. It concerns 5,8 mm- ethanol, methanol and FC-72 droplets placed on a polytetrafluoroethylene (PTFE) surface of constant temperature. The research consisted of three evaporation steps: the first one was heating the liquid from room temperature to ~44°C, the second focused on convection and droplet instabilities during evaporation and the third was stable droplet evaporation with distinct heat flux decrease. The convective instabilities inside the drop are explained by high overheating. In this case, the assumption of the axisymmetry is a far reaching simplification that results from the research presented below and from the mechanism of the drop interaction with the surface described in literature [15, 29]. In fact, during cooling processes, especially by the use of spray, the temperature at different points of the heating surface varies significantly. Therefore, the surface is locally supercooled and it is required to calculate local value of the heat flux versus time.

This paper concerns thermal infrared mapping of the water drop shape during its evaporation. The drop was placed on the copper substrate temperature in the range of film boiling and under ambient conditions. Particular emphasis is placed on the convective movement in the drop subsurface that affect the asymmetrical nature of the phenomenon. For this purpose an original test stand was set up.

2. The test site
In order to study the dynamic behaviour of the liquid drop evaporation on circular copper substrate of temperatures above the Leidenfrost point, an individual test site was established as shown in figure 1.
Large water drops were placed on the copper surface of the temperatures ranging from $T_w \approx 297.6$ to 404°C. Thanks to the electric wrapped heater the wall temperature was maintained at a constant level. In these case $T_w = 297.6°C = \text{const}$. The initial drop diameter and its mass was $D_0 \approx 1\text{cm}$ and $m_0 \approx 1\text{g}$ respectively. The cylinder diameter is slightly wider than the drop’s one and equals 3.5cm.

As it can be seen in figure 1, the main test site measurement channels are: cameras, scales and temperature. During the investigation the following characteristics are delivered: instantaneous mass loss of the drop ($d\text{m}$), the temperature of the external and visible drop surface ($T_d$) and the substrate ($T_w$) as well as the perpendicular drop projection on the heating base ($A$). What should be added, is that the mass registration was run with the weight of the single drop of ~1g. The frequency of mass change and thermal images registration was set to 2Hz. Total drop lifetime was approximately few minutes for an average surface temperature of the given range.

The precise description of the research procedure and methodology is presented in [20, 21].

3. Infrared and digital drop shape analysis

Part of the investigations involves mapping the Leidenfrost drop evaporation phenomenon. For each analysed wall temperatures in the range of $T_w \approx 297.6 \div 404°C$ a series of over 30 measurements was conducted. This number seems to be enough and proper from the statistical point of view.

On the basis of recorded thermal images and by the use of Irbis 3 thermography software, the average temperature over the water drop upper surface ($T_d$) was calculated. The value was estimated from the upper area of the drop seen by the THV camera. The emissivity of water was taken as 0.96.

In this case, for $T_w = 297.6°C$ the drop average temperature $T_d = 88.9°C$ which is approximately 11°C lower from the saturation one. This value is assessed for the first 200s of evaporation and with time step size $\Delta t = 0.5s$. It is worth noting that the drop surface temperature is highly variable and indicates a strong convection inside it. Therefore, the phenomenon cannot be considered as an axisymmetric one. This is due to the complex nature of heat and mass transfer.

Figure 2 displays selected thermal images of the drop evaporating on the copper substrate of exemplary temperature $T_w = 297.6°C$.
Figure 2. The exemplary thermal images of the drop evaporation at constant heating base temperature $T_w = 297.6\,^\circ C$.

In correspondence to exemplary images of the water drop evaporation presented in figure 2, basic parameters outcomes of statistical analysis are defined in table 1.

| Time ($t, s$) | Avg. ($T_{avg}, ^\circ C$) | Min ($T_{min}, ^\circ C$) | Max ($T_{max}, ^\circ C$) | Standard dev (SD, $^\circ C$) |
|---------------|-----------------------------|-----------------------------|-----------------------------|------------------------------|
| a             | 0                           | 90.82                       | 90.63                       | 91.00                        | 0.10                         |
| b             | 9.5                         | 90.40                       | 90.06                       | 90.71                        | 0.17                         |
| c             | 19.5                        | 89.72                       | 89.22                       | 90.15                        | 0.24                         |
| d             | 30                          | 88.69                       | 88.22                       | 88.96                        | 0.16                         |
| e             | 40                          | 90.57                       | 90.24                       | 90.93                        | 0.19                         |
| f             | 50.5                        | 89.95                       | 89.56                       | 90.35                        | 0.19                         |
| g             | 60.5                        | 88.84                       | 88.68                       | 89.08                        | 0.09                         |
| h             | 71                          | 86.20                       | 85.37                       | 87.15                        | 0.50                         |
| i             | 79.5                        | 89.76                       | 89.47                       | 89.94                        | 0.12                         |
| j             | 88.5                        | 87.30                       | 86.82                       | 87.84                        | 0.23                         |
| k             | 100                         | 87.04                       | 86.81                       | 87.41                        | 0.14                         |
| l             | 113.5                       | 87.53                       | 86.33                       | 89.05                        | 0.69                         |
| m             | 116                         | 86.59                       | 86.29                       | 87.09                        | 0.18                         |
| n             | 121                         | 89.63                       | 89.31                       | 89.94                        | 0.16                         |
| o             | 129                         | 89.26                       | 88.63                       | 89.73                        | 0.31                         |
What is more, by the use of thermal images, the minimum and maximum temperatures of the drop upper surface area are assessed and equal to: $T_{d, \text{min}} = 88.54^\circ C$ and $T_{d, \text{max}} = 89.40^\circ C$ respectively. More detailed information on statistics is included in table 2.

**Table 2.** Statistical descriptors related to Leidenfrost drop evaporation for $T_w = 297.6^\circ C$.

| Description                                      | $T$, $^\circ C$ | Min ($T$), $^\circ C$ | Max ($T$) | $SD$, $^\circ C$ |
|-------------------------------------------------|----------------|------------------------|-----------|------------------|
| 1 Average of the average droplet temperatures, $T_d$ | 88.95          | 84.38                  | 91.57     | 1.21             |
| 2 Average of the minimum droplet temperatures, $T_{d,\text{min}}$ | 88.54          | 84.07                  | 91.30     | 1.28             |
| 3 Average of the maximum droplet temperatures, $T_{d,\text{max}}$ | 89.40          | 84.76                  | 91.81     | 1.15             |

In some measurement series and in certain temperature ranges distinct instabilities of the drop evaporation are observed. In that case, the drop rotates around its own axis and changes its shape dramatically as it is reported in figure 3. Such instabilities result in deviations in the spherical droplet's shape. It takes the forms of multiple star (five- and three-pointed) or ellipse as is shown in figure 3a, 3b and 3c respectively.

![Figure 3](image)

**Figure 3.** Thermal and digital images of unstable water drop behavior during evaporation process.

### 4. Concluding remarks

The aim of this study is thermal infrared mapping of the Leidenfrost drop evaporation. The water drop was placed on the copper substrate of the temperatures in the range of film boiling and under ambient conditions. The most relevant remarks on the topic are as follows:

- The analysis is performed for exemplary wall temperature of $T_w = 297.6^\circ C$.
- The water drop floats on its own vapour cushion which extends the drop's lifetime. Unstable vapor outflows from the lower surface of the drop leads to intense subsurface convective motions. This is due to the complex nature of interrelated heat and mass transfer processes. Moreover, it results in the variation of the drop upper surface temperature as is presented in figure 2. At the average drop temperature $T_d = 88.9^\circ C$ the difference between extreme values can go above ~7°C.
- The maximum value of the standard deviation of the drop average temperature $T_d$ is $SD = 1.21^\circ C$ and was specified with 401 values ($88.9^\circ C \pm 1.21^\circ C$).
- As concluded from the analysis of other heating surface temperatures ($T_w \approx 297.6^\circ C \div 404^\circ C$), high values of standard deviation confirm each time the variability of thermal conditions on the upper drop surface area. In these cases the standard deviation reaches $SD \approx 2^\circ C$ and more. Intensive and turbulent convective motions may disturb the drop spherical shape. Consequently, the liquid drop evaporating from the heating surface under film boiling conditions cannot be considered as an axisymmetric phenomenon, while the literature models often adapt such far-reaching simplification.

5. References

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