Experimental Measurement of the Dynamic Leidenfrost Temperature at Evaporation of Liquid Droplets

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Abstract: The time of evaporation of a water drop from a strongly heated surface has been experimentally measured, and the temperature intervals for the time of rapid and slow evaporation (the Leidenfrost point) have been determined. The rate of droplet evaporation was calculated during direct heating of the thermal surface and during its cooling. The heat transfer coefficient for the evaporation of droplets from a heated and cooling surface is calculated. It was found that when the heating surface cools down, the temperature range of rapid evaporation is smaller than the temperature range of intense evaporation during direct heating. During cooling of the heated surface, the heat transfer coefficient is 2 times higher than with direct heating.

1 INTRODUCTION

The problem of studying the crisis of liquid boiling in a large volume is of both fundamental and practical scientific importance. In a number of industries, fast cooling of metal products heated to high temperatures takes place - this is the main way to obtain the required internal structure of the product during the hardening process. In the nuclear industry, the issues of the appearance of film boiling on the surface of the heater and the deterioration of heat transfer associated with it are topical. Occurrence of a steam explosion when the cooling of the reactor core deteriorates. From a scientific point of view, it is very important to understand the mechanisms of boiling processes occurring near the heating surface. To avoid the destruction of heat-stressed surfaces and reduce the likelihood of catastrophic consequences, it is necessary to control the temperature regimes of boiling liquids.

The occurrence of the "Leidenfrost" effect, when a liquid drop is folded into a spheroid, is not only an interesting fact, but also an important phenomenon, which often leads to a limitation of the heat flow from heat-stressed surfaces to the liquid (Quere, Ajdari, 2006; Dmitriev, Romanov, 2013; Cerro, Marín, Römer, 2012).

The study of the heat transfer process during the evaporation of a liquid drop from the heating surface has been the subject of many observations (Kutateladze, 1984; Borishansky, 1953; Hetsroni, Mosyak, Pogrebnyak, Sher, Segal, 2006; Emelyanov, Platunov, 2011). In most of these works, droplets of a larger diameter were used. This is due to the fact that the evaporation of droplets with a diameter of up to several millimeters proceeds very quickly. At high temperatures of the heating surface, the evaporation of droplets takes place in a fraction of a second, and therefore the measurement of the evaporation time is difficult (Yalmov, Kuzmin, 2005; Reva, Reva, Reva,

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Golovanchikov, 2011; Ovsyannik, 2010). The study of heat transfers during the evaporation of drops from highly heated surfaces is a topical issue for the metallurgical industry, thermal and nuclear energy.

2. EXPERIMENTAL TECHNIQUE

To study heat, transfer during the evaporation of liquid droplets, an experimental setup was developed. It included an apparatus with a heated surface, a flat carbon steel plate into which a chromel-copel thermocouple was soldered. The evaporation time was determined using an electronic stopwatch with an accuracy of 0.01 s.

The experiments carried out made it possible to obtain a number of interesting experimental data, which, undoubtedly, will be relevant for understanding the physical picture of heat transfer during cooling of strongly heated surfaces by a liquid.

When a drop falls at the initial moment of its contact with the surface, it “flattens out”, and then, under the action of the surface tension force, it contracts and takes the form of a hemisphere. Depending on the temperature of the heating surface, for some time, the drop is heated to saturation, then evaporates intensively. In this case, the drop retains an approximately constant area of the contact spot with the surface. After evaporation of the bulk of the liquid, a wet spot remains on the heating surface, which gradually dries out.

The amount of heat required to evaporate the droplets is determined as follows:

$$Q = Q_1 + Q_2 \tag{1}$$

Let us give an example of calculation for one drop.

$$Q = m_k \cdot c(t_{\text{boil}} - t_0) + m_k \cdot r \tag{2}$$

$$Q = 50 \cdot 10^{-6} \cdot 4200 \cdot (100 - 25) + 50 \cdot 10^{-6} \cdot 2256840 = 128{,}6 \text{ J}$$

where Q is the total amount of heat, J; Q1 is the amount of heat required to heat the liquid to the boiling point, J; Q2 is the amount of heat required to carry out the phase transition from liquid to vapor, J; mk is the mass of a liquid drop, kg; cp is the heat capacity of the liquid, J/(kg oC); tboil – liquid boiling point, oC t0 – initial drop temperature, oC; r is the latent heat of vaporization, J/kg. The volume of the evaporated drop is equal t.

$$V = \frac{m}{\rho} \tag{3}$$

$$V = \frac{50 \cdot 10^{-6}}{997} = 5 \cdot 10^{-8} \text{ m}^3$$

$$r = \sqrt[3]{\frac{3V}{4\pi}} \tag{4}$$

$$r = \sqrt[3]{\frac{3 \cdot 5 \cdot 10^{-8}}{4 \cdot 3{,}14}} = 0{,}0023 \text{ m}$$

The heat exchange surface area F_{n} of a boiling drop is determined as follows:

$$F_n = \frac{\pi \cdot (2 \cdot r)^2}{4} \tag{5}$$

$$F_n = \frac{3{,}14 \cdot (2 \cdot 0{,}0023)^2}{4} = 1{,}7 \cdot 10^{-5} \text{m}^2$$

The heat load required for the evaporation of a droplet is defined as:

$$N = \frac{Q}{\tau} \tag{6}$$

$$N = \frac{128{,}6}{13{,}2} = 9{,}7 \text{ W}$$

where τ is evaporation time (s).

Specific heat flux:

$$q = \frac{N}{F_n} \tag{7}$$

$$q = \frac{9{,}7}{1{,}7 \cdot 10^{-5}} = 570588 \text{ W / m}^2$$

Thermal head

$$\Delta t = t_{\text{st}} - t_{\text{boil}} \tag{8}$$

$$\Delta t = 110 - 100 = 10 \ {}^{\text{o}}\text{C}$$

where t_{st} is the surface heating temperature, (°C)

The heat transfer coefficient during the evaporation of a droplet is equal t_o:

$$\alpha = \frac{Q}{\Delta t \cdot F_n \cdot \tau} \tag{9}$$

$$\alpha = \frac{128,6}{10 \cdot 1,7 \cdot 10^{-5} \cdot 13,2} = 57308,4 \ \mathrm{W}/\left(\mathrm{m}^2 \cdot {}^\circ\mathrm{C}\right)$$

Drop Mass Evaporation Rate:

$$w = \frac{m_k}{\tau} \tag{10}$$

$$w = \frac{50 \cdot 10^{-6}}{13,2} 3,4 \cdot 10^{-6} \mathrm{kg/s.}$$

Specific productivity for evaporated moisture:

$$w = \frac{m_k}{\tau \cdot F_n} \tag{11}$$

$$w = \frac{50 \cdot 10^{-3}}{27 \cdot 0,0004} = 4,6 \ \mathrm{kg}/\left(\mathrm{m}^2 \cdot \mathrm{h}\right)$$

Similarly to the given example, the thermal characteristics of droplet evaporation were calculated with increasing and decreasing surface temperature. Processing of data obtained during drop boiling of water showed that the average

heat transfer coefficient from about 3,000 to 300,000 W/(m^2 °C).

Figure 1 shows the experimental time curve for the evaporation of water droplets.

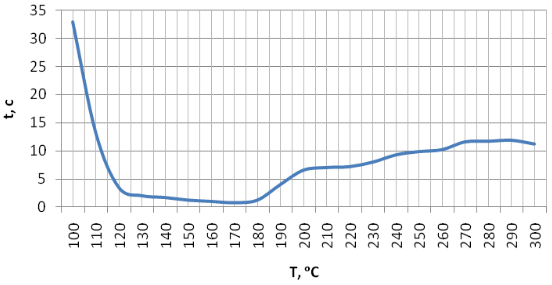


Figure 1: Dependence of the evaporation time of water drops on the temperature of the heater.

With an increase in the heater temperature, the evaporation time of a droplet on the heated surface decreases to a minimum value. The temperature range of the heater surface, when the drops quickly evaporated, is 160-170°C. With a further increase in the surface temperature, the droplets begin to break into smaller droplets and the evaporation time increases.

The experimental results obtained by us on the evaporation of water droplets are consistent with the data obtained by the infrared pattern of thermal fields in works (Quere, Ajdari, 2006; Dmitriev, Romanov, 2013; Cerro, Marín, Römer, 2012), where a high-resolution thermal imaging camera Artcam-320 was used.

When the heater surface cools down (Fig. 2), the rapid evaporation temperature range will shift towards lower temperatures by 10 °C.

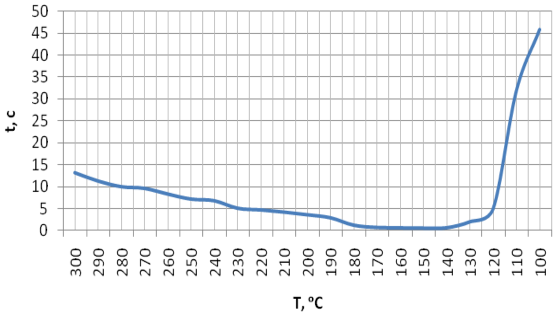
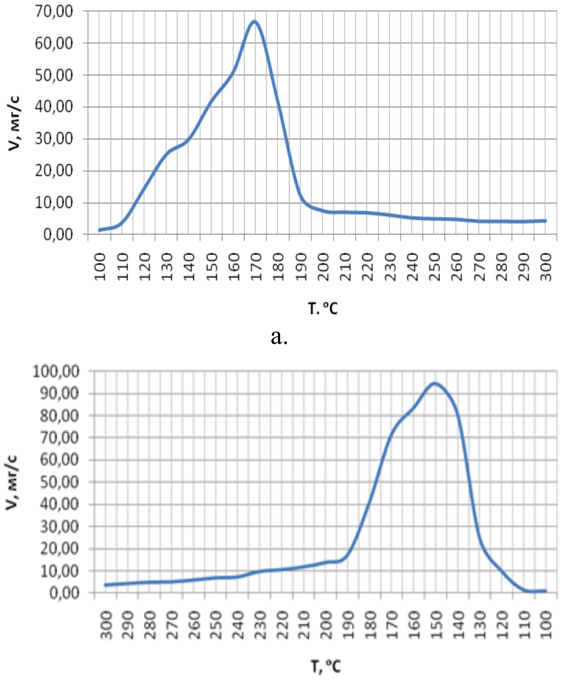


Figure 2: Evaporation time of a water drop during cooling of a heat-stressed surface.

Figure 3 shows the change in the droplet evaporation rate with an increase in the heater surface (Fig. 3a) and with a decrease in the heater surface temperature (Fig. 3b). It is calculated that the mass rate of evaporation of a drop from the surface increases to its maximum value, while, as can be seen from the graphs in Figure 3, the points of maximum evaporation rate fall on different temperature intervals. With direct heating, the surface temperature is 170 °C, the maximum evaporation rate is 60 mg/s, and when the surface temperature decreases, the maximum evaporation rate of the drop is 150 °C, while the evaporation rate is more than 90 mg/s.

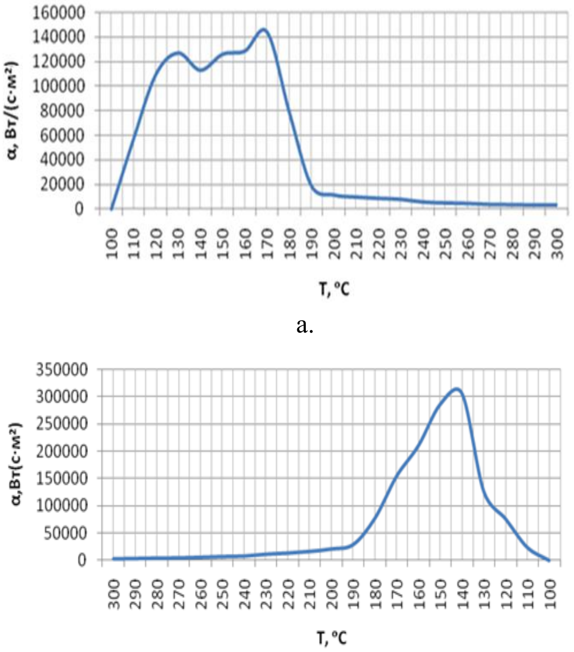


a.

b.

Figure 3: Dependence of the evaporation rate of a water drop: a – when heating a heat-stressed surface; b – during cooling of a heat-stressed surface.

Figure 4 (a and b) shows the results of the calculated heat transfer coefficients during the evaporation of a drop from a heated plate (Fig. 4a) and from a cooling one (Fig. 4b).



a.

b.

Figure 4: Dependence of the heat transfer coefficient on the temperature of the heater surface: a – with an increase in the surface temperature, b – with a decrease in the surface temperature of the heater.

Table 1 shows the results of the fastest evaporation time for droplets of a binary water-ethanol mixture at concentrations up to 70% by weight of ethanol.

Table 1: Results of the fastest evaporation time for droplets of a binary water-ethanol mixture at concentrations up to 70% by weight of ethanol.

X, %	t, c.	X, %	t, c.
10	0,66	40	0,56
20	0,41	50	0,59
30	0,5	60	0,6
		70	0,63

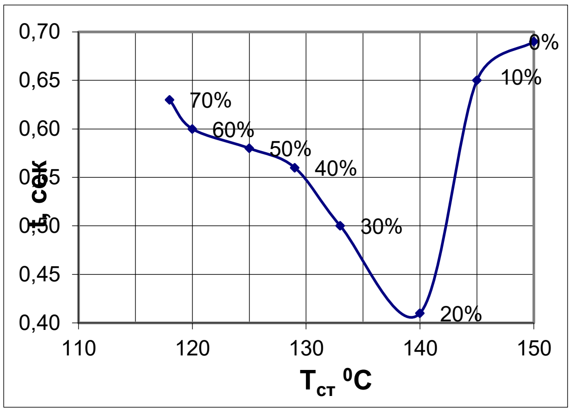


Figure 5: Curve of the dependence of the time of the fastest evaporation on the temperature of the heating surface for a binary mixture of water-ethanol.

According to this graph, with an increase in the concentration of alcohol in water, the time of the fastest evaporation and the surface temperature decrease; at 20% concentration, a minimum is observed on the t(Tst) curve. Further, with an increase in the content of the organic component in water, the evaporation time increases, while the surface temperature continues to decrease.

The data obtained can be visualized as follows.

If we compare the obtained values of the temperatures of the fastest evaporation Tst, for various concentrations of the water-ethanol mixture, with the values of their boiling points, at atmospheric pressure, we can see that the ratio is $\frac{t}{T_{st}}$ constant and lies in the range of 0,62-0,66. Table 2 reflects these results.

Table 2: Reflects these results.

$x,\%$	T_{st}, ° C	t,^0C	$\frac{t}{T_{st}}$
0	150	100	0,66
10	145	91,5	0,63
20	140	87,1	0,62
30	135	84,5	0,63
40	129	83,1	0,64
50	125	82,0	0,65
60	121	81,0	0,66
70	118	80	0,67

From the obtained value of the ratio $\frac{t}{T_{st}}$ it can be seen that their average value is 0,64. The relationship between the boiling point of the mixture and the temperature of the fastest evaporation can be written as the expression $T_0 = 0{,}64 \cdot T_{\mathrm{st}}$.

Thus, when processing the experimental data, an interesting regularity was found, the highest mass evaporation rate of binary water droplets is observed at the same concentrations of the organic component as the maximum critical heat load, when boiling in a large volume. A relationship has been established between these values, the greater the rate of evaporation of the mixture, the higher the critical heat load, it turned out that the value of the ratio $\frac{q_{\mathrm{kr}}}{V_{\max}}$ for each given composition of the mixture is constant and lies in the range of 0,15-0,18. In the future, this regularity should be given special attention, especially to the study of the processes of evaporation of droplets of binary mixtures on nanostructured surfaces.

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