Generation of levitating droplet clusters above the locally heated water surface: A thermal analysis of modified installation

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Abstract
A modified laboratory installation to generate levitating clusters of droplets above the locally heated water surface is presented. The laser-heated sitall plate with an opaque graphite coating is used as a substrate for the water layer which produces a levitating droplet cluster. The cluster is stabilized with the use of infrared heating as was recently demonstrated by the authors. A combined experimental and computational method is developed to obtain the axisymmetric quasi-steady temperature field in sitall plate and water and also to calculate the radial profile of heat flux at the water surface. Both the temperature and heat flux at the water surface are important boundary conditions for the upcoming computational modeling of cluster formation. The correlations between the laser power, the measured overall flow rate of steam at the water surface, and other important parameters of the problem are also examined.

1. Introduction
The levitating droplets which form the clusters of regularly positioned spherical droplets above the heated water surface were observed for the first time about twelve years ago [1]. The behavior of the levitating single droplets and droplet clusters in the incoming flow of water vapor and entrained air has been studied experimentally and the laboratory observations appeared to be useful for understanding this specific phenomenon [2–5]. The photographs of a droplet cluster and also a cloud of condensed steam far above the cluster are presented in Fig. 1.

In the present paper, we do not give additional references to early studies of various levitating droplet clusters. At the same time, more recent papers based on specific infrared properties of water should be mentioned. First of all, the absorption band of water at the wavelength about 3 μm [6,7] was used in paper [8] to retrieve the surface temperature of the upper surface of various water droplets from the measurements of their brightness temperature. The next step related with infrared heating of the cluster droplets enabled us to transfer from the passive observation to managing the process [9,10]. Moreover, it was experimentally demonstrated that wide-range infrared irradiation can be used to stabilize the droplet cluster by preventing the ordinary growth of single droplets because of predominant steam condensation on their surface.

The objective of the present study is three-fold: (1) to suggest a modified experimental procedure to generate stable droplet clusters above the locally heated water surface, (2) to develop a combined experimental and computational method to obtain the radial distribution of heat flux to the water surface and (3) to provide new data for evaporation of water under the stable levitating clusters.

2. Modified experimental procedure to generate levitating droplets
The schematic presentation of experimental installation presented in Fig. 2 includes the following designations: 1 is the droplet cluster, 2 is the horizontal water layer, 3 is the cylindrical cavity in the massive duralumin plate with the central orifice, 4 is the sitall plate/substrate with an absorbing opaque coating containing fine graphite particles at the irradiated side (the measurements showed that this coating absorbs more than 99.9% of the incident radiation flux), 5 is the annular groove filled with epoxy glue for fixing the substrate, 6 is the laser beam used to heat the substrate, 7 is the special plate to reflect a part of laser radiation, and 8 are the sources of infrared radiation used to stabilize the cluster.
The laser heating suggested in [6] has several advantages as compared with the electric heating used in previous studies [1–3,8]. Much lower inertia of heating and very smooth surface of sitall substrate are the main of these advantages. Note that smooth surface enabled one to avoid unfavorable centers of nucleation and the resulting collapse of the droplet cluster due to pop up...
gas bubbles. The glass substrate used in [9,10] appeared to be not a good choice because of insufficiently good mechanical properties of both the glass plate and opaque coating. A semiconductor laser with the wavelength of 808 ± 10 nm was used in the experiments. The laser power can be regulated from zero to \( W_0 = 600 \) mW. A reflected part of the laser beam was used to measure the current laser power during the experiment. The reflecting plate was also used before the experiment to analyze a distribution of radiative flux across the beam. The experimentally observed cross section of the beam looks like a square with the side length of \( \delta_1 = 0.8 \) mm, and the spatial distribution of radiative flux is almost uniform. To simplify the calculations, an equivalent circular beam was used in continuous observations of the cluster and the radiative flux was directed at the angle 45° to the vertical axis of the cluster, and the radiative flux was directed at the angle 45° to the axis [10]. The stereomicroscope Zeiss Discovery V8 equipped by a video camera was used in continuous observations of the water cluster behavior.

The thickness of water layer, \( d_w \), was controlled with error ±2 \( \mu \)m using the laser triangular sensor RF603-15/2 made by the company Riftec. The value of \( d_w = 150 \) \( \mu \)m was carefully supported to be constant during the experiment. Note that in the experiments with infrared stabilization of the cluster (Fig. 4) the value of \( d_w = 300 \) \( \mu \)m was used. The distilled water containing natural micro admixtures of surface-active substances was used in the experiments. The effect of these admixtures is favorable because they prevent thermal capillary flows on water surface [11].

The temperature of air in the laboratory room was maintained at the level of 21 ± 1 °C at the relative humidity about 20%. Five values of laser power for possible subsequent use have been determined at the preliminary stage of experiments. The value of \( d_w = 150 ± 2 \) \( \mu \)m was used, and the values of \( W_0 \) were chosen to obtain the maximum temperature of water surface from 50 to 70 °C with a step of five degrees. Radial profiles of temperature at the water surface was measured using the thermal imager Flir A655sc with the wavelength range from 7.5 to 14 \( \mu \)m, the matrix containing 640 × 480 pixels, and the temperature resolution of 50 mK. The lens Close-up IR 2.9× was sufficient to obtain infrared images with 50 × 50 \( \mu \)m size of a pixel. The frequency of the recording was equal to 50 frames per second. Typical examples of the measured temperature profiles are shown in Fig. 3. Note that effect of variation of \( d_w \) in the limits of few micrometers appears to be negligible for the measured values of temperature.

### 3. The use of external infrared heating to obtain stable cluster of droplets

The effect of infrared irradiation observed in recent papers [9,10] is illustrated in Fig. 4 where time variation of the droplet surface area, \( S = 4\pi a^2 \) at laser power of \( W_0 = 163 \) mW and variable power of infrared radiation, \( W_{\text{IR}} \), is presented. Infrared heating of cluster was made by four radiation sources EK-8520 produced by the firm Helioworks and characterized by an almost blackbody radiation at temperature \( T = 1223 \) K. The Mie theory calculations of this radiation in semi-transparent droplets [12–14]. To arrange relatively uniform irradiation of the droplet cluster, the infrared radiation sources were placed symmetrically with respect to the vertical axis of the cluster and the radiative flux was directed at the angle 45° to the axis (see Fig. 2). The maximum value of this power in the experiments of [10] was relatively small:

\[
W_{\text{IR}}^{\text{max}} < \frac{W_0}{4}
\]

The duration of every video record was equal to 60 s including (1) the initial period of \( t < 20 \) s without infrared irradiation, (2) the “active” period of \( 20 < t < 40 \) s with infrared heating the droplet cluster, and (3) the last period of \( 40 < t < 60 \) s without infrared heating.

Every part of the time dependence \( \tilde{S}(t) \) in Fig. 4 is almost linear and the rates of the droplet growth at the first and third periods are the same. It means that the droplet growth can be well described by the known d-squared law [15] or its modification called the elliptic law [16]. This appears to be true also in the case of infrared irradiation but the irradiation leads to a significant decrease in the growth rate of water droplets. The generalized experimental results can be found in recent paper [9]. It was shown that there is a simple linear dependence of \( \tilde{S}(W_{\text{IR}}) \) and one can obtain the value of \( W_{\text{IR}} \) which gives zero value of \( \tilde{S} \). It was shown that the ratio \( W_{\text{IR}}^0/W_0 \) is weakly sensitive to the laser power and can be estimated as follows [9]:

\[
W_{\text{IR}}^0 = W_{\text{IR}}^0/W_0 \approx 6\% \quad (3)
\]

### Fig. 3. Typical temperature profiles at the open water surface: 1 - \( W_0 = 208.6 \) mW, 2 - 297.1 mW, 3 - 411.4 mW.

### Fig. 4. Time variation of relative area of droplet surface \( \tilde{S} \) at the initial droplet radius of \( a = 17.1 \) \( \mu \)m: 1 - \( W_0 = 0 \), 2 - 9.3 mW, 3 - 19.1 mW, \( d_w = 300 \) \( \mu \)m [9,10].
Approximate relation (3) is convenient to obtain the required infrared radiation power to stabilize the levitating clusters at different conditions of the laser heating of water layer.

4. Temperature field calculations

It is difficult to formulate correctly thermal boundary conditions at the open surface of the evaporating water layer. Therefore, the temperature measurements for this surface are used to complete the conduction problem statement. The suggested approach can be treated as a combined method which enables one to obtain the temperature field in sitall plate and water layer and also the radial distribution of heat flux at the open water surface.

The steady-state temperature field in the computational region including the central parts of both the sitall substrate and the water layer is described by the following axisymmetric boundary-value conduction problem:

\[
\frac{\partial}{\partial r} \left( k \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) = 0 \quad 0 < r < R \quad 0 < x < D = d_s + d_w
\]

(4a)

\[
x = 0, -k \frac{\partial T}{\partial r} = \left\{ \begin{array}{ll}
h_1(T_{sat} - T) + q_{rad}, & r < r_1 \\
0, & r_1 \leq r < R \quad x = D, T = T_{exp} \\
\end{array} \right.
\]

(4b)

\[
r = R, \frac{\partial T}{\partial r} = 0 \quad r = 0, \frac{\partial T}{\partial r} = 0
\]

(4c)

where \( R = 6 \text{ mm} \) is the radius of the computational region and \( d_s = 0.5 \text{ mm} \) is the thickness of sitall plate. The thermal conductivity of substances is described by the following step-wise function:

\[
k(T) = \left\{ \begin{array}{ll}
k_s(T), & 0 < x < d_s \\
k_w(T), & d_s < x < D
\end{array} \right.
\]

(4d)

The thermal conductivity of sitall was assumed to be independent of temperature and equal to \( k_s = 1.4 \text{ Wm}^{-1} \text{K}^{-1} \) [117]. The dependence \( k_w(T) \) was obtained by a linear interpolation between the known values of \( k_w = 0.561 \text{ Wm}^{-1} \text{K}^{-1} \) at \( T = 273 \text{ K} \), \( 0.644 \text{ Wm}^{-1} \text{K}^{-1} \) at \( 323 \text{ K} \) and \( 0.679 \text{ Wm}^{-1} \text{K}^{-1} \) at \( 373 \text{ K} \).

Obviously, the laser irradiation takes place in the narrow region of \( r < r_1 \) only. The calculations showed that the use of constant value of the radiative flux, \( q_{rad} = W_{1L}(\pi T_1^4) \), is a good approach to the experimental conditions. The value of \( h_1 = 5 \text{ Wm}^{-2} \text{K}^{-1} \) obtained as an estimate for the stable stratification of air under the heated coating of the sitall plate was used in the calculations. Note that possible error in the \( h_1 \) value has a negligible effect on the computational results. The heat flux to be determined is calculated as follows:

\[
q_{w}(r, D) = -k_w \frac{\partial T}{\partial r} \bigg|_{x=0}
\]

(5)

The ordinary time-dependent technique with the uniform initial temperature \( T_0 = 295 \text{ K} \) and the so-called alternating-direction implicit finite-difference method [18–20] were employed to solve numerically the problem (4a–d). The same home code has been used in early papers by the second author on transient thermal state of solid-propellant rocket nozzles, in heat transfer analysis of possible severe accidents of nuclear reactors [21], and also in recent calculations of temperature field at a volumetric absorption of near-infrared radiation in human tissues during their thermal treatment [22]. The uniform rectangular grid with 65 axial and 100 radial intervals and an appropriate variable time step was used in numerical calculations of the present paper. The numerical results are shown in Figs. 5–7. One can see in Fig. 6 that calculated temperature of water at the surface of sitall plate at \( W_L = 411.4 \text{ mW} \) is a bit greater than the saturation temperature \( T_{sat} = 373 \text{ K} \). It means that water layer thickness should be reduced at laser power greater than about 400 mW.

The temperature fields (Fig. 5) and the radial profiles of temperature and heat flux at the water surface (Figs. 3 and 7) at different values of laser power are practically similar to each other. This observation makes possible to simplify the estimates of these profiles at intermediate values of \( W_L \).

5. The use of approximate similarity of temperature fields in analytical estimates

Strictly speaking, the conduction problem in not linear because of temperature dependence of thermal conductivity of water and not quite similar temperature profiles of water surface at various values of laser power. Typical profiles of temperature and heat flux at the water surface are compared in Fig. 8 using the following dimensionless functions:

\[
\theta(r) = \frac{T(r) - T(R)}{T(0) - T(R)} \quad \xi(r) = \frac{q_w(r)}{q_w(0)}
\]

(6)

One can see that the difference between the above introduced dimensional profiles is rather small even at very different values of laser power. It means that one can use analytical estimates of water temperature and heat flux for intermediate values of \( W_L \) using a linear interpolation between the profiles for minimum and maximum values of laser power:

\[
\theta|_{W_L} = \theta|_{W_L}^{min} + \left( \theta|_{W_L}^{max} - \theta|_{W_L}^{min} \right) \frac{W_L - W_L^{min}}{W_L^{max} - W_L^{min}}
\]

(7a)

\[
\xi|_{W_L} = \xi|_{W_L}^{min} + \left( \xi|_{W_L}^{max} - \xi|_{W_L}^{min} \right) \frac{W_L - W_L^{min}}{W_L^{max} - W_L^{min}}
\]

(7b)

One needs also a relation between the maximum values of temperature and heat flux at the water surface, \( T_{w}^{max} = T(0) \) and \( q_{w}^{max} = q_w(0) \), and the laser power to transfer from the dimensionless values of \( \theta(r) \) to the real temperature profile. An analysis of the experimental data enabled us to suggest the following analytical approximation for the dependence of \( T_{w}^{max}(W_L) \):

\[
T_{w}^{max} = T_0 + 15.6 W_L - 0.954 \frac{W_L}{W_1} \quad W_L = 100 \text{ mW}
\]

(8)

The following linear relation can be obtained from the computational results presented in Table 1:

\[
q_{w}^{max} = \xi W_L \quad \xi \approx 0.42 \cdot 10^{-3} \text{ m}^{-2}
\]

(9)

The errors of approximations (8) and (9) are less than about 5%, and one can easily obtain reliable estimates of the laser power effects on the key parameters of the process under investigation.

6. Effect of laser power on evaporation rate of water and size of levitating droplets

It is qualitatively clear that both the evaporation rate of water and maximum size of levitating water droplets increase with the local heating of water, i.e. with the power of incident laser beam. This statement has been confirmed in numerous laboratory experiments. At the same time, the evaporation and condensation processes in a combination with an upward flow of the steam–air mixture and formation of levitating cluster of water droplets are very complex and strongly interacting processes [23,24]. A complete picture could be clear only on the basis of the detailed physical and computational modeling.
Nevertheless, additional experimental data and their preliminary analysis is expected to be useful for better understanding some conditions at the interface of water layer and ambient gaseous medium. On the other hand, the experimental data for the levitating droplets are potentially interesting for validation of the elaborated computational models. Therefore, it seems correct to present here the experimental data for overall evaporation rate of water and also for maximum size of levitating droplets.

The system supporting the thickness of water layer was turned off to measure the reduction rate of the layer thickness, $d_w$. The initial value of $d_w = 152 \mu m$ and subsequent automatic measurements of $d_w$ during 250 s were used in this particular experiment.

These measurements were repeated three times at every of the above selected values of laser power. The resulting averaged values of $d_w$ are presented in Fig. 9 where the value of $d_w(W_L)$ corresponds to the case when the laser was turned off. It is a good surprise that dependence of $d_w(W_L)$ is well approximated by the following linear function:

Table 1

<table>
<thead>
<tr>
<th>$W_L$, mW</th>
<th>208.6</th>
<th>248.6</th>
<th>297.1</th>
<th>354.8</th>
<th>411.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{wmax}$, kW/m$^2$</td>
<td>87.29</td>
<td>99.62</td>
<td>125.7</td>
<td>156.7</td>
<td>180.9</td>
</tr>
</tbody>
</table>

Fig. 5. Calculated temperature fields at (a) $W_L = 208.6$ mW and (b) $W_L = 411.4$ mW.

Fig. 6. Temperature profile along the axis of the computational region: 1 – $W_L = 208.6$ mW, 2 – 297.1 mW, 3 – 411.4 mW.

Fig. 7. Radial profiles of heat flux at the open water surface: 1 – $W_L = 208.6$ mW, 2 – 297.1 mW, 3 – 411.4 mW.
The video records enabled us to measure the maximum radius of droplets just before the cluster collapse. This value is given in Table 2, but monotonic function $a_{\text{max}}(W_L)$ appeared to be not simple. Most likely, the radial flow rate of steam in the vicinity of water surface can be neglected. In this case, the mass balance at the interface can be written as follows:

$$\frac{d_w}{\mu m/s} = 0.016 + 3.8 \times 10^{-5} W_L \, [mW]$$

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Most likely, the radial flow rate of steam in the vicinity of water surface can be neglected. In this case, the mass balance at the interface can be written as follows:

$$\frac{d_w}{\mu m/s} = \frac{2}{\rho_w R^2} \int_0^R \rho_v(T_w) u_{w}(r)rdr$$

where $u_w$ is the initial normal velocity of steam. It is also assumed here that the density of water is constant in the temperature range typical of the heated water surface. Of course, the local density of steam, $\rho_v$, at atmospheric pressure can be easily determined. The integral Eq. (10) and approximate relation (9) are insufficient to retrieve the radial distribution of $u_w(r)$ without analysis of the variable evaporation conditions, but this can be done later to obtain one of the initial conditions for the flow-field problem to be solved for the region above the water surface.

7. Conclusions

A modified laboratory installation to generate levitating clusters of droplets above the locally heated water surface was presented. The laser-heated sitall plate with an opaque graphite coating was used as a substrate for the water layer which produces a levitating droplet cluster. The cluster was stabilized both thermally and mechanically with the use of infrared heating as was recently demonstrated by the authors.

A combined experimental and computational method was developed. The radial temperature profile at the open water surface was measured and then used as a boundary condition in heat conduction calculations. The numerical data for the steady-state axisymmetric temperature field in sitall plate and water layer as well as the radial profile of heat flux at the water surface were obtained.

Simple approximate relations were suggested for the local values of temperature and heat flux at the water surface. It is also interesting that evaporation rate is well described by a linear dependence on power of the heating laser radiation. The data obtained for the temperature and heat flux at the interface and also the relation for overall evaporation rate can be treated as important boundary conditions for the computational modeling to be developed for the upward steam–air flow and behavior of levitating clusters of water droplets in the most important range of local heating of water.

Conflict of interests

None declared.

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