Experimental studies of the evaporation of the spheroidal oblate water droplets in a single-axis non-resonant levitator

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Abstract: *This paper reports on experimental studies of the volume and the surface regression rate of the water droplets during evaporation in a single-axis non-resonant levitator. Spheroidal oblate water droplets with the volume in the range 3.5-4 □l were delivered manually through a capillary into one of the node points of the acoustic levitator. The obtained results clarly demonstrate that the evaporation process is not a completely linear function . It depends on the surface area of the droplet and therefore on the volume. The larger surface area leads to the faster evaporation of the droplets. Evaporation takes occurs at the surface of the liquid where some of the molecules with the highest kinetic energies are escaping into the gas phase. From the volume measurements, graphs were plotted. The evaporation graphs were fitted with regression lines trough the method of least squares and the speed of evaporation is estimated. The volume-equivalent diameter of the droplet follows the* D^2*-law. Based on the fit of the experimental data, the surface regression rates of the water droplets are determined. The changes of the aspect ratio of the droplet during time is also determined.*

Key Words: *acoustic levitation, evaporation, surface regression rate.*

1. INTRODUCTION:

Water evaporation has a significant influence on global warming, because water is the main greenhouse gas in the atmosphere [1-2]. The evaporation of drops and thus also their surface regression are influenced by many factors, such as, for example, the temperature of the drop and its surroundings and the pressure. Evaporation takes place at the surface of the liquid where some of the molecules with the highest kinetic energies are escaping into the gas phase.

In general, the evaporation processes of suspended liquid droplets in a gaseous environment can be described by a linear decrease of the surface area S with time t [3]:

$$S = S_0 - K \cdot t. \tag{1}$$

Evaporation takes place at the surface of the droplet, the process is dependent on the surface area of the droplet and therefore on the volume. Proportionality factor K in equation (1) is given by the relation [3]:

$$K = \frac{8\pi D_{ab} M}{\rho_l R}\left(\frac{P_s}{T_s} - \frac{P_\infty}{T_\infty}\right)\frac{Sh}{2}, \tag{2}$$

where ρ_l is the liquid density, M is the molecular mass, while D_{ab} is the binary gas-diffusion coefficient of the vapor in the surrounding gas. R is universal gas constant, Sherwood number Sh describing the ratio of mass transfer with and without convection in the gas, P is the partial vapor pressure and the temperature T at the drop surface (subscript s) and in the gaseous environment (subscript ∞). Within the stationary ultrasonic field in the acoustic levitator acoustic streaming leads to a higher mass transfer. When Sh number is a constant, the shrinkage of drops during evaporation, obeys the so called D^2-law [4]:

$$\frac{D^2(t)}{D_0^2} = 1 - K(t)\frac{t}{D_0^2}, \tag{3}$$

where D_0 and $D(t)$ are the initial and instantaneous drop diameters expressed in mm, respectively, t is time in seconds and $K(t)$ is the instantaneous surface regression rate in [mm^2/s]. When the drops analyzed in the node points of the levitator are elliptical, the volume-equivalent diameter D is computed as [5]:

$$D(t) = 2\sqrt[3]{s_L(t)^2 s_S(t)}, \tag{4}$$

where $s_L(t)$ and $s_S(t)$ are the lengths of the major and minor semiaxes of the fitted oblate ellipse. For a single compnent drops the surface regression rate is a constant.

Although models and theories of evaporation have been developed for over 100 years, experimental studies have lagged behind the theory [6-8]. Acoustic levitation is recognized as an efficient method for studying the evaporation of droplets without wall effects, which eliminates chemical and thermal contamination with surfaces [9-11]. Acoustic levitation has the potential to enable novel studies due to its ability to hold a wide variety of substances against gravity under container-less conditions.

In this paper we present our novel experimental results for the time dependent volume and the surface regression rate during evaporation of levitated water drops. Measurements were performed by using TinyLev acoustic levitator that composed of 72 simple ultrasonic emitters [12]. The average evaporation speed of water was calculated from the fit with regression lines. The surface regression rate is estimated from the slope of the curve showing $D^2(t)/D_o^2(t)$ as a function of $t/D_o^2(t)$. The aspect ratio of the droplet during evaporation is also determined.

2. EXPERIMENTAL SET-UP:

Measurements were performed by using a single-axis non-resonant levitator made with off-the-shelf low-cost components and shown in Figure 1. The TinyLev levitator produces stable trapping, is robust to changes in temperature and humidity and can operate for extended periods of time. The main components of the levitator are the transducers, elements that transform the electrical input signal into acoustic waves. The TinyLev levitator operates at voltage of 10V and frequency of 40 kHz which allows the levitation of samples of up to ≈4 mm. Detailed descriptions of used acoustic levitator is provided in reference [12].

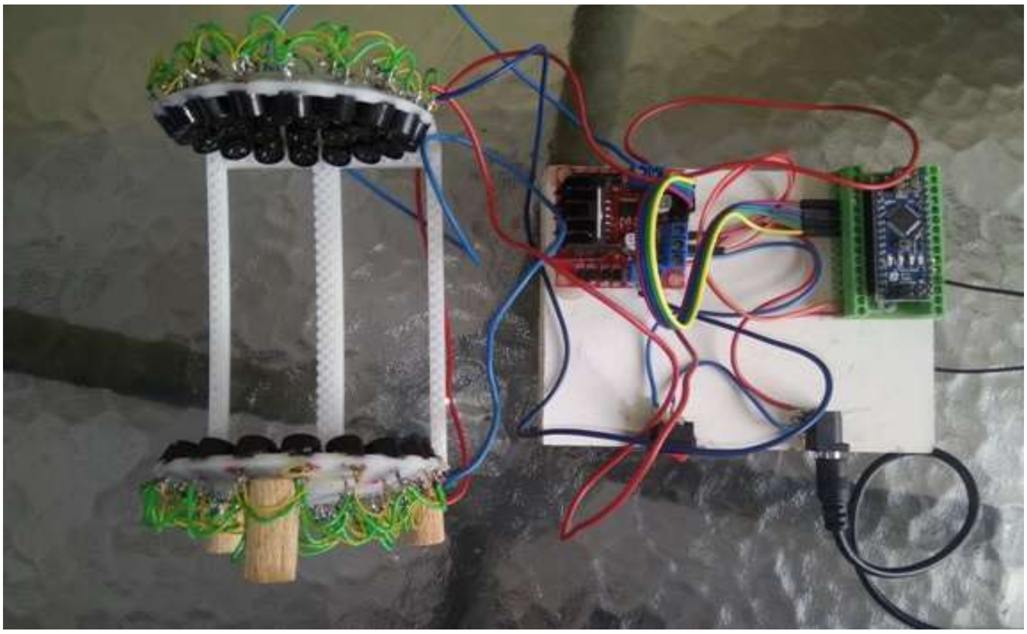

Figure 1. Experimental set-up composed of the driver board and 72 transducers asembled in accordance with instructions described in [12].

Evaporating water drops were delivered manually through a capillary into one of the node points of the acoustic levitator. 5 sets of measurements were carried out inder ambient pressure and the ambient temperature in the range from 20 ºC to 25ºC. The volume of the initial droplet was in the range from 3.5 to 4 μl. For each drop measurements were recorded by camera during 40 minute. Than, for the time interval of 300 s, frames are extracted by *Moviemaker* and than opened in *Paint* in order to determine lengths of the large and small semiaxis. Dimensions of the drop were determined by positioning above polystiren ball with know dimesnions.

3. RESULTS:

In order to find a reliable evaporation speed, droplets of different volumes were studied one by one. From the volume measurements graphs were plotted in Figure 2 showing the time dependence of the water droplet volume during evaporation process. Since evaporation occurs at the surface of the droplet, the process is dependent on the surface area of the droplet and therefore on the volume. As the evaporation time increases, the droplet volume decreases, but it is not a completely linear function. At the beginning evaporation curves is steeper which means a higher evaporation rate than the rest of the curve.

The evaporation graphs were fitted with regression lines trough the method of least squares. Table I shows the results for the five individual water droplets. An average speed of evaporation is $(10.3\pm0.4)\,\mathbf{x}10^{-4}$ μl/s. The appearance of the graphs showed similar characteristics which was a good sign for the reproducibility of volume measurements. When the drop evaporates it becomes smaller, the surface tension force becomes more dominant than the acoustic radiation stress and the droplet gets more spherical.

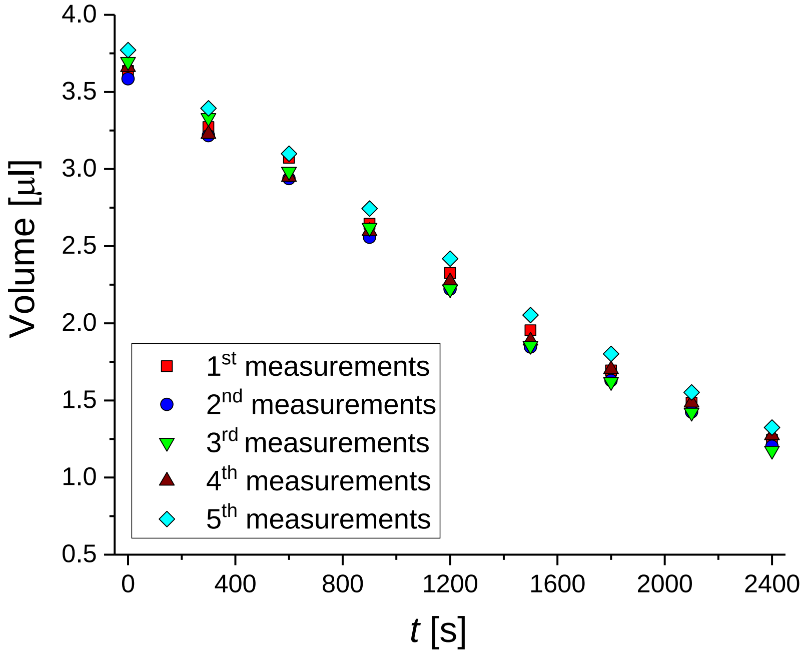

Figure 2. The droplet volume as a function of time during the evaporation.

	1st measurement	2nd measurement	3rd measurement	4th measurement	5th t measurement
Function of the regression line	y=-10.2E-4*x* + 3.59	y=-10.1E-4*x* + 3.51	y=-10.7E-4*x* + 3.61	y=-9..99E-4*x* + 3.54	y=-10.3E-4*x* + 3.70
R^2	0.98733	0.98877	0.98753	0.98618	0.99414
Evaporation speed [μl/s] x10^{-4}	**10.2**	**10.1**	**10.7**	**10.0**	**10.3**

Table 1. Regression line and speed of evaporation corresponding data shown in Figure 2.

Figure 3 shows $D^2(t)/D_o^2(t)$ versus $t/D_o^2(t)$ for the water droplets. The lines result from fits of equation (3) to the data points shown in Figure 2. The volume-equivalent diameter D is determined by using equation (4). From the slopes of the presented graphs, the surface regression rates are obtained and listed in Table 2. As expected, for a single compnent drops the surface regression rate is a contant. From our measurements we obtained an average value of the surface regression rate of $(6.9\pm0.6)\,\mathrm{x}10^{-4}\mathrm{mm}^2/\mathrm{s}$.

Finally, the aspect ratio (the length of the major semiaxis to the length of the minor semiaxis) as a function of time is depicted in Figure 4. As expected, during evaporation, the aspect ratio decreases and approaches 1 corresponding to the changes of the drop's shape from oblate eillipsoid to sphere. It could be explained by the fact that the droplet becomes smaller during evaporation, so the surface tension force becomes more dominant than the acoustic radiation stress and the droplet gets more spherical.

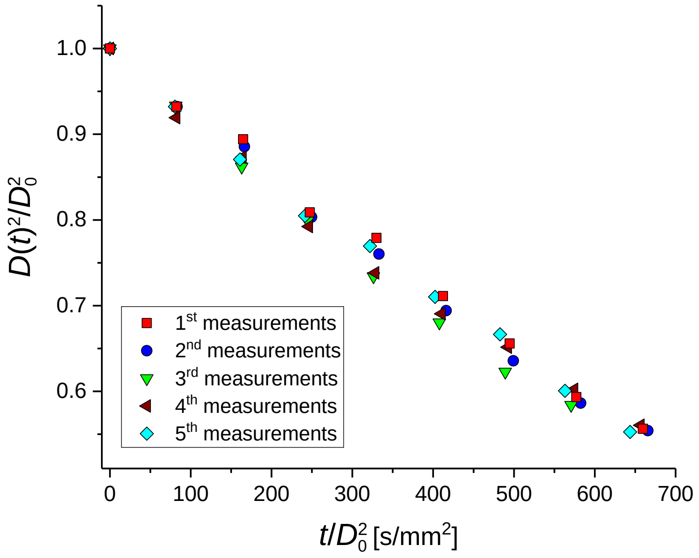

Figure 3. D^2-law in accordance with equation (3) for the water droplets.

	1st measurement	**2nd measurement**	**3rd measurement**	**4th measurement**	**5$^{th\ t}$ measurement**
Fitting line	y=-6.8E-4*x* + 0.99443	y=-6.9E-4*x* + 0.98996	y=-7.5E-4*x* + 0.9893	y=-6.6E-4*x* + 0.97565	y=-6.8E-4*x* + 0.98657
R^2	0.99527	0.99344	0.99574	0.98674	0.99599
Surface regresion rate [mm^2/s] x10^{-4}	**6.8**	**6.9**	**7.5**	**6.6**	**6.8**

Table 2. Fitting line and surface regresion rate corresponding data shown in Figure 3.

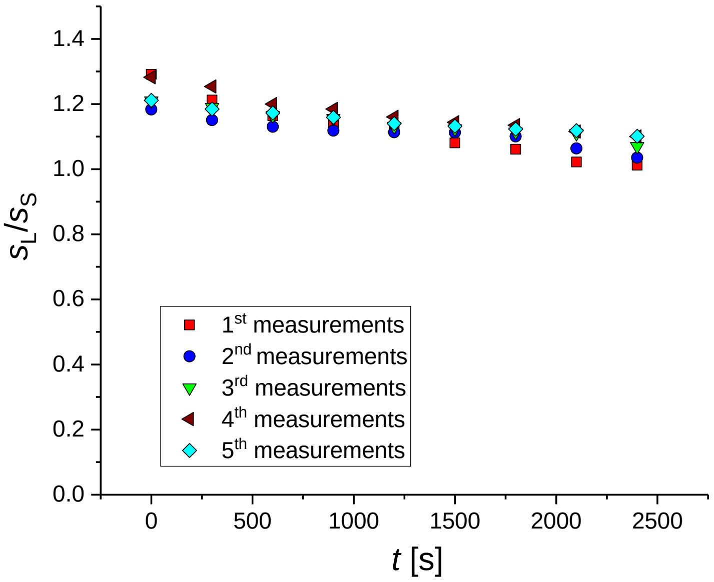

Figure 4. The dependence of the aspect ratio of the water droplets during evaporation.

4. CONCLUSIONS:

Despite the facts that numerous models and theories of evaporation have been developed, experimental studies have lagged behind the theory. In this paper the acoustic levitation technique was used to investigate the evaporation of an spheroidal oblate water droplets. Measurements were performed by using a single-axis non-resonant levitator standard atmospheric pressure and varying the ambient temperature from 20 ^oC to 25^oC. Individual droplets are gently placed in a node by a needle and recorded by the camera. From the lengths of the major and minor semiaxes volume of the droplet is calculated. The evaporation graphs were fitted with regression lines trough the method of least squares. We got an average speed of evaporation of $(10.3 \pm 0.4)\,x10^{-4}\mu l/s$. The evaporation follows the D^2-law. Based on the fit of the experimental data an average surface regression rate of $(6.9 \pm 0.6)\,x10^{-4} mm^2/s$ has been estimated. During evaporation, the aspect ratio of the water droplets tends to 1. The obtained results are in line with the expectations confirming that the acoustic levitation is an efficient method for studies of the droplet evaporation.

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