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Experimental investigation of the evaporation of droplets in diamagnetic levitation

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The time evolution of levitating pure water and water-ethanol droplets is investigated. Droplets are trapped in stable diamagnetic levitation in the magnetic well produced by a cylindrical permanent magnet. Radius of evaporating droplets and their temperature differences with air are monitored over time using a thermographic camera.

Experimental set-up

A cylindrical permanent magnet made by 8 NdFeB sectors with radial magnetization and covered by a pole piece (Figure 1(a)) is used to trap diamagnetic droplets in levitation. A screwed brass base maintains all the NdFeB sectors together. In addition, a cylindrical hole of 1.6 mm diameter is realized along the symmetry axis of this set up. The gap between the sectors and the pole piece is adjusted in order to produce a potential well where diamagnetic levitation can be achieved [1,2].

Droplets are generated by a piezoelectric jetting device. It consists of a tiny glass tube covered with a piezoelectric ceramic (Figure 1(b)). A capillary transports the liquid solution from a 15 mL test tube to the glass tube. The applied potential in the piezoelectric ceramic is computer-controlled. As the ceramic shrinks, pressure builds up in the glass tube and a jet of microdroplets (*i.e.* droplets with a radius of few tens of micrometers) is ejected from the tube nozzle (Figure 1(b)). The ejection energy depends upon the applied potential and therefore determines the properties of the jet. The main difficulty in this procedure consists in the requirement for microdroplets to fall into the magnetic well. As the jet is extremely sensitive to disturbances of environment, it tends to behave randomly. A confinement facility is used to limit this drawback. Once microdroplets are trapped in the magnetic well, they spontaneously coalesce after few seconds and form larger droplets. When millimeter-sized droplets are produced (*i.e.*, with a radius larger than 200 μm), the jetting is stopped.

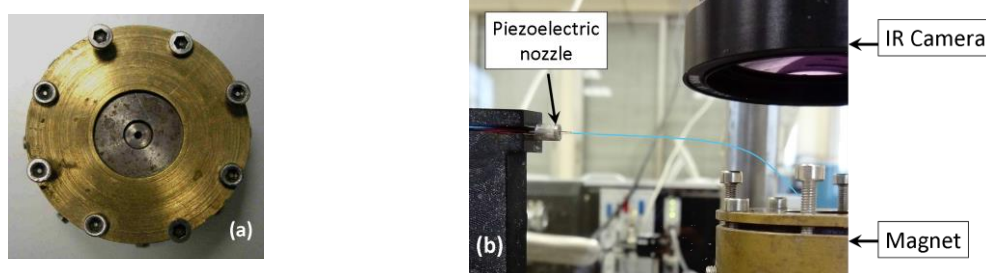


Figure 1. (a) Top view of the permanent magnet. (b) Experimental set-up made of a piezoelectric nozzle, the magnet and a thermographic camera. The microdroplet jet from the piezoelectric nozzle to the magnetic levitation site is schematically plotted with a full blue line.

A thermographic camera placed above the magnetic levitation site captures infrared (IR) radiation emitted by the droplet in the spectral wavelength range from 7 μm to 10 μm . It records a field of view (FOV) of $\sim 2.0 \text{ mm} \times 1.6 \text{ mm}$ and allows measuring the droplet size as well as the intensity of emitted IR radiation over time. Images are grabbed on a 160 x 128 matrix of sensors and post treated with the ImageJ software. The spatial resolution is about 12.8 μm . Thermography measurements depend on the IR emissivity and observation angles. Accessing to the temperature field in the full FOV is therefore not straightforward (although sensitivity of the camera is less than 20 mK), especially for ethanol that is transparent in the considered spectral range.

Used liquid solutions comprise pure water and water/ethanol mixtures (20%, 40%, 60% and 80%, 96% v/v). Water is deionized. In order to achieve a better reproducibility, experiments were carried out several times for each solution. Room temperature T and humidity H are $20 \pm 3 \text{ }^\circ\text{C}$ and $30 \pm 5\%$, respectively.

Results

Depending upon composition and size, droplets evaporate in periods of time ranging from seconds to hours. Evaporation time may be strongly affected by working conditions and in particular by the saturation of ambient air with the solution vapor. Controlling experimental conditions is therefore of fundamental importance and that is why experiments were repeated up to ten times.

Figure 2(a) presents a typical image of a levitating droplet right after creation. As temperature conditions are almost isothermal, color contrasts are low but the droplet is still clearly visible. Its diameter can therefore be evaluated and followed over time. For water/ethanol mixtures initial contrasts are usually worse due to transparency of ethanol. But, as time runs, evaporative cooling comes into play and temperature difference with the environment increases. Droplets become then clearly observable and their diameter easy to measure as illustrated in Figure 2(b).

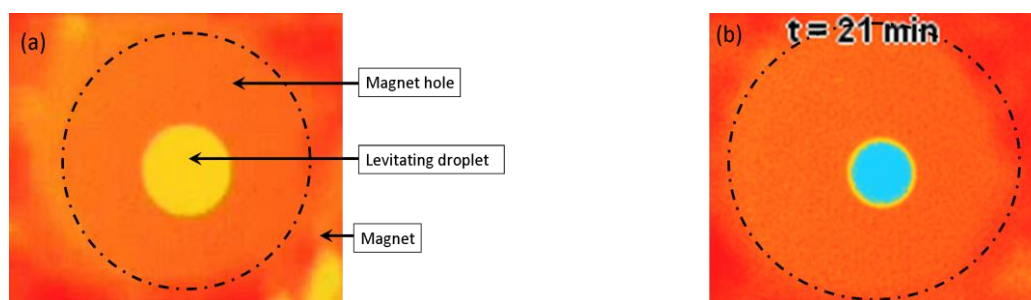


Figure 2. Thermographic images of levitating droplets. (a) A levitating water droplet ($r \approx 500 \mu\text{m}$) right after formation. Dashed circle indicates the border of the 1.6 mm-large magnet hole. (b) A levitating water/ethanol droplet (96% v/v ethanol) 21 minutes after its formation.

Figure 3 shows the time evolution of the volume $V(t)$ of a water and a water/ethanol (40% v/v) droplet in comparable working conditions with initial volume $V(0) \approx 0.04 \mu\text{L}$. Evaporation time t_{evap} is defined from a linear fitting as illustrated in this figure. As expected, ethanol mixtures evaporate faster than pure water droplets ($t_{\text{evap}} \approx 470 \text{ s}$ for 40% ethanol, $t_{\text{evap}} \approx 610 \text{ s}$ for pure water).

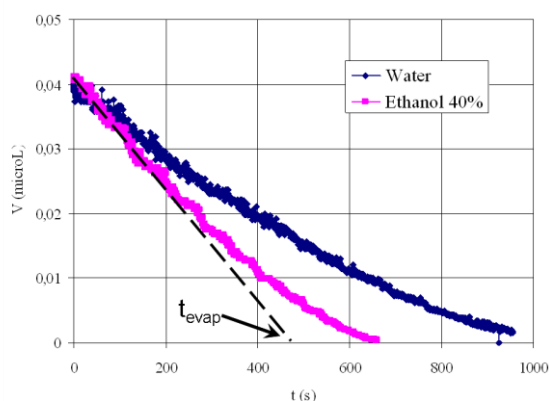


Figure 3 : Typical volume evolution $V(t)$ of a water and a water/ethanol (40% v/v) droplet. Initial volume $V(0) = 0.04 \mu\text{L}$, $T = 20,5^\circ\text{C}$ and $H = 27\%$. The dashed line is a fitting (for $t < 150 \text{ s}$ of the water/ethanol mixture) that defines evaporation time t_{evap} .

Conclusions

Diamagnetic levitation makes possible contactless experiments with evaporating droplets of deionized water and water/ethanol mixtures. Thermography has been used to follow the time evolution of droplet volume. Evolution of the IR signals captured by the camera indicates clear qualitative changes in the droplet temperature. However, they have not been fully exploited so far. Main limitation here is the non-trivial relation between angle-dependent IR emissivity of the droplets and their temperature. Despite this limitation, occurrence of evaporative cooling regimes could be detected and their influence on the overall mass flow quantitatively addressed.

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