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Supporting Information

Thermal Marangoni trapping driven by laser absorption in evaporating droplets for particle deposition

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In this supplementary information, we present additional data about laser characterization, temperature measurements, data dispersion and hydrodynamic equations. The ESI are organized in four sections as follows :

Section 1- Laser characterization

Section 2- Temperature measurements and calibration

Section 3- Discussion about data dispersion

Section 4- Models and equations

1 Laser characterization

A sketch of the experimental set-up is presented in figure S1-a. The infrared ($\lambda = 1470 \ nm$) laser beam is sent in the objective O_L (x2.5 Zeiss NA = 0.075 or x8 Nachet NA = 0.25). A beam profiler (DataRay Beam R'2) is placed on the beam trajectory and can be translated along the propagation axis (z). The beam profiler allows to map the intensity profile along the transverse plan (x,y) as illustrated by the images in figure S1-a. 2D-plot profiles at the laser focus are shown in figure S1-b for the renormalized intensity. Those profiles are well fitted by a Gaussian function : $I/I_0 = e^{-2r^2/w_0^2}$ whose width here is $w_0 = (320 \pm 10)\mu m$. Both directions x and y seem to have the same profile.

For a gaussian beam propagating along the z direction, it is possible to define the laser spot size w via the intensity profile :

$$I(r,z) = \frac{2P}{\pi w^2(z)} e^{-\frac{2r^2}{w^2(z)}}$$
(1)

where P is the incident laser power and r is the radial coordinate. The infrared laser is a high power laser diode and is not a perfect gaussian beam. It results that the size of the laser spot (waist) evolves along its propagation (z) due to diffraction as :

$$w^{2}(z) = w_{0}^{2} + \left(\frac{M^{2}\lambda}{\pi w_{0}}\right)^{2} (z - z_{0})^{2}$$
⁽²⁾



Figure 1: Laser's profile characterization. **a**) Sketch of the experimental set-up. The laser focus and divergence along the vertical axis are characterized by a beam profiler after passing through a microscope objective O_L . **b**) 2D plots of the laser intensity profile given by the beam profiler in a). A gaussian function fits $I/I_0 = e^{-2r^2/w^2}$ well the experimental data. **c**) The width of the gaussian fit versus the axial position, for a given power, where the origin is placed at the exit of O_L . **d**) The width of the gaussian fit versus the laser power for a given position. It does not depend on the power.

where w_0 is the laser waist (smallest laser size), z_0 the focus position, λ the wavelength, and M^2 is the beam quality factor ($M^2 = 1$ for perfect Gaussian beams). The two first parameters depend on the microscope objective, while the last ones depend on the laser quality. In our case, the laser beam is not a perfect Gaussian beam and the M^2 factor has to be taken into account.

To characterize each parameter, images of the intensity profile were taken, at a given power, for various z positions. We then extract for each image, the size w(z) and we plot w(z) versus z as shown in figure S1-c for the x2.5 objective. As expected, the same behaviour is observed for both x and y directions so the beam does not present any radial asymmetry. A general fit following equation (2) allows to get all laser's divergence parameters. For both objectives, we get : $M^2 \approx (28 \pm 2)$ even if each objective has a specific waist and a specific working distance as summarized in Tab S1.

Parameter / Objective	$w_0 \ (\mu m)$	$\Delta w_0 \; (\mu m)$	$z_0 \ (mm)$	$\Delta z_0 \ (mm)$
x2.5 Zeiss, NA = 0.075	320	10	9.4	0.3
x8 Nachet, NA = 0.25	110	15	2.5	0.5

Tab S1 : Summary of the various laser waists depending of the objectives used this work.

2 Temperature measurements and calibration

We used two methods to measure temperature : 1) we first used a method based on a thermosensitive fluorescent probe with Rhodamine B, 2) secondly, we used an infrared camera to characterize the temperature field.

2.1 Temperature measurement with RhB

2.1.1 Calibration of RhB

We first used Rhodamine B as a thermo-sensitive fluorescent dye to characterize the temperature rise induced by laser absorption.

Rhodamine B is prepared at 50 mg/L in an aqueous buffer (pH = 7) solution composed of HEPES at $50 \ \mu M$ (all purchased from Sigma-Aldrich, France). Its molecular structure allows fluorescence, but its quantum yield depends on the temperature [1]. A sketch of the calibration set-up is depicted in figure S2-a. A thin layer of Rhodamine B solution is confined between two microscope glass slides which are separated by spacers (H = 1 mm). The sample is heated by a Peltier system, and is imaged with an inverted fluorescent microscope. A thermocouple is placed directly inside the liquid layer to measure the temperature of the sample. The higher the temperature is, the darker the sample is. This is illustrated in figure S2-b where the intensity profile, initially homogeneous, is modified by the local laser heating. To avoid any effects due to inhomogeneous illumination, the measured intensity I of each pixel is renormalized by a reference fluorescent intensity I_0 defined as the intensity without heating, *i.e.* $I(T = T_{amb} = 20^{\circ}C = I_0)$, as shown in figure S2-c.

2.1.2 Temperature measurements inside RhB droplets

As this procedure was accurate enough for the case of thin liquid layers [2] and gave temperature profiles associated to standard Lorentzian functions, we tried to extend it to the case of droplets as shown in figure S3-a. As expected, the temperature field is still well fitted by a Lorentzian function as shown in figure S3-b. It is then possible to define a thermal width σ . However, this is only the case in the early stages of the evaporation process. The plot of the



Figure 2: Fluorescent thermo-sensitive dye Rhodamine B temperature calibration. **a**) Sketch of the experimental set-up : a layer of Rhodamine B solution is confined between two glass slides separated by H = 1 mm spacers. This layer is heated by a Peltier system, and is imaged by the inverted microscope. The temperature is simultaneously measured by a thermocouple. **b**) Images of Rhodamine B without and with the laser heating. Darker regions represent higher temperatures. Scale bar = 200 μm **c**) Calibration of the temperature against renormalized fluorescent intensity, where I_0 is the fluorescent intensity measured at ambient temperature $T_a = 20^{\circ}C$.

normalized thermal width $\tilde{\sigma}/R$ versus time t is shown in figure 3-c. As expected, the width increases until a time t_T associated to the transient time of heat diffusion $(t_T \sim H^2/\kappa_T)$, where $H \approx 100 \ \mu m$ and $\kappa_T \approx 10^{-7} \ m^2/s)$, and then it remains constant. However, from the time t_m , Marangoni flows appear and modify the measured fluorescent intensity distribution. The thermal width is then ill-defined as shown in figure S3-c.

This procedure is then not accurate enough for the case of evaporating droplets. However, at early times, the measured thermal width is similar to the one measured with the infrared camera (see main text).

2.2 Temperature calibration of the infrared camera

We first calibrate the infrared camera in order to take into account the emissivity of water (as particles are at low fraction, their influence is negligible), and to take into account the inclination angle of the camera φ which is imposed by geometrical constraints of the experiment setup. To do this calibration, a beaker of water is heated homogeneously by a heating plate combined with a magnetic stirrer. The infrared camera, with its objective, images the temperature of the interface. The camera is tilted by an angle φ from the vertical axis. Simultaneously, a thermocouple measures the temperature just under the interface as sketched on figure S4-a.



Figure 3: Temperature measurement with Rhodamine B of 0.1 μL droplet under laser irradiation with $P_{in} = 120 \text{ mW}$ and $w_0 = 110 \mu m$. a) Image sequence of the evaporation of the drop. The intensity decreases at the laser spot. The intensity profile can also be modified by Marangoni flows as observed in the third picture. b) The temperature profile measured at early times, at $t = t_T$: before Marangoni flows are well set. A Lorentzian fit can describe data at early times. c) Lorentzian width against time. As shown in the main text, the thermal width remains constant after a transient time t_T , but after a time t_m Marangoni recirculating flows disturb fluorescent distribution.

Figure S4-b shows the comparison between the thermocouple temperature and the arbitrary intensity measured by the IR camera. This intensity corresponds to a mean value obtained from ten images taken in 1s. This plot compares the initial calibration provided by the software (identified as $\varphi = 0^{\circ}$), and the experiment performed for $\varphi = 55^{\circ}$ (to get close to our experimental conditions). Both data are quite similar but a slight deviation appears when the temperature increases.

Despite a slight deviation (smaller than 10%) at a temperature near $50^{\circ}C$, which is generally the highest temperature rise induced in our experiment, we conclude that the inclination angle of the IR camera does not significantly affect the measured temperature.

3 Discussion about data dispersion

In this part, we present a study about the dispersion of data. We identify three main sources of dispersion that could explain the dispersion of our data for the Marangoni radius presented in



Figure 4: Calibration of the temperature measured by the infrared camera. **a**) Sketch of the experimental set-up. A beaker of water is heated by a hot plate. The infrared camera records 10 images in 1s of the temperature at the interface, under an angle φ from the vertical axis, which gives a mean detected intensity I (arbitrary). A thermocouple placed just under the interface gives the temperature of the imaged region. Experiments were performed for $\varphi = 55^{\circ}$. **b**) Temperature measured against arbitrary measured intensity. The initial calibration of the camera is represented by blue circles and is performed at $\varphi = 0^{\circ}$. The experiment represented by red triangles is performed at $\varphi = 55^{\circ}$ in order to get close to the experimental conditions of our study.

the main text. The three main sources of dispersion for the Marangoni radius r_m are :

- 1. dispersion of the initial drop radius due to drop deposition
- 2. ellipticity of the deposited drop
- 3. dispersion of the initial drop radius and initial height due to thermal expansion after laser absorption

3.1 Dispersion due to the initial drop radius

First, we present in this part a study about the dispersion of the initial contact line radius R of the colloidal suspension (water + 1 μm fluorescent latex particles at 0.1% wt). We plot in figure S-5a the initial drop radius for 80 depositions with similar conditions : same ambient conditions with $RH = (50\pm5)\%$, same deposited volume $V = 0.1 \,\mu L$ with a $5\mu L$ -syringe from SGE (precision : 2%) and same substrate properties (microscope glass slide from MENTZEL GLASER cleaned with (Acetone + Water + Ethanol + Argon drying jet) repeated twice). The average contact line radius is around $R = (750 \pm 80) \,\mu m$. The standard radius deviation is about 10%. This deviation comes from the uncertainty on the deposited volume and the variation of the substrate wetting properties due to the cleaning process. It results that the initial contact angle and especially the initial drop's apex height h_0 are affected by this dispersion. However, as we

use in our analysis the initial absorbed power as $P_{abs} = P_{in}(1 - e^{-\beta h_0})$ where P_{in} is the injected power and $\beta = 2354 \ m^{-1}$ is the absorption coefficient at the laser wavelength ($\lambda = 1470 \ nm$), where h_0 is deduced from the measured radius, we do not expect a strong dispersion of our data due to this effect.



Figure 5: Data dispersion of several parameters. **a**) Dispersion of the initial drop radius R. N represents the number of experiments. Only the experiment with $V = 0.1 \ \mu L$, $w_0 = 320 \ \mu m$ and RH = 50% is shown here. The average contact line radius is $R = (750 \pm 80) \ \mu m$ which corresponds to approximatively 10% of standard deviation. **b**) Spreading ratio defined as contact line radius after early heating stage divided by the contact line radius before switching on the laser versus the initial absorbed power : $P_{abs} = P_{inj}(1 - e^{-\beta h_0})$ for several experimental conditions (V, w_0, RH) . No additional spreading effect appear for $P_{abs} < 30 \ mW$. **c**) Dispersion of the ellipticity of R (blue circles) and r_m (red triangles) for the same experiment as a). The ellipticity is defined here as the ratio of the absolute difference between both axis divided by the sum of both axis. No correlation is revealed. **d**) Ellipticity of the Marangoni trapping zone versus the ellipticity of the drop for the same experiment as a) and c) and the same definition proposed in c). No correlation is observed.

3.2 The role of the ellipticity

In this part, we investigate the influence of the ellipticity of the drop and/or the ellipticity of the Marangoni zone as a source of dispersion of data. The ellipticity is defined here as the ratio between $R_{max} - R_{min}$ and $R_{max} + R_{min}$ where $R_{max} (R_{min} \text{ respectively})$ is the maximum (minimum respectively) initial contact line radius (the contact line radius is then $R = \sqrt{R_{max}R_{min}}$). Despite precautions to deposit the drop on the substrate, the deposition might not be perfect and leads to ellipsoidal drop. Figure S5-c shows the dispersion of the initial ellipticity of the drop for the same experiment described previously. In the same figure, the ellipticity of the Marangoni radius is also shown. We note that these ellipticities are small, indicating almost circular drop and circular Marangoni region. In addition, Figure S5-d shows that the Marangoni zone ellipticity and the drop ellipticity are not correlated. This shows that the ellipticity of the drop does not affect the ellipticity of the Marangoni zone. This can be explained by the fact that the Marangoni recirculating zone is essentially created at the center of the drop and is not affected significantly by the edge of the drop. We conclude that this effect is not the main source of dispersion of our data.

3.3 Dispersion of data due to thermal expansion

Another phenomenon must be taken into account to explain the dispersion of our data. When the injected power increases, and so the absorbed power, the temperature rise increases, which decreases locally the surface tension. When the absorbed power typically exceeds $30 \ mW$, the change in surface tension is strong enough to induce a new spreading of the drop. It results that the drop spreads and its initial drop radius is increased. Generally, this second stage spreading ends up after the first 2s of the laser heating. However, as the absorbed power increases, the dilatation ratio - defined as the ratio between the maximum value of R and its initial value increases. For strong absorbed power, the contact line radius can show an increase of 10%, and so an increase of the drop apex height of 20%. This quasi-instantaneous change in the drop geometry induces a strong decrease of the absorbed power which results in a dispersion of the Marangoni radius.

We conclude that thermal expansion is one of the significant source of data dispersion. However, others effects (off-centred laser, ellipticity, humidity, etc.), even small individually, add all together their contributions and lead to a general dispersion of data as presented in the main text. A more detailled analysis of these dispersion effects should be performed in order to optimize the final deposit.

4 Equations

In this part, we recall some useful equations from Hu and Larson's work [3, 4, 5, 6].

4.1 Evaporation driven flows in the case of pinned contact line with small contact angles : hypothesis and classical expression

Hu and Larson's calculations on evaporation driven flows are valid under several approximations. The first one is that the evaporation is a consequence of the diffusion process of the solvent (water) in the atmosphere. In this approximation, neither kinetic [7, 8] nor convective effects [9, 10] are taken into account, and diffusion transport is considered as quasi-stationary. The second one is that the contact line is pinned, meaning that only the drop apex height h_0 decreases over time due to mass conservation. Moreover, the drop radius R is smaller than the capillary length, meaning that the drop's profile is a spherical cap. Then the third one is that the initial contact angle θ is small. This assumption leads to h << R and allows to solve the problem in the lubrication approximation, with a drop profile : $h(r,t) = h_0(t) \left(1 - \left(\frac{r}{R}\right)^2\right)$, where $h_0(t) \approx R \frac{\theta(t)}{2}$. Finally flows are assumed to be incompressible (Boussinesq approximation) in a viscous (no slip condition) regime.

The conservation equation averaged over the drop thickness is:

$$\frac{\partial h}{\partial t} + \vec{\nabla} \cdot (h\vec{v}) = -\frac{J}{\rho} \tag{3}$$

which gives a radial velocity profile :

$$u_{r,e} = \frac{3}{8} \frac{R}{t_f} \frac{\frac{R}{r}}{1 - \frac{t}{t_f}} \left(1 - \left(\frac{r}{R}\right)^2 - \left(1 - \left(\frac{r}{R}\right)^2\right)^{-\lambda(\theta)} \right) \left(\left(\frac{z}{h(r)}\right)^2 - 2\frac{z}{h(r)} \right) + \frac{rh(r)}{R^2} \frac{dh_0}{dt} \left(\frac{J_0 t_f}{\rho h_0} \lambda(\theta) \left(1 - \left(\frac{r}{R}\right)^2 \right)^{-\lambda(\theta) - 1} - 1 \right) \left(\frac{z}{h(r)} - \frac{3}{2} \left(\frac{z}{h(r)}\right)^2 \right)$$
(4)

where $\lambda(\theta) = \frac{1}{2} - \frac{\theta}{\pi}$, coming from the evaporation rate : $J = J_0 \left(1 - \left(\frac{r}{R}\right)^2\right)^{-\lambda(\theta)}$ where J_0 is a constant : $J_0 \approx \frac{Dc_s(1-RH)}{R}(0.27\theta^2 + 1.3)$. Note that in our experimental conditions $0.27\theta^2 \ll 1$ and $\lambda(\theta) \approx 0.5$. Here *D* is the diffusion coefficient of the solvent in the atmosphere : $D = 26 \ mm^2/s$ for water in the air, c_s is the saturated concentration : $c_s = 2.3 \ 10^{-2} \ kg/m^3$ for water, and *RH* the relative humidity rate. In the equation (4), ρ denotes the liquid's volumic mass, while the loss rate dh_0/dt is constant. This means that the drop apex decreases linearly, giving : $\frac{dh_0}{dt} \approx -\frac{h_0}{t_f}$. Conservation equation leads to define the evaporation time : $t_f \approx \frac{h_0\rho}{J_0}$.

The axial velocity field is given by the local incompressibility equation $\vec{\nabla} \cdot \vec{u} = 0$ in cylindrical coordinates :

$$\frac{1}{r}\frac{\partial(r u_r)}{\partial r} + \frac{\partial u_z}{\partial z} = 0$$
(5)

4.2 Marangoni effect

4.2.1 Thermal effects and Marangoni flows

The laser absorption induces a thermal gradient which can be well described by a Lorentzian function :

$$\Delta T = \frac{\Delta T_m}{1 + \left(\frac{r}{\sigma}\right)^2} \tag{6}$$

This temperature gradient induces viscosity gradient $\eta(T)$, density gradient $\rho(T)$ and surface tension gradient $\gamma(T)$.

The first effect has already been studied by *Weinert et al.* [11, 12]. They showed that thermoviscous effect engender the motion of the fluid only if it is coupled to gravitational effects and if the heating source is moving inside the liquid, which it is not the case here. So thermoviscous effect is negligible.

The thermogravitational effect has also already been studied by Riviere and al. [2] but in the case of a confined fluid. However, in the case of a layer with a free interface, this effect is added to thermal Marangoni effect. As Reynolds number is low : $Re \sim \frac{\rho U h_0}{\eta} \approx 0.1$ for water with a typical drop's apex height of $h_0 \approx 100 \ \mu m$ and a typical velocity $U \approx 100 \ \mu m/s$, the system is described by the linear Stokes equation :

$$\eta \Delta \vec{u} = \vec{\nabla} P - \rho \vec{g} \tag{7}$$

In the incompressibility and lubrication regime ($h_0 \ll R \ll u_r \gg u_z$), it is possible to derive both individual expression with the following conditions :

- no-slip condition on the substrate : u(z = 0) = 0
- mass conservation : $\int_{z=0}^{z=h} u_r dz = 0$

- for gravitational effects : stress cancellation at the interface : $\left(\frac{\partial u_r}{\partial z}\right)_{z=h} = 0$

- for Marangoni effect: gravity suppression in Stokes' equation and stress continuity at the interface : $\eta \left(\frac{\partial u_r}{\partial z}\right)_{z=h} = \frac{d\gamma}{dr}$

Hence, the thermogravitational velocity is expressed by :

$$u_{r,g} = \frac{\rho_0 \alpha g}{12\eta} h(r)^3 \frac{\partial T}{\partial r} \left(2\left(\frac{z}{h(r)}\right)^3 - \frac{15}{4}\left(\frac{z}{h(r)}\right)^2 + \frac{3}{2}\left(\frac{z}{h(r)}\right) \right)$$
(8)

while the thermocapillary velocity is :

$$u_{r,m} = \frac{\Gamma}{2\eta} h(r) \frac{\partial T}{\partial r} \left(\frac{3}{2} \left(\frac{z}{h(r)} \right)^2 - \left(\frac{z}{h(r)} \right) \right)$$
(9)

where $g = 9.81 \ m/s^2$ the gravitational field, $\rho_0 = 10^3 \ kg/m^3$ the ambient density of water,

 $\eta = 10^{-3} Pa$ the water viscosity, $\alpha = -1.77 \ 10^{-3} \ K^{-1}$ the water dilatation coefficient, and $\Gamma = \frac{d\gamma}{dT} = -1.6 \ 10^{-4} \ N/m/K.$

Both effects are in the same direction because $\alpha < 0$ and $\Gamma < 0$ meaning that, without evaporation, the fluid goes to the coldest region. It is possible to compare both velocity field by defining the dynamical Bond number such as : $Bo_{DT} = \frac{U_g}{U_m}$, given by setting z = h in equations (8) and (9) :

$$Bo_{DT} = \frac{\rho_0 \alpha g h_0^2}{12\Gamma} \tag{10}$$

We find $Bo_{DT} \sim 10^{-4}$ for a water layer of $h_0 \approx 100 \ \mu m$. Hence, buoyancy effects are negligible here.

4.2.2 Solutal effect

Marangoni effect, *i.e.* surface tension gradient, can also be triggered by pollution or surfactants. Hence, the equation (9) for the Marangoni radial velocity would be the same except that the $\Gamma \partial_r T$ factor should just be replaced by $\frac{\partial \gamma}{\partial r}$. Hu and Larson [5, 6] proposed to include Langmuir's isotherms to the model to have $\gamma(r) = \gamma_0(T(r)) - \nu(r)k_BT_0$, where $\gamma_0(T(r))$ is the water-air surface tension, and the other term denotes the presence of pollution through the surface density ν . This last parameter dynamically depends on the velocity field of the interface through the advection-diffusion equation of impurities on the interface :

$$\frac{\partial\nu}{\partial r} = \frac{u_r(z=h)}{D_s}\nu\tag{11}$$

where D_s is the surface diffusion coefficient of impurities. It is now clear that the modified equation (9) is coupled with equation (11). From this coupling, Hu and Larson wrote that the total Marangoni speed at the drop surface should approximately be the same as the thermal part of it, but divided by a factor depending on ν as :

$$u_{r,m}(z=h) = \frac{u_{r,m}(z=h)_{(thermal)}}{1 + \frac{h(r)k_B T_0}{4nD_c}}\nu(r)$$
(12)

To rescale Marangoni velocity by a factor 1000, as suggested by the experimental data, this implies that $\frac{h(r)k_BT_0}{4\eta D_s}\nu(r) \approx 1000$, which leads to $\nu \approx 10^{16} molecules/m^2 = 5 \ 10^3 molecules/\mu m^2$ with $D_s \approx 10^{-9} \ m^2/s$, $\eta = 10^{-3} \ Pa.s$ and $h_0 \approx 200 \ \mu m$. Converted in surface concentration, it corresponds to an area per molecule around $A \approx 200 \ nm^2/molecule$. This represents a small impurity concentration. This concentration is of the same order of magnitude as indicated in the work done by Hu and Larson [5, 6]. Such small impurity concentrations are difficult to avoid for water solution even in clean room. This result explains why the surface velocity is significantly reduced by the presence of impurities at the interface through a counter solutal Marangoni effect.

References

- [1] María Luisa Cordero, Emilie Verneuil, François Gallaire, and Charles N Baroud. Timeresolved temperature rise in a thin liquid film due to laser absorption. *Physical Review E*, 79(1):011201, 2009.
- [2] David Rivière, Bertrand Selva, Hamza Chraibi, Ulysse Delabre, and Jean-Pierre Delville. Convection flows driven by laser heating of a liquid layer. *Physical Review E*, 93(2):023112, 2016.
- [3] Hua Hu and Ronald G Larson. Evaporation of a sessile droplet on a substrate. *The Journal of Physical Chemistry B*, 106(6):1334–1344, 2002.
- [4] Hua Hu and Ronald G Larson. Analysis of the microfluid flow in an evaporating sessile droplet. *Langmuir*, 21(9):3963–3971, 2005.
- [5] Hua Hu and Ronald G Larson. Analysis of the effects of marangoni stresses on the microflow in an evaporating sessile droplet. *Langmuir*, 21(9):3972–3980, 2005.
- [6] Hua Hu and Ronald G Larson. Marangoni effect reverses coffee-ring depositions. *The Journal of Physical Chemistry B*, 110(14):7090–7094, 2006.
- [7] Ronald G Larson. Transport and deposition patterns in drying sessile droplets. *AIChE Journal*, 60(5):1538–1571, 2014.
- [8] Tony M Yen, Xin Fu, Tao Wei, Roshan U Nayak, Yuesong Shi, and Yu-Hwa Lo. Reversing coffee-ring effect by laser-induced differential evaporation. *Scientific reports*, 8(1):3157, 2018.
- [9] Florian Carle, Benjamin Sobac, and David Brutin. Hydrothermal waves on ethanol droplets evaporating under terrestrial and reduced gravity levels. *Journal of fluid mechanics*, 712:614–623, 2012.
- [10] PL Kelly-Zion, CJ Pursell, Sawan Vaidya, and Jaskirat Batra. Evaporation of sessile drops under combined diffusion and natural convection. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 381(1-3):31–36, 2011.
- [11] Franz M Weinert, Jonas A Kraus, Thomas Franosch, and Dieter Braun. Microscale fluid flow induced by thermoviscous expansion along a traveling wave. *Physical review letters*, 100(16):164501, 2008.
- [12] Franz M Weinert and Dieter Braun. Optically driven fluid flow along arbitrary microscale patterns using thermoviscous expansion. *Journal of applied physics*, 104(10):104701, 2008.