Supplementary Information

TinyLev: a Multi-Emitter Single-axis Acoustic Levitator.

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1- Pressure and force model.

The complex acoustic pressure *P* at point ***r*** due to a piston source emitting at a single frequency can be modelled as:

$$P(\boldsymbol{r}) = P_0 V \frac{D_f(\theta)}{d} e^{i(\varphi + kd)}$$

Where P_0 is an amplitude constant that defines the transducer output power and V is the excitation signal peak-to-peak amplitude. D_f is a far-field directivity function that depends on the angle θ between the piston normal and ***r***. Here, $D_f = 2J_1(ka \sin\theta)/ka \sin\theta$, the directivity function of a piston source, where J_1 is a first order Bessel function of the first kind and a is the radius of the piston. This directivity function can also be simplified as $D_f = sinc(ka \sin\theta)$. The term $1/d$ accounts for divergence, where d is the propagation distance in free space. $k = 2\pi/\lambda$ is the wavenumber and λ is the wavelength (8.65mm in air at 25°C). φ is the emitting phase of the source.

The total acoustic field (*P*) generated by *N* transducers is the addition of the individual fields, i.e. $P = \sum_{j=1}^{N} P_j$.

To characterize a transducer the amplitude constant (P_0) and the piston radius (a) are needed; the amplitude constants for different transducers can be found in Supplementary Information 3, the radius of the piston was 4.5mm.

To calculate the force exerted on a sphere due to a complex pressure field, we can use the negative gradient of the Gork'ov potential $\boldsymbol{F} = -\boldsymbol{\nabla} U$:

$$U = 2K_1(|p|^2) - 2K_2(|p_x|^2 + |p_y|^2 + |p_z|^2)$$
$$K_1 = \frac{1}{4}V\left(\frac{1}{c_0^2\rho_0} - \frac{1}{c_p^2\rho_p}\right)$$
$$K_2 = \frac{3}{4}V\left(\frac{\rho_0 - \rho_p}{\omega^2\rho_0(\rho_0 + 2\rho_p)}\right)$$

where *V* is the volume of the spherical particle, ω is the frequency of the emitted waves, ρ is the density and *c* is the speed of sound (with the subscripts *0* and *p* referring to the host medium and the particle material respectively). p is the complex pressure and p_x is its derivate over *x*.

2 - Power consumption.

The current consumption of the system was measured, it is shown in Supplementary Figure 2.1. There was only a small dependency of current consumption at different phase differences between the top and bottom arrays supporting the hypothesis that the system can be approximated as non-resonant.

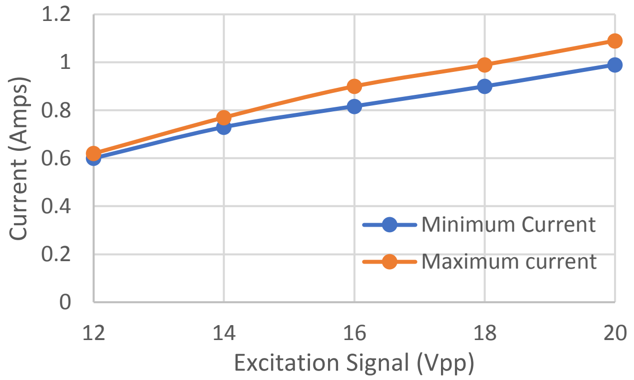


Figure 2.1. Current consumption of the levitator at different phase differences between the top and bottom array.

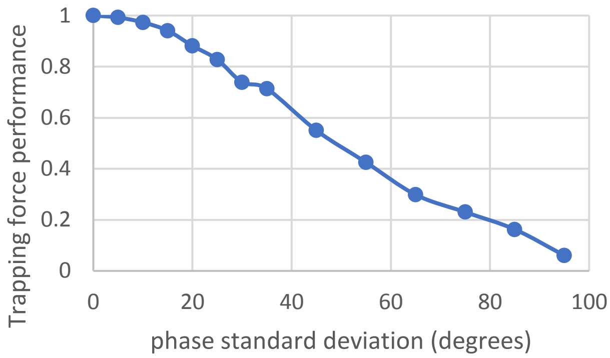
3 – Transducers analysis.

The transducers were excited with a square-wave of 10Vpp (generated with an Agilent 33210A) and measured with a wideband microphone (1/8" Brüel & Kjær calibrated microphone Type 4138-A-015) positioned 20cm away and connected to an oscilloscope able to read the peak-to-peak amplitude and phase deviation with respect to a reference signal. An important note is that the polarity of the transducers is not marked by the manufacturers and this was marked experimentally prior to these acoustic evaluations. The measures were repeated for 10 transducers.

Model	**Diameter (mm)**	**Acoustic output (Pascal/meter*volt)**	**Phase Standard Deviation (degrees)**
Manorshi MSO-P1640H10TR	16	0.25 SD=0.04	8.7
MSO-A1640H10T	16	0.36 SD=0.02	9.2
MSO-P1040H07T	10	0.13 SD=0.02	13.9
Ningbo FBULS1007P-T	10	0.14 SD=0.02	13.9
Murata MA40S4S	10	0.17 SD=0.01	3.8
MultiComp MCUST10P40B07RO	16	0.25 SD=0.04	33.1
MCUSD16A40S12RO	16	0.21 SD=0.03	18.3

Table 1. Evaluation of different commercially available 40kHz air transducers. The measures were repeated for 10 items.

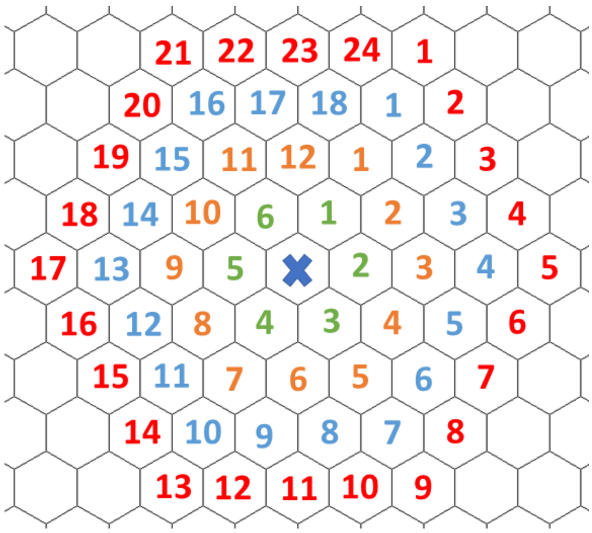
4- Phase deviation effect on trapping force.



Supplementary Figure 4.1. Simulation of the trapping force performance of TinyLev (System in Figure 1) depending on the phase standard deviation of the transducers. Note that the phase variation was modelled as zero mean Gaussian distribution.

5- Transducers packing.

We decided to pack the transducers following the optimal circle packing in a hexagonal pattern (Supplementary Figure 5.1). The first 3 rings have 6, 12 and 18 elements respectively. The fourth ring would have 24 transducers.



Supplementary Figure 5.1. Hexagonal packing. 4 rings overlaid into the hexagonal pattern.

6 - Placement on the bed.

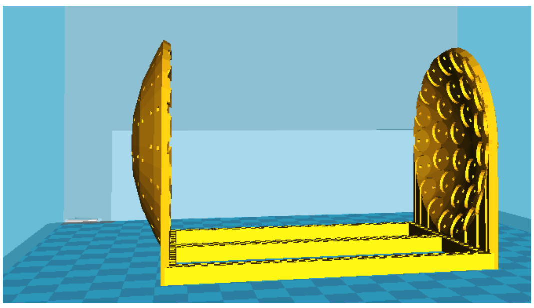


Figure 6.1. Placement of the base in the 3D printer. This position allows to print it without support but limits the maximum curvature of the bowls.

7 – Other arrangements.

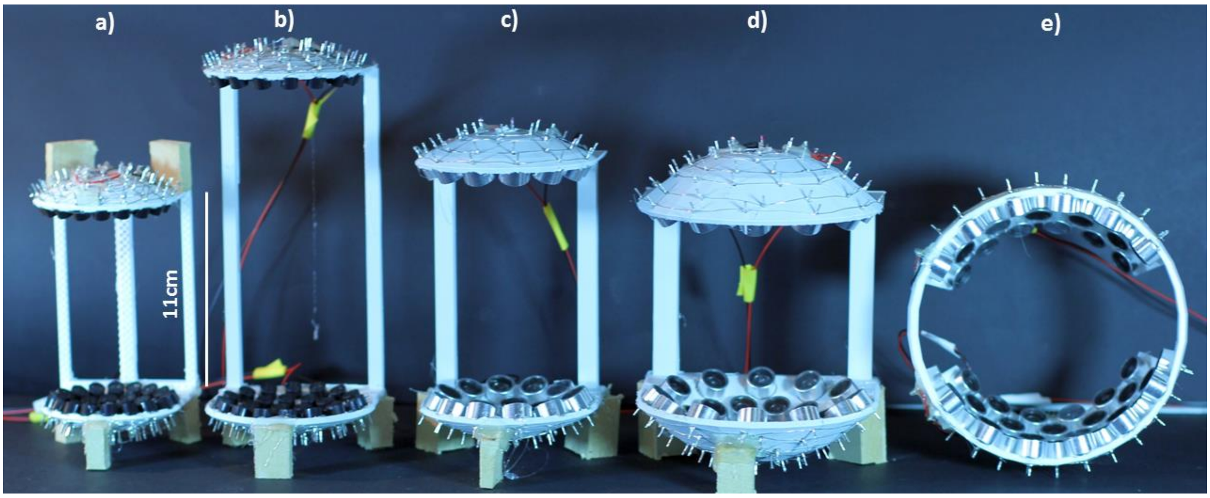


Figure 7.1. Some of the manufactured arrangements. a) TinyLev. c,d,e) use 16mm transducers. Only (a,d,e) can levitate liquids but (d) is slightly resonant and thus cannot move the samples up/down as well as being more sensitive to temperature and humidity; (e) only has 2 to 3 functional nodes.

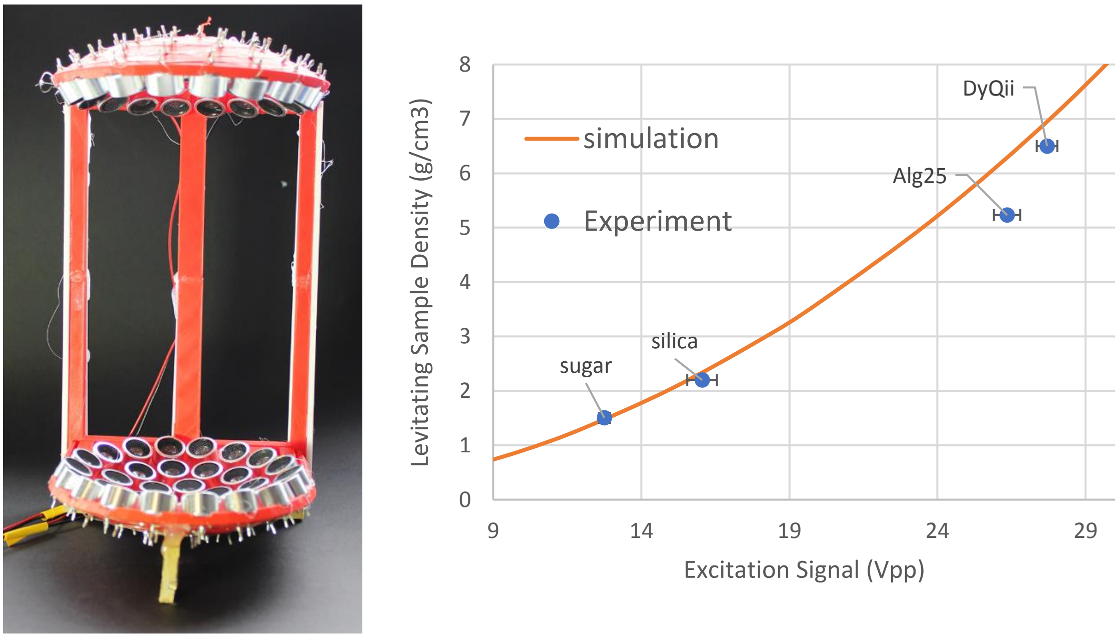


Figure 7.2. BigLev, a version of TinyLev scaled by 160% to use 16mm transducers. Left) It was manufactured in two parts to fit the 3D printer. Right) It could levitate spherical samples of up to 6.5 g/cm^3 density operating within the supported voltage range of the transducers.

8 - Transducer response.

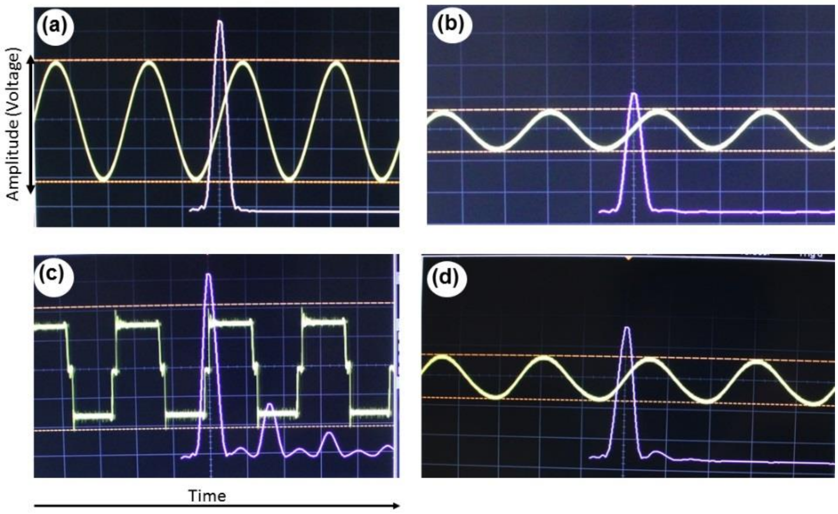


Figure 8.1. a) 20 Vpp 40kHz sinusoidal excitation signal generated with a signal generator and (b) output from the transducer measured with a microphone. c) excitation signal from the driver and (d) output from the transducer. The yellow line is the signal in the time domain and the purple line in the frequency domain with 40kHz at the central frequency and 200 kHz span.

9 – Driving Board circuit.

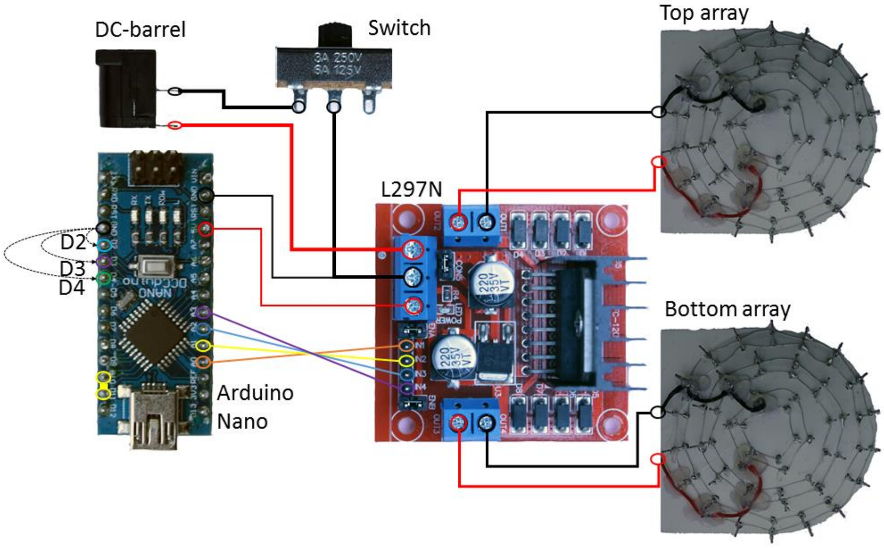


Figure 9.1. Schematic of the driving circuit. The main components are an Arduino Nano and a motor driver L278N. It can generate two driving signals and their relative phase is controlled by connecting ground to D2 or D3 in the Arduino Nano (D4 resets to the starting position).

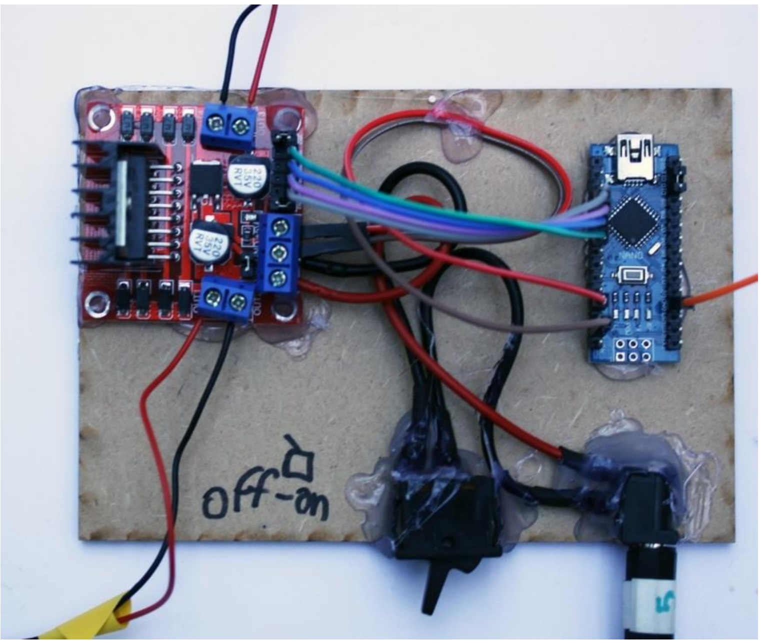


Figure 9.2. Assembled driver circuit.

10 - Levitation of samples.

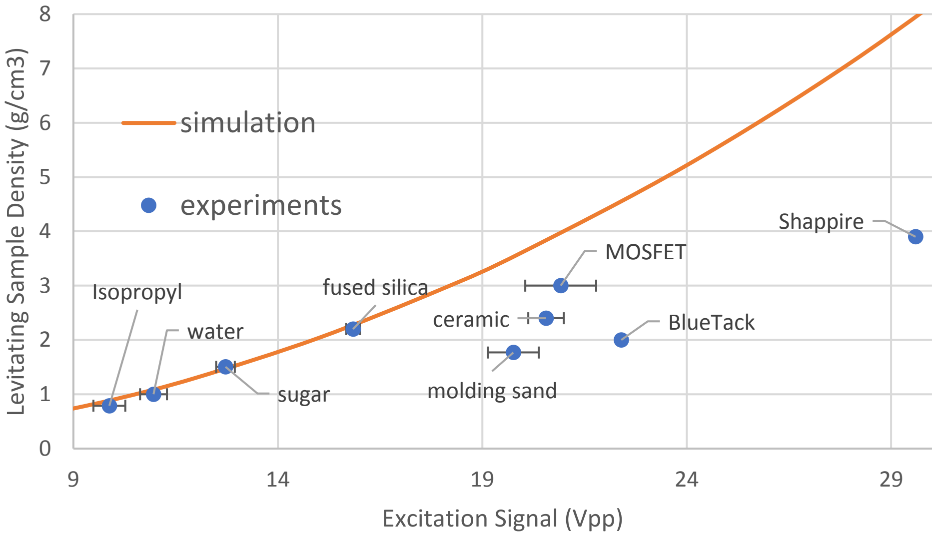


Figure 10.1. Required voltage for levitating different samples. After 19Vpp the predictions do not fit the simulations anymore. All the transducers were rated at 20Vpp maximum but starting to lose linear response after 16Vpp.

11 - Evaporation test over time.

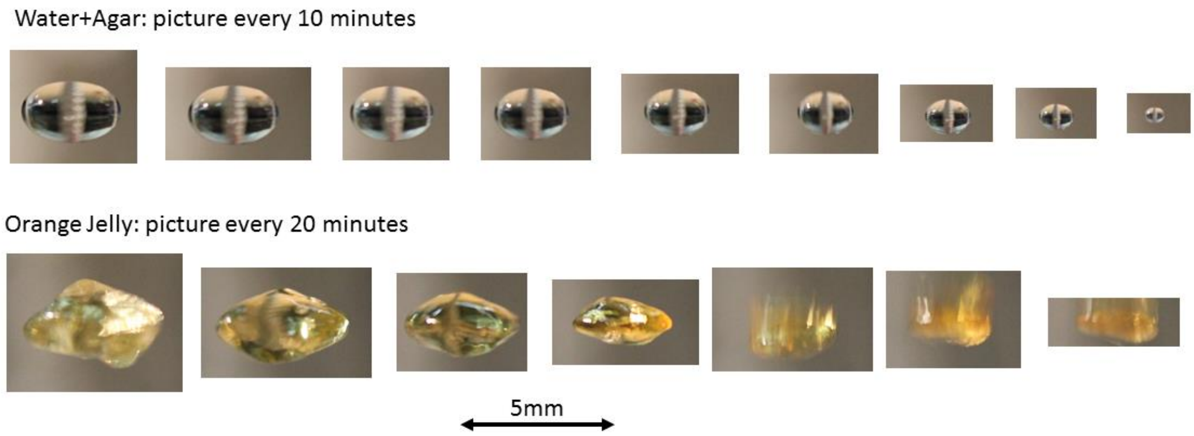


Figure 11.1. Evaporation of water and agar (top) and orange jelly over time.

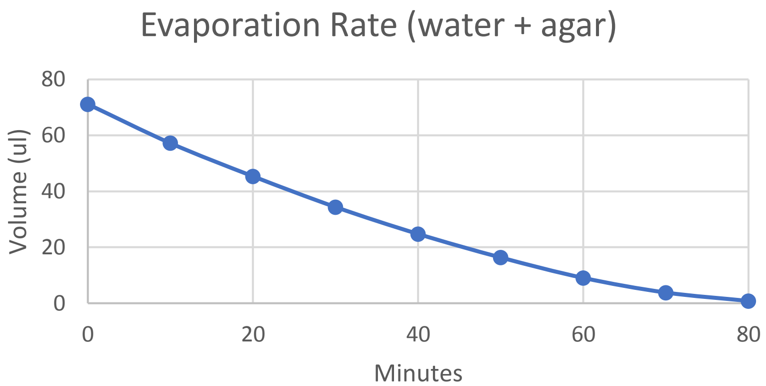


Figure 11.2. Reduction on volume of a droplet of water and agar over time.

12 – Humidity test and temperature test.

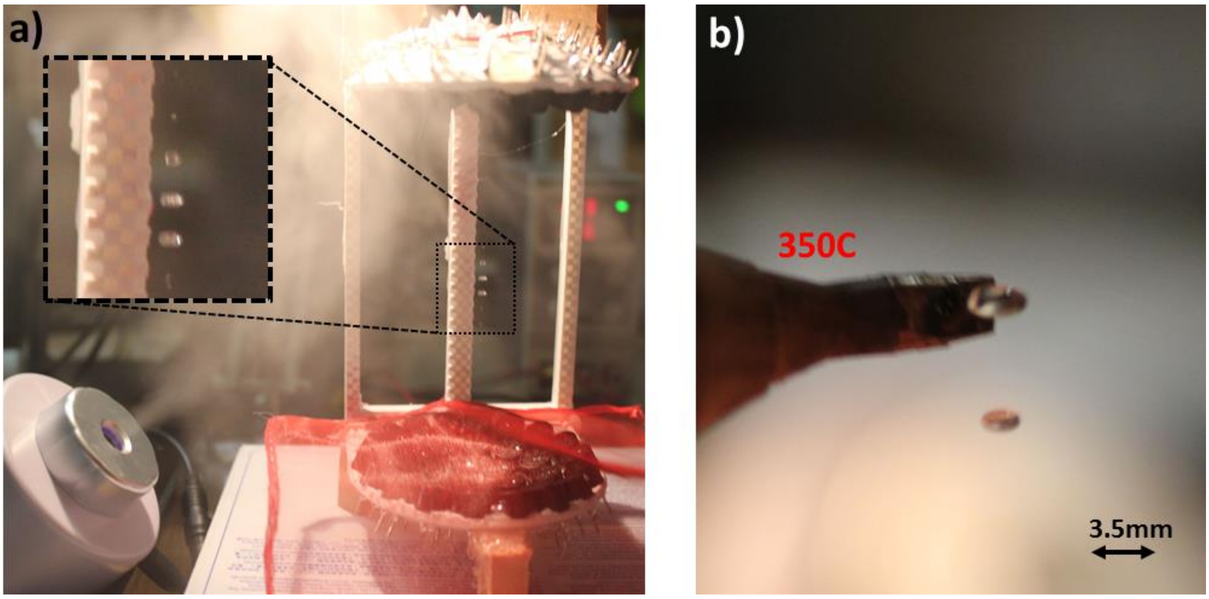


Figure 12.1. Condensation of droplets from an ultrasonic mister. b) soldering iron tip (at 350 Deg) positioned at 5mm from the levitated sample.

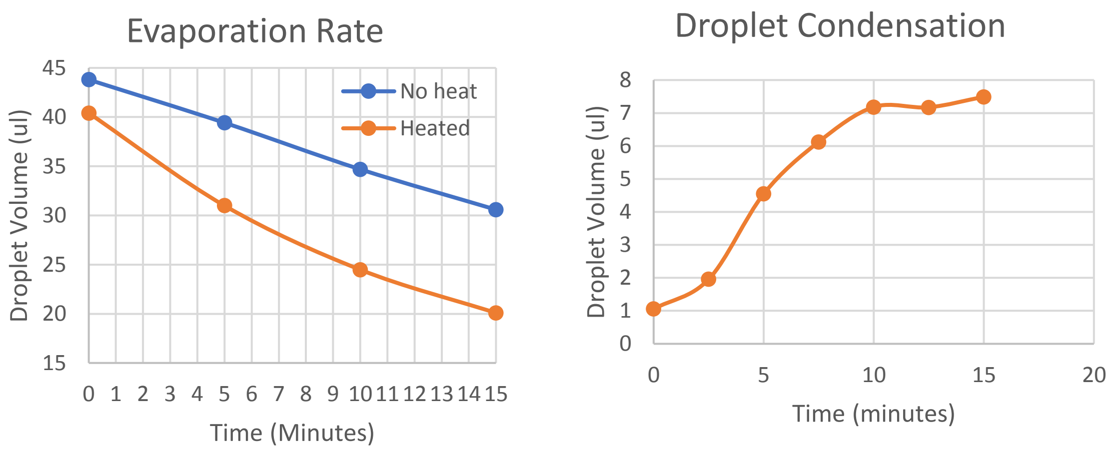


Figure 12.2. Left) Evaporation of a droplet over time without and with heat applied. Right) Condensation of vapor from an ultrasonic mister.