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ABSTRACT

Droplet drying has importance in a range of applications from aerosols and pollutant transport to manufacturing powdered drug formulations. Single droplet drying is often studied to provide insights into the drying process; however, the methods applied are often limited by an inability to dry at high temperatures without the need to attach the droplet to a solid surface—pendant or sessile droplets. This paper discusses the development of an easy to handle and in-expensive acoustic levitator to dry droplets from ambient temperature up to 90 °C. High-temperature drying is rarely achieved using acoustic levitation, apart from a few devices being extensively engineered and expensive. Integrating a TinyLev acoustic levitator, a bespoke compact heating system has been developed, providing stable drying conditions across a range of temperatures. Iterations of the heater design enabled issues of temperature fluctuations to be minimized when the acoustic levitation is triggered, as well as achieving spatial and temporal stability of the temperature field in the levitation zone. Pilot experiments on droplet drying of water and a complex fluid containing surfactants demonstrate the potential of the technique, providing fundamental insights into the drying process across a range of temperatures.

INTRODUCTION

Acoustic levitation is a developing technique used to study droplets in a contactless environment. Early acoustic levitators typically employed single or dual Langevin horn configurations to generate the acoustic field necessary for trapping samples. However, these systems were often difficult to calibrate and even minor temperature fluctuations could significantly impact their operating frequency and stability.[1]

Recent advancements, such as the TinyLev system,[2] have greatly improved the accessibility and usability of acoustic levitation for research. TinyLev utilizes two opposing arrays of 36 ultrasonic transducers, each to produce a stable, single-axis, non-resonant levitation field [Fig. 1(a)]. This design offers several advantages, including simplified setup, greater resilience to environmental changes, and cost-effectiveness. As a result, acoustic levitation has become more widely available for experimental studies in droplet physics, fluid dynamics, and materials science.

Most acoustic levitation studies are performed at ambient temperature[3–8] and typically require more sophisticated setups when applied to higher temperatures. This limitation has also restricted the range of systems that can be investigated. To date, high-temperature studies have primarily utilized single-transducer levitators enclosed within sealed chambers, where heated air is circulated.[9,10] This approach presents several challenges. Notably, the acoustic transducers are prone to overheating, necessitating additional cooling airflow to ensure stable operation. As a result, these systems are often bulky, complex to assemble, and introduce

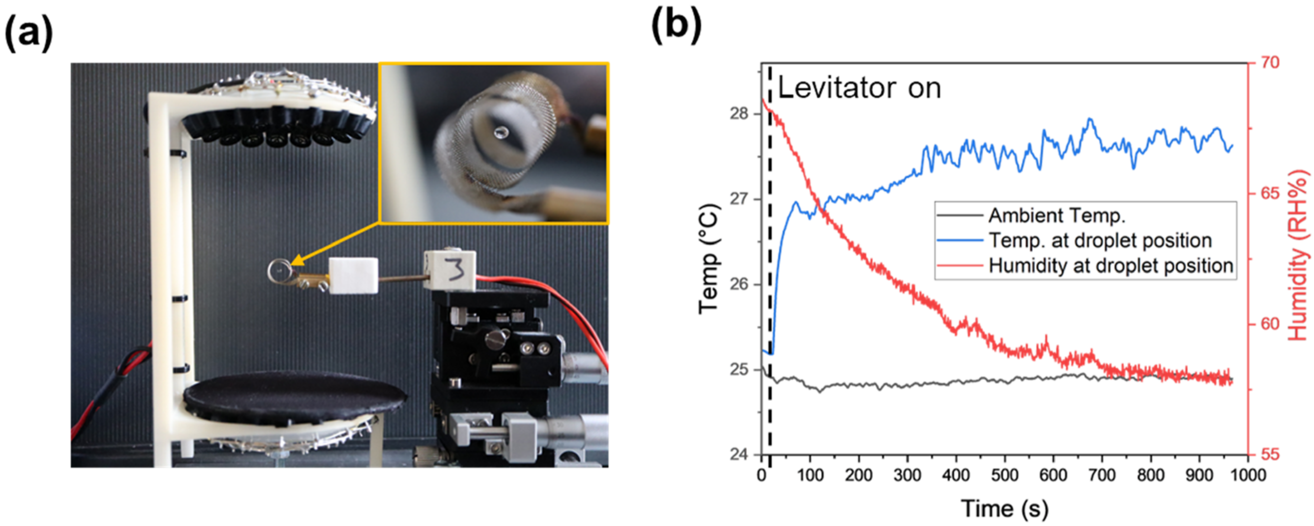

FIG. 1. Acoustic levitator setup used in the current study. (a) The inset shows the levitated droplet at the central node within a coil heater. Temperature and relative humidity measured at the levitation node (droplet position) and relative to the near surrounding ambient temperature. (b) Note the increase in temperature and decrease in humidity at the levitation node when the acoustic levitator is activated without heating.

further complications in droplet positioning due to the need for precise thermal and environmental control within the chamber. Moreover, the chambers must include optical windows to enable integrated techniques such as optical or x-ray analysis. These windows can limit the range of analytical methods and may degrade data quality, for example, by increasing background noise in x-ray measurements.

Furthermore, none of the existing heating methodologies were designed for use with the TinyLev system. Due to its exposed transducer arrays, TinyLev is not well suited to encapsulation-based heating approaches, as independently cooling the transducers would be difficult when they are enclosed within a heated environment. Alternative heating strategies, such as laser-based heating[1,11] or xenon lamp irradiation,[12] have been investigated as potential solutions for achieving localized temperature control while preserving the benefits of acoustic levitation.

In this study, we present the design of an easy-to-implement, portable, and affordable heating unit, specifically developed for the TinyLev acoustic levitator. The system enables stable droplet levitation and provides temperature control up to 90 °C, making it suitable for a broad range of analytical applications.

MATERIALS AND METHODS

All chemicals were used as received without further purification. Milli-Q water with a resistivity of 18.2 MΩ·cm was used in all tests. Alpha Olefin Sulfonate (AOS), a commercial surfactant was supplied by Innospec Ltd. (UK) at 70 wt. % and then diluted to 20 wt. % using Milli-Q water prior to use.

The experimental setup [Fig. 1(a)] utilizes the TinyLev acoustic levitator, with full specifications detailed previously.[2] Briefly, the system comprises 72 ultrasonic transducers, each 10 mm in diameter and operating at 40 kHz, arranged in two opposing arrays to generate the acoustic field required for levitation. The levitator is powered by a DC power supply with an operational voltage range of 6–12 V, with a voltage of 7.8 V used in this study to levitate both water and AOS solution droplets. Droplets with a volume of 1.8 μl were produced using a 0.1–2.5 μl Eppendorf Research G Plus pipette (Eppendorf, Germany). Each droplet was then transferred from the pipette tip to the levitation node using a 0.2 mm silver-plated copper wire (Leoni AG, Germany), which facilitated precise placement within the heated region of the levitator. The temperature in the droplet drying region was measured using a K-type thermocouple (Generic, U.K.), with the humidity measured at the same position using a humidity probe (HM1500LF, TE Connectivity, Ireland), connected via a terminal board (PR121, Pico Technology, U.K.). All sensor data were recorded using a data logger (TC-08, Pico Technology, U.K.).

The droplet was imaged using a digital camera (acA1920-150uc, Basler, Germany) equipped with a 0.8× magnification telecentric lens (TEC-M08110MP, Computar, U.K.) and illuminated by a collimated backlight (CSBack, TPL Vision, U.K.). Images were captured at 5 s intervals. These images were processed using a custom MATLAB (MathWorks, U.S.A.) script to extract the major and minor axes of the droplet. From these measurements, the volume-equivalent diameter, d_0, was calculated, with a standard deviation of 0.01 mm for each droplet. Images were captured every 40 ms to track the droplet's position over time using the TrackMate plugin (FIJI).[13]

Background-oriented schlieren imaging was performed using a digital camera (Canon M50, Canon, Japan) equipped with a 15–45 mm f/3.5–6.3 IS STM lens (EF-M, Canon, Japan) and illuminated by an LED light source (SLZ-W1, Dino-Lite, Taiwan) to enhance the visibility of the speckle pattern. The captured images were processed using the MATLAB toolbox *comBOS*.

X-ray diffraction (XRD) experiments for studying the phase changes within the AOS droplet was performed by mounting the

TinyLev rig [Fig. 1(a)] on an XY stage within a XtaLab Synergy Custom X-ray Diffractometer (Rigaku, Japan), allowing the x-ray beam to pass through the center of the coil and the levitated droplet at the central node.

HEATER DESIGN

Preliminary characterization of the levitator system revealed that the temperature and relative humidity at the levitation node, where the droplet is acoustically trapped, differed markedly from the surrounding ambient conditions [Fig. 1(b)]. Upon activation of the levitator (without heating), a notable rise in temperature was observed, along with a significant drop in relative humidity at the droplet position [Fig. 1(b)]. These findings critically highlight the importance of measuring thermal effects directly at the droplet location and under operational levitation conditions to ensure accuracy and relevance to real experimental scenarios.

To assess heater performance and compatibility with the acoustic field, several heater designs were fabricated [Fig. 2(a)] and tested. Flat heaters [Fig. 2(a-1)] were constructed using Nichrome wires of varying diameters (0.4, 0.6, and 0.8 mm) and were initially intended to deliver heat via convection from beneath the droplet, without disturbing the acoustic field. In contrast, coil designs were developed to surround the droplet, including both wire coils made from 0.4, 0.6, and 0.8 mm Nichrome wires [Fig. 2(a-2)] and mesh coils made from NI80 Nichrome [Fig. 2(a-3)].

The heating behavior of each design was evaluated by monitoring the temperature at the levitated droplet location, focusing on both heat-up time and thermal stability after levitator activation. The flat heater exhibited significantly slower heating, requiring over one-hundred seconds longer to reach the target temperature compared to the coil designs. Once the levitator was turned on, the temperature at the droplet site (levitation node) dropped sharply in all configurations; however, the flat heater experienced the most pronounced cooling, with temperatures approaching ambient levels [Fig. 2(b)]. In contrast, both wire and mesh coil heaters maintained slightly higher temperatures than ambient after levitation commenced, although not the target temperature.

To investigate this abrupt heat loss, background-oriented schlieren imaging was employed. These visualizations revealed strong convective airflows directed away from the heater upon levitator activation [Fig. 2(c)]. Notably, increasing the electrical current supplied to the flat heaters did not result in a significant temperature increase. A maximum temperature of 45 °C was achieved at 5 A, leading to the rejection of this design. However, with the coil heaters, particularly at elevated currents, temperatures as high as 90 °C were achieved [Fig. 4(b)], highlighting their superior thermal efficiency and suitability for integration with acoustic levitation systems.

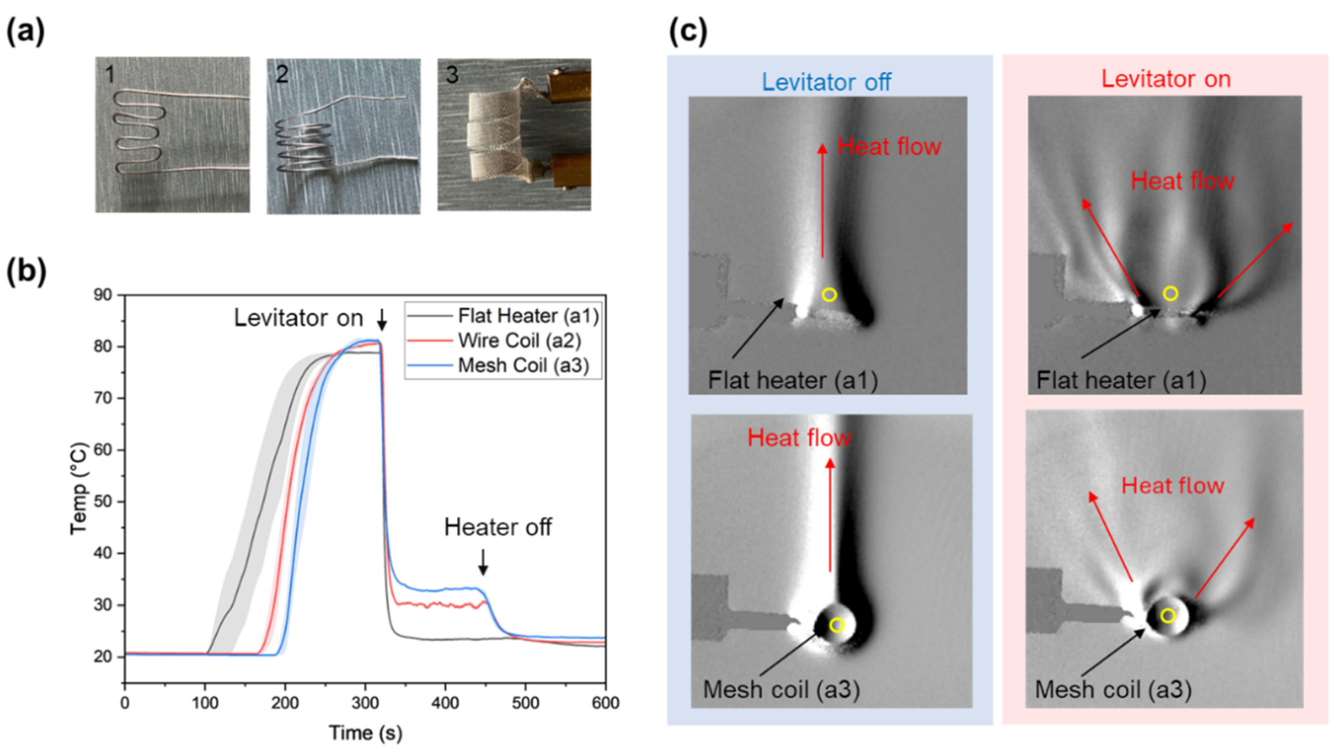

FIG. 2. Different designs of the heating elements tested in the acoustic levitator. (a) 1. Flat wire heater, 2. coil heater, and 3. mesh coil heater. Temperature profiles showing the heating time required to reach the target temperature with the acoustic levitator off, and then, the decrease in temperature once the acoustic levitator is activated (b) for all three heating elements shown in panel (a). Schlieren images of the flow field around the heaters in the absence (left) and presence (right) of the acoustic field (c). The position of a droplet in the levitation node is marked with the yellow circle.

Thin wire coil heaters exhibited poor mechanical stability during extended operation. In addition, the wire segments outside the levitation node reached temperatures exceeding 200 °C while the droplet location remained around 80 °C, posing a potential risk to the surrounding acoustic transducers. These issues were resolved in the final heater design, which incorporated a ceramic block and brass connectors capable of handling currents up to 10 A. This configuration effectively confined the heating element to the levitation node, preventing the wire from extending into sensitive regions outside the node. This is evident in the schlieren imaging [Fig. 2(c)], which shows that convection occurs only from the heater unit, with no noticeable convection from any other part of the setup. The wire coils were capable of reaching temperatures up to 90 °C; however, the maximum temperature achievable for a droplet was 50 °C. Beyond this point, the droplet was ejected from the node due to instability caused by convection currents generated by the individual wires beneath it. Thus to enhance stability, the wire coil [Fig. 2(a-2)] was replaced with a Ni80 100-mesh material. The mesh enhanced droplet stability by promoting more uniform heating across its surface. This was achieved through even spacing of the wires and small gap size of ~0.15 mm, which produced a more uniform convection current [Figs. 2a-3 and 3a]. An optimal mesh coil diameter of 7.5–8.5 mm was determined, balancing efficient heat delivery with sufficient clearance to prevent oscillating droplets from contacting the surrounding mesh at temperatures above 70 °C. The temperature at the transducers, located at the top of the levitator, was measured to be 45 °C when the heater operated at its maximum temperature of 90 °C. This value is well below the transducers' maximum operational limit of 80 °C, indicating that the heater could be used safely without causing any damage to the levitator. The mesh coil heater was calibrated by varying the applied current and measuring the temperature at the coil center using a thermocouple [Fig. 3(b)] until the desired temperature was reached and stabilized [Fig. 4(b)]. This calibration procedure must be repeated whenever there is a significant change in ambient temperature or transducer voltage.

RESULTS AND DISCUSSION

The thermal performance of the heating system and the spatial stability of levitated droplets were initially evaluated using 1.8 μl water droplets positioned within the mesh coil heater [Fig. 4(a)]. This configuration enabled temperatures of up to 90 °C at the levitation node, allowing for independent analysis of droplet stability and evaporation across a wide temperature range of 30–80 °C [Fig. 4(b)]. The target temperature was reached within 30 s and remained relatively stable throughout the extended drying period.

The position of the droplet center [Fig. 4(a)] was optically tracked during evaporation at various temperatures to assess spatial stability [Fig. 4(c)]. The droplet remained within a typical ±0.25 mm range of the central starting position [Fig. 4(c)]. A maximum lateral deviation of 0.57 mm was recorded at 80 °C after 100 s, which is attributed to the substantial reduction in droplet volume during evaporation.

The drying rates of water droplets with practically identical initial diameters (d_0) were characterized at various temperatures using the volume-equivalent diameter (d), as shown in Fig. 5(a). The temporal evolution of the squared normalized diameter, $(d/d_0)^2$, exhibited an approximately linear decrease with increasing time, indicating a constant volumetric evaporation rate throughout the drying process. This observation is consistent with previous experimental studies that reported similar linear behavior for the drying

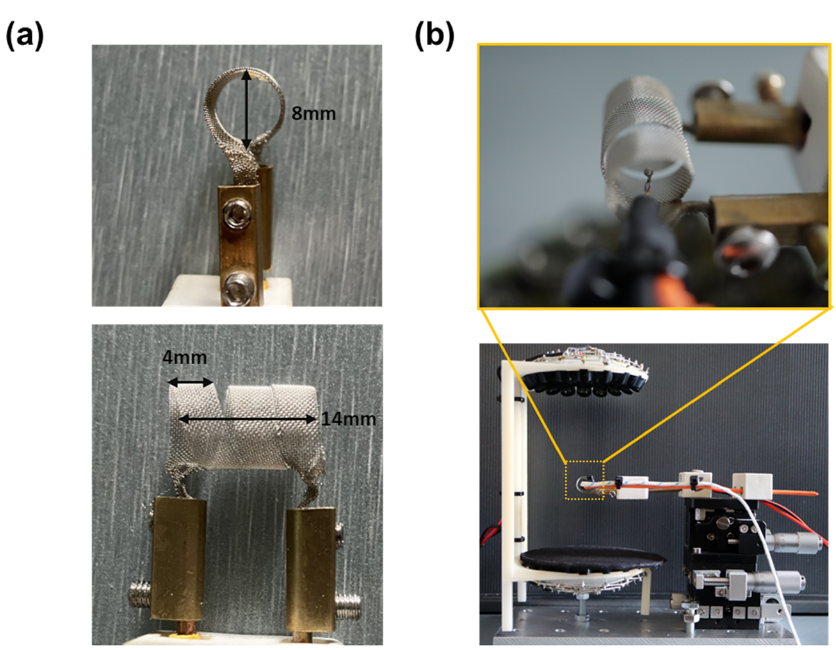

FIG. 3. Dimensions and mounting fixtures of the final design of the mesh coil heater. (a) Coil heater design and the thermal calibration sensor mounted in the acoustic levitator. (b) Expanded image showing the position of the temperature sensor within the coiled heater mounted at the center of the levitation node.

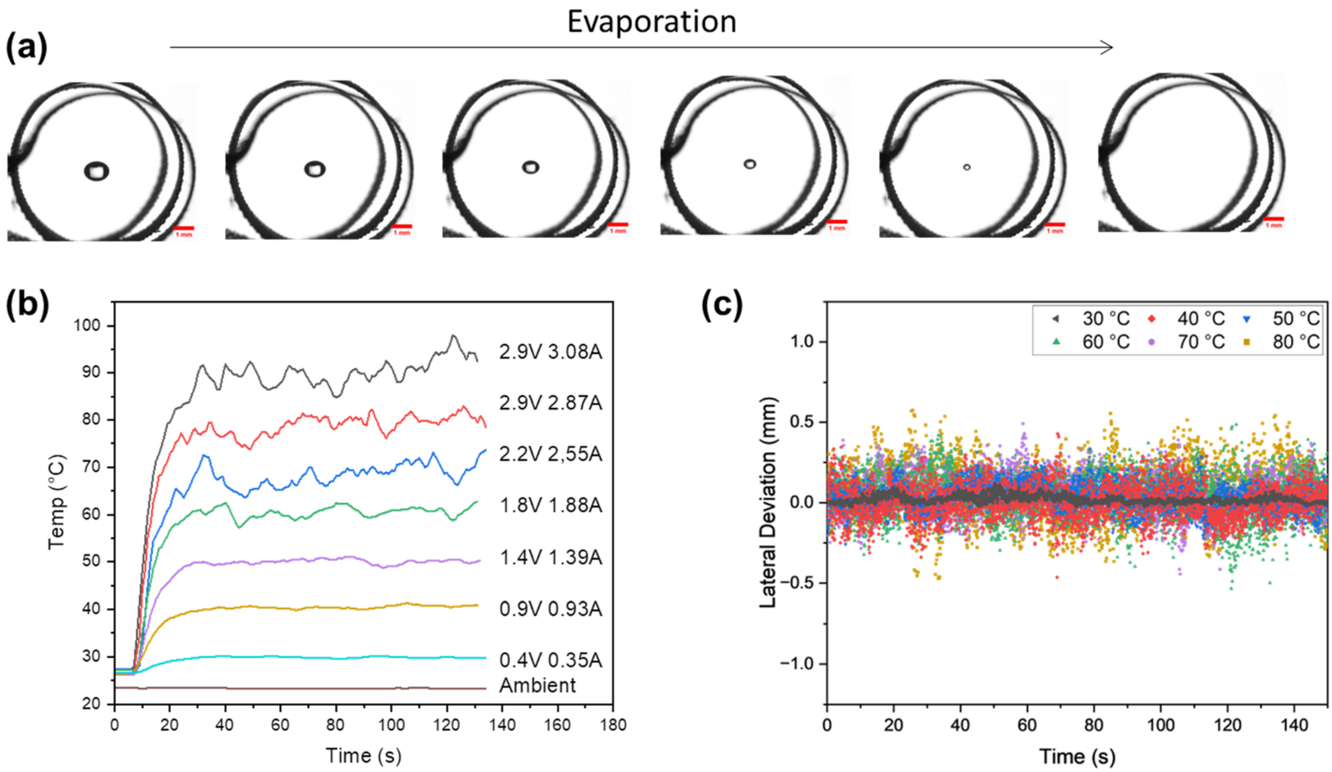

FIG. 4. Optical images of an evaporating water droplet mounted at the central node of the acoustic levitator within the mesh coil heater at 50 °C. (a) Temporal variation of the temperature measured at the location of the droplet over 150 s for experiments performed at different supplied electrical current to the heater. (b) Data show the temperature ramp-up during the first 30 s and then the steady-state regime. Lateral deviation of the water droplet center relative to the central node showing droplet motion during the experiment; data sampled every 40 ms (c).

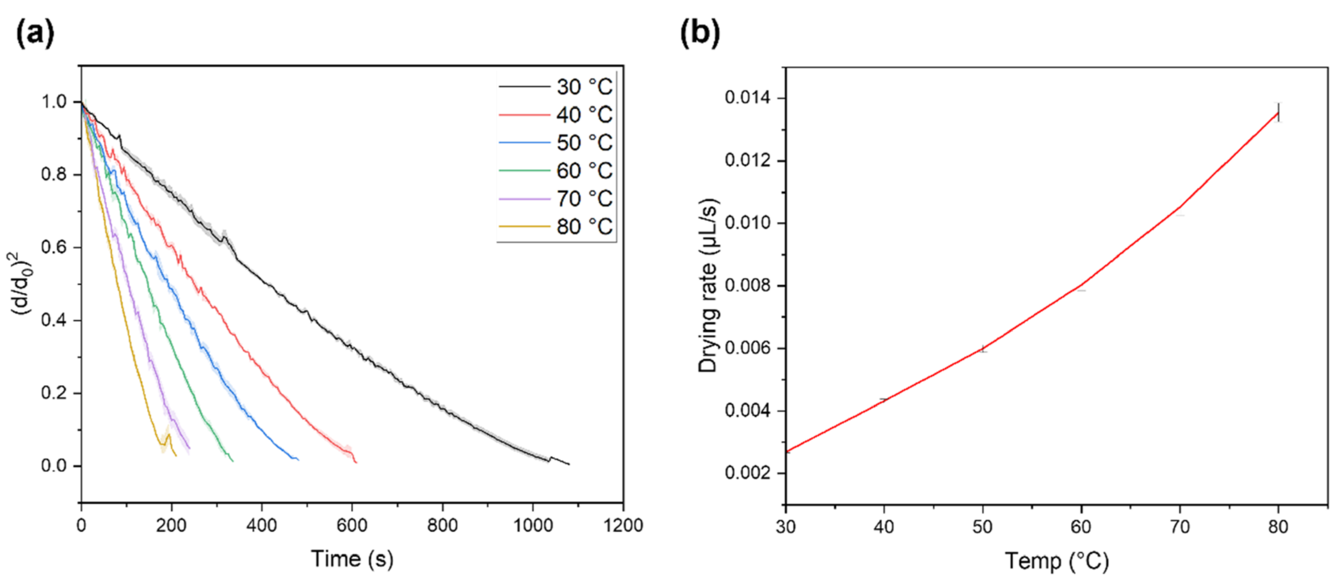

FIG. 5. Drying of 1.8 μl levitated water droplets at different temperatures. (a) The droplet diameter d is normalized by the initial diameter d_0 to allow for comparative analysis at different temperatures. Volumetric drying rate based on the reduction in the measured volume-equivalent diameter d when drying at different temperatures (b).

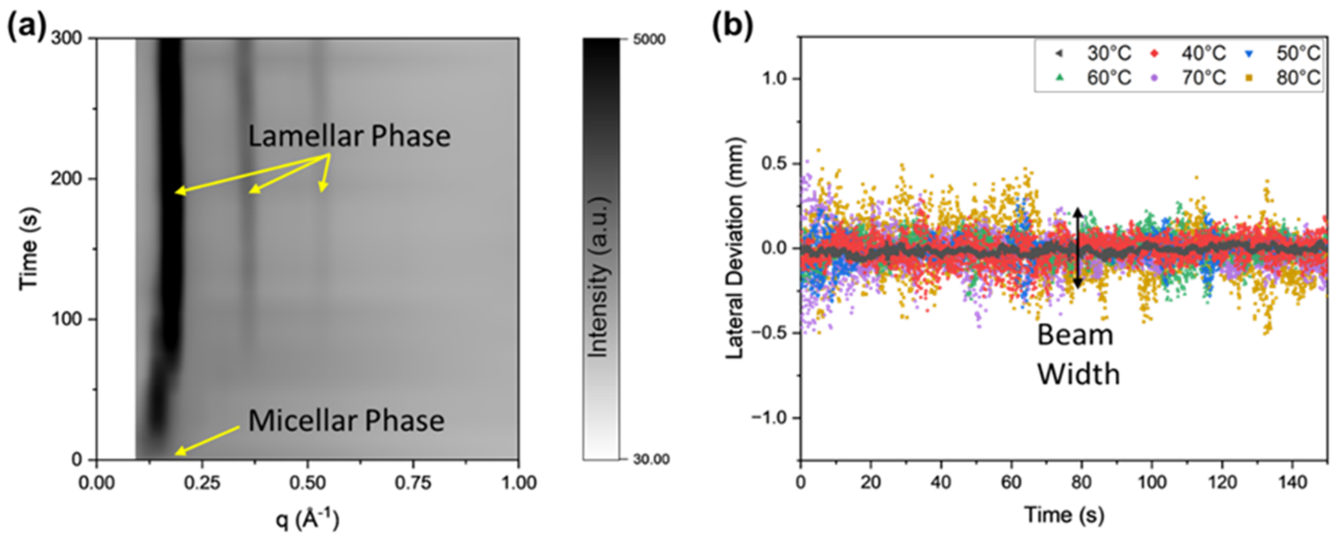

FIG. 6. XRD contour plot displaying an isotropic micellar to the lamellar phase transition of AOS in an aqueous levitated droplet drying at 80 °C (a). Lateral deviation of the AOS droplet center relative to the central node showing droplet motion during drying at different temperatures; data sampled every 40 ms (b). The double arrow indicates the 0.5 mm diameter of the direct x-ray beam.

of water droplets.[4,14,15] Repeated trials demonstrated minimal variation in drying time, as indicated by the narrow-shaded regions representing the standard deviation shown in Fig. 5(a). As a result, the calculated drying rates across the 30–80 °C temperature range [Fig. 5(b)] showed low variability, with small standard deviations confirming the repeatability and robustness of the measurement approach.

Having established the reliability of the custom-designed heater for drying water droplets, the high-temperature TinyLev system was evaluated to measure phase transitions of aqueous surfactant solutions during droplet drying. The complete transformation of the surfactant (AOS) self-assemblies, from an isotropic liquid to a solid particle, was studied using XRD. The representative XRD contour plot shown in Fig. 6(a) illustrates a clear phase transition. Initially, the droplet exhibits a broad peak cantered at q = 0.15 Å^{-1}, corresponding to a micellar phase with an approximate diameter of 42 Å. As drying progresses, this evolves into a lamellar phase characterized by a bilayer spacing of 36 Å, with the first three diffraction orders clearly visible (yellow arrows). This phase behavior is consistent with previous studies on sodium dodecyl sulfate, which also demonstrated water concentration-dependent transitions between micellar and lamellar structures.[16–18]

Spatial stability analysis of the levitated surfactant droplet during drying at 80 °C showed a maximum lateral deviation of 0.58 mm [Fig. 6(b)], confirming the system's ability to maintain precise droplet positioning during dynamic structural changes. The approximate size of the x-ray beam is indicated by the double arrow shown in Fig. 6(b). This illustrates that the droplet remained within the beam throughout the experiment, and even at the point of maximum lateral deviation at the highest temperature, a sufficient portion of the droplet remained exposed to the beam. This proof-of-concept study highlights the versatility and suitability of the heated levitator system for real-time, container-less analysis of phase transitions in soft matter systems.

CONCLUSION

This study presents the development of a compact, cost-effective, and easily integrated heating system for acoustic levitation platforms, enabling droplet drying at temperatures up to 90 °C, conditions rarely achieved in levitated systems without complex and expensive instrumentation. By addressing key challenges such as thermal stability, spatial control, and compatibility with the TinyLev system, the heater design enables precise, container-less analysis of the drying dynamics in both simple and complex fluids.

The system's performance was validated through reproducible drying experiments with water droplets and extended to phase transition studies in surfactant solutions studied with x-ray diffraction. These pilot experiments highlight the platform's potential for real-time, high-temperature studies of evaporation, crystallization, and self-assembly processes in a contact-free environment. This work opens new avenues for accessible, high-resolution investigations of droplet behavior in fields ranging from pharmaceutical formulation to soft matter physics, offering a versatile tool for researchers seeking to explore thermally driven transformations without the limitations of substrate-supporting techniques.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Robin Winder: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Sepideh Khodaparast**: Formal analysis (equal); Supervision (equal); Writing – original draft (equal). **Andrew Bayly**: Formal analysis (equal); Supervision (equal); Writing – original draft (equal). **Ian McRobbie**: Formal analysis (equal); Funding acquisition (equal); Supervision (equal). **Michael Rappolt**: Formal analysis (equal); Supervision (equal); Writing – review & editing (equal). **David Harbottle**: Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Supervision (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data associated with this paper are openly available from the University of Leeds Data repository https://doi.org/10.5518/1769.

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