

# Exploring the Influence of Temperature on the Generation and Stability of Bulk Nanobubbles

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## Abstract

Nanobubbles are stable, gas-filled bubbles on the nanoscale that challenge traditional models of bubble dissolution. Despite predictions that they should rapidly dissolve due to high internal pressure, nanobubbles have shown remarkable stability. This study investigates the formation and behaviour of nanobubbles in high-purity water subjected to temperature variation. High-purity water, filtered through sub-20 nm filters and stored at low temperatures, was gradually heated to 45°C. Dynamic light scattering (DLS) and nanoparticle tracking analysis (NTA) were employed to monitor particle size and concentration before and after the temperature increase. DLS results indicated an initial increase in particle size as the temperature rose, suggesting the nucleation of nanoparticles. A subsequent decrease in size likely reflected the coalescence and formation of larger bubbles, which impacted measurement accuracy. NTA, however, showed no significant change in particle concentration, suggesting that it was less sensitive to the lower particle concentration in this experiment. Adjustments in experimental design are recommended to reduce interference from larger bubbles in future investigations, potentially providing a reliable methodology for nanobubble generation and characterization.

**Keywords:** Nanobubbles, Temperature, Colloids, Nanoparticles

## 1. Introduction

Nanobubbles present unique challenges for our understanding of bubble behaviour [1,2]. Experimental findings show that nanobubbles can remain stable for extended periods, contrasting with the classical Epstein and Plesset model, which suggests they should dissolve within approximately 10 microseconds due to high internal Laplace pressure [3]. This calculation is based on a typical bubble radius of about 100 nm and a gas diffusion coefficient around  $1 \times 10^{-9} \text{ m}^2/\text{s}$  [3,4]. One hypothesis is that a negative charge accumulates at the gas-water boundary, creating an electrostatic double-layer repulsion that helps sustain nanobubbles. Bulk nanobubbles possess a negative zeta potential, typically ranging from about  $-15$  to  $-60$  mV, which appears prevent them from dissipating, merging, or floating to the surface [5,6]. Nonetheless, this theory is still debated, as research remains divided, and no single accepted model fully explains the long-term stability of bulk nanobubbles. Ongoing studies are essential to resolve these discrepancies and advance fundamental knowledge in this area. Over the past 20 years, the intriguing persistence of bulk nanobubbles has sparked considerable interest, prompting applications and several theoretical explanations for their stability.

A range of methods has been reported to generate bulk nanobubbles, including electrolysis of water, solvent exchange processes, temperature modulation, ultrasonication, pressure-induced supersaturation, mechanical agitation, and exposure to cosmic radiation. [7–11]. Najafi et al. [12] reported the generation of nanobubbles in a sealed cuvette by raising the temperature to measure zeta potential. This approach lowered the solubility of dissolved gases, causing nanobubbles to form, with an average size of 290 nm. The recorded zeta potential values aligned with those typically observed for larger bubbles. Initially, there was no scattering observed before the temperature increase. Notably, increasing temperature generally enhances solubility for most substances, especially potential contaminants like hydrocarbons, further reinforcing their claim that the particles observed were indeed nanobubbles.

While Najafi et al. demonstrated nanobubble generation in a sealed cuvette through temperature-induced modulation of gas solubility, further research is essential to confirm the stability, spatial distribution, and behaviour of nanobubbles across a wider range of thermal conditions. The precise impact of varying temperatures on nanobubble formation dynamics and longevity remains insufficiently explored, particularly regarding how incremental temperature changes influence the nucleation and stability of these entities. This study aims to address these gaps by systematically examining nanobubble behaviour under controlled temperature variations, thereby enhancing our understanding of temperature-dependent processes in nanobubble dynamics

## 2. Materials and Methods

### Materials

For all investigations, high-purity water (ELGA Purelab Chorus 3 system with a resistivity of 18.2 M $\Omega$ ) was used. Water underwent filtration through 0.02  $\mu$ m Whatman Anotop 10 filters, which contain an Al<sub>2</sub>O<sub>3</sub> membrane, prior to use. To minimize nanoparticle contamination from the filters, 10 ml of purified water was passed through each filter to rinse them beforehand. All glassware was thoroughly cleaned in a 10% NaOH solution (AR Grade, Aldrich) for 10 minutes, then extensively rinsed with purified water before use.

### Dynamic light Scattering

Particle sizes in solution were determined through dynamic light scattering (DLS) using a Zetasizer Nano ZS (Malvern) equipped with a 633-nm He-Ne laser at a 173° scattering angle. Measurements were conducted with an automated attenuator positioned 4.65 mm from the cuvette wall. Each DLS reading reflects the mean of three separate measurements, with each measurement consisting of 13 data sets, each collected over a period of 10 seconds.

### Nanoparticle Tracking Analysis (NTA)

Nanoparticle size distribution and concentration were assessed using Nanoparticle Tracking Analysis (NTA) on a NanoSight NS300 (Malvern, software version 3.1) featuring a 70 mW blue laser ( $\lambda = 405$  nm). A high-speed camera, capturing at 25 frames per second, recorded a 60-second video of light scattered by particles in a flow field to enable tracking, measurement, and counting of nanoparticles. To ensure a steady sample flow into the measurement chamber, a syringe pump was set at a rate of 30 (units unspecified). The final results represent an average of five measurements, with camera settings fixed at level 13 and a threshold of 3. Data analysis assumed a water viscosity of 0.888 cP at 25 °C..

## 3. Results and Discussion

It has been reported that increasing the temperature of aqueous solutions promotes the formation of bulk nanobubbles, a claim investigated in the present study. Near room temperature, an increase in solution temperature reduces the solubility of dissolved gases. High-purity water was filtered once through a sub-20 nm filter and then stored at 6–10°C in a glass flask for 24 hours. Following this cooling period, the sample was measured immediately at cold temperature using dynamic light scattering (DLS), which registered no detectable particles. The same sample was subsequently placed in the DLS, and the temperature was gradually increased to 45°C over 20 minutes. During this period, a gradual increase in particle size was observed, as shown in Figure 1, followed by a decrease toward the end of the heating interval. This behaviour was consistently observed across three independent measurements.

The observed increase in particle size with rising temperature suggests that bubble formation may be occurring within the sample. This is consistent with the known behaviour of dissolved gases becoming less soluble as temperature increases, potentially leading to nanobubble nucleation. The subsequent reduction in particle size observed in the last measurement is likely due to the formation of larger bubbles, which may result in coalescence of the initially formed smaller bubbles. This

phenomenon can explain the sudden decrease in particle size after approximately 30 minutes, as the larger bubbles begin to dominate the system and then collapse. Such larger bubbles could significantly impact the accuracy of the size measurements, as they may not be properly detected by the dynamic light scattering (DLS) technique, which is more sensitive to larger particles. An image of the cuvette cell after the temperature increase, shown in Figure 2, provides further visual confirmation of this bubble formation. The presence of larger bubbles compromised the accuracy of the measurements. Future experiments could be redesigned to reduce or eliminate interference from these larger bubbles. If nanobubbles are detected under these improved conditions, this production method could offer a straightforward approach for generating nanobubbles effectively.

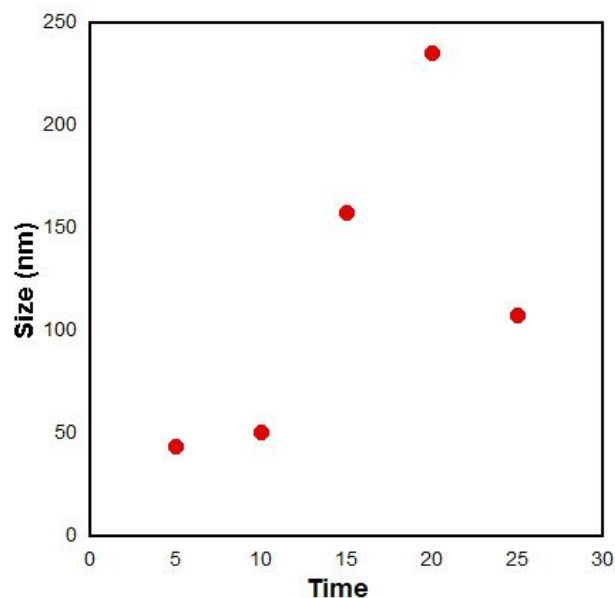


Figure 1: Dynamic light scattering (DLS) measurements of high-purity water, filtered through a sub-20 nm filter, after a temperature increase.

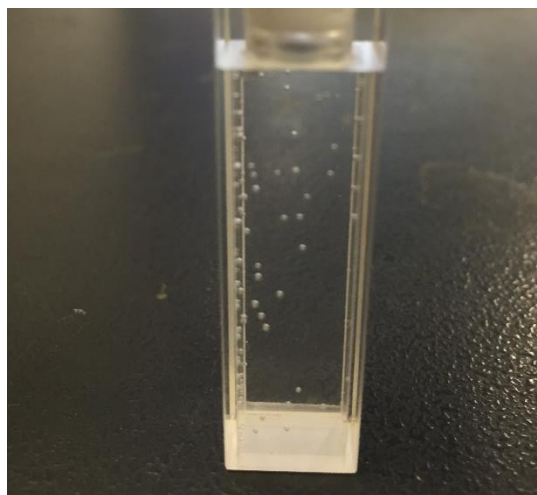


Figure 2: Cuvette containing large bubbles formed due to the increase in temperature

The same sample was also analysed using the Nanosight technique to further investigate the behaviour of the nanoparticles. The data, shown in Figure 2, illustrate the size and concentration of the nanoparticles before and after the temperature increase. No significant changes in either the size or concentration of the nanoparticles were detected after the temperature was raised to 45°C, indicating that the detected particles in the measurements are the same. Further the detected particles are below the sensitivity limit of the NanoSight, which is approximately  $10^7$ - $10^9$  particles per millimetre.

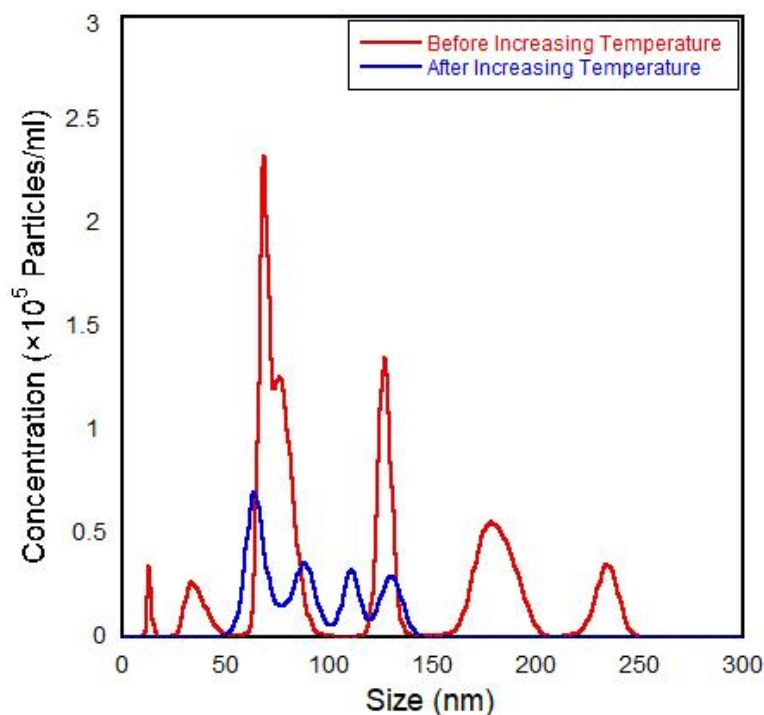


Figure 3: Nanoparticle size distribution and concentration analysis using NanoSight, showing the scattered light patterns and tracked particle movement in the sample

#### 4. Conclusion

This study provides insights into the temperature-dependent dynamics of nanobubble formation in high-purity water. As temperature increased, DLS measurements showed a gradual rise in particle size, likely due to nanobubble nucleation driven by reduced gas solubility. This was followed by a decrease in particle size, interpreted as the formation and coalescence of larger bubbles that could affect measurement reliability. Despite these limitations, our findings align with previous research indicating that temperature increase can trigger nanobubble formation in high-purity solutions. While NTA results showed no significant change in concentration, highlighting limitations in sensitivity at low concentrations, this study underscores the potential of temperature modulation as a method for nanobubble production. Future work should aim to refine this methodology to mitigate interference from larger bubbles and verify nanobubble formation across varying conditions.

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