Effects of Nanoparticles and Surfactants on Hydrometeor Behavior

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This study investigates the behavior of levitating hydrometeors inside a vertical wind tunnel to better understand the laws governing the formation, dissipation, distribution, and precipitation of raindrops as they achieve terminal velocity in the atmosphere. Moreover, this study sheds light on the complex relationship between airflow dynamics and water drop behavior in vertical wind tunnel setups, with findings that are pertinent to various applications ranging from atmospheric research to industrial processes involving drop manipulation and control. Instead of sucking air from the top, we blow air into the wind tunnel from the bottom, an unconventional design that reduces the flow disturbance induced by components in the experimental setup. Moreover, our wind tunnel's open-top design allows for drops to be easily introduced into the tunnel. We allow drops of varying sizes and concentrations of surfactants and nanoparticles to suspend freely in a velocity well induced by a crosswire screen. The velocity well facilitates the collision of drops levitating in the wind tunnel. From high-speed camera videos, we use image processing to measure the major and minor axes, oscillation frequencies, shape, and volume of the drops. Larger drops exhibited a decreased oscillation frequency and are more stable in the wind tunnel. Surfactant-laden drops tend to flatten to a disc-like shape as opposed to a more spherical shape exhibited by surfactant-free nanofluids. Such disc shape results in a larger surface area normal to the airflow and consequently higher normal force for the same air speed, thus increasing drop stability as well as facilitating levitation of the same drop mass at lower air speeds or heavier drops at the same air speeds. This research thus sheds light on the intricate dynamics of drop precipitation and the potential for controlling drop behavior through chemical additives.

I. Introduction

For this experiment we investigated the behavior of falling hydrometeors in a vertical wind tunnel. To conduct this experiment, we used high-speed photography and MATLAB software to analyze the effects of modifying the fluid makeup of the drops. Using SiO2(silicon Dioxide) nanoparticles and TritonX-100 surfactant we were able to better understand the properties that determine how droplets fall.

II. Experimental Method

Hydrometeor Properties

In our experiments, we controlled three variables to alter the properties of the hydrometeors: needle size, nanoparticle presence, and surfactant presence. Silicon Dioxide Nanopowder (SiO2), 99.5% 15-20nm spherical, was used for nanoparticles, while Triton X-100 served as the surfactant. Distilled water (DW) served as the base for all hydrometeors, and experimental groups are defined in Table 1.

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ID #	Acronym	Fluid Makeup
1	DW	distilled water
2	N1	1% silicon dioxide
3	N2	0.5% silicon dioxide
4	N3	0.1% silicon dioxide
5	N1S1	1% silicon dioxide with surfactant at 0.02% concentration
6	N2S1	0.5% silicon dioxide with surfactant at 0.02% concentration
7	N3S1	0.1% silicon dioxide with surfactant at 0.02% concentration
8	S1	surfactant at .02% concentration

Table 1 definitions of hydrometeor contents and abbreviations

To make the fluid we took 50 ml of water or water-Triton mixture and powdered SiO2 that was weighed to equal the specified percentage. For example, we used 50 ml of water and .5g of SiO2 to make N1. Nanoparticles were suspended in the solution by stirring the mixture of DW and dry particles for at least 90 minutes on a magnetic mixing plate, followed by placement in an ultrasonic bath for 30 minutes. Samples were discarded if experiments using that fluid were not conducted within 24 hours. Other research has concluded that solutions of SiO2 have the most significant degradation during the first two days of formation as seen in Fig. 1. Zhang's experiment measures the surface tension and the light absorbance to track the stability of the solution to understand the degradation of this type of solution [1]. Therefore, to achieve more accurate results we decided to conduct experiments using fluid that is less than one day old.

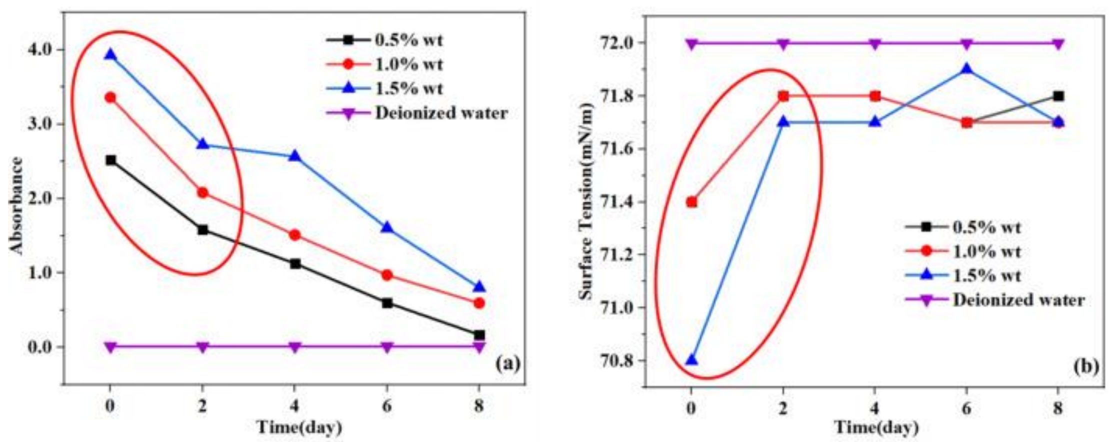

Fig. 1 The abrupt changes of absorbance values and surface tension values in 0–2 days.[1]

Vertical Wind Tunnel Setup

The experiment utilized a specially designed vertical wind tunnel to levitate hydrometeors. This tunnel, created by the UTK FaST Lab, features a pusher-style fan that generates airflow from the bottom up, contrasting with the traditional puller method seen in most vertical wind tunnels. One feature of our innovative design is the open-top configuration, which offers enhanced versatility by allowing easy insertion of hydrometeors for levitation studies.

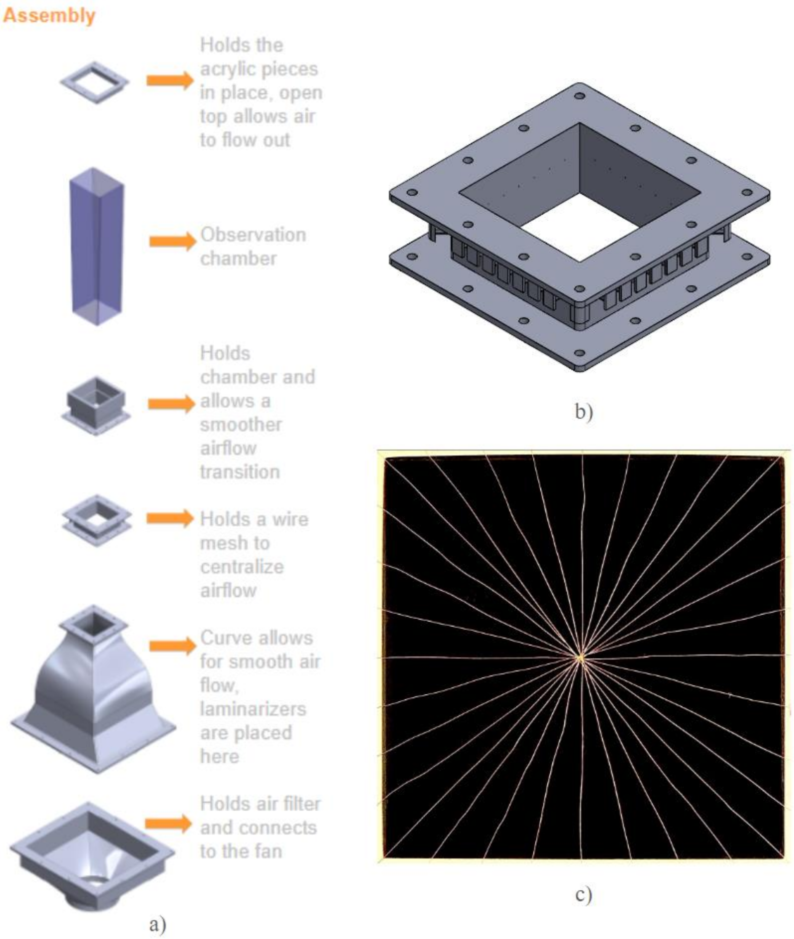

Fig. 2 a) the assembly components of the tunnel in an exploded view, b) The cartridge housing, and c) The wire mesh that forms a velocity well at the point where the wires meet. [2]

Looking at the wind tunnel with a bottom-up approach as seen in Fig. 2 a. First, a fan is linked to a housing unit that channels the airflow upwards through an air filter. This filter housing is then attached to a laminarizer, which ensures the airflow is stable and directed efficiently into the tunnel. The design of this section, with its smooth contours, guides the air into the tunnel's smaller cross-sectional area seamlessly. Above this, a specially designed cartridge holds wires in a pattern resembling a star or wagon wheel as seen in Fig. 2 b, c. This design creates a "velocity well" at the center of the tunnel, which is crucial for the experiments. The velocity well forms a region where the flow encourages drops to settle in the center of the tunnel. The cartridge is then connected to the viewing section, made of vertical plexiglass panels, allowing for an unobstructed observation area. hydrometeors can be introduced into the tunnel from the top using syringes of differing sizes as defined in Table 2. The needle sizes allow for another variable that is controllable to understand how drop sizing affects the behavior.

ID #	Color Designation	Needle Specifications
1	Olive	JG14-1.0HP (1")
2	Green	JG18-1.0HP (1")
3	Purple	JG21-1.0HP (1")

Table 2 Syringe specifications and designators

Levitation and Recording Process

The project's testing strategy was designed to assess the interaction between all fluid types and needle sizes. For each fluid and needle combination, we conducted three trials to guarantee data reliability. During these experiments, a variable AC controller was employed to fine-tune the fan speed. By adjusting the wind speed, we could achieve the ideal terminal velocity for each drop, essential for accurate levitation and observation. This precision control was also critical for ensuring that hydrometeors were optimally positioned within the recording camera's field of view. After each experiment, the terminal velocity of the drops was measured using a TSI 9515 air velocity meter placed at the center of the wind tunnel's exit.

For the recording phase, we deployed high-speed imaging technology capable of capturing the dynamics of the drops at a rate of 2000 frames per second, recording for a total of 2001 frames per iteration. This high frame rate was instrumental in providing a clear, uninterrupted view of the drops' behavior, limiting any potential for digital aliasing in the recordings. The setup included two Photron high-speed cameras strategically placed adjacent to the tunnel to film from two orthogonal viewpoints—0 degrees and 90 degrees. This arrangement allowed for the comprehensive capture of the drops' trajectories and oscillations in three-dimensional space, covering the x, y, and z axes, and offering a complete visual analysis of their movement and interaction with the airflow.

III. Image Processing

Following the video recordings of droplets within the wind tunnel, we developed a suite of MATLAB scripts to analyze the footage and process data. Our analytical process is rooted in a two-step methodology. Initially, we transform the video frames into binary images, delineating the droplets in white contrasting against the black background. This binary conversion makes it possible to leverage MATLAB's regionprops function to collect data. Utilizing binary images enables the application of the regionprops function to conduct a detailed, frame-by-frame analysis, the outcomes of which are archived for subsequent examination. The regionprops function can extract critical metrics such as droplet locations, area, and lengths of major and minor axes. These parameters were then used to study the droplets' shapes and oscillatory behaviors, facilitating a comparative analysis across different fluid compositions over time. Upon the compilation of data from our image analysis, we input this information into another script designed for advanced processing. This subsequent script transforms the raw data into a series of plots and computes relevant metrics, offering a comprehensive and insightful exploration of the droplets' dynamics within the wind tunnel environment.

Analysis of Perspective Shift in Hydrometeor Levitation

When observing objects moving through space, we can often notice that as an object moves away from the viewer, the object appears to be smaller than it is. To account for this perceived depth distortion would be an issue so we conducted a test to determine if this could be a factor that needs to be accounted for. To study the perspective shifts as these drops moved closer to or further from the camera, we developed a calibration technique. After completing the recordings of the droplets, we utilized the same experimental setup to capture the movement of a solid object across the tunnel's interior. By analyzing this footage, we tracked the object's position along the x-axis with one camera and assessed its width from a second camera positioned along the y-axis. To find the distortion of a drop as it moves, we measured the object's width in each frame, then normalized these measurements by the width at the tunnel's midpoint. We used the tunnel’s midpoint because this is where visual distortion is minimized, and this is the most common location for drops to settle. This process yielded a non-dimensional ratio, facilitating the scaling of droplet dimensions across the x-axis. By correlating the x-axis position of the drop with its midpoint location, we derived a non-dimensional value indicating the object's relative position to the point of least distortion.

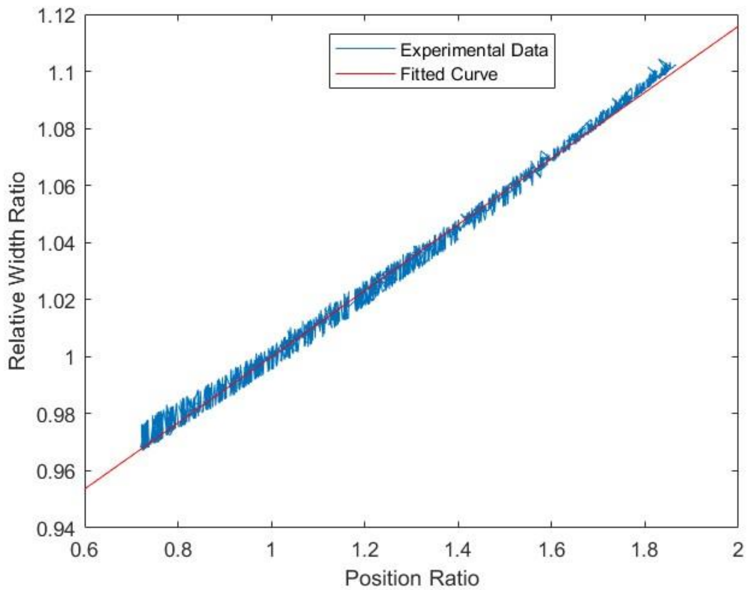

Fig. 3 The non-dimensional scaling ratio as a function of the relative x-axis position.

The plot in Fig. 3 demonstrates the linear relationship between an object's position in the tunnel and the relative size distortion. The linear correlation is described by equation (1) when y is the distortion ratio and x is the ratio of position relative to the midpoint.

$$y = 0.1159x + 0.8841 \tag{1}$$

Analysis of this equation revealed that distortion effects within our tunnel are minimal, as most drops remained within 50 pixels of the tunnel's center. Using Eq. (1) we calculated the distortion for positions 50 pixels from the center indicating a maximum distortion effect of 1.2% on the calculated drop width, suggesting that such a level of distortion is unlikely to impact the experiment's outcomes.

IV.Results and Discussion

The results of the experiments showed a multitude of physical trends and patterns between the hydrometeors' composition, size, and dynamics inside the vertical wind tunnel. The needle size, surfactant, and nanopowder were all factors that affected the droplets volume, surface tension, shape, and density. The larger the needle diameter, the larger the droplet size. This change in size had a sizable effect on the stability of the droplet within the vertical wind tunnel. The surfactant also improved the stability of the droplet inside the air stream. This is because the decrease in surface tension of the drop is less spherical, increasing the drop’s contact with the wind stream. The increased contact area results in a greater reactionary force making the drop more stable, especially at lower air speeds. The presence of nanopowder did not appear to change the droplets dynamics or stability, but we would like more data to confirm this conclusion.

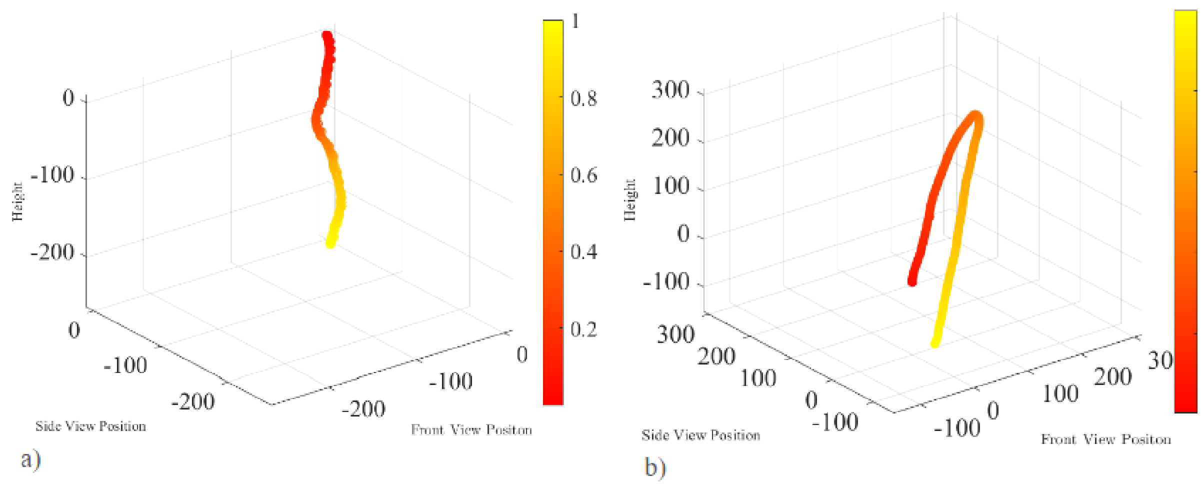

Fig. 4 Relative Position of Droplet a) S1 b) DW

Figure 4 provides a detailed comparison of the trajectories of two hydrometeors within the observation zone of the wind tunnel, charting each drop's path from its initial position. This figure employs a dynamic colormap to track the passage of time throughout the experiment: red hues denote the start of the recording, transitioning to yellow towards the conclusion. The DW droplet in Fig. 4 b) is depicted moving in the tunnel with erratic movements, highlighting its instability during levitation. In contrast, Figure 4 a) showcases a droplet infused with surfactant, which maneuvers with noticeably more steadiness. This observation underscores the enhanced stability gained by adding surfactant to droplets, a pattern that remains consistent across needle sizes.

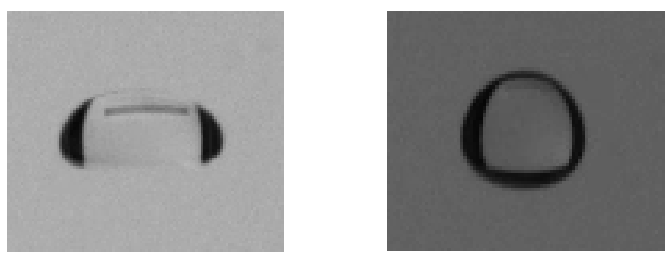

Fig. 5 Surfactant Droplet Left Versus DW Droplet Right

Figure 5 shows the shape of a DW droplet and a surfactant droplet while they are levitating. The DW droplet appears to have a spherical shape while levitating, but when you add surfactant to the droplet, it typically assumes a disc-like shape while levitating. This has been attributed to the fact that the surfactant lowers the surface tension of the droplet, which allows it to form a less symmetrical, but more effective levitating shape. The air speed required for the surfactant droplet is only 6.65 m/s, which is substantially less than the required air speed of 7.87 m/s for the DW droplet.

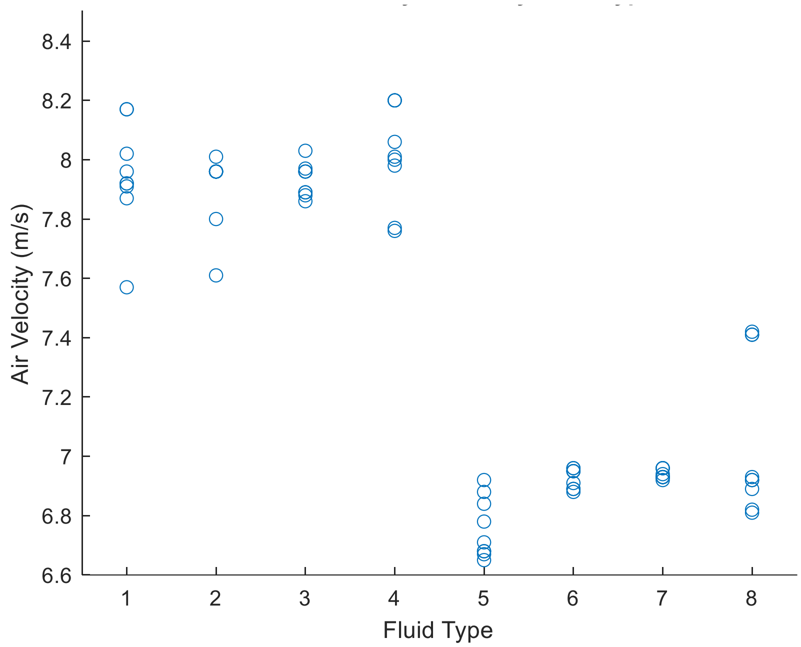

Fig. 6 This plot shows the terminal velocity of each hydrometeor sorted by their fluid types as defined in Table 1

By analyzing the air speed measurements collected from each experiment, Fig.6 provides a comparative insight into how our experimental fluid mixtures influence the levitation velocity of hydrometeors. This analysis resolves two distinct behavioral patterns across the fluids tested: fluids 1 to 4 demonstrate closely aligned velocity ranges, suggesting uniform behavior, whereas fluids 5 to 8 showcase a similar coherence within their group but noticeably deviate from the characteristics of the first set. The average velocity of non-surfactant-laden drops is 7.95 m/s when the surfactant-laden drops average a velocity of 6.92 m/s. This 14.9 % change in terminal velocity is significant. One conclusion from this plot is the influence of surfactants on the terminal velocity of hydrometeors; drops containing surfactants exhibit significantly lower terminal velocities compared to those devoid of surfactants. This coincides with our other observation indicating that surfactant-laden drops achieve a more regulated and stable descent when contrasted with their surfactant-free counterparts. This case underscores the hypothesis that the diminished surface tension in surfactant-containing drops, leading to a disc-like shape, facilitates their levitation at lower air speeds.

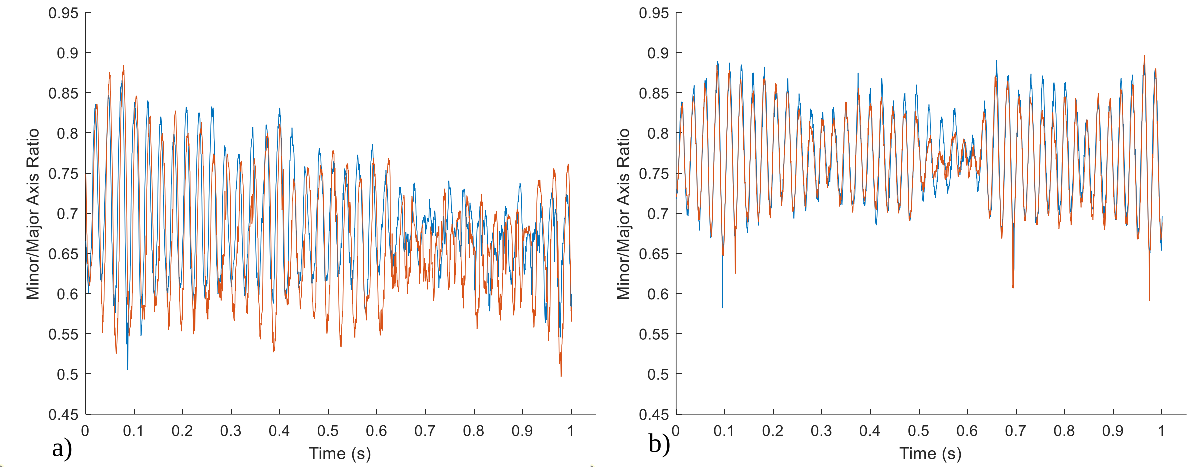

Fig. 7 Ratio of minor axis and major axis for levitating droplet a) S1 b) D1

Figure 7 shows the ratio of the droplet's minor axis and major axis over time. The droplet in plot a) is DW mixed with surfactant while plot b) shows a DW drop. The blue line refers to the ratio from the front view while the red line is the ratio from the side view. The plot a) initially begins with large deviations in the ratio, but as time progresses, the ratio begins to converge towards a ratio of .67, meaning the drop's height is 67% of its width. The figure shows that the droplet's axis ratio is more erratic with no discernable pattern. The droplets axis ratio initially begins to converge, but then diverges back to its starting state. This shows that the DW droplet is struggling to stabilize inside the observation chamber. There is a notable difference when comparing the DW droplet to the surfactant laden drop. It is important to note the video is 1.0005 seconds long, so it is possible that the DW droplet would eventually stabilize. However, it would be difficult to test due to the droplet's rapid evaporation rate and the chance for the drop to collide with the wall of the tunnel as DW is an unstable drop.

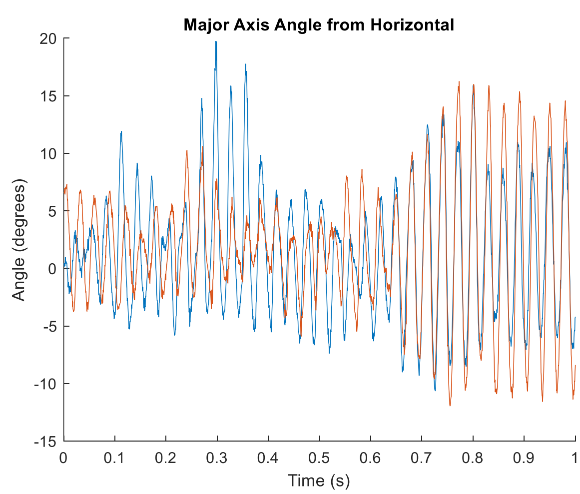

Fig. 8 Angle of Major and Minor Axes

Figure 8 shows the angle of the major axis relative to the horizontal through time. Pure lateral oscillation would be observed at an angle of zero, while pure vertical oscillation would be observed at an angle of 90. Interestingly, the major axis angle never measures greater than 45 degrees in distilled water, indicating that the droplet maintains a state of lateral axis oscillation and never enters a state of vertical axis oscillation. We believe this is due to the compressive force of gravity acting in opposition to the levitating force due to the wind tunnel. Additionally, the phase of the angles alludes to the orientation of the droplet. Similarly, we can look at the phase of the axis ratio for each camera view seen in Figure 7a to describe the orientation of the axis of lateral oscillation. When the axis ratio is in phase (phase = 0 degrees) the axis of lateral oscillation is orthogonal direction, and when phase = 180 degrees, then the axis of lateral oscillation is along the plane of the camera view.

An accurate volume estimate may also be possible utilizing the phase angles. We use a spherical model to approximate an equivalent volume of the drop through time. An equivalent diameter is created from approximating the diameter required to create a circle with area apparent of the drop in each camera view. An average equivalent diameter is derived from the equivalent diameter of the observed drop in each camera view. The volume of a sphere is then computed with equivalent volume to the drop. We hypothesize that the equivalent volume would also change with respect to time and that the most accurate calculations would be at the major and minor axis when the axis ratio is close to one, however this seems to never happen, instead the droplet takes on a disk like shape in a state of lateral oscillation. In this case, the volume approximation would best happen when the major axis angle is zero and as an ellipsoid. This leads to an interesting implication: the hydrometeors would be best approximated with an ellipsoid when in phase.

Finally, we used the minor/major axis ratio data and performed a Fast Fourier Transformation(fft) to determine the oscillation frequencies of the drops. Upon completion of this analysis, we found that the fluid types can control the frequency and magnitude of droplet oscillation.

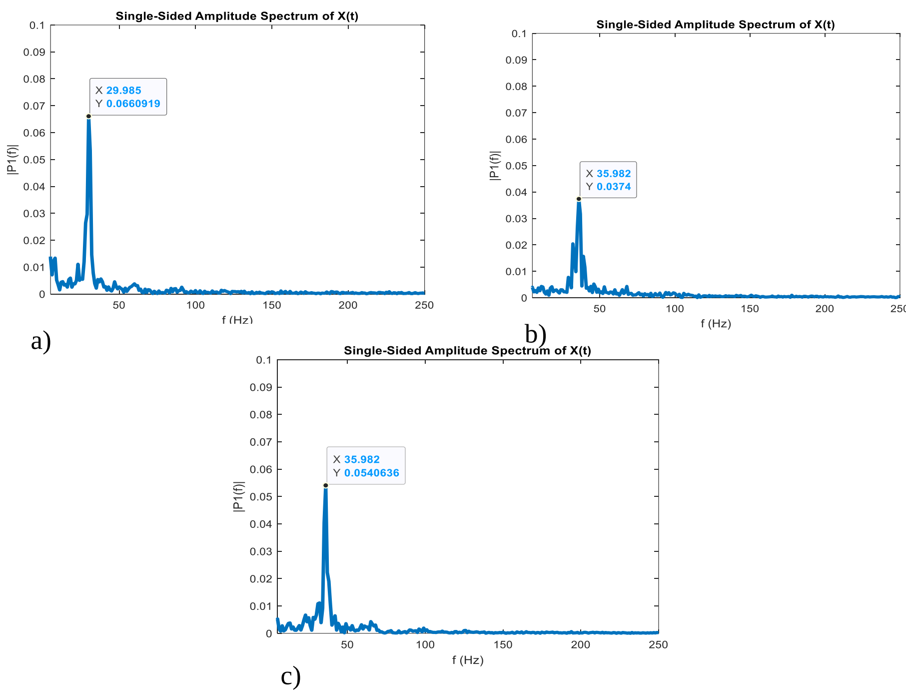

Fig. 9 The FFT of Major to Minor Axis Ratio a) DW b) N1 c) N1S1

Figure 8 shows that the shapes of each curve are similar, each having one frequency where the magnitude of oscillation is largest. While they all appear very similar, we see that the frequencies and magnitudes for each fluid type are unique. The DW drop has the lowest frequency, 29.9 Hz, but has the highest magnitude at 0.066. When the nanopowder is added to create N1 the frequency jumps to 35.98 Hz. It is interesting to note that this stays the same when surfactant is added to produce N1S1. We also find from these plots that the magnitude is almost halved for N1 but then returns nearly back to the DW's levels for our N1S1 drop. From this data we suggest that surfactants did not significantly affect the oscillation frequencies of our drops but appear to mostly be controlled by the nanoparticle concentration. Furthermore, we find that the oscillation frequency is controllable by the presence of surfactant in the solution.

V. Conclusion

This study's innovative approach to investigating hydrometeor behavior in a vertical wind tunnel offers a novel perspective on drop levitation dynamics. The unconventional bottom-up airflow design, combined with high-speed imaging and MATLAB-based image processing, has provided insightful data on the effects of surfactants and nanoparticles on drop stability and shape. Our findings highlight the potential for controlling drop behavior through chemical additives, sparking interest and the desire for further research into this topic. The research underscores the intricate relationship between fluid properties and the effects they have on hydrometeor behavior.

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