Raindrop Collision Dynamics in a Vertical Wind Tunnel with Velocity Well

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This paper discusses a literature review of hydrometeor collisions in relation to preliminary and planned future experiments. Drop on drop collision experiments are performed in a vertical wind tunnel with a radial lateral velocity well and linear vertical velocity gradient, in an effort to understand weather phenomena such as cloud formation, cloud dissipation, and precipitation. Silicon dioxide nanoparticles are mixed with distilled water to create nanofluid whereas a surfactant, Triton X-100, is added to decrease the surface tension of the fluid. I look at interactions of N0 (distilled water), N1 (1% silicon dioxide), S1 (0.02% Triton X-100), and N1S1 (1% silicon dioxide, 0.02% Triton X-100) drops. Only two colliding water drops are observed at a time. From preliminary experiments, it is observed that when drops of varying nanoparticle concentration collide, merge, and break apart, there is little to no mixing that occurs so that the final drops are almost identical to the initial drops prior to the collision. I further discuss in this paper the methods to test several hypotheses and preliminary findings on drop coalescence, breakup phenomena, drop shapes, drop motion, drop oscillation, and drop sizes resulting from collision events.

I. Nomenclature

N0	=	distilled water
N1	=	1% silicon dioxide dissolved in distilled water
S1	=	0.02% Triton X-100 dissolved in distilled water
N1S1	=	1% silicon dioxide and 0.02% Triton X-100 dissolved in distilled water

II. Introduction

Hydrometeors encompass a diverse array of water and fluidic particles traversing the atmosphere, manifesting as rainfall, cloud formations, ice particles, and any resultant product arising from the condensation of water vapor. The examination of droplet interactions assumes significance in clarifying atmospheric reactions and their implications for environmental dynamics. A notable instance is the phenomenon of coalescence, where smaller water particles within clouds form together to create larger droplets, precipitating down as rain.

Experimental investigations into these interactions are structured around the utilization of distinct droplet types denoted as N0, N1, S1, and N1S1. Notably, the composition of atmospheric hydrometeors typically incorporates secondary particulate matter; this puts influence on the physical properties of the droplets, modifying their inter and intra-droplet dynamics. Parameters under investigation encompass droplet dimensions, surface tension, velocity, viscosity, and impact orientation. The integration of nanoparticles and surfactants into the droplet matrix facilitates the refined observation of these varied characteristics during experimental procedures.

A subsonic, vertically oriented wind tunnel is utilized within the protocol of these experiments. Within the observation chamber, a stainless-steel wire mesh is positioned at the base, configured to generate a horizontal, radial velocity gradient in the airflow, thereby maintaining droplet centralization. The chamber walls exhibit an outward angle, serving to induce a vertical velocity gradient. The angle of inclination is chosen to strike a balance, ensuring that airflow velocities are sufficiently elevated at the chamber base to propel droplets upward while tapering off towards the chamber apex to forestall droplet escape.

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A. Scope

The overall focus of this work is discovering more about different phenomena resulting from drop collision events that take place in the atmosphere. The perspective of this review is written from an engineering student reiterating hydrometeor research and experiments with the end goal of applying the knowledge to future findings and observations. This paper is divided in to two parts. Firstly, an overview on the different droplet collision events will be discussed, in addition to a background on nanofluids and surfactants used in previous experiments. The second portion of this paper will discuss more in depth the method and set-up of initial experiments that will be later performed in the vertical wind tunnel.

III. Drop Collision Parameters

The collision of drops typically resolves in two different ways: coalescence or the merging of the two drops, or the two drops involved in the event split into more, smaller drops. These two events are impacted by a multitude of different parameters. The factors that are more easily measurable while also having an impact on the outcome of the collision event include the drop shape, size, motion, and oscillation. The implementation of nanofluids can alter those measurable factors which, in turn, influence the outcomes of drop collisions.

A. Drop Coalescence

Schlottke et al. [1] discusses how whether or not drops merge or breakup after a collision can be determined by the eccentricity of the drops involved in the collision. Which involves looking at the ratio of the droplet diameters. It was determined that drops are more likely to coalesce if their eccentricity is lower. Meaning that if droplets are closer in size merging is more likely to be observed compared to the collision of droplets with a larger difference in size.

B. Breakup Phenomena

The aftermath of droplet collisions often results in additional smaller drops. Though at times drops will combine to form a larger single droplet, the difference in results depend on varying factors. Larger drops are more likely to breakup in comparison to smaller drops due to the increase in size making them more unstable hydrodynamically Szakáll et al. [2].

C. Drop Shapes and Size

As droplets move through the wind tunnel, shape will be altered by the airflow and speed of fall, so it is impossible to maintain a consistent shape throughout experiments. It was reported from Szakáll et al. [3] that changes in drop shape resulted in no notable differences of outcomes in collisions from experiments of moderately sized (0.5-2.5mm) drops. Jones and Saylor [4] observed the shape as a ratio between the vertical and horizontal chords of the droplets. Drops that were larger typically had a more oblique shape which results in a higher vertical to horizontal chord ratio. On the other hand, smaller drops had a more stable and uniform shape resulting in a closer one to one chord ratio.

The size of the droplets makes an impression on the stability and shape during free-fall through air as discussed by Szakáll et al. [2]. If the diameter of the droplets is less than 1 mm, they can be considered rigid spheres. The reason that droplets any larger than that cannot be considered a rigid sphere is because the surface tension of the droplet becomes weaker due to the increase in weight.

D. Drop Motion

Szakáll et al. [3] determined that natural collision process of droplets was obtained in experiments and noted no significant deviation from collision outcome characteristics. In droplets with a diameter over 1 mm, Szakáll et al. [5] observed that the internal circulation of the drops is irregular and turbulent with continually changing vorticities. Buoyancy-forces creates the non-straight path of motion, discussed by Ern et al. [6] as the droplets fall through the air. The shape of the drops and the paths both influence each other due to intra-droplet movement.

E. Drop Oscillation

Following a collision of moderately sized droplets Szakáll et al. [3] reported an axis ratio increase within the larger droplets. Though overall, the droplet axis ratio did not have a significant change of orientation. The cause of this was concluded to be from the whole-body rotation of the droplets. For experiments with larger droplets (2.5-7.5 mm), Szakáll et al. [5] reported that an increase in drop size, increases amplitude of oscillation. Szakáll et al. [2] talks about how drop behavior is impacted by oscillations as well. It is discussed how an increase in amplitude causes a decrease in the oscillation frequency which also results in a higher deformation of the drop.

F. Nanofluids

Nanofluids alter different characteristics of the droplets during experiments with the purpose to create different visualizations. Especially with larger droplets, just using water can create an unstable form. Ranjbarzadeh et al. [7] noted graphene oxide increased the friction coefficient of droplets significantly compared to using pure water. It was found that the use of this nanofluid improved heat transfer in addition to adding stability to the physical shape of the drops. Changing the thermal conductivity was tested by Mohammadian et al. [8]. It was found that the inclusion of silver nanoparticles in deionized water increases the thermal conduciveness of the drops, which increases the amount of heat transfer.

While suspended in the wind tunnel, evaporation of the droplets still occurs causing them to become lighter and smaller. Ahumada-Lazo and Chen [9] recorded the evaporation factor of droplets with varying concentrations of nanoparticles. It was found that as the concentration of aqueous nanoparticles increases, the evaporation factor decreases. The implementation of this discovery was used to increase the amount of time that the droplets stay suspended in the wind tunnel. The influence that nanoparticles have in evaporation rate was tested by Sefiane and Bennacer [10] using aluminum nanoparticles. In these experiments, varying concentrations of the aluminum nanoparticles were suspended in ethanol. It was observed that as the concentrations increased so did the viscosity of the fluid. In turn, this decreased the amount of time it took the ethanol to evaporate. Chen et al. [11] tested concentrations of varying nanoparticles and surfactants to record how the increase or decrease in the rate of evaporation influences heat transfer. For example, it was found that aqueous iron oxide nanoparticles decrease evaporation which increases the latent heat of vaporization. The surfactant was observed to increase the rate of evaporation and helped stabilize drops. Overall, the utilization of nanoparticles can help to test different factors by altering the characteristics of droplets.

IV. Experiment and Initial Observations

A. Vertical Wind Tunnel

The final design goal of this wind tunnel was to push air from the fan at the base up through the top opening and freely suspend drops within the observation chamber. This is so the formation, break-up, interaction with additional particles, and air currents could be observed and recorded. Fig. 1 shows a picture of the wind tunnel that will be discussed in the remainder of this paper. This design has the capabilities of performing the same types of experiments as some very advance, expensive wind tunnels in other research labs while maintaining a smaller profile and being relatively inexpensive to manufacture. Though the entire structure is sealed, it has the capabilities to be disassembled for transport and maintenance. The modular versatility allows for flexibility on the types of experiments that this wind tunnel can be utilized for.

Fig. 1 Vertical wind tunnel used for initial experiments.

A disassembled breakdown of the wind tunnel is shown in fig. 2 to display the different design components. Going through the components from bottom to top, following the airflow through the wind tunnel. The base section connects to the fan and holds an air filter to prevent any unwanted air contaminants from being pushed through. The next section holds honeycomb laminarizers to help straighten out the airflow, the curve of this section was designed to allow a more streamline flow to the reduced area Sargison et al. [12]. The following section contains the stainless-steel wire mesh. A cross-section of the formation of the wires is shown in fig. 3. The purpose of this mesh is to create a horizontal, radial velocity gradient Emersic et al. [13]. The condensed formation of the wires in the center slow down the velocity, while the more open space towards the outer perimeter of the wire mesh allows for a faster air flow Bhalwanker et al. [14]. This is to keep the hydrometeors centralized in the observation chamber and prevent the drops from hitting the side walls. The section following where the wire mesh is holds the acrylic glass that forms the observation chamber. A linear area transition ratio of 1.25 is maintained in this section from the outward angle that the acrylic glass is set to. The observation chamber is the location of where all experiments will be performed. The final and top piece is put into place to support the angle of the acrylic glass and to ensure an open top to allow air to flow out of the tunnel. Which also allows an opening for droplets to enter the wind tunnel system.

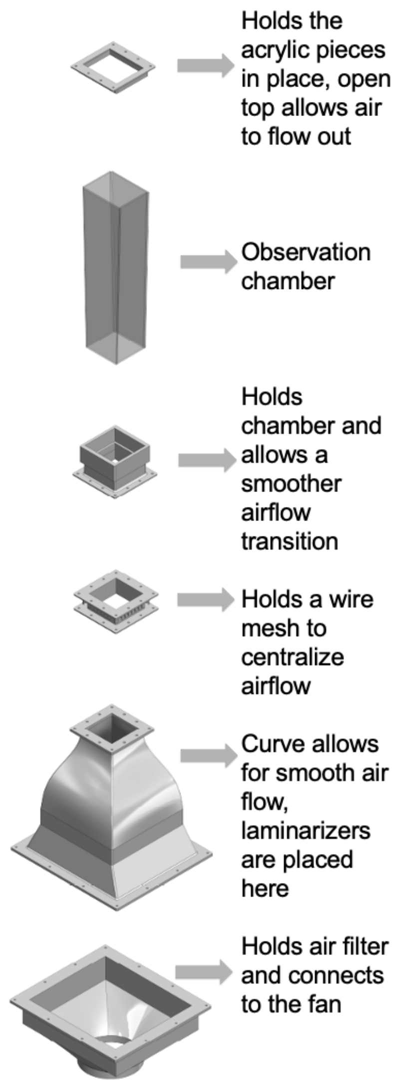

Fig. 2 Vertical wind tunnel disassembled with part descriptions from Sebek et al. [15].

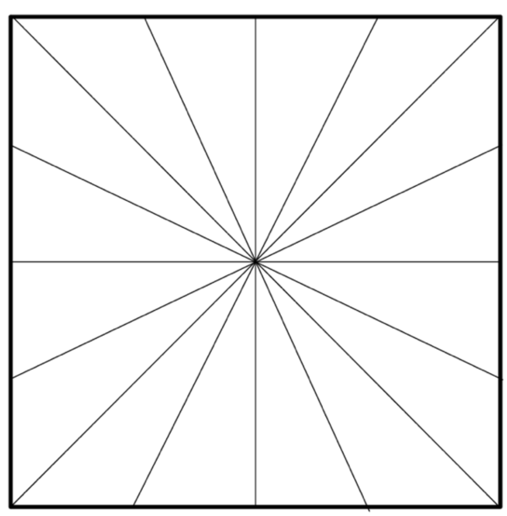

Fig. 3 Intersection stainless-steel wires at base of vertical wind tunnel observation chamber.

With this current design, velocity of the airflow at any time is unmeasurable. Although later implementation of anemometers will be used to measure the entrance and exit velocities. The current set up measures the voltage supply which powers the fan. The voltage can be altered to change the speed of the airflow. The entire structure is sealed with rubber gaskets and a non-water-soluble sealant to ensure no unwanted air leaks are present. The overall shape of this tunnel is a more rectangular design versus a rounder, more cylindrical shape for several reasons. Acknowledging that a cylindrical design could have resulted in a more efficient system of airflow due to the rounder nature, it wasn't a realistic design choice for the needs of this research. The rectangular design allows for a non-distorted recording and viewing of the droplets suspended in the observation chamber. Additionally, a cylindrical design would have been more expensive to build and maintain.

B. Experimental Set-up

To suspend the droplets, the voltage of the power source connected to the fan at the base of the wind tunnel was set to 100 volts. Two high speed cameras were placed on either side of the observation chamber and synchronized to capture multiple angles. The 100 volts setting allowed for the air flow to be powerful enough to suspend the droplets within the frames of the cameras. The different substances being tested where premixed and put into needle syringes to drop through the opening at the top of the observation chamber.

Preliminary experiments were performed to obtain base observations and gauge what additional tests should be performed. The videos collected from the cameras were put through a MATLAB code programed to track the drops. Fig. 4 shows a screenshot from the tracking system that was created for these experiments. In this particular image, it shows two distilled water drops before collision. The program is able to recognize the two drops and tracks their movement for the duration of the entire collision event.

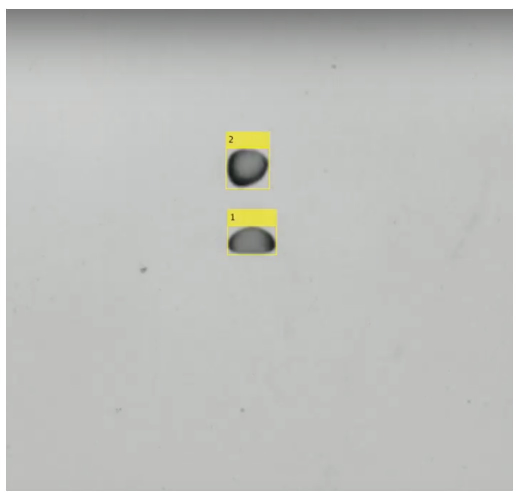

Fig. 4 Drop collision tracking system monitoring drops within a video.

An image sequence from a video of two distilled water drops colliding is shown in fig. 5 to further display the tracking capabilities. Throughout the video, the droplets are traced before, during, and after the collision event. Even after the breakup of the droplets after the collision, the additional and smaller droplets that were formed were also monitored. Along with the movement, the shape, size, and orientation of the droplets can be monitored at different points throughout the video. This increases the precision at which the recorded data is able to be analyzed and discussed.

Fig. 5 Image sequence of drop collision tracking.

C. Initial Observations

The initial experiments performed revealed various observations that can be connected to previous research. One notable variable observed with an N0 drop on N0 drop was the size of the droplets. If there was one droplet noticeably larger in size than another, the droplets were less likely to merge. More often than not, the drops would not get close enough to each other to touch. It was observed that as the drops got closer, the smaller droplet appeared to change normal course of oscillation and fly into the side wall of the observation chamber.

The following three figures are image sequences from different collision events with two distilled water drops. Fig. 6 shows the collision and coalescence of the droplets. In this video, it can be observed that two drops of a similar shape had a direct collision in which they merged and formed one single drop. This drop continued to stabilize and remain suspended in the wind tunnel after the collision event.

Fig. 7 displays an image sequence of the collision and immediate breakup of the droplets. The event that takes place in the video can be observed as two droplets, though they are of similar size, have an indirect collision. It can be seen how one droplet sideswipes the other during the collision. This could be why the collision immediately resulted in a breakup collision verses merging together into one single drop. The force of the impact caused the droplets after the collision to lose stability and careen into the walls of the observation chamber.

The events observed in fig. 8 appear to be a combination of the events that occur in both fig. 6 and fig. 7. The two droplets appear to be a similar size but have a slightly indirect impact of collision. At first, after the initial collision, the drops appear to coalesce and form one drop. Though the size and shape of the drop seems unstable due to the disk shape it forms. This instability is the most likely cause of a smaller drop to break off towards the end of the sequence and flies into the wall of the observation chamber. Once the smaller droplet separates, the larger drop that was formed after the collision appears to stabilize and remains suspended in the wind tunnel.

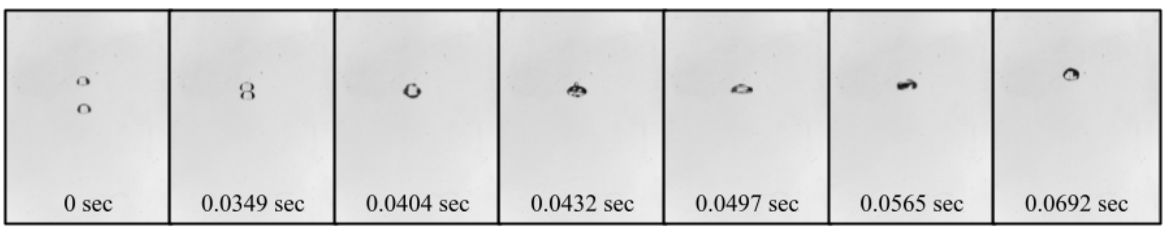

Fig. 6 N0 drop on N0 drop collision and coalescence.

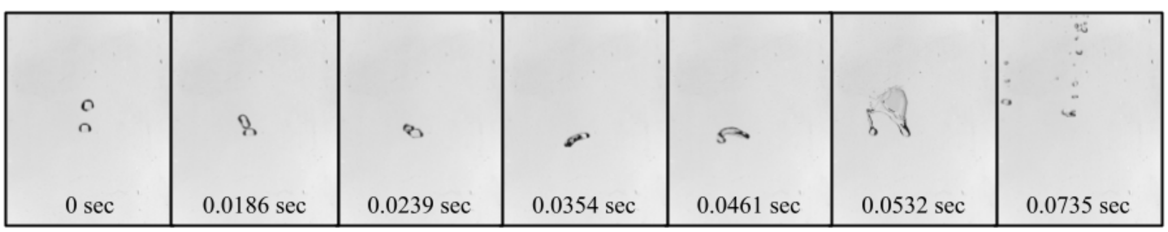

Fig. 7 N0 drop on N0 drop collision and break-up.

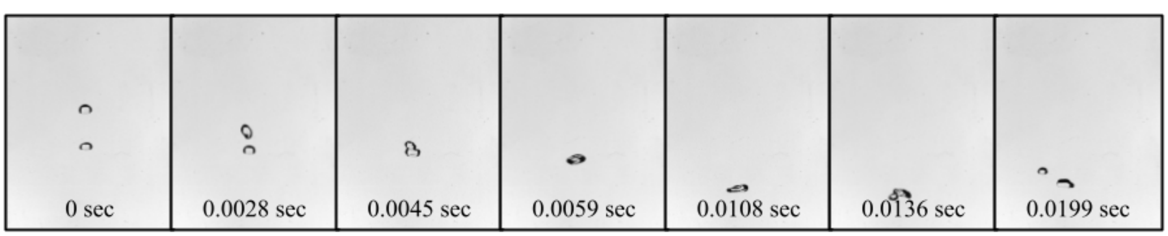

Fig. 8 N0 drop on N0 drop collision, coalescence then eventual breakup.

Inside the observation chamber of the vertical wind tunnel, the distilled water droplets show to be unstable. With the implementation of the silicon dioxide nanoparticles and the Triton X-100, the droplets start becoming more stable. Overall, the droplets with these inclusions can remain suspended in the observation chamber when the fan is set to a lower voltage compared to just distilled water droplets. The Triton X-100 decreases the surface tension in the droplets which allows them to take a more elastic shape compared to droplets without. Silicon dioxide nanoparticles are going to be used to change the rate of evaporation in the drops. There have currently been no tests of drop collision with the nanoparticles or surfactant performed in this wind tunnel, but it will be observed in the near future. Parameters including oscillation frequency, shape, and terminal velocity will also be observed in comparison to the distilled droplets and how impact collision events will be impacted.

V. Conclusion

The observations collected from the initial experiments performed matched previous research carried out on the collision phenomena of droplets. The data collected will be utilized as an introduction to future experiments that will be executed using the vertical wind tunnel. Possibilities for future experiments include observing droplet collisions utilizing N0, N1, S1, and N1S1 droplets. The initial drop on drop experiments were just performed using distilled water, so refining the procedure to make additional observations involving the nanoparticles and surfactants will be the next step.

Additional ideas for future experiments involve observing the collision events of more than just two droplets at a time. And recording the types of phenomena that appear to see if findings are still consistent with the current research. Changes in the conditions of the experiments could also be a factor to observe. Since currently everything is performed at room temperature, an increase or decrease in the environmental temperature of the experiments could be very insightful. The temperature of the fluids used for the droplets is another compelling component. The different variations of these experiments are countless and will continue to shine light on the different parameters that impact droplet collision outcomes.

Acknowledgments

I thank Gene Patrick Rible and members of his research team who are working on the vertical wind tunnel at the Fluids and Structures Laboratory at the University of Tennessee, Knoxville. I also thank Dr. Andrew Dickerson, the laboratory head, for supporting this project and the National Science Foundation (NSF GEO 2201828) for the financial support.

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