Controlling Motion of Levitating Drops in a Vertical Wind Tunnel Using Velocity Wells

Aaron Matheny*
University of Tennessee, Knoxville, Tennessee, 37996, USA

Previous vertical wind tunnel experiments use a crosswire insert to create a velocity well, wherein the slowest wind velocity occurs at the center of the crosswire, allowing water drops to levitate at the center of the tunnel. However, such an approach has notable limitations: the wires gradually lose tension and sag, introducing unwanted turbulence, and the insert is difficult to modify for specialized applications. To address these issues, we develop a 3D printed honeycomb insert, reducing turbulence, enhancing precision in generating a velocity gradient, and allowing for specialized modifications in the velocity well. In this work, we design a honeycomb insert capable of generating a unique velocity gradient to trap a water drop in a ring around the center of the wind tunnel. We assess the effectiveness of the honeycomb structure for future velocity well experiments using Computational Fluid Dynamics (CFD) simulations to generate velocity and vorticity surface plots. Our simulations indicate that with our current design, we can achieve and maintain the desired velocity gradient throughout most of the wind tunnel with minimal vorticity, validating the potential of the honeycomb structure for further applications.

I. Introduction

Studying the shape and movement of drops can prove useful regarding the study of weather patterns and drop size distribution [1]. Where standard horizontally-oriented wind tunnels are used for most aeronautical research, studying raindrop behavior requires a vertical configuration to accurately recreate the conditions under which raindrops form. Low velocity vertically oriented wind tunnels are employed to levitate drops, allowing experiments to be conducted that examine the shape of falling drops [2]. Additionally, vertical wind tunnels are used to study the mechanics of drop interaction and breakup, which is relevant to study of raindrop formation and precipitation [3].

Vertical wind tunnels (VWT) have been used to examine the mechanics of drop interaction and hydrometeor behavior [4]. Previous experiments use a crosswire inserted into the VWT to centralize airflow [5] [6]. The wires obstruct the flow in the center of the wind tunnel, creating a low-velocity region in which drops will levitate. The crosswire method has several shortcomings. Wires gradually lose tension and sag, producing unwanted turbulence. The crosswire also introduces methodological inconsistencies since the wire inserts are created by hand.

To address these issues, a 3D printed honeycomb insert was developed in a previous experiment [7]. The honeycomb structure allows for greater precision in creating velocity gradients and is easily replicable. Additionally, where the crosswire structure was limited in its possibilities, the honeycomb structure allows for various designs to produce specialized velocity gradients. Where the crosswire merely produced a central velocity gradient to levitate drops in the center of the VWT, the honeycomb method could potentially be employed to levitate drops in a spiral pattern. The objective of this experiment is to create a honeycomb insert to achieve spiral motion in a levitating drop, referred to as a spiral honeycomb (SHC) insert, proving the viability and potential of the honeycomb structure.

II. Methods

A. Vertical Wind Tunnel

The Vertical Wind Tunnel (VWT) employed in these experiments is comprised of six parts as shown in figure 1. For simulations, only parts 1-4 are used. The honeycomb and wire inserts go into part 4, with different versions of part 4 to accommodate the wire and honeycomb inserts. The observation area of the wind tunnel has a 120 mm x 120 mm base and height of approximately 7 m.

*Undergraduate Student, Mechanical, Aerospace, and Biomedical Engineering, Student Member, 1810514

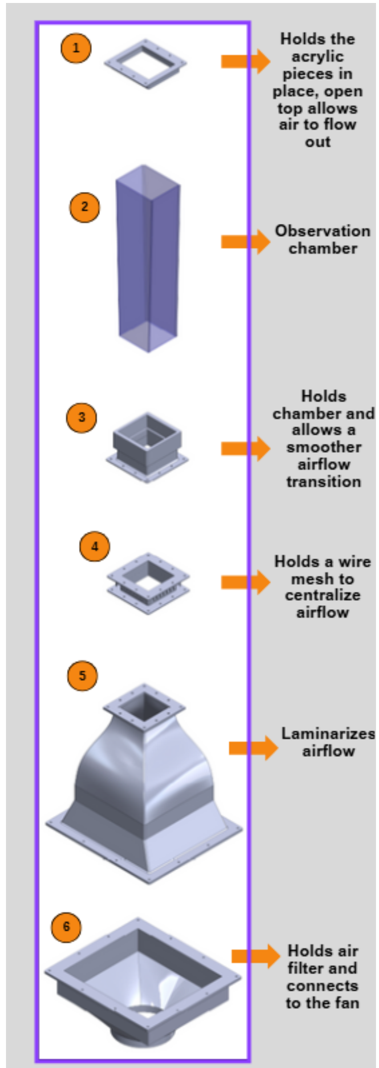

Fig. 1 VWT assembly.

B. VWT Insert Models

16 wires of 0.1397 mm diameter are strung through the 32 evenly spaced holes along the midsection of the wirepart to form the crosswire. The holes have a slight tolerance to fit the wires, but do not affect airflow. The wires overlap in the middle of the VWT, obstructing the wind flow in the center, creating a centralized velocity well as shown in Figure 2.

The honeycomb inserts are designed on the principle that airflow is slower through areas with smaller diameter hexagons. This allows for precise control over airspeed within the VWT since the flow velocity is easily manipulated by adjusting the hexagon diameter.

The honeycomb inserts are held in the VWT by a slider that is inserted into a modified wirepart as shown in figure 3. This part replaces the original wirepart in the assembly. The honeycomb models are printed with an attachment to hold it in the slider without affecting airflow. SolidWorks and the SolidWorks Flow Simulation toolbox were employed for modeling and simulating the honeycomb inserts. After finishing a model, CFD analysis is performed to asses the viability of the model before 3D printing.

C. Honeycomb Modeling

Two projects with the honeycomb inserts are ongoing: the spiral honeycomb (SHC) structure that is the subject of this paper and a central honeycomb (CHC) structure. The CHC is intended to create a central velocity well similar to

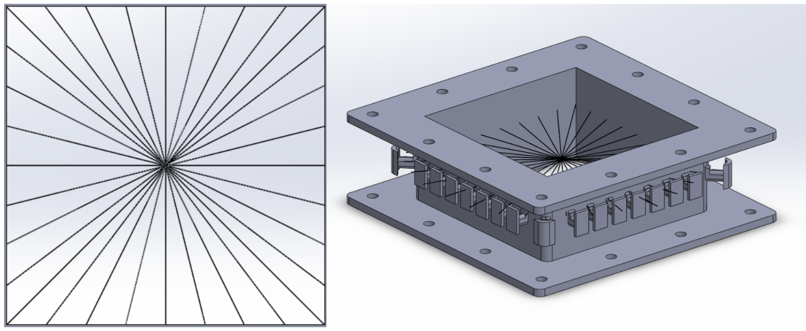

Fig. 2 Wire insert top view and wirepart.

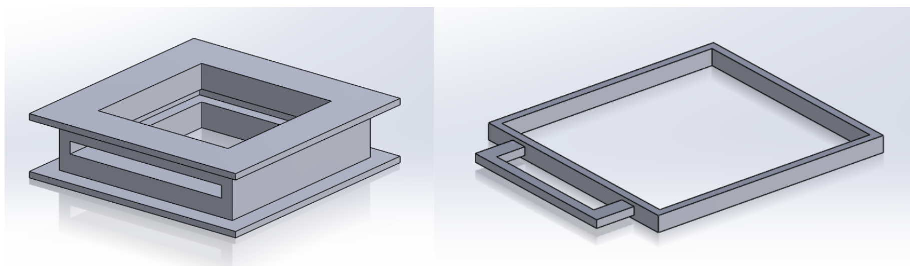

Fig. 3 Slider with modified wirepart.

the crosswire, but with greater precision and less vorticity. The CHC has smallest hexagon diameter in the center with the diameter increasing outward as shown in figure 4.

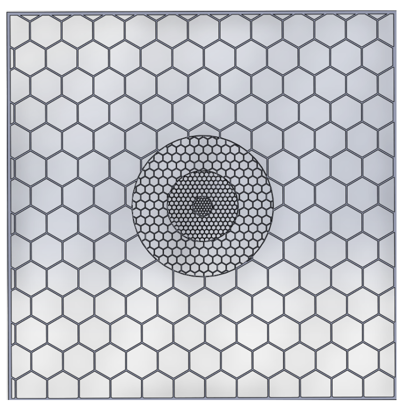

Fig. 4 CHC top view

The SHC structures are assembled of an inner ring, center ring, and outer ring with the outer ring also including the corners. Three SHC configurations were tested in this experiment. The first model, SHC 1, has a constant diameter center ring as well as additional inner and outer rings with higher diameter hexagons to create a more gradual velocity gradient as shown in the left panel of figure 5. The second model, SHC 7, has a variable hexagon diameter center ring with simple rectangular supports for the inner and outer areas. SHC 13 has a similar center ring to SHC 7, but utilizes the honeycomb pattern for the inner and outer areas. The areas in each model that have the smallest hexagon diameter is the area over which the wind velocity will be at its slowest. This velocity well will cause the drops to levitate in this area, called a center of levitation (COL).

The rings are classified by their starting and ending radii as measured from the center of the VWT. The rings are comprised of hexagons with a different diameter in each ring. The inner and outer rings have uniform hexagon diameter while the center ring has radially varying hexagon diameter. This creates a smoothly increasingly velocity gradient through the center ring in which the drop will levitate. Each "slice" of the center ring is created as a separate part. These slices are then assembled to form a complete ring. Multiple inserts were modeled and simulated to determine the fitness of the model before 3D printing.

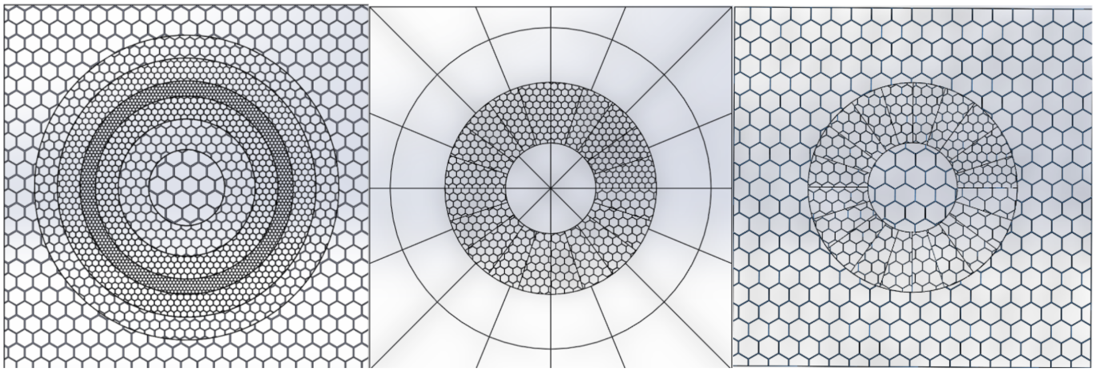

Fig. 5   SHC 1 (left), SHC 7 (middle), and SHC 13 (right).

D. CFD Test Procedure

The main characteristics of importance are flow velocity and vorticity. The flow velocity is related to the formation of the velocity wells in which the drops will levitate. Vorticity is a measure of rotationality i.e. turbulence [8]. Minimizing vorticity is paramount, as excessive turbulence will impact the stability of drop levitation.

Once a model is developed, CFD analysis is performed to gather information on vorticity and to observe if the desired velocity gradient was maintained throughout the entire VWT. For the geometry, a SolidWorks assembly of the VWT was used which was identical to the model as shown in figure 1, but without parts 5 and 6. Removing these parts cuts back on the size of the computational domain, significantly reducing computation time while having little impact on the simulation. The SHC insert was placed in the wire part with the wires removed. This was simpler than including the slider while having no effect on the fluid behavior.

A basic rectangular mesh was used with a higher level of refinement around the area containing the insert to capture the fluid behavior around the fine details of the honeycomb inserts while cutting down on computation time. SolidWorks Flow Simulation utilizes a basic global mesh that allows for higher levels of refinement locally as defined by the user. For all simulations, a global mesh of 50 x 50 x 100 cells was used with 100 cells along the vertical axis of the wind tunnel. A rectangular local mesh with level 2 refinement is used 100 mm above and 50 mm below the insert, for a total of roughly 2 million cells.

Boundary conditions are defined at the bottom and top of the VWT. The top acts as a pressure opening with atmospheric pressure and room temperature. The bottom is defined with a flow velocity of 8 m/s. The fluid used for the simulation is air with gravity acting down along the vertical axis of the VWT. All other surfaces in the assembly are defined as fixed walls.

SolidWorks Flow Simulation has various tools for recording relevant data. To collect data on flow velocity, a cut plot is used to observe the velocity gradient at a contour 100 mm above the top of the insert. The plot is this far above the insert to observe that the velocity gradient is maintained throughout the observation window, as 100 mm above the insert is typically where drops are expected to levitate and be recorded in experiments. Vorticity is recorded using a cut plot at the same position as the velocity plot.

III. Results and Discussion

A. Wirepart CFD Results

Results from CFD of the crosswire show a smaller flow velocity in the center of the crosswire with much higher velocity around it as shown in figure 6. The flow velocity in the center is around 0.926 m/s while the velocity surrounding the center is approximately 8.175 m/s. These data show that the intended velocity gradient is achieved from the crosswire. This is confirmed from live use of the crosswire in the VWT as the drops can be observed levitating in the center. Vorticity is high around the wires and the walls of the VWT, with the highest vorticity in the center of the crosswire.

The vorticity in the center of the crosswire is around 6000 1/s, while it is nearly 0 in the areas away from the center. This is confirmed by the extensive live use of the crosswire in previous experiments, as the drops levitate in the center with a fair degree of stability.

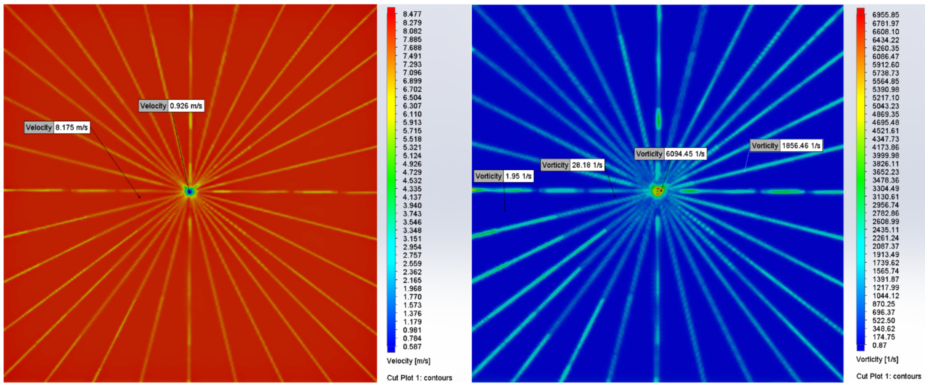

Fig. 6 Velocity plot (left) and vorticity plot (right) for crosswire.

B. CHC CFD Results

As shown in figure 7, the CHC has a flow velocity in the center of 3.738 m/s, with flow velocity increasing outward from the center until it reaches a peak of around 9.121 m/s surrounding the center. Vorticity behaves the same, with vorticity ranging from 51.03 1/s in the center to 533.85 1/s around the center. Compared to the crosswire, the CHC has a similar velocity gradient, but different vorticity. The CHC has much lower peak vorticity than the crosswire, but non-negligible vorticity is present throughout the entire area, while the crosswire saw nearly no vorticity away from the center.

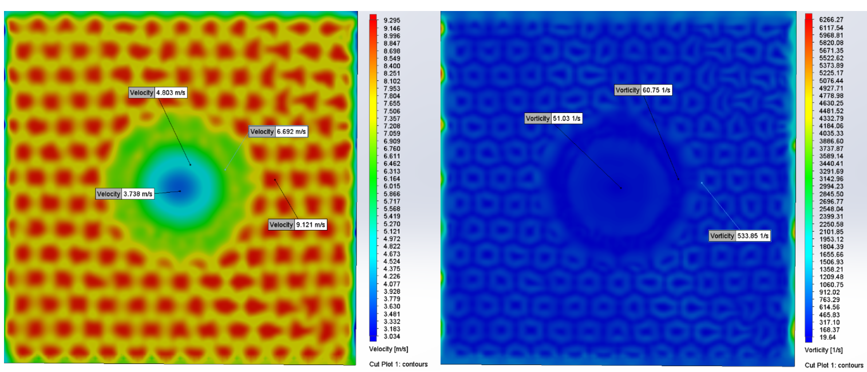

Fig. 7 Velocity plot (left) and vorticity plot (right) for CHC

C. SHC 1 CFD Results

Of the 19 SHC variants modeled and simulated, three were printed for future live VWT testing after displaying promising results in CFD.

SHC 1 lacks the variable diameter centering of the later models. It also has 7 rings instead of 3 for a more gradual velocity gradient, with the smallest hexagon diameter in the center ring and the largest in the outer and innermost rings as shown in figure 8.

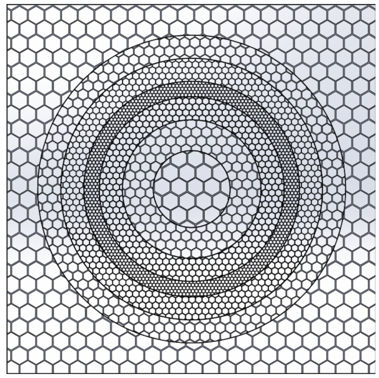

Fig. 8 Top View of SHC 1

As shown in figure 9, a velocity gradient is achieved with the lowest velocity in the COL. The velocity increases outward in both directions from the COL. The low velocity is 5.926 m/s with the velocity increasing outward from the COL up to 9.089 m/s. Vorticity has similar behavior to the CHC, with a vorticity in the COL of around 116.62 1/s and a vorticity of 312.96 1/s around the COL. Like the CHC, the vorticity is more uniform than the crosswire, with lower peak vorticity but higher vorticity on average.

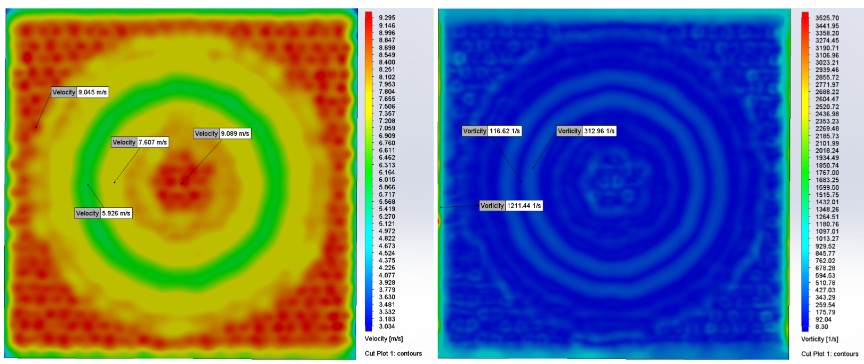

Fig. 9 Velocity plot (left) and vorticity plot (right) for SHC 1.

D. SHC 7 CFD Results

SHC 7 has a center ring that utilizes the honeycomb structure with rectangular supports in the inner and outer areas as shown in figure 10. The center ring is made of 20 equally sized slices with the hexagon diameter of each section increasing around the ring. The smallest hexagon diameter is 2.00 mm with the diameter increasing by 0.05 mm in each subsequent slice such that the final slice has a diameter of 2.95 mm. The thickness of the hexagon walls as well as the supports is 0.150 mm which is roughly equal to the thickness of the wires used for the crosswire.

SHC 7 has a roughly uniform velocity gradient across the COL, with the velocity being slightly higher over the larger diameter slices. The velocity outside the COL is 8.772 m/s with the velocity in the COL varying from about 6.387 m/s to 7.226 m/s as shown in figure 11. The vorticity across the COL is approximately uniform with vorticity of roughly 375 1/s along the edge of the COL. While the intended velocity gradient is created, the effect could be made stronger. The vorticity is comparable to that of the CHC and SHC 1.

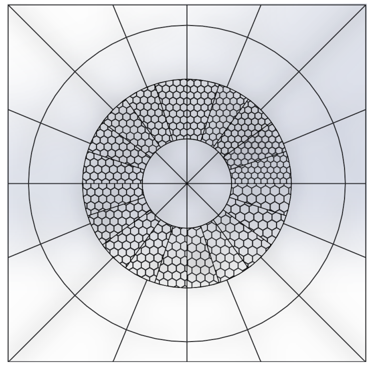

Fig. 10 Top view of SHC 7

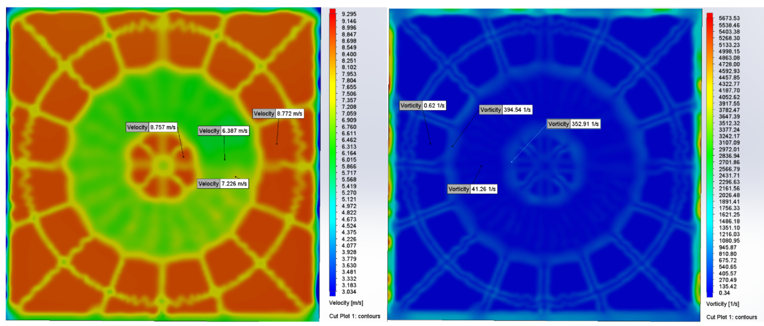

Fig. 11 Velocity plot (left) and vorticity plot (right) for SHC 7

E. SHC 13 CFD Results

The final model is SHC 13 which is similar to SHC 7 but with a greater increment in hexagon diameter across each section and with an inner and outer area that uses the honeycomb structure as opposed to the rectangular supports of SHC 7. The smallest hexagon diameter is 3.000 mm and is incremented by 0.100 mm in each slice to a maximum diameter of 4.900 mm in the final slice. The hexagon diameter of the inner and outer sections is 6.500 mm.

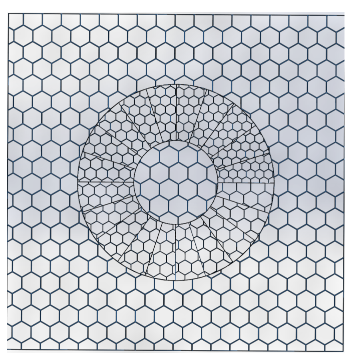

Fig. 12 SHC 13 top view

The velocity gradient shows an increase along the COL, but the gradient is not very smooth. The velocity in the COL ranges from about 7.218 m/s to 8.377 m/s with the velocity in the inner and outer areas being around 8.679 m/s. While the velocity gradient along the COL is more pronounced than in SHC 7, the gradient is very uneven. The vorticity is also larger than either SHC 1 or SHC 7 with a vorticity of 216.28 1/s in the largest diameter slice, and vorticity of 450.95 1/s along the inner and outer edges of the COL.

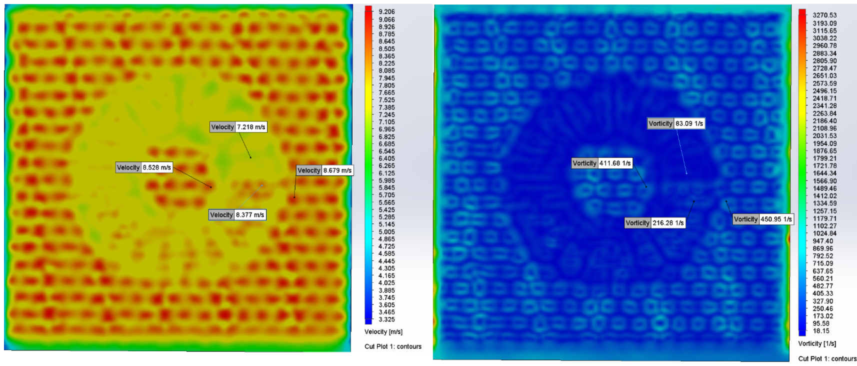

Fig. 13 SHC 13 top view

IV. Conclusion and Future Work

Based on data gathered from CFD, the CHC and SHC models produce the desired velocity well that will allow drops to levitate in a spiral. Compared to the crosswire, the models utilizing the honeycomb structure have lower peak vorticity, but have higher average vorticity. These results prove the viability of the honeycomb structure for the creation of specialized velocity wells with less peak vorticity than the previously employed crosswire. Reducing the vorticity produced by the honeycomb models will be the main priority going forward. Future experiments will seek to develop an SHC model that creates a more pronounced and more stable velocity gradient than the ones discussed in this paper, but with less average vorticity.

V. Acknowledgments

I thank Gene Patrick Rible and members of his research team who are working on the VWT 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.

References

[1] Bhalwankar, R. V., and Kamra, A. K., “A wind tunnel investigation of the deformation of water drops in the vertical and horizontal electric fields,” *Journal of Geophysical Research: Atmospheres*, Vol. 112, No. D10, 2007. https://doi.org/https://doi.org/10.1029/2006JD007863, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JD007863.

[2] Jones, B. K., and Saylor, J. R., “Axis Ratios of Water Drops Levitated in a Vertical Wind Tunnel,” *Journal of Atmospheric and Oceanic Technology*, Vol. 26, No. 11, 2009, pp. 2413 – 2419. https://doi.org/10.1175/2009JTECHA1275.1, URL https://journals.ametsoc.org/view/journals/atot/26/11/2009jtecha1275_1.xml.

[3] Emersic, C., and Connolly, P. J., “The breakup of levitating water drops observed with a high speed camera,” *Atmospheric Chemistry and Physics*, Vol. 11, No. 19, 2011, pp. 10205–10218. https://doi.org/10.5194/acp-11-10205-2011, URL https://acp.copernicus.org/articles/11/10205/2011/.

[4] Sebek, H., *Raindrop Collision Dynamics in a Vertical Wind Tunnel with Velocity Well*, American Institute of Aeronautics and Astronautics, 2024. https://doi.org/10.2514/6.2024-85464, URL https://arc.aiaa.org/doi/abs/10.2514/6.2024-85464.

[5] Bhalwankar, R. V., and Kamra, A. K., “A wind tunnel investigation of the deformation of water drops in the vertical and horizontal electric fields,” *Journal of Geophysical Research: Atmospheres*, Vol. 112, No. D10, 2007. https://doi.org/https://doi.org/10.1029/2006JD007863, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JD007863.

[6] Mehta, R., and Bradshaw, P., “Design rules for small low speed wind tunnels,” *The Aeronautical Journal*, Vol. 83, No. 827, 1979, p. 443–453. https://doi.org/10.1017/S0001924000031985.

[7] Ferber, E., *Creating Velocity Wells in a Vertical Wind Tunnel*, American Institute of Aeronautics and Astronautics, 2024. https://doi.org/10.2514/6.2024-84458, URL https://arc.aiaa.org/doi/abs/10.2514/6.2024-84458.

[8] Frank M. White, H. X., *Fluid Mechanics*, 9th ed., McGraw Hill, 2021.