Creating Velocity Wells in a Vertical Wind Tunnel

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This experiment serves as a baseline for studying the effects of variously sized spherical obstacles and their velocity wells created by crosswire screens typically used in recent vertical wind tunnel drop studies. Comparing the velocity wells induced by a typical crosswire which consists of wires arranged in a circular mesh with that of a modified honeycomb. The hole diameter of the honeycomb is designed to increase linearly with increasing radial distance from the center. By changing the geometrical parameters of the honeycomb, aiming to eliminate turbulence in an effort to better understand drop behavior in the atmosphere. CFD simulations of the velocity wells of the crosswire and various honeycomb designs were verified using drop levitation experiments. Thicker wires in the crosswire increased turbulence. Similarly, thicker honeycomb layers and thicker walls of hexagonal cells increased flow turbulence. Moreover, decreasing the number of wires in the crosswire and increasing the hole diameters of the honeycomb reduced turbulence. Observing that adding more circular sections of equal hole diameters so that there are more diameter sizes in the honeycomb resulted in reduced velocity gradients for a qualitatively smoother velocity well.

I. Nomenclature

d	=	diameter
k	=	constant for radial calculations
r_o	=	outer radius
r_i	=	force coefficient in the *x* direction
r	=	force coefficient in the *y* direction
w	=	width of the wind tunnel base

II. Introduction

As weather patterns across the globe change, it becomes more important that meteorologic predictions are accurate. Part of understanding weather phenomena is studying drop distortion, vibration, and turbulence. When rain drops fall from the sky at terminal velocity, their shape is not a perfect sphere with a predictable volume. A better understanding of how droplets move at these conditions will provide hints on improving our metrology equipment, so that we can more accurately understand and predict the trends and amounts of precipitation in various regions of the globe. However, naturally existing droplets in the atmosphere are difficult to study on their own, and various atmospheric conditions must be replicated in a controlled laboratory environment to make it make it possible for researchers to learn more about the behavior of levitating drops, drop interactions with other drops, chemical additives, or nanoparticles.

Vertical wind tunnels provide a powerful and innovative solution. Vertical wind tunnels differ from other standard wind tunnels that are used for various forms of aeronautical research, in that their flow is vertical, against gravity rather than horizontal. Within vertical wind tunnels, researchers can levitate drops as they occur in the atmosphere to study their behavior. A vertical velocity gradient stabilizes the altitude of levitating drops, and a radial velocity gradient centralizes the drop laterally to prevent it from hitting any of the tunnel walls and keep the drop within the

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observation frame of the camera. For instance, turbulence may be induced by various particles, or droplets may interact and collide. But how can this testing be modified to be improved to allow for different parameters to be researched.

The need to make these velocity wells smoother and less turbulent so as to not interfere with the natural drop behaviors we are aiming to observe. That is the motivation to attempt to the honeycomb part instead of just the screen-wire. Also, with the honeycomb, it becomes easier to model, modify, and control the velocity well while minimizing the possibility of methodological inconsistencies and biases such as manually tying screens with the screen wire that varies based on the skill of the researcher, quality of the wire if it has imperfections or how rough it is , the way everything was glued, and the irregularity of the holes of the screen wire. Making a model that can be 3D-printed with the same printer and ink anywhere in the world makes the whole process easily replicable and thus the results verifiable which is the aim of scientific research experiments. Using the honeycomb also allows us to place various shapes such as spheres as turbulence-inducing bodies for further experimentation.

III. Relevant Theory

Since droplets falling from the sky travel at terminal velocity, their shape is not a perfect sphere, they oscillate. Thus, distorting the axis ratio used to predict the volume. The under or over estimation of the drops volume can lead to errors in precipitation predictions [1]. Part of creating the velocity well is making the drops easier to study. High speed cameras are used to film drops in the wind tunnel and various software platforms are used to analyze the videos. By stabilizing the drops in a velocity well it makes them easier to study by keeping them levitating in the same altitude within the wind tunnel [2]. With the velocity well, for desired results the velocity should have a radial gradient with the slowest velocity at the center and the fastest along the edge. Previously, laboratories have found success in using a wire grate or mesh similar to the crosswire in this project. Since it allows drops to be dropped from the top of the tunnel which would allow researchers to study collisions like that would happen in the atmosphere. For example, with one drop stabilized in the wind tunnel a second larger drop is dropped to collide with the first then the collision is studied and analyzed [2]. From current understanding there are 3 main ways drops interact with each other the first being they absorb each other's masses to make a bigger drop, the second they bounce off each other and retain their initial mass, and the third they can shatter into droplets [3]. The parts of this project are designed to increase the testing conditions so these drops can continue to be studied.

IV. Experimental Method

The following was conducted in SolidWorks utilizing the flow simulation toolbox. This was done first to test potential results before investing in 3d-printed the parts and testing them in the wind tunnel.

A. Wind Tunnel Assembly

The University of Tennessee FaST research group's vertical wind tunnel is composed of 6 components seen in Figure 4 In the figure each part is labeled and described [4] For this project, only the middle section that holds the wire mesh and honeycombs was modified. For simulation purposes from the wire/honeycomb, acrylic, and top piece were used.

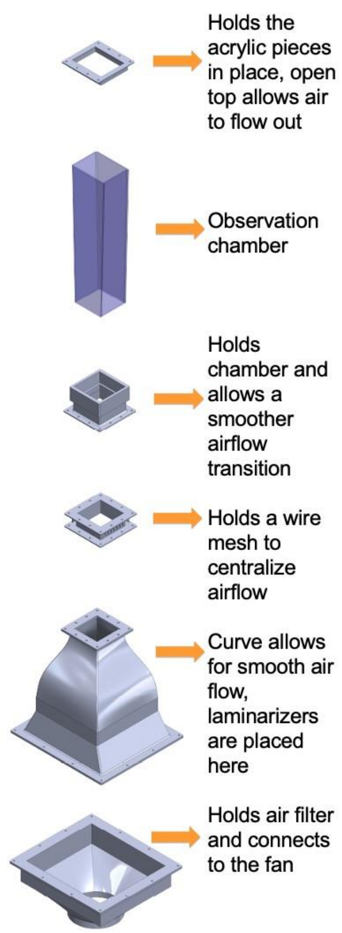

Fig 1 Wind Tunnel Assembly Description [4]

B. Models

For this study there are three main models: Cross wire, a 1mm honeycomb, and a 2mm honeycomb. The cross wire was the initial part created to construct the velocity well. Using 0.1397mm diameter wire, stringing 16 pieces through the 32 holes evenly spaced along the interior midsection of the base part. The wires were secured on the exterior of the part so there was no slack in any of the wires. The holes along the sides had a slightly larger diameter to allow for wire thickness variation, but not large enough to affect airflow. The wires were strung such that the middles all overlapped making a circular mesh that would modify the airflow to make a velocity well.

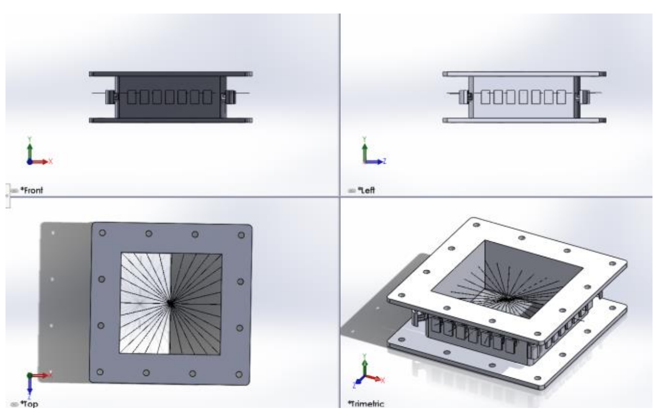

Fig 2 Multiple views of the cross wire

The honeycomb parts are composed of an assembly of eight different circular rings with varying hexagon radii composing a honeycomb pattern. The base of the wind tunnel is 120mm by 120mm, and the eight circular radii are primarily evenly divided. The largest ring is tangent with the edge of the base, with a radius of 120mm. The smallest circle has a diameter of 0.6mm because the drops used for testing in the Wind Tunnel have an average of 6mm which gives a $1/10^{th}$ threshold between the smallest hexagon and the drop. The radius of the remaining rings was distributed between 6mm and 120mm.

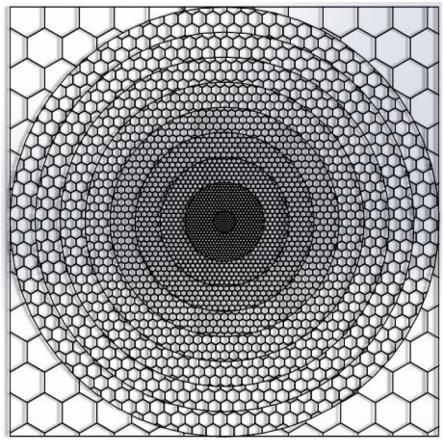

Fig 3 Top view of the honeycomb part

For the hexagons, in SOLIDWORKS the hexagon sketch tool allows for a radius that is tangent to the sides of the shape. Hexagons were the chosen shape because it was the greatest number of sides that would fit together similarly to jig saw pieces without having to supplement with other polygons. To find the hexagon radius equation 1 was used. This relationship provided a linearly increasing hexagon radius that was proportional to the circular radius. To solve for k in the equation, the inner most hexagon diameter had to meet a constraint of 0.6mm. Solving equation 1 for k provides a constant value of $0.6/9$ which is a repeating decimal 0.066667. When solving for the radius of the other rings the average radius was used in a modified version of equation 1 giving equation 2. The average radius being taken of the inner side diameter, ri and the outer side diameter, ro. The corners also have hexagons using equation 3. In addition, the wall thickness of the honeycombs is 75μm. An array of hexagons was constructed for each ring to make the honeycomb structure. In between each ring a wall of the same wall thickness as the hexagons was placed to help eliminate additional turbulence from the edges of the honeycomb rings not always being perfect polygons.

$$\mathbf{d} = \boldsymbol{k}\boldsymbol{r}^{2} \tag{1}$$

$$\mathbf{d} = \boldsymbol{k}\mathbf{r} \tag{2}$$

$$\frac{w\sqrt{2}-w}{2} + w = r \tag{3}$$

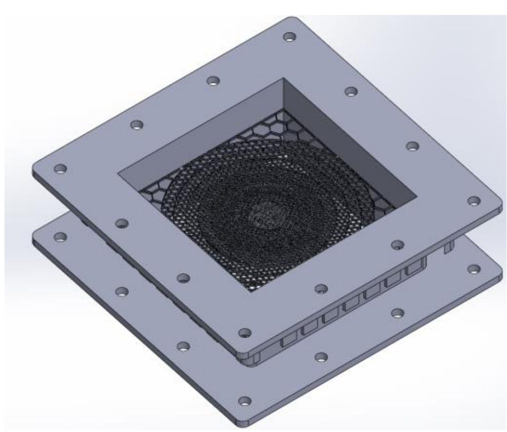

Fig 4: Angled view of honeycomb part

C. Test Procedure

Once the honeycombs and cross wires were modeled in SOLIDWORKS they were added to the full wind tunnel assembly. For the computational fluid dynamics calculations, CFD, the honeycomb or cross wire served as the base with the remainder of the assembly staying the same. A lid was added to bottom of the honeycomb and cross wire to solidify the fluid volume in the software. For simulation conditions air was used and gravity was applied in the negative y-direction. The mesh sized was increased to 7 for the most precise results. For boundary conditions the following were used, inlet velocity 8m/s, atmospheric pressure, and room temperature.

D. Flow Visualization

Once the flow simulation was run and results were loaded. To determine the velocity well, the flow trajectory was modeled from the base to the lid (not fully developed flow). This provided a helpful visual model of how the air interacted with the parts in the wind tunnel. The surface plots for vorticity and velocity were created on lids placed within the wind tunnel assembly after the calculations had been run. The surface plots were placed and measured from the same point in the wind tunnel for all three parts.

V. Results and Discussion

Since the cross wire, with the circular mesh, served as the baseline and is in many recent vertical wind tunnel experiments, it was modeled first [7]. Once the simulations were run, a surface plot was placed at the bottom of the acrylic and velocity and vorticity were projected on top. The wire mesh did create a small velocity well in the middle of the test section with a low velocity of 6.231 m/s and a radial gradient to the outside of the test section with the highest velocity of 6.882 m/s. This is not an extreme difference but a difference nonetheless which can be seen in figure 5. In figure 6, on the same plane as figure 5, a vorticity surface plot was graphed. Vorticity is important to the study because circulation is the surface area integral of the vorticity curl of the vector field. So simply put vorticity is an indicator of turbulence. It is worth noting that the vorticity gets extremely small to the value of 2.33e-9 1/s, but never to zero. It is more consistent, with an increase along the boundary.

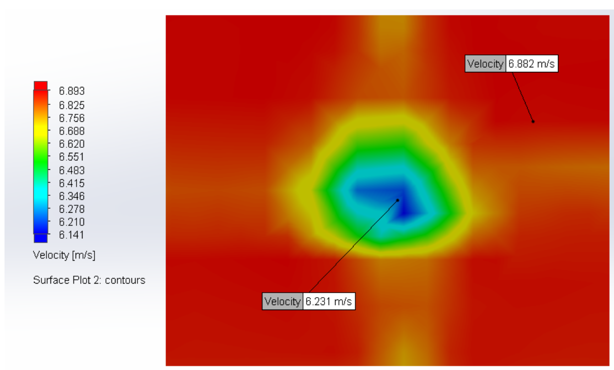

Fig 5 Cross wire Velocity Surface Plot

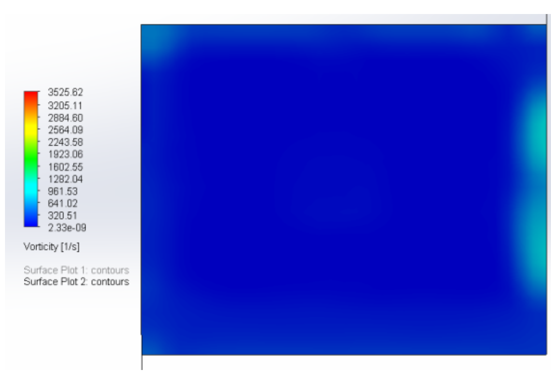

Fig 6 Cross wire Vorticity Surface Plot

Next, the 1mm honeycomb part. The velocity surface plot, as seen in figure 7 does not show a perfect radial gradient, but it does have a greater change in velocity from the center of the plot to the border. The area of the well is larger than the cross wire and has much more variation than the cross wire. The vorticity of the part is shadow like of the velocity plot, with stronger signs of turbulence along areas of greater velocity change. In addition, the vorticity plot goes to zero unlike the cross wire.

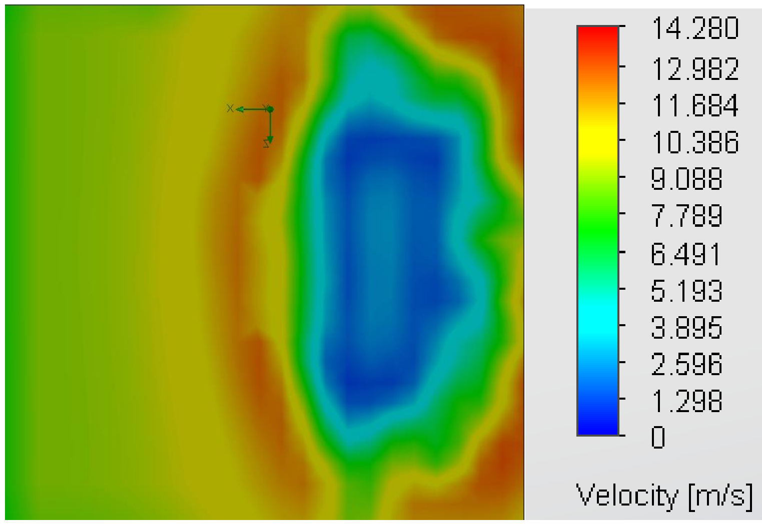

Figure 7 1mm honeycomb part velocity plot

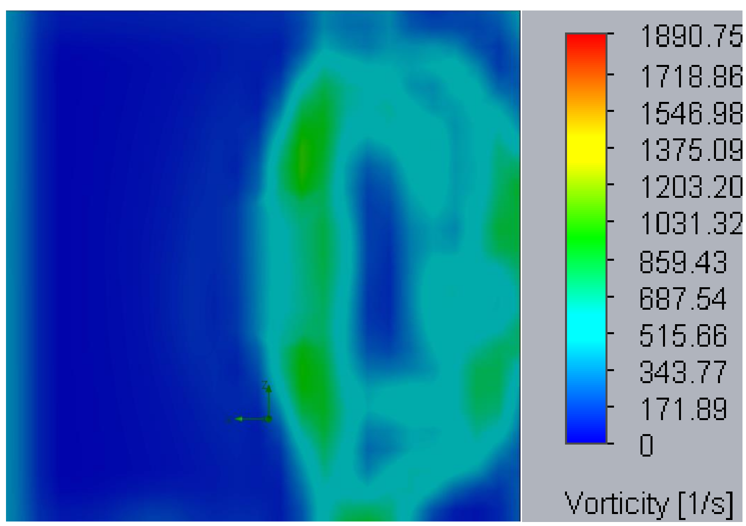

Figure 8 1mm honeycomb part vorticity plot

Finally, the 2mm honeycomb part. Again, two plots measured at the same point, which was also the same point for the 1mm honeycomb part. The 2mm honeycomb part has a much larger velocity well than either the 1mm honeycomb or the cross wire. It also has the most variation and highest speed which can be seen in figure 9. The velocity gradient isn't as circular as the cross wire, but it is more circular than the 1mm honeycomb part. This plot follows more of the physical structure of the part with the different velocity rings. The 2mm vorticity plot can be seen in figure 10. The vorticity increases when the velocity has a sudden increase as expected. Like the 1mm honeycomb and unlike the cross wire the vorticity does go to zero. It also shadows the velocity rings like the 1mm part did. The sides have low vorticity unlike the cross wire where the most vorticity was away from the boundary.

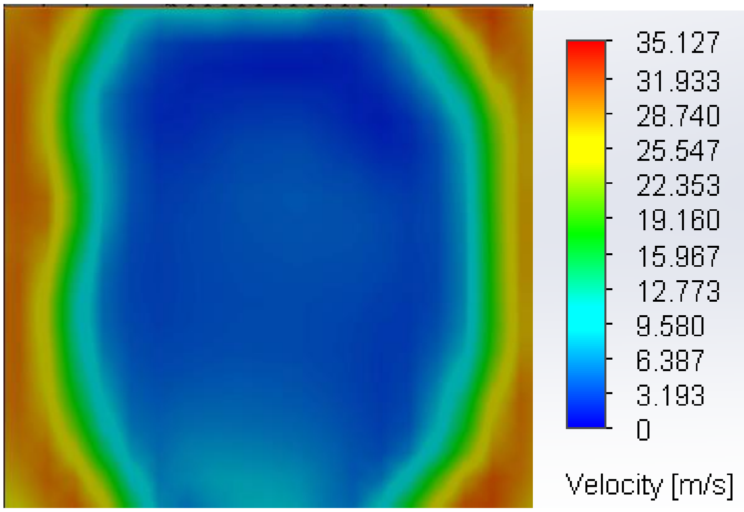

Figure 9 2mm honeycomb part velocity plot

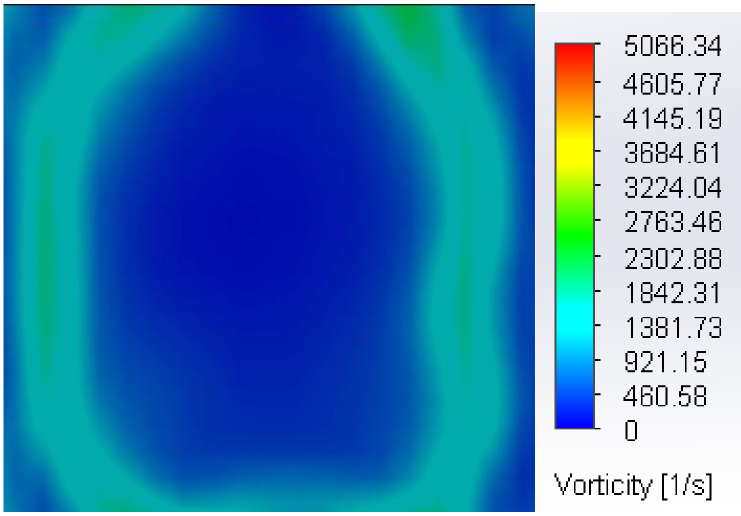

Figure 10 2mm honeycomb part vorticity plot

VI. Conclusion

In conclusion, the CFD results provided enough promise to invest in the 3-d resin printed parts and test them in the wind tunnel. The honeycomb was able to create a better velocity well than the cross wire. The honeycomb part also provides the opportunity for more variety in the air flow in the wind tunnel with modified hexagon structures. The vorticity was not as constant with the honeycomb part as the crosswire, but it was overall lower. It is interesting to note how vastly different the 1mm and 2mm honeycomb parts are for having the exact same structure with the only variable being thickness. The thicker honeycomb, 2mm, had a larger velocity well than the 1mm, but the 2mm honeycomb had a higher boarder velocity. In the wind tunnel, previous experiments can be repeated to compare physical results of the honeycomb to the cross wire to ultimately learn more about drop behavior with various collision types as well.

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