Application of Wind Power Density Compressors Would Significantly Improve the Efficiency of Wind Turbines

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Abstract

What is a smart city to you? There are numerous factors that you can think of; among those, using energy that is harmless to the environment is one of the most considerable factors. How should we improve the amount of renewable energy in efficient ways? We can improve some features of current renewable energy generators by changing their designs. Our main focus is on wind power generators specifically. Wind power density is what determines the amount of energy that is generated by the wind turbines; density of air and wind speed are positively proportional to wind power density. While there are numerous wind turbine designs in the world, we supposed there are two main types - horizontal-axis wind turbines(HAWTs) and vertical-axis wind turbines(VAWTs). By applying Bernoulli's principle, we have come up with designs that can lead to an increase in wind speed at the wind turbine propellers: 3 designs for HAWTs and 4 designs for VAWTs. We would call these as 'wind power density compressors.' We also expect that air density would increase in the region: air particles would be compressed because of the shape of our models. We have collected data through running Solidworks Flow Simulations with our 7 models. The results showed that all of our models led to a significant increase in wind velocity at the part where the turbine's propellers would be located. Model One-3 increased the wind speed by roughly 70%, and Model All-4 increased the wind speed by roughly 18%. We also observed that air density increases at the propeller region in the presence of our wind power density compressors. By computing the results with the formula for wind power density, we expect around 5 times and 1.7 times increase in the amount of energy that is generated by HAWTs and VAWTs respectively. We've also determined what factors would improve the efficiency of wind power density compressors by comparing the results of different models. By adjusting some features of the compressors, we expect to build better models in the future.

Introduction

The trend of the energy industry has been drastically changed in the modern world: scientists, economists, and engineers have sought for ways to reduce rates of carbon emission caused by natural gas usage. Because it causes air pollution and climate change, a large number of people have focused on adapting renewable energy technologies widely and improving the energy-generating rates of the generators. Among numerous alternative technologies, we are going to focus on an innovative way to increase the generating rates of wind turbines in this paper. In the United States, 7.3% of total electricity generation is from wind energy sources [1]. In 2019, 198 million metric tons of CO2 emissions in the US are prevented by wind energy, and 103 billion gallons of water consumption are saved every year [2]. Even though the portion of wind energy in the total electricity generation is small, it effectively reduces carbon emission. Improving such technology further would lead us to generate more green energy.

Wind Power Density

The main factor that affects the yielding rates of wind turbine is a wind power density($\boldsymbol{\delta}$), which is often measured in kiloWatts per meter square (kW/m2). The wind power density is determined by how fast the wind speed (V) is and density ($\boldsymbol{\rho}$) of the air passing through the blades.

$$\boldsymbol{\delta}=\tfrac{1}{2}\,\boldsymbol{\rho}V^3$$

*An equation that determines the wind power generating rates [3].

Bernoulli Principle

Bernoulli's principle is “Within a horizontal flow of fluid, points of higher fluid speed will have less pressure than points of slower fluid speed”. Incompressible fluids should accelerate when they pass a narrow part to maintain a constant volume flow rate. If the water accelerates, its kinetic energy also increases. In figure 1, the force from pressure P1 pushes towards the right which is the same direction as the motion of the fluid.

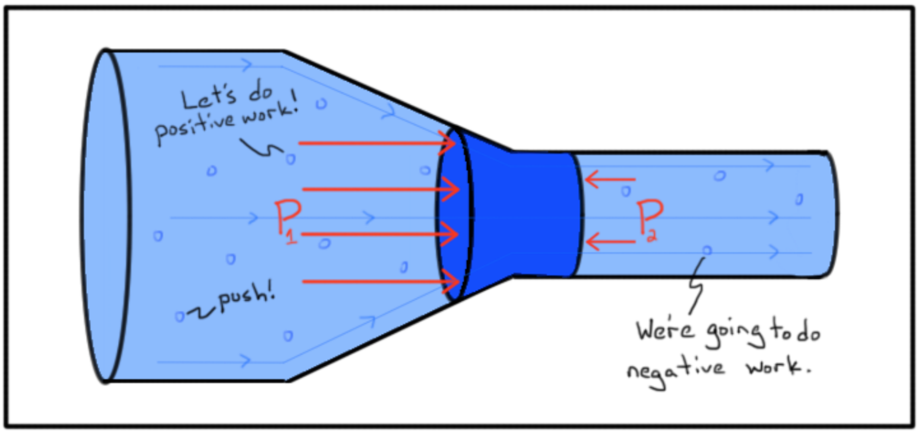

Figure 1. A picture describing Bernoulli’s principle [4]

The force from pressure P2 pushes to the left which is the opposite direction as the motion of the fluid. Since the water should accelerate (due to the continuity equation), there should be a positive amount of work done on the fluid. So P1 should be larger than P2. This inverse relationship between the pressure and speed of the fluid is called Bernoulli's principle.

*P1= pressure in the larger area.

*P2= pressure in the smaller area.

Bernoulli’s Equation for Incompressible Fluid

P=pressure

ρ= mass density

v=velocity of the flow

g= gravity acceleration

z= elevation of the point above a reference point.

$$\frac{dP}{\rho} + vdv + gdz = 0$$

$$\int \frac{dP}{\rho} + \int vdv + \int gdz = c$$

$$\int \frac{dP}{\rho} + \frac{v^2}{2} + gz = c$$

(With compressible fluid & isothermal condition)

Let $\frac{P}{\rho} = c1$

$$\int \frac{dP}{\rho} = c1 \int \frac{dP}{P} = c1 * \ln P \Rightarrow \frac{P}{\rho} \ln P$$

=> $\frac{P}{\rho}\ln P+\frac{v^2}{2}+ gz = c$ (c = constant)

As velocity increases and mass density increases, pressure decreases.

(If the fluid is incompressible)

$\int\frac{dP}{\rho}+\frac{v^2}{2}+ gz = c$ (c = constant)

=>$\frac{p}{\rho}+\frac{v^2}{2}+ gz = c$ (c= constant)

As v increases, p decreases(since the fluid is incompressible, mass density remains almost constant) [5].

Aim and Methodology

In this research, we aim to design the outer cover of the wind turbine(called wind power) that can increase the energy efficiency of the wind turbine in the city by increasing the wind power density. To find the most suitable design, we will use the Solidworks Flow Simulation to visualize the change in wind speed when the wind goes through the designed model. Simulating with different sizes and shapes of the models, we will collect the simulation data and compare and analyze them to find the most effective and efficient design in the city.

Hypotheses

1) If we build our models using Bernoulli's Principle, we would be able to increase the velocity of the fluid passing through them.
2) Application of this principle would cause the denser wind to pass through the wind power density compressor since air would be partially compressed as the air particles hit our models.

3D Modeling and Simulations

We have come up with two different types of wind power density compressors because their designs aim for different types of wind energy generators. Models One-1, 2, 3 were designed for wind energy generators that are fixed for one direction, and models All-1, 2, 3, 4 were designed for vertical axis wind turbines.

We used the Solidworks Flow Simulation to visualize the change in the speed of the air when it passes through the compressor models. Using different colors, the simulation shows the difference in speed in each section of the 3D model.

Set-up Values

All models were set for the same simulation settings:

Inlet velocity: 40 inch/s

- Direction: from right to left

Fluid: Air

Pressure: 14.6959473 lbf/in^2

Temperature: 68.09 F

Brief Results (Table)

	Model 1			Mode2			Model 3			Model 4		
	Initial Speed (inch/s)	Final Speed (inch/s)	Percentage Change(%)	Initial Speed (inch/s)	Final Speed (inch/s)	Percentage Change(%)	Initial Speed (inch/s)	Final Speed (inch/s)	Percentage Change(%)	Initial Speed (inch/s)	Final Speed (inch/s)	Percentage Change(%)
One Direction (HAWTs)	40	20	-50	40	44	10	40	70	75			

All Direction (for VAWTs)	40	44	10	40	46	15	40	44	10	40	47	18

Figure 2. Results of simulations. (Final Speed = maximum value at the narrowest region)

<u>One direction Wind Power Density Compressor</u>

To find the effect of the size of the hole on the air speed, the diameter of the cross section varies. Except that, all other variables are fixed.

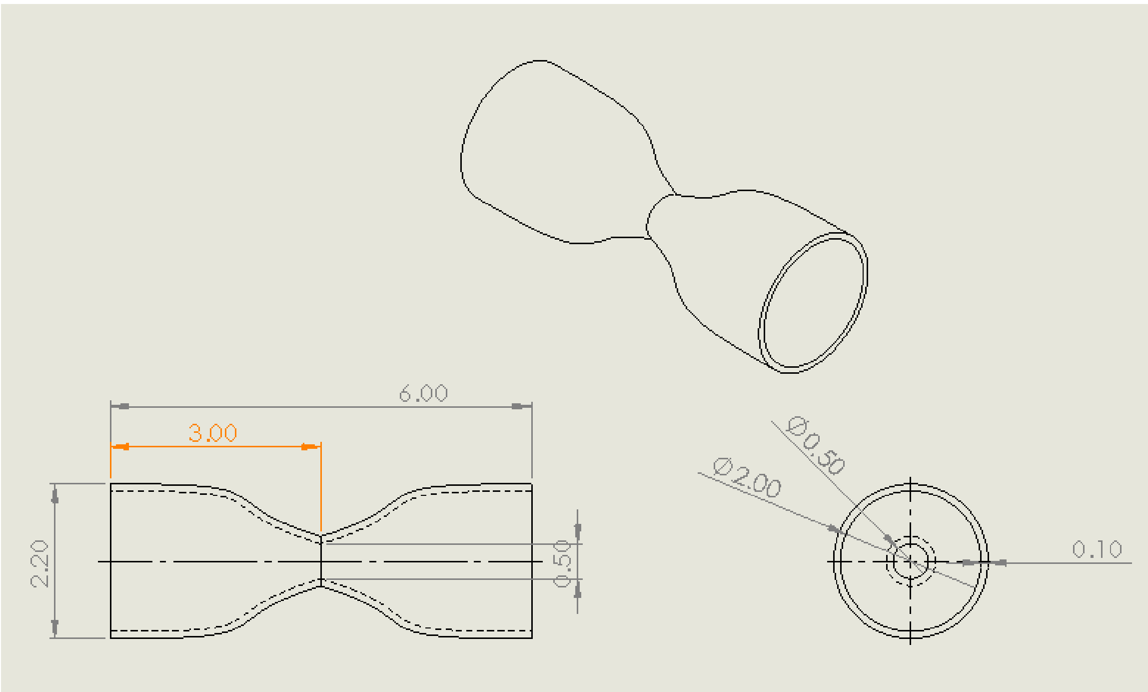

Figure 3. Solidworks Drawing of Model One-1(unit - inch)

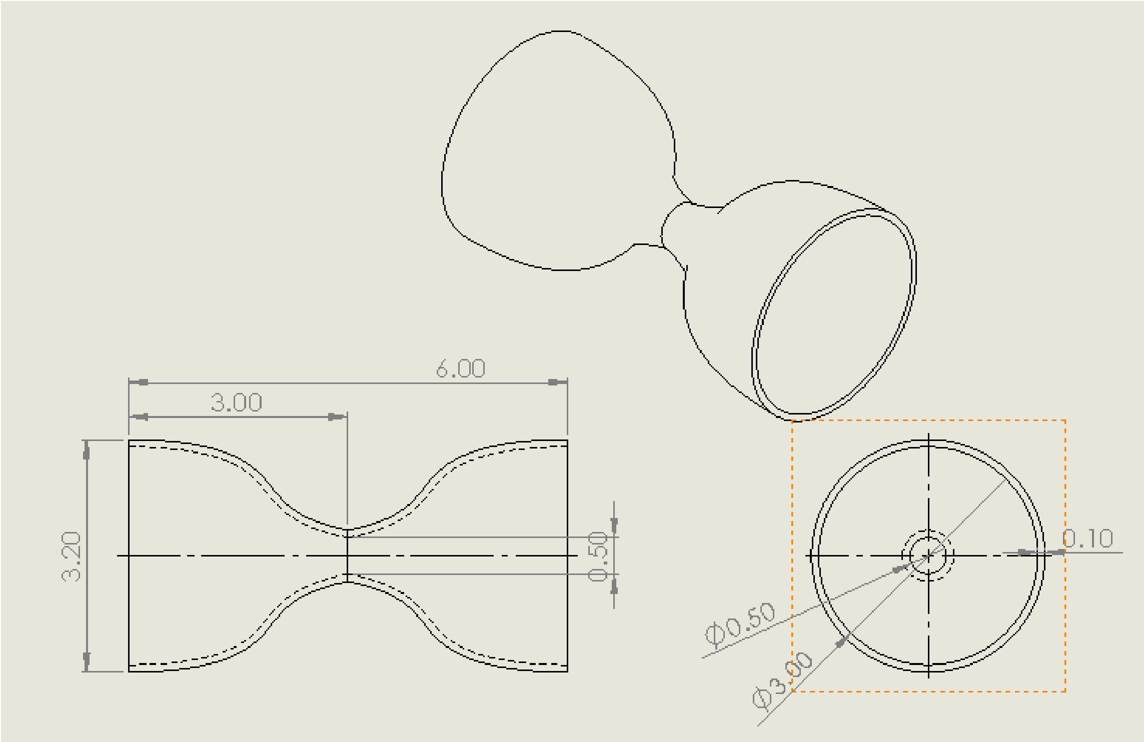

Figure 4. Solidworks Drawing of Model One-2(unit - inch)

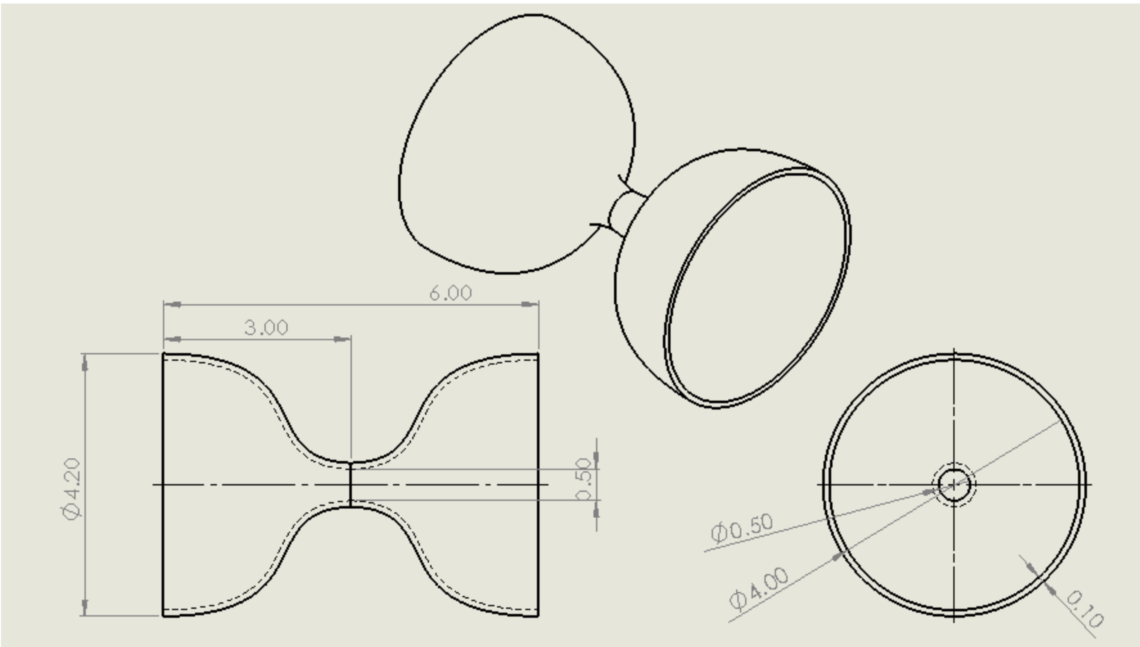

Figure 5. Solidworks Drawing of Model One-3(unit - inch)

Model One-1

Firstly, the picture shows the compressor which diameter of the outer circle is 2 inch.

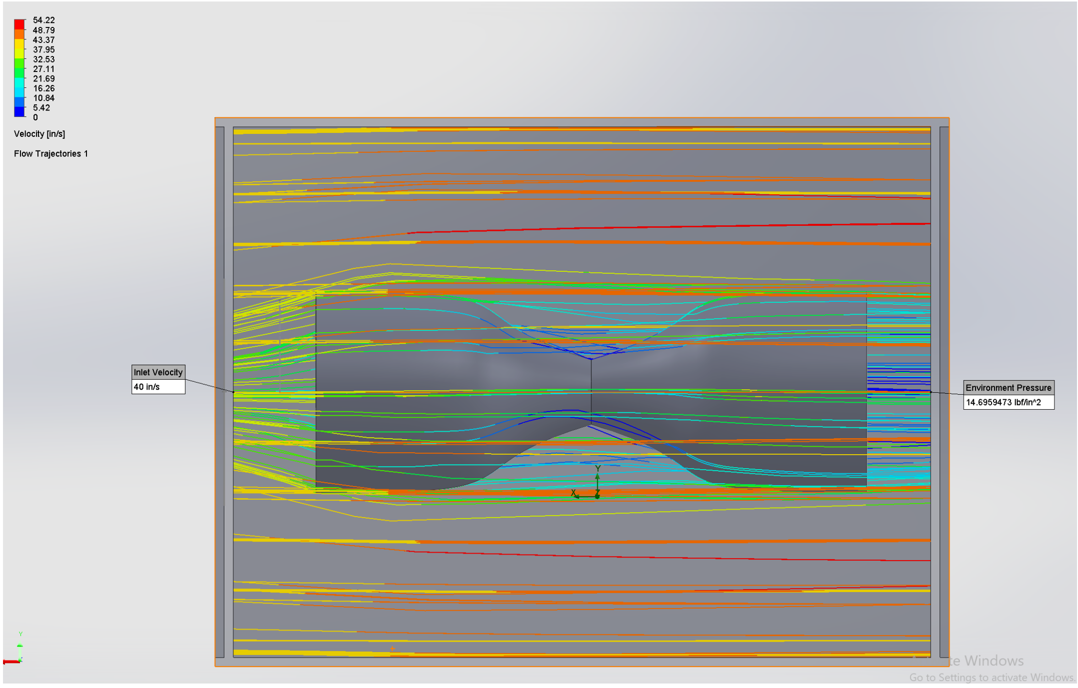

Figure 6. One-1 Side View

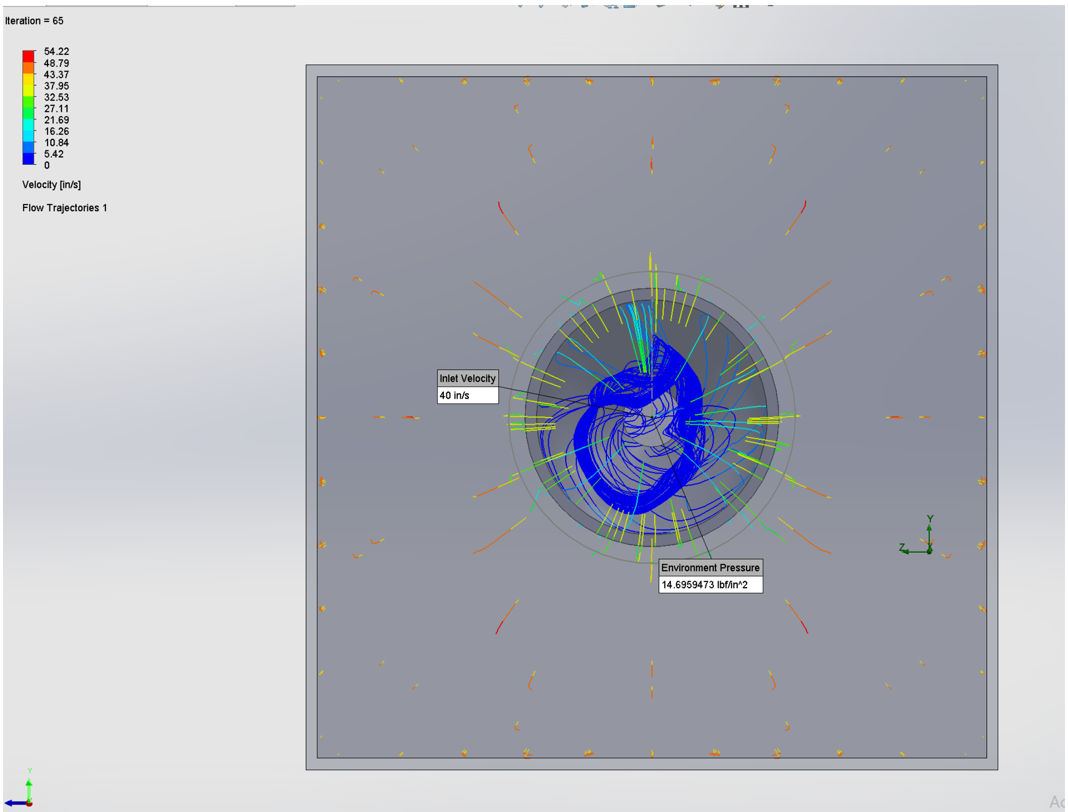

Figure 7. One-1 Front View

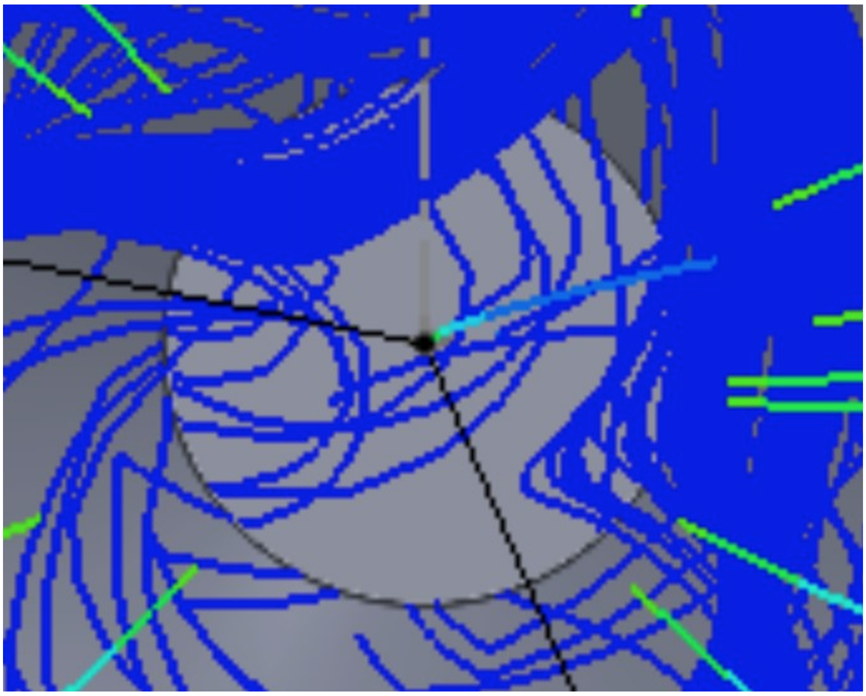

Figure 8. One-1 Front View (Zoom in at the narrowest part)

According to the image above, the speed of the air decreases when it encounters the compressor. It is because due to the small diameter, the air cannot pass through the compressor smoothly due to resistance and reflection. The increase in airspeed in the outer area of the compressor is ignorable because it is caused by the enclosed container.

In the second picture, we can see the airspeed change inside of the compressor. The airspeed close to the surface shows a blue color, which means the air speed is about 5 in/s. There is a huge decrease in speed at the start, but airspeed increases to about 20 in/s in the middle of the compressor. This model proves that the compressor increases the speed of the air in the middle part which enters the compressor, but it needs some improvements to allow more air to enter the compressor smoothly.

<u>Model One-2</u>

Secondly, the picture shows the compressor which diameter of the outer circle is 3 inch.

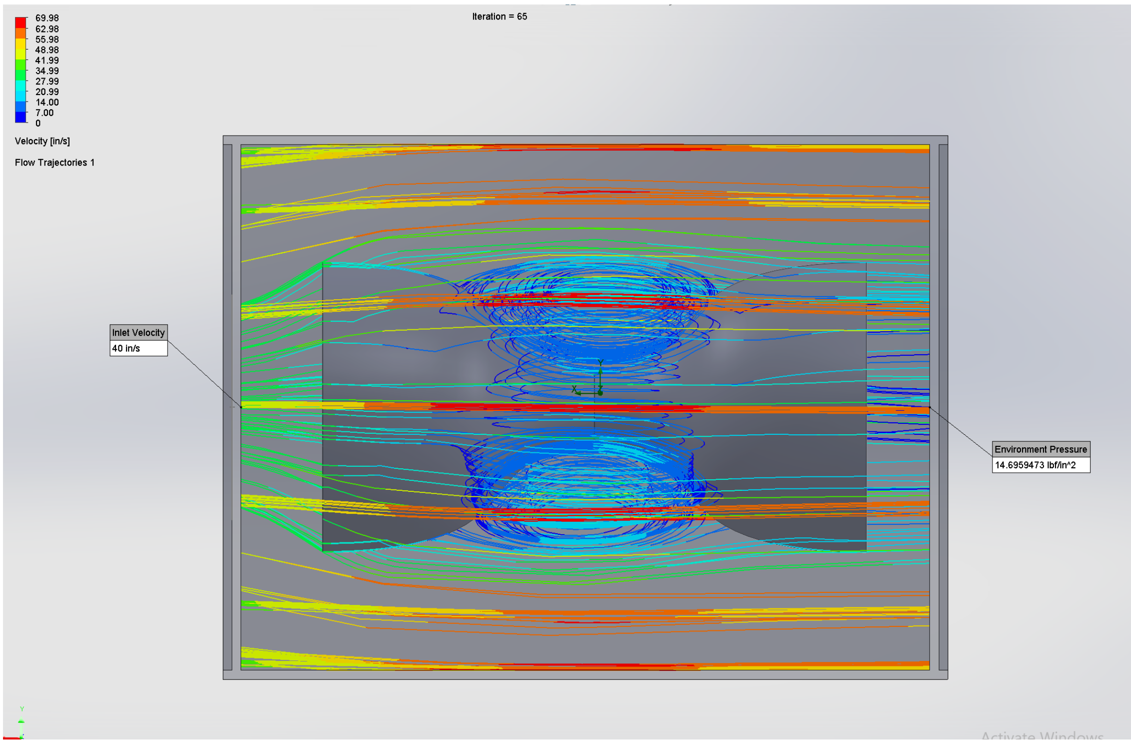

Figure 9. One-2 Side View

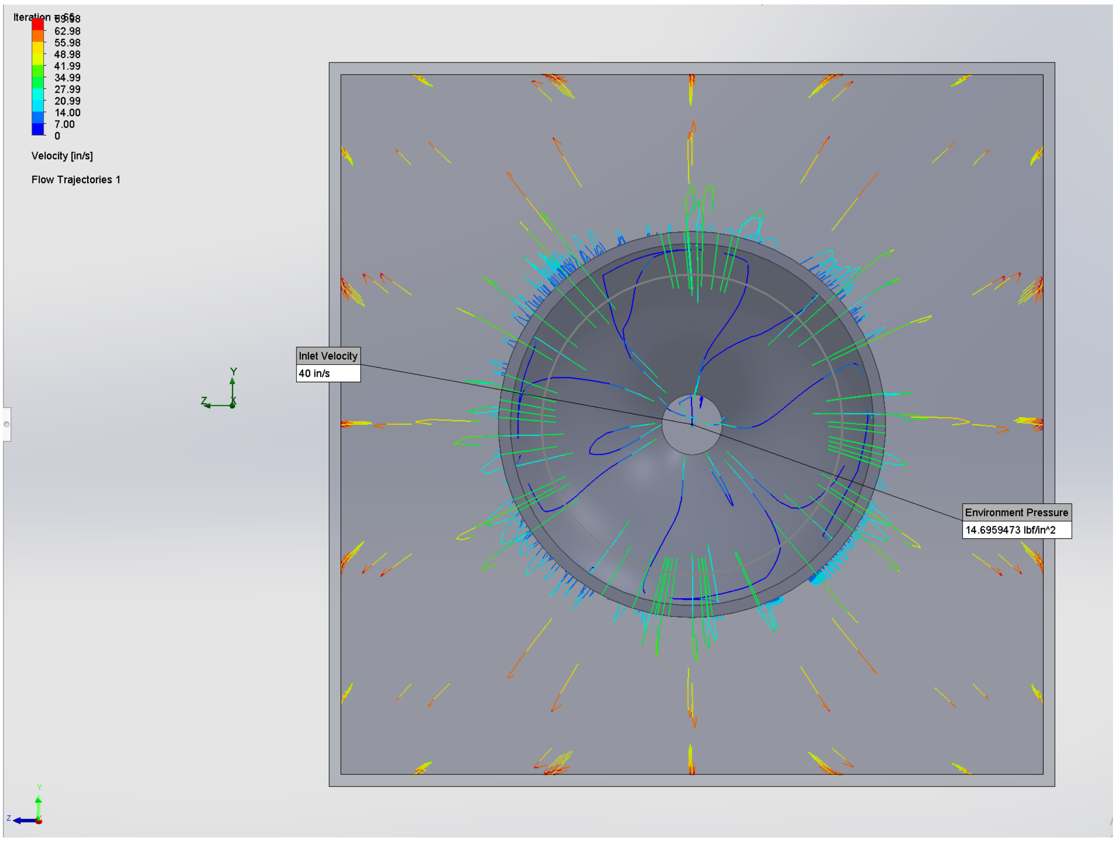

Figure 10. One-2 Front View

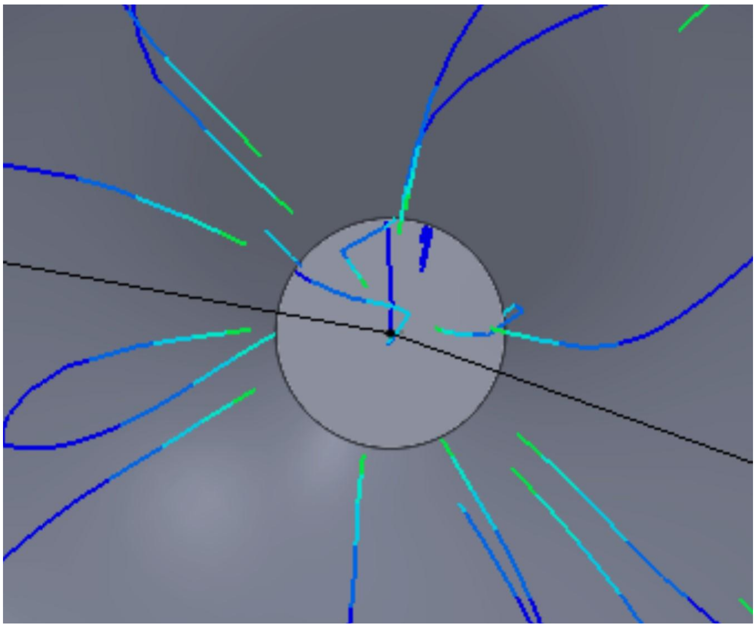

Figure 11. One-2 Front View (Zoom in at the narrowest part)

Compared to the first model, there is less decrease in the airspeed at the beginning due to the larger cross-sectional area. The airspeed at the start is decreased to 7 in/s, but the speed in the middle part is increased to about 44 in/s. Compared to the first model, the airspeed is increased due to an increase in the diameter of the outer cross-section.

Model One-3

Thirdly, the picture shows the compressor which diameter of the outer circle is 4 inch.

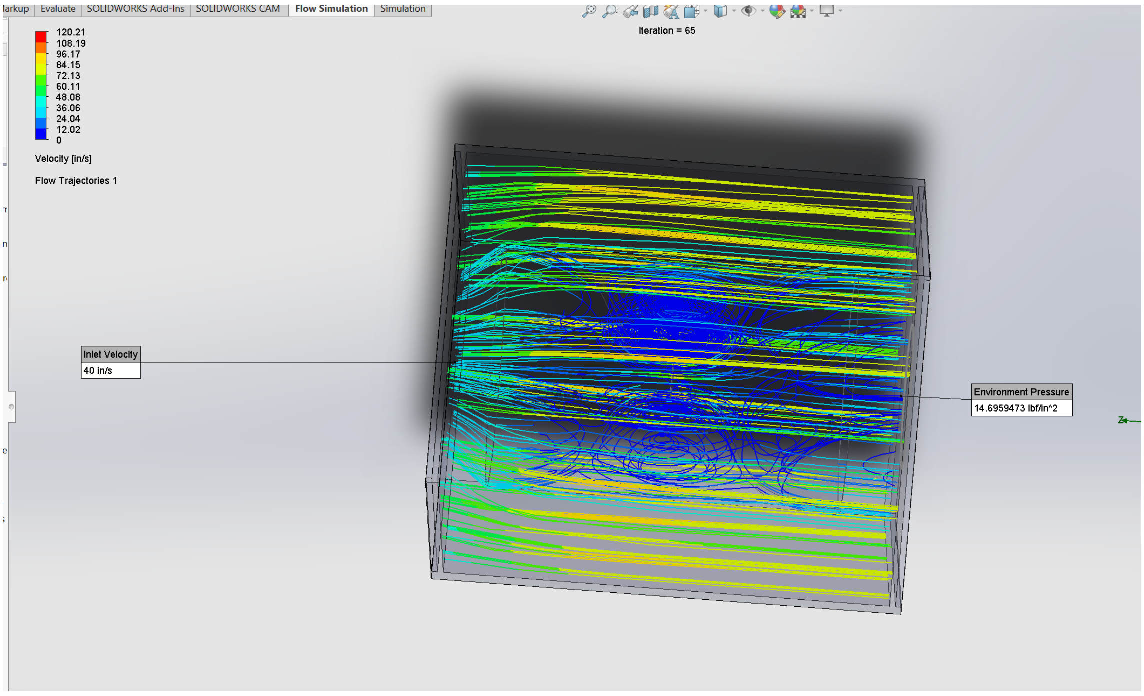

Figure 12. One-3 Side View

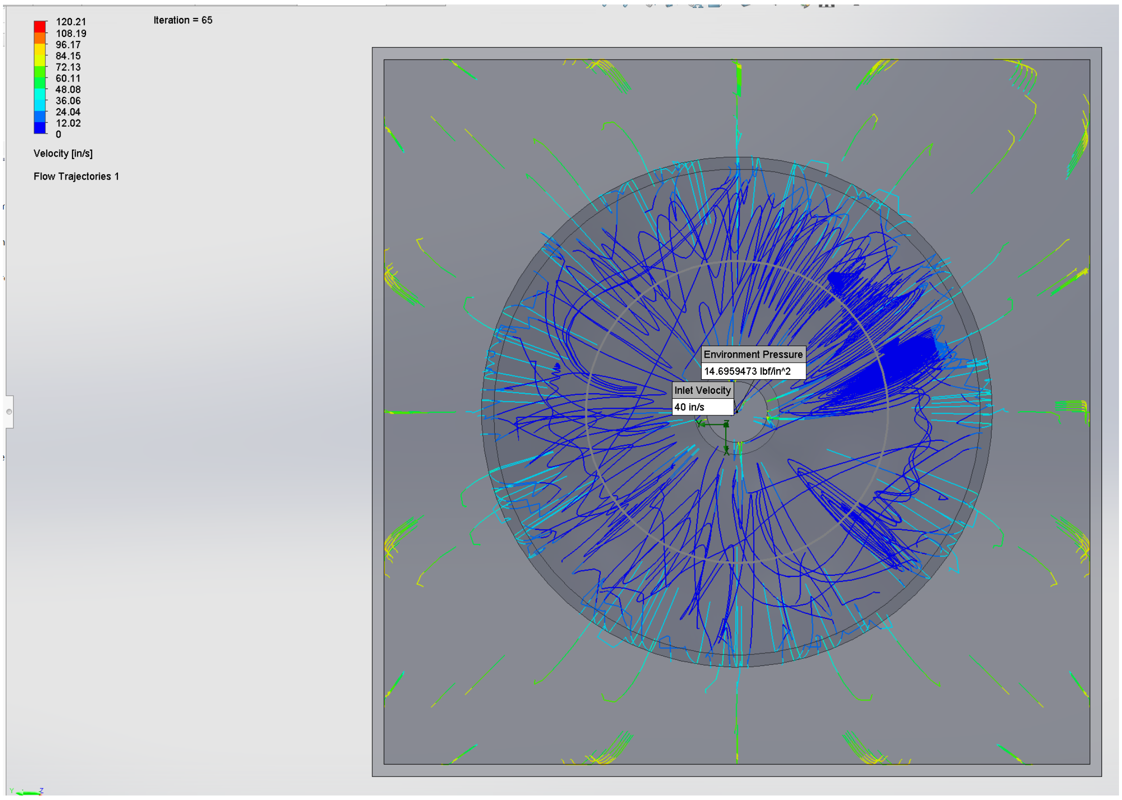

Figure 13. One-3 Front View

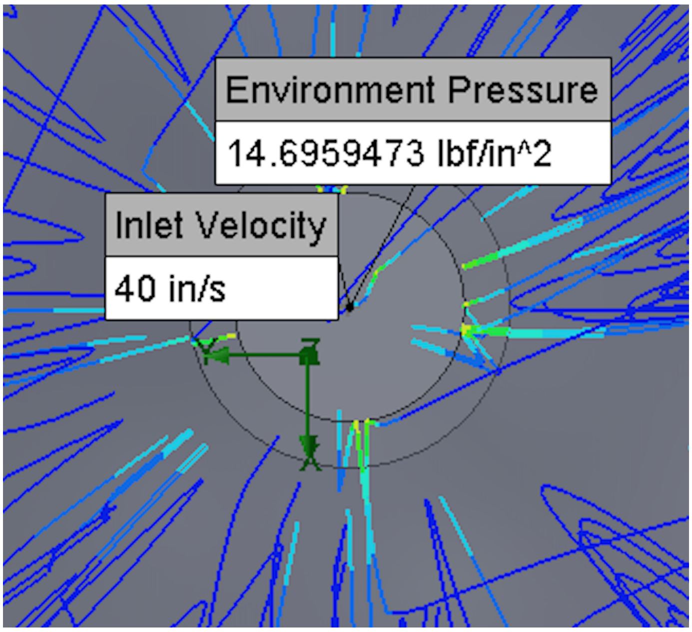

Figure 14. One-3 Front View (Zoom in at the narrowest part)

In the third model, the airspeed near the surface of the compressor decreased t0 6 in/s, but the speed increased to 70in/s in the middle part. So this model increases the airspeed by about 75%. Through these results, we can conclude that in the horizontal axis model, the larger the difference in the diameter of the cross-section, the larger the increase in airspeed.

<u>All direction Wind Power Density Compressor</u>

We have also measured the change in velocity for wind power density compressors that are made for wind coming from any direction. All the models have been designed by attaching two equivalent parts(up and bottom parts). Solidworks Drawings and Solidworks Flow Simulations of our models have been attached below:

*Values of Model All-1 are set for standard to compare with those of other models.

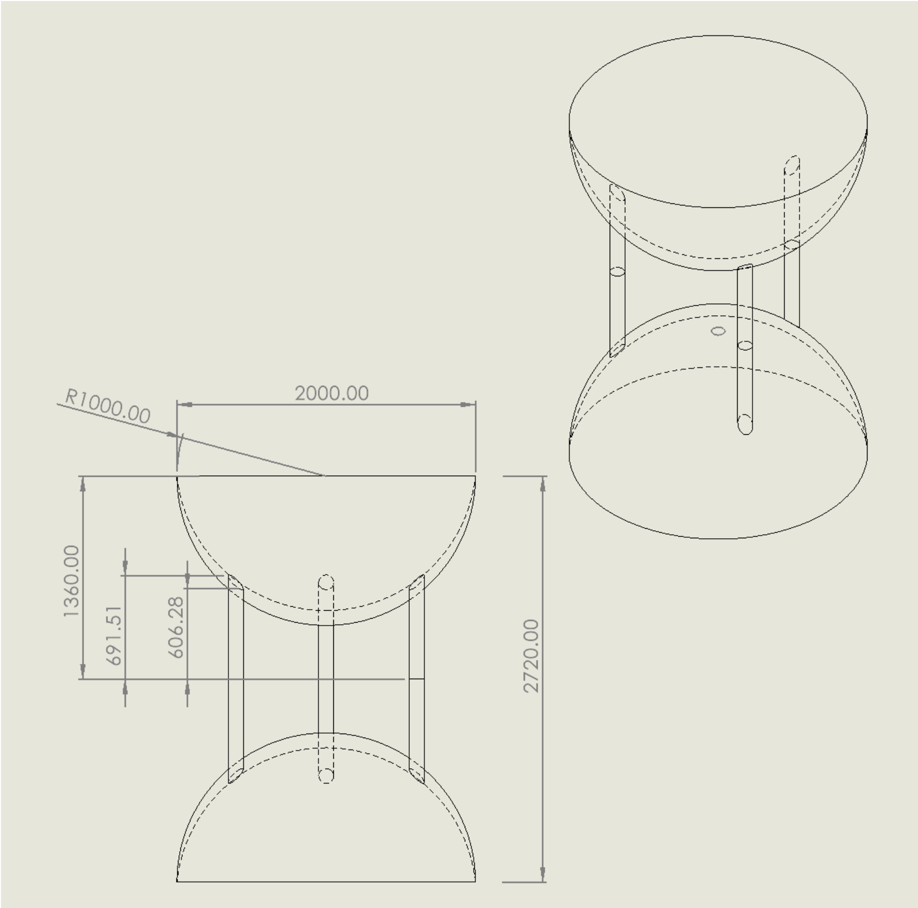

Figure 15. Solidworks Drawing of Model All-1

Properties

- Radius of hemisphere = 1000mm
- Height of the model = 2720mm
- The narrowest section = 720mm

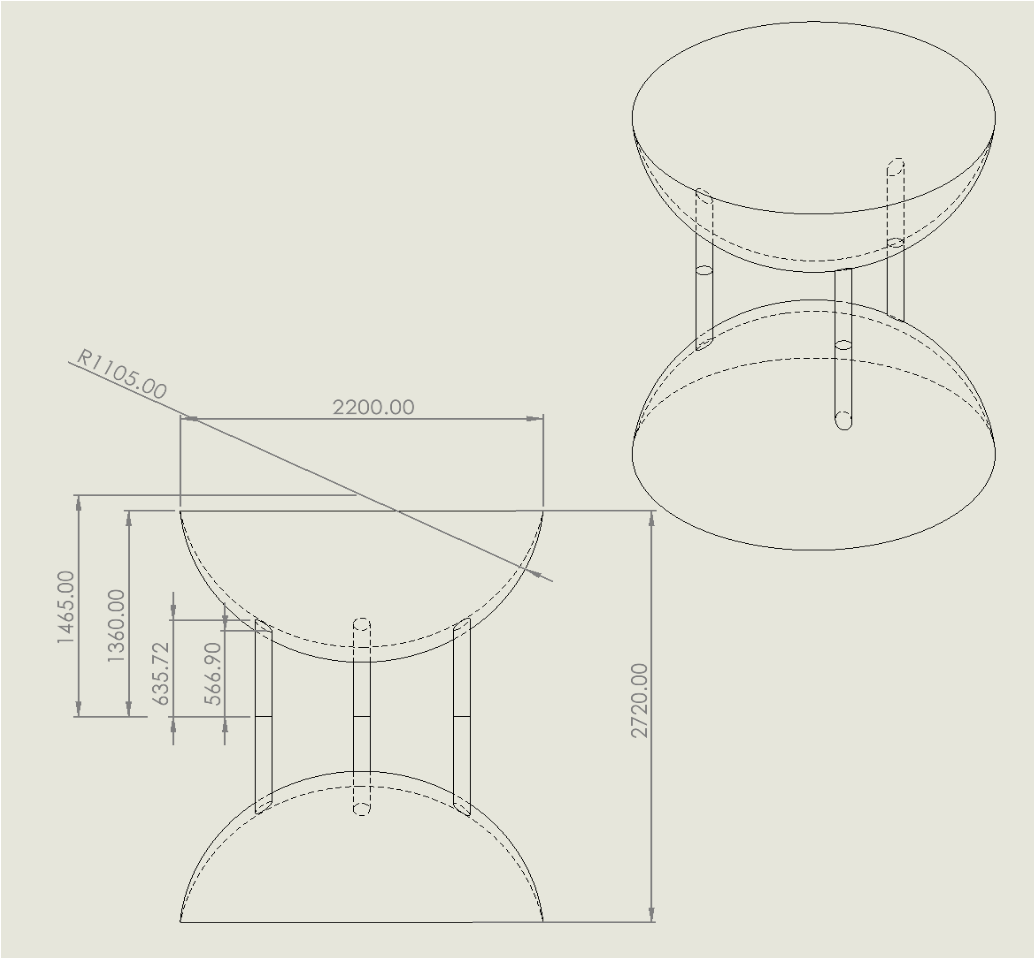

Figure 16. Solidworks Drawing of Model All-2

Properties

- Radius of top and bottom spherical caps = 1105mm
    - Around 10% increase in the length of radius of the spherical caps.
- Height of the model = 2720mm
- The narrowest section = 720mm

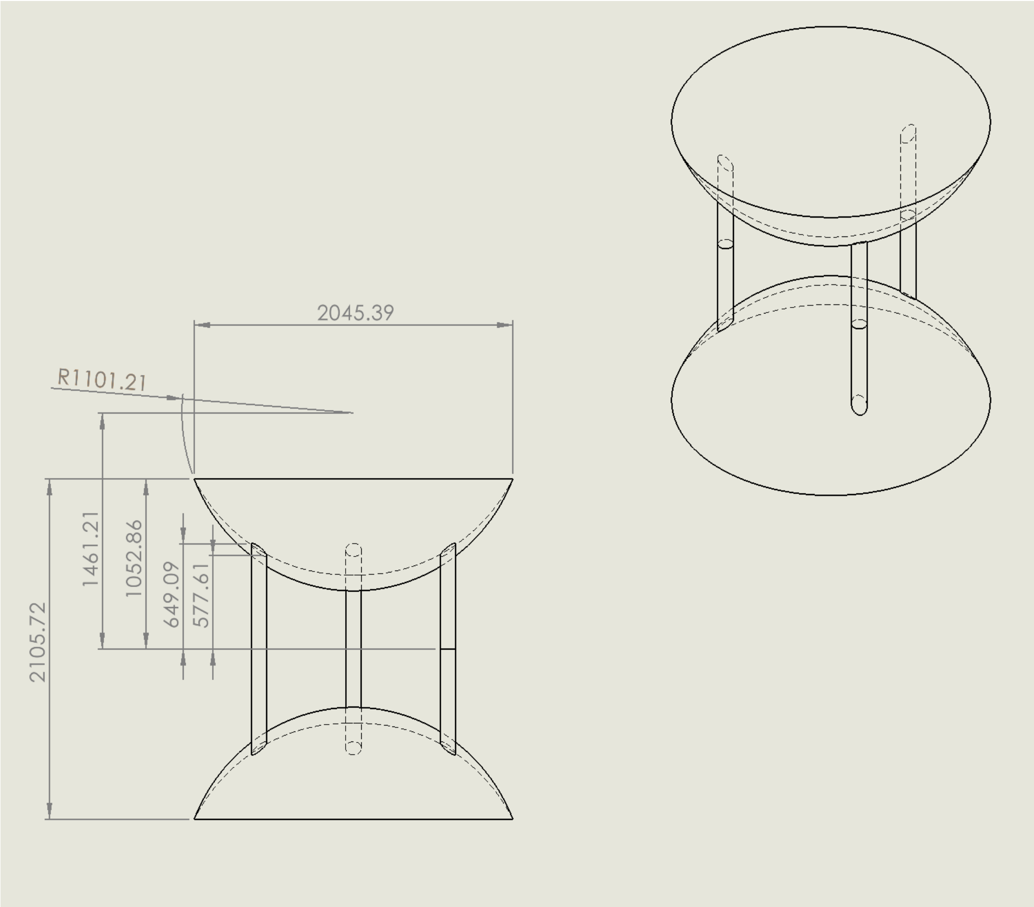

Figure 17. Solidworks Drawing of Model All-3

Properties:

- Radius of top and bottom spherical caps = 1101.21mm
    - Around 10% increase in the length of radius of the spherical caps
- Height of the model = 2105.72mm
    - Around 25% decrease in height
- The narrowest section = 720mm

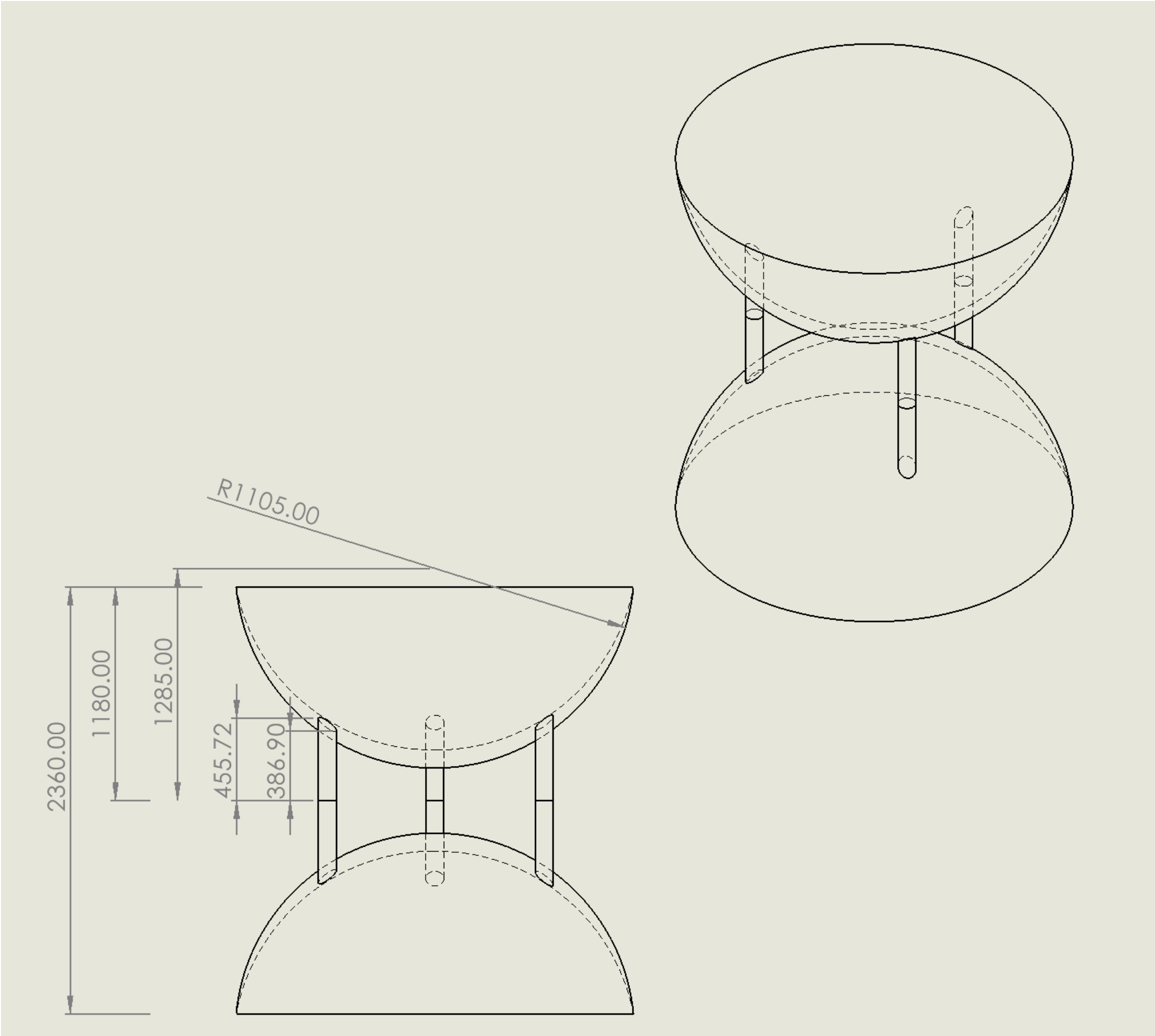

Figure 18. Solidworks Drawing of Model All-4

Properties:

- Radius of top and bottom spherical caps = 1101.21mm
    - Around 10% increase in the length of radius of the spherical caps
- Height of the model = 2720mm
- The narrowest section = 360mm
    - Around 50% decrease in height of the narrowest section

<u>Model All-1</u>

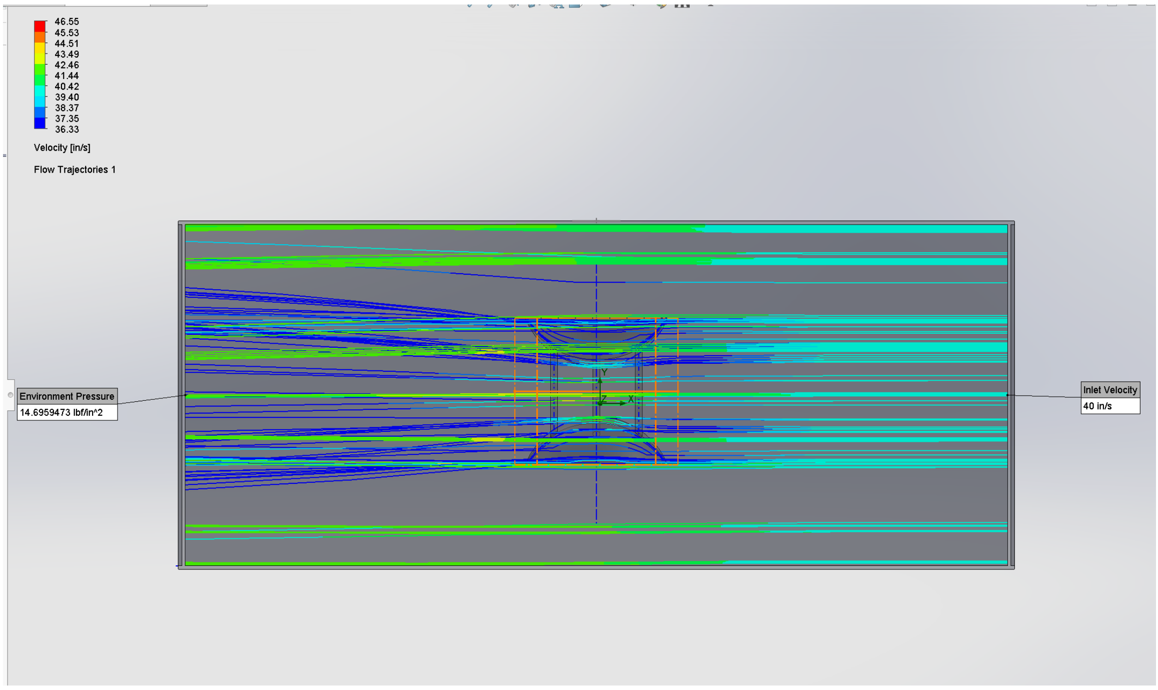

Figure 19. All-1 Side View

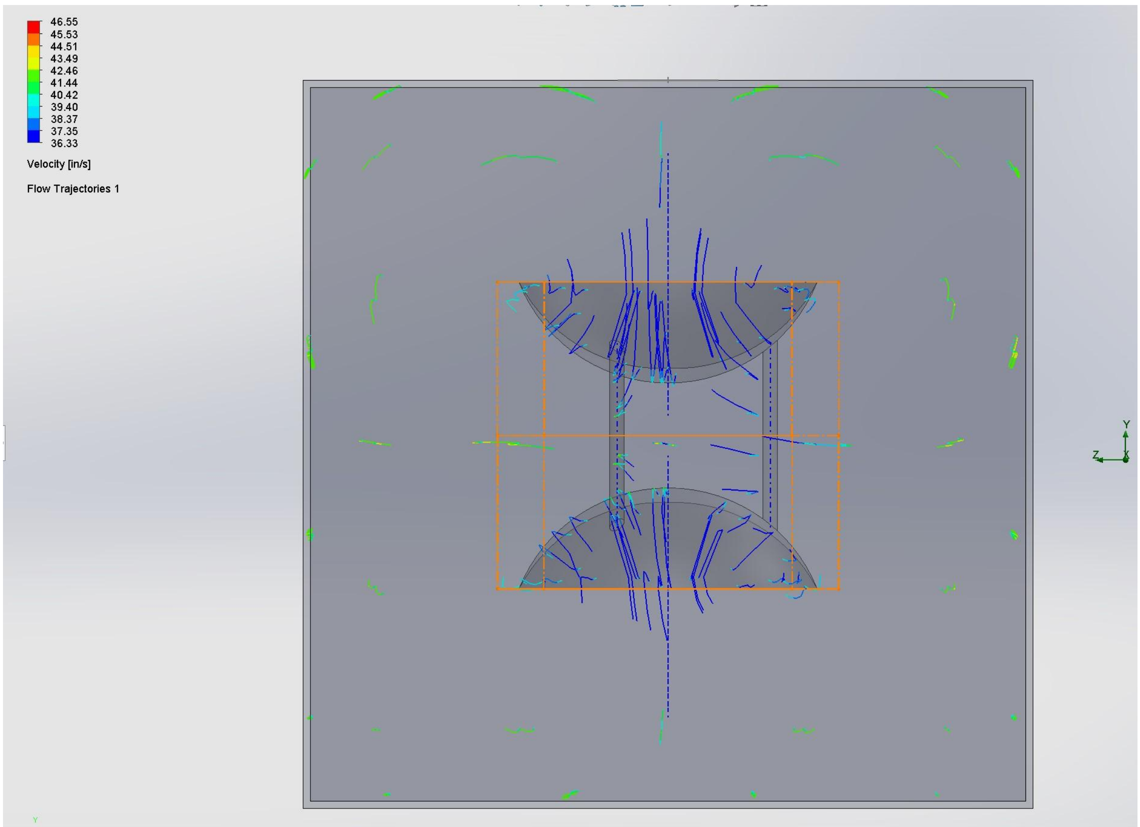

Figure 20. Model All-1 Front View

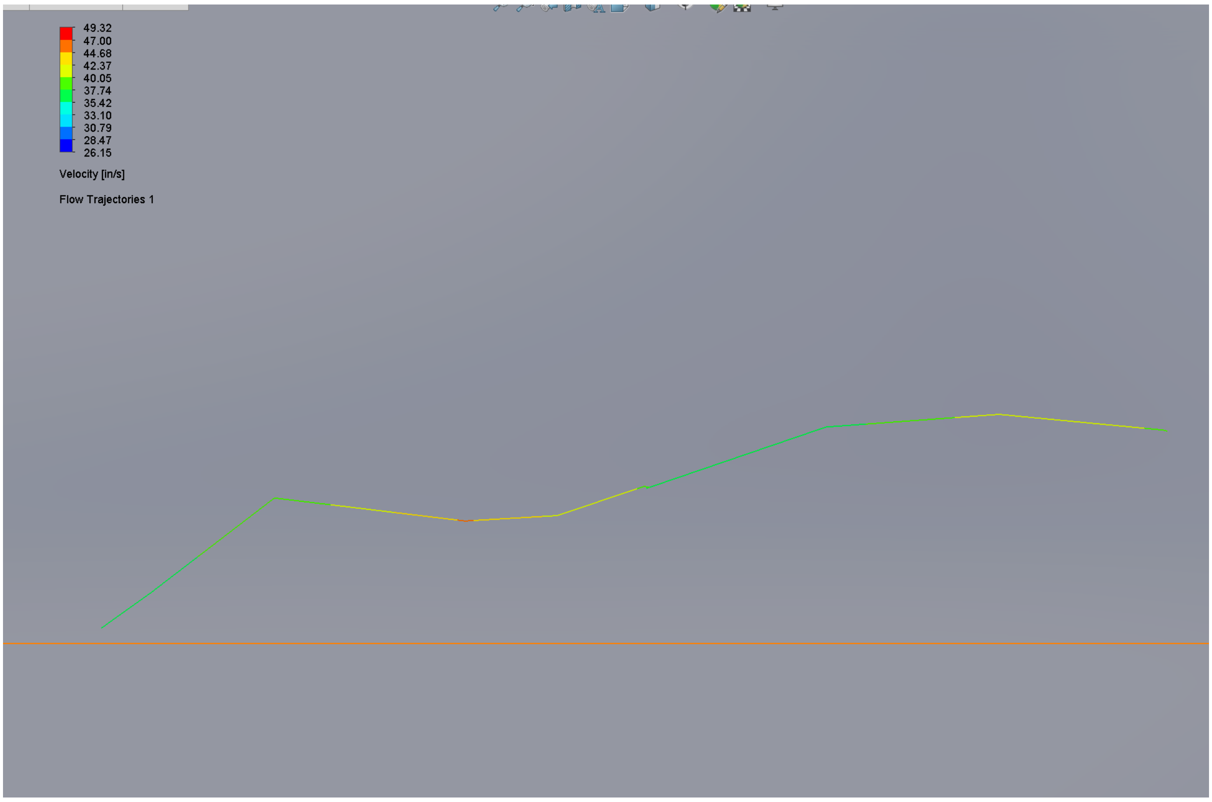

Figure 21. All-1 Front View (Zoom in at the narrowest part)

All-1's simulation shows us that there is 10% increase in wind velocity at the narrowest space.

Model All-2

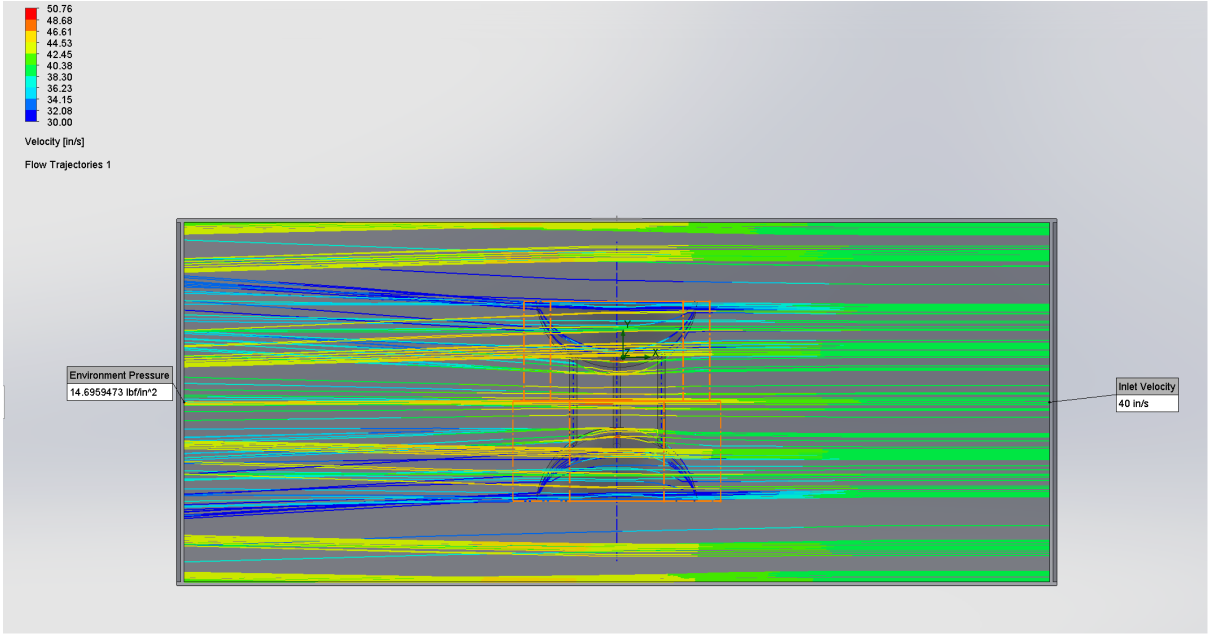

Figure 22. All-2 Side View

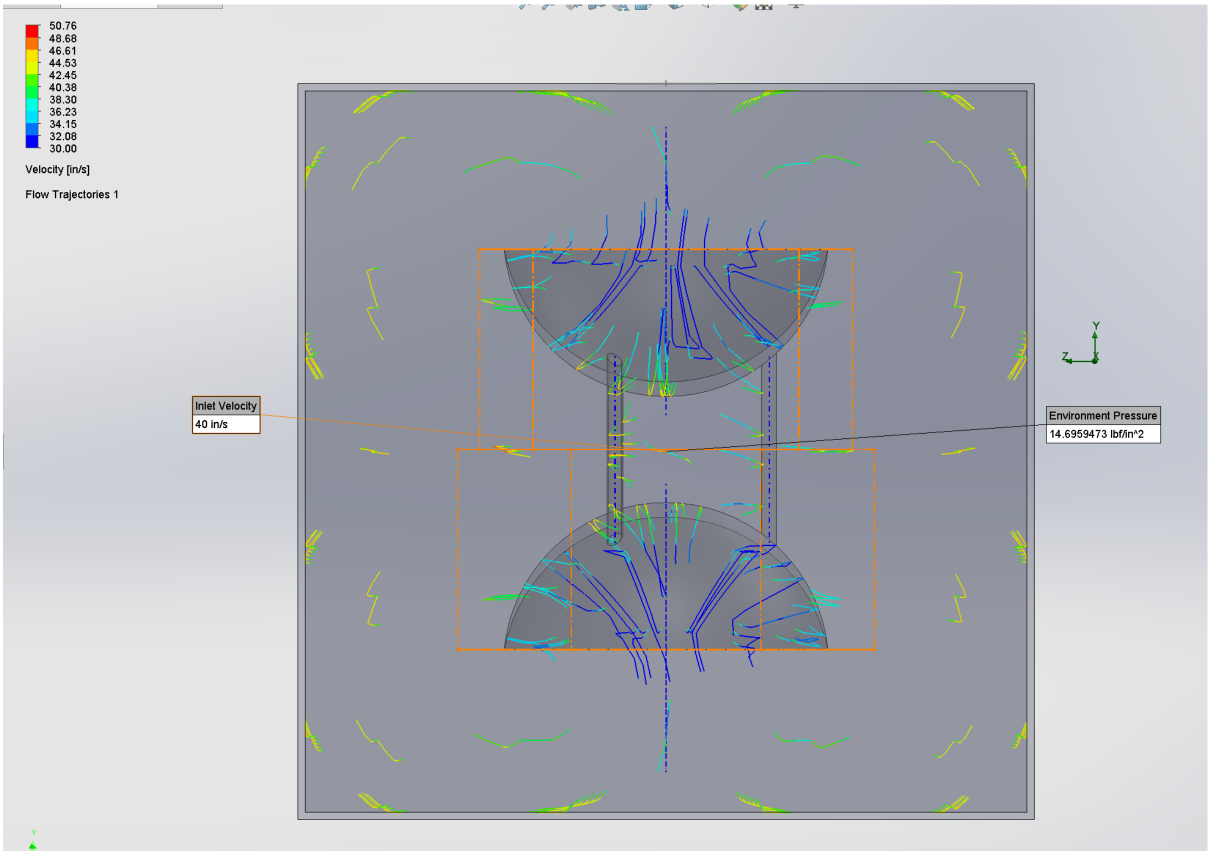

Figure 23. All-2 Front View

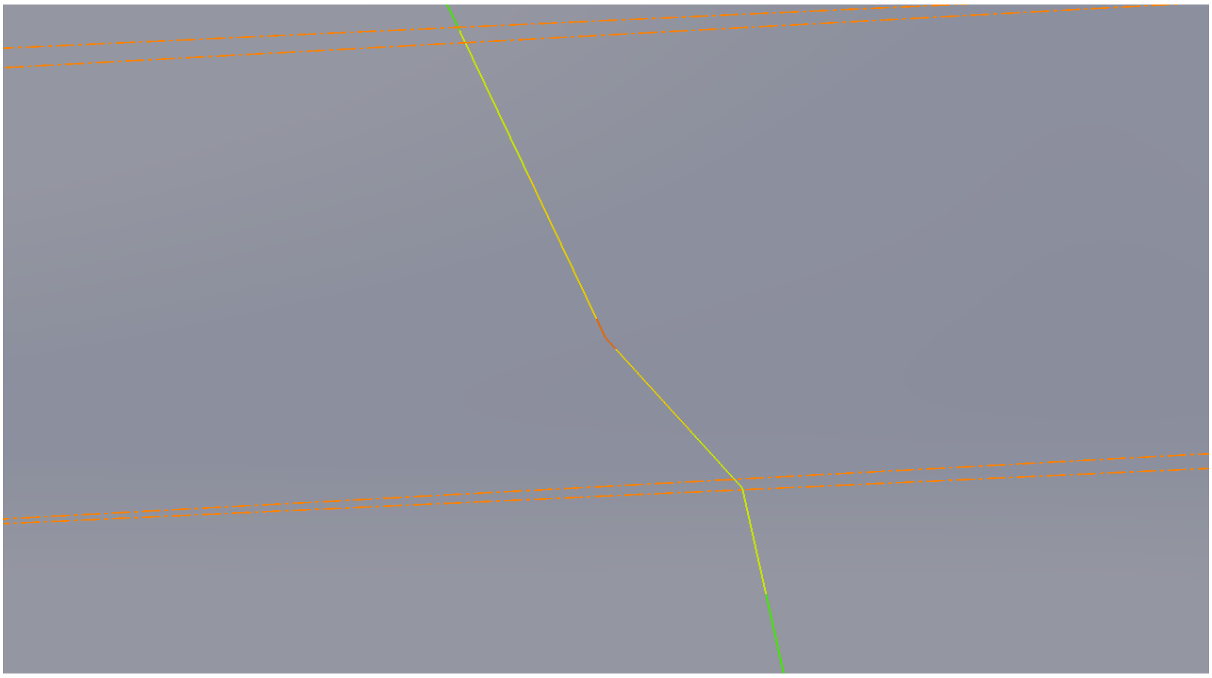

Figure 24. All-2 Front View (Zoom in at the narrowest part)

10% increase in the length of radius of top and bottom spherical caps resulted in 15% increase in wind velocity at the narrowest part.

Model All-3

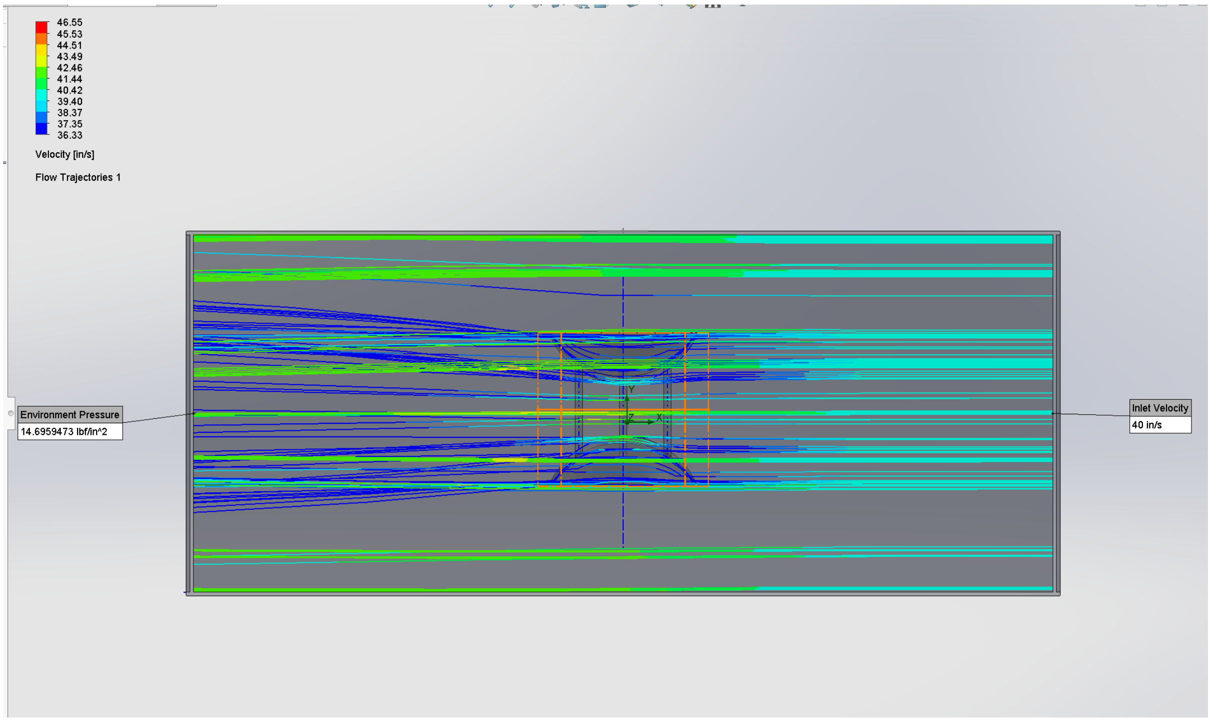

Figure 25. All-3 Side View

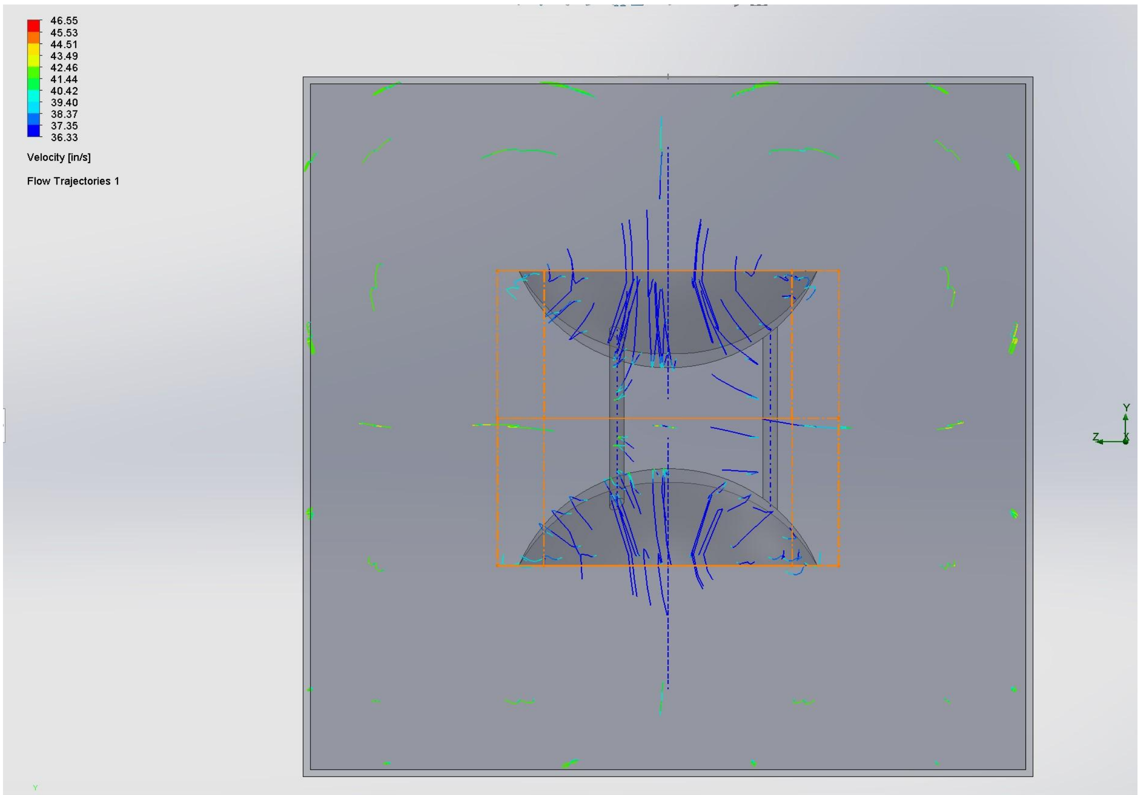

Figure 26. All-3 Front View

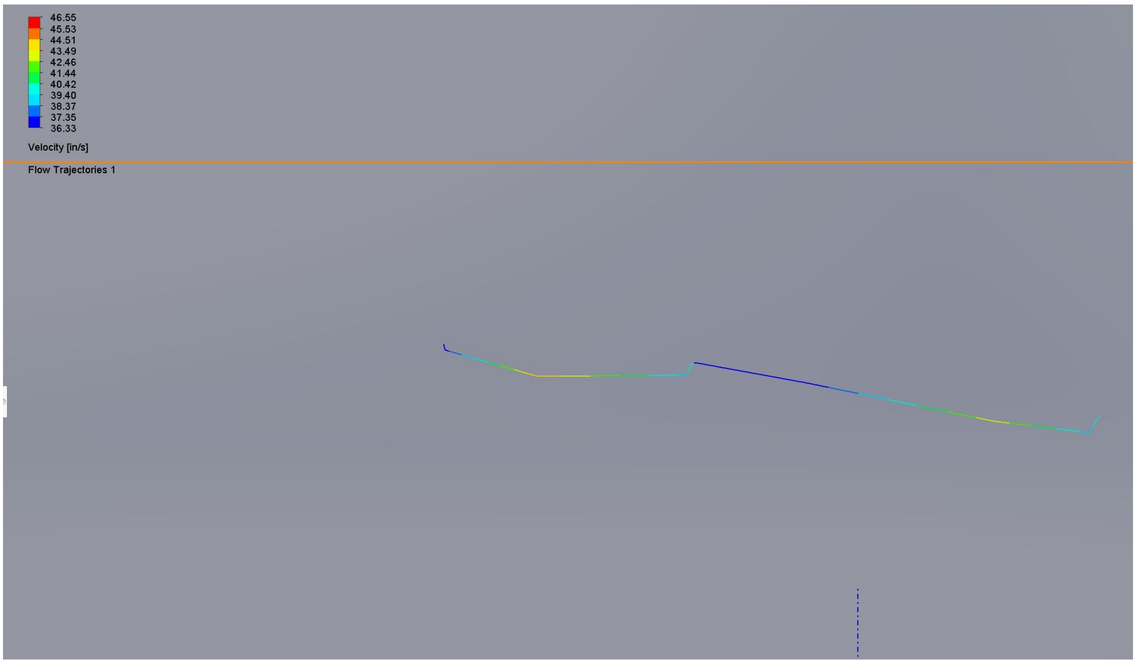

Figure 27. All-3 Front View (Zoom in at the narrowest part)

Model All-3's simulation shows us that there is around a 10% velocity increase in the narrow section compared to its initial wind velocity. The difference between All-2 and All-3 is that All-3's height was decreased by 25%; this resulted in a decrease in its efficiency.

<u>Model All-4</u>

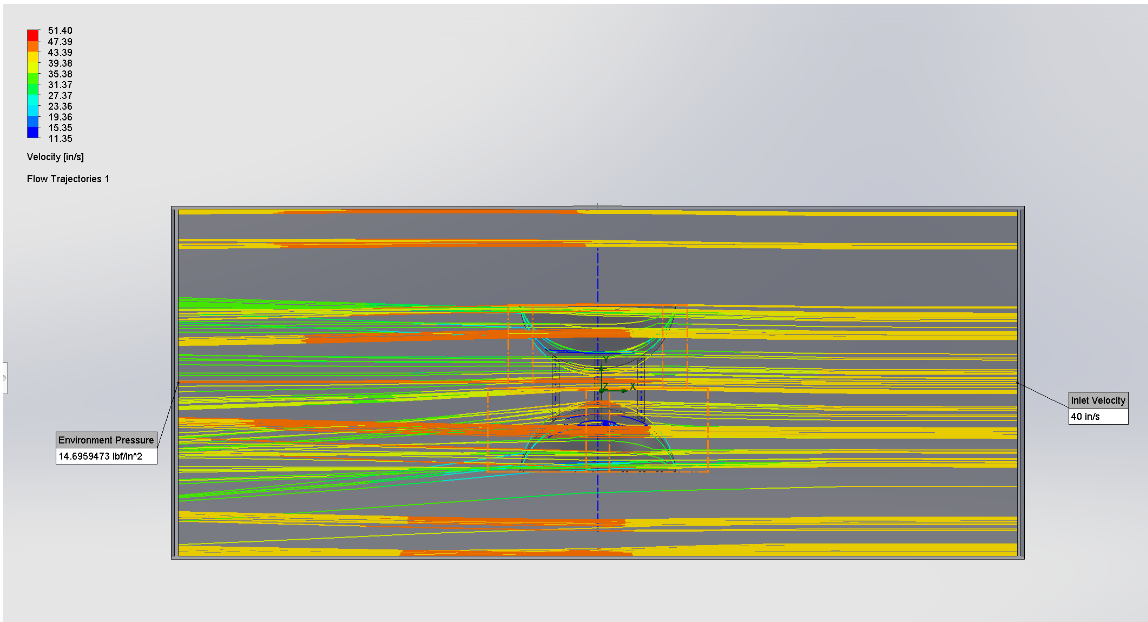

Figure 28. All-4 Side View

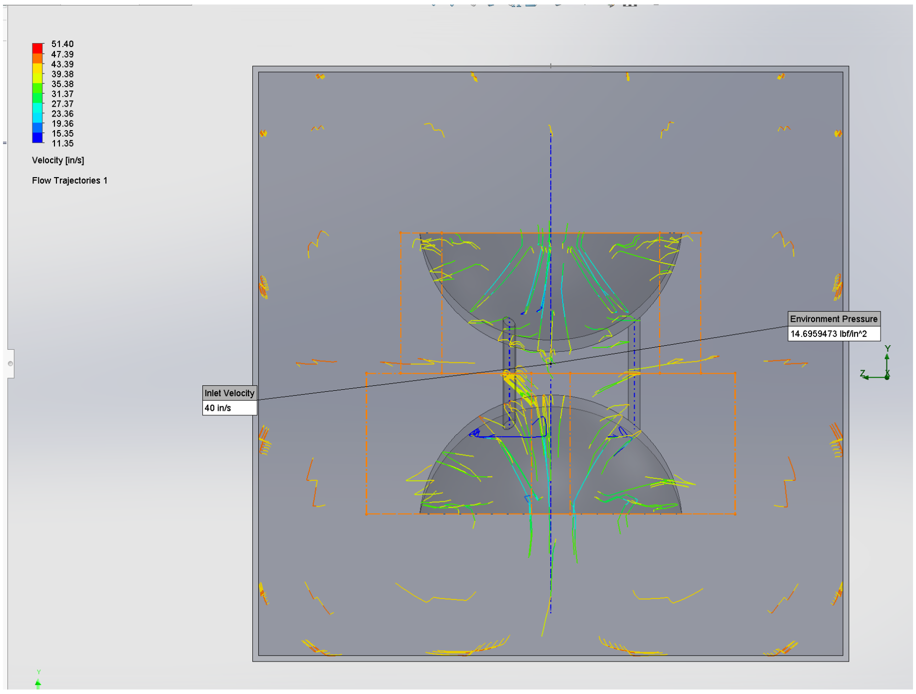

Figure 29. All-4 Front View

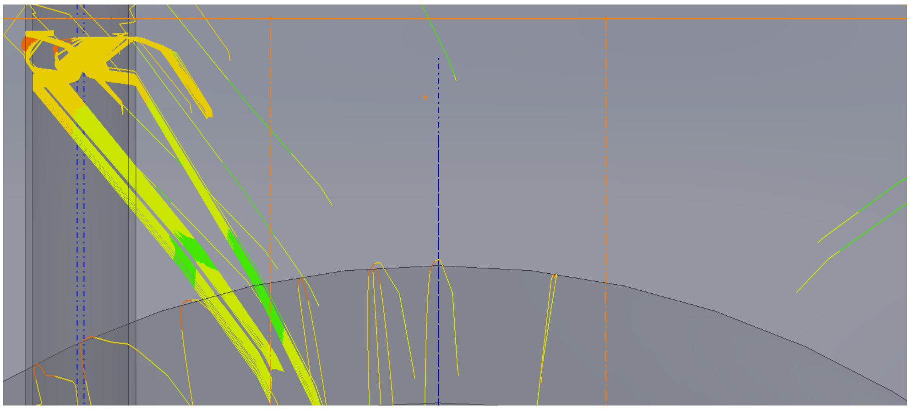

Figure 30. All-4 Front View (Zoom in at the narrowest part)

This model has shown the greatest increase in wind velocity - around 18%. The difference between All-2 and All-4 models is that height of the narrowest section has been reduced by 50% from All-2 to All-4.

Brief Analysis of simulations with All-1, 2, 3, 4

Based on our simulations with All-1,2,3,4 models, we can conclude that wind velocity can be maximized when the wind power density compressor has the following properties:

1. Increasing height of the entire model
2. Decreasing height of the narrowest section
3. Increasing the radius of top and bottom spherical caps

Additional Simulations Figuring Out Changes in Wind Density

Testing Change in density of air particles with All-4

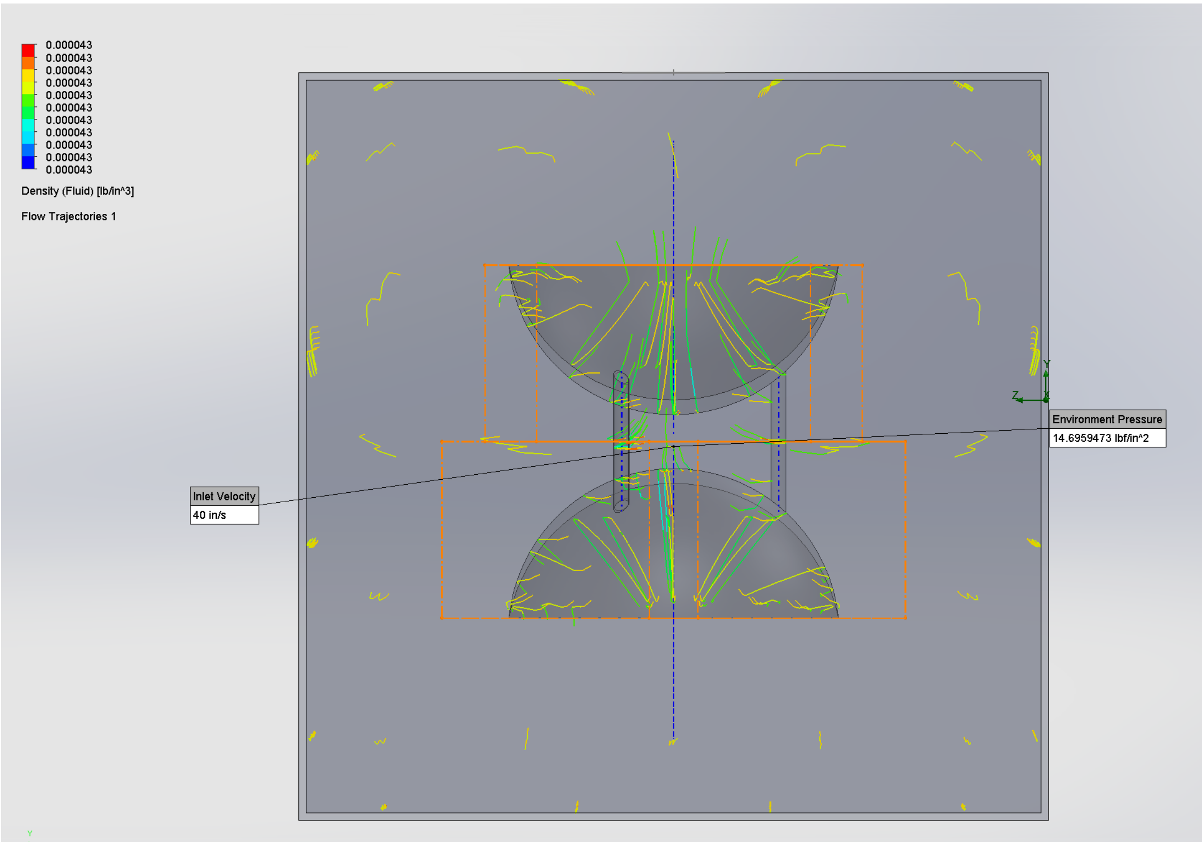

Figure 31. All-4 Wind Density Variation

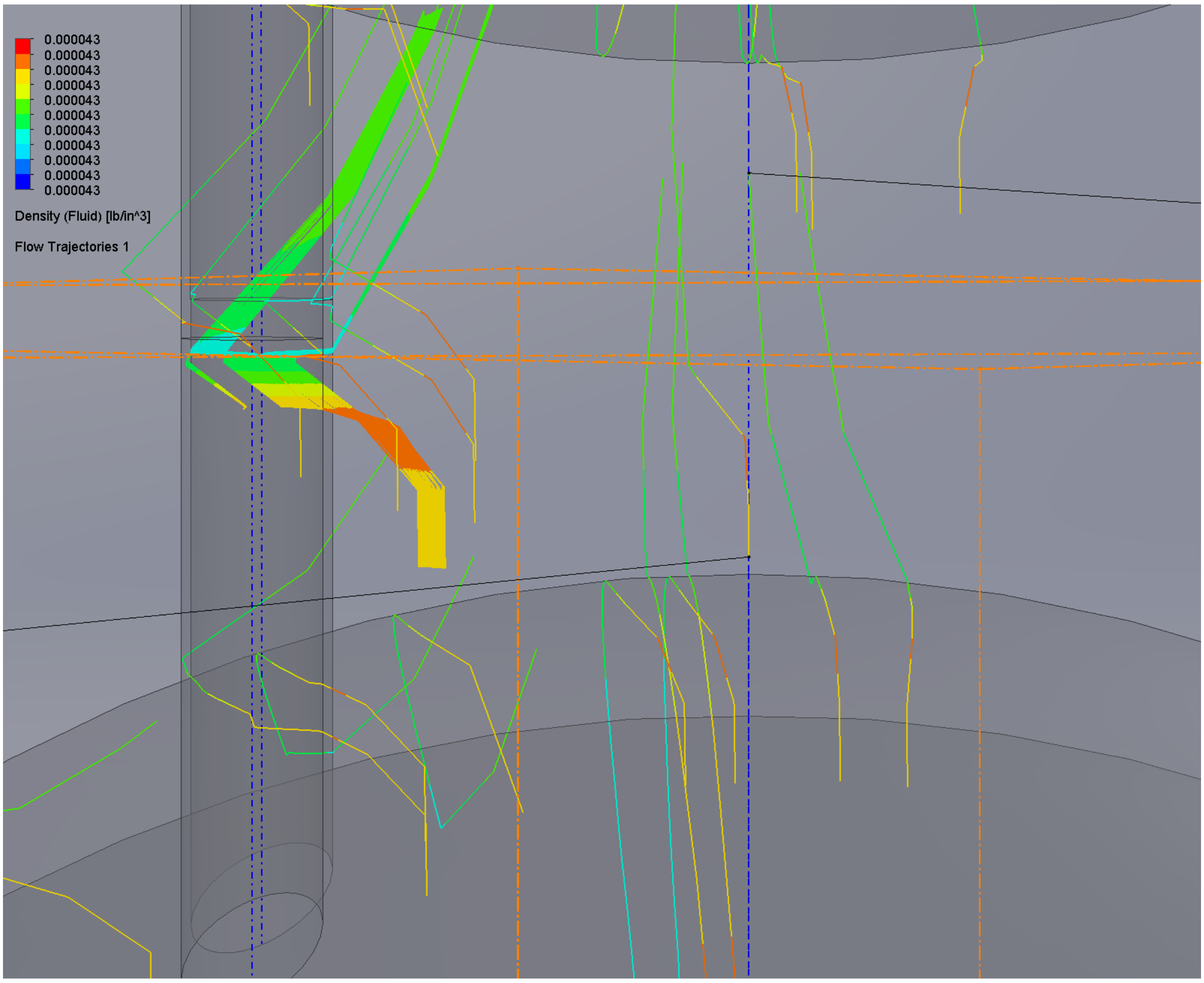

Figure 32. All-4 Wind Density Variation (Zoom in)

Throughout this simulation, we observed that wind density gets denser at the narrowest section. However, getting exact data of how much air density increases was quite a challenging task because the simulation was run with a low-density environmental setting that we could not adjust. The result from this simulation is remarkable in the sense that the flow of incompressible fluid results in more compact particles passing at a higher speed than the original flow(without the presence of our model).

Conclusion

Since we have relied on simulations only, the actual results might come out differently. However, we expect that our models would also highly improve the efficiency of all kinds of wind turbines in the real world. By adapting our models widely, we can take steps further to make a completely green, smart city where we do not use carbon fuels which cause various kinds of pollution.

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