Design and Analysis of an Optimized Rotational Molded Defroster Plenum

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Final Report

MECH 4860 ENGINEERING DESIGN

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- MECH 4860 PROJECT LETTER OF TRANSMITTAL -

Dr. Labossiere,

Our design group is pleased to present to you our report entitled *Design and Analysis of an Optimized Rotational Molded Defroster Plenum* on this the Monday the 7th of December.

This report discusses the redesign and analysis of a defroster plenum used to redistribute air from the defroster to the driver's windshield.

If there are any inquiries regarding this report do not hesitate to contact any members of the team via their University of Manitoba email.

Sincerely,

Amanda Gbur

Executive Summary

Our team has worked to optimize New Flyer's Xcelsior defroster plenum in terms of air distribution, defrost time, noise level, weight, installation time, and number of points on the assembly line in which the plenum can be installed. We have also analyzed the feasibility of rotational molding for the plenum based on cost, longevity, and the number of pieces it will take to manufacture the plenum.

Research was conducted into the benefits and downfalls of the rotational molding process. New Flyer's vendor, Plasticom, was contacted for cost estimates and further feedback. Using the information gathered, our team determined that rotational molding was not a feasible manufacturing method due to the large probability of thermal expansion. Upon recommendation from Plasticom, our team then explored the manufacturing method of vacuum forming to determine whether this would be a suitable option. Research was once again conducted along with a cost analysis, and it was concluded that vacuum forming would be the most appropriate and cost effective method for manufacturing the plenum.

In order to optimize the plenum, the various design requirements were weighted and concept generation and scoring took place. The main focus of the new concepts was redesigning the middle wedge and adding fins. However, the focus changed to that of redesigning the vents when New Flyer purchased a competing bus manufacturer and examined their more reliable defroster system.

After much CFD analysis and consideration of designs, it was proposed to maintain the current shape of the plenum. This ensures that the cost per piece of the plenum does not increase, since its complexity does not increase. Instead it is proposed that the vents located in the dash be altered. The new vents are large, with a width of 0.8 inches and a length of 7 inches. The total outlet area of the vents is 44.574 in^2. It is also recommended to eliminate the fins within the vents, and instead maintain an open vent area. This will prevent a choking phenomenon and air will be able to easily flow through the openings, as proven by our CFD models provided.

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1. Problem Statement and Background

Our team has been tasked with redesigning New Flyer's current Xcelsior defroster plenum, and determining whether rotational molding would suit this part.

New Flyer Industries Inc. is North America's leading bus manufacturer [1]. New Flyer's headquarters are located in Winnipeg, Manitoba, with other manufacturing facilities located throughout Canada and the United States. The Winnipeg manufacturing and assembly facility completes approximately 50% of the heavy-duty bus manufacturing [2]. Engineers at the Winnipeg headquarters are always looking to improve current bus designs, whether the changes are large or small. Small changes in the design of individual components can greatly impact the overall lead time and cost of bus manufacturing due to the high production rate (approximately 34 buses a week [2]).

Heating, ventilation and air conditioning (HVAC) are some of the many components in all buses. HVAC maintains the comfort of the passengers as well as the driver. In addition, HVAC ensures proper air distribution throughout the buses. The defroster plenum is the part of the bus which is responsible for redistributing air from the defroster to the driver's front and side windows, eliminating the accumulated ice and frost. Therefore the plenum plays a large role in enabling the driver to see through the window. On a cold winter day, good ventilation will ensure that the driver's windows are properly defrosted. An image of the structure of the front of the bus is shown in Figure 1.

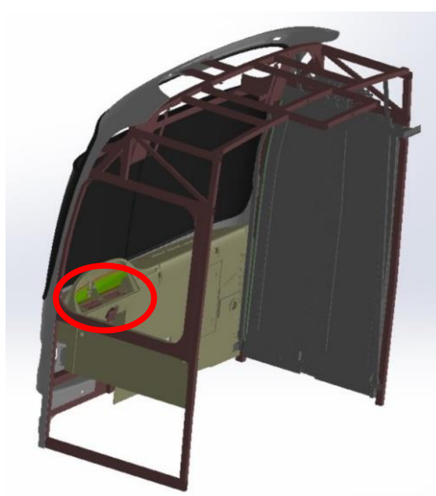

Figure 1 - Front end of an Excelsior bus, with the plenum circled in red.

The defroster plenum is partially shown in green and orange in the center left of the dash, where the driver's gages will be attached.

New Flyer's current design for the Xcelsior defroster plenum causes multiple problems. Mainly the cost of the current plenum is too high. Other problems are those relating to the plenum's functionality, of which the most important is that it creates poor air distribution. The sides of the driver's main window receive minimal air, and the driver's side windows do not receive any air.

The goal of last year's Capstone project was to fix some of these problems by redesigning the plenum. Upon the completion of the redesign, the 2014 Capstone group recommended vacuum forming as the manufacturing method for New Flyer's new plenum. However, this manufacturing process has multiple downfalls, the largest being long term longevity concerns. Namely, the upfront cost for creating a mold is extremely high, and if New Flyer wanted to change the plenum design in the future, a new mold would need to be purchased. New Flyer has tasked our group with exploring the feasibility of rotational molding as the manufacturing process. Additionally, our group is tasked with optimizing the redesigned plenum in terms of weight, installation time, airflow distribution and noise.

2. Project Objectives

There are many requirements for this project that have been identified through meetings between New Flyer and our group including; optimizing the manufacturing method, improving the air distribution, and improving the features of installation. Therefore, our group has established a methodology, which will be discussed in more detail in the preceding sections. This methodology is to be followed in order to ensure that each of the needs are met. New Flyer will receive continuous updates outlining the progress our group will be making in the redesign.

2.1 Design Requirements

There are numerous aspects of the current plenum that our team is expected to optimize. One of the aspects is the manufacturing method. The current method of manufacturing the plenum is sheet metal bending which is very costly. New Flyer would like our team to determine whether rotational molding would be feasible. This evaluation will primarily be based on cost and longevity. Whether or not the plenum can be manufactured as a single part will also be taken into account. Presently, there are misalignments of the plastic pieces that cover the plenum, due to the fact that the current plenum is manufactured in three pieces.

Air distribution is another aspect that New Flyer would like our team to optimize. The current plenum design diverts most of the air to the center of the driver's front window. This is a concern, as the sides of the front window as well as the driver's side windows receive minimal hot air, and therefore do not defrost fast enough. New Flyer would also like our team to decrease the level of noise that is caused by air exiting the defroster plenum. Noise level is related to air distribution since the noise is caused by high air velocity, and a better distribution will require a lower velocity of air in order to defrost the windows within the mandatory time.

Other aspects of the design that our team is expected to optimize are minimizing the weight of the plenum, reducing the installation time, and increasing the number of points on the assembly line at which the plenum can be installed.

Specifications for all of the needs are discussed in Sections 3.3 and 4.0 in terms of ideal targets that our group will aim to meet. Section 4.0 also addresses the hierarchy of the needs, to guide the focus of our efforts in the redesign.

2.2 Methodology

In order to meet the needs of the client, our group has established an approach which will ensure that we stay on track with our goals:

- A CFD analysis will be done on the current plenum design in order to establish a baseline for optimization
- Our team will then optimize the design using CFD analysis, stress analysis, and heat transfer analysis
- For analyzing the feasibility of rotational molding, our group will research the process using online resources and compare the information gathered to the requirements presented by the client.
- The method of manufacturing using rotational molding will be compared to last year's recommendation of vacuum forming. This will be done by analyzing the previous year's report in comparison to the research our group will have completed in relation to the new plenum design.

A more detailed description and visual representation of our methodology is defined in Section 5.1 through the use of a Work Breakdown Structure.

2.3 Deliverables

Our project has many deliverables that will allow our group to gain continuous feedback from the client. Outlining our deliverables will ensure that the client is up to date on how far along our group is in the project.

Throughout the redesign process, multiple reports will be submitted to New Flyer. The first of these is the Project Definition Report, outlining the needs and constraints of the project. The second is the Concept Design Report, which contains possible plenum designs, along with the design that our group has chosen to analyze further. Lastly will be the Final Project Report, which will contain an analysis of our redesigned plenum, along with an analysis of the rotational molding manufacturing process.

Our group will deliver two presentations regarding our project. The first presentation outlines the scope of the project, the needs of the client, and the constraints imposed upon the project. A PowerPoint presentation will accompany the first presentation. The second presentation will describe our plenum redesign and how the needs and constraints were met. It will also include a final evaluation of the rotational molding manufacturing method. A poster and PowerPoint presentation will accompany the second presentation.

Our group will provide the client with a CFD analysis on the current plenum design, as well as the final redesign. The two CFD analyses will allow the client to easily observe changes in air distribution and noise level between the two designs. CAD drawings will be created for the redesigned plenum, and the files will be sent to the client. These drawings will provide clear dimensions of the plenum.

3. Needs, Constraints, and Limitations

The new defroster plenum design must adhere to certain constraints and limitations, which govern the feasibility of the design. The constraints and limitations for this design can be broadly categorized into codes and standards, and internal constraints and limitations that are determined by New Flyer. Codes and standards can be sub-categorized as Safety and Performance, and internal constraints and limitations can be sub-categorized into size, manufacturing, and installation constraints. The following sub-sections of this report outline these constraints in further detail.

3.1 Codes and Standards Governing Safety and Performance Constraints

The codes and standards of the automotive industry are governed and regulated by certain Associations and Societies. For the defroster plenum design, there are three major regulating entities; the Society of Automotive Engineers (SAE), the Federal Motor Vehicle Safety Standards (FMVSS), and the American Public Transportation Association (APTA). Each of these governing entities has certain standards and performance requirements for defroster systems, with standards that are specifically tailored to the passenger vehicle industry. The standards for each of these three governing entities are outlined in further detail in the following sub-sections.

3.1.1 American Public Transportation Association (APTA) TS - 54.2

The American Public Transportation Association Technical Specification 54.2 [3] outlines the required amount of air flow to the Driver's Area of a passenger bus, which is 100 cfm. The standard states that adjustable nozzles shall allow for variable control of the airflow, as well as a shutdown method of the airflow. The standard also states that the airflow in the heating mode should be reduced proportionally to airflow reduction in the passenger area. In accordance with this Technical Specification, the windshield defroster must meet the requirements of SAE Recommended Practice J381, which is detailed below. Lastly, the defroster system must divert heat to the driver's feet and legs, and must maintain visibility through the driver's side window.

Due to the scope of the new defroster plenum design, some points of APTA's Technical Specification 54.2 do not apply to our design. The only hard constraints the team must adhere to in this standard are that the defroster plenum must provide 100 cfm of air to the driver's area, the design must provide sufficient air flow to maintain visibility through the driver's side window, and the design must adhere to SAE's Recommended Practice J381. The other constraints within this technical specification refer to dash controls for air flow diversion, or specifications on the proportionality of air flow reduction from the driver's area to the passenger area, or the ability to divert air to the driver's feet and legs. In these circumstances, the dash vents and controls are used to control those air flow reductions or diversions, and therefore they are outside the scope of this design.

3.1.2 Federal Motor Vehicle Safety Standards (FMVSS) – 302

The Federal Motor Vehicle Safety Standard 302 [4] outlines flammability requirements for all interior materials and components that are within 0.5 inches of the occupant compartment air space. These components include, but are not limited to, seat cushions, instrument panel padding, engine compartment covers and wheel housing covers. FMVSS's Standard 302 requires that all materials within 0.5 inch of the occupant compartment air space must not burn, or transmit a flame across its surface, at a rate of more than 4 inches per minute. The test is conducted in a flame proof metal cabinet or combustion chamber, and the material must be maintained at specific environmental conditions for a minimum of 24 hours.

This standard is essential for passenger vehicles, because fire hazards can present themselves in the event of an accident, and the safety of the passengers is paramount. The defroster plenum is within half an inch of the occupant compartment air space, and thus the material that the new defroster plenum is made of must meet the requirements of this test standard.

3.1.3 Society of Automotive Engineers (SAE) – J381

The Society of Automotive Engineers Recommended Practice J381 [5] requires that the windshield and the left- and right-hand side windows must be defrosted after 30 minutes of defrost time in specific environmental situations. This test standard is for defrosting systems of enclosed cab trucks, buses, and multipurpose vehicles. The tests done for this standard require a cold chamber temperature of -18°C wherein the vehicle must soak in for either 4 hours or until it is stabilized at the test temperature, whichever comes first. The environmental chamber must be held at the test temperature for a minimum of 24 hours. The wind velocity for the test must not exceed 3.2 km/hr. A maximum of two occupants can be in the vehicle during the test, and the windshield wipers may be operated during the test. A layer of ice is applied with specific conditions using a spray gun until a layer thickness of 0.05 mL/cm^2 is achieved. This test condition represents a more severe scenario than the situations that would be encountered under practical use, because the ice layers that are applied to the windshield would be scraped off under conventional use.

SAE's Recommended Practice J381 is essential for many jurisdictions where New Flyer's buses are used, and thus it is a constraint that must be met with our team's design. The constraint that must be met for this testing standard is a defrost time on the windshield and left- and right-hand windows of less than 30 minutes, with the testing conditions mentioned above.

3.1.4 Requirements for Testing and Testing Approximations

In some circumstances, specific cities have passenger area heating requirements that New Flyer must meet. For example, New Flyer's Xcelsior coach is sold in New York, where New Flyer is required to adhere to a "New York Passenger Area Heating Test" (NYPAHT) [6] and a "New York Driver's Area Heating Test" (NYDAHT) [6], which govern a maximum defrost time of the windshield and side windows in accordance with SAE's Recommended Practice J381, as well as a minimum driver and passenger area temperature. Both of these tests have the same requirements, but under different conditions. The NYDAHT requires that the defroster system must be capable of heating the driver's area to 60°F within 60 minutes during the process of cycling the doors. The NYDAHT requires the interior of the bus to be cold soaked at 6°F for 5 hours. The NYPAHT has the same requirements for the passenger area temperature as the driver's area temperature, but the interior must be cold soaked to 20°F for 5 hours. The NYDAHT and the NYPAHT are required for passenger buses in New York, but their standards are relevant to many cities. Therefore, these constraints are applicable to any province or state, whether they require them or not because the constraints are required in New York.

The tests outlined in the previous three sub-sections require testing laboratories with corresponding specialized equipment to ensure the standards are met. The completion of the tests outlined above is outside of the project scope, and thus it is assumed that New Flyer will conduct the relevant tests to ensure standard compliance. However, the team will conduct Computational Fluid Dynamics (CFD) analyses on both the current plenum design, as well as the team's finalized design to ensure that there are improvements on the old design and that New Flyer's requirements are met.

3.2 Size Constraints

The new defroster plenum design must fit into the current bus frame, such that it does not interfere with the adjacent defroster assembly, and does not exceed the space it is designed to fit within [2]. The plenum must be firmly fastened in the bus frame because standard use depends on road conditions, and under certain road conditions the plenum could be subjected to jolts and vibrations. If the plenum shifts in these scenario, air may leak out of the system causing air flow distribution issues and increased defrost time. An image of the bus frame where the plenum will be installed is shown in Figure 2.

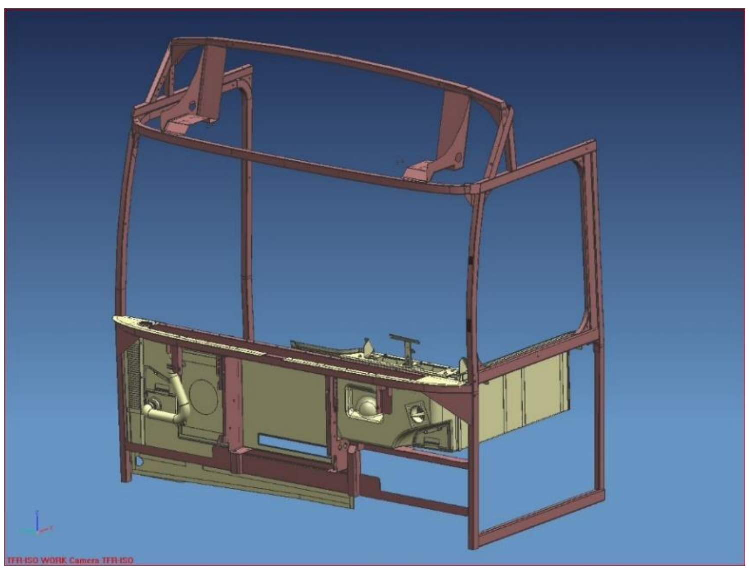

Figure 2: An image of the bus frame where the defroster plenum is to be installed *[2]*.

The defroster plenum is manufactured in several pieces, and then assembled and installed in the bus frame. Two pieces of the defroster plenum are shown in the upper left and right hand sides of Figure 3.

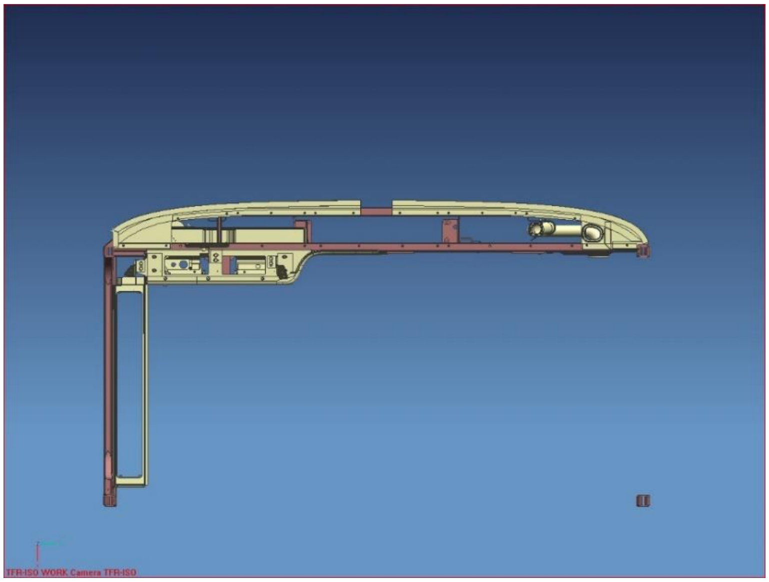

Figure 3: An image of the dash covers in the left and right corners of the bus frame *[2]*.

The main plenum piece is shown in orange, green, and blue in Figure 4, along with the other two plenum pieces previously illustrated in Figure 3. Figure 4 illustrates the installation process for the entire plenum assembly.

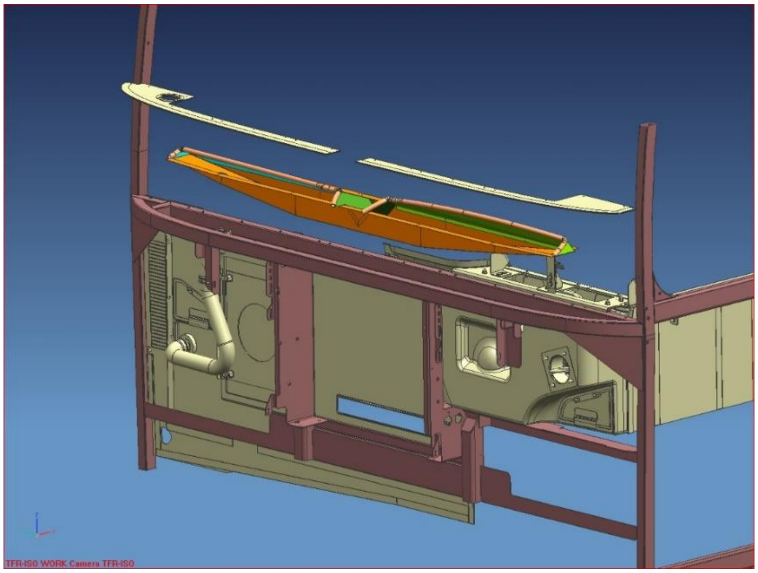

Figure 4: An image of the complete plenum assembly installation process *[2]*.

In terms of size, the plenum is restricted to a trapezoidal area in the bus frame. The short base piece is currently 55 inches, the total plenum length is 89.11 inches, and the width of the plenum is 5.21 inches. The frame area can accommodate a maximum height of 3 inches, and therefore the plenum design must be under 3 inches in height. The size constraints provide a basis in terms of size, but the project also has manufacturing and installation constraints and limitations. The manufacturing and installation constraints and limitations are detailed in Section 1.2.3.

3.3 Manufacturing and Installation Constraints

The constraints for the manufacturing process for the new defroster plenum design include cost, time, and manufacturing material availability [2]. The vendor that will be used to manufacture the new defroster plenum must be capable of a production volume of 2000 parts per year, and the manufacturing material must be available to the vendor. The manufacturing material must also be cheap enough to reduce the cost of the plenum, otherwise there would be no reduction in cost compared to the current plenum design. The manufacturing method for the design is defined within the project scope to be a rotational molding process, and thus it is assumed that the vendor that New Flyer uses is capable of manufacturing parts with that molding process. The constraint in terms of cost for the new defroster plenum design must be less than the current plenum cost, which is $230 per part. The costs associated with the new defroster plenum design must have a payback period of less than one year, based on the production volume of 2000 parts per year. Therefore, the cost savings for each plenum will have to be significant, with a likely target of under $200 per plenum.

The installation time constraints require that the plenum be installed in under 2 hours, as this is the installation time for the current plenum design. The installation must be completed by one person, and the plenum must set-up and firmly fastened to the bus frame within the installation time that is allotted.

3.4 Summary of Constraints

TABLE I summarizes the constraints and limitations that have been outlined in this section of the report for the new defroster plenum design. Where testing standards are being referenced, the testing procedure is listed, as well as the benchmark test results that determine standard compliance. Where manufacturing and installation constraints are referenced, the requirement for that constraint is listed and the required metric for that constraint is listed.

TABLE I: SUMMARY OF THE CONSTRAINTS AND LIMITATIONS.

Constraints for Testing and Standards		
Standard	**Testing Procedure**	**Results for Standard Compliance**
APTA TS 54.2 [3]	Measure the air flow to the driver's seating area	Air flow must be larger than 100 cfm, and must maintain clear visibility through the driver's side window.
FMVSS-302 [4]	Test Specimen is placed in a combustion chamber, ignited, and the burn rate is determined	The burn rate must be less than 4 inches per minute
SAE J381 [5]	Cold soaked at -18°C with 0.05 mL/cm^2 of water applied to the windshield	Windshield must be clear of ice in less than 30 minutes
NYDAHT [6]	The bus interior is cold soaked to 6°F, the doors are cycled and a 0.05 mL/cm^2 layer of water is applied to the windshield	Defroster clears windshield in less than 30 mins according to SAE's J381 practice and heats the driver's area to 60°F in less than an hour
NYPAHT [6]	The bus interior is cold soaked to 20°F, and the doors are cycled.	The defroster heats the passenger's area to 60°F in less than an hour
Manufacturing and Installation Constraints and Limitations [2]		
Requirement	**Required Metric**	
Manufacturing Process	Rotational Molding Process	
Material Availability	Material must be commercially available	
Material Cost	Must result in part cost reduction	
Payback Period	Less than one year	
Plenum Cost	Current Cost: $230	
Installation Personnel	One person	
Installation Time	Less than 2 hours	
Sizing Constraints [2]		
Requirement	**Required Metric**	
Must fit in the intended bus frame area	Must be securely fastened in the frame area. Dimensions of the frame area are detailed in Section 1.2.2	

The constraints and limitations for this project offer a basis for determining the target specifications for the defroster plenum design. The next section outlines the target specifications for this project.

4. Target Specifications

Target specifications are specifications designed to meet the clients need for the design and optimization process. There are two types of specifications the team will consider throughout the design and analysis process of the new defroster plenum. The first type is the essential specifications that we must meet for the customer needs throughout the project, and they are necessary for the new design. The second type of specifications are secondary specifications, which the team will try to meet but are not required for the project. Manufacturing process, manufacturing cost, air flow distribution, noise, installation time and number of parts in the plenum are our essential specifications for designing new defroster plenum. Our secondary specifications are defrosting time, weight, payback period and number of installation points in the assembly line.

4.1 Essential specifications

Our main focus is to use a rotational molding process for the new plenum design instead of the bending process that currently using by New Flyer industries. The team is tasked with determining the feasibility of using a rotational molding process for the new defroster plenum design and the total cost for making one plenum as well as mold cost of plenum. If rotational molding process is not feasible for defroster plenum than our team research new process of manufacturing, and we will recommend new process.

The second essential specification is to reduce the cost per plenum to be less than $168 [7]. New Flyer produces approximately 2000 buses per year [2], so cost is an important factor for the company. Our team will work to reduce the cost of the defroster plenum and increase savings for New Flyer industries.

Our team is tasked with designing a new defroster plenum that has a uniform air flow distribution across the windshield and side windows, and we will achieve this by doing CFD analysis. Our team will attempt to reduce noise by 2dB [2], and achieve this goal by lowering the air flow velocity. The air flow velocity is directly associated with noise level, and thus a reduction in the air flow velocity should reduce the noise level in the bus.

The fourth essential specification is installation time, which is directly proportional to labor cost. The higher the installation time for each plenum per bus, the higher the labor cost is for New

Flyer. Our goal is to reduce installation time by around 20 minutes (from 120 minutes to 100 minutes) which increases savings, and allows laborers to install more defroster plenums per day. Our team will choose right fastening method for installing defroster plenum into the bus, and achieve this goal.

The fifth essential specification is the assembly of the defroster plenum in one piece instead of multiple parts. The current plenum has multiple parts, and it takes more time to assemble the plenum due to tolerance and fit issues between pieces. A one piece plenum design will save installation time as well as improve assembly performance. Our task is to use a rotational molding process for manufacturing our new plenum design, and preliminary research indicates that a one piece plenum is viable.

4.2 Secondary Specifications

Our first goal is to reduce defrosting time by 5 minutes. The standard time (SAE-J381) required for defrosting the windshield is 30 minutes [5], and our goal is to achieve a defrost time of 25 minutes with the new design.

A second goal is to reduce the weight of the new plenum. The team will research different kinds of materials that could be used to reduce the defroster plenum weight. In the rotational molding process, 97% of parts are manufactured using polyethylene, which is lighter than most other materials used in molding processes [8]. We can achieve our goal for reducing weight by using polyethylene material.

The third non-essential specification is a payback period, and our target is to maintain that period less than one year. Payback period is defined as the time in which any associated cost for creating a mold, tooling and prototyping, has to be paid back utilizing the reduction in plenum cost [2].

The last specification is to use one technician to install the plenum in the assembly line. The current plenum is installed by one person, and the team will create a design that renders a single person installation method feasible. Also the team will design the new plenum in a way that the technicians install the plenum at multiple stages in the assembly line. The current plenum is installed in two installation points in the assembly line, and our goal is to have the capability of installing the plenum in three points on the assembly line.

4.3 Summary of Target Specifications

TABLE II shows the summary of the target specifications listed above. An importance level of 5 indicates that the specification is most important, and an importance level of 1 indicates a specification that is least important.

TABLE II: SUMMARY OF THE TARGET SPECIFICATION.

Target Specifications				
Imp	**Metric**	**Units**	**Ideal**	**Marginal**
5	Manufacturing cost	CDN dollars/unit	<168	230
5	Air Flow distribution	N/A	N/A	N/A
5	Noise	dB	2	N/A
4	Installation Time	Minutes	100	120
4	Number of Parts in the plenum	Parts	1	3
3	Defrosting Time	Minutes	25	30
3	Number of installation point in assembly	Points	3	2
2	Low weight plenum assembly	kg	<=4.15	4.15

Note: Air flow distribution is quantitative data, so there is no unit for that. We can get the results from CFD analysis results.

5. Manufacturing Using Rotational Molding

In order to determine whether rotational molding is a feasible method for manufacturing the plenum, our team researched the method in terms of benefits, downfalls, what materials can be used, cost, and what types of geometries can be manufactured.

5.1 The Process

Manufacturing a part using rotational molding is accomplished in four steps, as shown in Figure 5. First a hollow mold is created. This is usually accomplished using cast aluminum or sheet metal [8].

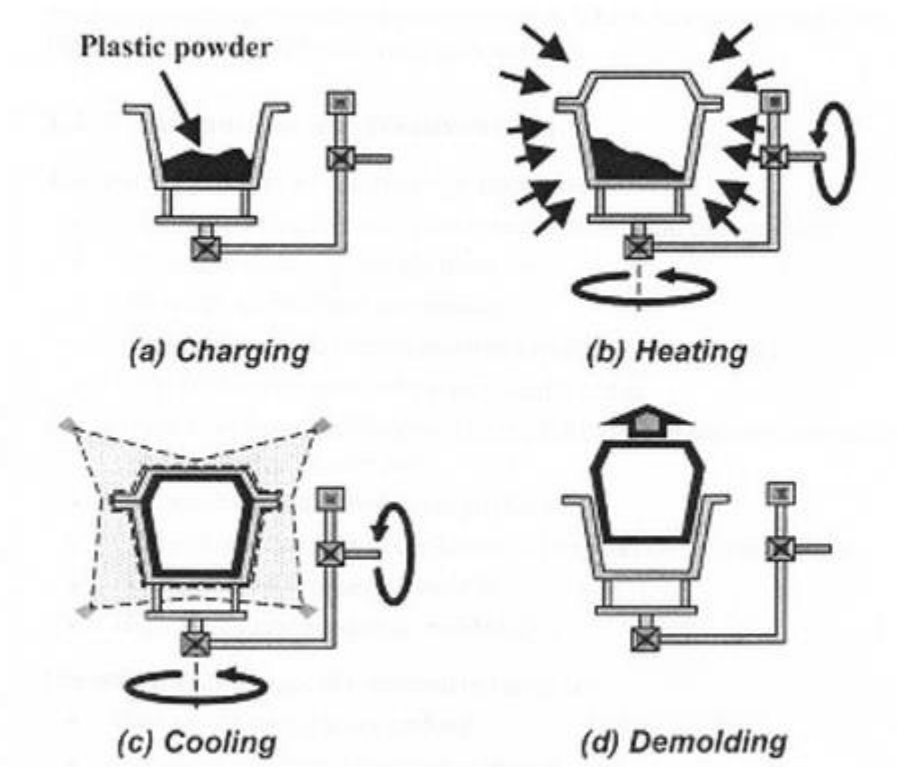

Figure 5: Basic four-step process of rotational molding, used with permission from *[9]*.

This mold is then filled with a finely ground powder or liquid resin. Next, the mold is rotated on multiple axes in an oven. This continues until the resin has melted and entirely coated the inside of the mold cavity. The mold is then cooled, in order to harden the part. Lastly, the part is removed from the mold [10].

5.2 Advantages of Rotational Molding

Compared to other manufacturing techniques using molds, rotational molding has many benefits:

- There is no limit to part size [10]
- There is no limit to the complexity of the part [10]
- Parts have high durability and strength due to being manufactured in one solid piece [10]
- Stresses are not present in the parts due to the absence of stress inducing manufacturing techniques, such as sheet metal bending [10]
- Decreased lead times [10]
- Wall thickness consistency [10]
- Cost effective [11]

5.3 Disadvantages of Rotational Molding

There are two main problems that must be taken into consideration when determining whether rotational molding is suitable for manufacturing a part. These include limitations to material selection as well as part geometry.

Currently, 97% of parts manufactured using rotational molding are made of polyethylene [8]. Other, less commonly used materials are polymers such as PVC, Polypropylene and Polyamide [8]. These materials are found to be more difficult to grind down to a fine powder, as required for rotational molding. There is an option to freeze-grind the materials, however this is more costly, and is therefore rarely used [8].

Due to the material properties of polyethylene, the "rotationally molded parts would have a relatively high coefficient of thermal expansion" [12]. Since the plenum is located at the front of the bus, it would be subject to very low temperatures in the winter, while the air flowing through the plenum would be hot. This would result in the part both "shrinking and expanding when subjected to [these] changes in environmental temperature" [12]. As well, the plenum is mounted to the dash using rivets. This mounting method does not accommodate for changes in part shape and might therefore cause the plenum to crack.

Parts that have been manufactured using rotational molding have a tendency to bow, and they may not retain flatness over the length of the part [12]. This is due to both the material properties of polyethylene and the manufacturing process in itself. This would pose a problem for installation, since it would be difficult to mount the plenum to the dash in places where the plenum's edges are not flat. Even if the plenum were able to be mounted, there would be complications with sealing along the non-flat edges. The air flowing through the plenum would escape through the openings where the plenum is not perfectly flush against the dash. This would affect the air distribution resulting in an increased defrosting time.

Due to the complex shape of the plenum, rotational molding would still require that the part be manufactured in a minimum of two pieces [12]. The number of pieces would increase as more wedges and fins are added to the part. Since the plenum's ability to distribute air effectively largely depends on the number of fins and wedges, it is more than likely that manufacturing would be accomplished in at least four pieces.

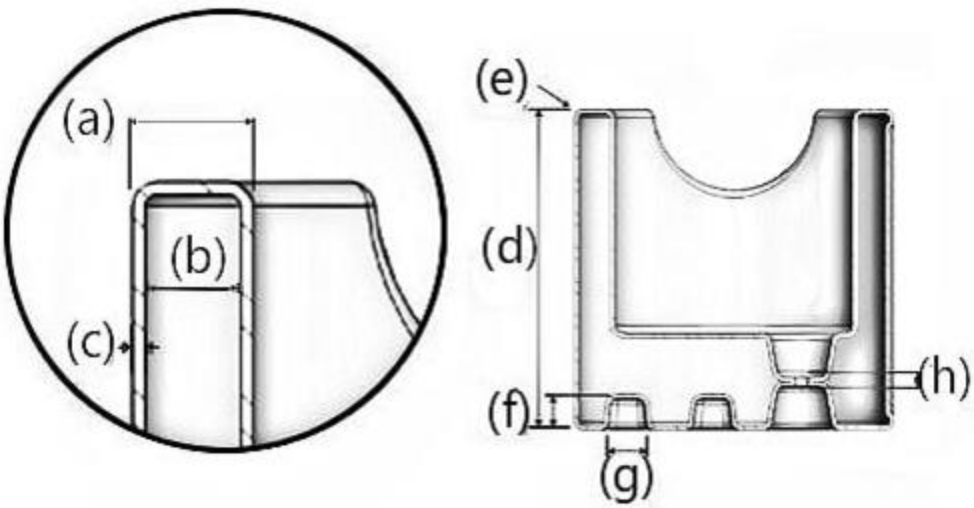

Figure 6: Design limitations of rotational molding, recreated from *[10]*.

Rotational molding has certain limitations in terms of part geometry. The limitations that are most important to the design of the plenum include wall thickness, separation, and radii at corners. Using Figure 6 as a reference;

- The outer wall separation (a) must be no less than five times the wall thickness (c) [13]
- The inner wall separation (b) must be no less than three times the wall thickness (c) [13]
- Consistency in wall thickness (c) is limited to +/-20%, where +/-10% is considered precision [13]
- Wall thickness can vary from 0.090inch to 1.00inch [13]

- The minimum radius for corners is 3/16inch [13]
- The width of any section (g) must be no less than five times the wall thickness (c) [14]
- The height of any section (f) must be no less than three times the wall thickness (c) [14]

Using the guidelines above, the current plenum design must be evaluated to determine whether the design fits meets the guidelines.

5.4 Cost Analysis of Rotational Molding

A cost analysis was completed by contacting New Flyer's current vendor, Plasticom, for rotationally molded parts. The estimate received from Plasticom is based on the current plenum design. Any modifications to the design that would result in a higher complexity of the part will also result in an increase in cost. All prices were estimated in US Dollars. TABLE III gives a summary of the costs, as well as the Canadian Dollar equivalent utilizing the current exchange rate of 1 US Dollar to 1.33 Canadian Dollars.

TABLE III: ROTATIONAL MOLDING COST ANALYSIS *[12]*

	US Dollars	Canadian Dollars
Tooling	\$8,000 - \$12,000	\$10,644.78 - \$15,976.14
Cost Per Plenum	\$40 - \$60	\$53.22 - \$79.84
Assembly and Hardware	No Estimate Available	No Estimate Available

Since one of the technical requirements from New Flyer is that the payback period must be less than one year, we must calculate the payback period using Equation 1. The savings per part are calculated using the current plenum cost of \$230.00 Canadian Dollars. The payback period is calculated using conservative cost estimates, with a production rate of 2000 parts per year.

$$Payback\ Period = \frac{\frac{Tooling\ Cost}{Savings\ per\ Part}}{parts\ produced\ per\ year} = \frac{\frac{\$15{,}976.14}{(\$230 - \$79.84)/part}}{2000\ parts\ per\ year} = 0.05\ years \quad [1]$$

Our technical requirements provided by New Flyer state that the payback period must be less than one year. Since rotational molding meets this criterion, a rotational molding manufacturing method is considered feasible in terms of cost analysis.

5.5 Conclusion of Rotational Molding

Rotational molding proves to be a very cost effective solution for the manufacturing of the plenum of an Xcelsior bus. With a saving of approximately $150.16 per part, it results in a large cost reduction compared to the current sheet metal bending manufacturing method. While the upfront cost of tooling is high, this would be paid back by part savings in less than one year.

Nevertheless, there are several design challenges that make rotational molding infeasible. These consist of limitations in material, thermal expansion causing problems with mounting and the tendency of the parts to bow. For these reasons, our team has determined that rotational molding is not a feasible manufacturing method for the Xcelsior bus plenum.

Furthermore, our team has conducted research regarding a vacuum forming manufacturing process for the plenum. We believe a vacuum forming method more suited for the given application. Section 7 will discuss this method in depth, and provide a detailed analysis of its feasibility.

7. Manufacturing Using Vacuum Forming

Due to the infeasibility of a rotationally molded plenum, our team is recommending that New Flyer use vacuum forming method for manufacturing. The following sections will outline the vacuum forming process, describing its benefits and downfalls. A cost analysis will be completed to determine whether the savings per part are sufficient to move forward with this method.

7.1 The Process of Vacuum Forming

Manufacturing a part using vacuum forming is accomplished in seven steps [15]:

1. First, a mould must be created. This is generally done using a soft wood. It is important to create a mold such that the part can easily be removed when processing is complete.
2. Next, the mold is placed in a vacuum former, and a sheet of plastic is mounded above the mold.

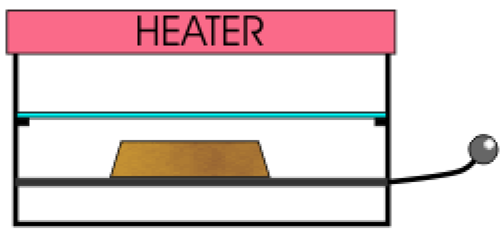

Figure 7: Mold placed inside vacuum former with plastic sheet above, used with permission from *[15]*.

3. The heater is then turned on, causing the plastic to become soft and malleable.

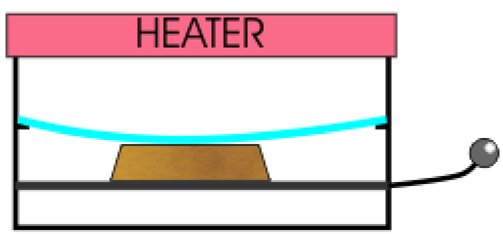

Figure 8: Heated plastic becomes malleable, used with permission from *[15]*.

4. Once the plastic is soft enough, the heater is turned off and the manufacturer moves the mold upward, closer to the plastic.

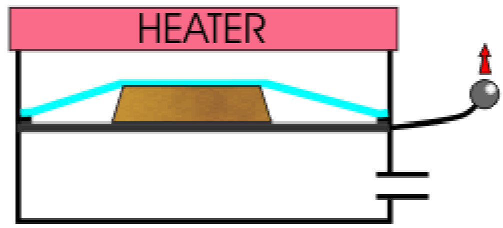

Figure 9: "Mold moved upwards," used with permission from *[15]*.

5. At this point, the vacuum is turned on causing the plastic to be stretched and pushed down onto the mould.

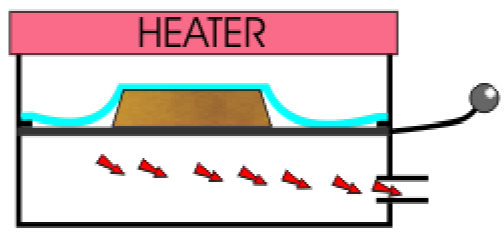

Figure 10: Vacuum causing plastic to form over mold, used with permission from *[15]*.

6. Once the plastic sheet has cooled, the vacuum is turned off and the "plastic is removed from the vacuum former" [15].
7. Post processing requires the plastic to be trimmed and cleaned.

7.2 Analysis of Vacuum Forming

Vacuum forming has several benefits over other manufacturing methods:

- Easy to produce multiple parts at a quick pace [16].
- The finished product will be lightweight [16].
- Design flexibility [17].
- Materials available are impact, corrosion, and U.V. resistant [17].
- Parts manufacturing using this method are durable and last a long time [17].
- Materials available have the ability to be bonded, welded or taped [17].

Although vacuum forming also has several disadvantages, their impact does not severely affect the quality of the plenum to be produced. One of the disadvantages is that any imperfections in the mold will be seen in the final part due to the thin plastics that are used [16]. However, this is not a major concern due to the fact that we are assuming the manufacturers are experienced and will be able to produce a quality mold.

Another disadvantage of vacuum forming is that the final part's edges will not be as sharp as the edges of the mold [18]. This is caused by the plastic being stretched over the mold, therefore producing a softer edge [18]. This does not pose a problem for the plenum, since the plenum's edges are not required to be sharp for the plenum to function properly.

One of the more significant disadvantages of vacuum forming is that the shape of the parts produced is limited [19], since the part must be able to be easily removed from the mold. One solution to this would be to manufacture the part in multiple pieces. This would not comply with the technical requirements provided by New Flyer, which state that the plenum must be produced in one piece. Nevertheless, it must be recognized that it is difficult to identify a manufacturing method where the plenum can be produced in one piece, while remaining feasible and cost effective.

7.3 Cost Analysis of Vacuum Forming

A cost analysis was completed by contacting Plasticom, the same vendor used for rotationally molded parts. The estimate received from Plasticom is based on the current plenum design using ABS. Any modifications to the design that would result in a higher complexity of the part will also result in an increase in cost. All prices were estimated in US Dollars. Table 2 gives a summary of the costs, as well as the Canadian Dollar equivalent utilizing the current exchange rate of 1 US Dollar to 1.33 Canadian Dollars.

TABLE IV: COST ANALYSIS OF VACUUM FORMING *[12]*

	US Dollars	Canadian Dollars
Tooling and Trim Fixtures	$21,000	$27,905.32
Cost Per Plenum	$76	$100.99

Since one of the technical requirements from New Flyer is that the payback period must be less than one year, we must calculate the payback period using Equation 2. The saving per part are calculated using the current plenum cost of $230.00 Canadian Dollars. The payback period is calculated using conservative cost estimates, with a production rate of 2000 parts per year.

$$Payback\ Period = \frac{\frac{Tooling\ Cost}{Savings\ per\ Part}}{parts\ produced\ per\ year} = \frac{\frac{\$27,905.32}{(\$230 - \$100.99)/part}}{2000\ parts\ per\ year} = 0.1\ years \quad [2]$$

Our technical requirements provided by New Flyer state that the payback period must be less than one year. Since vacuum forming meets this criterion, a vacuum forming manufacturing method is considered feasible in terms of cost analysis.

7.4 Conclusion of Vacuum Forming

Although the payback period for vacuum forming is greater than that of rotational molding, vacuum forming is still considered cost effective in comparison to the current manufacturing method of sheet metal bending. It is important to note that cost is not the most important factor to consider when choosing a method for manufacturing. If the final plenum will not be functional nor durable, the cost in the long run will be much greater.

As well, the benefits of vacuum forming, including the durability of the parts, greatly outweigh its disadvantages such as not being able to have sharp edges, which prove to be insignificant. For these reasons, our team has decided to propose vacuum forming as the future manufacturing method for the plenum of the Xcelsior bus.

8. Fastening Methods

Fastening methods are to use for joining two parts of either the same material or different materials such as; metal to metal, plastic to plastic, or plastic to metal. Mechanical fasteners are made of metals, plastics or a combination of the two. There are many mechanical fasteners available in the market such as screws, nuts, inserts and rivets, which are all are made of metal or plastic.

Our goal was to use a rotational molding process for manufacturing the defroster plenum. This proved to not be feasible, and instead a vacuum forming method was recommended. In this process, ABS (Acrylonitrile-Butadiene-Styrene) is the common material used for manufacturing any part. Our task is to find the correct fastener to join the ABS plenum to the metal body of the bus. Currently New Flyer Industries are using a riveting method (pop rivet or blind) for joining plenum the assembly to the bus. This is the same method which we recommend for the ABS plenum.

Rivets are designed to join two pieces of metal or plastics together through a pre drilled hole. The advantages of rivets are [20]:

1. Lower cost
2. Lower cost of labor
3. Lower setting time in parts than threaded fasteners
4. Useful in high speed assembly operations
5. Dissimilar materials joined easily
6. Assemblies are less susceptible to vibration
7. Easy installation of parts

There are a number of riveted joints available for different types of applications, but for our project the basic riveted joint used is a lap joint as shown in Figure 11.

Figure 11: Lap Joint *[21]*

New Flyer Industries uses blind rivets for joining the current defroster plenum, which is also suitable for our new design. Blind rivets are popular because of ease of installation and versatility. As well, they can be used for various types of material. The governing factors for any riveting method are strength, corrosion resistance and material to be fastened. Blind rivets have two parts; the pin and the rivet. Rivet pliers are used to pull the pin through the rivet, and as this happens, the rivet is deformed slightly so that it joins the metal or plastic pieces. Figure 12 shows the blind riveting process [22].

[redacted]

Figure 12: Blind Riveting Process *[22]*

The material used for joining metal to ABS is the same as for joining two metal parts. This decreases the cost of establish a new riveting method and the same set of skills and instruments may be used for the redesigned plenum. For joining plastic to metal, it is better to make allowances for a small washer on the plastic side of the joint. This will stop the pressing of rivet onto the plastic side while it is being attached, and it will decrease the chances of weakening the joint between metal to ABS. Figure 13 shows the typical blind riveting for metal to plastic with a small washer [23].

[redacted]

Figure 13: Rivets with small washer *[23]*

9. Patent Review and Design Research

Our team conducted a patent search to ensure that any designs we generate are not infringing on any existing patents. The search networks our team utilized are the United States Patent and Trademark Office [24] and the Global Patent Search Network [25]. Our team searched each of these networks with many different combinations of phrases describing air distribution systems, such as “Defroster Plenum”, “Heated Air Delivery”, “Vehicle Air Distribution”, as well as many other combinations. Terms and phrases that describe defroster plenums were brainstormed and used to search for any designs that may come close to our teams’ design. Our team found many different patents on defroster systems, but many did not contain any information about air delivery systems or air distribution under the dashboard or across the windshield. Since the defroster is outside the scope of this project, all of the patents for defroster systems that do not have air distribution methods are not pertinent to this design, and therefore they will be omitted from this patent search. The patents discussed in this report have either an air plenum or air distribution device, but they differ from our designs by having completely different shapes or defrosting systems. The first patent contains an air delivery system that consists of an air plenum.

The first patent our team found that performs a similar function as our design is United States Patent 6,966,829 [26]. The patent outlines an air delivery system that contains an air plenum which connects to a coupling joint that transfers air through the dash to concealed vents. The largest difference between the design in this patent and our designs is that the main function of the patent design is to deliver heated air from the defroster to the cab of the vehicle through concealed vents on the dashboard. The main function of our teams design is to have an air plenum with better air distribution on the windshield of the bus, as well as heat the driver’s area. In our designs, the driver’s area is heated through the same vents that defrost the windshield. The scope of the design in the patent is to provide an air delivery system that directs air within a civilian vehicle, rather than a commercial vehicle. Therefore, our design is considered sufficiently different from United States Patent 6,966,829, and our team will not infringe on this patent with any of our designs based on shape or utility.

The second patent our team found that supplies air to a passenger area in a vehicle is United States Patent 6,881,140 [27]. The purpose of the design in this patent is to control the temperature of air that is supplied to the passenger air of a vehicle by utilizing a mixing chamber. The mixing chamber has a cold inlet and a warm inlet, as well as at least one outlet, and consists of at least one air diversion device which causes the warm and cold air to mix. The largest difference between our design and the patent design is that our design does not serve the purpose of mixing air. Our design has one inlet, and serves only the purposes of distributing air across the windshield and supplying air to the driver's area. The patent design does not detail the outlet air distribution method, or any air distribution method on the windshield of the vehicle. The purpose of the patent design is to control the temperature of air to the passenger compartment. Since our designs do not consist of a mixing chamber, and only serve to distribute air across the windshield by directing air from one inlet, our designs will not infringement on this patent with any of our designs based on shape or utility.

The third patent that our team has found which serves the purpose of distributing air into a vehicle interior is United States Patent 6,547,152 [28]. The patent design consists of a module with a central plenum that receives two layers of air flow, forces them through an arcuate (or mixing) duct, and discharges the air flow into the passenger area. This patent design serves a similar purpose as United States Patent 6,881,140 [27] in that it mixes two air flows and supplies the mixed area to the passenger area. Our designs focus entirely on diverting air that is fed through one inlet, and does not mix two different air flows. The scope of our design differs from the scope of the patent design in that the main function of this patent is to mix air and deliver it to the driver`s area, whereas our design scope serves to distribute air from a singular inlet onto the bus windshield. The shape and function of this patent design compared to our designs differ significantly enough to ensure there is no patent infringement.

The fourth patent that our team found that serves the purpose of motor home or recreational use vehicle heating and air-conditioning is United States Patent 5,934,988 [29]. The patent design consists of an air plenum which is fed with air by two variable speed blowers. The plenum has three outlet ducts which extend to the windshield, the driver`s side, and the passenger`s side of the vehicle. One blower is typically used to defrost the windows in the patent design, and the other blower is optional should more air be required in the driver`s or passenger`s area, each of which can be controlled separately. The patent design differs from our design in that the patent design utilizes a main blower and an optional blower, with different ducts to three different areas. Our designs utilize one defroster and the duct only extends to the windshield vents. The shape and function of this patent design are sufficiently different from our designs to ensure that there is no patent infringement.

The fifth patent that our team found that serves the purpose of heating and cooling for vehicles is United States Patent 5,265,668 [30]. The design in this patent is to provide a heating and cooling system for a vehicle which has a main housing with separate ducts for defrosting the windshield, and for cool air and heated air. The design also specifies that the main housing may have a secondary housing which directs air to the main housing through the use of a blower. The function of this patent design is to provide a main housing or chamber with ducts connected to it to distribute different air flows without using tubes. This patent design utilizes multiple pieces and ducts to divert air where it`s required, and may or may not consist of more than one blower. The purpose of our teams' designs is to divert air from a singular inlet across the windshield of the bus with a one piece defroster plenum. Therefore, the function of our designs is sufficiently different from the design in the patent, and therefore there will be no patent infringement.

The sixth patent our team found that serves the purpose of distributing air for vans, trucks, and buses is United States Patent 5,131,886 [31]. The main function of the design in this patent is to defrost the windshield of a van, truck, or bus through the use of a centrally placed defroster nozzle on the dashboard. The air is distributed through a single heated air compartment, and may have pipes bled from the compartment to heat the driver`s area, passenger`s area, or stairwell of a bus. The system relies on a baffle plate which ensures that the air distribution is uniform even when the heated air volume is changed. The air is directed onto the windshield through a singular nozzle that has blades that direct it in a V-shaped pattern onto the windshield. Our design differs from this patent design by having the plenum span the whole width of the vehicle, thereby causing a more uniform flow to all sections of the windshield, rather than a V-shape defrost pattern. The function of the patent design and our design is the same, but the methods of achieving the function are different. Therefore, there will be no patent infringement with any of our designs.

The seventh patent our team found that serves the purpose of defrosting a windshield is United States Patent 4,766,805 [32]. The purpose of the patent design is to defrost windshields that have a large angle to them, which is typically seen in civilian cars. The defroster system consists of a cowl box, a defroster duct, and an air plenum. The cowl box is an air compartment, and the defroster duct and the air plenum connect to the air compartment. The ductwork that extends to the base of the windshield is separated into multiple different ducts and diffusers that direct the airflow to the windshield. The system is made of many different ducts and parts, rather than a single piece design. Our design differs by utilizing a single piece defroster plenum that directs and distributes the air from the defroster onto the windshield, rather than a multiple piece design. Our designs do not incorporate cowl boxes or air compartments other than the defroster plenum. Therefore, our design is sufficiently different from this patent design and will not constitute patent infringement.

The seven patents listed above were the closest patent designs our team was able to find that related to the project we are undertaking. Any other patents that we found differed too greatly in terms of design or functionality to be considered for patent review.

10. FMEA

The Failure Mode and Effect Analysis (FMEA) is a powerful design tool that provides a means to compare, from a risk point of view, alternative machine system configurations. It is also useful for considering designs improvements. It is a formalized but subjective analysis for the systematic identification of possible Root Causes and Failure Modes and the estimation of their relative risks. The main goal of our FMEA is to identify, and then limit or avoid, risk within the design of plenum. For our project, the air distribution to both the front windshield and the side windows and the degree of loudness of noise when the air passes through the plenum are very important factors to decide if our design will fail. Therefore we have to take these factors as critical parameters of our plenum design. Also, the FMEA drives towards higher reliability, higher quality, and enhanced safety. Hence we will use these to assess and optimize our manufacturing process, such as in the installation of the plenum and vacuum forming manufacturing process.

It is vitally important to realize that a failure mode is not the cause of a failure, but the way in which a failure has occurred. The FMEA procedure assigns a numerical value to each risk associated with causing a failure, using severity, occurrence and detection as metrics. As the risk increases, the values of the ranking rise. These are then combined into a risk priority number (RPN), which can be used to analyze the system. By targeting high value RPNs the most risky elements of the design can be addressed. RPN is calculated by multiplying the severity by the occurrence and by the detection of the risk. Severity refers to the magnitude of the end effect of a system failure. The more severe the consequence, the higher the value of severity will be assigned to the effect. Occurrence refers to the frequency that a root cause is likely to occur, described in a qualitative way. That is not in the form of a period of time but rather in terms such as remote or occasional. Detection refers to the likelihood of detecting a root cause before a failure can occur [33]. The severity, occurrence and detection factors are individually rated using a numerical scale, typically ranging from 1 to 10. A high value represents a poor score. Once a standard is selected it must be used throughout the FMEA. The risk ranking system table is shown below.

TABLE V: RISK RANKING SYSTEM

Qualitative Ranking	Risk factors		
	Severity	**Occurrence**	**Detection**
10	Extremely serious impact	Certain probability	No chance that the error will be detected, no mechanism exists
9	Very serious impact	Inevitable and predicable failure	Remote or low likelihood of detection
7,8	Serious impact	Very high probability	Remote chance of detection only
5,6	Moderate severity	Moderate high probability	Moderate chance that error will be detected
3,4	Low to moderate severity	Moderate probability-occasional failures	High probability of detection
2	Slightly serious impact	Low probability-rare failure	Very high probability that error will be detected
1	Slight annoyance-no impact	Remote-no known occurrence	Certain-will always be detected

After the risk ranking standard is clarified, our team decided 6 critical process inputs to conduct the Failure Mode and Effect Analysis, the 6 critical inputs are air flow to the side windows, air flow noise, air flow to the front windshield, installation process, fastening method and vacuum forming manufacturing process. Our FMEA is shown in TABLE VI.

TABLE VI: A TABLE ILLUSTRATING OUR FMEA.

0 Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Action Results				
											Actions Taken	SEV	OCC	DET	RPN
Air flow to side windows	Compared to the current plenum,there is less air going to the side windows through the plenum	The defroster system can not meet the Codes and Standards Governing Safety, and affect the bus defroster system performance	4	The new plenum design is fail	*10*	None	1	40	Improve the design and conduct more CFD analysis	team 16	None	4	5	1	20
Air flow noise	Compared to the current plenum,the noise increases when the air pass through the plenum with higher velocity	Affect the bus performance and can not satisfy the customer needs	3	The new design of the plenum increase the air velocity when the air passes through the plenum	*5*	none	1	15	Improve the design and conduct more CFD analysis	team 16	None	3	4	1	12
Air flow to windshield	There is less air going to the windshield through the plenum and Windshield is not clear of ice in less than 30	The defroster system can not meet the Codes and Standards Governing Safety,and affect the bus defroster system	8	The new plenum design is fail	*5*		1	40	Improve the design and conduct more CFD analysis	team 16	None	8	3	1	24
Installation of the plenum	There is more than 1 technician doing the installation and the time taken of the installation process longer than 2 hours per plenum	Installation of component at inappropriate places leading to inadequate performance of the bus, also it will lead to higher cost and longer time taken	4	The technician is not well trained and inexperienced	*4*	None	1	16	Give the technician proper training or hire experienced technicians	New Flyer empoyee	None	4	2	1	8
Fastening method	The plenum is not fastened in long term run	The plenum is not fastened in long term run and affect the bus defroster system performance	6	Wrong fastening method was chosen;The technician is not well trained and inexperienced	*8*	None	8	384	Research new Fastening method and change the fasteners to other materials	New Flyer empoyee	None	6	5	7	210
Vacuum Forming process	Many imperfections are found on the plenum; Thermal expansion happens to the plenum	the plenum quality will be affected; the plenum can not fit the bus	6	The technician is not well trained and inexperienced; Thermal expansion happens to the plenum due to the	4	None	3	72	Change to other manufacturing process	Plasticom	None	6	2	3	36

To analyse the system, the RPNs are then ranked to allow prioritization of the failure modes and to highlight the failure modes that exceed acceptable limits and should therefore be targeted for changed. The highest RPN is assigned to the plenum fastening method. Therefore it should be prioritized for corrective action. Regardless of the RPN, attention should always focus on any domain where the severity ranking is high. The air flow to the windshield has a very high severity ranking and it is a key input to determine if our plenum design is successful. Therefore it also has to be prioritized in the design process. Those steps with low RPNs (and therefore of low impact in the spectrum of failure) are unlikely to affect the process and should not be prioritized. Referring to the criticality chart which is shown in TABLE VII, the criticality is divided in to 4 different levels. The RPNs as well as the criticality level is shown in TABLE VIII below. After Prioritized of the RPNs, the corresponding proposed actions are listed in TABLE IX. The recommended actions are to help decrease the occurrence of failure modes. They will not affect the severity and detection of the failure modes very much.

TABLE VII: CRITICALITY CHART

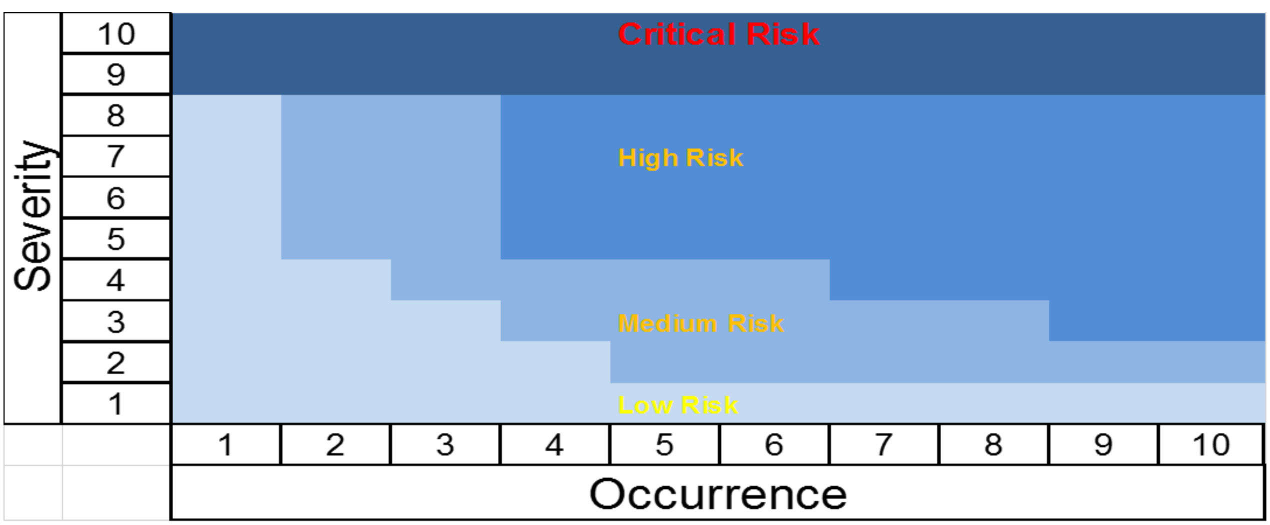

TABLE VIII: EVALUATION OF THE RPNS AND CRITICALITY LEVEL

Evaluation of the Severity Score, the Probability of Occurrence Score, and the Probability of Detection Score					
Failure mode	**Severity**	**Occurrence**	**Detection**	**RPN**	**Criticality**
Compared to the current plenum, there is less air going to the side windows through the plenum	*4*	*10*	*1*	*40*	*High risk*
Compared to the current plenum, the noise increases when the air pass through the plenum with higher velocity	*3*	*5*	*1*	*15*	*Medium risk*
There is less air going to the windshield through the plenum and Windshield is not clear of ice in less than 30 minutes	*8*	*5*	*1*	*40*	*High risk*
There is more than 1 technician doing the installation and the time taken of the installation process longer than 2 hours per plenum	*4*	*4*	*1*	*16*	*Medium risk*
The plenum is not fastened in long term run	*6*	*8*	*8*	*384*	*High risk*
Many imperfections are found on the plenum; Thermal expansion happens to the plenum	*6*	*4*	*3*	*72*	*High risk*

TABLE IX: PRIORITIZATION OF THE RPNS, WITH CORRESPONDING PROPOSED ACTIONS

Prioritization of the RPNs, with Corresponding Proposed Actions to Be Implemented to Avoid the Occurrence of the Individual Failure Modes			
Failure mode	**RPN**	**Actions recommended**	**Responsible person/team**
The plenum is not fastened in long term run	*384*	Research new Fastening method and change the fasteners to other materials instead of metal	New Flyer employee
Many imperfections are found on the plenum; Thermal expansion happens to the plenum	*72*	Research and change vacuum forming manufacturing process to other manufacturing process	Plasticom
Compared to the current plenum, there is less air going to the side windows through the plenum	*40*	Improve the design and conduct more accurate CFD analysis	Team 16
There is less air going to the windshield through the plenum and Windshield is not clear of ice in less than 30 minutes	*40*	Improve the design and conduct more accurate CFD analysis	Team 16
There is more than 1 technician doing the installation and the time taken of the installation process longer than 2 hours per plenum	*16*	Give the technicians proper training or hire experienced technicians	New Flyer employee
Compared to the current plenum, the noise increases when the air pass through the plenum with higher velocity	*15*	Improve the design and conduct more accurate CFD analysis	Team 16

11.0 Detailed Design Analysis

This section of the report will outline the procedure and methodology of evaluating each plenum design using ANSYS Computational Fluid Dynamics (CFD). In collaboration with Dr. Ormiston [34], our team set up many different simulations for a variety of boundary conditions, meshing options, and inlet air conditions. Two different inlet air conditions were used for our simulations, which are summarized in Section 11.1.

11.1 Inlet Air Conditions

The two different air conditions used for the simulations were air at 25°C and air at 120°C. Initially, air at 25°C was used to attempt convergence for the current plenum. Once convergence was achieved using typical air, our team moved forward with air at 120°C for the remainder of our simulations. It should be noted that there was a misunderstanding about the inlet air conditions, and the inlet air conditions were 120°F rather than 120°C. However, the results shown in this report are compared using the same boundary conditions, and the final designs determined from those comparisons will be run again with 120°F air. The properties of air at these three temperatures are shown in TABLE *X*.

TABLE X: AIR PROPERTIES AT 25°C, 50°C, and 120°C.

	Air at 25°C	Air at 120°C [35]	Air at 50°C [35]
Air Density (kg/m^3)	1.185	0.898	1.097
Specific Heat (kJ/kg*K)	1.0044	1.013	1.007
Thermal Conductivity	0.0261	0.0328	0.0278
Expansion Coefficient (1/K)	0.003356	0.00255	0.0031

After the final air properties were determined, our team looked more in depth into the meshing types that ANSYS offers. Throughout the course of the simulations, our team used two different meshing types, which are illustrated in Section 11.2.

11.2 Tetrahedral and Hexahedral Mesh

The two types of mesh our team used are Tetrahedral and Hex Dominant (Hexahedral) mesh. An image of a tetrahedral mesh for the entire plenum is shown in Figure 14.

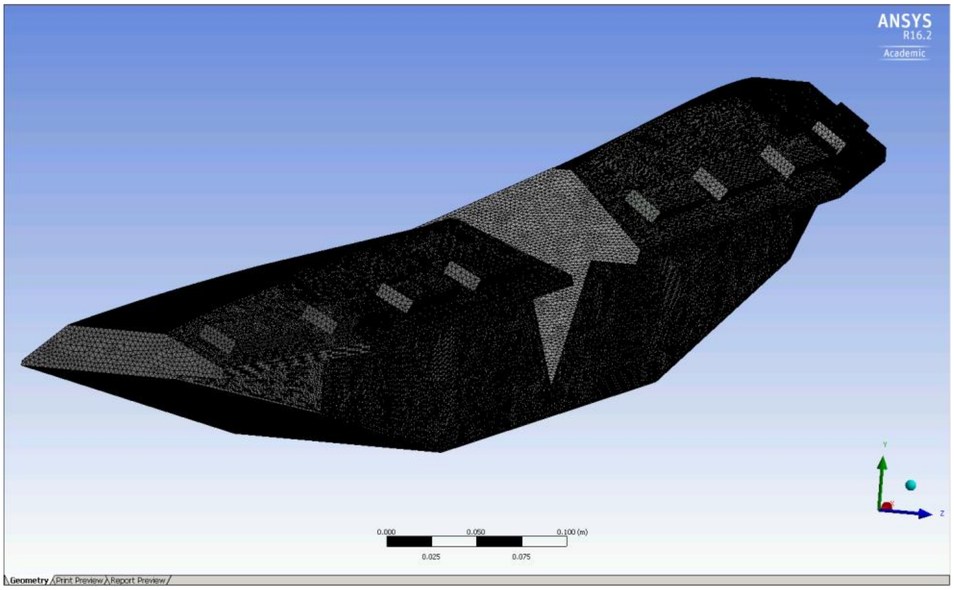

Figure 14: An image of a tetrahedral mesh for the current plenum.

The mesh for the entire mesh is difficult to see, and therefore a close up of the mesh is for one end of the plenum is shown in Figure 15.

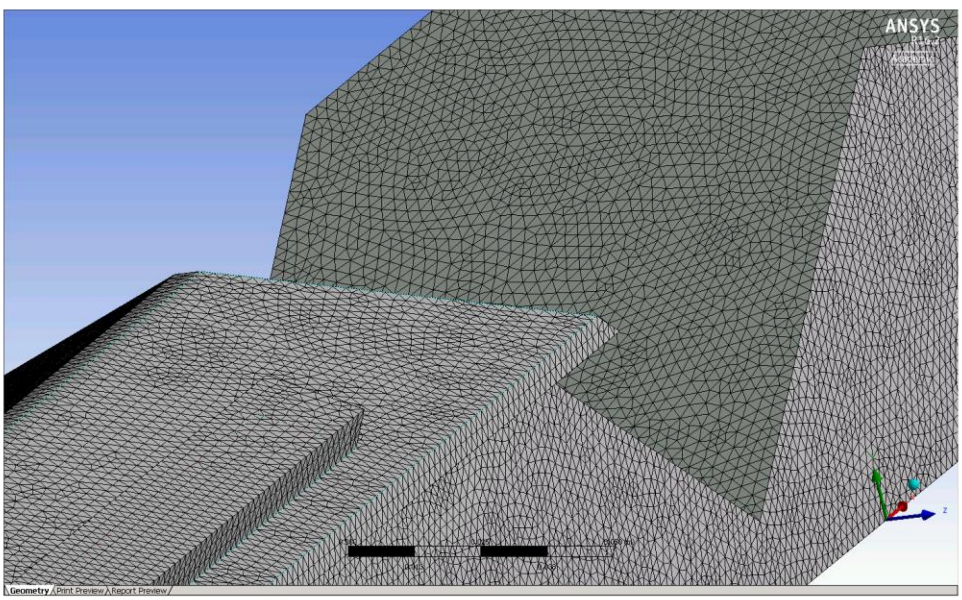

Figure 15: A close up image of a tetrahedral mesh.

The primary element shape for a tetrahedral mesh is a tetrahedron, which is triangular based. The entire volume is meshed with tetrahedrons, and has a high element to node ratio. The node limit for the teaching license is 512K nodes, which results in approximately 2.8 million elements using a tetrahedral mesh. Hexahedral mesh, on the other hand, has a significantly lower element to node ratio, which can be seen in Figure 3.

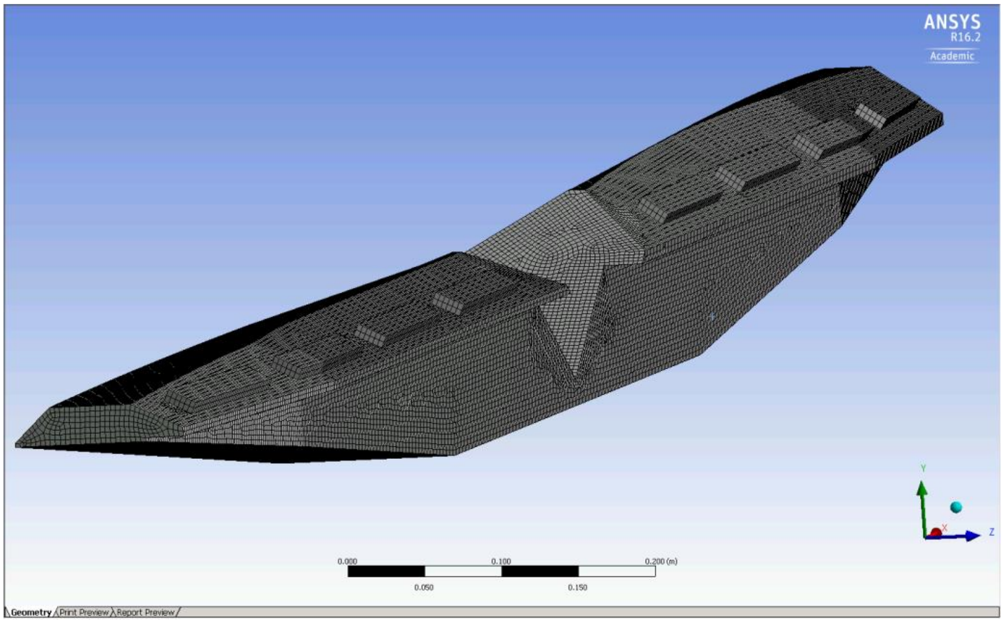

Figure 16: An image of a hexahedral mesh.

As with the tetrahedral mesh, the element size and shape are difficult to see in Figure 16. A close up of the Hexahedral mesh is shown in Figure 17.

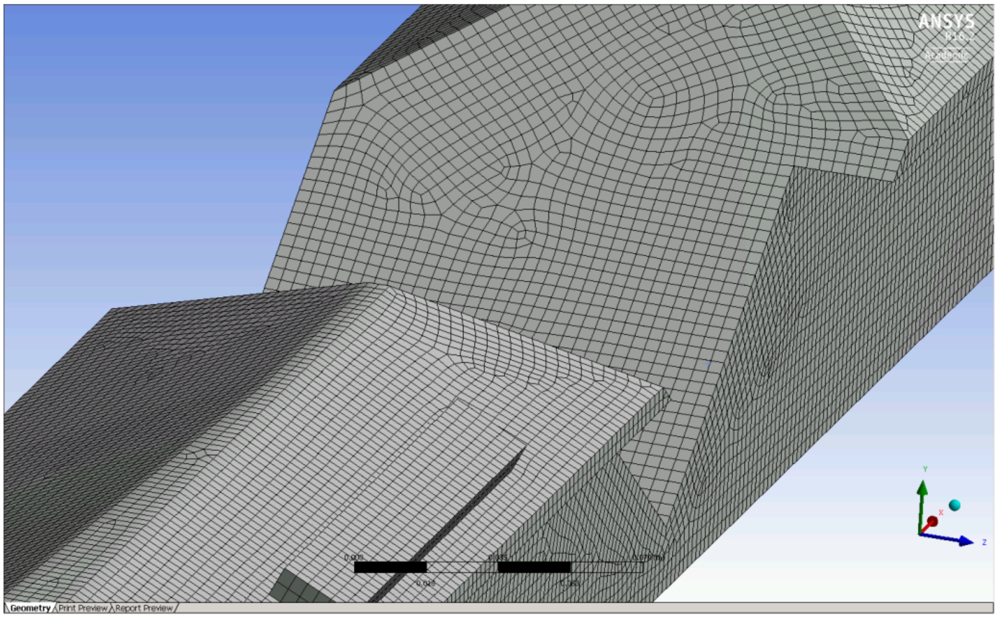

Figure 17: A close up image of hexahedral mesh.

Hexahedral mesh is based on square face elements that are larger than the elements for a tetrahedral mesh, which results in significantly less elements for an equivalent node amount. This indicates that the solution will be quicker, but the mesh time will be longer. ANSYS states that a hexahedral mesh is more accurate than a tetrahedral mesh, but it takes longer to generate

[36]. The hexahedral meshes take in excess of 30 minutes to mesh, but they reduce the solution time, while simultaneously producing a more accurate result. Tetrahedral meshes were attempted for the approximately 15 simulations, but there were issues with convergence that can be seen in Appendix B. The next section will illustrate the problems our team encountered when using a tetrahedral mesh.

11.3 Convergence using Tetrahedral Mesh

The first task our team had to complete was to achieve a converged result for the current plenum. The requirement for a converged result is to have the momentum in the X, Y, and Z directions converge to a specified residual target. In many instances, our simulations did not converge. In every case where the simulation did not converge, a new set of boundary conditions had to be used in an attempt to reach momentum and mass convergence. In general, the tetrahedral mesh did not solve very well, and we had to use less accurate boundary conditions to achieve convergence. The worst case of non-convergence our team encountered is shown in Figure 18.

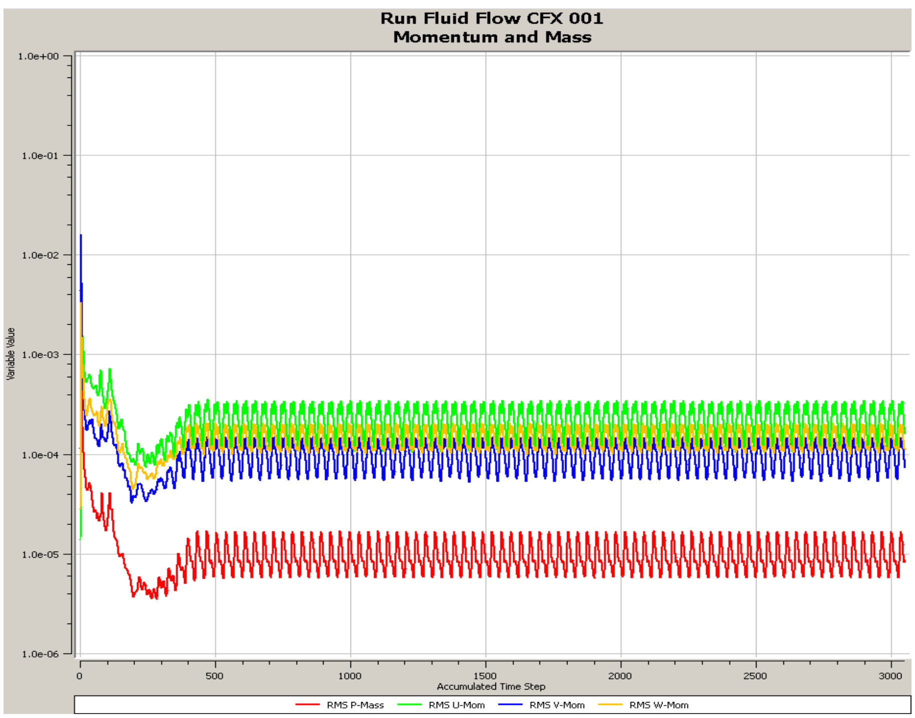

Figure 18: Non-convergence plot for a tetrahedral mesh.

A properly converged result would result in all of the lines dropping below the plot area, at a residual target of 1E-06. The result seen in Figure 18 started oscillating about a higher residual point, and thus it did not converge to our required residual target. Our team attempted using a

High Resolution simulation, however the result in Figure 18 was the outcome of that simulation. For accurate solutions, high resolution should be used. An Upwind solution is less accurate, but is capable of convergence in many instances where High Resolution does not. ANSYS is capable of using a blend factor between the two. Our team attempted many blend factors, but the solution did not converge. Eventually, we achieved convergence by using a complete upwind solution. The convergence plot of the upwind solution is shown in Figure *19*.

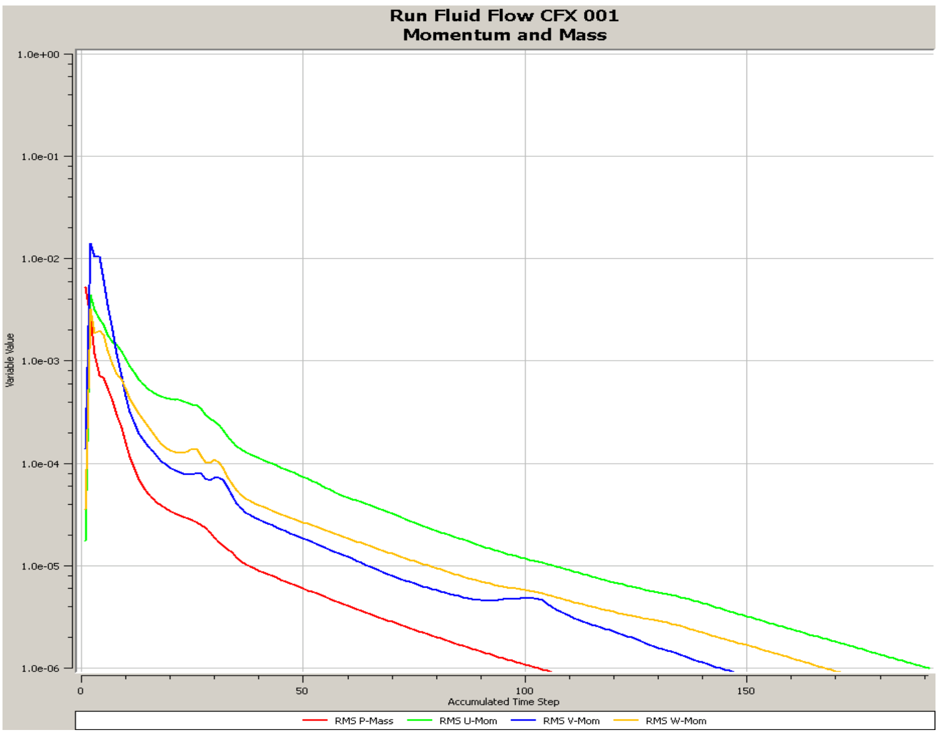

Figure 19: Converged result for a tetrahedral mesh.

Even though our team was able to achieve convergence with a tetrahedral mesh, we were only able to do so with an upwind solution. An upwind solution is not entirely accurate, and therefore we moved forward with a hexahedral mesh. The convergence plots for our hexahedral simulations are shown in the next section.

11.4 Convergence using Hexahedral Mesh

In general, hexahedral meshes are more accurate but take longer to mesh a volume. Therefore, the trade-off between tetrahedral and hexahedral meshes are that the tetrahedral meshes can mesh a volume quicker but hexahedral meshes can produce a solution quicker. Through some preliminary simulations, our team determined that the decrease in solution time far outweighed the mesh time for hexahedral mesh, and the total run time was significantly less than tetrahedral mesh. In all cases where our team attempted hexahedral mesh, the simulation converged with the most accurate boundary conditions. An example of a converged solution for hexahedral mesh is shown in Figure *20*.

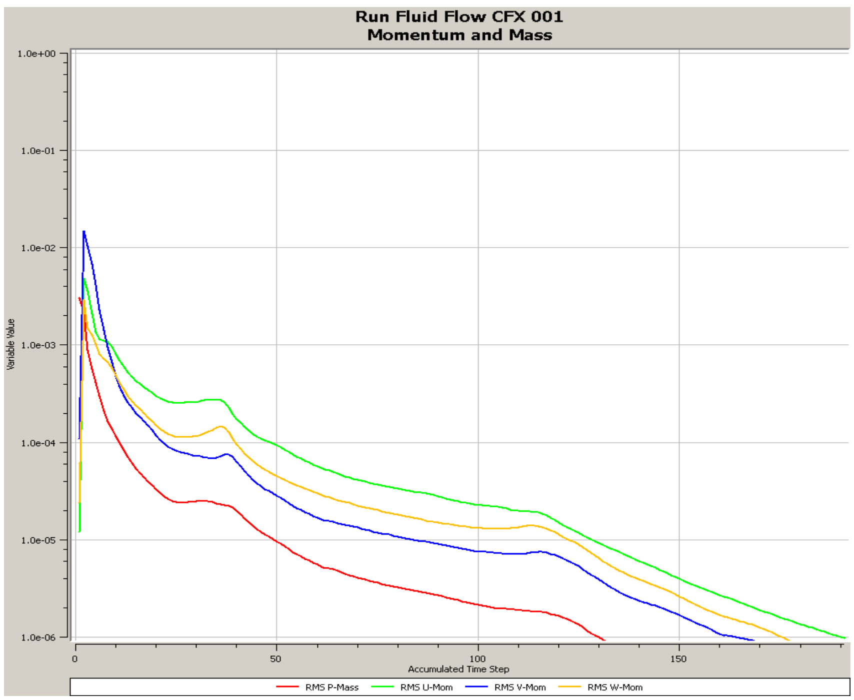

Figure 20: A convergence plot for a hexahedral mesh.

Our team achieved convergence for all hexahedral meshes with High Resolution, with a maximum node limit of 512k nodes. Our team received access to an ANSYS research license towards the end of the semester. An ANSYS research license has no node limit, and therefore our team attempted to increase the amount of nodes in the current plenum. The results of increasing the amount of nodes are shown in the next section.

11.5 Mesh Convergence with a Higher Node Limit

Our team gained access to an ANSYS research license in the final week of simulations. With no node limit on an ANSYS research license, our team had the capability to test whether the current plenum would converge with a significantly finer mesh. Our team ran a simulation with 5.1 million nodes, and the convergence plot for that simulation is shown in Figure *21*.

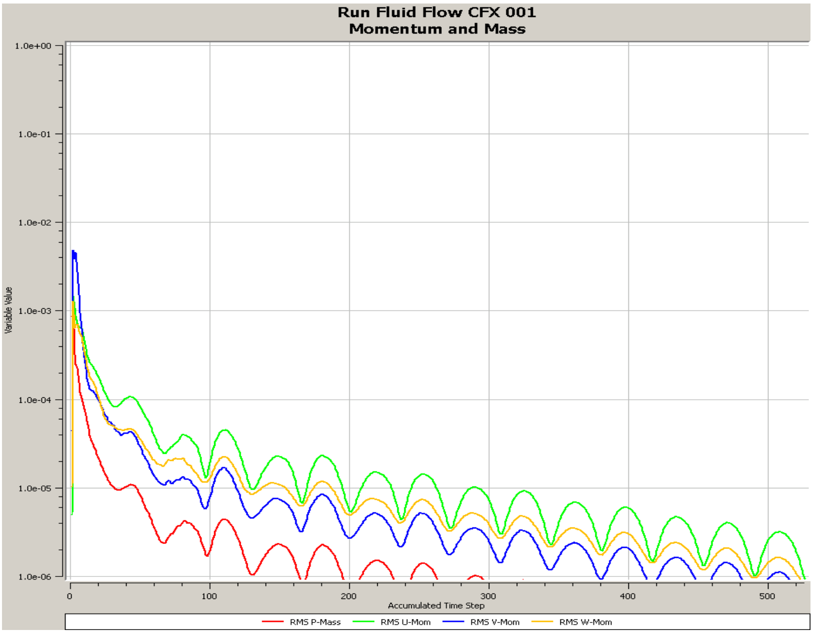

Figure 21: A convergence plot for a hexahedral mesh with 5.1 million nodes.

The simulation with 5.1 million nodes converged, however the simulation converged poorly. Figure 21 shows a significant amount of oscillation as the simulation approaches convergence, which indicates that the fine mesh would require additional boundary conditions to achieve a better convergence. The total run time for this simulation was over 20 hours. Our team was limited in the amount of time remaining in the semester, and therefore we were not able to pursue the results for a finer mesh on either the current plenum or any of the designs that have been selected for analysis. The boundary conditions and mesh type were fully defined, and the analyses of the designs generated in Appendix A were conducted. The Post-Processing results of each of the designs that were considered are shown in the next section.

11.6 Analyses of the Selected Designs

This section of the report will illustrate the results of the analyses of the selected designs. The main designs that will be outlined are the Double-Curve Wedge design, the V-Curve Wedge design, and various shapes and sizes of vents. The vent designs were made with the intent of decreasing the maximum velocity while increasing the airflow distribution across the plenum. The fin designs shown in Appendix A were not included in our CFD analysis, as their shape results in a cost that would outweigh the benefits of better airflow distribution. The results for the current plenum are shown in the next subsection.

11.6.1 Current Plenum CFD Analysis

The boundary conditions for this analysis are a k-Epsilon turbulence model, a High Resolution solution, air properties at 120°C, hexahedral mesh, and an auto timescale. The velocity contours and streamlines of the current plenum with approximately 500K nodes are shown in Figure *22*.

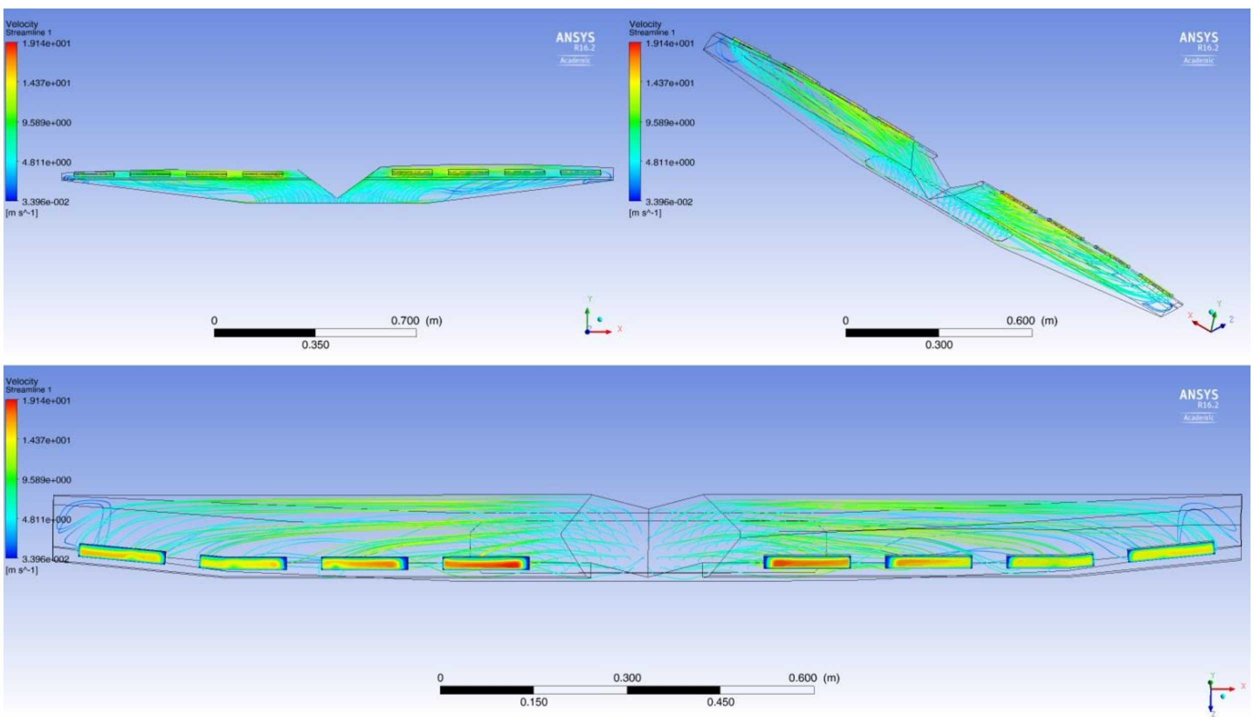

Figure 22: Streamline and velocity contour results for the current plenum.

The maximum velocity occurs in the central vents of the current plenum design, which is expected because the flow encounters those vents first. The maximum velocity in the central vents is 19.14 m/s, and the maximum velocity at the outer vents is approximately 15 m/s. The streamlines show a decent distribution of air between the drivers and passengers side of the windshield. It should be noted that these results would have to be verified experimentally to determine the accuracy of the solution using CFD. The same condition would have to be met to verify the accuracy of any designs we illustrate in this report. Our team attempted a solution with the same boundary conditions as above, except with 5.1 million nodes. The velocity contours and streamlines for that simulation are shown in Figure 23.

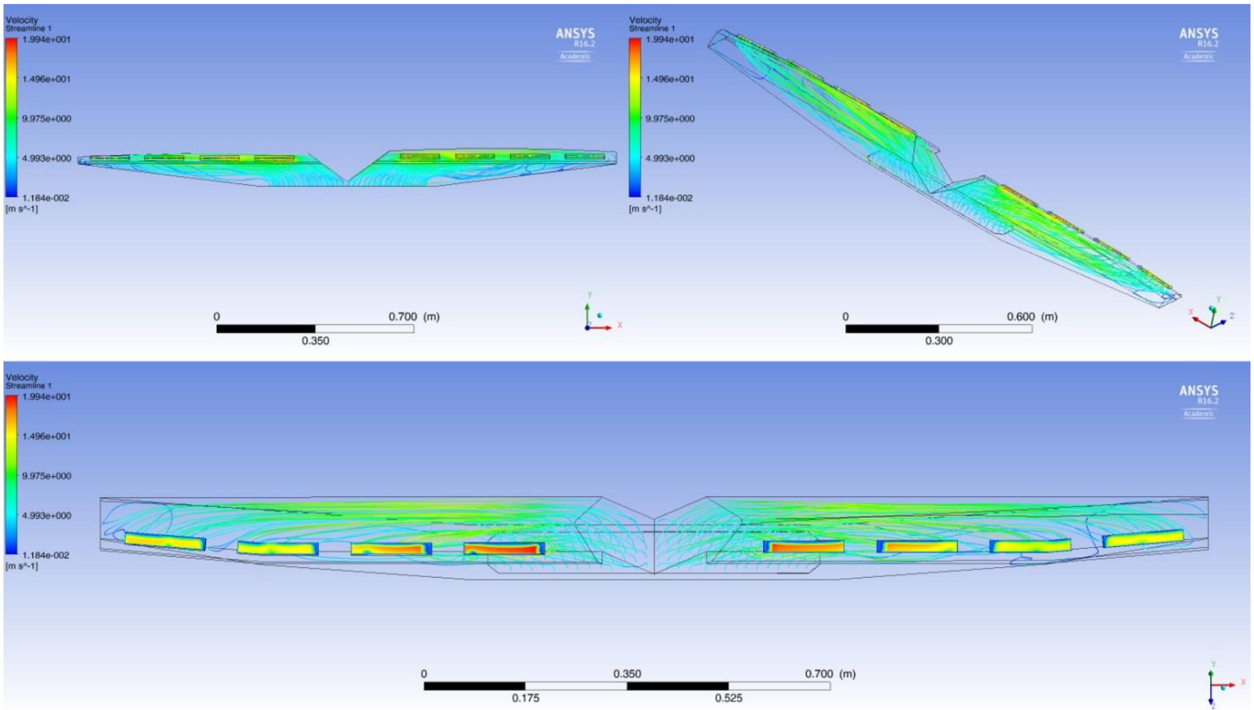

Figure 23: CFD results of the current plenum with 5.1 million nodes.

As shown in a previous section, the simulation with 5.1 million nodes converged poorly. Therefore, these results may not be entirely reliable. Due to time restrictions, our team were unable to pursue a larger amount of nodes, as it would require running many simulations which take a minimum of 20 hours to solve. Therefore, our team did not use these results for a comparison between designs. The next design our team considered the double-curved wedge.

11.6.2 Double Curve Wedge Design

The double curved wedge design is shown in Appendix A in the concept generation section. The results for the double curved wedge design are shown in Figure *24*.

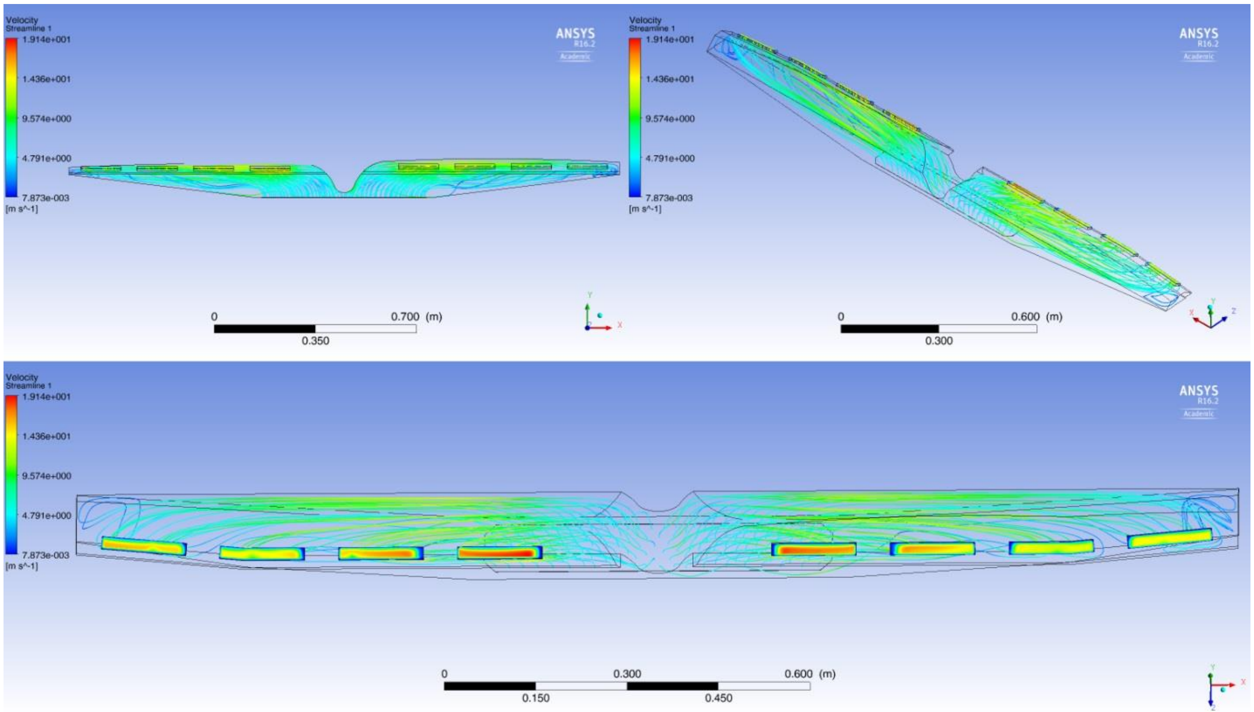

Figure 24: Streamline and velocity contour results of the double curve wedge design.

The results of the double curve wedge design has a maximum velocity equal to the straight wedge, with a marginal increase in velocity on the outer vents of the plenum. Since the additional complexity of a double curve wedge far outweighs the marginal benefits, the double curve wedge design is not recommended as a final design. The next design that was considered is a V-Curve wedge design.

11.6.3 V-Curve Wedge Design

The V-curve wedge design is similar to the double curve wedge design, except the central portion meets at a sharp point, which will split the airflow without reducing the air flow velocity. The streamline and velocity contour results of the V-curve wedge design are shown in Figure *25*.

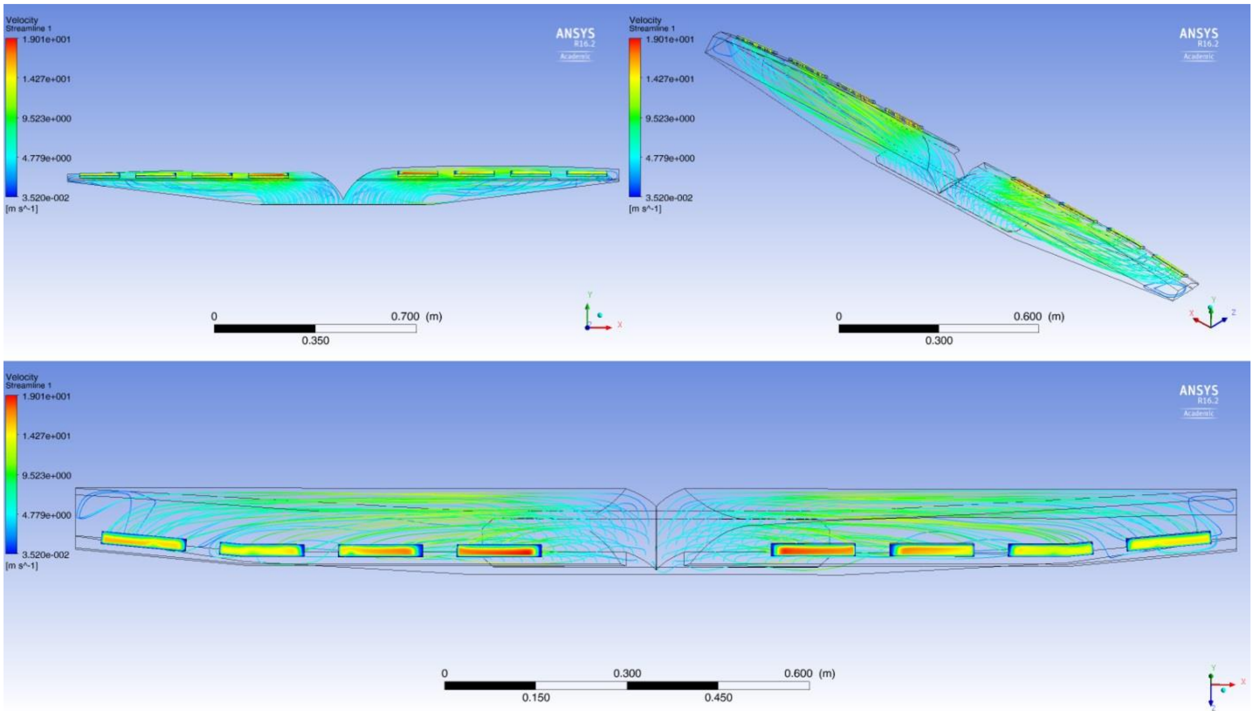

Figure 25: Streamline and velocity contour results of the V-curve design.

The maximum velocity for the V-curve design is 19.01 m/s, which is slightly smaller than the maximum velocity for the double curve design, which was 19.14 m/s. The velocities at the outer vents of the plenum are very similar, with no noticeable difference between the two designs. Therefore, this design was also eliminated, as the complexity of the wedge outweighs the marginal benefit in air velocity. After determining that the wedge designs that were generated were infeasible, our team consulted our client [Client], he requested that we look into changing the sizes of the vents of the plenum. Therefore, our team started increasing the vent size in order to reduce the maximum flow velocity.

11.6.4 Vent Design 1

The inlet area of the plenum from the defroster is 77.625 in^2, which is a constant for all of the designs shown in this report. The total outlet area for Vent Design 1 is 73.261 in^2. By significantly increasing the outlet area, the flow velocity should be reduced by an equally significant amount. However, there has to be a certain limit on the maximum flow velocity, because a maximum flow velocity that is too low may not defrost the outer extremities of the windshield. Therefore, we've set a tentative goal of around 15 m/s for the central vents on the plenum. The reason for this is to ensure proper windshield defrosting. The streamline and velocity contour results are shown in Figure *26*.

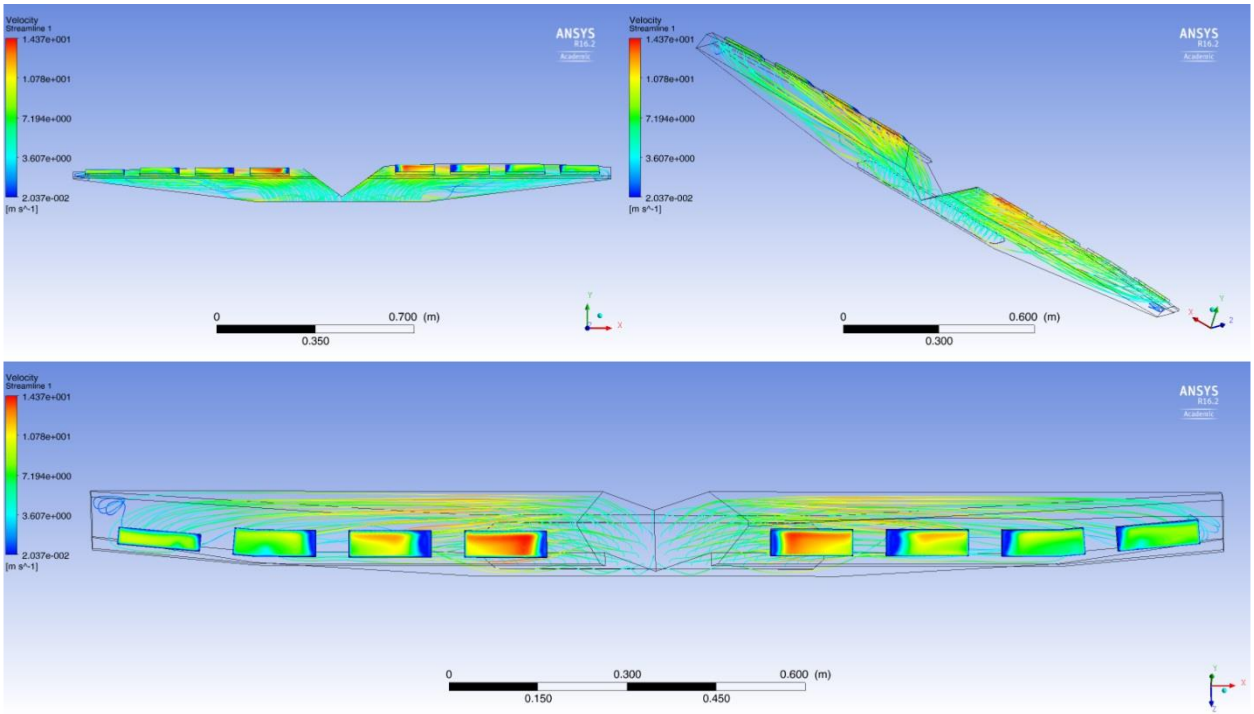

Figure 26: Streamline and velocity contours of the first vent design.

The maximum flow velocity of vent design 1 is 14.37 m/s, with maximum velocities of approximately 11 m/s on the outer vents. The maximum flow velocity for this design is fairly low, so the capability of defrosting the windshield is questionable. Our team has eliminated this design based on our assumption that a maximum flow velocity below 15 m/s would be too low to provide sufficient defrosting. The next vent design uses slightly larger vent sizes in order to determine the effect of minor changes in area on the maximum flow velocity.

11.6.5 Vent Design 2

The second vent design our team conducted a simulation on had a total outlet area of 80.0 in^2. The slight increase in total outlet area should decrease the maximum velocity in the plenum. This simulation was conducted to determine how significant of a change there is in the maximum flow velocity when the area is changed by small amounts. The streamline and velocity contour results are shown in Figure *27*.

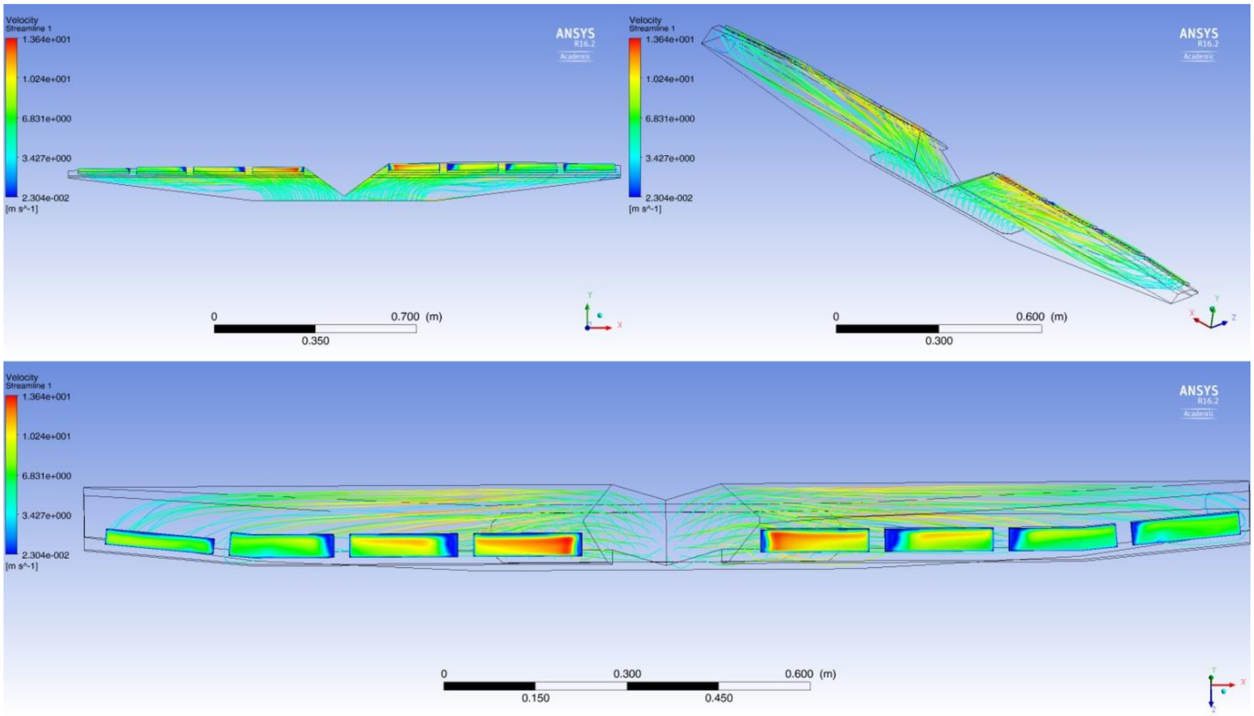

Figure 27: Streamline and velocity contour results for the second vent design.

The maximum velocity at the central vents is 13.46 m/s, which is almost 1 m/s lower than the results in Vent Design 1. Therefore, an increase in outlet area to an area greater than the inlet area yields even significant maximum flow velocity changes. Due to the further decreased maximum flow velocity, our team eliminated this design also. The next vent design features a small vent area, which is meant to increase the maximum flow velocity.

11.6.6 Vent Design 3

This vent design has a total outlet area of 62.663 in^2, which is lower than the previous two vent designs. Therefore, the expected result from this simulation is a higher maximum flow velocity, and a higher velocity at the ends of the plenum. The streamline and velocity contour results for Vent Design 3 are shown in Figure *28*.

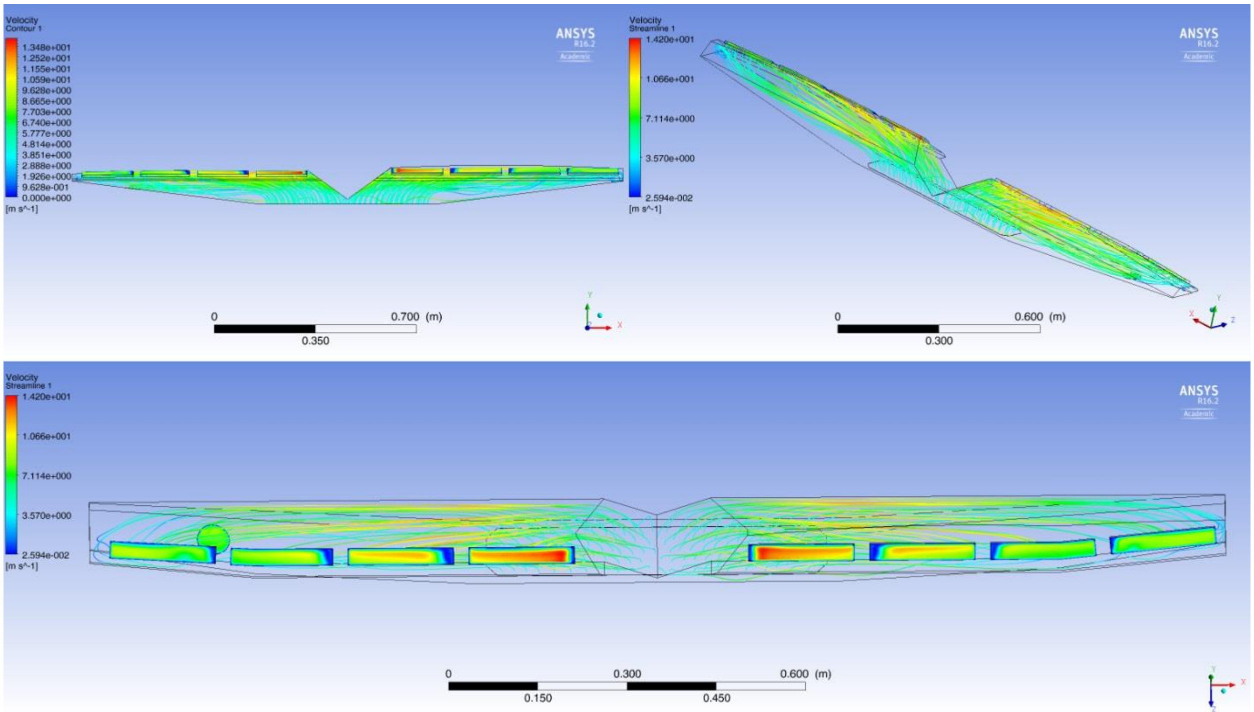

Figure 28: Streamline and velocity contour results of vent design 3.

The maximum velocity in vent design 3 is 14.20 m/s, which is higher than vent design 2, but is lower than the first vent design. Therefore, a significant decrease in outlet area hardly changed the flow velocity out of the vents. However, a bleed off vent was added to the passenger side to conform to the current plenum that New Flyer is producing. The bleed off could be affecting the flow in the plenum, but the end result is more accurate for the application that New Flyer will be using the plenum in. The maximum flow velocity is still not high enough to hit our maximum velocity target, and therefore our team reduced the total outlet area even further.

11.6.7 Vent Design 4

The total outlet area for vent design 4 is 55.701 in^2. Therefore, the maximum flow velocity should be higher than Vent Design 3. The streamline and velocity contour results for Vent Design 4 are shown in Figure *29*.

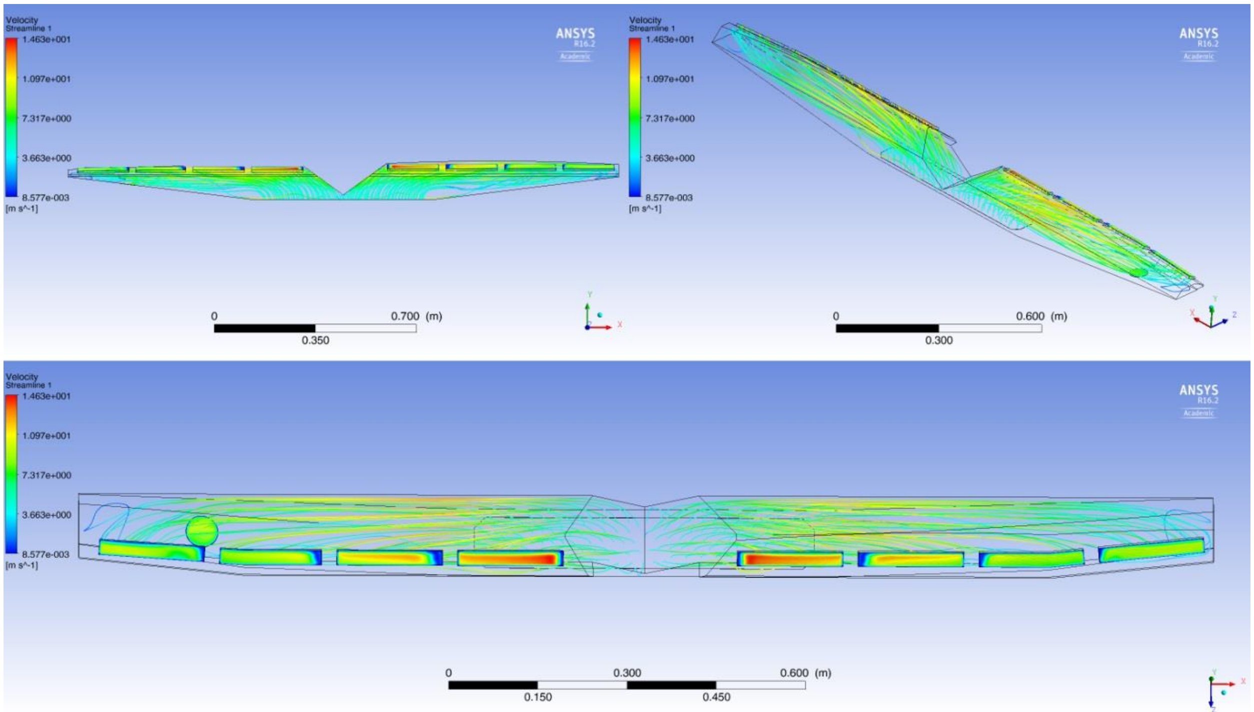

Figure 29: Streamline and velocity contour results for vent design 4.

The maximum velocity at the central vent on the plenum is 14.63 m/s, which is still below our target of 15 m/s. Therefore, our team reduced the vent sizes further in order to increase the velocity in the central vents.

11.6.8 Vent Design 5

The total outlet area of Vent Design 5 is 44.574 in^2. The streamline and velocity contour results for Vent Design 5 are shown in Figure *30*.

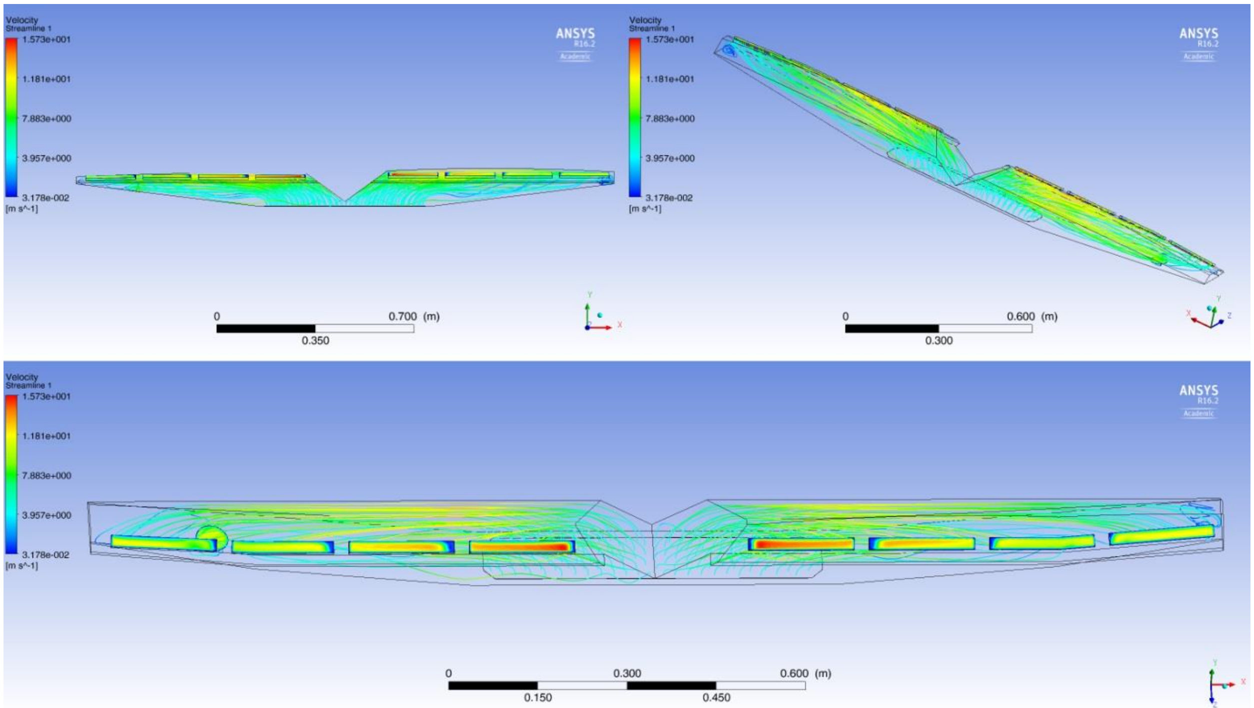

Figure 30: Streamline and velocity contour results of vent design 5.

The maximum velocity for Vent Design 5 is 15.73 m/s, which exceeds our target of 15 m/s. Therefore, this design will function as our final vent size recommendation. However, as stated previously, all of these designs were compared at an inlet temperature of 120°C. The actual inlet temperatures are approximately 50°C, and therefore the simulation for the current plenum and Vent Design 5 were conducted again to reflect the boundary and inlet condition changes.

11.6.9 Current Plenum with 50°C Air

The simulation for the current plenum was conducted again with the new inlet air temperature of 50°C. The boundary conditions used to simulate the current plenum will also be used to simulate vent design 5. The streamline and velocity contour results for the current plenum with 50°C inlet air temperature are shown in Figure *31*.

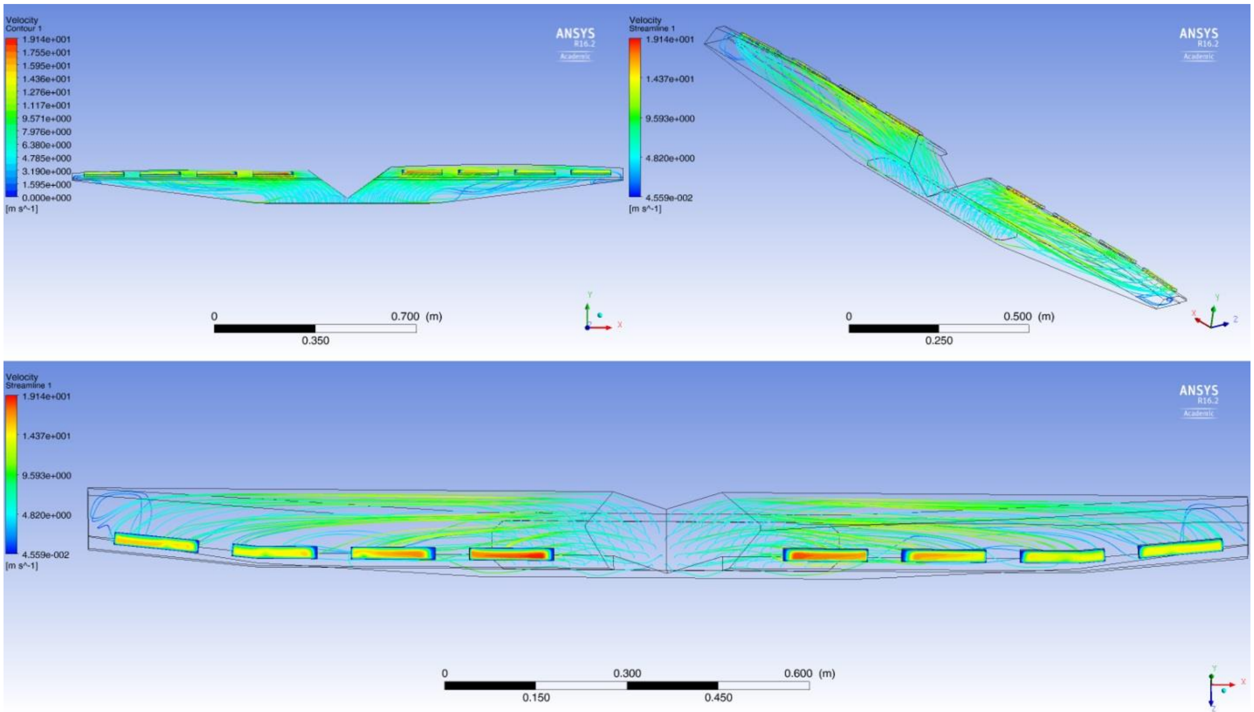

Figure 31: Streamline and velocity contour results for the current plenum.

The maximum velocity for the current plenum agrees with the result for the current plenum with different inlet air conditions. Therefore, the inlet air temperature doesn`t seem to significantly affect the flow as long as the properties of air are scaled accordingly with the temperature. The final design featuring Vent Design 5 is summarized in the next sub-section.

11.7 Final Design Summary

The final design that is recommended for this report is Vent Design 5, which has a total inlet area of 44.574 in^2. Due to time limitations, the vent design could not be fully optimized. However, we have completed enough simulations to recommend this as a basis for further analysis in future. An Isometric view of the final design is shown in Figure *32*.

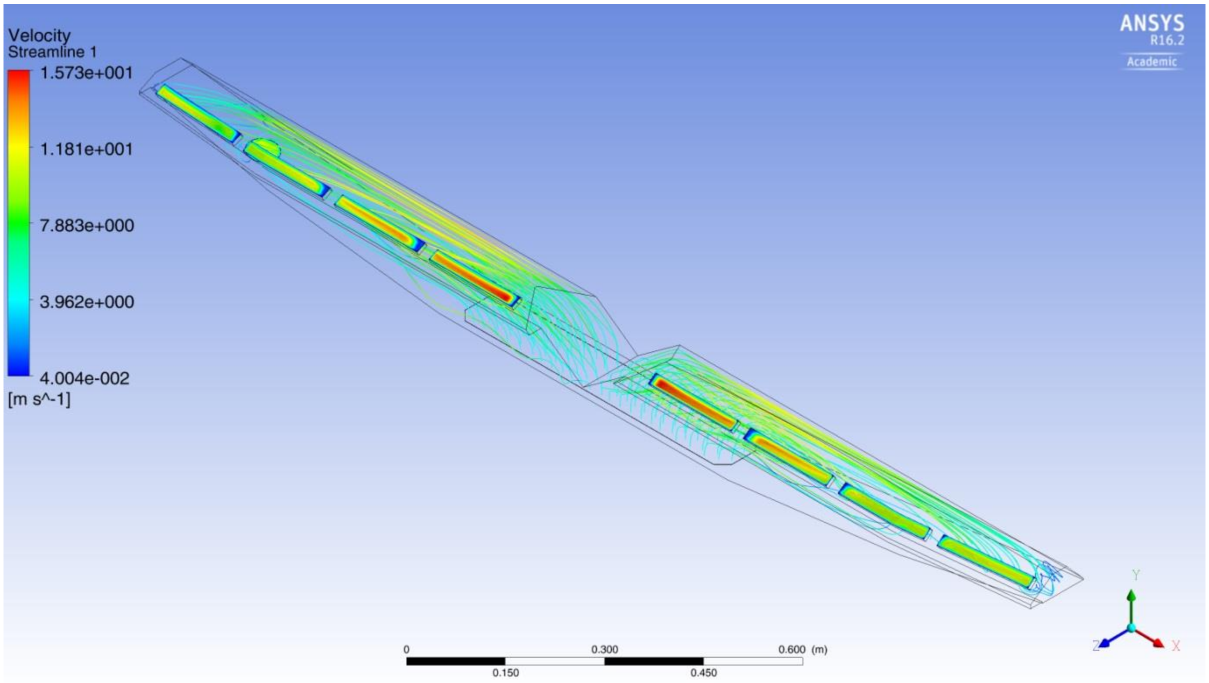

Figure 32: An isometric view of the final design.

A close up view of the passenger side vents is shown in Figure *33*.

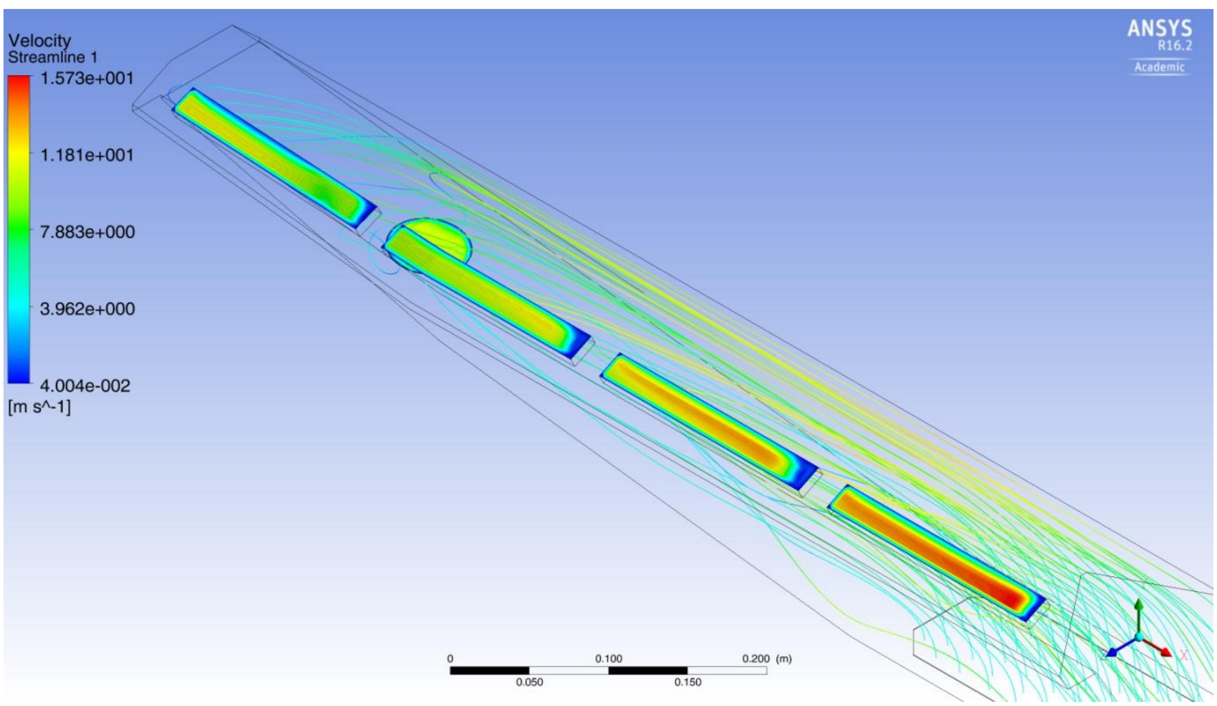

Figure 33: A close up view of the passenger's side vents.

A close up view of the driver`s side vents is shown in Figure *34*.

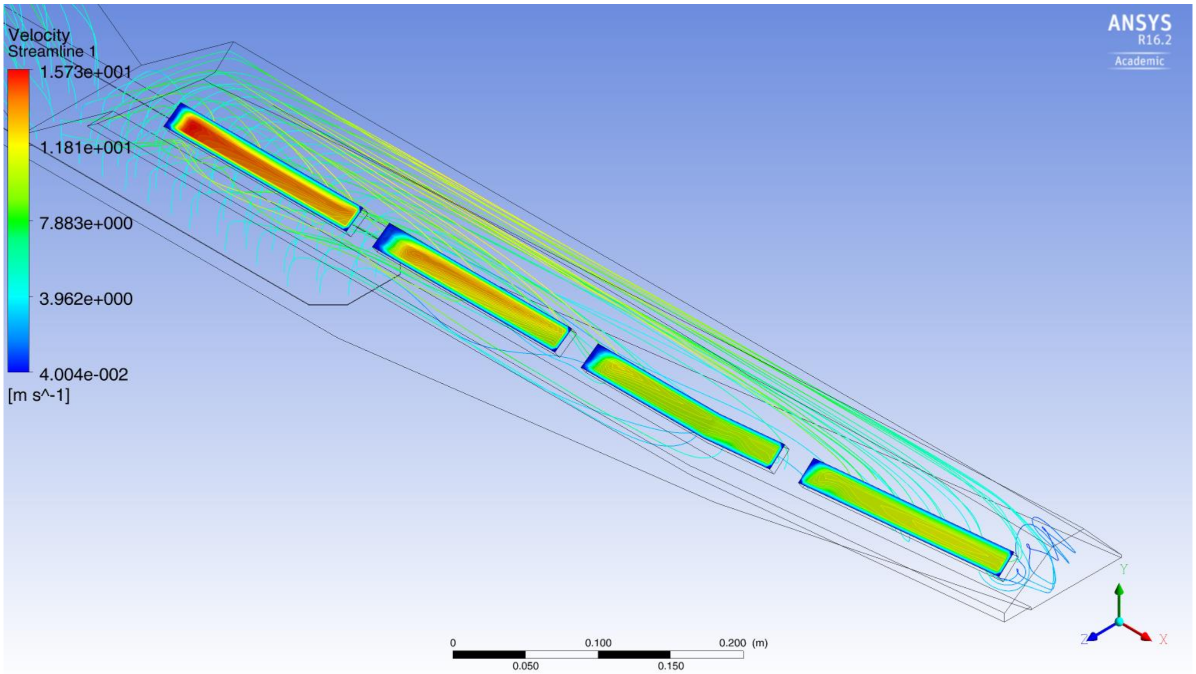

Figure 34: A close up view of the driver`s side vents.

A side view of the streamlines for the final vent design is shown in Figure *35*.

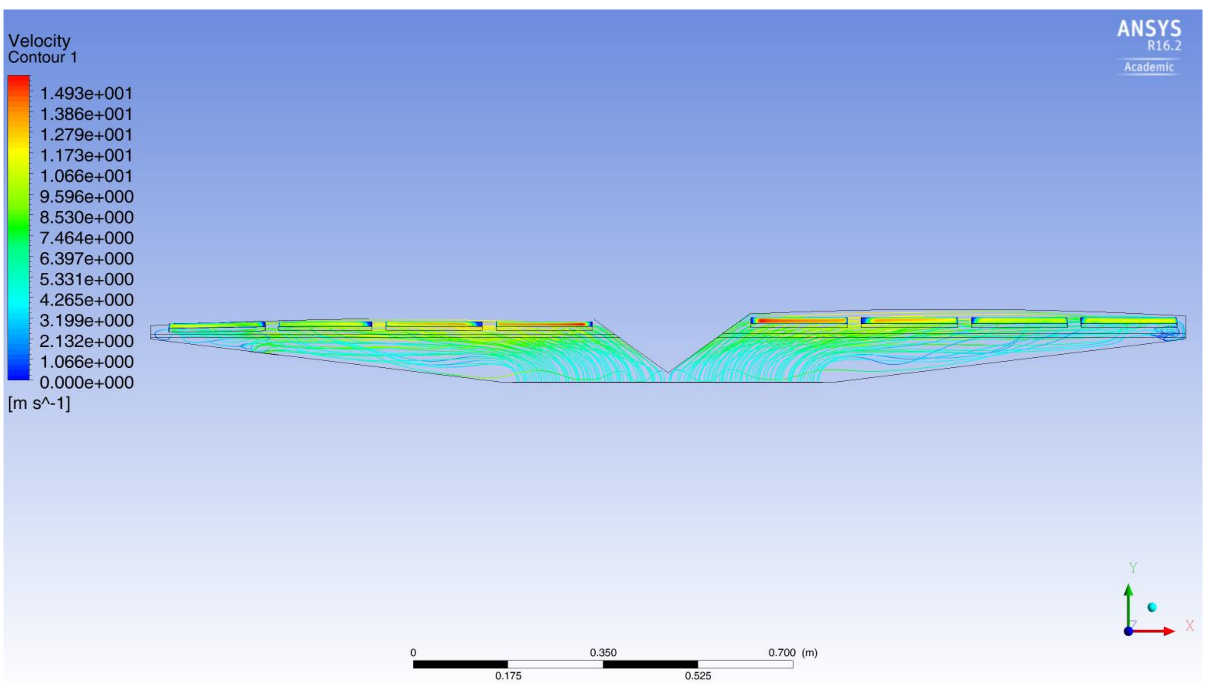

Figure 35: A side view of the streamlines for the final vent design.

The final design is not complete optimized, as our team ran out of time to run more simulations. The vents are sized to a point where the velocity is reasonable, however the results should be verified experimentally to ensure that CFD is producing accurate results. The final recommendation for this report is to perform further analyses both experimentally and analytically to find an optimum solution for air flow distribution and reduced noise. In terms of noise reduction, noise is directly related to flow velocity. Therefore, lower air velocities will be less noisy, but there has to be a minimum allowable air velocity due to defrosting requirements. Due to time constraints, our team was unable to pursue noise simulations using ANSYS, and therefore noise is being inferred from the maximum velocity for each design. Our final recommendation has a lower velocity than the current plenum, indicating that the noise level is reduced. The maximum velocity of the final recommended design is above 15 m/s, and therefore should be capable of defrosting the entire windshield of the bus.

15. Summary

Our team worked to optimize New Flyer's Xcelsior defroster plenum in terms of air distribution, defrost time, noise level, weight, installation time, and number of points on the assembly line in which the plenum can be installed. Our team also analyzed the feasibility of rotational molding for the plenum based on cost, longevity, and the number of pieces it will take to manufacture the plenum.

Multiple constraints and limitations are imposed on the redesign. Many of the constraints are safety codes and standards that are imposed by various associations and societies. The APTA requires that airflow must be greater than 100 cfm, and must maintain visibility through the driver's front and side windows. The FMVSS requires a material burn rate of less than 4 inches per minute. The SAE requires the windshield to be cleared of ice in less than 30 minutes. The NYDAHT and NYPAHT require that the driver's and passenger's areas may be heated to 60°C in less than one hour.

Numerous constraints and limitations are also imposed by New Flyer. These specify that the material used for the plenum design must be commercially available, the payback period must be less than one year, the cost of the part must be no greater than $230.00, and one person must be able to install the part in under two hours.

The rotational molding process has been researched and summarized in this report, along with both advantages and disadvantages. After contacting the vendor, Plasticom, who will be manufacturing the plenum, the Rotational Molding manufacturing method was found to be infeasible. Plasticom recommended that a Vacuum forming process be used instead of a rotational molding process. The Vacuum forming method was analyzed in the report, and is the final recommendation for manufacturing the defroster plenum. The final mold cost for the defroster plenum is $27,905.32 CAD, and the cost per plenum is $100.99 CAD. The payback period based on those costs is 0.1 years.

Our team has conducted a Patent and Design search to avoid patent infringement if there are any defroster plenum designs that are similar in shape or function. There were seven similar patents found, but either their function or shape differed sufficiently enough to avoid patent infringement. Therefore, our team moved forward with concept generation and scoring.

The concept generation process yielded 11 different concept designs that were initially compared to the current plenum design. The designs were scored based on a positive, negative, or neutral rating when compared with the current plenum. This analysis yielded unsatisfactory results, as it did not take into account the unequal level of importance that each criteria has. Therefore, the team set up a criteria scoring matrix where each criteria is weighed against the others. The result of the criteria scoring matrix was a definitive value for the weight for each criteria. The concepts were scored again incorporating the assigned weights, and the top four concepts were selected to move forward with. In addition to the top four concepts, our team combined some of the best features into three additional concepts. However, in discussion with both the client and Plasticom, the fin designs were deemed cost prohibitive, and therefore were not analyzed using CFD.

The two different wedge designs, namely the double curve and v-curve wedges, were analyzed using CFD, but only had marginal improvements in air flow velocity across the plenum. Therefore, the new wedge designs were not feasible. After consultation with our client, the next feature of the plenum that was requested to be looked at was the vent designs. With the remainder of our time on the project, our team focused on changing the vent shapes and sizes, and converged on a preliminary solution that has vents with 0.8 inch width and 7 inch length, with a total vent area of 44.574 in^2. Furthermore, it is recommended to not have any fins or louvers in the vents, as they will impede the airflow and cause uneven distribution across the windshield. The final recommendation for vents is not optimized, and the CFD results will have to be verified experimentally to ensure consistency between simulation and reality.

Our team believes we have completed a sufficient amount of simulations to make a recommendation on the vent sizes, but the CFD results will have to be verified experimentally before taking the results to be accurate. The final recommendation is to use Vent Design 5.

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Design and Analysis of an Optimized Rotational Molded Defroster Plenum

Appendices

MECH 4860 ENGINEERING DESIGN

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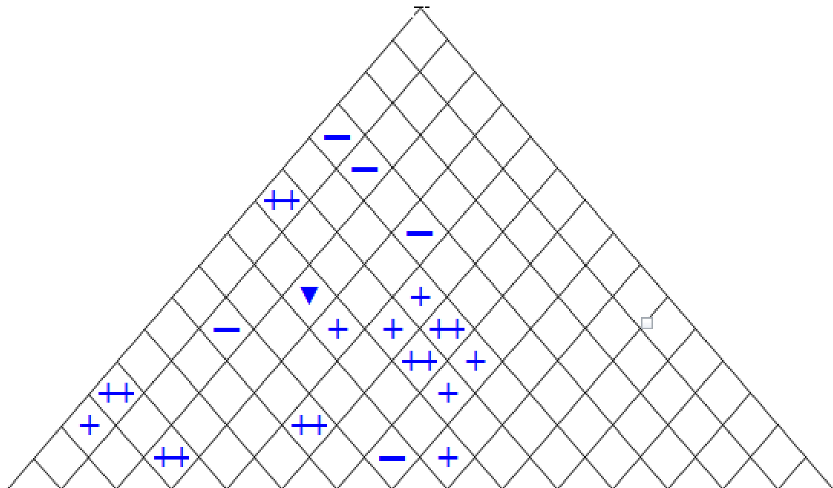
Appendix A: House of Quality



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	x	x	▲	▼	▼	▼	▼	▼	x	▲	x			
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Defrost Time	Burn Rate of Material	Time to Heat Driver's Area	Air Flow	Payback Period	Installation Time	Cost	Number of Parts of Plenum	Noise	Number of Technicians to Install	Number of Locationf of Installation on Assembly Line	Weight			
1	9	3.8	1.0	Ease of Installation						Θ		▲		Θ	O	O			
2	9	3.8	1.0	Lightweight		▲				O				Θ		Θ			
3	9	15.4	4.0	Safe		Θ													
4	9	19.2	5.0	Improvement in Defrosting of Front Window	Θ			Θ											
5	9	11.5	3.0	Maintains Comfort of Driver			Θ						Θ						
6	9	19.2	5.0	Cost Effective					O		Θ								
7	9	15.4	4.0	Able to Defrost Driver's Side Windows	O			Θ											
8	3	11.5	3.0	Maintains Comfort of Passengers									O						
				Target or Limit Value	30 min	4 inch/min	60 deg F in 1 hr	100 cfm	1 year	2 hrs	$230.00	1	2 dBa	1	2	4.15 kg			
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	9	3	7	9	3	2	5	9	9	5	4	2			
				Max Relationship Value in Column	9	9	9	9	3	9	9	1	9	9	3	9			
				Weight / Importance	219.2	142.3	103.8	311.5	57.7	46.2	173.1	3.8	138.5	69.2	11.5	46.2			
				Relative Weight	16.6	10.8	7.8	23.5	4.4	3.5	13.1	0.3	10.5	5.2	0.9	3.5			

Figure 1: House of quality for the concept generation of the defroster plenum.

Figure 1 shows the House of Quality (HOQ) used to generate the concepts displayed in Appendix A1. One of the reasons a HOQ was created was to allow our team to gauge which requirements were most important in the design of the plenum. Quantitative characteristics were determined, and their relationship to each of the requirements was gauged. This allowed our team to clearly visualize how to assess whether requirements have been met. Table XX describes the meanings of the symbols assigned to describe the strength of the relationships.

Furthermore, the "direction of improvement" for each of the quantitative characteristics gave our team a visual summary of whether we should be aiming to increase, decrease or maintain the current values of the characteristics. The HOQ also allowed our team to discover how each of the quantitative characteristics correlated with one another. TABLE *I* describes the meanings of the symbols assigned to describe the correlations as seen in the "roof" portion of the house. This would ensure that when improving one of the characteristics, we would be aware that another characteristic may be influenced.

TABLE I: HOUSE OF QUALITY LEGEND

Legend		
⊖	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
X	Objective Is To Hit Target	

Commonly, a HOQ will include a comparison to competitive products. This was not possible for the case of the plenum due to a lack of available information on the functionality and performance of other plenums that have been manufactured in this industry.

Appendix B: Concept Generation

Our team set up several meetings to brainstorm new concept ideas for the new defroster plenum design. Each team member brought forth several designs, which are detailed below.

B.1 Current Plenum

The current defroster plenum is shown in Figure 2 below.

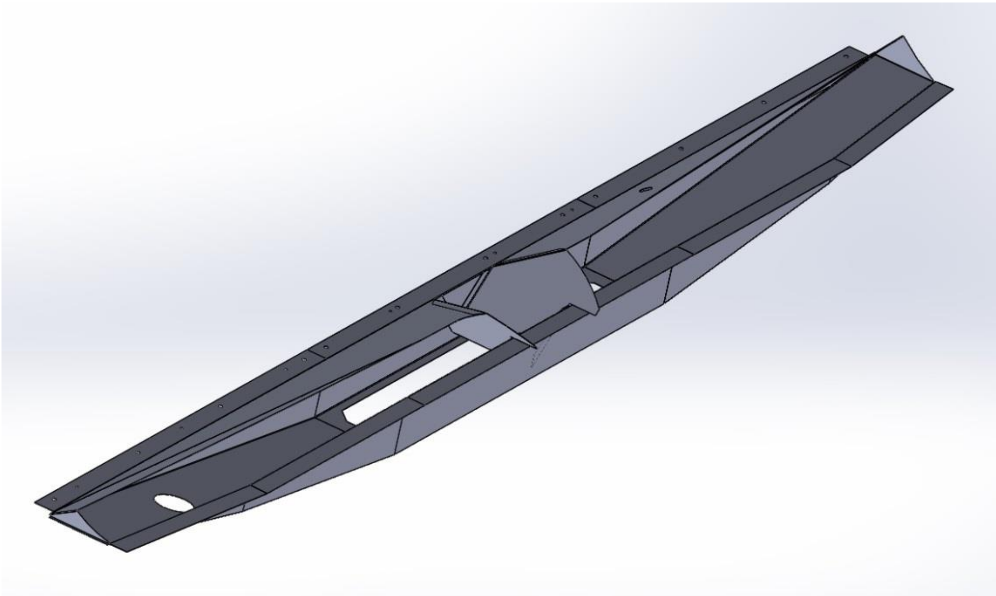


Figure 2: Current Plenum Design *[1]*

The concepts that were generated are based on the shape of the shell of the current plenum. The concepts only alter the interior components of the plenum with the intent of redistributing the airflow and reducing the noise within the plenum.

1. B.2 Concept Generation

This section of the report will outline eleven different designs that our team developed as possible solutions to re-designing the defroster plenum. Each design will have a hand drawn sketch as well as an explanation describing the intent of the concept.

Concept 1 – Multi-Slotted Wedge

Our first concept for re-designing the defroster plenum is shown in Figure 3 below.

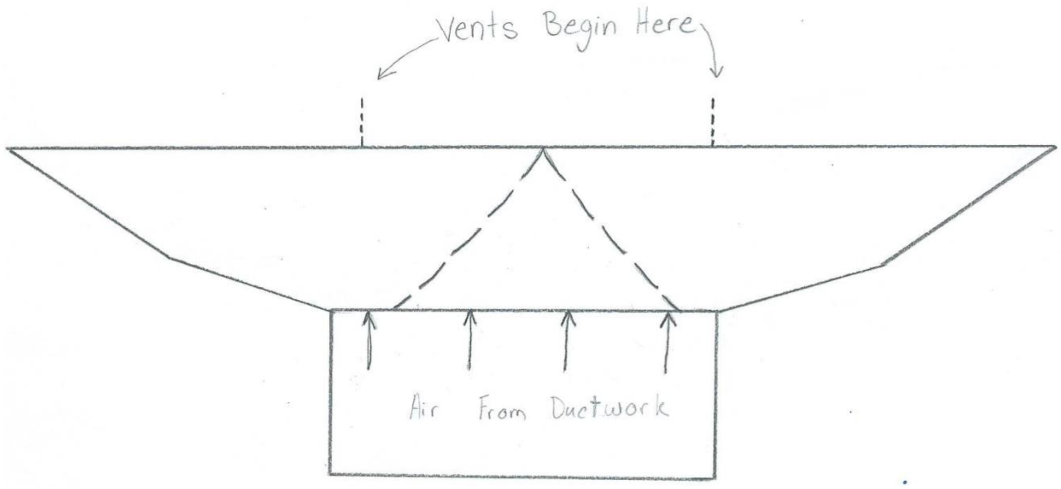


Figure 3: Design concept 1 with an inverse wedge, which has slits cut throughout.

The design shown in Figure 3 was aimed at increasing the air flow to the sides of the plenum by creating slits in the wedge. These slits would allow some of the air to be passed upwards, while the rest would be diverted to the sides wherever the angle of the wedge is too great to allow for a linear moment of air. One of the main problems with this design was that it was conceived before our team had a good understanding of the dash covering the plenum. Since the middle portion, before the vents begin, it completely covered from the top, the flow of air would be restricted. This may cause the air flow to be disrupted and eddies may occur, creating noise.

Concept 2 – Curved Wedge

Our second concept for re-distributing the airflow is shown in Figure 4.

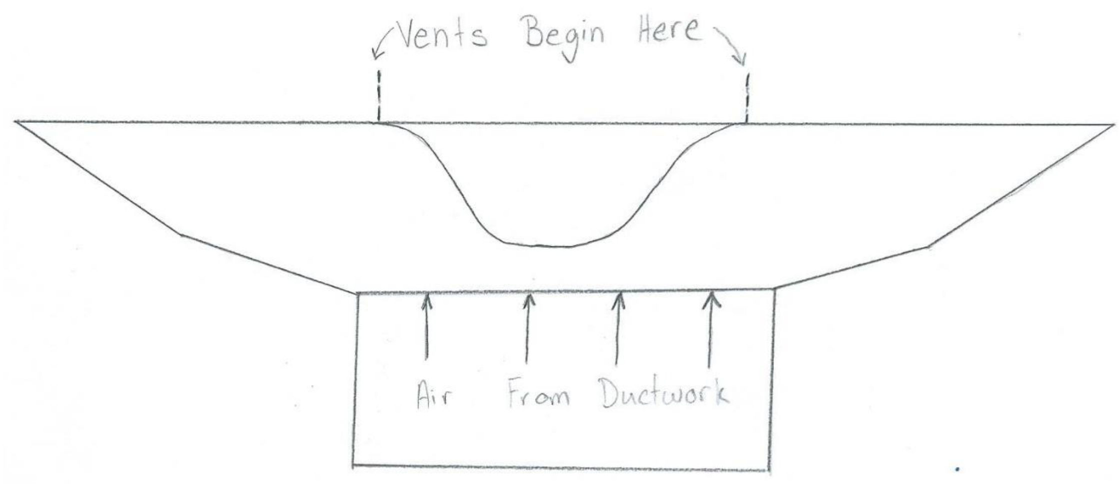


Figure 4: Design concept 2 with a rounded wedge.

The design shown in Figure 4 is composed of a rounded wedge, in lieu of the V-shaped wedge in the current design. The idea was to create a larger slope on the sides of the wedge, to better divert air to the sides of the plenum. The curved shape of the wedge would also allow air to flow more smoothly around the center, instead of hitting straight wall. Appropriate and effective dimensions for the slope of the wedge, as well as the width of the bottom of the wedge should be determined through CFD analysis if the concept is chosen for further study.

Concept 3 – Curved Wedge with Vanes

Our third concept for re-distributing the airflow is shown in Figure 5 below.

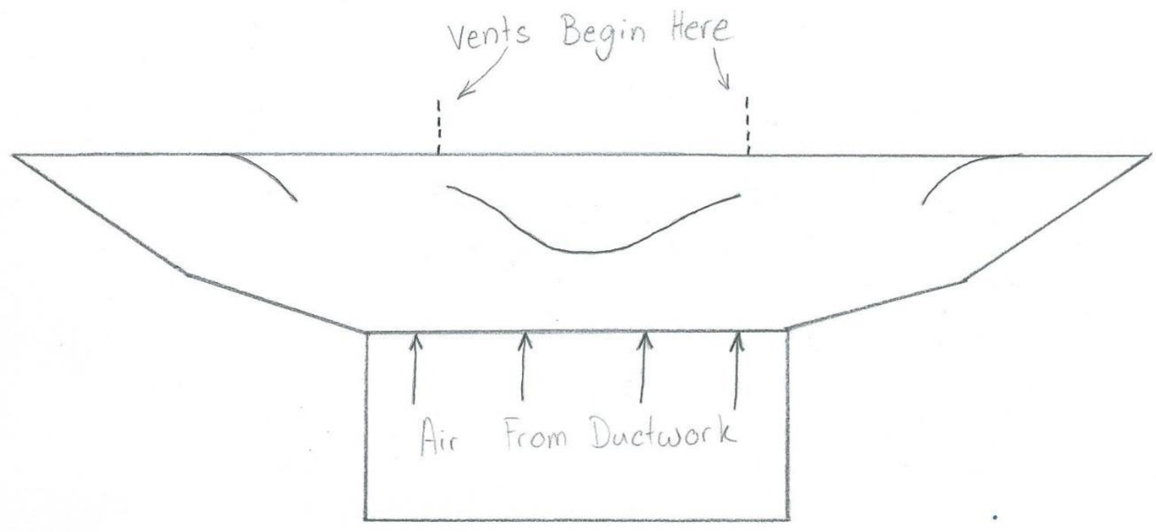


Figure 5: Design concept 3 with a wedge in the middle, and two wedges on the sides.

The design shown in Figure 5 is a modified version of Design Concept 2. The wedge in this design is still rounded, however it does not extend all of the way to the top of the plenum. Instead it is attached only to the side walls of the plenum. This will reduce the weight since less material will be used. In order to improve the air flow distribution even more, two separate wedges were added to the sides. These wedges would presumably be placed in between the second and third vents. The wedges would divert the air to the farthest vents, while keeping the weight of the plenum to a minimum. The spaces between the center wedge and the two side wedges act as ducts.

Concept 4 – V-Shape with Curvature

Our fourth concept for re-distributing the airflow is shown in Figure 6 below.

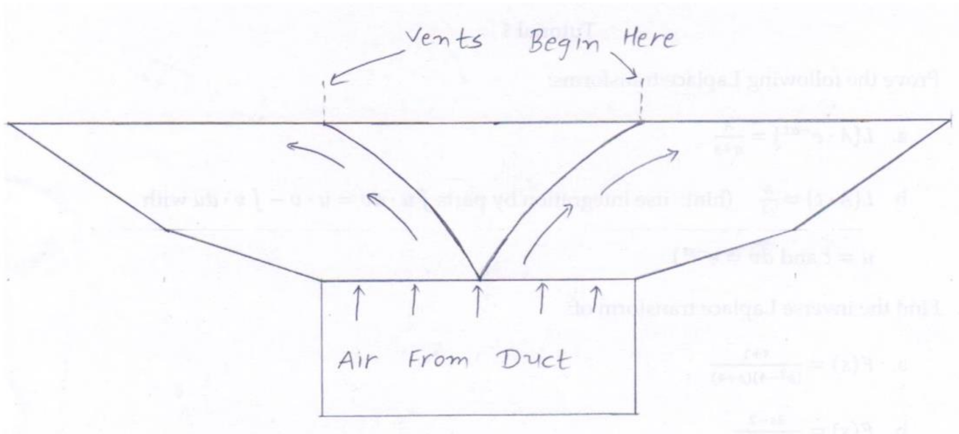


Figure 6: Design concept 4 with two wedges in a V shape with curvature.

The design shown in Figure 6 is one of the concepts that were generated for the new defroster plenum. The main design idea behind this concept is the same as the current plenum, with wedges placed at the center of the plenum. Two wedges are start at one point and end at the edge of the first. Two wedges are angled to divert the air in the wedge direction. Ideally, this design will decrease noise levels as well as improve air flow distribution. However this design is very similar to the current plenum, and therefore the chances of getting good air flow distribution are low because the current plenum has minimal airflow in the vents furthest from the wedge.

Concept 5 – Curved V-Shape with Vanes

Our fifth concept for re-distributing the airflow is shown in Figure 7 below.

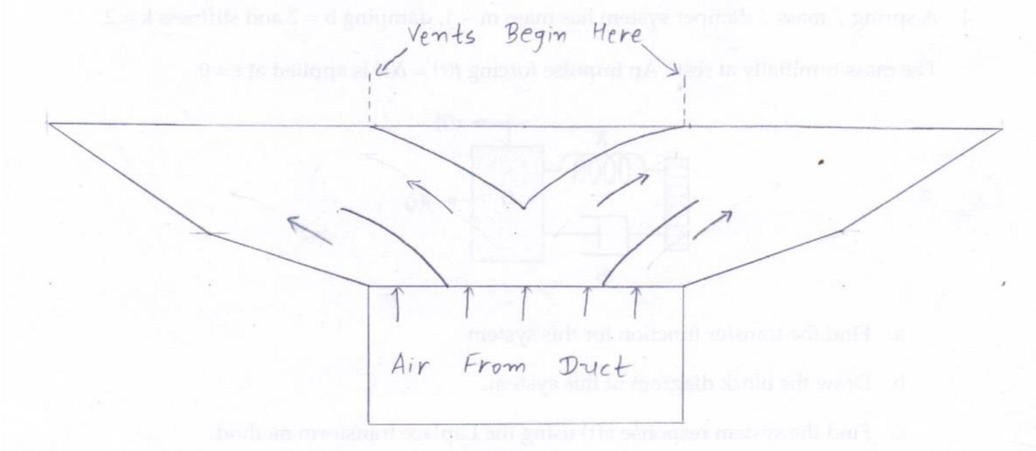


Figure 7: Design concept 5 with small V shape and two curved wedges.

The design shown Figure 7 is a combination of a V-Shape angle wedge as well as two single wedges on each side. This design has a V-Shape wedge in the center in a way that it ends at the edges of the first vents. The V angle wedge covers half of the area, which provides more space for the air to flow into the first two vents. Two wedges are placed on each side of the plenum that diverts the air into the vents on the end of the plenum for the side windows. The main concern about this design is to separate the airflow in half, with half of the air directed towards the first two vents and half of the air directed to the remaining vents on the end of the plenum, which directs the airflow to the side windows. Our design team is tasked with getting better air flow distribution on the windshield as well as decreasing noise. This design may reduce the noise by efficiently splitting the airflow using a sharp wedge.

Concept 6 – Wide V-Shape

Our sixth concept for re-distributing the airflow is shown in Figure 8 below.

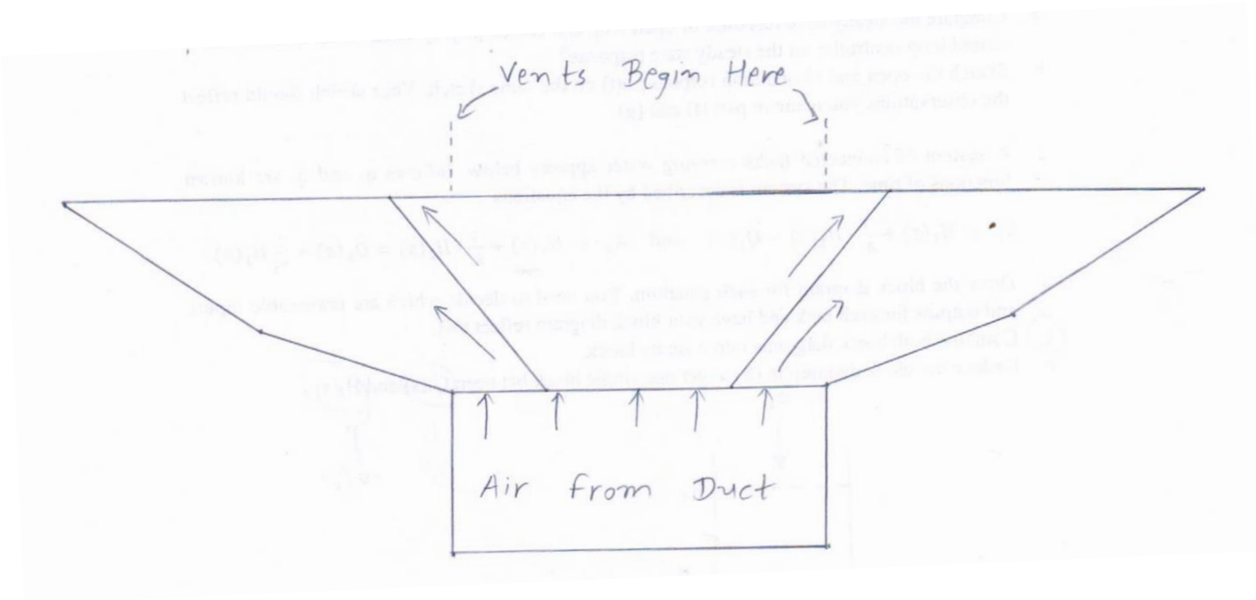


Figure 8: Design concept 6 with two wedges equal distance from center with angle.

The design shown in Figure 8 is one of the concepts that were generated for the new defroster plenum. This design has two wedges placed further from the center instead of a V shape wedge. The wedges are angled to divert the air towards the outer vents. The center portion is open so some air is able to pass through to first vent and the remaining airflow is diverted to the side windows through the outer vents. One problem with this design is that the center portion of the dash is fully closed between the first two vents, which means that the airflow will be diverted sharply to either side. Having the flow diverted at a sharp angle may increase the noise in the plenum.

Concept 7 – 3D Wedge

Our seventh concept for re-distributing the airflow is shown in Figure 9 below.

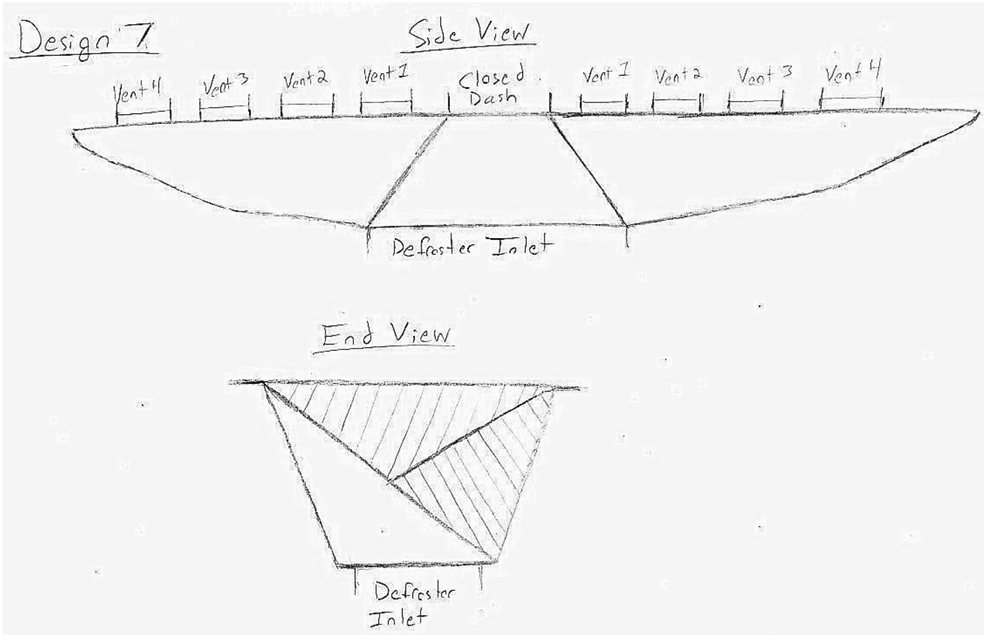


Figure 9: Concept 7 featuring a 3D wedge system.

Concept 7 features a 3D wedge system that extends from the back wall to the front wall of the defroster plenum shell. The idea behind this design was to redirect the airflow from the closed off dash towards the vents. The purpose of the secondary angle on the sides was to curve the airflow towards the outer vents, without allowing too much airflow through the first vent, which is the current issue with the defroster plenum.

Concept 8 – Modified 3D Wedge

Our eight concept for re-distributing the airflow is shown in Figure 10 below.

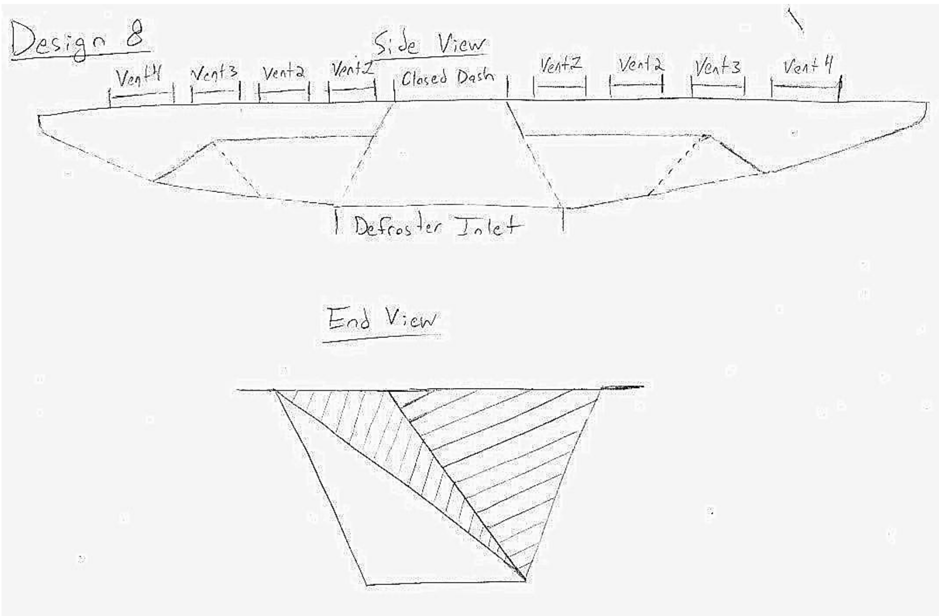


Figure 10: Concept 8 featuring a modified 3D wedge system.

Concept 8 features a modified 3D wedge in a similar design to concept 7, except the wedge system extends wider across the plenum, and limits the airspace around the first and second vents. The idea behind this design was to limit the airspace in the entire plenum, which would increase the pressure for a given mass flow rate from the defroster. The intent of this design was to increase the pressure in the entire plenum, and therefore cause a better airflow distribution across all of the vents.

Concept 9 – Plenum with Flaps

Our ninth concept for re-distributing the airflow is shown in Figure 11 below.

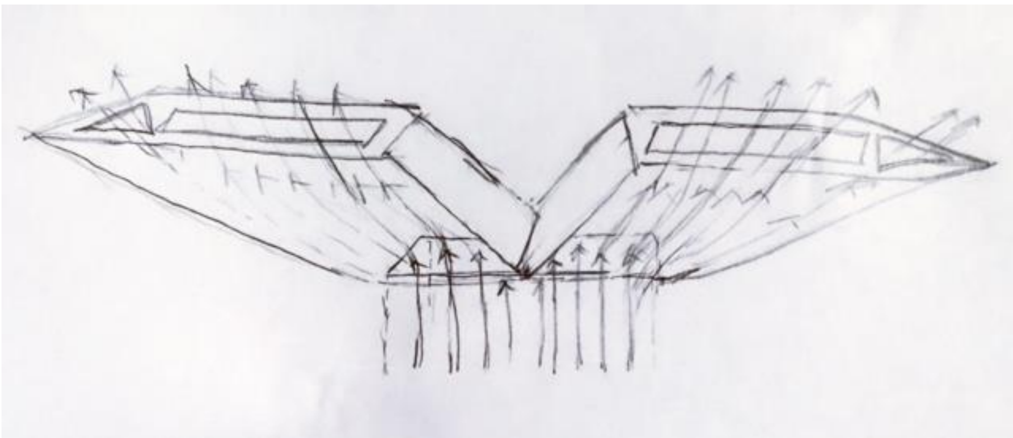


Figure 11: Design concept 9 with four air outlets.

Concept design 9 has four air outlets on top of the plenum. Each side has two outlets, one with a triangular shape and the other with a rectangular shape. The design of the triangular shape air outlet is to increase the air distribution to the side windows, and the rectangular shape air outlet was made much narrower compared to the current plenum air outlet to the windshield. This narrower rectangular shape air outlet can increase the velocity of the air to the windshield, also it can prevent all of the air going to the windshield. Since we may use rotational molding process to manufacture the plenum, compared to current plenum, this plenum has more air impermeability. This indicates that it can avoid air escaping through other parts of the plenum except for the four air outlets.

Concept 10 – V-Shape with Vanes

Our tenth concept for re-distributing the airflow is shown in Figure 12 below.

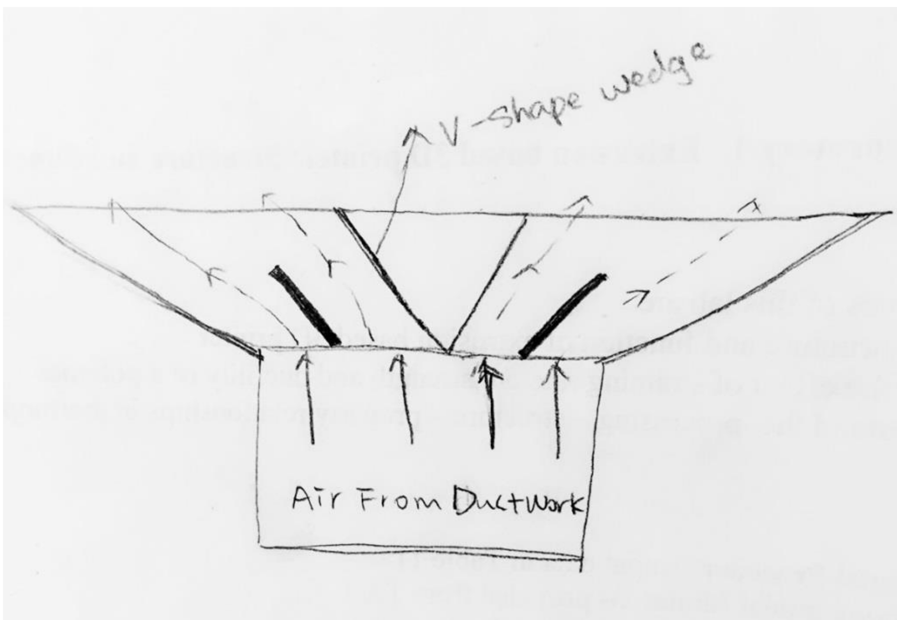


Figure 12: Design concept 10 with two separate wedges adding on the bottom.

This design does not differ much in comparison to the current design. The only difference is that two separate wedges have been added to both sides of the V-shape wedge, on the bottom of the plenum. When the air comes from the duct work, the wedges can divide the air into four routes to improve the air distribution and more air will be directed to the side window by these two separate wedges.

Concept 11 – Slotted Wedge

Our eleventh concept for re-distributing the airflow is shown in Figure 13 below.

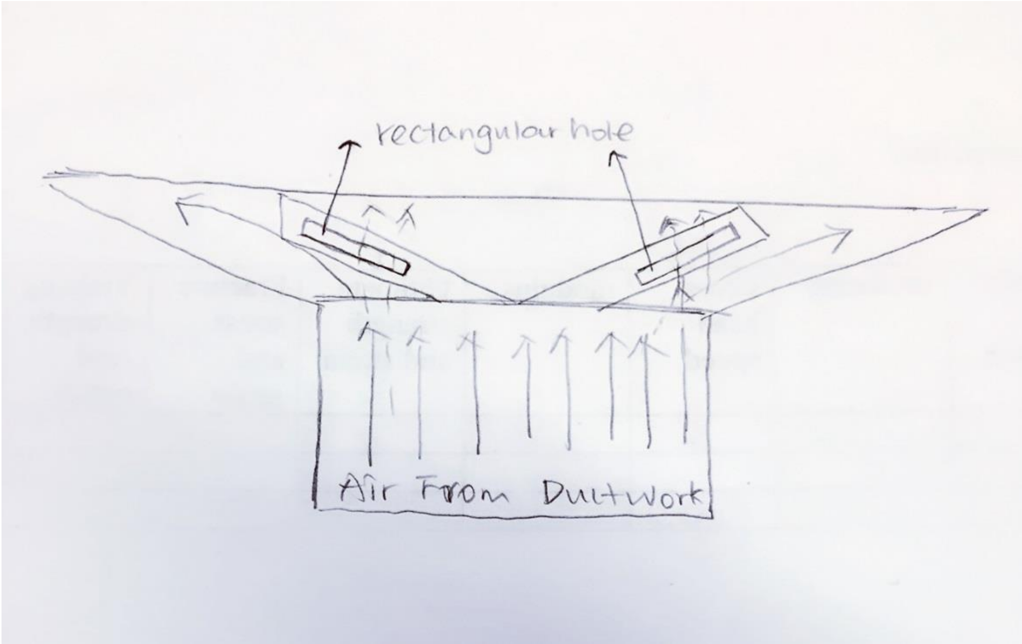


Figure 13: Design concept 11 with a wide V shaped wedge, with rectangular holes.

The design shown in Figure 13 will increase the air flow to the sides of the plenum by widening the V shaped wedge. When the air comes from the duct work, the V shaped wedge design will divert most of air to the sides instead of to the windshield. Two separate rectangular shaped holes were also made on the V shaped wedge in order to allow some of the air to be passed to the windshield. This design will create more noise but the weight of the plenum will not increase significantly.

Appendix C: Concept Scoring Criteria and Results

After generating the designs seen in the Concept Generation section, our team defined scoring parameters that will be used to score each concept. The criteria our team used to score each concept are listed below:

A. Good Air Distribution
B. Durability
C. Low Complexity
D. Lightweight
E. Ease of Install/Handling
F. Manufacturability
G. Noise

Our team used a Pugh chart to score the different concepts that were generated based on the criteria listed above. A Pugh chart compares a baseline concept, which is the current plenum design in our case, and compares with a simple scoring system. If the new design is better than the current plenum, then it is given a “+”. If the new design is comparable to the current design, then it is given a “0”; and if it is worse than the current plenum design, it is given a “-“. The net score is then calculated by subtracting the sum of negatives from the sum of the positives. The designs are then ranked based on their net score. The Pugh chart for our concept scoring is shown in TABLE *II*.

TABLE II: PUGH CHART FOR CONCEPT SCORING.

Selection Criteria	Multi-Slotted Wedge	Curved Wedge	Curved Wedge with Vanes	V-Shape with Curvature	Curved V-shape with Vanes	Wide V-Shape	3D Wedge	Modified 3D Wedge	Plenum with Flaps	V-Shape with Vanes	Slotted Wedge	Current Plenum
Good Air Distribution	-	+	+	+	+	+	+	0	+	+	0	0
Durability	0	0	-	-	-	0	0	-	-	-	0	0
Low Complexity	-	+	+	-	-	+	-	-	-	-	-	0
Light Weight	+	0	+	-	0	0	-	-	-	-	0	0
Ease of Install/Handling	0	0	0	0	0	0	0	0	0	0	0	0
Manufacturability	-	+	-	-	-	+	-	-	-	-	-	0
Noise	-	+	+	0	+	-	-	+	-	-	0	0
Total -'s	4	0	2	4	3	1	4	4	5	5	2	0
Total +'s	1	4	4	1	2	3	1	1	1	1	0	0
Net	-3	4	2	-3	-1	2	-3	-3	-4	-4	-2	0
Rank	6	1	2	6	4	3	6	6	7	7	5	

The ranking of each design based on a simple positive, negative, or neutral rating does not provide an accurate enough estimate of the best designs for concept scoring. In some circumstances, the criteria are subjective. For example, it is hard to estimate the air distribution without doing CFD analyses. Therefore, where the criteria are subjective we have used our best intuition to differentiate whether a design is better or worse than the current plenum. The Pugh chart assumes that each of the criteria are weighted equally, when their actual importance may vary significantly. For example, good air distribution is more important than having a less complex design. Therefore, our team developed a criteria scoring matrix to determine which criteria are most important.

The criteria listed above have varying degrees of importance, and therefore our team set up a weighting matrix to assign weights to the most important criteria. Our criteria weighting matrix is shown in TABLE *III* below.

TABLE III: CRITERIA SCORING MATRIX

Criteria		Air Distribution	Durability	Low Complexity	Light Weight	Ease of Install/Handling	Manufacturability	Low Noise
		A	B	C	D	E	F	G
A	Air Distribution		A	A	A	A	A	A
B	Durability			B	B	B	F	G
C	Low Complexity				C	E	F	G
D	Light Weight					E	F	G
E	Ease of Install/Handling						E	G
F	Manufacturability							G
G	Noise							
Total Hits		6	3	1	0	3	3	5
Weightings		0.286	0.143	0.048	0	0.143	0.143	0.238

The final weights found in TABLE III are the final scoring weights that will be used in our concept scoring, and will provide a basis for differentiating similarly ranked designs in the Pugh chart. The most important criteria is good air flow distribution, with a weighting of 28.6%. The least important criteria is having a light weight design, which has an importance of 0%. However, due to the nature of a criteria scoring matrix, the lowest weight criteria may still be important. The criteria scoring matrix simply compares criteria to one another, and the lowest weight criteria did not win in any comparison as all of the other criteria were more important in having a successful design. However, if the design exceeds the weight of the current plenum then there will be feasibility concerns. For the purposes of scoring each concept, we have eliminated the light weight criteria because the weight is 0%. The weight of the final design will still be considered, as we have a target specification that requires the new plenum to be on par or better in terms of weight. Our team then used the new weights for each criteria to score the 11 generated designs.

Our final concept scoring matrix utilized both the Pugh chart ratings as well as the weights for each criteria that were determined in the criteria scoring matrix. The weighted concept scoring results are shown in TABLE IV and TABLE V below.

TABLE IV: WEIGHTED CONCEPT SCORING FOR CONCEPTS 1 TO 6.

		Concepts											
		Multi-Slotted Wedge		Curved Wedge		Curved Wedge with Vanes		V-Shape with Curvature		Curved V-Shape with Vanes		Wide V-Shape	
Selection Criteria	**Weight**	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Good Air Distribution	28.60 %	1	0.286	3	0.858	3	0.858	3	0.858	3	0.858	3	0.858
Durability	14.30 %	2	0.286	2	0.286	1	0.143	1	0.143	1	0.143	2	0.286
Low Complexity	4.70%	1	0.047	3	0.141	3	0.141	1	0.047	1	0.047	3	0.141
Ease of Install/Handling	14.30 %	2	0.286	2	0.286	2	0.286	2	0.286	2	0.286	2	0.286
Manufacturability	14.30 %	1	0.143	3	0.429	1	0.143	1	0.143	1	0.143	3	0.429
Noise	23.80 %	1	0.238	3	0.714	2	0.476	2	0.476	3	0.714	1	0.238
Total Score		1.286		2.714		2.047		1.953		2.191		2.238	
Rank		10		1		4		5		3		2	
Develop?		NO		YES		YES		NO		YES		YES	

TABLE V: WEIGHTED CONCEPT SCORING FOR CONCEPTS 7 TO 11.

		Concepts									
		3D Wedge		Modified 3D Wedge		Plenum with Flaps		V-Shape with Vanes		Slotted Wedge	
Selection Criteria	**Weight**	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Good Air Distribution	28.60 %	3	0.858	2	0.572	3	0.858	3	0.858	2	0.572
Durability	14.30 %	2	0.286	1	0.143	1	0.143	1	0.143	2	0.286
Low Complexity	4.70%	1	0.047	1	0.047	1	0.047	1	0.047	1	0.047
Ease of Install/Handling	14.30 %	2	0.286	2	0.286	2	0.286	2	0.286	2	0.286
Manufacturability	14.30 %	1	0.143	1	0.143	1	0.143	1	0.143	1	0.143
Noise	23.80 %	1	0.238	3	0.714	1	0.238	1	0.238	2	0.476
Total Score		1.858		1.905		1.715		1.715		1.81	
Rank		7		6		9		9		8	
Develop?		NO		NO		NO		NO		NO	

The weighted scoring matrix has proved that there are significant enough differences between each concept when the importance of each criteria is taken into account. Therefore, a sensitivity analysis does not need to be conducted, as the weights were sufficient to differentiate the designs from one another. The concepts that scored the highest net score (greater than 2.0) are considered the best of the 11 concepts that were initially generated. Therefore, we will move forward with concepts 2, 3, 5, and 6. Our team will not limit the final design to exactly those shapes and concepts, rather we will try different combinations of the best ideas. The concepts that scored the highest are feasible in all other criteria that can be intuitively measured, however their airflow distribution and noise are subjective. Therefore, a CFD analysis will be conducted on many different combinations of the best designs to converge on a final optimized design.

Appendix D: Combined Designs for Further Analysis

Our team discussed the four concepts that scored the highest in the weighted concept scoring matrix, and developed three combinations of concepts that we would like to move forward with, along with the four concepts that scored the best.

D.1 Combined Concept Design 1

The first combined concept design is shown in Figure 14 below.

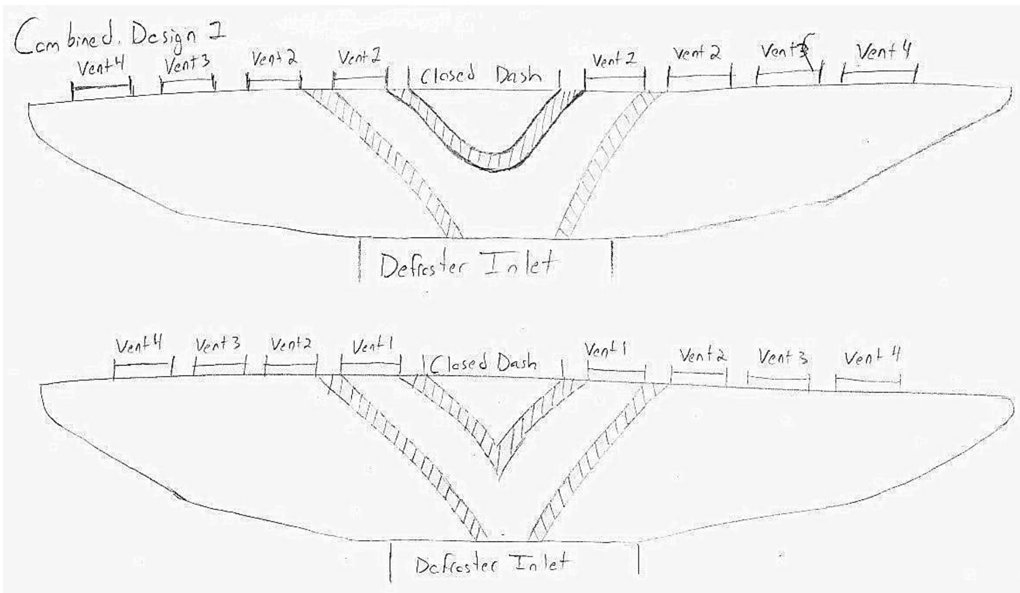


Figure 14: Combined Concept Design 1.

The first combined concept design utilizes aspects of Design 2, 3, and 5. The idea behind this design is to limit the amount of airflow to vent 1 on either side, which will increase the airflow through the other vents. A comparison between the curved wedge and the sharp V-shape wedge will be conducted using CFD to determine which one provides better airflow distribution and lower noise. The wedge comparison will be conducted once, and our team will move forward with one wedge for the other designs. A CFD analysis will have to be conducted to determine whether the full height fin design is feasible when compared to the four concepts that scored the highest in the weighted concept scoring matrix.

D.2 Combined Concept Design 2

The second combined concept design is shown in Figure 15 below.

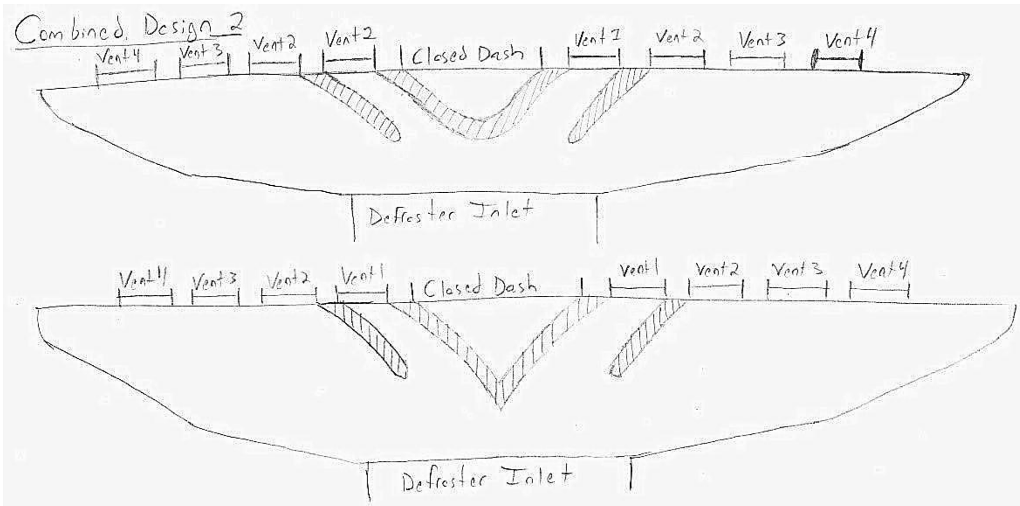


Figure 15: Combined Concept Design 2.

The second combined concept design is similar to the first combined concept design, except the fins do not extend to the bottom of the plenum. This design is not limited to top mounted fins, as they are drawn, but could incorporate bottom mounted fins alone or in combination with top mounted fins. The intent of this design is to ensure that the outer vents are receiving more airflow than the current plenum design, thus resulting in better airflow distribution along the plenum and reducing the noise.

D.3 Combined Concept Design 3

The third combined concept design is shown in Figure 16 below.

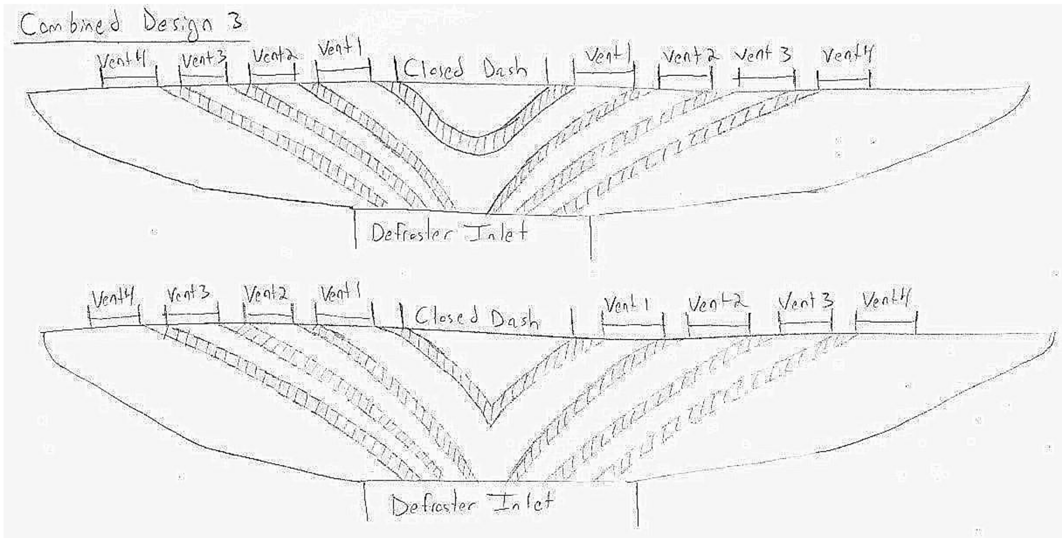


Figure 16: Combined Concept Design 3.

The third combined concept design is similar in design to the other two combined concept designs, except that this design utilizes multiple full length fins to control the airflow to each vent accurately. The intent of the design is to be able to finely control the airflow by optimizing the inlet size to each vent. As with the other designs, a CFD analysis will have to be conducted to determine the performance capabilities of this design.

The final combined designs as well as the four concepts that scored the best in the weighted scoring matrix will be analyzed using CFD, and the most promising design will be selected as the final design. From there, the final design will be optimized in terms of airflow distribution as well as noise reduction.

Appendix E: Convergence Plots for CFD Simulations

This section of the report will show the convergence plots for all of the simulations that were run for all of the designs considered in this report.

Simulation 1

Figure *17* illustrates Simulation 1 with High Resolution, Auto Timescale, Steady State, k-Epsilon turbulence model and tetrahedral mesh.

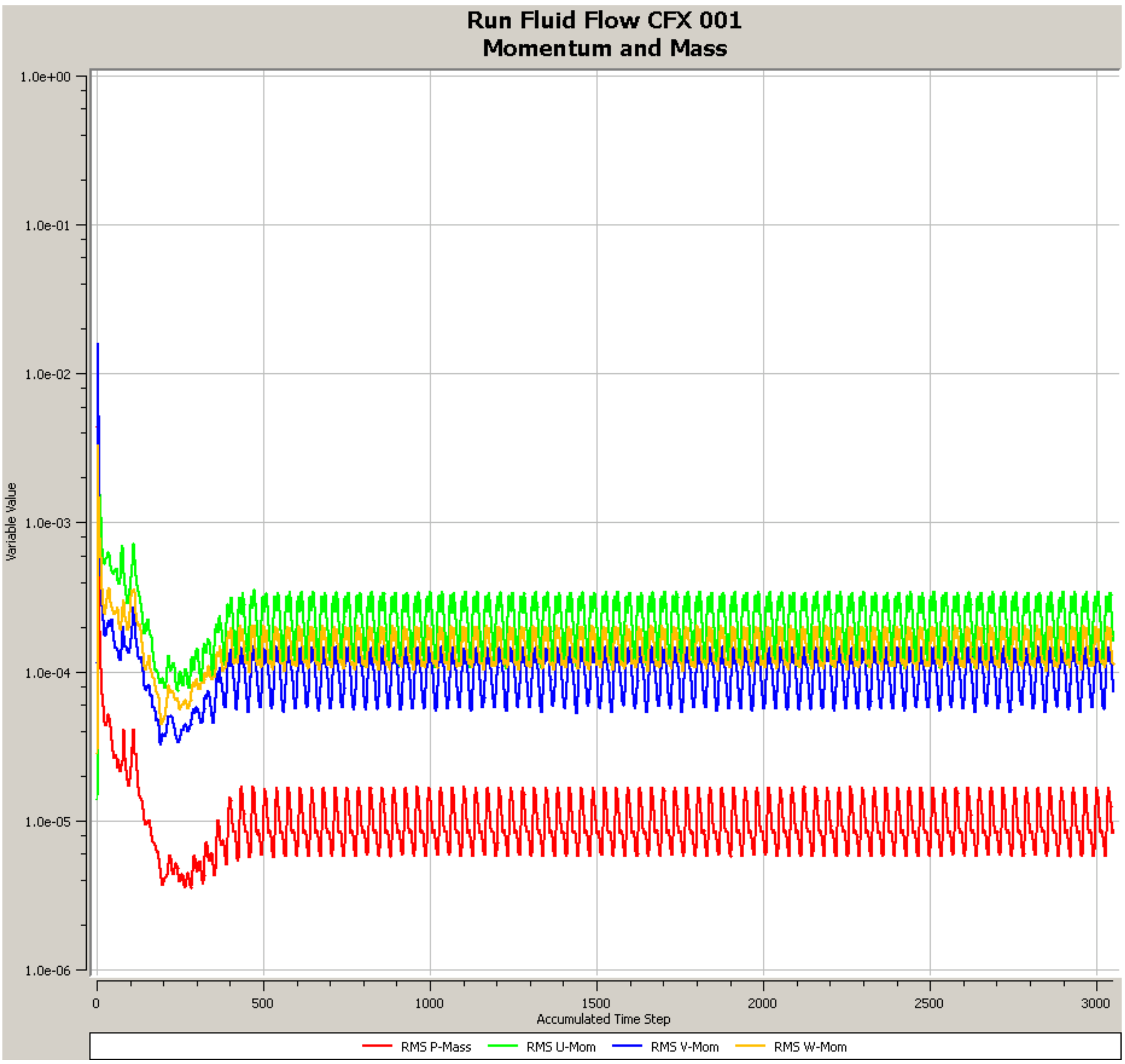


Figure 17: An image of the convergence plot for Simulation 1.

The plot shows that Simulation 1 did not converge to our residual target of 1E-06.

Simulation 2

Figure *18* illustrates Simulation 2 with High Resolution, Auto Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

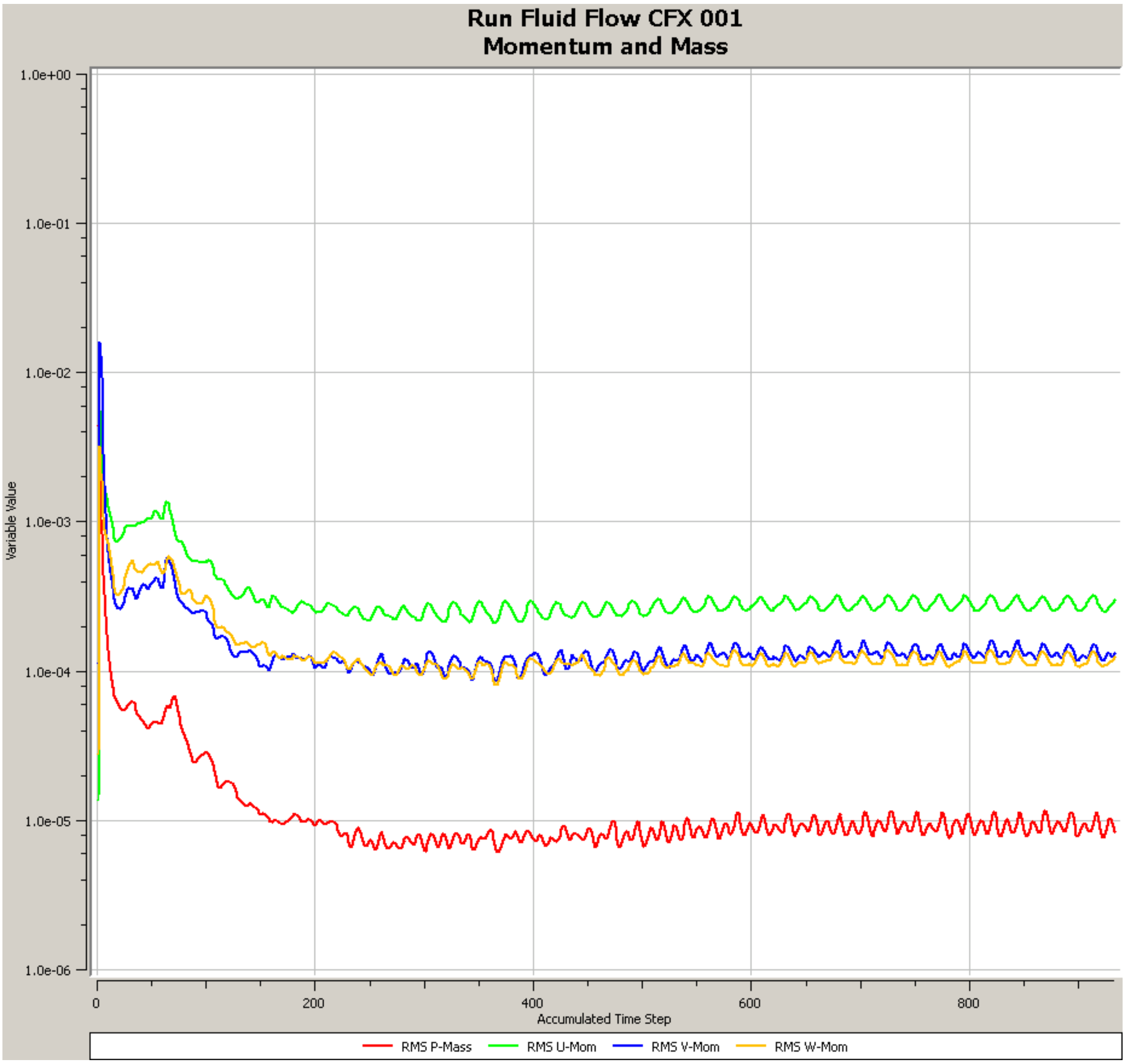


Figure 18: An image of the convergence plot for Simulation 2.

The plot shows that Simulation 2 did not converge to our residual target of 1E-06.

Simulation 3

Figure *19* illustrates Simulation 3 with High Resolution, Auto Timescale, Steady State, Shear Stress Transport (SST) turbulence model and tetrahedral mesh.

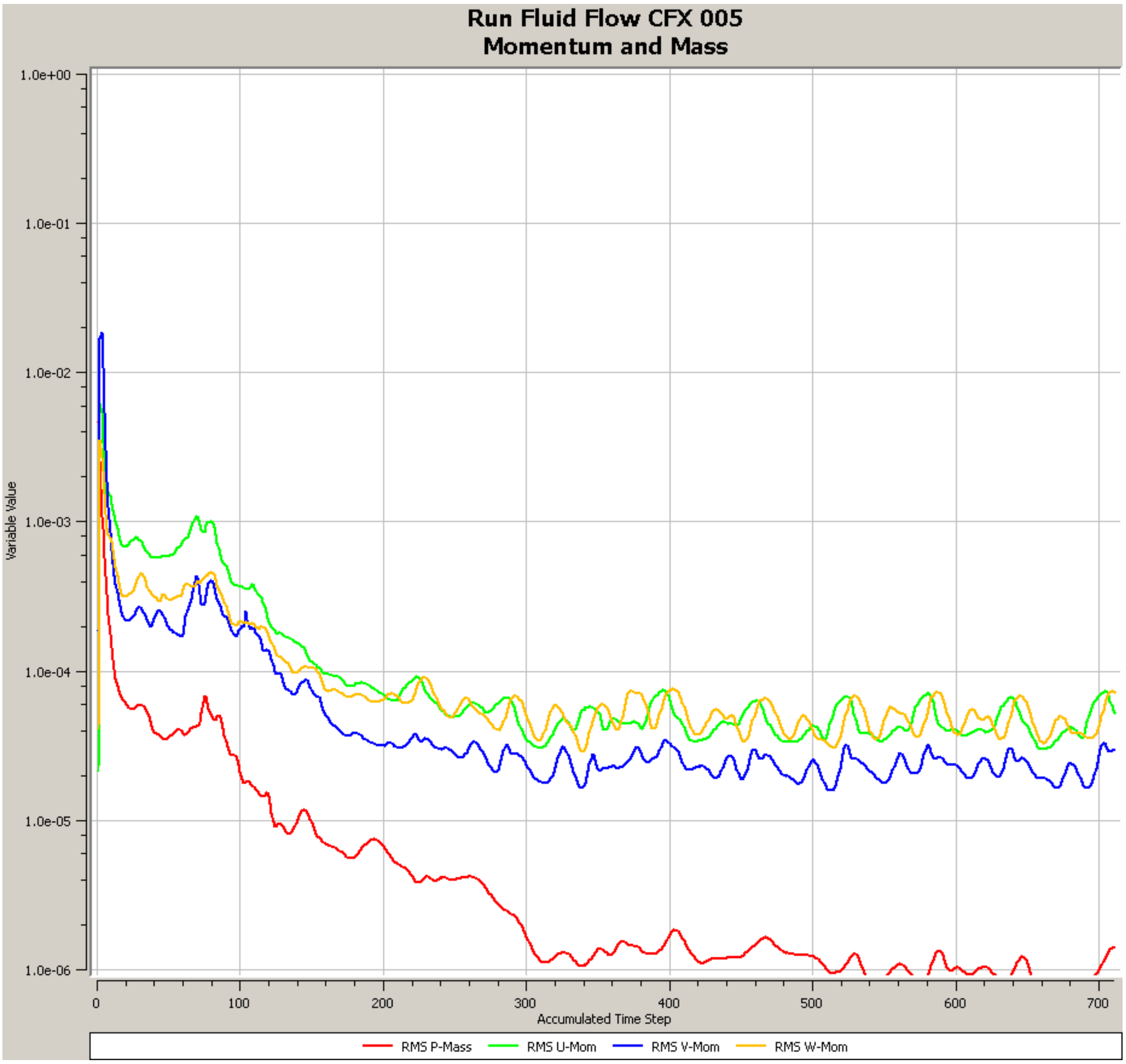


Figure 19: An image of the convergence plot for Simulation 3.

The plot shows that Simulation 3 did not converge to our residual target of 1E-06.

Simulation 4

Figure *20* illustrates Simulation 4 with High Resolution, 0.031 Physical Timescale, Steady State, Shear Stress Transport (SST) turbulence model and tetrahedral mesh.

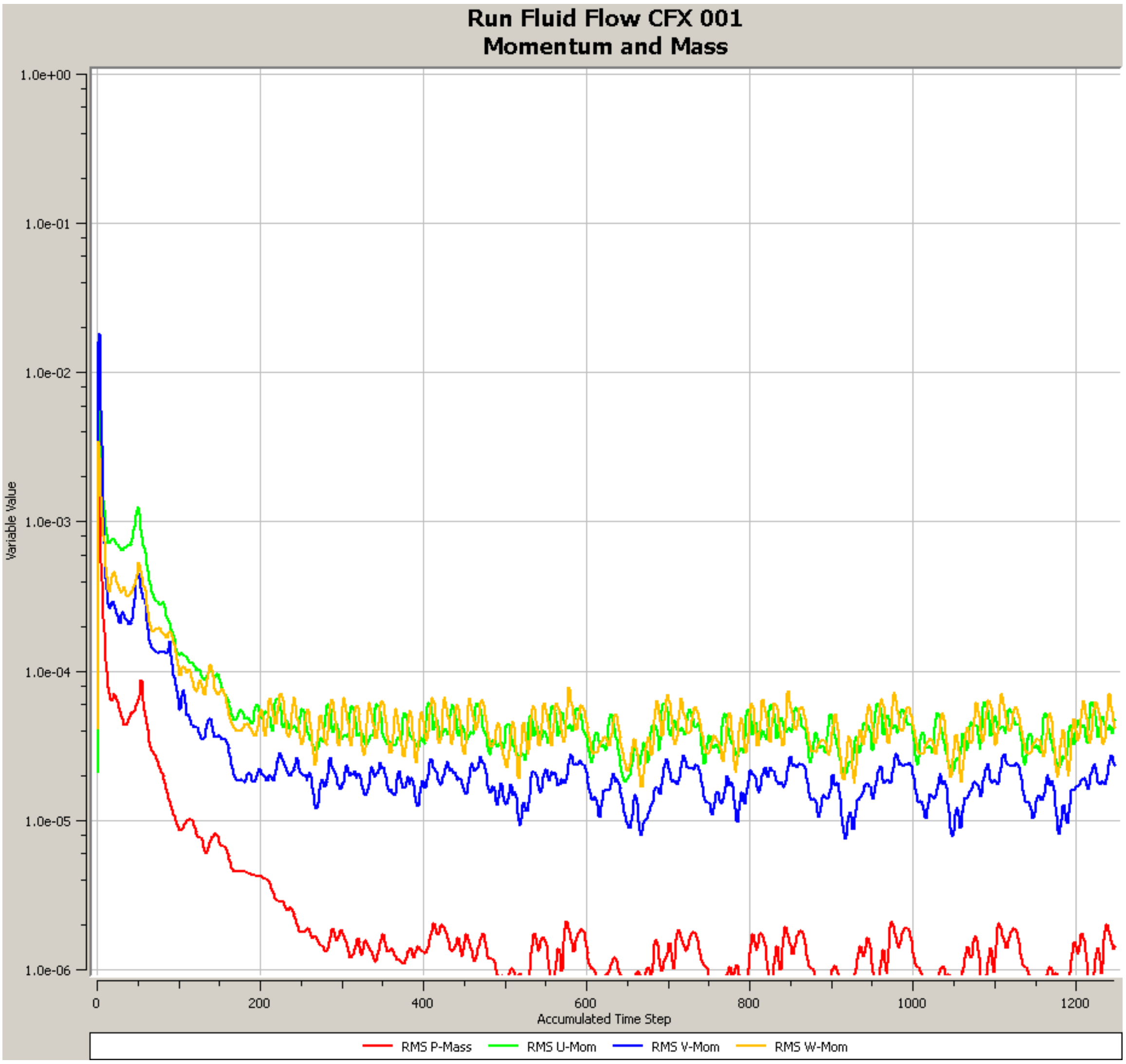


Figure 20: An image of the convergence plot for Simulation 4.

The plot shows that Simulation 4 did not converge to our residual target of 1E-06.

Simulation 5

Figure *21* illustrates Simulation 5 with High Resolution, 0.001 Physical Timescale, Steady State, Shear Stress Transport (SST) turbulence model and tetrahedral mesh.

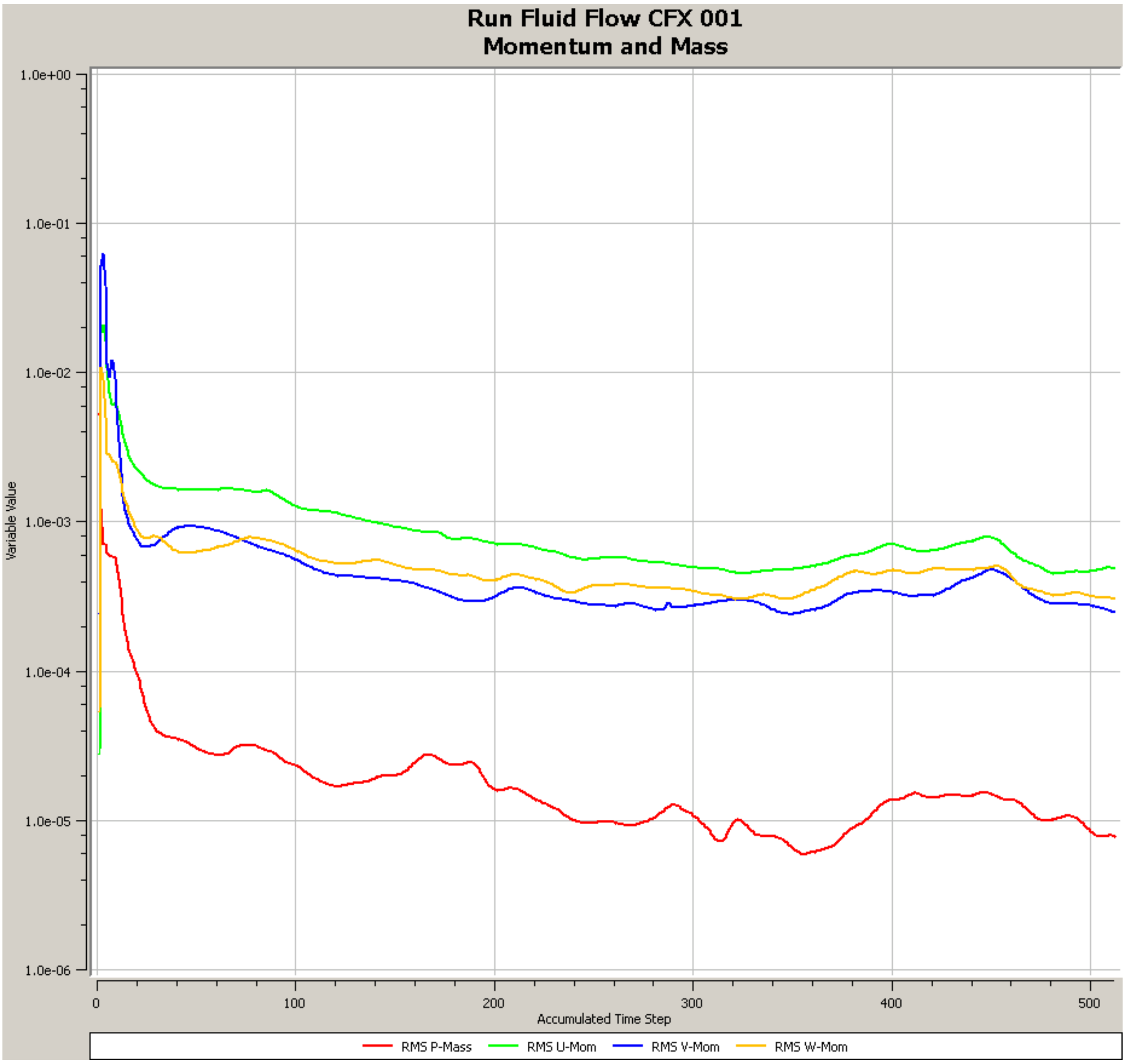


Figure 21: An image of the convergence plot for Simulation 5.

The plot shows that Simulation 5 did not converge to our residual target of 1E-06.

Simulation 6

Simulation 6 was lost due to the server being shut down, but the initial convergence plot for the first couple hundred iterations did not look like it would converge, and therefore it was not run again.

Simulation 7

Figure *22* illustrates Simulation 7 with 0.25 blend between High Resolution and Upwind, 0.001 Physical Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

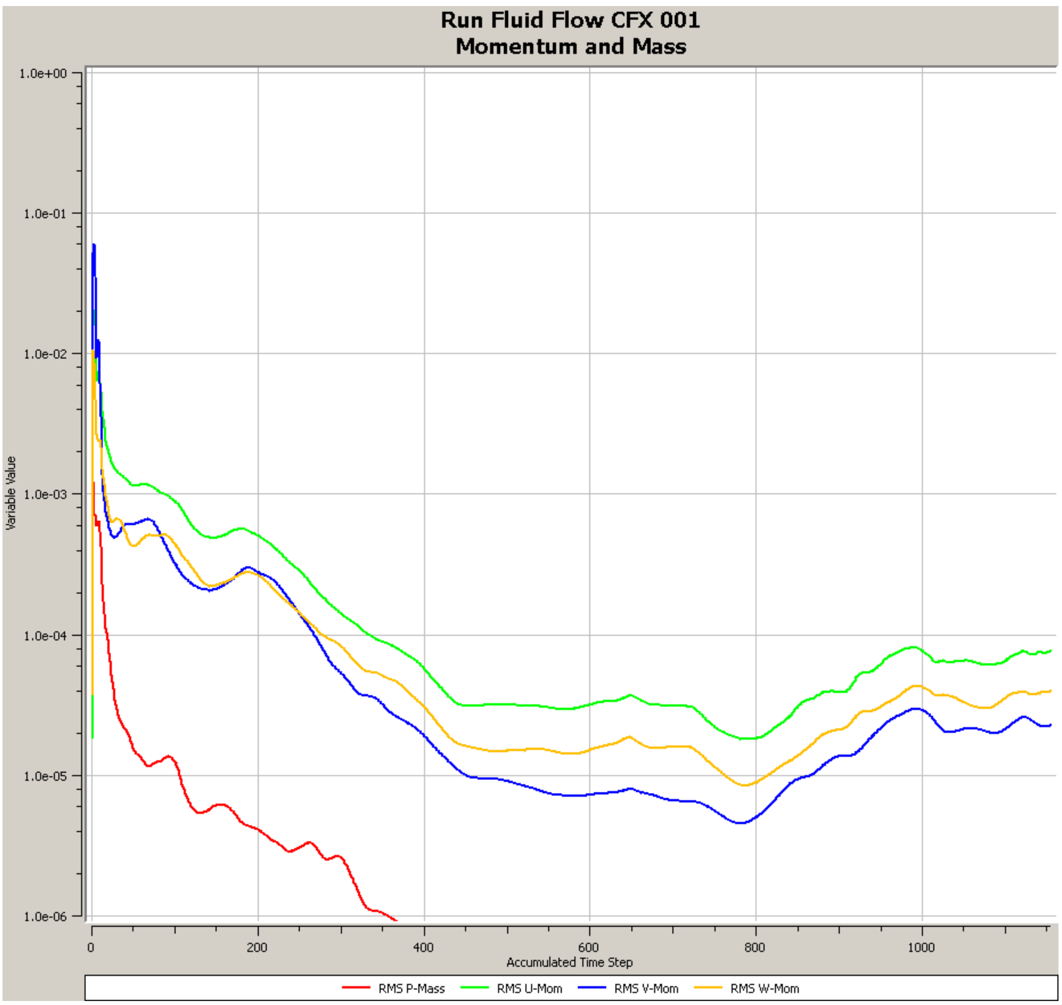


Figure 22: An image of the convergence plot for Simulation 7.

The plot shows that Simulation 7 did not converge to our residual target of 1E-06.

Simulation 8

Simulation 8 was lost due to the server being shut down, but the initial convergence plot for the first couple hundred iterations did not look like it would converge, and therefore it was not run again.

Simulation 9

Figure *23* illustrates Simulation 9 with Upwind, 0.001 Physical Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

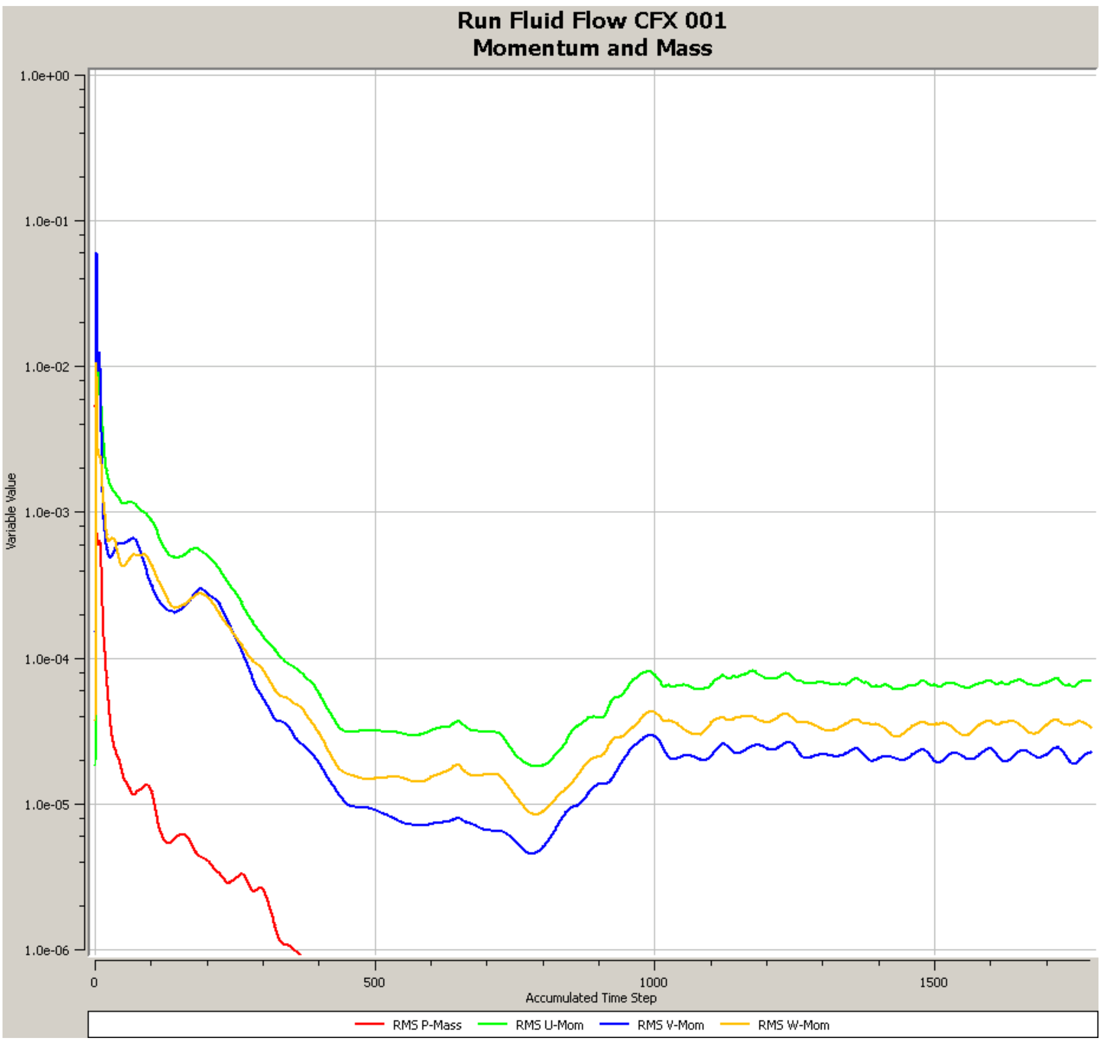


Figure 23: An image of the convergence plot for Simulation 9.

The plot shows that Simulation 9 did not converge to our residual target of 1E-06.

Simulation 10

Figure *24* illustrates Simulation 10 with Upwind, Auto Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

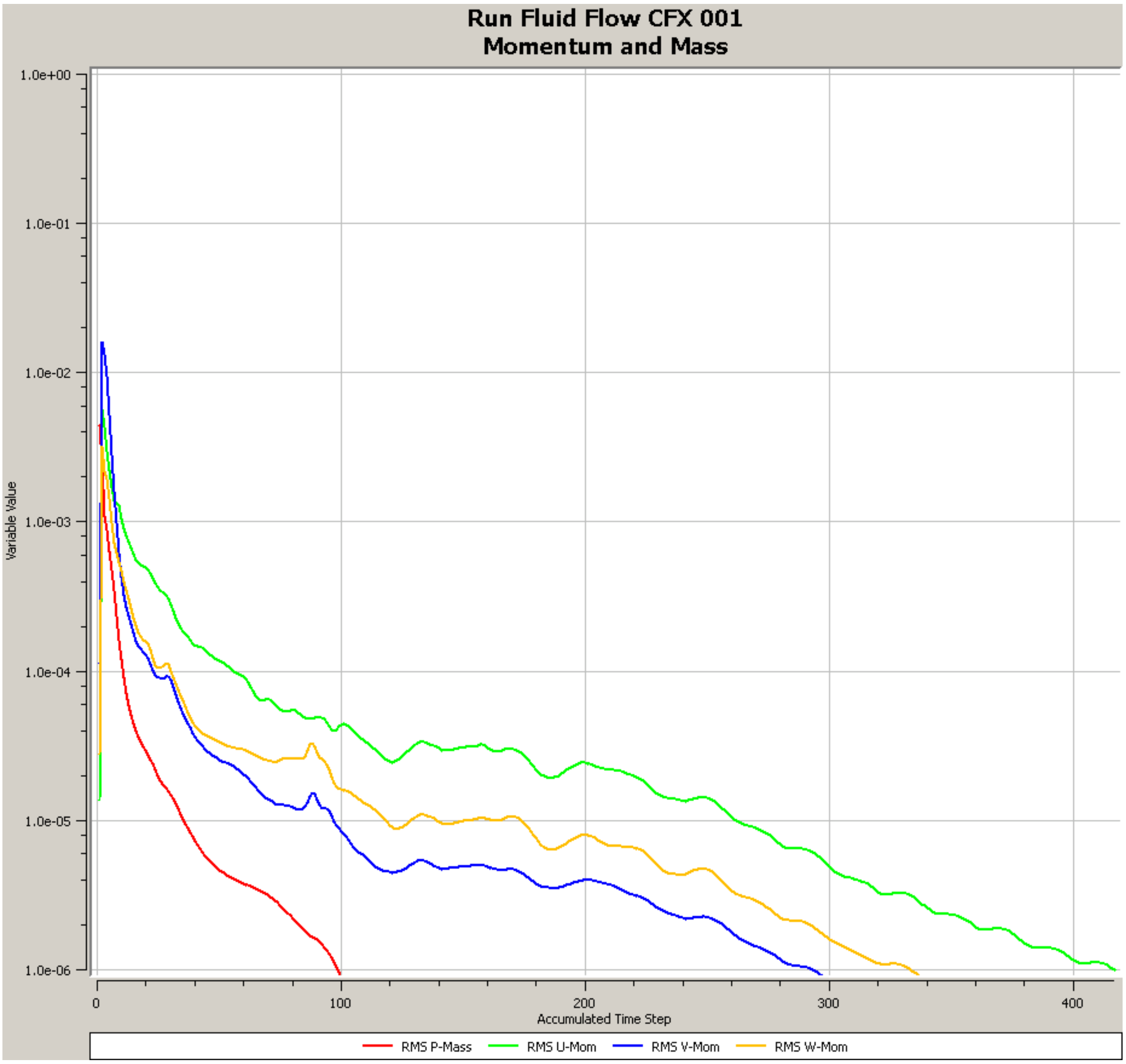


Figure 24: An image of the convergence plot for Simulation 10.

The plot shows that Simulation 10 did not converge to our residual target of 1E-06.

Simulation 11

Figure *25* illustrates Simulation 11 with Upwind, 0.001 Physical Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

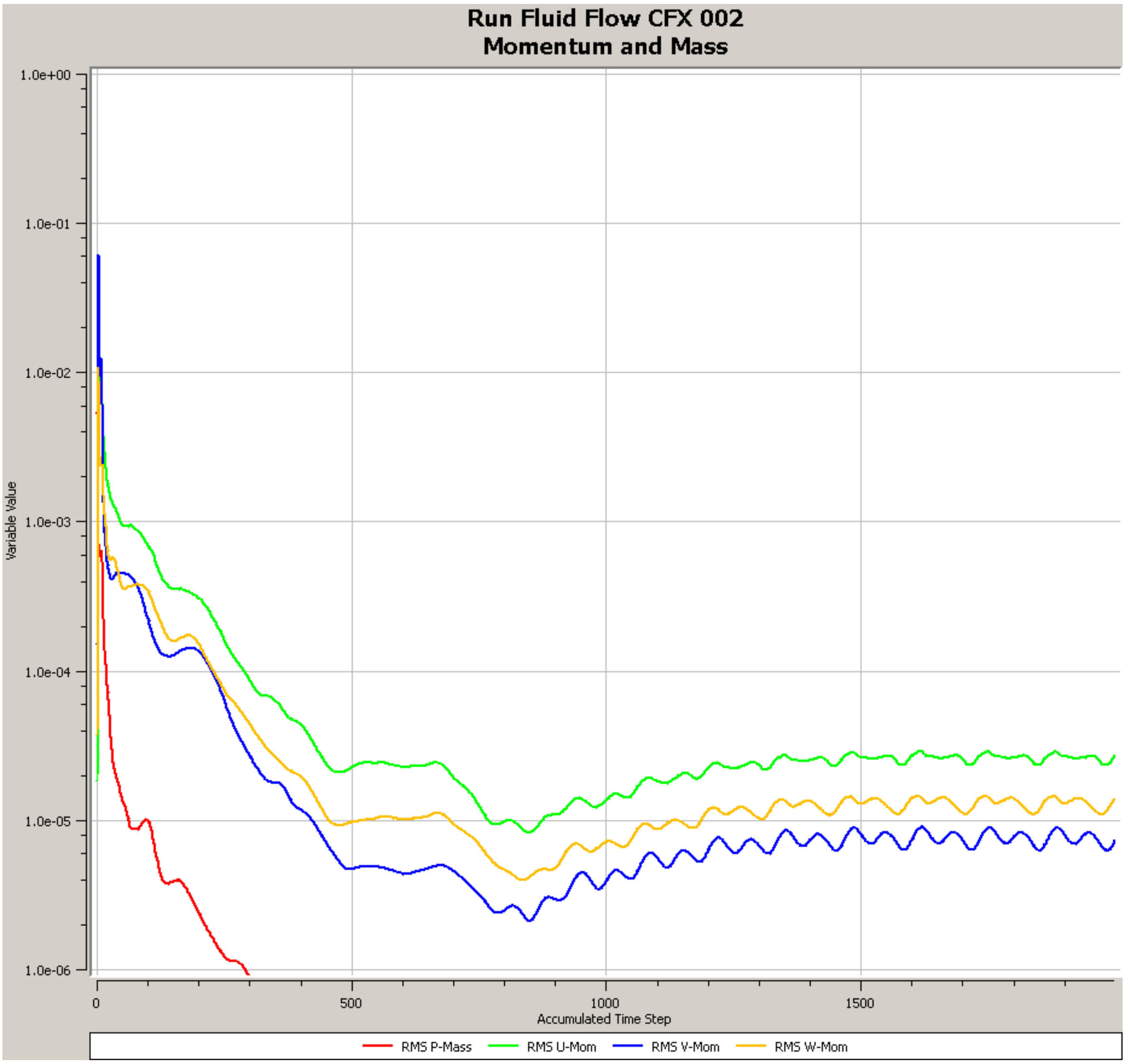


Figure 25: An image of the convergence plot for Simulation 11.

The plot shows that Simulation 11 did not converge to our residual target of 1E-06.

Simulation 12

Figure *26* illustrates Simulation 12 with Upwind, 0.01 Physical Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

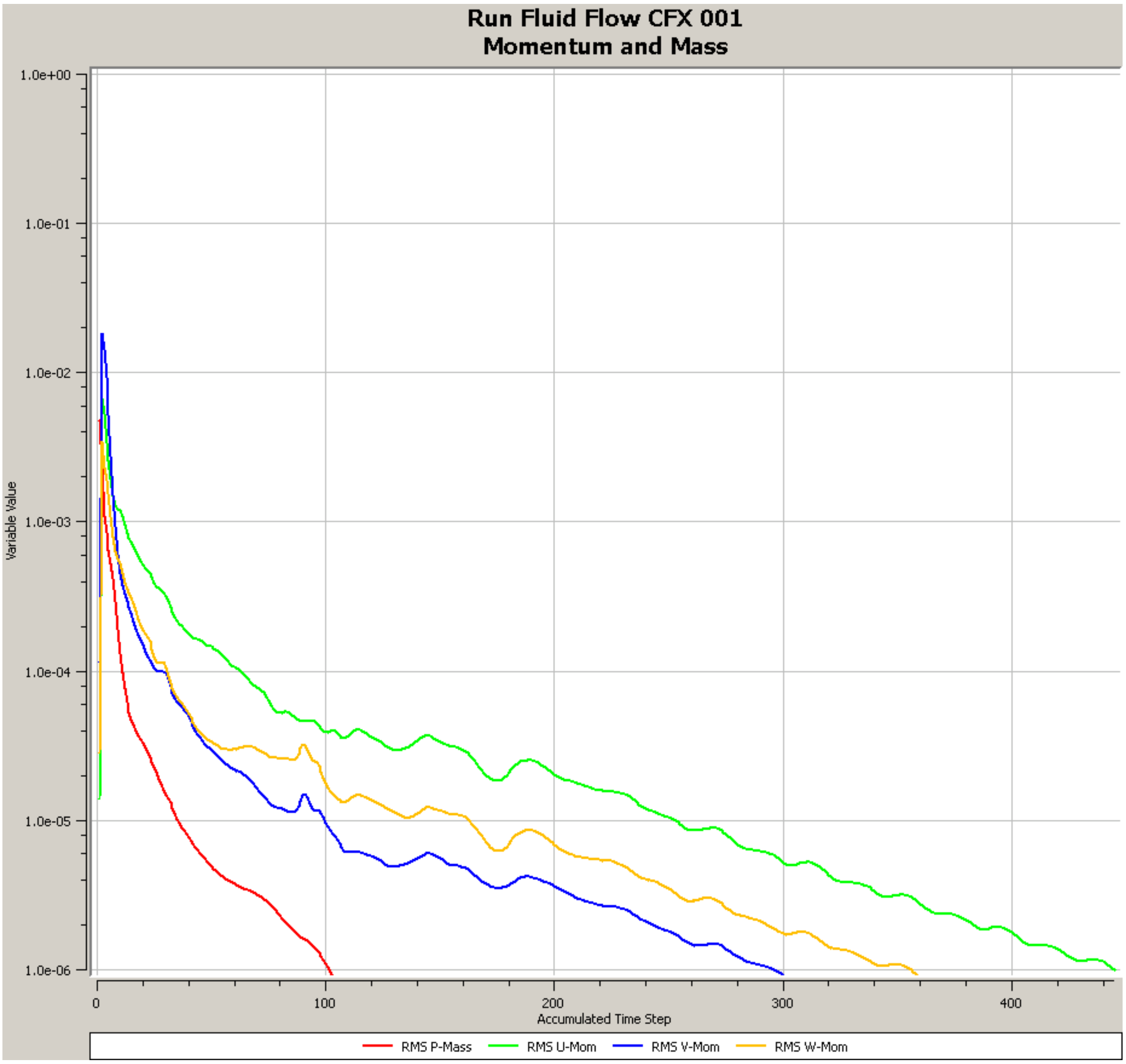


Figure 26: An image of the convergence plot for Simulation 12.

The plot shows that Simulation 12 did converge to our residual target of 1E-06.

Simulation 13

Figure *27* illustrates Simulation 13 with 120˚C air, Upwind, 0.01 Physical Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

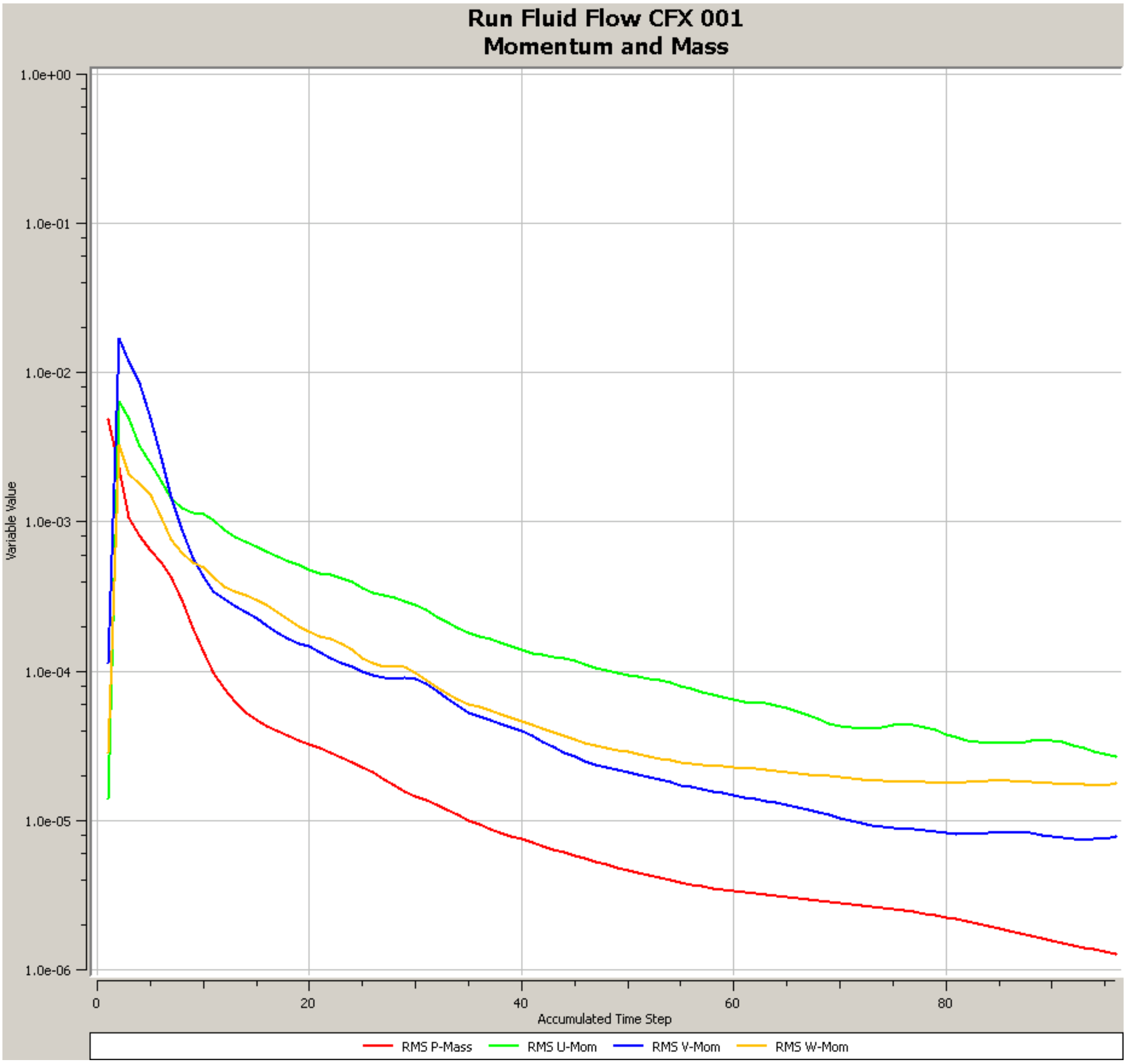


Figure 27: An image of the convergence plot for Simulation 13.

The plot shows that Simulation 13 was not going to converge to our residual target of 0.000001.

Simulation 14

Figure *28* illustrates Simulation 14 with the first vent design, 120˚C air, High Resolution, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

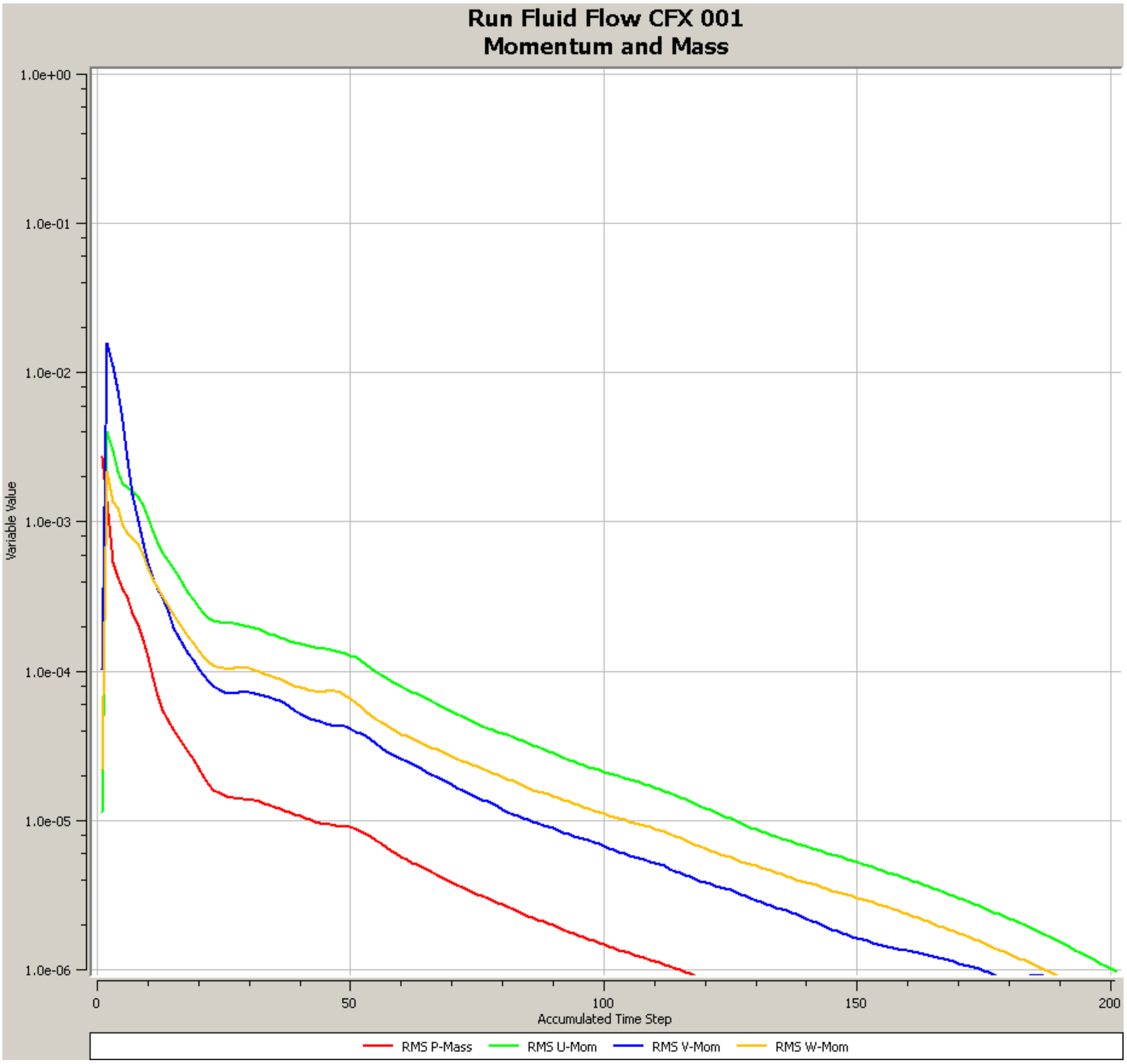


Figure 28: An image of the convergence plot for Simulation 14.

The plot shows that Simulation 14 did converge to our residual target of 1E-06.

Simulation 15

Figure *29* illustrates Simulation 15 with a 0.25 blend between High Resolution and Upwind, 120˚C air, Auto Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

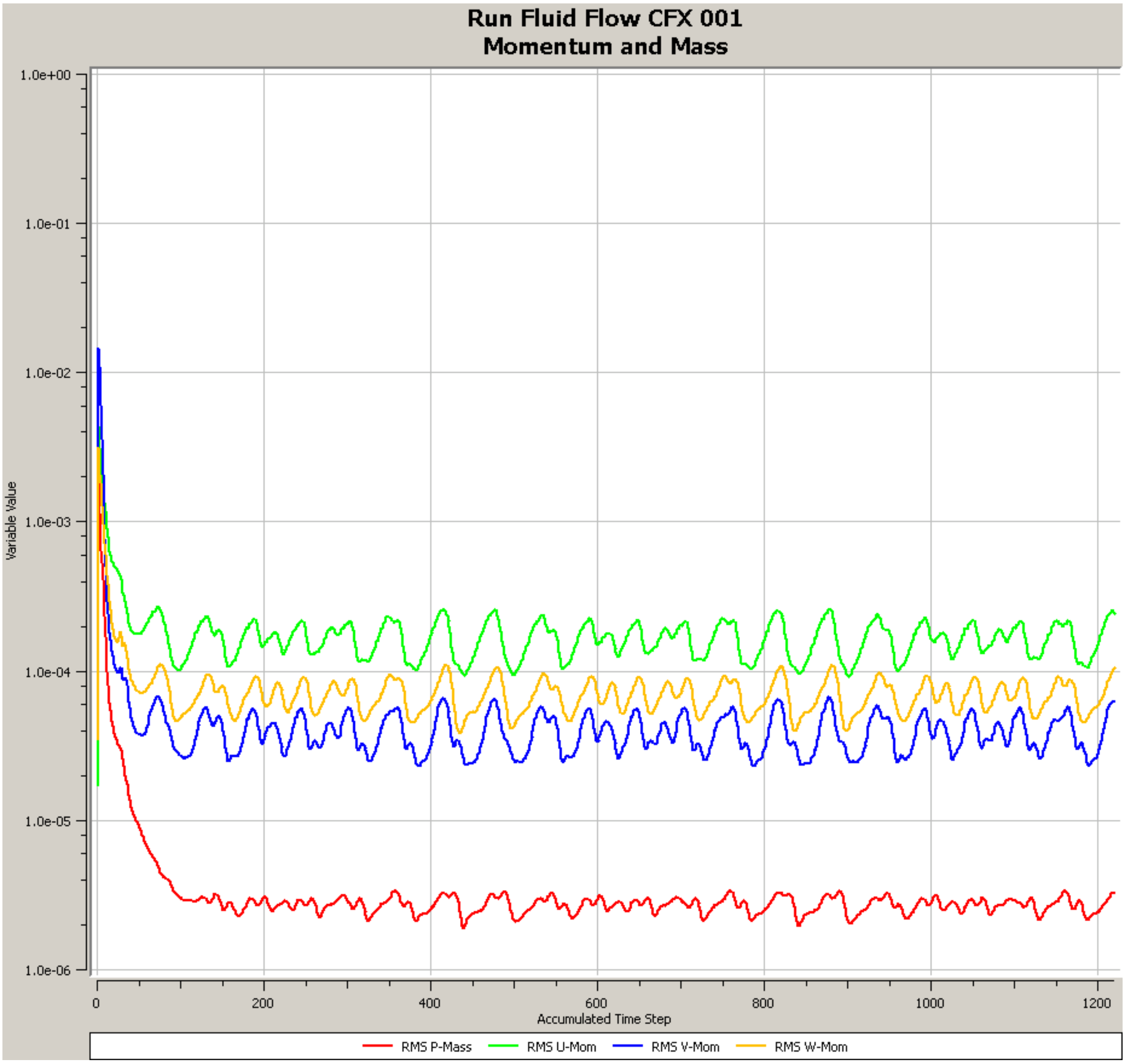


Figure 29: An image of the convergence plot for Simulation 15.

The plot shows that Simulation 15 did not converge to our residual target of 1E-06.

Simulation 16

Simulation 16 was lost due to the server being shut down, but the initial convergence plot for the first couple hundred iterations did not look like it would converge, and therefore it was not run again.

Simulation 17

Figure 30 illustrates Simulation 17 with Upwind, 120˚C air, Auto Timescale, Steady State, RNG k-Epsilon turbulence model and tetrahedral mesh.

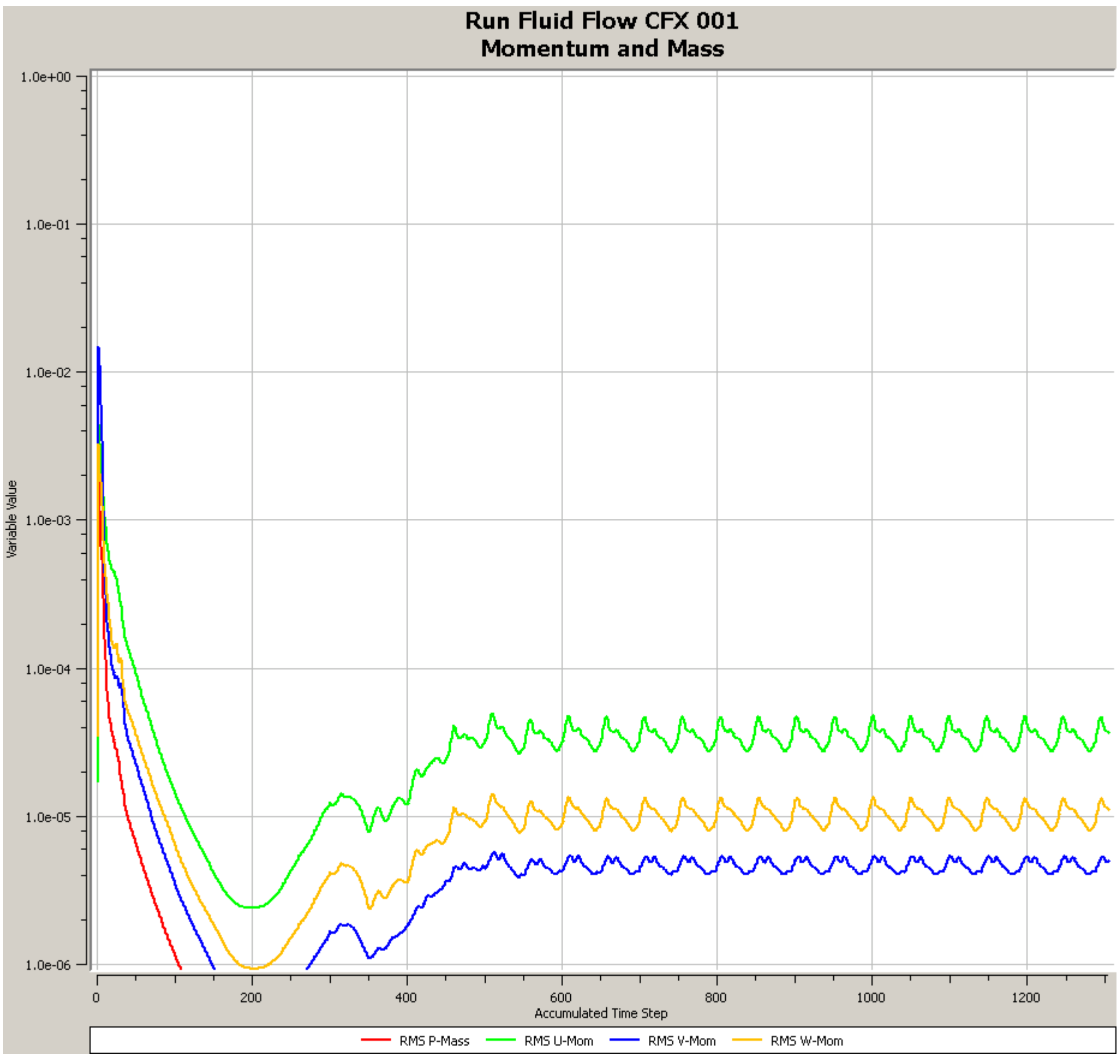


Figure 30: An image of the convergence plot for Simulation 17.

The plot shows that Simulation 17 did not converge to our residual target of 1E-06.

Simulation 18

Figure *31* illustrates Simulation 18 with a 0.25 blend between High Resolution and Upwind, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and tetrahedral mesh.

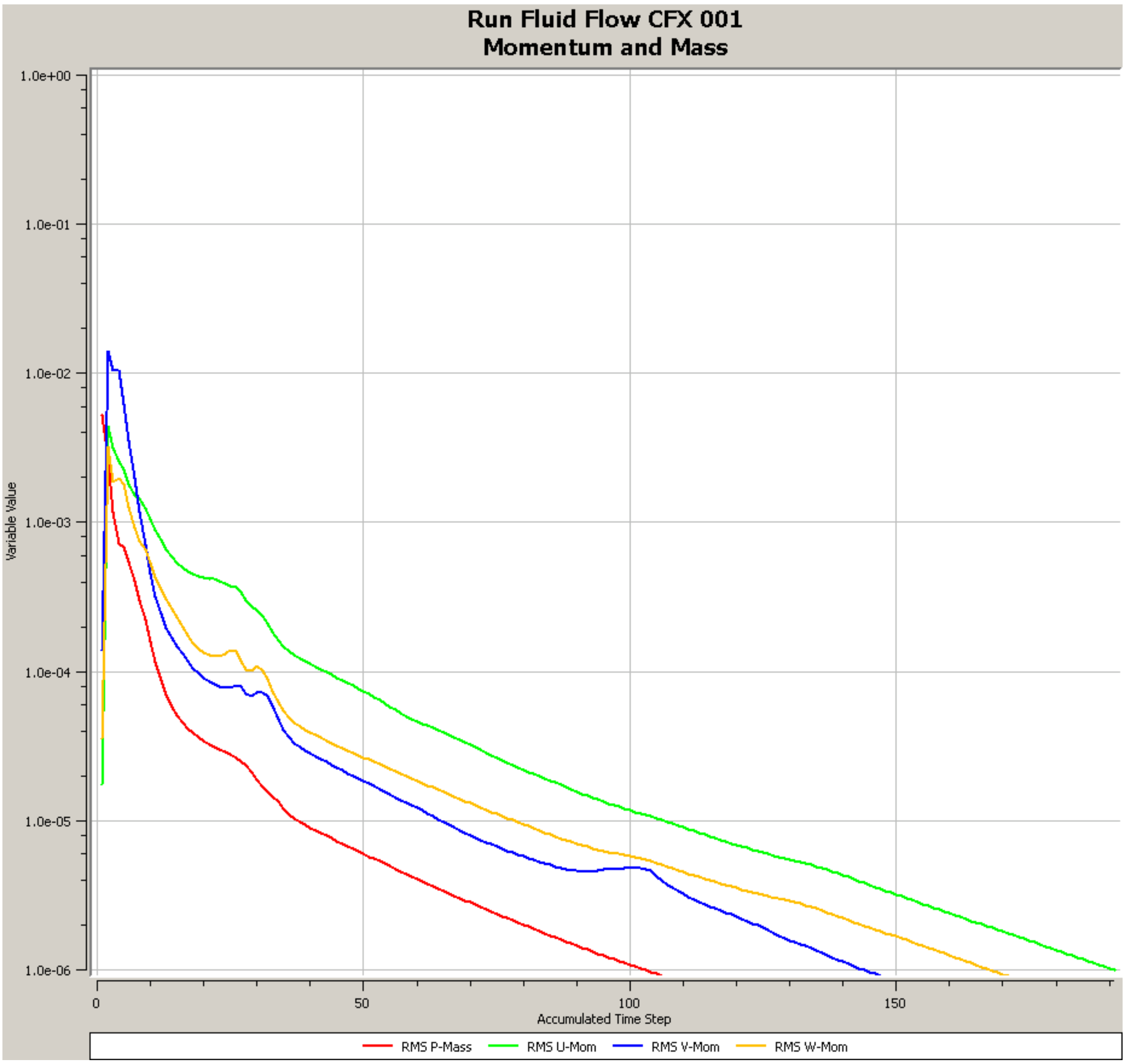


Figure 31: An image of the convergence plot for Simulation 18.

The plot shows that Simulation 18 did converge to our residual target of 1E-06.

Simulation 19

Figure *32* illustrates Simulation 19 with Upwind, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

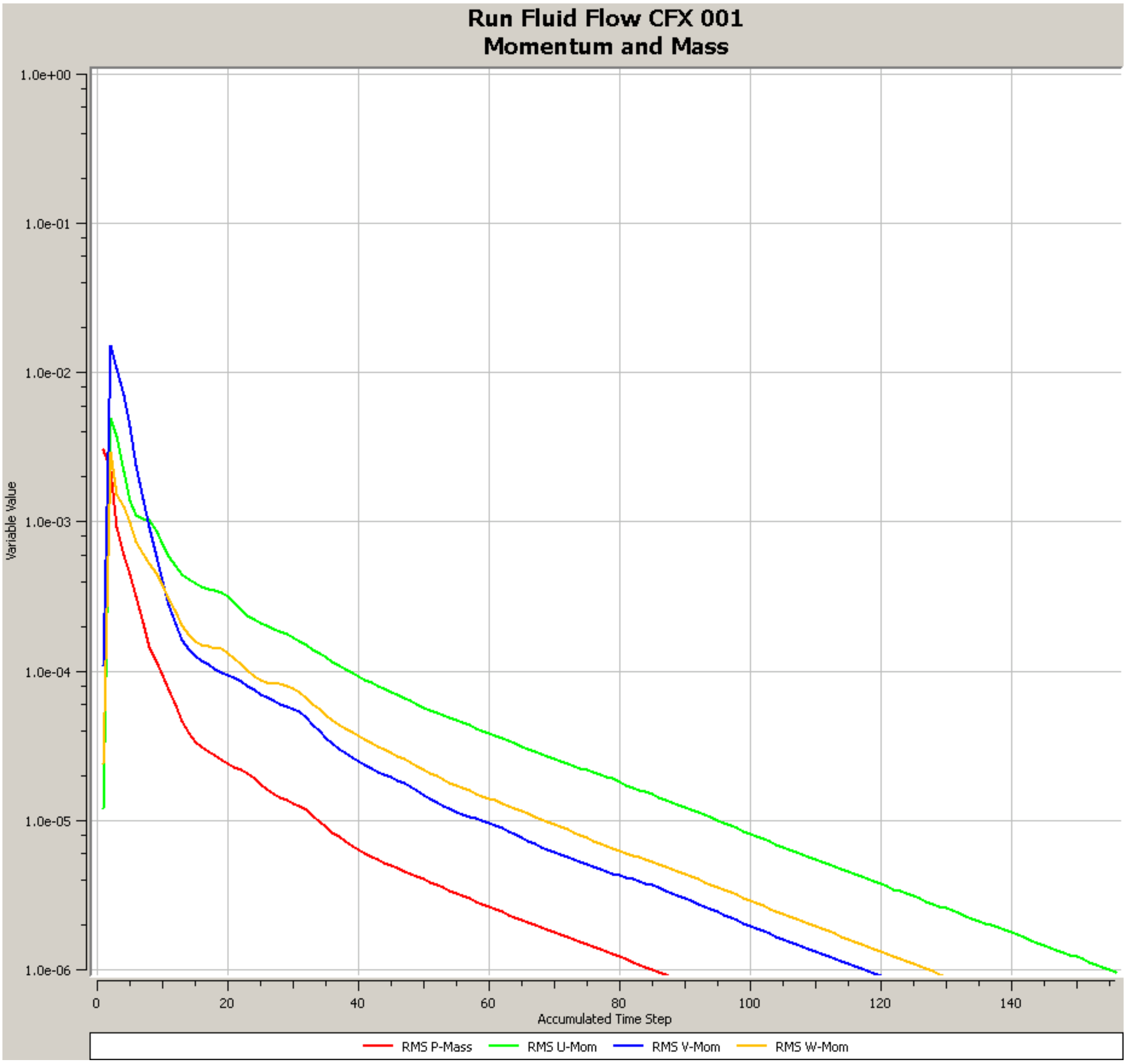


Figure 32: An image of the convergence plot for Simulation 19.

The plot shows that Simulation 19 did converge to our residual target of 1E-06.

Simulation 20

Figure *33* illustrates Simulation 20 with a 0.25 blend between High Resolution and Upwind, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

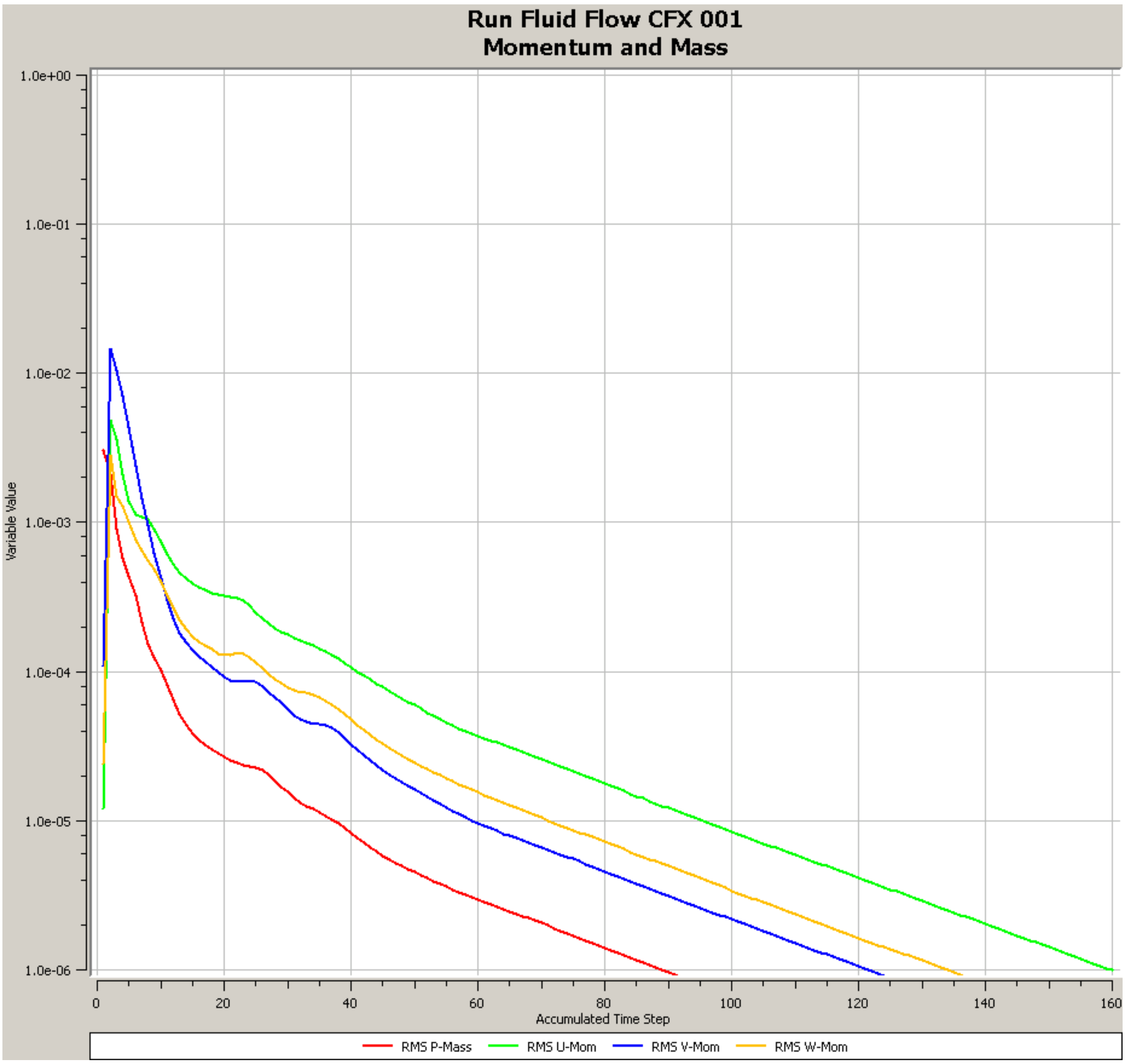


Figure 33: An image of the convergence plot for Simulation 20.

The plot shows that Simulation 20 did converge to our residual target of 1E-06.

Simulation 21

Figure 34 illustrates Simulation 21 with High Resolution, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

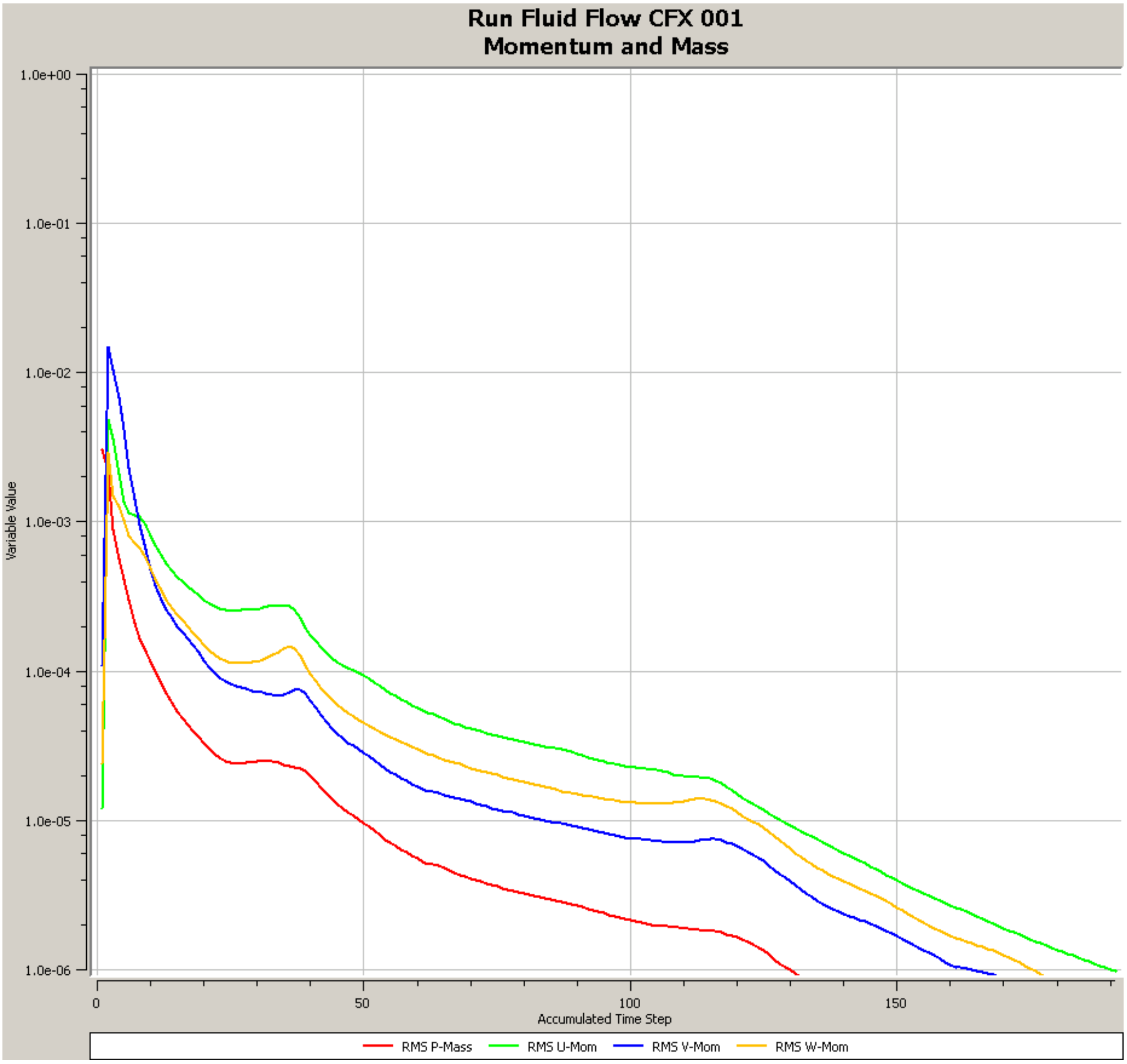


Figure 34: An image of the convergence plot for Simulation 21.

The plot shows that Simulation 21 did converge to our residual target of 1E-06.

Simulation 22

Figure *35* illustrates Simulation 22 with a double curved wedge, High Resolution, 120˚C, air Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

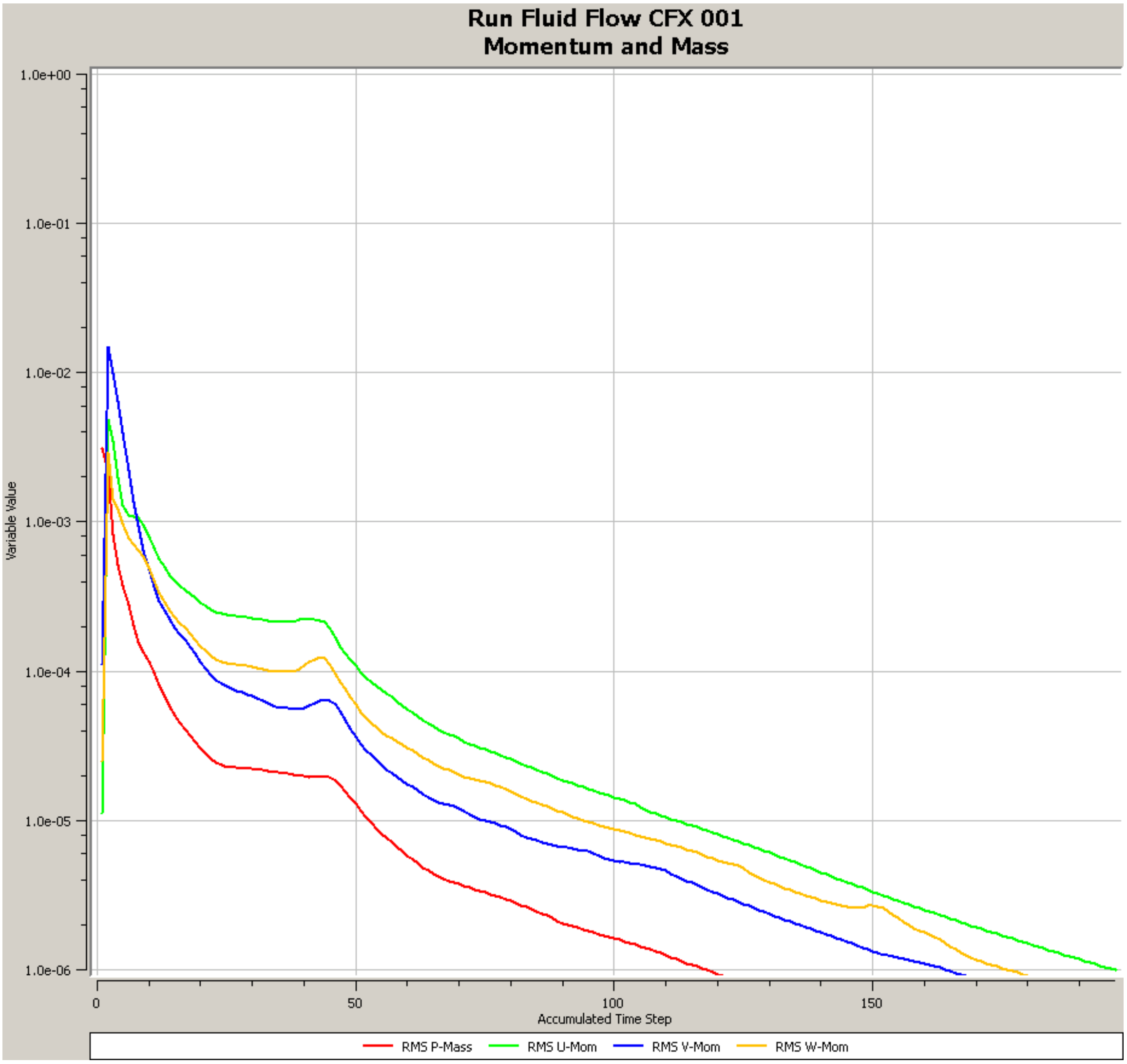


Figure 35: An image of the convergence plot for Simulation 22.

The plot shows that Simulation 22 did converge to our residual target of 1E-06.

Simulation 23

Figure *36* illustrates Simulation 23 with a V-curve wedge, High Resolution, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

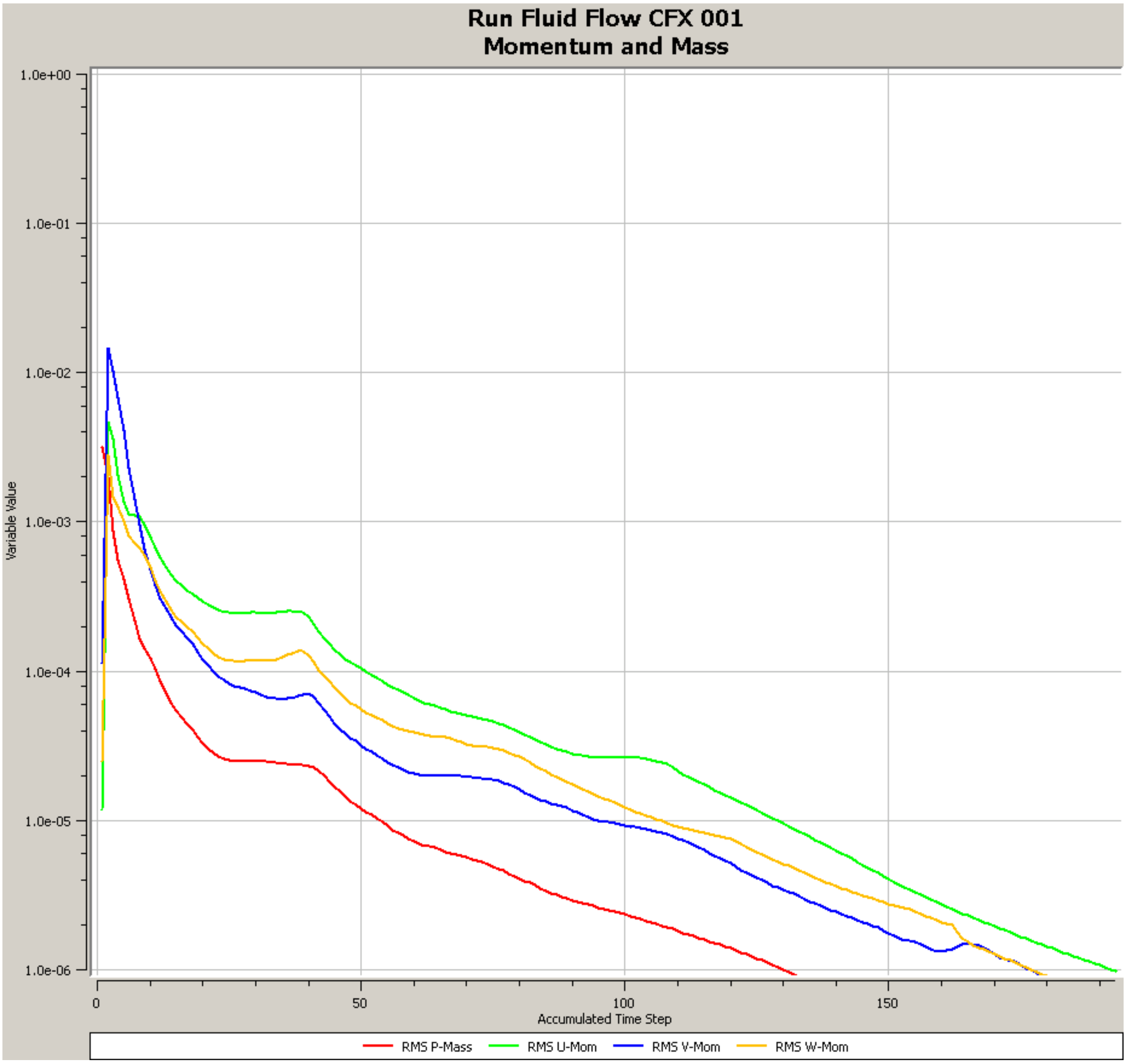


Figure 36: An image of the convergence plot for Simulation 23.

The plot shows that Simulation 23 did converge to our residual target of 1E-06.

Simulation 24

Figure *37* illustrates Simulation 24 with 5.1 million nodes, High Resolution, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

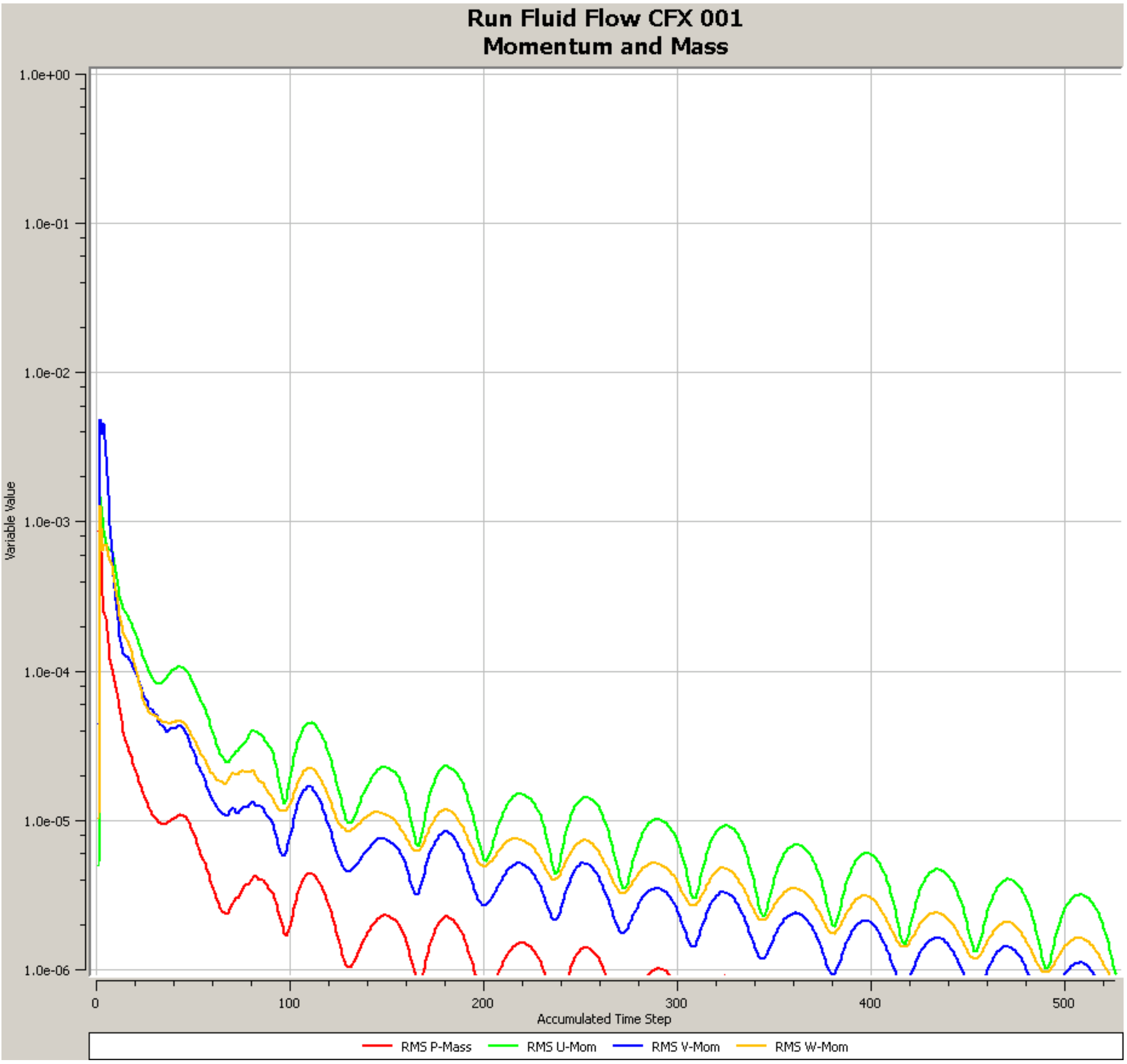


Figure 37: An image of the convergence plot for Simulation 24.

The plot shows that Simulation 24 did converge to our residual target of 1E-06.

Simulation 25

Figure *38* illustrates Simulation 25 with the second vent design, High Resolution, 120˚C air, air Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

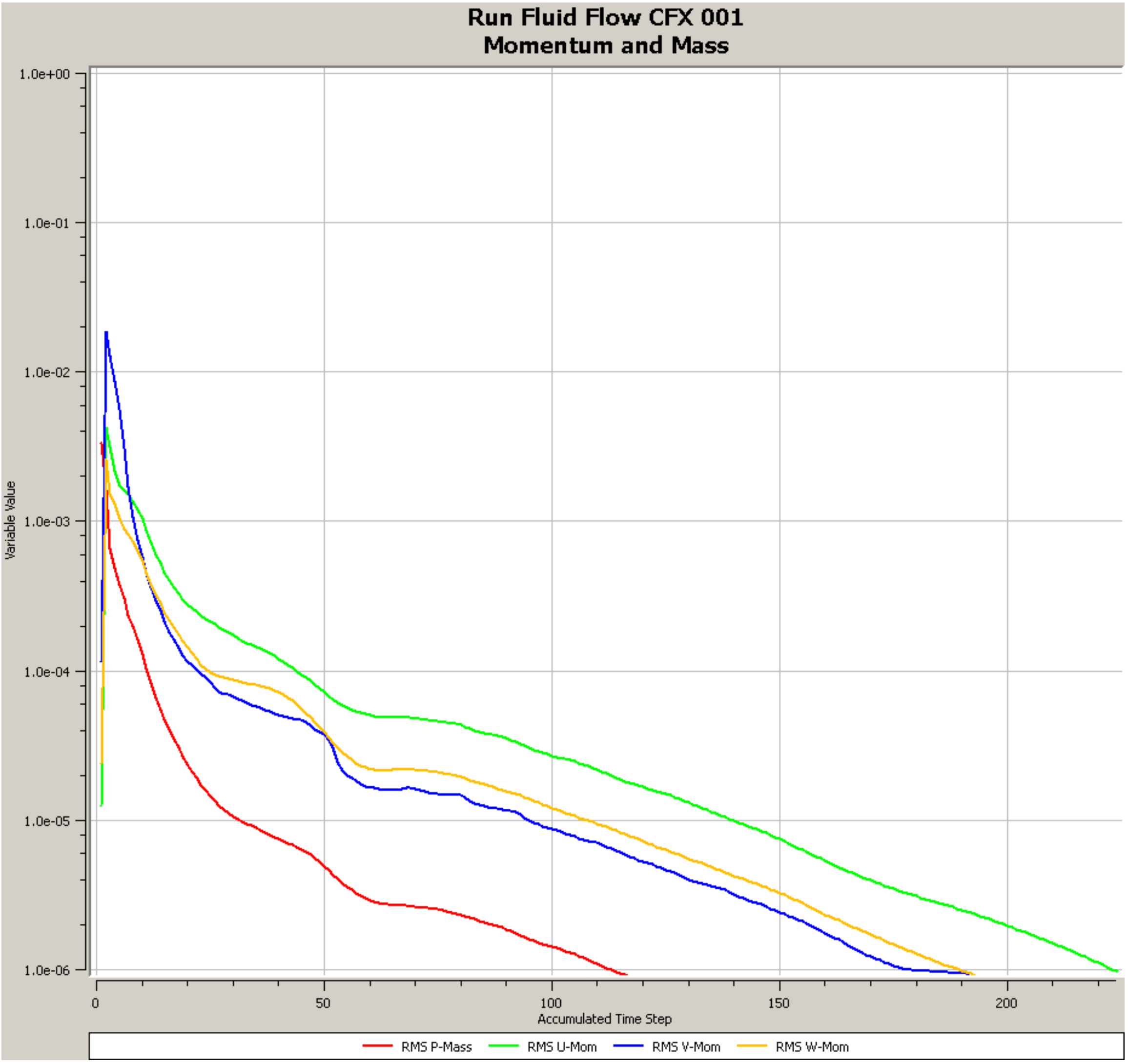


Figure 38: An image of the convergence plot for Simulation 25.

The plot shows that Simulation 25 did converge to our residual target of 1E-06.

Simulation 26

Figure *39* illustrates Simulation 26 with the third vent design, High Resolution, a bleed flow to the doorway, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

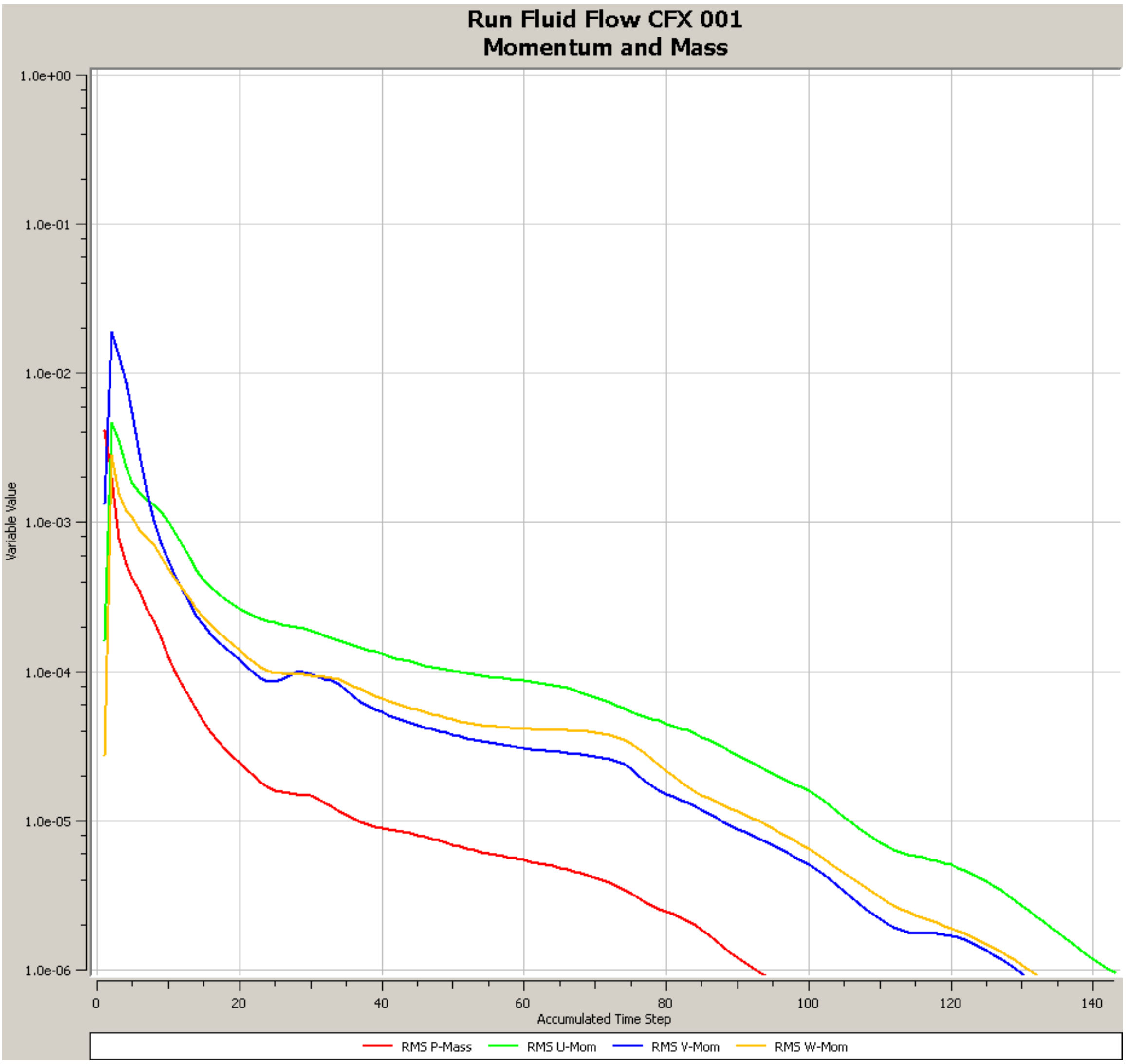


Figure 39: An image of the convergence plot for Simulation 26.

The plot shows that Simulation 26 did converge to our residual target of 1E-06.

Simulation 27

Figure 40 illustrates Simulation 27 with the fourth vent design, High Resolution, a bleed flow to the doorway, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

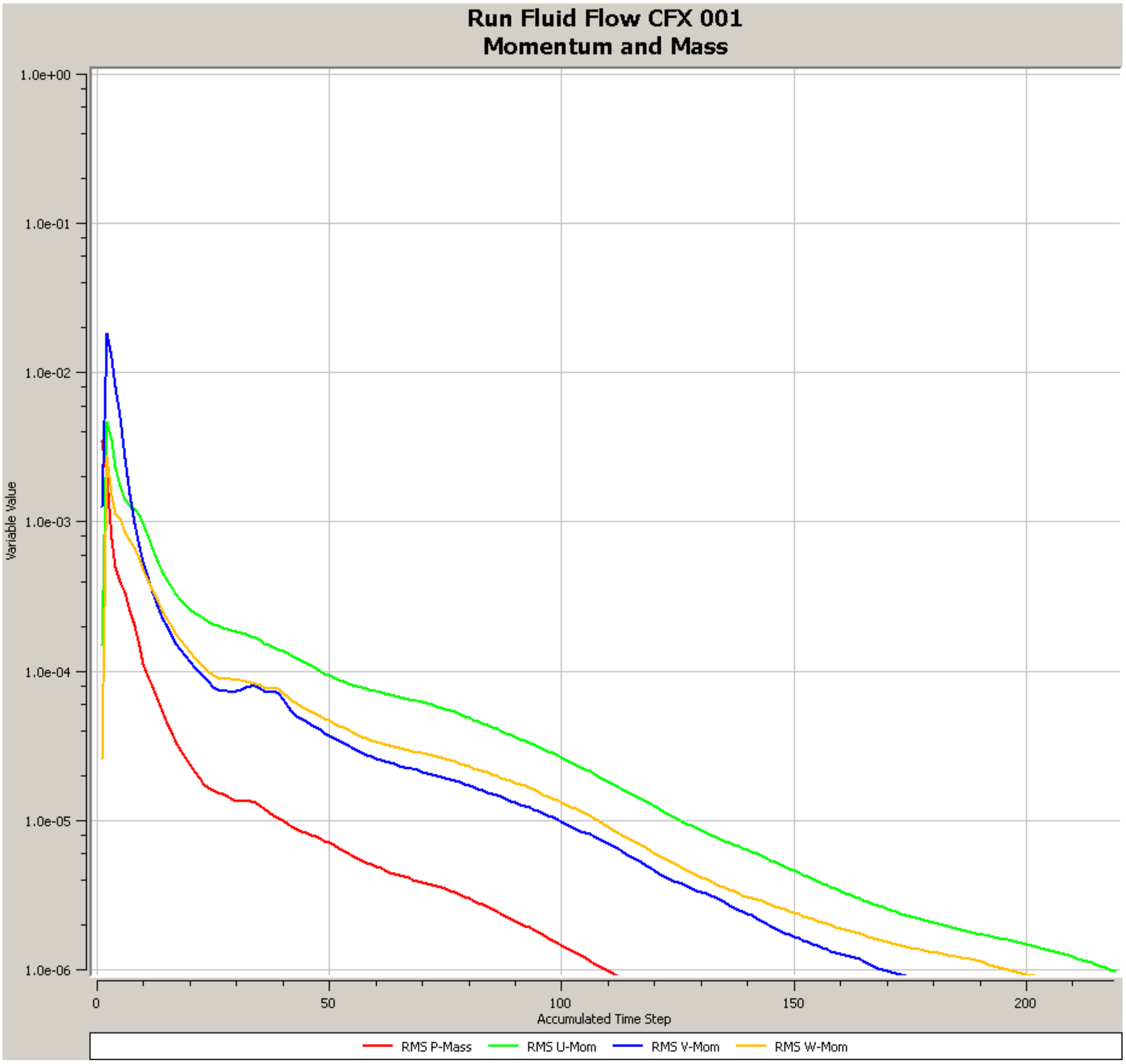


Figure 40: An image of the convergence plot for Simulation 27.

The plot shows that Simulation 27 did converge to our residual target of 1E-06.

Simulation 28

Figure *41* illustrates Simulation 28 with the fifth vent design, High Resolution, a bleed flow to the doorway, 120˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

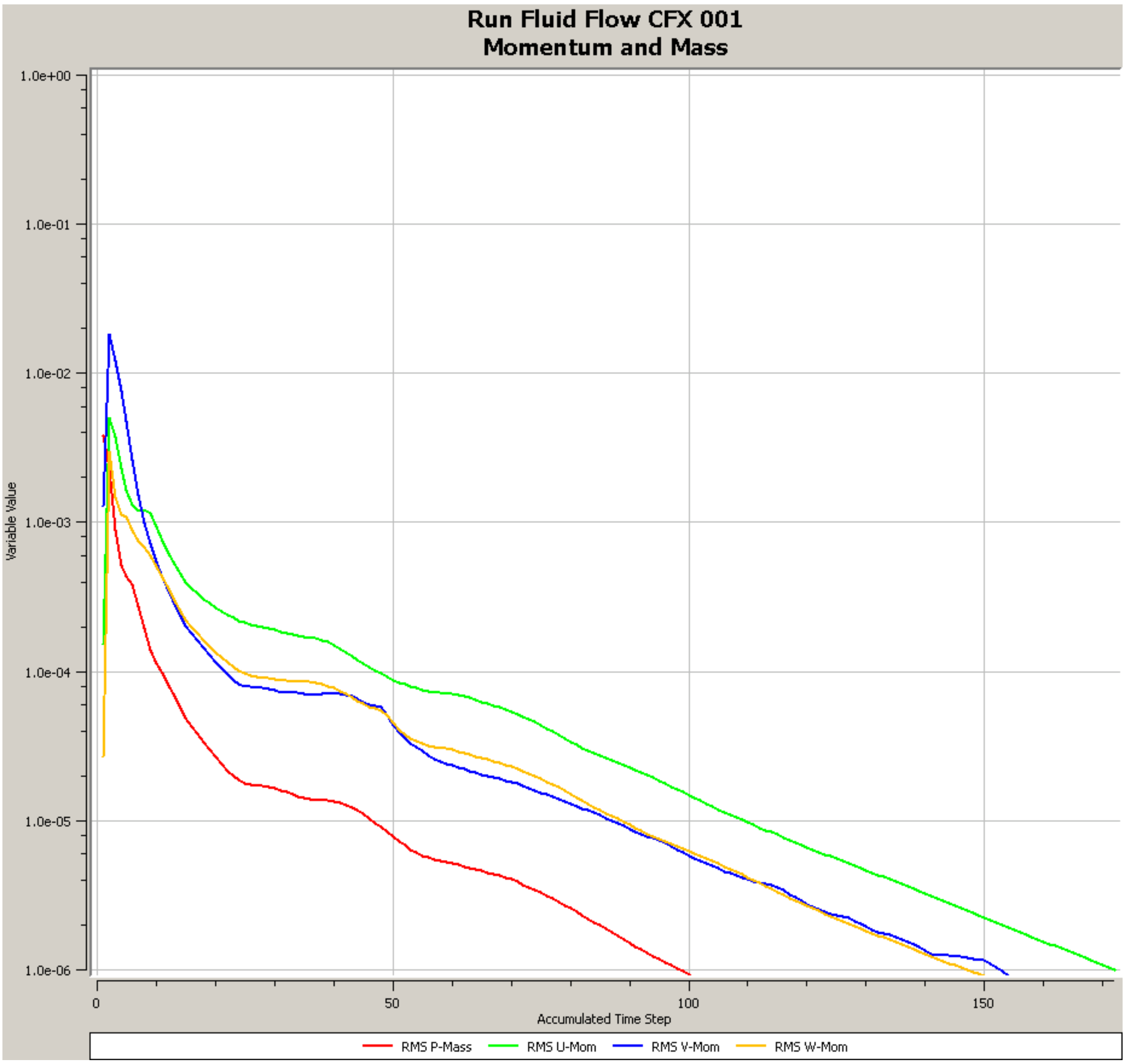


Figure 41: An image of the convergence plot for Simulation 28.

The plot shows that Simulation 28 did converge to our residual target of 1E-06.

Simulation 29

Figure *42* illustrates Simulation 29 with the fifth vent design, High Resolution, a bleed flow to the doorway, 50 ̊C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

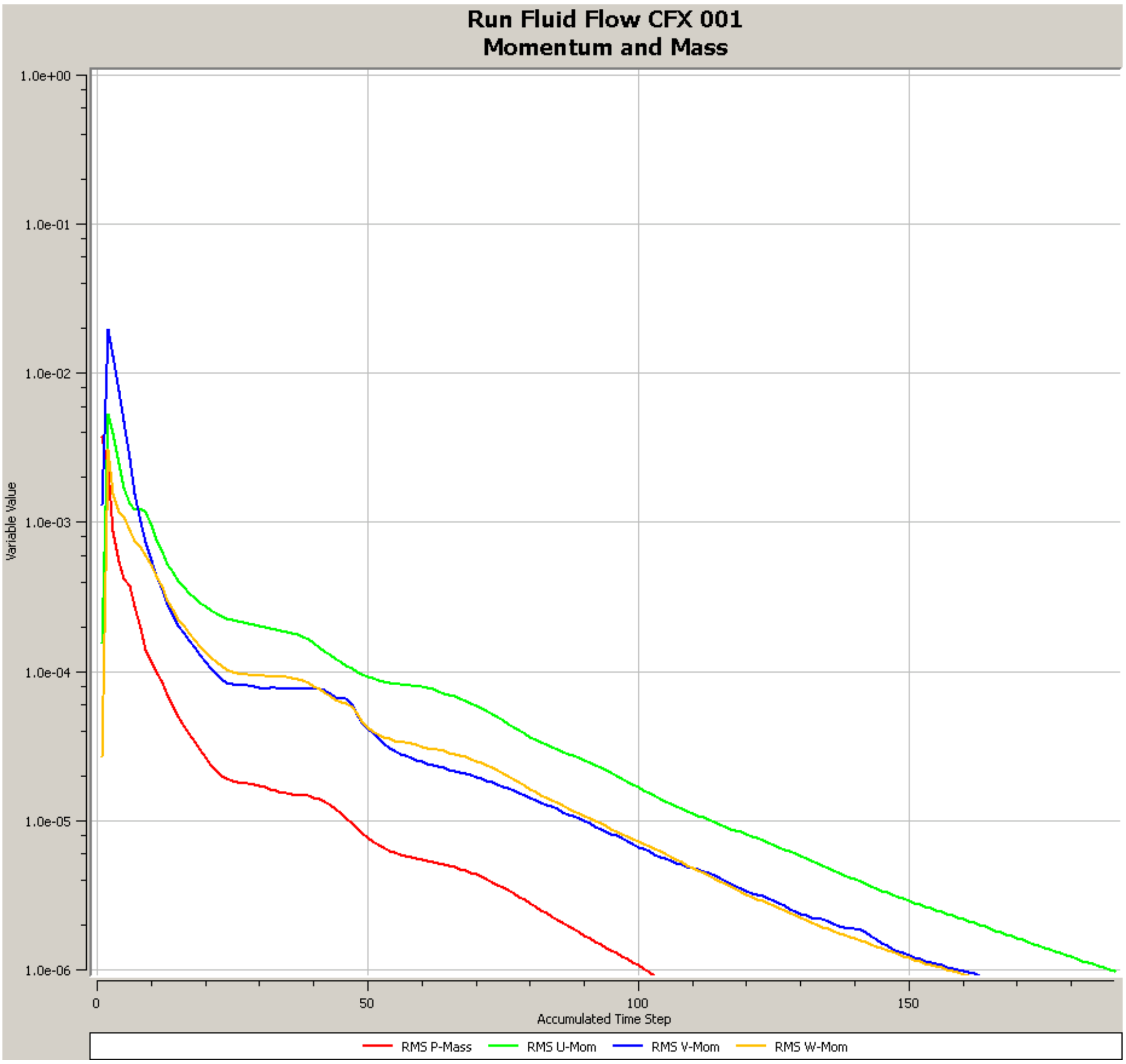


Figure 42: An image of the convergence plot for Simulation 29.

The plot shows that Simulation 29 did converge to our residual target of 1E-06.

Simulation 30

Figure 43 illustrates Simulation 30 with the current plenum, High Resolution, a bleed flow to the doorway, 50˚C air, Auto Timescale, Steady State, k-Epsilon turbulence model and hexahedral mesh.

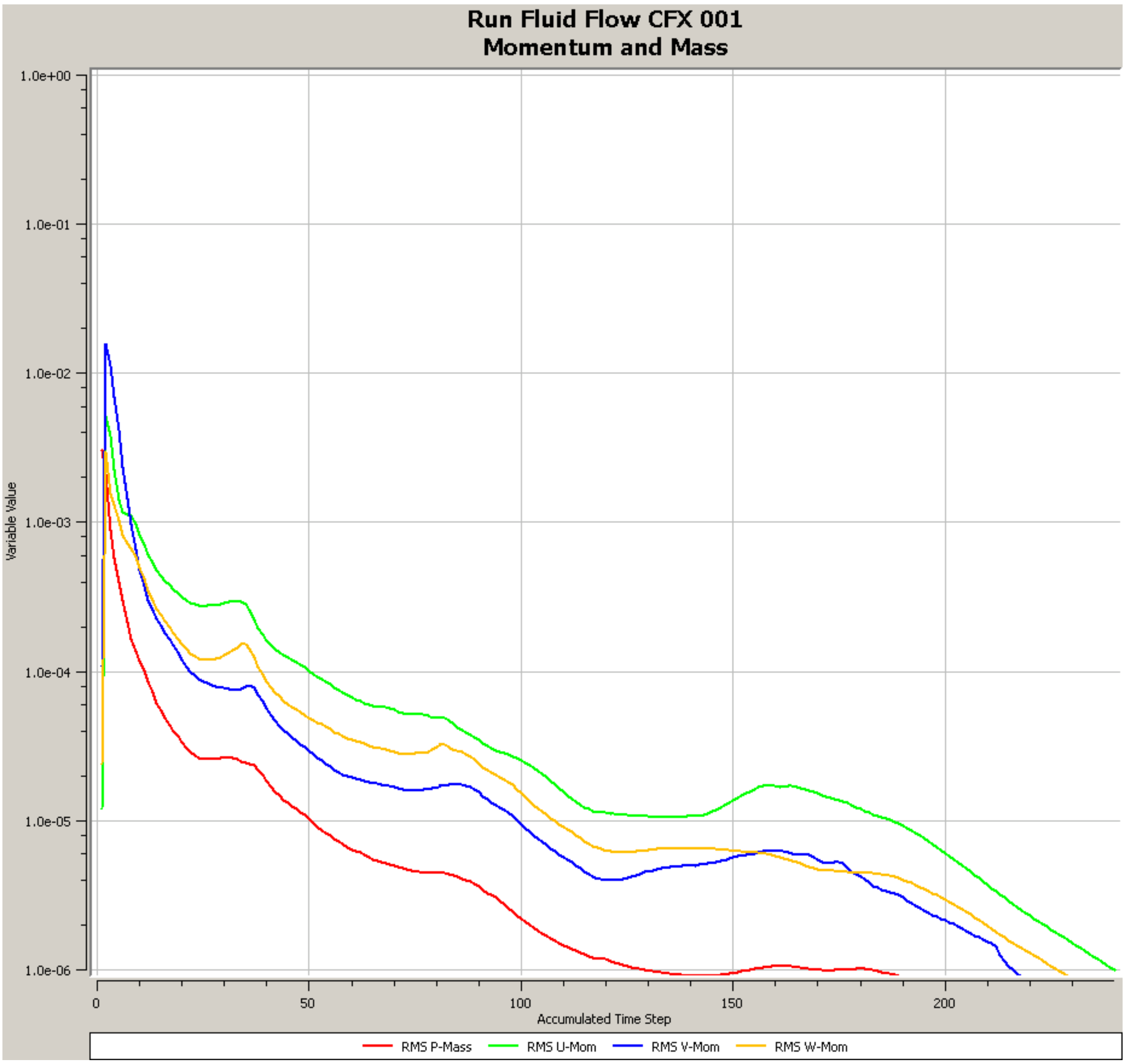


Figure 43: An image of the convergence plot for Simulation 30.

The plot shows that Simulation 30 did converge to our residual target of 1E-06.

References

[1] J. Cherwinski, Interviewee, *Technical Lead Systems - HVAC.* [Interview]. September 2015.