

HVAC Project

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1 Executive Summary

The goal of this project was to design a cost-reduced cooling system for a one-story residential house that resides in the warm Texas climate. Short and long-term costs were considered in designing a system that meets necessary cooling criteria based on established conditions imposed by the hot climate and size of the house. This project first accumulates designs of the house with specific dimensions and subsequently designs a supporting crawl space duct system consisting of one main trunk of duct delivering line air flow to 6 branching pipes with subsequent air vents. This duct system supplies air from a living room air handler which obtains room air through suction and pushes it into the crawl space duct system. 5 different air flows ranging from 1000-1800 cubic feet per minute (CFM) were arbitrarily selected for analysis based on the size of the house and residing climate. Using fundamentals of fluid dynamics and heat transfer, theoretical characterizations of these flows were extracted to determine static pressures of air flows and subsequent electricity uses for the air handler. Next, the material composition of the house was used to determine thermal resistances for overall insulation effects which were used to predict thermal behaviors inside the house for different conditions. These behaviors were used for determining necessary air handler usages which ultimately determine theoretical seasonal cooling cost for the house. These theoretical results were validated by creating air flow simulations through the duct system with available software to check for any significant deviations in critical values used to determine results. Additional recommendations are provided based on these simulations to improve pneumatics of duct system from the initial duct system design. Available air handler models were suggested based on designated flow rate. Cost of the created duct system was \$700. Costs for suggested air handler models ranged from \$1330 to \$1830. Yearly operational costs ranged from \$154 to \$557. A more in-depth overview of the project is provided in the introduction section.

2 Background

I spent the summer of 2022 building a house with my father from the ground up in the hot heat of Texas. The work was repetitive but grueling which allowed for a lot of thought on the possibilities and outlook of the project. Both my father and I have a background in HVAC (Heating Ventilation and Air Conditioning) installation which altered my perspective of the project that was largely masonry work. While we were building this house, we were living at another house nearby that had a non-operational HVAC system, causing the inside temperatures to shoot up to a peak temperature of 85 Fahrenheit. This was in the month of May. We took the initiative to repair the system by installing refrigeration lines from the air conditioning unit outside, through the crawl space, up into the air handler. We were not sure if this would revive the system but upon initial testing, we were relieved that our house would no longer reassembly an oven. Despite the outdoor temperatures hitting record highs the next month, the indoor temperatures stayed in a desirable range. Before the HVAC system was attended to, I was losing sleep due to difficulties in adapting to the hot temperatures (even at night) which caused my performance in building the house to decrease for the time being. While this HVAC system was up-and-running, the old warn-down system had to run for hours on end resulting in an extra 100-150 dollars of energy costs a month. These issues were likely due to insulation insufficiencies but could have been also due to the geometry of the duct system that ran through the ceiling. Regardless, I became keenly aware of the importance of adequate and efficient cooling throughout those experiences from both from a comfort and financial standpoint.

These realizations along with my background compelled me to take on the challenge of designing an HVAC system for the house that is being built. The house has an estimated finish date around the summer of 2023, to which utilities are expected to be installed in the Spring of 2023, so there was a deadline of some time prior to the April for my father to consider this created design and its findings. This was my first time building such a design, but I felt reasonably confident in myself with the resources I had available and the people I had supporting me. Below are some pictures of the buildup of the house over the last several months (Figure 2.1). There are more pictures posted in Appendix H.





Figure 2.1. Construcution Pictures

Like any design project, the initiation was the most difficult step due to the variety of approaches that can be selected from. It was necessary to first establish the fixed variables for this project, that is parameters that are very unlikely to change. I had my father's established floor plans to refer to in establishing fixed variables and recognizing voids that needed to be filled in this design process. The aim of this project is aid in the implementation of an HVAC system for this house as well as demonstrate competencies in organization, efficiency, as well as sound judgement for future job searches. Regardless of whether this paper serves for either of these endeavors, I had a blast doing taking on this project.

3 Introduction

HVAC is a critical component of any house residing in northern Texas. In the summer of 2022, temperatures averaged 100 °F for two weeks straight and while these temperatures can be adapted to when moving outside during the day, they are extremely unsettling when trying to relax indoors. Creating an HVAC system for the house being constructed was deemed not only a great learning experience for a future engineer but also financially useful for relevant parties. This project utilizes on-site experience at the house as well as the climate for better judgement on estimations made throughout this paper. Many values are taken from typical ranges and adjusted based on recognized differences of this application.

The initial stages of this project consisted of determining what to test for when designing this system. There are several aspects of HVAC that can be considered, the big three being the cooling, heating, and air conditioning needed to provide refrigerant to the cooling system. The project was narrowed down between these subjects to avoid overcomplicating matters which allowed for a more dynamic focus on this project which produced considerably more accurate results. The cooling was considered the most necessary component of these subjects given the hot climate and so it was the selected as the subject of interest. The refrigeration goes hand-in-hand with the cooling, but they are separate components and so a simplification was made that everything designed in this system with regard to air handlers would have be receiving an adequate amount of cooling.

With a scope of the project determined, the approach had to be determined as well. This process consisted of determining the knowns and unknowns of the project. It was established that the house

with its walls, floor, and ceiling would be fixed a fixed variable but utilities such as air conditioning were still up in the air. An intricate balance in exploring routes of this project was between creating something interesting and abiding with the ongoing construction plans. There are plenty of references in this paper to the geometry and materials of the house itself. To clarify, the house was not designed in this research since previously created sketched drawings were referred to beforehand. The dimensions of this house and subsequent equipment very closely aligned with drawings. To implement and display such precision, 2-dimensional drawings were done with AutoCAD software. From there, 3-dimensional drawings were created using SOLIDWORKS software. Understanding the geometry of this house is critical for interpreting the language used in this paper as numerous references are made.

With the design of the house established, a duct and piping system was designed that would supply air to the entirety of the house. This system is commonly referred to as the duct system. The biggest feature of this system is the underground setting in the crawl space (miniature basement) which for a cooling system seems backwards since hot air is notable for rising and cool air for falling due to density discrepancies. The biggest consideration that offset this preference is the lack of availability in area to install a duct system up into the attic as well as the sheer difference in material required for such design. The additional material would require the air handler to work even harder to push the air to its destination due to the extra rise in height as well as the extra fittings required which redirect the flow. Also, it would be more difficult to maintain this system if it were in the attic opposed to the basement. A perk of this designed system is that the air handler is easily accessible so that a furnace modification can be installed for the cold seasons to deliver warm air which would utilize the elevation setting.

With a duct system established, theoretical calculations were performed to see how this system would perform under different air handler flow rates (CFM), that is how much cold air is pushed into the house over a given amount of time. Air velocities at different sections were found using conservation of mass principles while fluid pressures were found with these velocities and Bernoulli equations for each flow rate. The selected flow rates ranged over values based on a theoretical amount of air needed which depended on the size of the house and environmental climate. When determining this range, it was determined that the specific value of interest would be up to the user. This incentivized research into a case study between the flow rate and resulting costs. This also allowed for a broader model comparison when recommending air handler models based on what is available. Most air handler models have varying flow rate modes, but that would complicate the findings of this study and so it was deemed unnecessary to account for this variability. If an air handler with varying flow rate is intended for use and function then the air handler recommendation can be ignored and the findings based on particular flow rates can be used to estimate results for a given air handler based on how its individual variability in flow rate.

Using MATLAB software, numerous calculations were performed for characterizing the air flow through this duct system. This involved breaking down behavior of individual sections of this system (a pipe for example) and predicting how it would compare to other sections in culminating the system behavior. Air handler pressures were found which in turn were used to find static pressures for electrical power requirements per time.

The material composition of the house was then used to find resistances through all sides of the house to gauge how the inside air temperature fluctuates under expected conditions in the absence of an air

handler (cold air supply). This was done using predicted heat transfer through these surfaces as a function of time throughout a given day. These results were later used in combination with cooling capacities to determine the operational time of the air handler for a typical day and thus for a typical season.

Set temperatures are a huge part of cooling systems as thermostats are typically used with a dead band control system to revert between a high and low temperature based on the user's preferences. Like the air handler flow rate, case studies were performed for this undetermined varying input for each flow rate, with values ranging from 24°C to 30°C, to provide illustrations of inside air temperature behaviors for from each starting point.

Economics were then provided for the different scenarios, that is each flow rate and each set high temperature in terms of the amount of money expected to be spent towards operating the air handler for a given hot season which is approximately a given year. Additional economics were provided for theoretical money spent on the duct system with a breakdown of duct system portions. Lastly, a set of air handlers were provided for each side of the CFM range mentioned that have similar functionality to the requirements of this established system. Each air handler has listed price as well as referenced specification sheet.

Flow simulations were run through SOLIDWORKS flow simulation feature which provided flow trajectories of air flow through a particular region which distinguished velocity and pressure values at different points in the system. These simulations were done for the duct system air flow to show air from the air handler, through the duct and pipes, all the way to the air vents. These simulations are useful for visualizing stagnation points in the duct. Analysis was performed towards one of these flow rates (1800 CFM) as the behavior observed in the respective figures corresponded to the other 4 flow rates but was simply more pronounced since it was the largest flow rate. Such analysis yielded recommendations for simple improvements that would ultimately reduce the amount of electricity required to power the air handler. Velocity values observed in these simulations were compared to the predicted values previously used for Bernoulli calculations.

All subjects in this paper correspond to the order they were listed in this introduction section.

4 Assumptions

These assumptions address concepts that could be considered but knowing the overall impact have been deemed significant. Taking such things into consideration would not greatly obstruct this project but the impact of such findings would be close to insignificant.

4.1 Gravity

Gravitational forces will act perpendicular to the level house at all times of operation in a consistent, expected manner.

4.2 Corrosion of Materials is Negligible

Sustainability amongst materials including but not limited to walls, ceilings, floors, doors, windows, ductile material, AC Units, etc. are assumed to be upheld throughout any designed period of operation. Any value assigned to material such as resistances will be held constant.

4.3 All Materials Will Be Installed Correctly

This assumption states every object involved in operation will be installed into its designated condition so that repairs will not be expected.

4.4 No Chemical Reactions Will Ensur

This assumption states that all chemicals involved (nitrogen, oxygen, freon, etc.) will not interact with each other in such a way that a reaction will ensue. All components are therefore assumed to be conserved throughout operation period.

4.5 Windows Installed Will Have Typical Resistances

This assumption states that the windows installed throughout the house will be uniform in resistance values amongst themselves and align with the median resistance value from the population of all reduced windows.

4.6 Project Budget Will Be Minimal

This assumption is to clarify that no advanced materials will be used to enhance the performance of relevant structures.

4.7 Furniture Volume is Negligible Towards Flow Distribution

The volumetric occupation of furniture in each room will not be considered for interference when evaluating air pathways.

4.8 Heat Loss Through Duct/Pipes to Surroundings Is Negligible

The temperature in which the air leaves the handler and which the air enters the room are expected to be the same.

4.9 Outside Doors Will Be Kept Closed

The doors connecting to the outside of the house will remain closed as an effort to prevent bug infestation inside of the house. These doors cannot be considered an air outlet for the purpose of this project.

4.10 Air Will Not Leak

No air will be air will leak through the duct system or through the walls, floors, ceilings of the house.

4.11 Metallic Roof Has No Resistance

The metal roofing material installed will not be considered an insulator for any purpose as the R-value for metal is low enough to deem negligible.

4.12 Crawlspace Utility Outlets Will Not Be Considered

There are several outlets in the walls of the crawlspace for such utilities as electricity, plumbing, etc. These will not be considered when assessing overall resistance values of the walls.

4.13 Air: Incompressible Fluid

Air will be treated as an incompressible fluid these calculations and procedures. Pressures notated will not be big enough to alter this feature and so assumption stands.

4.14 Duct System Hangers

Duct and piping systems need hangers to attached to nearby surfaces. Upcoming drawings and models of the house will not show such hangers since they are not important to this project in that regard. They do need to be considered in that accessible ceiling (bottom of floor) needs to be available.

5 Simplifications

This section is implemented as a way of simplifying calculation processes. Many environments, depending on the scale, can be taken as a culmination of a variety of materials. For calculations, it is best to narrow down the variables in these calculations so that processes displayed are more dynamic and easier to interpret. Simplifications can be thought of as assumptions with the distinction that simplifications address concepts that are significant to the findings of this paper but these concepts are dismissed since the the process of unraveling this information is not feasible. Assumptions are dismissals towards concepts that are a lot less significant regardless of the feasibility.

5.1 Air Pressure Inside House is Atmospheric

The air pressure inside the house will be assumed as standard conditions (101325 Pa).

5.2 House Floors Will Be Wooden

None of the installed flooring material will be carpet as all of it will be wood. This will be considered when doing an insulation analysis (11.1) as the two materials have different resistances to heat transfer.

5.3 Window Pains are Negligible

The frame material is negligible as only the glass material of a window will be used as the makeup of the windows for resistance calculations (Section 11).

5.4 Air Handler Reductions are Negligible

Researched air handler models are expected to have expansion adapters fittings that connect its supply air to the duct system. These expansions are ignored in calculating static pressures.

5.5 Furniture Interference with Air Flow is Negligible

Realistically there are resistances on the air flow that cause head loss from the point of the air vent to the point the air returns to the air handler. These effects are ignored due to the complex geometry of the furniture orientation.

6 Clarifications

This project has concepts that are significant to the results but have different methods of investigation. This section therefore describes which approach is used.

6.1 HVAC System Will Be Typical (Air-Handler, Condenser, and Flow System)

The HVAC system for this project will consist of an outside conditioner that pulls outside air and transfers freon to an inside air-handler which cycles the air throughout. The air will be collected by means of a return vent above the air handler and distributed by means of floor vents provided by the duct system.

6.2 Duct/Pipe Structure Designations

This duct system system will follow standard practices and implement a tree-branch structure in which smaller, round and aluminum pipe will stem off larger, rectangular, and galvanized steel duct. Theoretically, piping could be used everywhere but this would be spatially inefficient with more structures involved due to the inorganic geometry of the surrounding crawl space (the crawl space is only ~2.5~ feet).

6.3 Pipe Structure Will Be Organic

The pipes stemming off the main duct will assume the shortest pathway towards their respective vents so long as enough space to access the material is maintained (Clarification 6.4). This will preserve material and lower costs. It is also noteworthy that softer angles (approaching 0°) are aerodynamically favorable with less turbulence and thus head loss which improve performance.

6.4 Piping Structure Maneuvering

The main duct portion will be in coincident height with the parallel floor joists while the piping will branch off orthogonally. The main duct will travel through a slight opening in the cinderblock medium that divides the crawlspace area.

6.5 Roofing Will Be More Insulated Than Walls

The ceiling will be better insulated (R-49) than the walls (R-15). The cinderblock adjacent the wall insulation is much better insulation support than the copper roof which overhangs the roof insulation. Furthermore, the roof will be subjected to a larger share of the solar heat source.

6.6 Girder Support

There are two sets of five square concrete blocks that host vertically positioned 4x4 wooden blocks. Each of these sets supports an individual girder joist that runs perpendicular to the floor joists and serves as structural support for the floor. (Figure 8.3)

6.7 Duct Height

The duct will remain flush with the parallel floor joists but will decline reduced in size by means of height (from 8 inches to 6) for flow distribution accommodation and material saving.

6.8 Duct System Priority

The duct system residing in the crawl space will take priority about spatial arrangements over other equipment such as plumbing and electrical. The reason for this is that air duct/pipe is simply more expensive due to its greater volumetric occupation per length and therefore is provided the most efficient pathway by removing any potential obstacles.

6.9 Floor Joist Support Removal

As will be shown in upcoming drawings, one of the middle joists supports will be withdrawn from use due to make for the duct system.

6.10 Two Layer of Insulation in Attic

There will be two separate levels of insulation in the attic as shown later in Drawing 11.1.1. The ceiling joists are limited in height and so an additional, bigger layer of insulation is fitted on top of the former one.

6.11 Type of Insulation Used

Rolled blanket insulation will be the type of insulation that will be used throughout the house, that is for both walls and attic spaces.

6.12 Actual Size of Studs

Drawings will reveal that the actual size of studs and joists are ½ inch smaller in each dimension except length. A 2x4 for example is a 1.5x3.5.

6.13 Stud Spacings

The stud spacings will for floors, walls and ceilings in this project will be 16 inches off center except for the region used for the duct system.

6.14 Floors Will Be Wooden

None of the installed flooring material will be carpet as all of it will be wood. This will be considered when doing an insulation analysis.

6.15 Air Conditioner is Not Considered

As noted in the introduction, this research does not consider the air conditioning system which provides refrigerant to air handler for cooling.

6.16 Unit Systems

Both SI and British Imperial systems are used in this paper based on the presentation needs. Flow rates are often described in cubic feet per minute (CFM) and temperatures in Fahrenheit (°F) but calculations are done in cubic meters per second (m³/s) and Celsius (°C). Whatever unit used is shown in respective figures to alleviate confusion.

6.17 Source Notation

Sources referencing a piece of information listed in the references section are denoted with brackets []. There will be numerous numerical references throughout this paper towards tables, figures, drawings,

etc. A variety of these pathways are referenced very close to each other on occasion so it is helpful to note the respective labels when referencing back to a previous paragraph/section.

7 Considerations

7.1 Single-Story Home

One interesting facet of the single-story home is that it is significantly more efficient than a multi-story home in terms of heat transfer and insulation. Things heat to which temperatures rise and eventually penetrate ceilings to inadvertently change the temperature of the upper level. This is not only inevitable but also difficult to plan around as the temperature variances and therefore the temperature requirements are not constant around the year. This suggests that there is variance throughout the house and more manually attention will be required to correct these differences. Also noteworthy is that while two-story homes have less roofing area per square footage, they have more total surface area in contact with outside air for a given floor area.

7.2 Air Distribution.

Air vents will be designed so that they are evenly placed around the perimeter of the house such that air is efficiently transported consistently throughout. While there is an expected number of vents per room, the sizes and accessibility of the rooms need to be considered to skew this distribution appropriately. One air vent might deliver air more effectively than another pending the amount of air space it is subjected to.

7.3 Temperature Variances Throughout Room Orientation

Continuing off Consideration 7.2, fluctuations in mass distribution will result in correlating temperature difference such that temperatures will differ at the edge of a given room and even more so in the corners of that room. A dome-shaped, igloo like house is uniquely most energy-efficient because of the uniform temperature differences. The presence of variations of this sort results in HVAC systems being designed to slightly overshoot the expected air requirement.

7.4 Duct Roughness

Two types of material will be used for portions of the duct system: aluminum and galvanized steel. Roughness coefficients will need to be considered because of their effects drag effect on the fluid flow. Aluminum has a very low roughness coefficient ($0.0015 \cdot 10^{-3}$ meters) [7.4.1]. Galvanized steel is a rougher ($0.15 \cdot 10^{-3}$ meters) material and this value will have more of an impact on the friction factor, f [7.4.1]. Notable is that a material's roughness increases with time and usage such that system performance decreases over time which is why new material will be invested in.

7.5 Head Loss Pressure (Static Pressure)

There is expected to be numerous bends and lengths amongst the duct system which will impact the pressure of the flow. The maximum allowable bend at a single change in direction is 90 degrees but this is not preferable. Anything more will result in extremely favorable pneumatics that will induce a significant amount of stress on the air handler. The magnitude of the stagnation region correlates with a larger degree turn. The turn for a given angle is more favorable with smoothed edges and a longer turn

radius. Duct or pipe lengths will also contribute to energy losses as flow as turbulence will increase due to frictional forces imposed by the walls onto the flows. Air vents and flow expansions will also contribute to energy losses.

7.6 Floor Vent Sizes

Floor Vents are designed with grills inhibiting airflow to a certain extent (Consideration 7.5). It would be better to therefore use an air vent that has a larger cross-sectional area than the pipe extending to it to reduce the expected amount of turbulence that would occur because of this grill. 6-inch pipes will be extending to these vents which is about 28 sq. inches in cross sectional area.

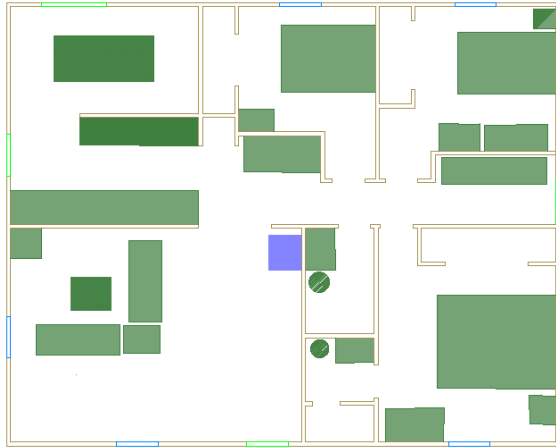
7.7 Piping Sizes

Aluminum metal is the flagship piping material amongst HVAC material produces due to its light weight and low roughness factor. The size of standardized pipe is 4" or 6" diameter for an individual room supply. As will be shown later in this research (Section 9), the latter is selected because while it is the more expensive of the two options per unit length, the larger diameter implements less frictional resistance on the flow and therefore less pressure/energy loss. Since there is a larger diameter, a flow of similar velocity will not experience near as much turbulence due to the wall boundaries. The major, long-term expense of an HVAC system is the static pressure that the air handler must work against which requires a proportional amount of electricity.

8 House Design

The predetermined house design is shown in Drawing 8.1 in which the basic wall outline of this building is displayed. Expected furniture orientation is significant to establish expected regions of air vents, along with expected available volumes for each room that will be used for further calculations. Windows and doors are significant for insulation purposes which will be important when discussing heat transfer in future sections. Below are sketches of the basic floor plan (Drawing 8.1) and a three-dimensional view (Figure 8.1).





(c)

Drawing 8.1: Expected (a) wall, (b) furniture (air handler in blue), and (c) door(green)/window(blue) orientation

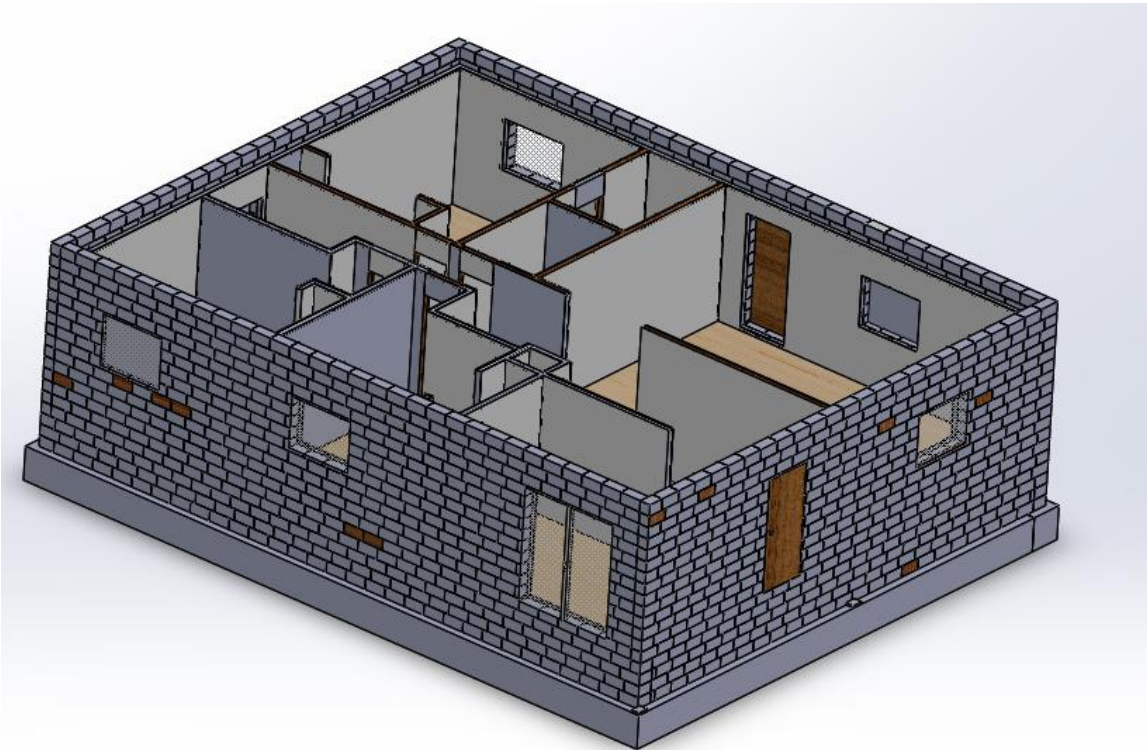
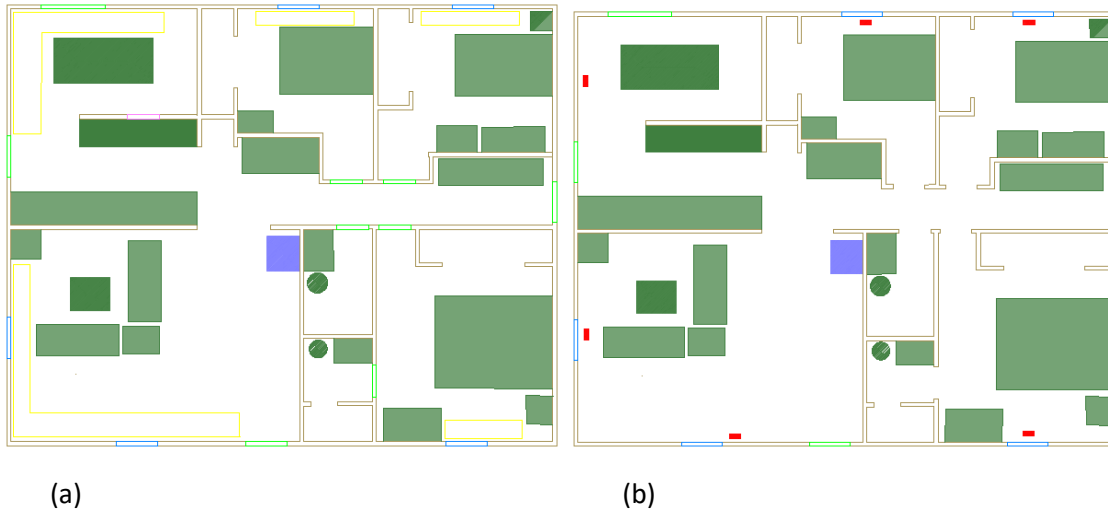


Figure 8.1: Overhead view of 3D house with walls, doors and windows

From these orientations, expected regions of the air vents in the house are established based on principles discussed in Consideration 7.2. One criterion considered is that air flow will be directed inwards towards the air handler in the middle of the house (Blue in Drawing 8.1) resulting in a preference towards the outside of house for more distributed air flow. An additional criterion is the heat transfer through walls which is more pronounced in the through the windows and doors (lower R values). The selected regions of these air vents is shown in Drawing 8.2 and Figure 8.2:



Drawing 8.2: (a) Expected regions of air vents based on furniture, door, window, orientation and (b) selected locations of air vents

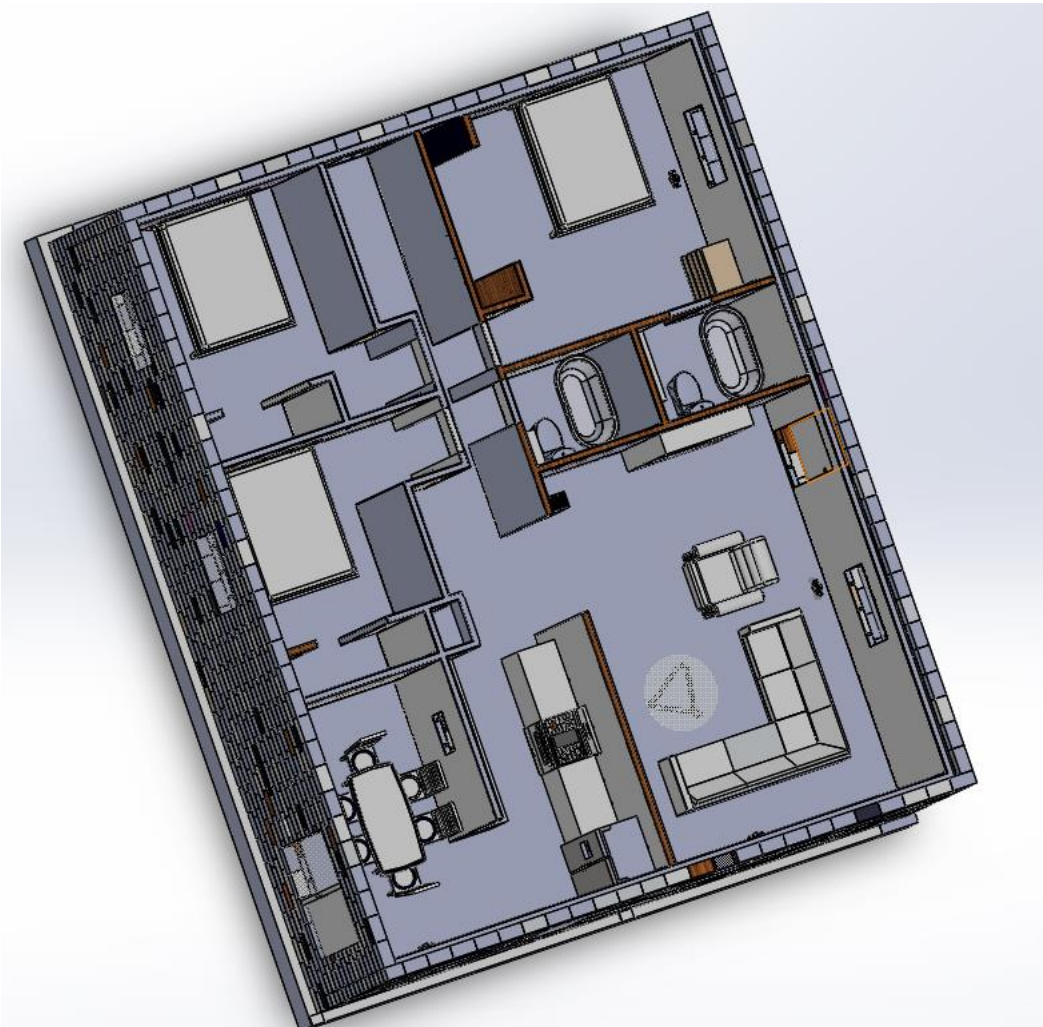


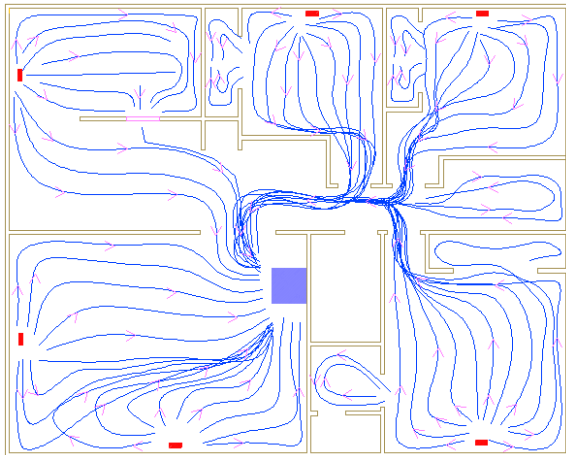
Figure 8.2: Overhead 3D view of house with furniture and air vents [8.1]

Labels of the rooms are created for reference and are listed below in Table 8.1:

Table 8.1: Room Labels

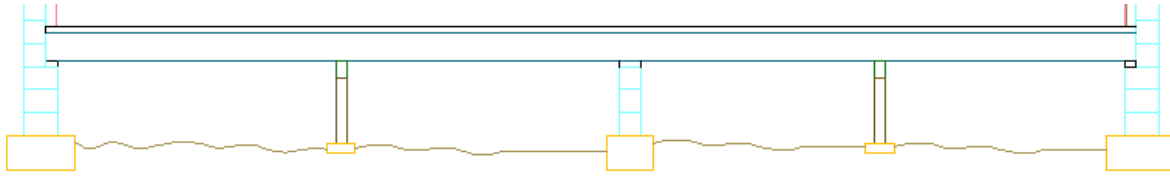
Room	Label	Location in Drawing 8.2
Living Room	LR	Bottom Left
Kitchen	KI	Mid Left
Dining Room	DR	Upper Left
Guest Bedroom – West	BR1	Top Middle
Guest Bedroom – Northwest	BR2	Top Right
Master Bedroom	BR3	Bottom Right
Guest Bathroom	BA1	Middle
Master Bathroom	BA2	Bottom Middle
Hallway	HW	Middle

Furthermore, sources for externally created furniture models seen in Figure 8.2 are listed in the references [8.1]. From Drawing 8.2, expected airflow can be determined to validate air vent location selections as well as gauge preliminary air flow throughout the house. This theoretical airflow is shown below in Drawing 8.3:



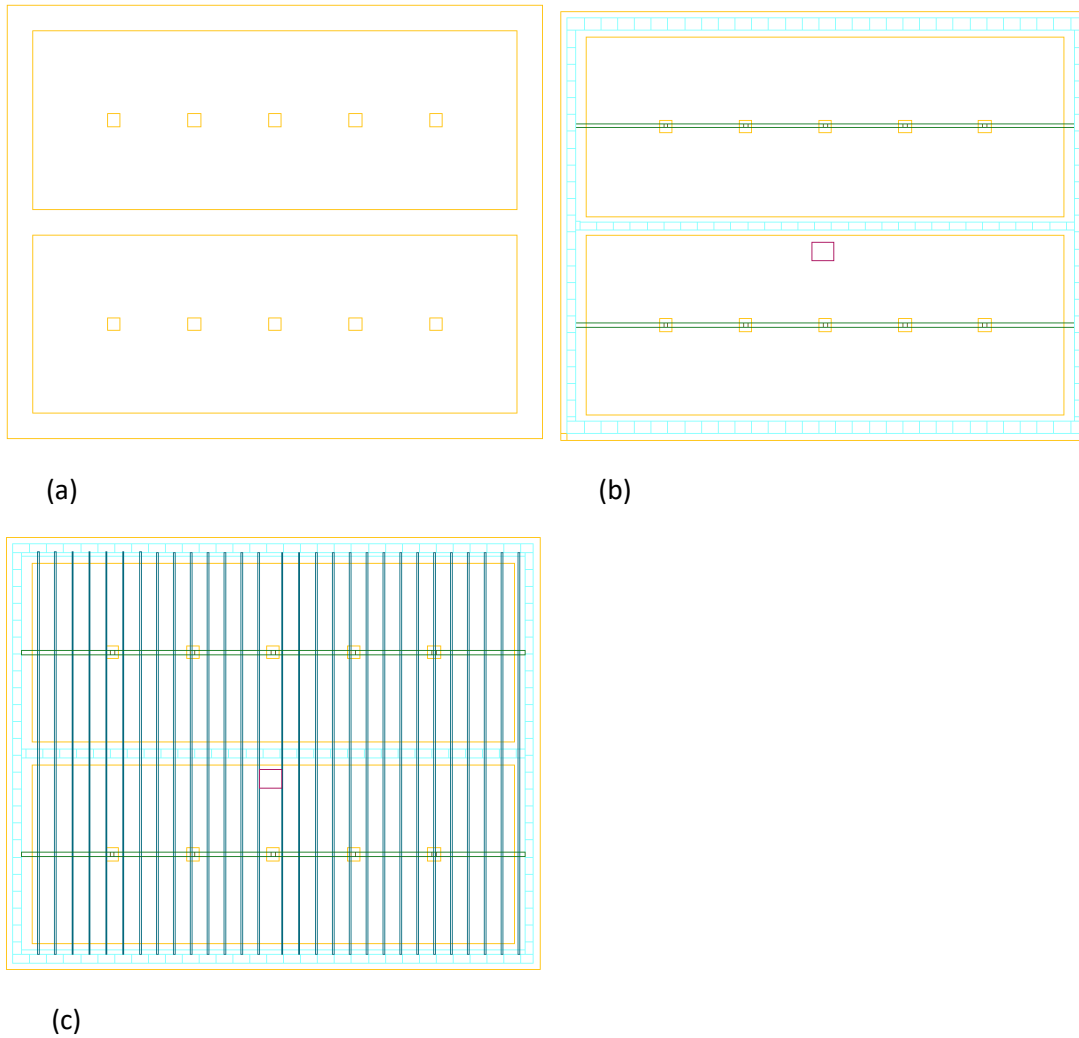
Drawing 8.3: Expected air flow pathways throughout house from air vents

The airflow resulting from the selected air vent locations (Drawing 8.3) covers most of the house. It is important to reiterate the lack of insulation in inside walls such that heat can feasibly travel from bedroom to bathroom where there is and is not an air vent placed. Knowing the selected locations of the air vents, a duct system can be and is designed which resides in the crawl space. The concrete foundation and cinderblock walls need to be established to know the outside boundaries of the crawl space. The girders in each section of the foundation serve as a support for the floor joists which support the floor structure and should be considered. A side view drawing of this crawls space is shown below to contextualize the geometry of this space (Drawing 8.4):



Drawing 8.4: Side view of crawl space region (short side)

From a different angle, the overhead view with components (concrete, cinderblock walls, floor joists) gradually added on, is displayed below in Drawing 8.5. A 3-dimensional model is shown in Figure 8.3.



Drawing 8.5: (a) Concrete foundation, (b) cinderblock wall, girder, and air handler orientation, and (c) floor joist orientation

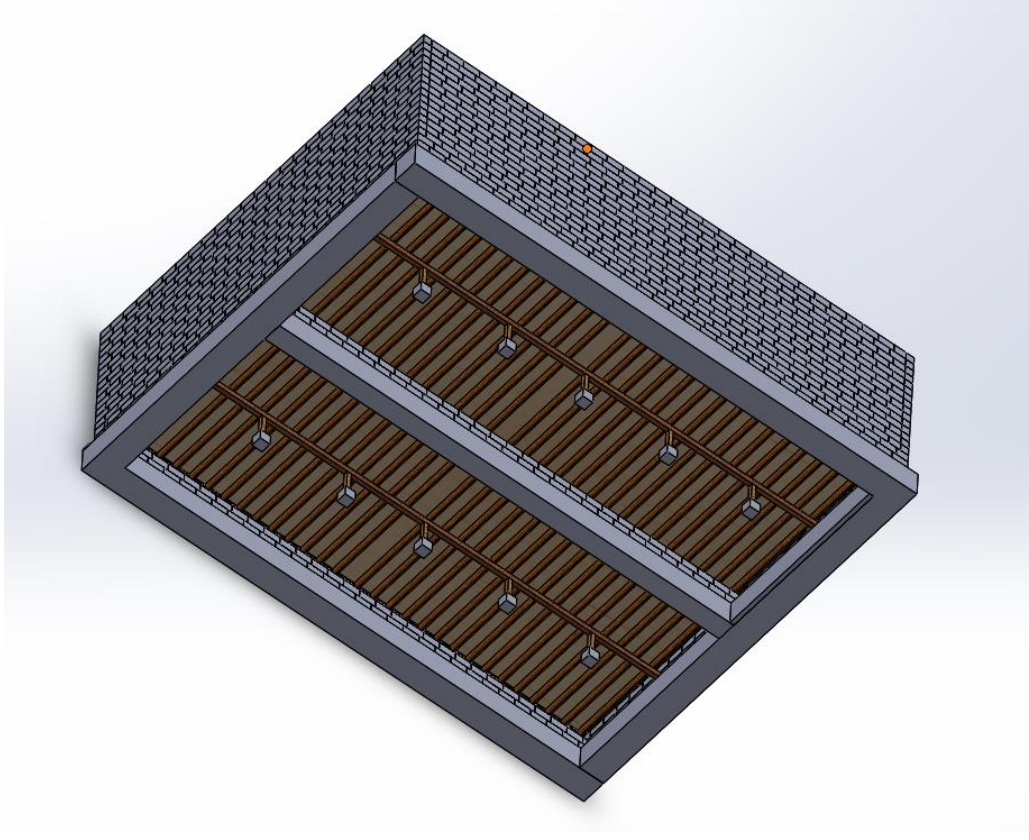
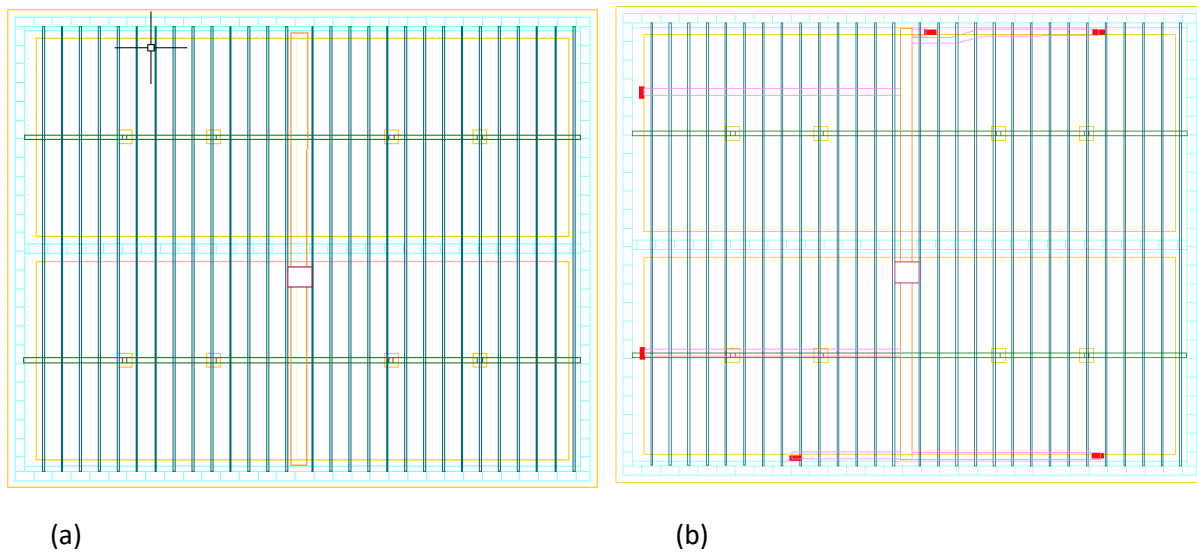


Figure 8.3: Bottom view of house crawl space without duct system (includes entirety of concrete walls)

Knowing the boundaries of the crawl space along with the locations of the air vents, the following system (Drawing 8.6) consisting of duct and pipe was designed using principles mentioned in previous sections (Clarifications 6.2 – 6.4). A 3-dimensional view of the crawl space with the duct system installed is shown in Figure 8.4.



Drawing 8.6: (a) Main duct line (orange) and (b) branching piping (pink) of crawl space

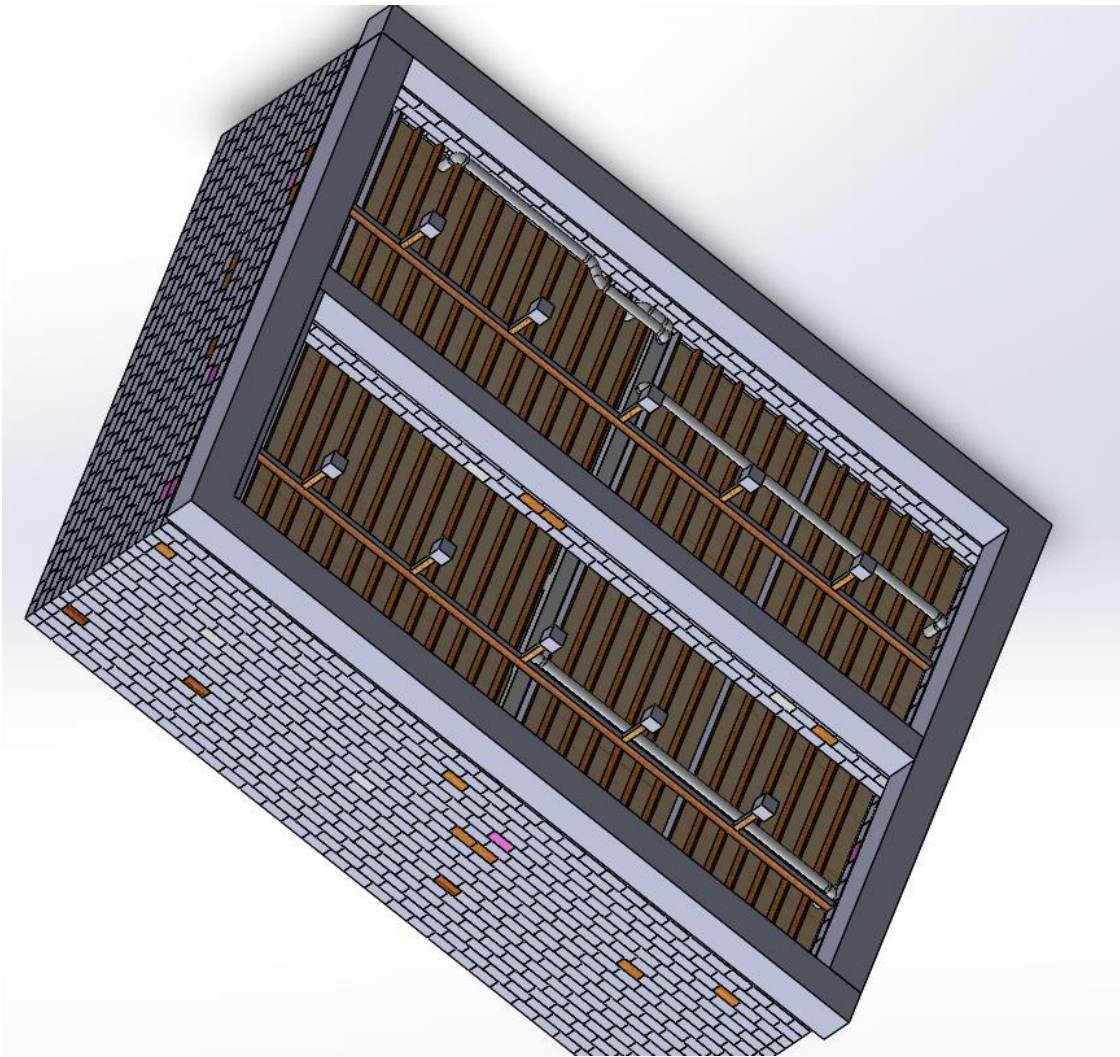
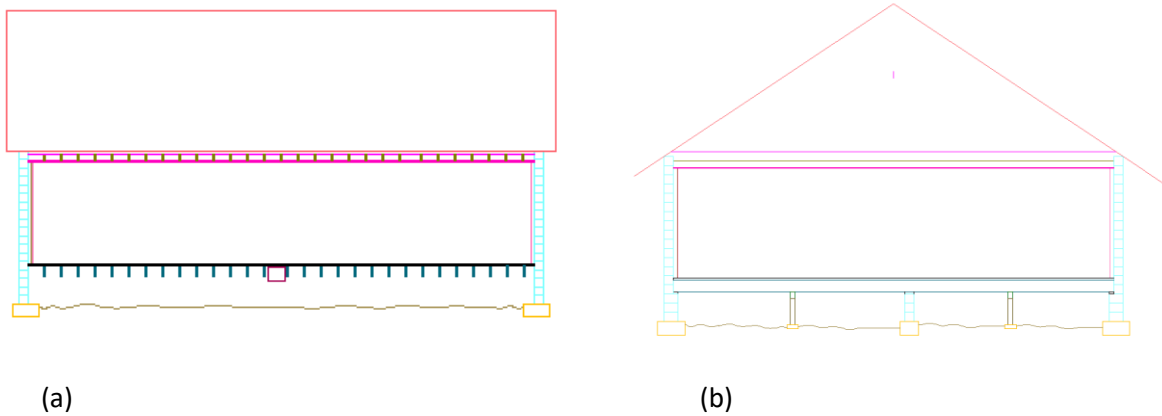


Figure 8.4: Bottom view of crawl space with duct system installed

Drawing 8.6 shows the duct system where the main line of duct is installed parallel to the floor joists such and the six pipes that branch off this duct line are positioned underneath these ceiling joists (Figure 8.4). The pipes could have been at the height of the ceiling joists like the duct line but would have required holes to be cut in these joists, weakening the foundation of the floor system. Since aluminum piping material will be used (relatively light), the piping will simply be hung below the perpendicular joists. Some general designs of the house are provided below for an overview of the structure. Specific, relevant dimensions are mentioned in the appendices (C). Side profiles of the house are shown below in Drawing 8.7 and Figure 8.5:



Drawing 8.7: Side-profile (a) long side and (b) short side of house

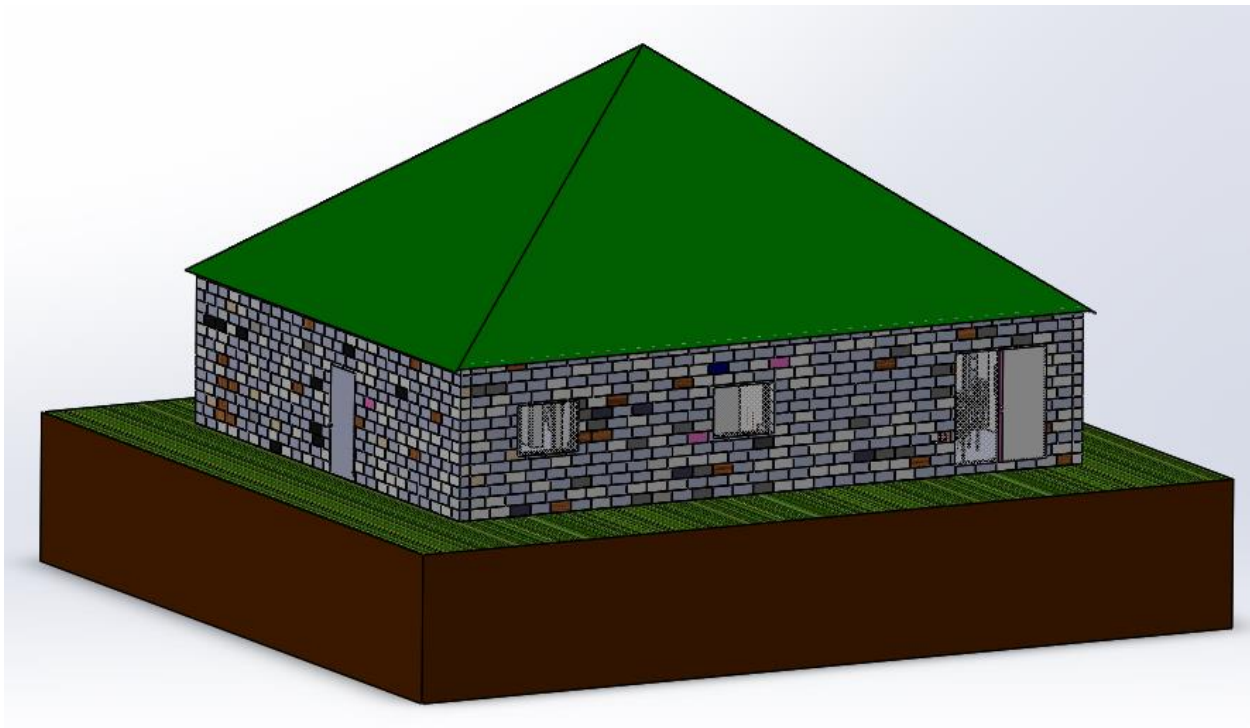


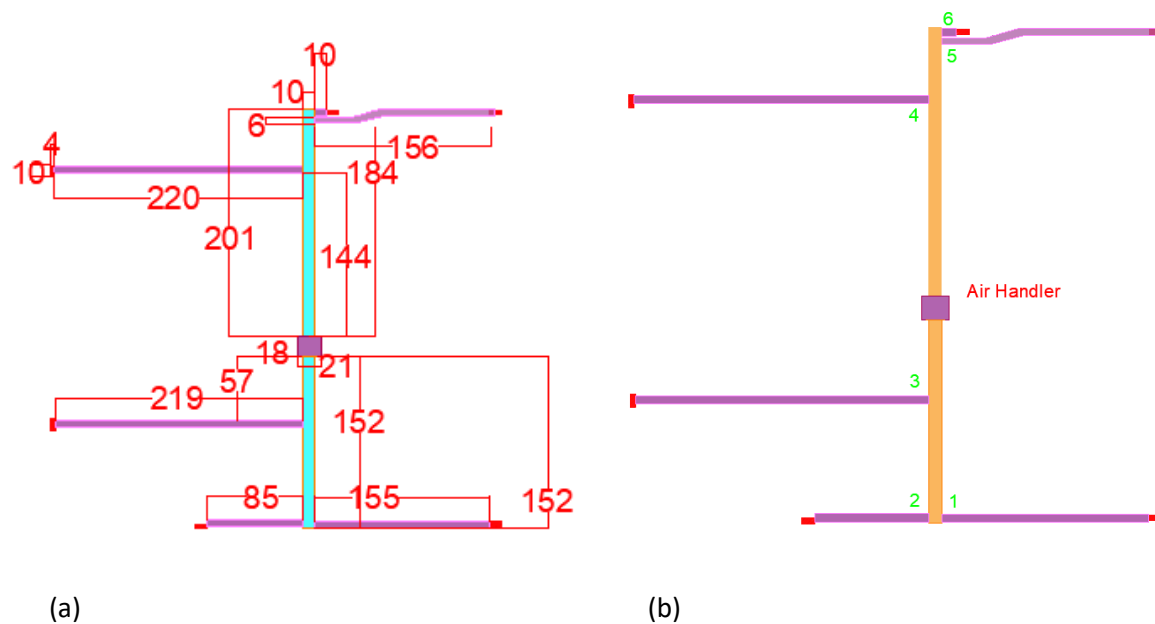
Figure 8.5: 3D side view of house with roof and ground

****Disclaimer:** the discoloring of parts within the 3D models was due to a lack of processing power of the computer used.

9 Duct System Design

Using established dimensions of the house (Appendix C), a duct system alluded to in Drawings 8.6 (b) and Figure 8.5 designed in further detail. Beginning, further drawings of Drawing 8.6(b) are shown below

which show dimensions and labeling for future calculations (Drawing 9.1).



Drawing 9.1: Duct system (a) dimensions and (b) numerical labeling of branching pipes

3-dimensional figures of the duct system above Drawing 9.1 were designed using the SOLIDWORKS program with matching pipe labels. The dimensions in the 2D and 3D models are slightly different due to the elbows and fittings which skewed the results slightly, but these differences are negligible. The 2-dimensional drawing is expanded such that elevation changes, i.e. pipe stemming under the duct, is illustrated in the 3D figures. The first 3D figure of the duct system is provided below (Figure 9.1):

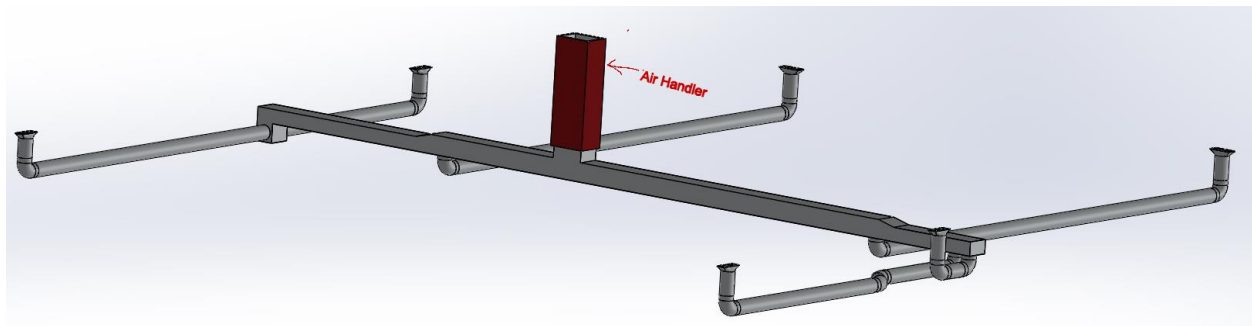


Figure 9.1: Overall 3-D Duct System

This system (Figure 9.1) shows the changes in height that occur as well as the decrease in duct size along its length. It would be mechanical unfavorable to design a system that pushes air into a diminishing region because pressure would thus increase. Because of this, base duct sizes were compared to stemming duct/pipe sizes to ensure that there was a slight increase in the cumulative cross-sectional area between the trunk of a point and its connected branches. There are two commonly found fittings in the duct system and those are the 6-inch elbow, used to redirect flow, and the air vent, used to transfer airflow from pipes to rooms. These two fittings are shown below in Figure 9.2:

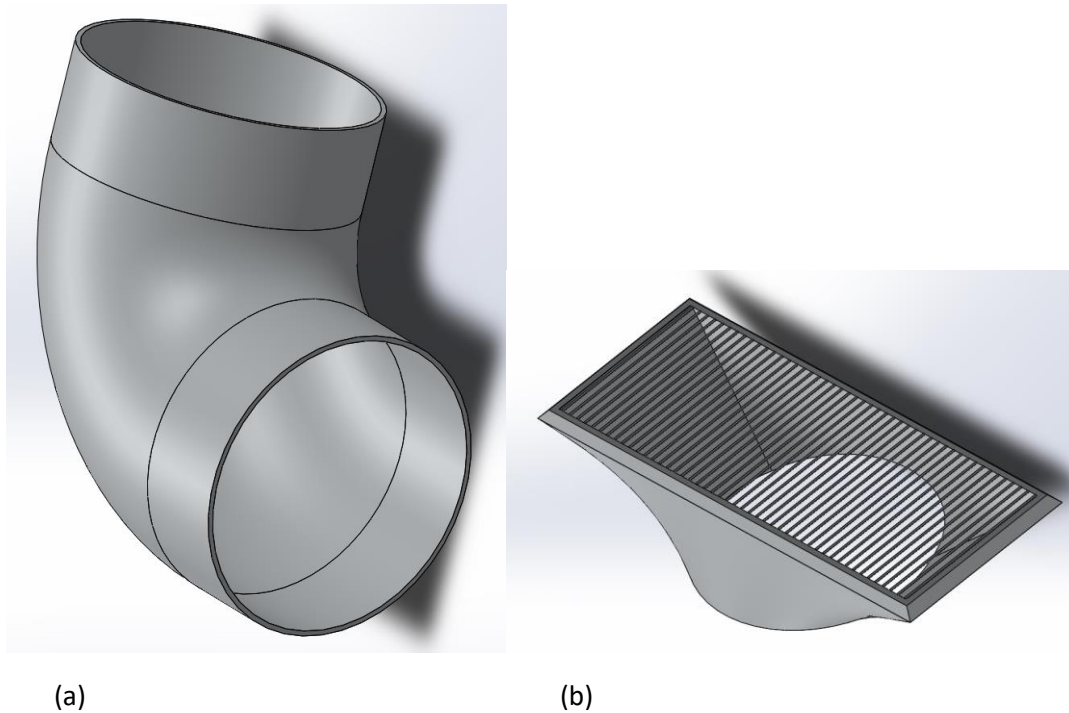


Figure 9.2: 3-D Drawings of (a) 90-degree elbow and (b) ventilation cover

The ventilation covers shown above (Figure 9.2) have a circular side that attaches the pipe, which is lofted to the other rectangular side. This rectangular side that has the grill is 10" x 4" which results in a cross-sectional area (40") slightly larger than that of the 6-in diameter pipe (~28"). Moving onto the duct system, the general 3-dimensional display of the singular duct line and its sub sections are listed in Figure 9.3. Note that duct was notated as D, length as L, fitting as F; all of which were numerically labeled outwardly from the air handler and formatted as "Duct.DuctNumber – Length/Fitting.Length/Fitting Number." The same labeling structure was used for pipe with the exception of the P notation opposed to the D notation.

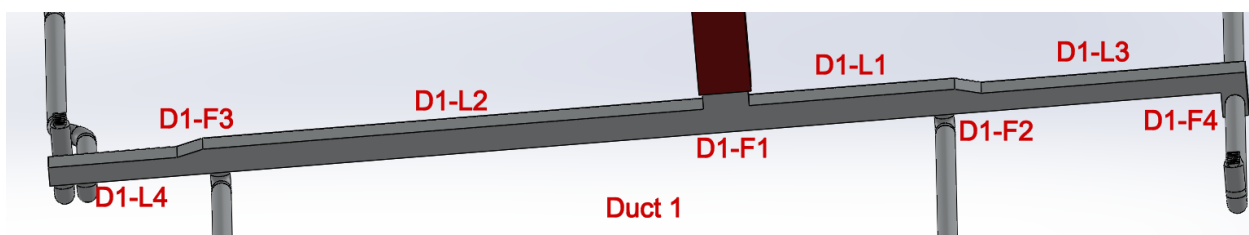


Figure 9.3: Duct (1) fittings(F) and lengths(L)

The dimensions of these lengths and fittings (Figure 9.3) are shown below in Table 9.1.

Table 9.1: Duct sub-section dimensions

Section	Length(in)	Height(in)	Width(in)
Duct-Length 1 (D1-L1)	63	8	10
Duct-Length 2 (D1-L2)	153.6	8	10
Duct-Length 3 (D1-L3)	81	6	10

Duct-Length 4 (D1-L4)	39.5	6	10
Duct-Fitting 1 (D1-F1)	10	8	14
Duct-Fitting 2 (D1-F2)	8.25	8 drop to 6	10
Duct-Fitting 3 (D1-F3)	8.25	8 drop to 6	10
Duct-Fitting 4 (D1-F4)	8	8	10

The junctions (J), regions that distribute or combine flow, are defined as J_i with the following labeling (Figure 9.4):

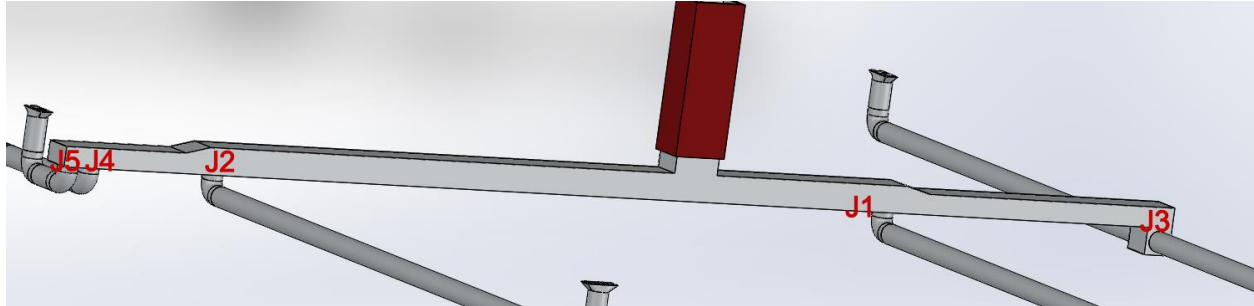


Figure 9.4. Junction (J) labeling of duct system

The displayed junction labeling distributes flow as follows Table 9.2:

Table 9.2. Pipe junction descriptions

Junction	Flow Directed	Notes
J1	Main duct flow (D1-L1) to Pipe 3 (P3)	
J2	Main duct flow (D1-L2) to Pipe 4 (P4)	
J3	Main duct flow (D1-L3) to Pipe 1 and 2 (P1 and P2)	Main duct flow is after reduced duct height (D1-F2)
J4	Main duct flow (D1-L4) to Pipe 5 (P5)	Main duct flow is after reduced duct height (D1-F3)
J5	Main duct flow (D1-L4) to Pipe 6 (P6)	Main duct flow is after reduced duct height (D1-F3)

The pipe labeling (numerical) on the south side of the air handler, corresponding the bottom side of Drawing 8.6(b) is shown below in Figure 9.5.

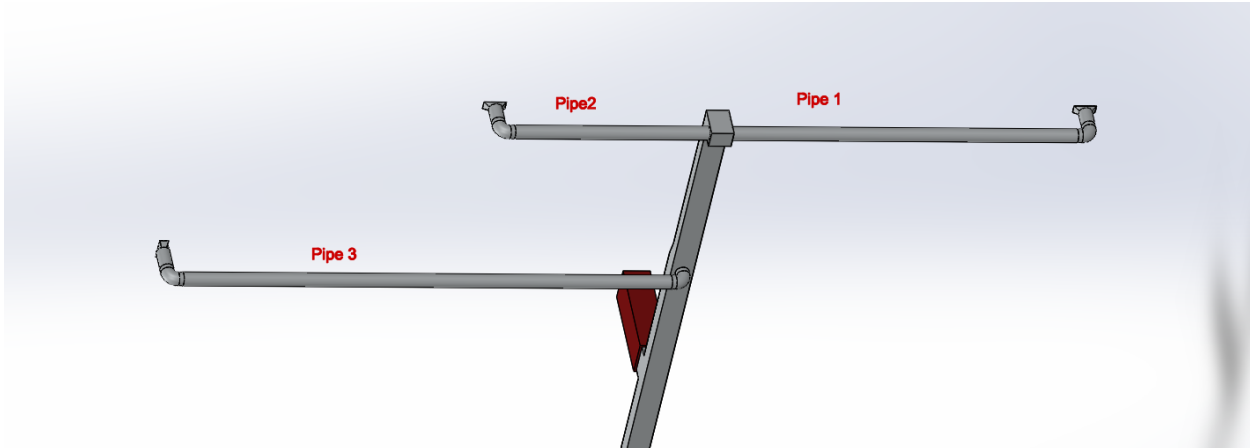
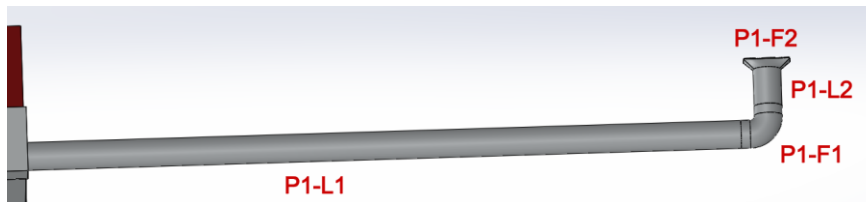
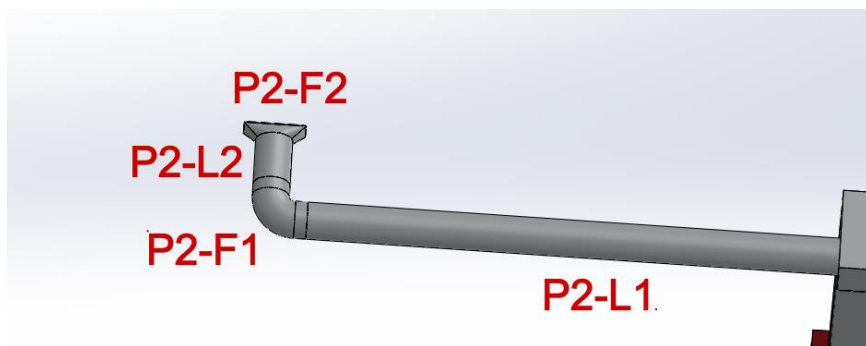


Figure 9.5: Pipe labeling of southern section of duct system

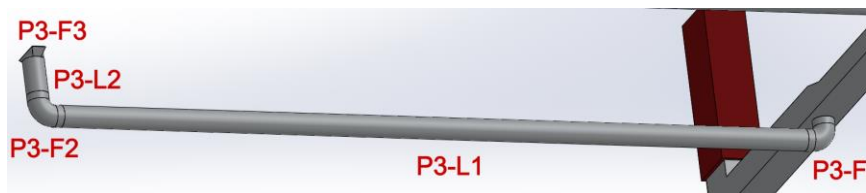
The sub-section labeling (fittings, lengths) of the 3 pipes shown in Figure 9.5 are displayed below in Figure 9.6.



(a)



(b)



(c)

Figure 9.6: Sub-section labeling of (a) Pipe 1, (b) Pipe 2, and (c) Pipe 3

The resulting dimensions of these subsections (Figure 9.6) are shown below in Table 9.3.

Table 9.3: Pipes 1-3 subsection dimensions

Subsection	Length(in)
Pipe1-Length1 (P1-L1)	153
Pipe1-Length2 (P1-L2)	8
Pipe2-Length1 (P2-L1)	86
Pipe2-Length2 (P2-L2)	8
Pipe3-Length1 (P3-L1)	216
Pipe3-Length2 (P3-L2)	10

Next, the labeling of the other 3 pipes (north side of air handler, top side of Drawing 8.6 (b)) are shown below in Figure 9.7:

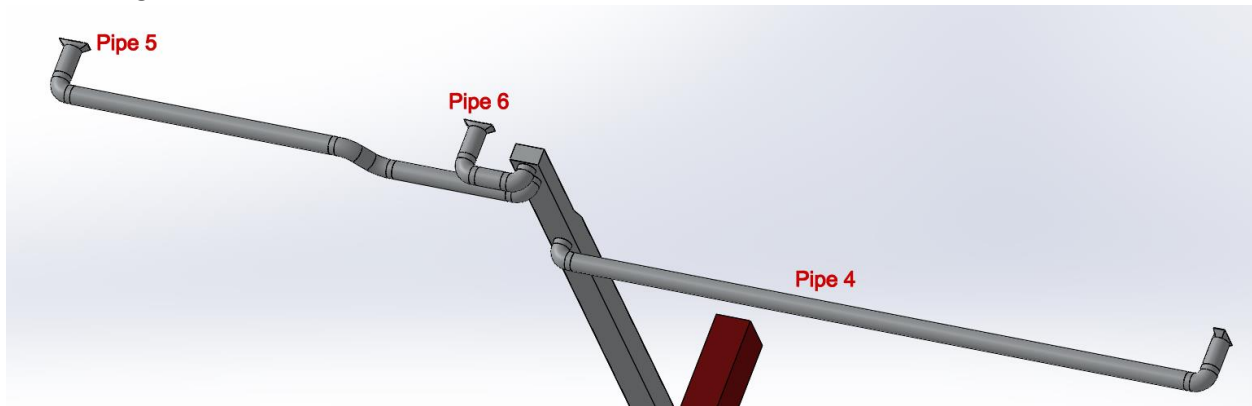
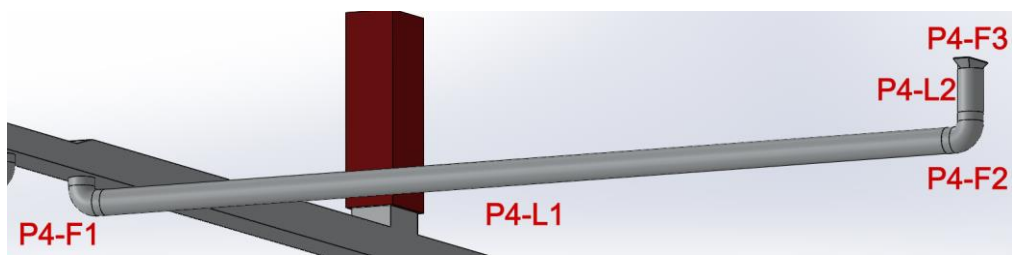
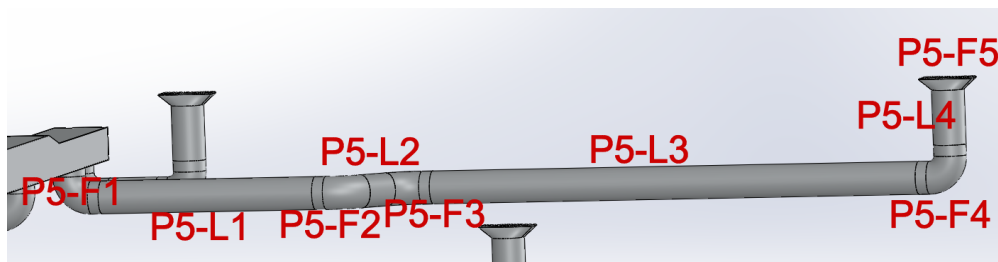


Figure 9.7: Pipe labeling of northern section of duct system

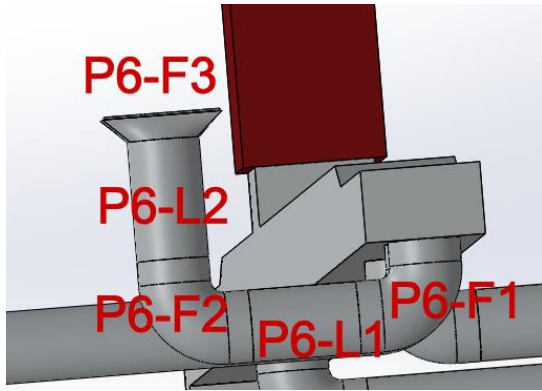
The subsections of these pipes (Figure 9.7) are shown below in Figure 9.8:



(a)



(b)



(c)

Figure 9.8: Sub-section labeling of (a) Pipe 4, (b) Pipe 5, and (c) Pipe 6

The subsequent dimensions of these subsections (Figure 9.8) are shown below in Table 9.4:

Table 9.4: Pipes 4-6 subsection dimensions

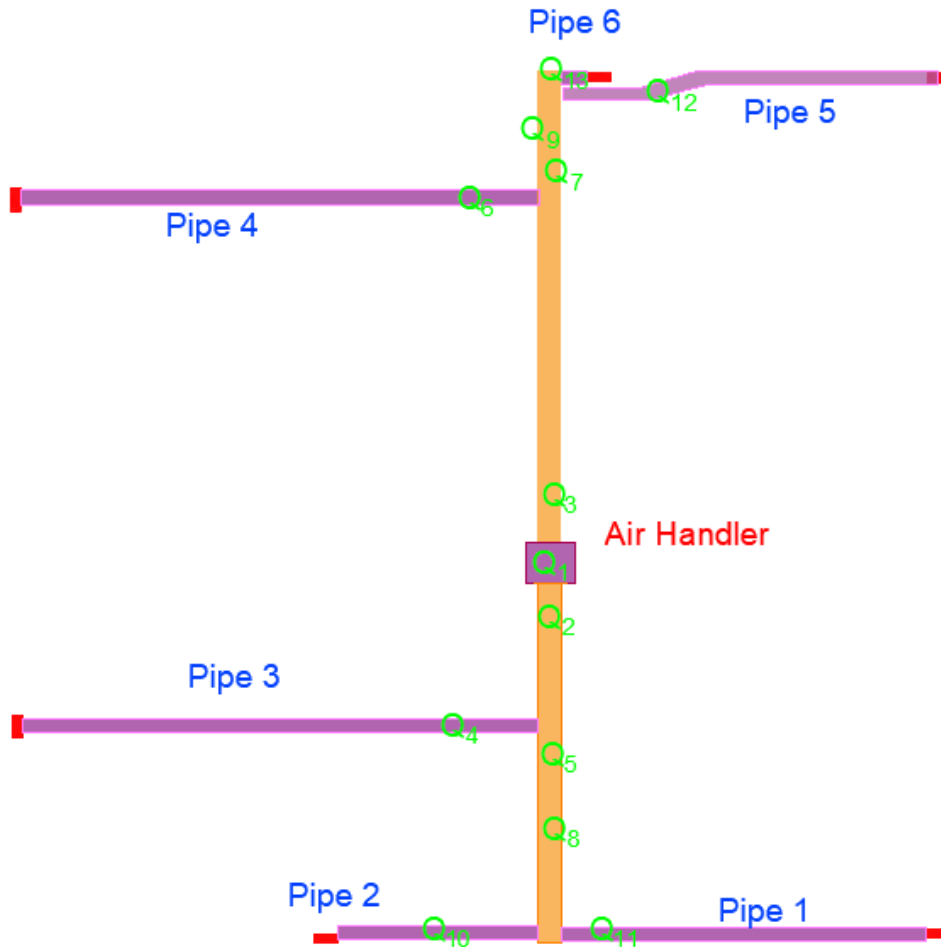
Subsection	Length(in)	Notes
Pipe4-Length1 (P4-L1)	215	
Pipe4-Length2 (P4-L2)	10	
Pipe5-Length1 (P5-L1)	40	
Pipe5-Length2 (P5-L2)	5.43	
Pipe5-Length3 (P5-L3)	91	
Pipe5-Length4 (P5-L4)	10	
Pipe6-Length1 (P6-L1)	9	
Pipe6-Length2 (P6-L2)	10	
Pipe5-Fitting2 (P5-F2)	4.51	45-degree elbow
Pipe5-Fitting3 (P5-F3)	4.51	45-degree elbow

10 Duct System Air Distribution

The velocity distribution of flow through the duct system needs to be determined so that subsequent energy loss calculations can be performed. Assuming the flow is incompressible, conservation of mass theory can be applied for this flow such that any flow that enters the system as return air will be delivered into subsequent rooms as return air. This concept can be applied on a smaller scale to individual junctions in the duct system which distribute flow by splitting a flow into a greater number of streams. Beginning at the air handler, the flow is sent to the main duct supply to encounter the T-junction split (D1-F1) that divides the duct into two, equally sized (in terms of cross-sectional area) subsections of duct that point in opposite directions. This junction is labeled D1-F1 from above, and knowing its uniform geometry with directions the volumetric flow rate will also be distributed evenly, that is (Equation 10.1):

$$Q_2 = Q_3 = \frac{Q_1}{2} \quad (10.1)$$

where Q_1 is the flow rate of air coming out of the air handler and Q_2, Q_3 are the flow rates of air going into duct sections D1-L1 and D1-L2 respectively. The following drawing shows the complete labeling of the flows throughout the duct system (10.1):



Drawing 10.1: Flow rate (Q_i) labels for duct and pipe sections

Flows Q_8 and Q_9 , modifications of flows Q_5 and Q_7 , respectively, represent the height reductions in the duct (D1-F2 and D1-F3 respectively) not visible in this 2-D figure (Drawing 10.1). While the first relationship between Q_1 , Q_2 , and Q_3 is provided in equation 10.1, additional relationships (Equations 10.2-10.7) are listed below:

$$Q_2 = Q_4 + Q_5 \quad (10.2)$$

$$Q_3 = Q_6 + Q_7 \quad (10.3)$$

$$Q_5 \neq Q_8 \quad (10.4)$$

$$Q_7 \neq Q_9 \quad (10.5)$$

$$Q_{10} = Q_{11} = \frac{Q_8}{2} \quad (10.6)$$

$$Q_9 = Q_{12} + Q_{13} \quad (10.7)$$

All these relationships are founded from knowing that the amount of mass is conserved through the progression along the duct system. This proportion can be used to find the amount of flow continuing in the duct through the following relationships which relate flow rates to velocities (Equations 10.8, 10.9):

$$Q_{in}A_{in} = Q_{out,1}A_{out,1} + Q_{out,2}A_{out,2} \quad (10.8)$$

$$Q_i = v_i \cdot A_i \quad (10.9)$$

The velocity changes discussed are due to fittings and reductions with the first two changes occurring at stemming junctions (J1, J2) for the first two duct flows (Q_2 , Q_3). At these junctions is where air is redirected from the main duct to branching 6-inch pipes. Unlike the first junction (D1-F1), the flow distribution at these junctions (J1-J4) cannot be considered uniform in the sense that the flow continuing through the duct (line flow) and the flow leaving through the pipe (branching flow) are not simply defined through Equation 10.8. That is their velocities are not simply proportional to their cross-sectional areas. Research was found to characterize this distribution based on geometries of the system. Below is a figure showing dividing line and branch flows through a pipe T-junction along with velocity contours labeled in color (displayed – Figure 10.1):

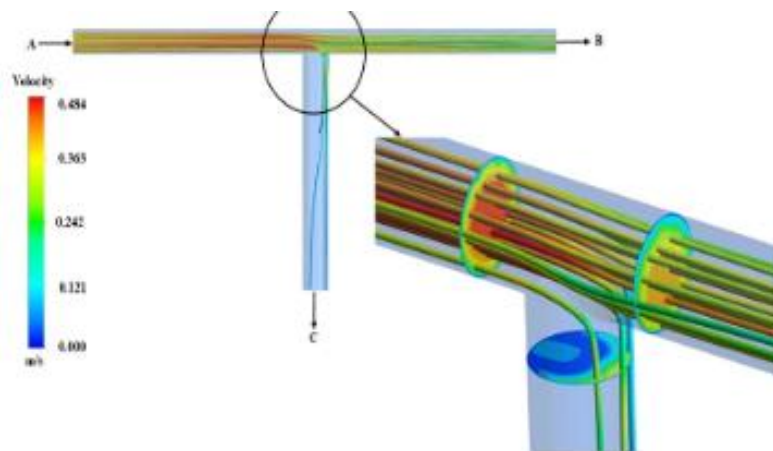


Figure 10.1: Velocity simulation through pipe T-junction [10.1]

A couple things to note are that while this section aims to predict things theoretically, some values such as these that induce a large amount of variability on the results are used from different simulations. Ideally, literature could be reference to characterize flow at these junctions but studies are very geometry sensitive and so no equations were available in literature. This figure (10.1) shows pipe flow rather than a duct flow and so the results are adjusted based on expected contributions of duct material opposed to piping material on the entering flow. The value of interest from this figure (10.1) is the velocity ratio of the branching flow (bottom) to the entering flow (left) which applied to this project. Looking at the axis provided and averaging the flow trajectory pipes for the highlighted disks, the exiting velocity is 0.24 m/s while the entering is 0.45 m/s. These values result in a ratio (Vratio – used in MATLAB code) of $(0.24/0.45) = 0.53$. Now factoring in a duct adjustment to this value, it is expected that this value is about 20 percent lower because of the greater pressure loss due to the harder turn. The value that will be used for this research is therefore $(0.8 \cdot 0.53) = 0.43$. This value is used for all junctions (J1, J2, J4) in the MATLAB calculation code listed in Appendix E where further values are determined.

Next, flow rates of the air handler had to be arbitrarily selected based on recommendations using the square footage of the house. The house is approximately 1200 square feet and standards recommend 1 cubic foot per minute (CFM) of air per square footage of house area (10.2). This is a general American standard and so the value was inflated slightly to 1400 CFM to account for the warmer southern conditions in Texas. 4 more values around this average (1000, 1200, 1600, and 1800 CFM) are used to get a better idea of the theoretically desirable air supply amount. These feed rates were plugged into MATLAB code to find the pressure that the air handler would operate at to provide an air flow.

10.1 Duct System Flows/Velocities

For the 5 selected flow rates through the air handler, the flow rates at each point in the duct system were found using the established flow distributions through the junctions (specialized, Figure 10.1) and through fittings (standardized, Equations 10.1 – 10.7). Knowing the flow rates through these duct sections, velocities through the pipes were found using Equation 10.8 as shown below in Table 10.1.1:

Table 10.1.1: Velocities (m/s) for different air handler models

	CFM = 1000	CFM = 1200	CFM = 1400	CFM = 1600	CFM = 1800
v_1	5.21	6.27	7.32	8.36	9.41
v_2	4.57	5.49	6.40	7.32	8.22
v_3	4.57	5.49	6.40	7.32	8.22
v_4	1.97	2.36	2.75	3.15	3.54
v_5	3.87	4.65	5.43	6.20	6.98
v_6	1.97	2.36	2.75	3.15	3.54
v_7	3.88	4.65	5.43	6.20	6.98
v_8	5.17	6.20	7.24	8.27	9.31
v_9	5.17	6.20	7.24	8.27	9.31
v_{10}	5.49	6.58	7.68	8.78	9.87
v_{11}	5.49	6.58	7.68	8.78	9.87
v_{12}	2.22	2.67	3.11	3.56	4.00
v_{13}	8.74	10.5	12.2	14.0	15.7

$v_4, v_6, v_{10}, v_{11}, v_{12}, v_{13}$ are the velocities of the flows that head directly through pipes and into the house. The flow rates used to derive these velocities (Table 10.1.1) are shown below in Table 10.1.2:

Table 10.1.2: Flow rates (CFM) for different Air handler models

	CFM = 1000	CFM = 1200	CFM = 1400	CFM = 1600	CFM = 1800
Q_1	997	1200	1401	1600	1801
Q_2	500	600	1225	801	899
Q_3	500	600	1225	801	899
Q_4	76	91	526	122	137
Q_5	370	445	1039	593	668
Q_6	76	91	526	122	137
Q_7	371	445	1039	593	668
Q_8	424	509	1386	678	764
Q_{10}	424	509	1386	678	764

Q ₁₁	212	254	1470	339	381
Q ₁₂	212	254	1470	339	381
Q ₁₃	86	103	595	138	155

10.2 Bernoulli's Equation

In analyzing the energy losses through the duct system, Bernoulli's equation (10.2.1) is used for an incompressible, inviscid fluid as shown below:

$$\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + h_f + h_{ff} \quad (10.2.1)$$

This equation is shown from one point (1) to another (2) in the system where h_f is major head loss due to pipe friction and h_{ff} is minor head loss due to pipe fittings. These points are connected to each other such that any apparatus (fitting, length, etc.) is taken into consideration in this formula, either through major or minor head losses. Knowing the complexity of the duct/piping system from previous sections due to fittings and cross-sectional area changes, it cannot simply be applied to the from the initial point (air handler) to the final point (air vent) as the equation must be implemented over any region where a change in fluid velocity occurs.

An additional complexity in finding these flow characteristics is that each of them are dependent on previously found/known values. For example, the head losses (major and minor) are both dependent on velocity of the fluid at that point, a variable that is initial unknown and must be derived from previous Bernoulli calculations. In essence, the solving process for this duct system involves implementing a Bernoulli equation in one region of the system and carrying it over to the previous or succeeding region in the system.

10.3 Major Head Losses

To calculate the major head losses that flow faces due to counteracting friction forces in the pipe, the friction factors are calculated by first determining the Reynolds number, Re (Equation 10.3.1) based on system geometries as well as fluid characteristics. If the Reynolds value is greater than 2300, the flow is turbulent. If this value is between 2000 and 2300, the flow is transient, and if the flow is less than 2000, the flow is laminar. The friction factor, f , is calculated as follows (Equation 10.3.1) using the Moody equation for flows that have Reynolds values between 4000 and $5 \cdot 10^8$. This equation was derived from the Moody chart to give more precise values using inputs of ϵ_i , roughness coefficient (Appendix B), and Re , Reynolds value. The roughness coefficient differs for the duct (galvanized steel) and pipe (aluminum) materials. The friction factor equation (10.3.1) is implemented below [10.3.1]:

$$f = 0.0055 \cdot \left(1 + \left(2 \cdot 10^4 \cdot \frac{\epsilon_i}{D_i} + \frac{10^6}{Re} \right)^{1/3} \right) \quad (10.3.1)$$

The Friction factors that were calculated are listed below (Table 10.3.1) for each flow rate. Note that the section of the friction factor matches the section of the flow rate (i.e. $Q_i = f_i$). The MATLAB calculation code used is shown in Appendix E.

Table 10.3.1: Friction factors per air handler flow rate

	CFM = 1000	CFM = 1200	CFM = 1400	CFM = 1600	CFM = 1800
f_1	1.20	1.20	1.19	1.20	1.20
f_2	1.31	1.31	1.31	1.31	1.31
f_3	1.31	1.31	1.31	1.31	1.31
f_4	0.026	0.025	0.024	0.023	0.023
f_5	1.34	1.34	1.34	1.34	1.34
f_6	0.026	0.025	0.024	0.023	0.023
f_7	1.49	1.49	1.49	1.49	1.49
f_8	1.49	1.49	1.49	1.49	1.49
f_9	1.49	1.49	1.49	1.49	1.49
f_{10}	0.02	0.019	0.019	0.018	0.018
f_{11}	0.02	0.019	0.019	0.018	0.018
f_{12}	0.025	0.24	0.023	0.023	0.022
f_{13}	0.018	0.017	0.017	0.016	0.016

Observing the results in Table 10.3.1, there appears to be significantly more variability in friction factor magnitude with changing flowrates in the pipes compared to such trends for the duct portion. This suggests that cross-sectional area, not roughness factors, are the critical variable in reducing head losses over length. These friction factors are then plugged into the Darcy Equation (10.3.2) to find the major head losses, h_f , due to frictional forces exerted from the pipe onto the flowing air over length L .

$$h_f = f \cdot \frac{L}{D_i} \cdot \frac{v^2}{2 \cdot g} \quad (10.3.2)$$

10.4 Minor Head Losses

Minor head losses are pressure increases in fluid flow due to fittings in which flow is redirected to which stagnation regions occurs and turbulence results. As shown by Figure 9.1, there are several fittings that need to be considered whose head loss coefficient values, C_i , are listed below in Table 10.4.1.

Table 10.4.1: Head Loss Coefficients [10.4.1] [10.4.2] [10.4.3]

Fitting/Junction Type	Fitting/Junction Location(s) in Duct System	Head Loss Coefficient, C_i
Room to Duct	Before Air Handler	0.35
90-degree Duct T-Split – Sharp Exit	D1-F1 J3	2
8 to 6-inch Duct Height Reduction	D1-F2 D1-F3	0
90-degree Pipe Stem Point Line Flow (Sharp Entrance)	J1, J2, J4, J5	0.9
90-degree Pipe Stem Point Exiting Flow (Sharp Entrance)	J1, J2, J4, J5	1
90-degree Duct Elbow - Sharp	D1-F4	1.3
90-degree 6-inch Pipe Elbow	P1-F1	0.5

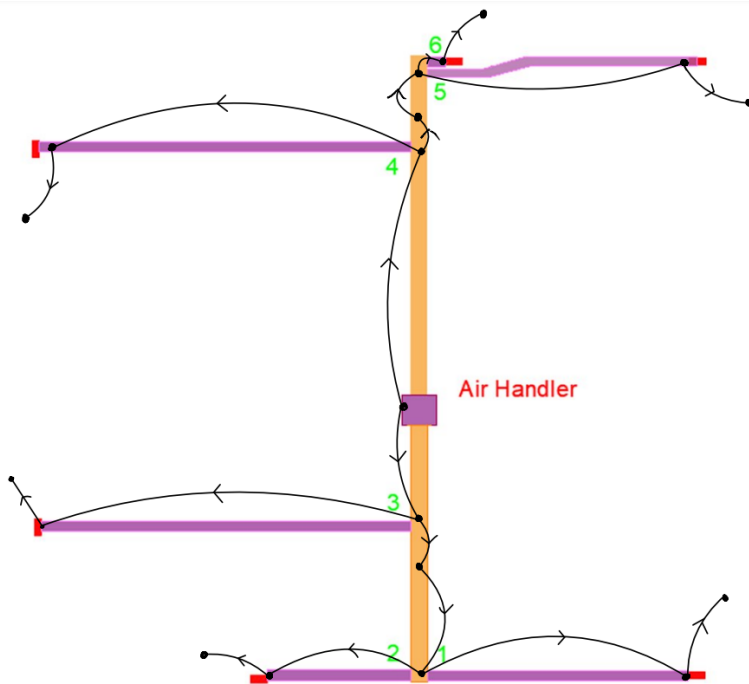
	P1-F2 P2-F1 P2-F2 P3-F1 P3-F2 P4-F1 P4-F2 P5-F1 P5-F4 P6-F1 P6-F2	
45-degree 6-inch Pipe Elbow	P5-F2 P5-F3	0.3
Air Vent (Grill) – 0.7 ratio	P1-F3 P2-F3 P3-F3 P4-F3 P5-F5 P6-F6	3
Duct to Room Flow	After Air Vent Locations	1

Using these coefficients, the minor head loss, h_{ff} , is calculated using the following equation (10.4.1):

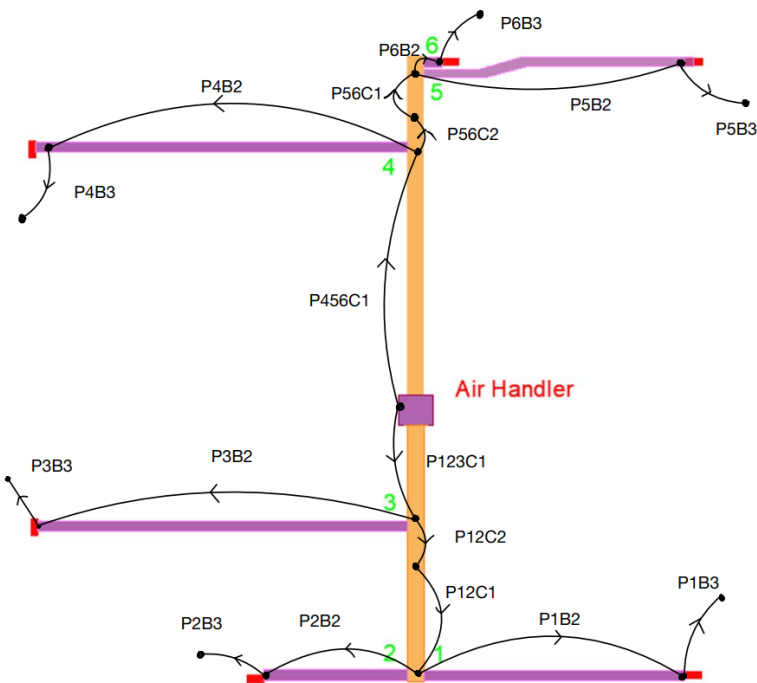
$$h_{ff} = C_i \bullet \frac{v^2}{2 \bullet g} \quad (10.4.1)$$

10.5 Air Handler Pressures

Bernoulli equations were implemented from one section of the duct system to the other using all available information on the system, whether that information was found or assumed. All of the flow rates and velocities of the system were found, but a starting point around the system (final location for a given Bernoulli equation is point 2 which is the later point in the system where air travels to) needed to be implemented to build equations off of. Since the origin of the duct system (air handler) was being solved for, the outside of the duct system was designated as the starting point for these iterations. The velocity of the air as it leaves air vents and settles in the rooms approaches zero and so the velocity at this point was assumed to be zero. Furthermore, the pressure in this environment, as alluded to in Simplification 5.1, is atmospheric. This information was enough to work backwards to find information on the preceding section of the duct system, and from there the section of the duct system before that. The general iteration process involving Bernoulli equation implementation is shown below in Drawing 10.5.1.



(a)



(b)

Drawing 10.5.1: (a) Section Separation with flow directions (arrows) and (b) MATLAB code labels

There is a lot of information depicted in Drawing 10.5.1 and the fittings in their respective orientations within these sections are not clearly distinguished. So, each code is listed in Table 10.5.1 along with subsequent lengths and fittings included in that region. The labeling of the code titles is formatted by pipe number (P_i) for piping sections or pipe combination (P_{ii}/P_{iii}) for duct sections; along with section labels (B_i) for pipes and (C_i) for duct. The sections shown in Drawing 10.5.1 at the end of the pipes are the flows that go into the rooms, that is one point is below the air vent and the other is a specified height in the room.

Table 10.5.1: MATLAB Code information for air handler pressure calculations

Code	Lengths Incorporated	Fittings/Junctions Incorporated	Notes
P1B3	Room	P1-F2	From below pipe air vent to room
P1B2	P1-L1 P1-L2	P1-F1 J3	From before splitting junction (J3) to just below air vent
P2B3	Room	P2-F2	From below pipe air vent to room
P2B2	P1-L1 P1-L2	P2-F1 J3	From before splitting junction (J3) to just below air vent
P3B3	Room	P3-F3	From below pipe air vent to room
P3B2	P3-L1 P3-L2	P3-F1 P3-F2 J1	From before branching junction (J1) to just below air vent
P4B3	Room	P4-F3	From below pipe air vent to room
P4B2	P4-L1 P4-L2	P4-F1 P4-F2 J2	From before branching junction (J2) to just below air vent
P5B3	Room	P5-F5	From below pipe air vent to room
P5B2	P5-L1 P5-L2 P5-L3	P5-F1 P5-F2 P5-F3 P5-F4 J4	From before branching junction (J4) to just below air vent
P6B3	Room	P6-F3	From below pipe air vent to room
P6B2	P6-L1 P6-L2	P6-F1 P6-F2 J5	From before branching junction (J4) to just below air vent
P12C1	D1-L3	N/A	Just after reduction piece (D1-F2) to J3
P12C2	D1-F2	N/A	Before to after reduction piece (D1-F2)
P123C1	D1-L1	D1-F1	Before duct split (D1-F1) to before reduction (D1-F2)
P45C1	D1-L4	N/A	Just after reduction piece (D1-F2) to J3
P45C2	D1-F3	N/A	Before to after reduction piece (D1-F3)
P456C1	D1-L2	D1-F1	Before duct split (D1-F1) to before reduction (D1-F3)

Each of these codes results in a pressure value, that is the pressure of the fluid going into that section of the duct system. For points in the system where sections are combined, the average of the two results is taken for that point and plugged into further calculations. This is done in all the duct code files but most notably the “totalpressure” file in Appendix E, to which the theoretical pressure of the air handler is shown. Calculating these theoretical pressures yield the following Results (Table 10.5.2):

Table 10.5.2: Air handler pressures with flow rates

Flow Rate (CFM)	Air Handler Pressure (Pa)
CFM = 1000	1.0296e5
CFM = 1200	1.0368e5
CFM = 1400	1.0453e5
CFM = 1600	1.0551e5
CFM = 1800	1.0663e5

10.6 Air Handler Energy Requirements

The air handler will be plugged into an electrical outlet and run using electricity. Using the pressure values provided in Table 10.5.2, the amount of work can be calculated via the first law of thermodynamics (Equation 10.6.1) applied to an open system. The control volume is the amount of air that the system pushes in each time interval, and since air can be pushed as easily as it can be pulled back in, the system is considered reversible for these calculations.

$$\begin{aligned}
 W_{\text{rev}} &= \int_{p_i}^{p_f} V \cdot dP & (10.6.1) \\
 &= \int_{AP}^{AHP} CFM \cdot dP \\
 &= CFM \cdot (\text{AirHandlerPressure} - \text{Atmospheric Pressure}) \\
 &= CFM \cdot (\text{Static Pressure})
 \end{aligned}$$

The flow rates are adjusted into SI units to get work values in Joules over seconds. These work values are then used to calculate the rate of electricity used in kW. The amount of time that this system will be needed to run varies and so studies will be run in further sections (13.1) to get estimated electricity usage based on systems efficiency. Most available air handlers have efficiencies around 70 percent in terms of converting electricity into actual work which will also be considered [10.6.1]. Below is a table (10.6.1) with the work values in kW before efficiency adjustment based on model.

Table 10.6.1: Work values to push air through air handler

Flow Rate (CFM)	Work (kW)
CFM = 1000	0.77
CFM = 1200	1.33
CFM = 1400	2.12
CFM = 1600	3.16
CFM = 1800	4.51

11 House Heat Transfer

Accounting for the insulation throughout the surfaces of the house is necessary for determining the heat loss for certain conditions. This section will compile the material composition that it is expected for all the surfaces and find respective thermal resistances. A table of R values (11.1) for materials whose values can be easily found.

Table 11.1: R-values of Relevant Materials

Material	R-value in $F^{\circ}\cdot ft^2\cdot h/BTU$	R-value in $m^2\cdot K/W$
Drywall	0.5	0.1
Wall Insulation	12.4	2.2
Windows	2.1	0.4
Cinderblock (8-inch)	1.11	0.14
Cinderblock (12-inch)	1.3	0.2
Roof Insulation (Upper)	30	5.3
Roof Insulation (Lower)	19.1	3.4
Wall Insulation	15	2.64
Doors	2.2	0.4

For materials whose geometries vary, resistances must be calculated by finding conductivities using thermal conductances listed in Table 11.2.

Table 11.2: Thermal Conductance of Materials

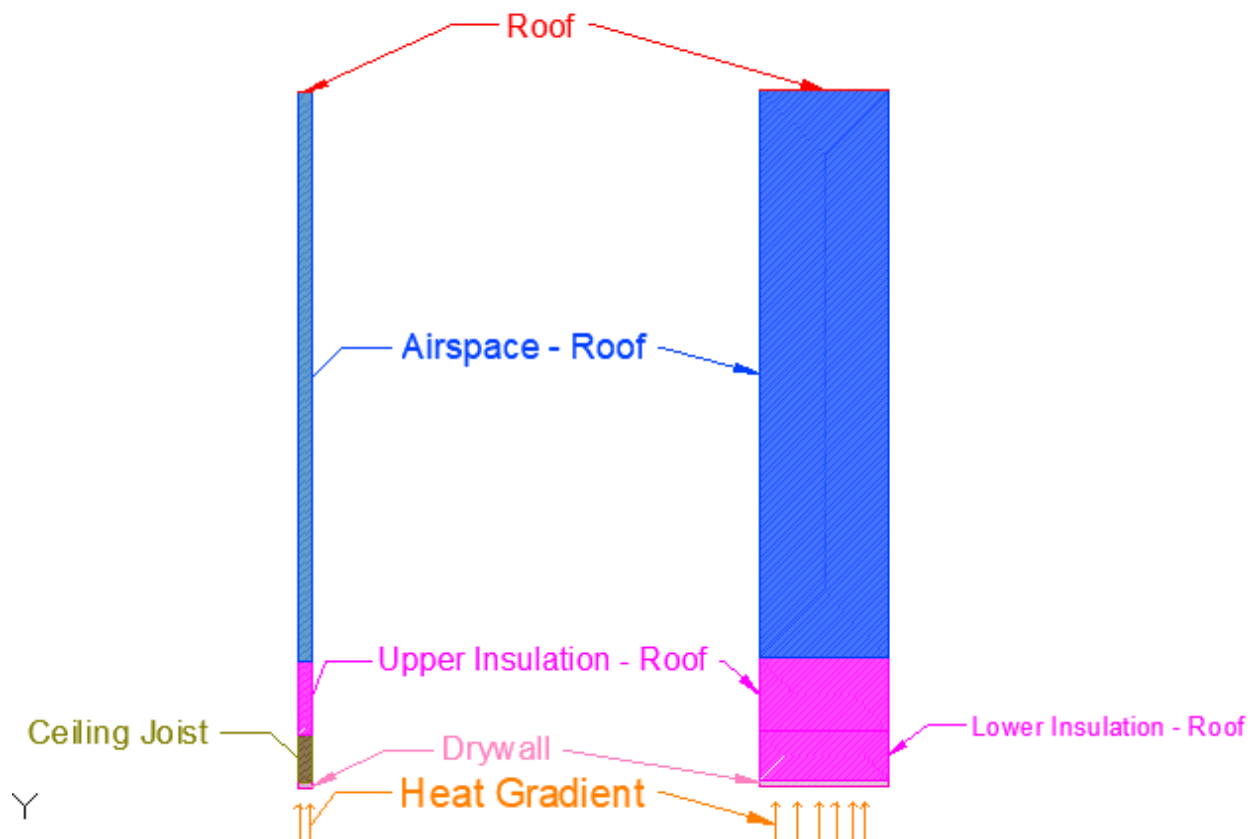
Material	Thermal Conductivity ($W/m^2\cdot K$)	Source
Copper (Roofing)	413	[11.2]
Wood	1.5	[11.3]
Air	26.24	[11.4]

A flux through the vertical plane includes the roof and crawl space which is discussed in Section 11.1. The flux through the short side of the house, that is the north and south facing walls, is discussed in Section 11.2. The flux through the long side of the house, that is the east and west walls, is discussed in Section 11.3. The fluxes are considered through the areas that are adjacent to the inside air geometry. That is, the fluxes do not consider regions of the house that are diagonally coincident with this inside air volume.

11.1 Roof and Crawl Space Resistances

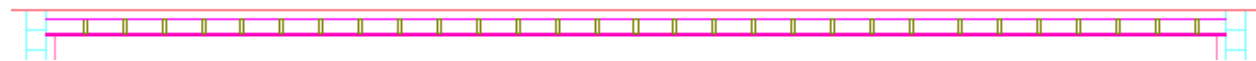
The first temperature flux considered will be that perpendicular to the vertical plane, that is the heat traveling through the roof and the floors. From a material standpoint, the top section of the house

contains drywall, upper roof insulation, lower roof insulation/ceiling joists (wood). Drawing 11.1.1 is below for reference:



Drawing 11.1.1: Roofing insulation material

In calculating the heat transferred through these regions the area of the regions is calculated and shown through Drawing 11.1.2 and Table 11.1.1. Using the different sections listed with their respective areas, along with previously shown ceiling/attic dimensions, cross-sectional areas were calculated.



Drawing 11.1.2: Side view of attic showing proportion of ceiling that is ceiling joist or insulation

Table 11.1.1: Cross-sectional Area Calculations

Section	Number of Sections	Area of Individual Sections(m ²)	Total Area (m ²)
Non-Ceiling Joist	29.75	$((14.5 \cdot 0.0254) \cdot (473 \cdot 0.0254)) = 4.42$	$(29.75 \cdot 4.42) = 131.6$
Ceiling Joist	29	$((1.5 \cdot 0.0254) \cdot (473 \cdot 0.0254)) = 0.45$	$(29 \cdot 0.45) = 13.3$

Overall resistance of this flux in the upper part of the house is calculated by taking a linear combination of the two scenarios, that is a vertical heat flux traveling through a ceiling joist (less likely) or a vertical

heat flux not traveling through a ceiling joist (insulated portion, more likely). The likelihood of each scenario is proportional to the area (width shown in Drawing 11.1.1) of each flux. Calculating the overall resistance for a present ceiling joist, distinguishment between insulation R-values (units Kelvin/Watts) and resistances (units $\text{m}^2\text{-K/W}$) are made, with adjustments made by considering cross-sectional areas found in Table 11.1.1 to equate units. The combined resistance through the portions of the attic with ceiling joist are calculated below (Equation 11.1.1).

$$\begin{aligned}
 R_{\text{Total}} &= (R_{\text{Drywall}} + R_{\text{CeilingJoist}} + R_{\text{UpperInsulation}} + R_{\text{AtticAirSpace}} + R_{\text{Roof}})/A_{\text{cs}} \quad (11.1.1) \\
 &= ((R_{\text{Drywall}} + \frac{dL}{k_{\text{CeilingJoist}}} + R_{\text{UpperInsulation}} + \frac{dL}{k_{\text{AtticAirSpace}}} + \frac{dL}{k_{\text{Roof}}}) \text{m}^2\text{-K/W})/A_{\text{cs}} \\
 &= ((0.1 + \frac{(5.5 \cdot 0.0254)}{1.5} + 5.3 + \frac{(64 \cdot 0.0254)}{26.24} + \frac{(0.5 \cdot 0.0254)}{413}) \text{m}^2\text{-K/W})/(13.3\text{m}^2) \\
 &= 0.418 \text{ K/W}
 \end{aligned}$$

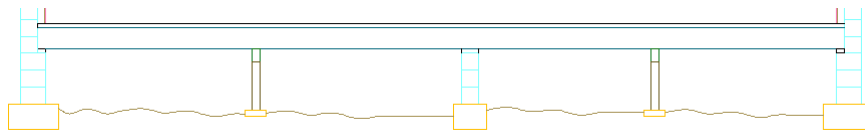
Calculating the overall resistance for no ceiling joist (Equation 11.1.2):

$$\begin{aligned}
 R_{\text{total}} &= (R_{\text{Drywall}} + R_{\text{LowerInsulation}} + R_{\text{UpperInsulation}} + R_{\text{AtticAirSpace}} + R_{\text{Roof}})/A_{\text{cs}} \quad (11.1.2) \\
 &= ((R_{\text{Drywall}} + R_{\text{LowerInsulation}} + R_{\text{UpperInsulation}} + \frac{1}{k_{\text{AtticAirSpace}} \cdot dL} + \frac{1}{k_{\text{Roof}} \cdot dL}) \text{m}^2\text{-K/W})/A_{\text{cs}} \\
 &= ((0.1 + 3.4 + 5.3 + \frac{(64 \cdot 0.0254)}{26.24} + \frac{(0.5 \cdot 0.0254)}{413}) \text{m}^2\text{-K/W})/(131.6\text{m}^2) \\
 &= 0.067 \text{ K/W}
 \end{aligned}$$

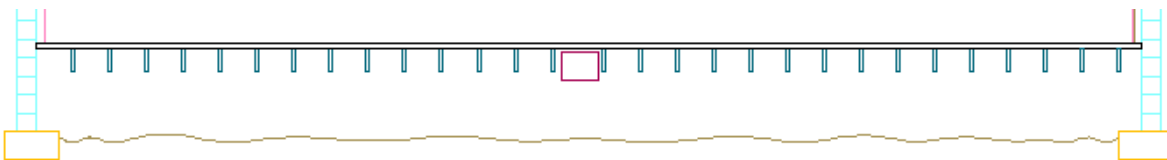
The weighted average of these values (according to area proportionality) will represent the overall resistance of this side of the house. This value is calculated below (Equation 11.1.3):

$$\begin{aligned}
 \bar{R}_{\text{Total}} &= \frac{13.3}{13.3+131.6} \cdot (0.418 \text{ K/W}) + \frac{131.6}{13.3+131.6} \cdot (0.067 \text{ K/W}) \quad (11.1.3) \\
 &= 0.099 \text{ K/W}
 \end{aligned}$$

In the same plane is the lower section of the house which contains insulation materials flooring and floor joists (wood). Below is an illustration of diagrams representing the expected schematic of insulation materials that heat fluxes will encounter.



(a)



(b)

Drawing 11.1.3: a) Short side and b) long side of house for floor-crawl space region

For this section, assumptions mentioned regarding dividing areas for different material layer compositions apply, that is vertical heat fluxes in this portion of the house will be considered to either travel through a floor joist or not a floor joist. These calculations will not consider the air space of the crawl space below the floor joists. The areas are therefore calculated in Table 11.1.2:

Table 11.1.2: Cross-sectional areas of crawl space regions

Section	Number of Sections	Section Area m ²	Total Area m ²
Floor Joist	29	$((1.5 \cdot 0.0254) \cdot (372 \cdot 0.0254)) = 0.36$	$(29 \cdot 0.36) = 10.44$
No Floor Joist	29.5	$((14.5 \cdot 0.0254) \cdot (372 \cdot 0.0254)) = 3.47$	$(29.5 \cdot 3.47) = 102.7$

The overall resistances are calculated the same way as for the attic sections. The overall resistance of the floor joist sections is shown below (Equation 11.1.4):

$$\begin{aligned}
 R_{\text{Total}} &= (R_{\text{Floor}} + R_{\text{FloorJoist}})/A_{\text{cs}} & (11.1.4) \\
 &= \left(\frac{dL}{k_{\text{Floor}}} + \frac{dL}{k_{\text{FloorJoist}}} \right) / A_{\text{cs}} \\
 &= \left(\left(\frac{2 \cdot 0.0254}{1.5} + \frac{10 \cdot 0.0254}{1.5} \right) \text{m}^2\text{-K/W} \right) / (10.44 \text{m}^2) \\
 &= 0.019 \text{ K/W}
 \end{aligned}$$

The overall resistance of the non-floor joist section is calculated as follows (Equation 11.1.5):

$$\begin{aligned}
 R_{\text{Total}} &= (R_{\text{Floor}} + R_{\text{Airspace}})/A_{\text{cs}} & (11.1.5) \\
 &= \left(\frac{dL}{k_{\text{Floor}}} + \frac{dL}{k_{\text{Airspace}}} \right) / A_{\text{cs}} \\
 &= \left(\left(\frac{2 \cdot 0.0254}{1.5} + \frac{10 \cdot 0.0254}{26.24} \right) \text{m}^2\text{-K/W} \right) / (102.7 \text{m}^2) \\
 &= 0.00042 \text{ k/W}
 \end{aligned}$$

The weighted overall resistance, based on respective cross-sectional areas, is calculated as follows (Equation 11.1.6):

$$\begin{aligned}
 \bar{R}_{\text{Total}} &= \frac{10.44}{10.44+102.7} \cdot 0.019 \text{ K/W} + \frac{102.7}{10.44+102.7} \cdot 0.00042 \text{ K/W} & (11.1.6) \\
 &= 0.0022 \text{ k/W}
 \end{aligned}$$

11.2 Short-side Wall Resistances

Resistances will be calculated in the same way done in Section 11.1 but through the walls of the short sides of the houses. For such calculations, the cross-sectional area of doors and windows need to be considered (Table 11.2.1).

Table 11.2.1: Door and Window Dimensions

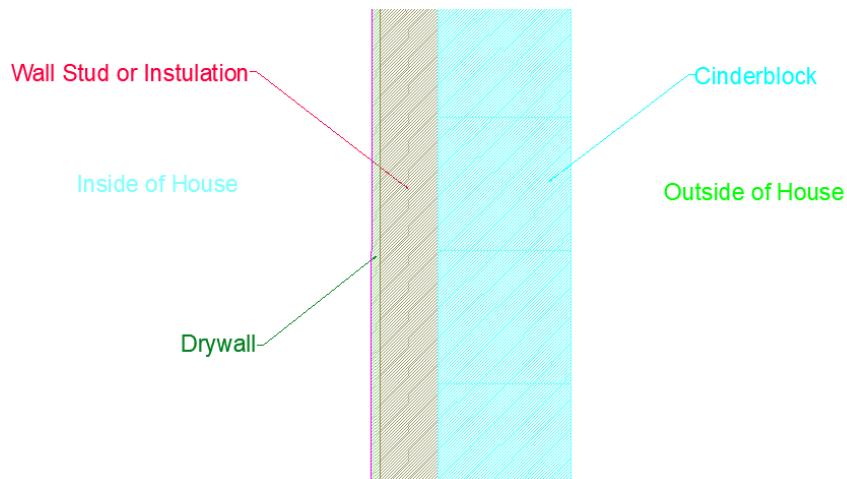
Object	Cross-sectional Area (Width x Height) m ²
Outside Door (Standard)	$((36 \cdot 0.0254) \cdot (80 \cdot 0.0254)) = 1.86$
Outside Door (Double-wide)	$((72 \cdot 0.0254) \cdot (80 \cdot 0.0254)) = 3.72$
Window (Standard)	$((48 \cdot 0.0254) \cdot (36 \cdot 0.0254)) = 1.11$

These cross-sectional areas will be used to calculate the overall resistance of a given wall considering that these areas make up a portion of the overall wall. The subsequent compositions of each wall's cross-sectional area are calculated in Table 11.2.2:

Table 11.2.2: Cross-sectional composition of exterior walls

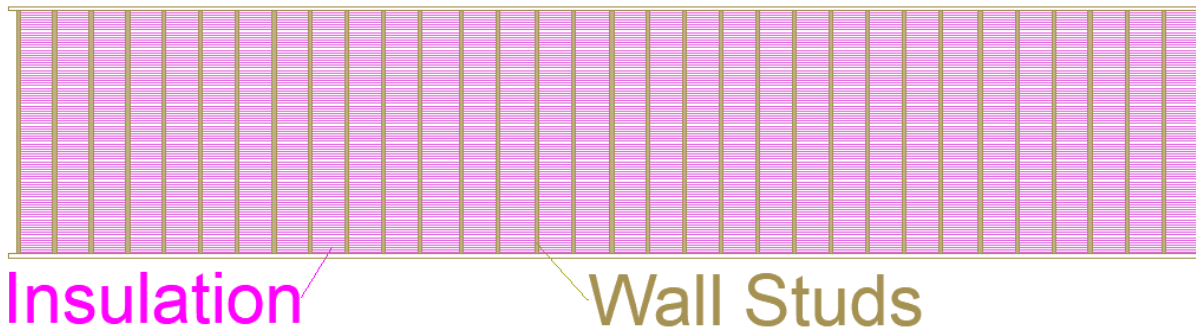
Wall	Area m ² – Doors	Area m ² – Windows	Area m ² - Total	Area m ² - Wall
North	$1 \cdot (1.86) = 1.86$	0	$(377 \cdot 0.0254) \cdot (8 \cdot 0.3048) = 23.35$	$23.35 - 1.86 = 21.49$
South	$1 \cdot (1.86) = 1.86$	$1 \cdot (1.11) = 1.11$	$(377 \cdot 0.0254) \cdot (8 \cdot 0.3048) = 23.35$	$23.35 - 1.86 - 1.11 = 20.38$
East	$1 \cdot (1.86) = 1.86$	$2 \cdot (1.11) = 2.22$	$(473 \cdot 0.0254) \cdot (8 \cdot 0.3048) = 29.29$	$29.29 - 1.86 - 2.22 = 25.21$
West	$1 \cdot (3.72) = 3.72$	$2 \cdot (1.11) = 2.22$	$(473 \cdot 0.0254) \cdot (8 \cdot 0.3048) = 29.29$	$29.29 - 3.72 - 2.22 = 23.35$

The next thing that needs to be accounted for is the material composition of the wall. Both of north-south facing walls (short-side), as denoted by Drawing 8.5, consist of 8-inch wide (thickness) cinderblocks where the long-side walls (East, west facing) consist of 12-inch cinderblocks. A side-view schematic of the materials composition of the wall is shown below in Drawing 11.2.1:



Drawing 11.2.1: Side-view of wall – material composition

The exterior wall consists of either wall studs or insulations, shown from a front-facing view in Drawing 11.2.2:



Drawing 11.2.2: Front facing view of wall interior (doors and windows ignored) – scaled properly

Knowing the cross-sectional area of the walls (Table 11.2.2), the cross-sectional area of the portions occupied by insulation and subsequently wall studs was calculated for each wall as shown in Table 11.2.3. This was done by knowing the distance between each stud (14.5 inches) as well as the width of the studs (1.5 inches).

Table 11.2.3: Cross-sectional areas of insulation and stud portions of walls

Wall	Cumulative Cross-sectional Area m ²	Insulation Area m ²	Stud Material m ²
North	21.49	$\frac{13}{1.5+13} \cdot 21.49 = 19.27$	$\frac{1.5}{1.5+13} \cdot 21.49 = 2.22$
South	20.38	$\frac{13}{1.5+13} \cdot 20.38 = 18.27$	$\frac{1.5}{1.5+13} \cdot 20.38 = 2.11$
East	25.21	$\frac{13}{1.5+13} \cdot 25.21 = 22.6$	$\frac{1.5}{1.5+13} \cdot 25.21 = 2.61$
West	23.35	$\frac{13}{1.5+13} \cdot 23.35 = 20.93$	$\frac{1.5}{1.5+13} \cdot 20.93 = 2.42$

From the design and dimensions of the house (Appendix C), overall resistances were derived for each exterior wall of the house. The overall resistance of the wall section consisting of insulation is as follows (this applies for both the north and south walls since they both have 8-inch cinderblocks)(Equation 11.2.1):

$$R_{\text{Wall-Insulation}} = (R_{\text{Drywall}} + R_{\text{Insulation}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.2.1)$$

$$= ((0.1 + 2.64 + 0.14) \text{ m}^2\text{-K/W}) / (19.27 \text{ m}^2)$$

$$= 0.149 \text{ K/W}$$

The overall resistance of the wall consisting of studs is calculated as follows (Equation 11.2.2):

$$R_{\text{Wall-Stud}} = (R_{\text{Drywall}} + R_{\text{WallStud}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.2.2)$$

$$= ((R_{\text{Drywall}} + \frac{dL}{k_{\text{Wallstud}}} + R_{\text{Cinderblock}}) \text{ m}^2\text{-K/W}) / (2.22 \text{ m}^2)$$

$$= ((0.1 + \frac{3.5 \cdot 0.0254}{1.5} + 0.14) \text{ m}^2\text{-K/W}) / (2.22 \text{ m}^2)$$

$$= 0.135 \text{ K/W}$$

The weighted average overall resistance of the north wall, taking both the insulation and wall studs into consideration, is calculated as follows (Equation 11.2.3):

$$\bar{R}_{\text{Wall}} = \frac{19.27}{2.22+19.27} \cdot 0.149 + \frac{2.22}{2.22+19.27} \cdot 0.135 \quad (11.2.3)$$

$$= 0.134 \text{ K/W}$$

Taking into consideration the windows and doors that occupy the northern wall, the overall resistance of that wall is calculated using the cross-sectional areas in Table 11.2.2 as shown below (Equation 11.2.4):

$$R_{\text{NorthWall}} = \frac{A_{\text{Door}}}{A_{\text{Door}}+A_{\text{Wall}}} \cdot R_{\text{Door}} + \frac{A_{\text{Wall}}}{A_{\text{Door}}+A_{\text{Wall}}} \cdot R_{\text{Wall}} \quad (11.2.4)$$

$$= \frac{A_{\text{Door}}}{A_{\text{Door}}+A_{\text{Wall}}} \cdot \frac{dL}{k_{\text{wood}}} + \frac{A_{\text{Wall}}}{A_{\text{Door}}+A_{\text{Wall}}} \cdot R_{\text{Wall}}$$

$$= \frac{1.86}{23.35} \cdot \frac{2 \cdot 0.0254}{1.5} + \frac{21.49}{23.35} \cdot 0.134$$

$$= 0.126 \text{ K/W}$$

Using the same process for the south wall, the overall resistances for the insulated and studded portion of the wall are as follows (Equations 11.2.5, 11.2.6):

$$R_{\text{Wall-Insulation}} = (R_{\text{Drywall}} + R_{\text{Insulation}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.2.5)$$

$$= ((0.1 + 2.64 + 0.14) \text{ m}^2\text{-K/W}) / (18.27 \text{ m}^2)$$

$$= 0.158 \text{ K/W}$$

$$R_{\text{Wall-Stud}} = (R_{\text{Drywall}} + R_{\text{WallStud}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.2.6)$$

$$= ((R_{\text{Drywall}} + \frac{dL}{k_{\text{WallStud}}} + R_{\text{Cinderblock}}) \text{ m}^2\text{-K/W}) / (2.11 \text{ m}^2)$$

$$= ((0.1 + \frac{3.5 \cdot 0.0254}{1.5} + 0.14) \text{ m}^2\text{-K/W}) / (2.11 \text{ m}^2)$$

$$= 0.142 \text{ K/W}$$

The weighted average overall resistance of the south wall, taking both the insulation and wall studs into consideration, is calculated as follows (Equation 11.2.7):

$$\bar{R}_{\text{Wall}} = \frac{18.27}{2.11+18.27} \cdot 0.158 + \frac{2.11}{2.11+18.27} \cdot 0.142 \quad (11.2.7)$$

$$= 0.156 \text{ K/W}$$

The overall resistance of the southern wall, accounting for the doors and windows, is calculated as follows (Equation 11.2.8):

$$\begin{aligned}
R_{\text{SouthWall}} &= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Door}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
&= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot \frac{dL}{k_{\text{wood}}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
&= \frac{1.11}{23.35} \cdot 0.4 + \frac{1.86}{23.35} \cdot \frac{2 \cdot 0.0254}{1.5} + \frac{20.38}{23.35} \cdot 0.156 \quad (11.2.8) \\
&= 0.158 \text{ K/W}
\end{aligned}$$

11.3 Long-side Wall Resistances

The cross-sectional areas of the wall occupied by insulation and studs is shown in Table 11.2.3 and the cross-sectional areas of the windows and doors are shown in Table 11.2.2. These values will be used in this section to calculate the overall resistance. Beginning with the resistance of the east wall, the resistances of the wall due to insulation and wall studs are calculated as follows (Equations 11.3.1, 11.3.2):

$$\begin{aligned}
R_{\text{Wall-Insulation}} &= (R_{\text{Drywall}} + R_{\text{Insulation}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.3.1) \\
&= ((0.1 + 2.64 + 0.14) \text{ m}^2\text{-K/W}) / (22.6 \text{ m}^2) \\
&= 0.127 \text{ K/W}
\end{aligned}$$

$$\begin{aligned}
R_{\text{Wall-Stud}} &= (R_{\text{Drywall}} + R_{\text{WallStud}} + R_{\text{Cinderblock}}) / A_{\text{cs}} \quad (11.3.2) \\
&= ((R_{\text{Drywall}} + \frac{dL}{k_{\text{WallStud}}} + R_{\text{Cinderblock}}) \text{ m}^2\text{-K/W}) / (2.61 \text{ m}^2) \\
&= ((0.1 + \frac{3.5 \cdot 0.0254}{1.5} + 0.14) \text{ m}^2\text{-K/W}) / (2.61 \text{ m}^2) \\
&= 0.115 \text{ K/W}
\end{aligned}$$

The weighted average overall resistance of the south wall, taking both the insulation and wall studs into consideration, is calculated as follows (Equation 11.3.3):

$$\begin{aligned}
\bar{R}_{\text{Wall}} &= \frac{22.6}{2.61 + 22.6} \cdot 0.127 + \frac{2.61}{2.61 + 22.6} \cdot 0.115 \quad (11.3.3) \\
&= 0.126 \text{ K/W}
\end{aligned}$$

The overall resistance of the southern wall, accounting for the doors and windows, is calculated as follows (Equation 11.3.4):

$$\begin{aligned}
R_{\text{EastWall}} &= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Door}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
&= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot \frac{dL}{k_{\text{wood}}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
&= \frac{2.22}{29.29} \cdot 0.4 + \frac{1.86}{29.29} \cdot \frac{2 \cdot 0.0254}{1.5} + \frac{25.21}{29.29} \cdot 0.126 \quad (11.3.4) \\
&= 0.141 \text{ K/W}
\end{aligned}$$

Using the same method, the overall resistance of the western wall is calculated by first finding individual contributions of insulation material and wall studs on resistances (Equations 11.3.5, 11.3.6):

$$\begin{aligned}
 R_{\text{Wall-Insulation}} &= (R_{\text{Drywall}} + R_{\text{Insulation}} + R_{\text{Cinderblock}}) / A_{\text{cs}} & (11.3.5) \\
 &= ((0.1 + 2.64 + 0.14) \text{ m}^2\text{-K/W}) / (20.9 \text{ m}^2) \\
 &= 0.138 \text{ K/W}
 \end{aligned}$$

$$\begin{aligned}
 R_{\text{Wall-Stud}} &= (R_{\text{Drywall}} + R_{\text{WallStud}} + R_{\text{Cinderblock}}) / A_{\text{cs}} & (11.3.6) \\
 &= ((R_{\text{Drywall}} + \frac{dL}{k_{\text{Wallstud}}} + R_{\text{Cinderblock}}) \text{ m}^2\text{-K/W}) / (2.42 \text{ m}^2) \\
 &= ((0.1 + \frac{3.5 \cdot 0.0254}{1.5} + 0.14) \text{ m}^2\text{-K/W}) / (2.42 \text{ m}^2) \\
 &= 0.124 \text{ K/W}
 \end{aligned}$$

The weighted average overall resistance of the south wall, taking both the insulation and wall studs into consideration, is calculated as follows (Equation 11.3.7):

$$\begin{aligned}
 \bar{R}_{\text{Wall}} &= \frac{20.93}{2.42 + 20.93} \cdot 0.124 + \frac{2.42}{2.42 + 20.93} \cdot 0.138 & (11.3.7) \\
 &= 0.125 \text{ K/W}
 \end{aligned}$$

The overall resistance of the southern wall, accounting for the doors and windows, is calculated as follows (Equation 11.3.8):

$$\begin{aligned}
 R_{\text{WestWall}} &= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Door}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
 &= \frac{A_{\text{Window}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Window}} + \frac{A_{\text{Door}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot \frac{dL}{k_{\text{wood}}} + \frac{A_{\text{Wall}}}{A_{\text{Door}} + A_{\text{Wall}} + A_{\text{Window}}} \cdot R_{\text{Wall}} \\
 &= \frac{3.72}{29.29} \cdot 0.4 + \frac{2.22}{29.29} \cdot \frac{2 \cdot 0.0254}{1.5} + \frac{23.35}{29.29} \cdot 0.125 & (11.3.8) \\
 &= 0.153 \text{ K/W}
 \end{aligned}$$

12 Inside Air Temperature Behavior

The amount of heat that enters the house needs to be calculated and analyzed to determine how much and to what extent the cooling system needs to run for adequate cooling. There are several variables that come into play when determining this, so a brief recap of assumptions taken will be useful. The heat flux subjected on the house will be setup as if a typical, sunny day in Texas is occurring in which the temperature is 90 degrees Fahrenheit for most of the day, which will be the value used for calculations. Realistically, a heat flux induced by the sun will contact some surfaces of the house more than others, but for the purposes of this research a uniform flux will be considered such that heat is striking all 5 visible portions of the house (roof and 4 walls) equally. To recap from previous sections, the relevant resistance values of these surfaces is provided below as well as their respective surface areas in Table 12.1:

Table 12.1: Resistances of house surfaces

Surface	Resistance (K/W)
Roof	0.099
North Wall	0.126

South Wall	0.158
East Wall	0.141
West Wall	0.153

The amount of heat transferred through the surface house is calculated using the following equation (12.1):

$$\dot{q} = \frac{\Delta T_{overall}}{R_{T,overall}} \quad (12.1)$$

where the overall temperature change is between the inside and outside temperature of the house. The inside temperature will be room temperature (25° C) and the outside temperature is the previously discussed 90 °F (32.22 °C) value. The resistance term in the denominator is the sum of values shown in Table 12.1, that is the overall resistance of the house. Equation 12.1 simplifies to the below equation (12.2)

$$\begin{aligned} \dot{q} &= \sum_i^n \frac{T_{outside} - T_{inside}}{R_{wall,i}} \\ &= \frac{(32.22 - 25)^\circ\text{C}}{(0.099(K/W))} + \frac{(32.22 - 25)^\circ\text{C}}{(0.126(K/W))} + \frac{(32.22 - 25)^\circ\text{C}}{(0.158(K/W))} + \frac{(32.22 - 25)^\circ\text{C}}{(0.141(K/W))} + \frac{(32.22 - 25)^\circ\text{C}}{(0.153(K/W))} \\ &= 273.7 \text{ W} \\ &= 9.85 \cdot 10^5 \text{ J/hr} \end{aligned} \quad (12.2)$$

This is the amount of heat (per time) that enters through the walls and acts upon the inside air of the house. Now considering the inside air, the amount of volume needs to be considered based on dimensions provided (Appendix C). The total amount of air in the house (assuming closed system and neglecting interior walls) is 275 m³. Knowing the heat capacity and density of air, a function for the resulting temperature of air is derived below (Equation 12.3). Note that this equation is under the uniform temperature assumption as realistically air will have thermal contours from the center to the outside of the house.

$$\begin{aligned} \dot{q} &= \dot{m} \cdot C_p \cdot \Delta T \\ &= \rho \cdot \dot{V}_R \cdot C_p \cdot \Delta T \end{aligned} \quad (12.3)$$

Rearranging for the final (f) temperature after one hour of heating (Equation 12.4)):

$$\begin{aligned} T_f &= \frac{q}{\rho \cdot V_R \cdot C_p} + T_i \\ &= \frac{9.85 \cdot 10^5 \text{ J}}{1.293 \left(\frac{\text{kg}}{\text{m}^3}\right) \cdot 275(\text{m}^3) \cdot 700\left(\frac{\text{J}}{\text{kg} \cdot \text{K}}\right)} + 25^\circ\text{C} \\ &= 28.95^\circ\text{C} \end{aligned} \quad (12.4)$$

This is about a 4 °C temperature change which will continuously add up over time (per hour). The properties of air will change as this temperature goes up such that the denominator in the first term of Equation 12.4 will decrease resulting in a slightly larger temperature change with higher initial (i) temperatures of air. This example calculation was for a constant outside temperature of

90°F (32.22°C), other outside temperatures and their resulting rate of inside temperatures changes are shown below in Table 12.2.

Table 12.2: Initial inside temperature rates (from room Temperature) for hot outside temperatures

Outside Temperature (°F)	Outside Temperature (°C)	Rate of Change (°C/hr)
80	26.66	0.91
85	29.44	2.43
90	32.22	3.95
95	35.00	5.48
100	37.77	7.00
105	40.55	8.53

Note that the same properties of air were used for these values (Table 12.2). Using the actual values would not result in a substantial difference and so such iteration was neglected. There is clearly a linear relationship between outside temperature and the discussed rate as shown in Table 12.2, but these values are derived with a starting temperature of room conditions. Realistically, the temperature rate would decrease over time since the initial temperature (temperature of inside air in Equation 12.2) would be higher and have less of thermal difference to the outside temperature. This table (12.2) is still displayed since it is the most relevant considering that this situation would be encountered the most often since the HVAC system would be turned off for small intervals for which the listed changes would take place. Using an extreme example in which the HVAC system is non-operational during these hot days, the following trends would take place for a constant temperature of 90°F (Figure 12.1):

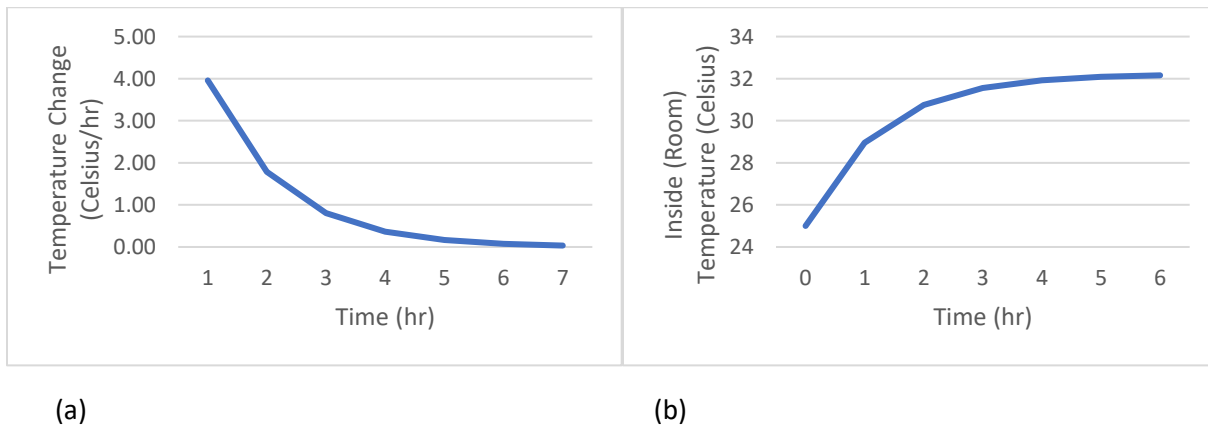


Figure 12.1: (a) Inside air temperature rate and (b) inside room temperature vs time for constant outside temperature of 90°F (32.22°C)

The behavior shown in both parts of Figure 12.1 are expected for any outside temperature, that is that more heat is required for the last part of convergence between the inside room temperature and the outside air temperature. Realistically, the outside air temperature is not constant throughout the day as it shows the following behavior (Figure 12.2):

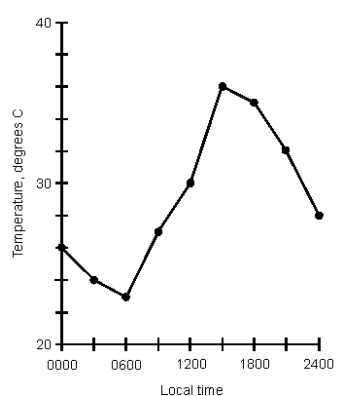
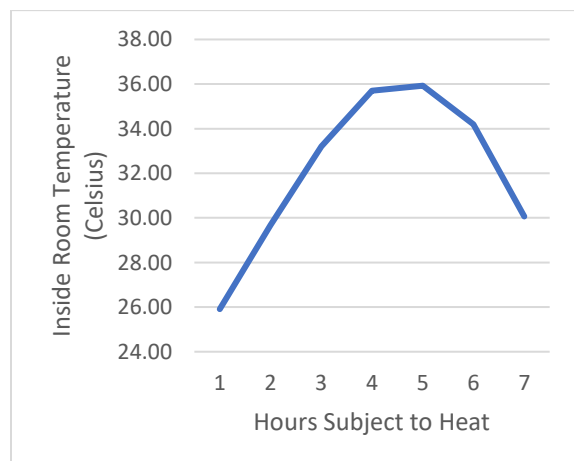
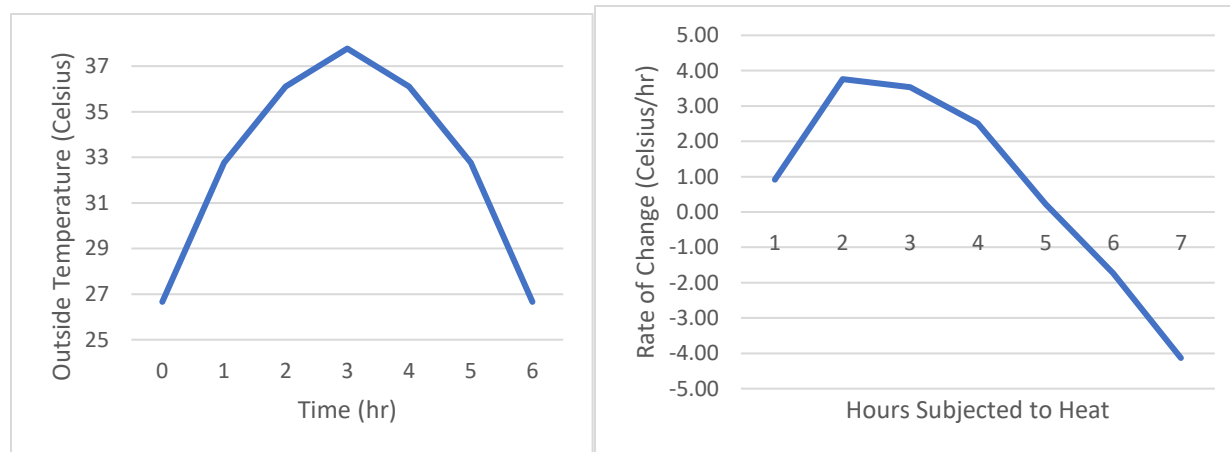


Figure 12.2: Typical time-temperature behavior of outside weather throughout day

It is observed that the region of containing the maximum temperature ($\sim T=1400$ at 2pm) shows parabolic behavior with a concave down behavior. Using the following arbitrary temperature points resembling parabolic behavior, graphs showing adjusted temperature behavior with time of day are derived in Figure 12.3. This figure shows adjusted temperature changes throughout this maximum temperature period. For these results, the average value of this maximum is around 90°F such that minimum of the parabola is 80°F and the maximum is 100°F .



(c)

Figure 12.3: (a) Outside temperature vs time into hottest part of day (6-hour time window), (b) Rate of temperature change of inside air temperature per hour vs time elapsed in which heat acts on house, (c) Resulting inside room temperatures vs time in which heat was subjected to house

This figure (12.3(b)) shows a greater fluctuation in indoor temperature change because the inside air temperature is converging away from and diverging towards the outside air temperature. The first half of the parabola (b) corresponds to heating of the indoor temperature whereas the second half (mind the delay in temperature emitted vs received) reflects the state in which the indoor temperature catches up to the decreasing outdoor temperature and begins cooling (negative values shown).

This model is for the case in which cooling is not provided in the house. It also serves as guidelines for the best times to operate at relative to temperature maximums of the days. Seeing that there is an exponential increase in the behavior of the rates into the hot part of the day, it is better to operate the system in accordance with when these temperature rates (values in b) are the highest relative to a hot period. This is indicating that operating the in an increasing such with increasing frequency corresponding to these rates is the best option for avoiding temperature spikes. Hotter days, defined as days with higher maximum temperatures, will have wider parabolas which reflect longer periods of heat induction. In the peak months of summer, the sun is not only closer to the relevant surface but is more perpendicular to the axis of rotation such that the sun is closer for a longer period, which for Texas means sunsets at modest conditions of 80°F.

12.1 Cooling Times

Unlike the previous section (Section 12), this section will use mass/volume balances to determine the time it takes to cool a room given a particular room temperature. This is more practical approach for predicting cooling scenarios since the only variable that is absolutely known by the user is the inside temperature. The previous section required the user to consider the time of year and the subsequent hot zone of the day. Based on this inside temperature, the amount of time it takes to cool will be used with the volume of inside air before cooling (V_I) and the volume inside air produced from the duct system (V_A). These two volumes will occupy the total volume of air inside the house (V_T) consisting of V_I entirely for the initial stages and gradually shifting to V_A over time through the following relationship (Equation 12.1.1):

$$V_T = V_I + V_A \quad \text{with Initial Conditions } V_A = 0 \text{ at } t = 0 \quad (12.1.1)$$

Equation 12.1.1 implies that the volume of the house expands with time, but this is not the case as air is vacuumed back into the air handler such that V_I diminishes with time. This return flow is cooled and pushed through the duct system as supply air (V_A) such that the entirety of the room is eventually occupied by. The temperature of supply air is 15°C and so the long term behavior of the system results in inside air temperatures of 15°C but this system will not practically be ran that long. Because of this, the behavior of Equation 12.1.1 is analyzed over time to determine practical cooling times.

Coefficients were derived which account for the volumetric composition of the inside air as a function of time (Equations 12.1.2, 12.1.3).

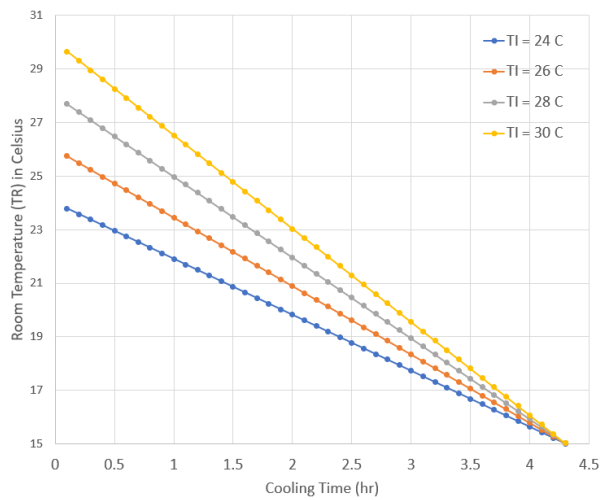
$$C_I = 1 - \frac{\dot{V}_A}{V_I} \cdot t \quad (12.1.2)$$

$$C_A = \frac{\dot{V}_A}{V_I} \cdot t \quad (12.1.3)$$

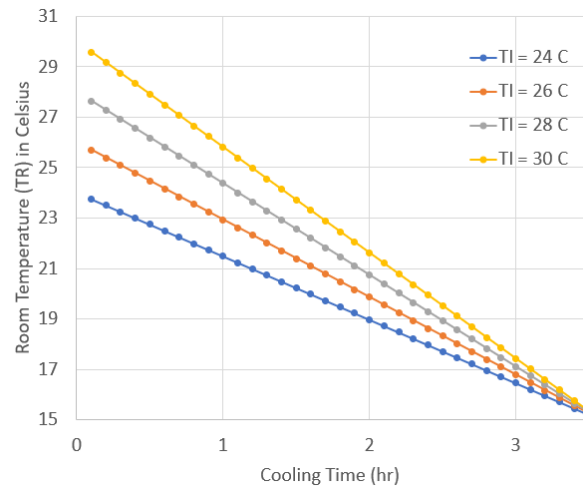
Using these coefficients, the following equation is derived for the overall temperature of the inside air, T_R , which is shown below in Equation 12.1.4:

$$T_R = \frac{C_I \cdot V_I}{C_A \cdot V_A + C_I \cdot V_I} \cdot T_I + \frac{C_A \cdot V_A}{C_A \cdot V_A + C_I \cdot V_I} \cdot T_A \quad (12.1.4)$$

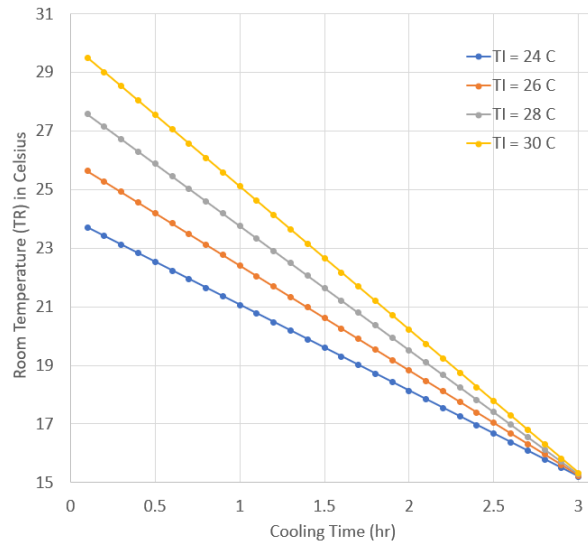
There are different air temperatures (T_I) that this system will be run at, and simulations will therefore be run individually. The first simulation will be run at 1000 CFM, with starting temperatures of 24, 26, 28, and 30 °C which are 75.2, 78.8, 82.4, and 86°F, respectively. These temperatures (T_I) range over possible values that this house would heat up to because of hot outdoor temperatures. The figure below (12.1.1) shows how each initial temperature will progress with time because of cooling for the five different flow rates.



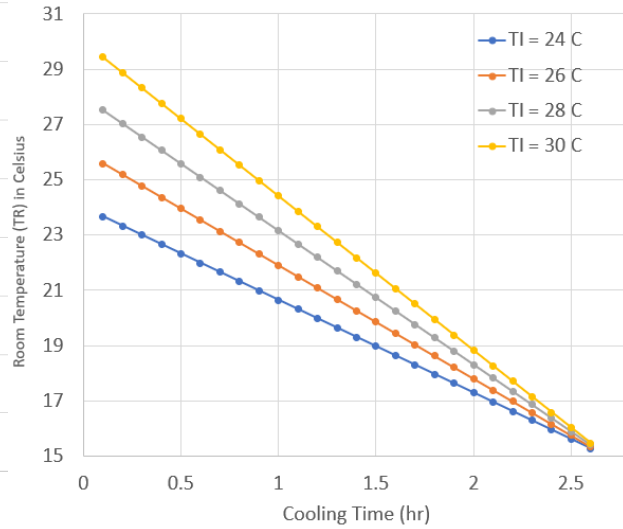
(a)



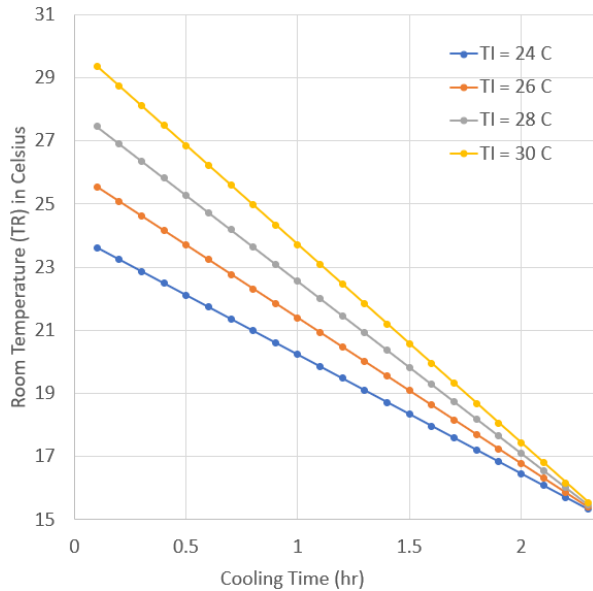
(b)



(c)



(d)



(e)

Figure 12.1.1: Room Temperature (T_R) decreases over time with (a) 1000 CFM (b) 1200 CFM (c) 1400 CFM (d) 1600 CFM and (e) 1800 CFM

Observing Figure 12.1.1 above, the inside air (room) temperatures approach the duct system air temperature a lot faster for higher flow rates (CFM) which is expected. All these graphs shown long term behavior, that is the system running a cooling interval on the scale of hours that is much longer than what will practically happen. The long-term behavior is useful because it gives a picture of how the system behaves start to finish. Realistically, only the first portion of each graph (where room temperature T_R reaches $\sim 24^\circ\text{C}$) should be considered in which the temperature is lowered from its starting value, slightly above room temperature, to around room temperature. The time in which this

takes ranges from 45 minutes to 90 minutes depending on flow rate and initial condition. All these trends are linear since the linear combination that was implemented is just a superposition of the two states: initial air temperature and duct air temperature. Also notable is the cooling difference in cooling rates (slopes) that exist for the different initial room temperatures indicative that it is easier and more cost effective to cool the house from hotter temperatures which would correspond to having the thermostat set higher.

13 Economics

To see how much a system will be typically used, it is necessary to first compare the amount of heat absorbed by the house and the amount of cooling generated within it. The process for estimating time contributions is considering both the results in Figure 12.1.1 (cooling times) and Figure 12.3 (part c, heating times) and combining these results. From Figure 12.3 for the most critical heating part of the day, it is observed that a typical heating surge will result in a 10-15 degree (Celsius) change of inside air temperature over the time span of 5-6 hours. This means that for the time it takes to heat the house by 10-15 degree Celsius can be proportioned to the amount of time it takes to cool the house by 10-15. Taking the slopes of these values (change in temperature/change in time) it is known that the sun heats the house at about 2.3 degrees celsius per hour (HR) while the system cools at rate depending on the air handler flow rate, all values that are calculated and shown below in Table 13.1:

Table 13.1: Cooling Rates (°C/hr) of different air handler flow rates

	$T_i = 24\text{ }^{\circ}\text{C}$	$T_i = 26\text{ }^{\circ}\text{C}$	$T_i = 28\text{ }^{\circ}\text{C}$	$T_i = 30\text{ }^{\circ}\text{C}$
CFM = 1000	-1.87	-2.29	-2.71	-3.13
CFM = 1200	-2.26	-2.76	-3.26	-3.77
CFM = 1400	-2.64	-3.22	-3.81	-4.40
CFM = 1600	-3.01	-3.68	-4.35	-5.02
CFM = 1800	-3.39	-4.14	-4.90	-5.65

Using the cooling rates (CR) and the heating rates (HR), the following is derived to determine the time needed to cool the house such that the accelerated heating of inside air is minimized (Equation 13.1):

$$t_{\text{cooling}} = t_{\text{heating}} \cdot HR + \frac{\Delta T}{CR} \quad (13.1)$$

Using this equation (13.1), cooling times are calculated for each of the following scenarios in which the inside temperatures being at the different T_i 's (24, 26, 28, and 30 °C) and end at 24 °C (Table 13.2).

Table 13.2: Cooling times(hr) to inside temperature of 24 °C for each CFM and initial inside temperature (T_i)

	$T_i = 24\text{ }^{\circ}\text{C}$	$T_i = 26\text{ }^{\circ}\text{C}$	$T_i = 28\text{ }^{\circ}\text{C}$	$T_i = 30\text{ }^{\circ}\text{C}$
CFM = 1000	3.69	3.89	4.02	4.12
CFM = 1200	3.05	3.22	3.34	3.42
CFM = 1400	2.61	2.76	2.86	2.93
CFM = 1600	2.29	2.42	2.51	2.57
CFM = 1800	2.04	2.15	2.22	2.28

It is observed that most of the models need around 3 hours of cooling time to alleviate the mid-day heat surge for a 100 °F maximum temperature. Referring to Figure 12.2 (Temperature vs time of day graph) and the parabolic assumption that was applied to it, an equal amount of required cooling can be assumed due to the symmetric nature of the outside temperature. Since conduction/convection is a linear process, the amount of cooling is proportional to the amount of time a behavior occurs. Translated to this scenario, the amount of cooling needed to prevent the temperature rise during the mid-day climate surge is the same amount of cooling that is needed to keep the room temperature constant during the afternoon/evening cool down. Using results from Table 13.2 and simply doubling them, the amount of cooling is calculated and shown below in Table 13.3:

Table 13.3: Cumulative cooling times (hr) 100 °F for day.

	T _i = 24 °C	T _i = 26 °C	T _i = 28 °C	T _i = 30 °C
CFM = 1000	7.38	7.77	8.04	8.24
CFM = 1200	6.11	6.45	6.69	6.84
CFM = 1400	5.23	5.53	5.72	5.86
CFM = 1600	4.58	4.84	5.01	5.14
CFM = 1800	4.07	4.30	4.45	4.57

The cheapest option would be to only operate the cooling system during necessary times which are from early May through September. Using data provided online (13.1), the average daily high temperature in Amarillo (nearby city) was 91.1°F. This value is 91.1 % of the value used above in Tables 13.2 and 13.3 so the amount of cooling will be assumed linear to this proportion such that the times are 92.6% of the values shown above. The results are shown in Table 13.4:

Table 13.4: Average operating times (hr) for summer day

	T _i = 24 °C	T _i = 26 °C	T _i = 28 °C	T _i = 30 °C
CFM = 1000	6.72	7.08	7.33	7.51
CFM = 1200	5.56	5.88	6.09	6.23
CFM = 1400	4.76	5.04	5.21	5.34
CFM = 1600	4.18	4.41	4.57	4.68
CFM = 1800	3.71	3.92	4.05	4.16

13.1 Electricity Estimates

Using the daily cooling times (Table 13.3) along with air handler work values (Table 10.6.1), the amount of electricity required to operate an air handler for a day is calculated. The efficiency of a given air handler model was assumed to be 70 percent which is the typical values amongst available models [13.1.1]. The daily electricity usage per scenario is calculated using this efficiency and the results are shown below in Table 13.1.1:

Table 13.1.1: Average price (USD) for daily electricity use during hot season

	T _i = 24 °C	T _i = 26 °C	T _i = 28 °C	T _i = 30 °C
CFM = 1000	1.09	1.15	1.19	1.22
CFM = 1200	1.57	1.65	1.71	1.75

CFM = 1400	2.13	2.25	2.33	2.39
CFM = 1600	2.78	2.94	3.04	3.12
CFM = 1800	3.53	3.72	3.85	3.96

Note that these prices were derived using the typical cost per kilowatt-hour in the state of Texas (14.77 cents/kWh) [13.1.2]. Multiplying these daily values by the number of days in the summer period (105), the amount of money spent due to the HVAC air handler over the summer period for different scenarios is calculated as follows (Table 13.1.2) [13.1.3]:

Table 13.1.2: Expected price (USD) of air handler operation for hot season (total)

	$T_i = 24\text{ }^{\circ}\text{C}$	$T_i = 26\text{ }^{\circ}\text{C}$	$T_i = 28\text{ }^{\circ}\text{C}$	$T_i = 30\text{ }^{\circ}\text{C}$
CFM = 1000	154.3	162.6	168.2	172.4
CFM = 1200	220.7	233.1	241.7	247.4
CFM = 1400	300.0	317.3	328.4	336.5
CFM = 1600	392.7	414.3	429.2	440.2
CFM = 1800	497.2	525.2	543.4	557.8

Using this table (13.1.2) the results are graphed to visualize the financial behavior for the different scenarios (Figure 13.1.1):

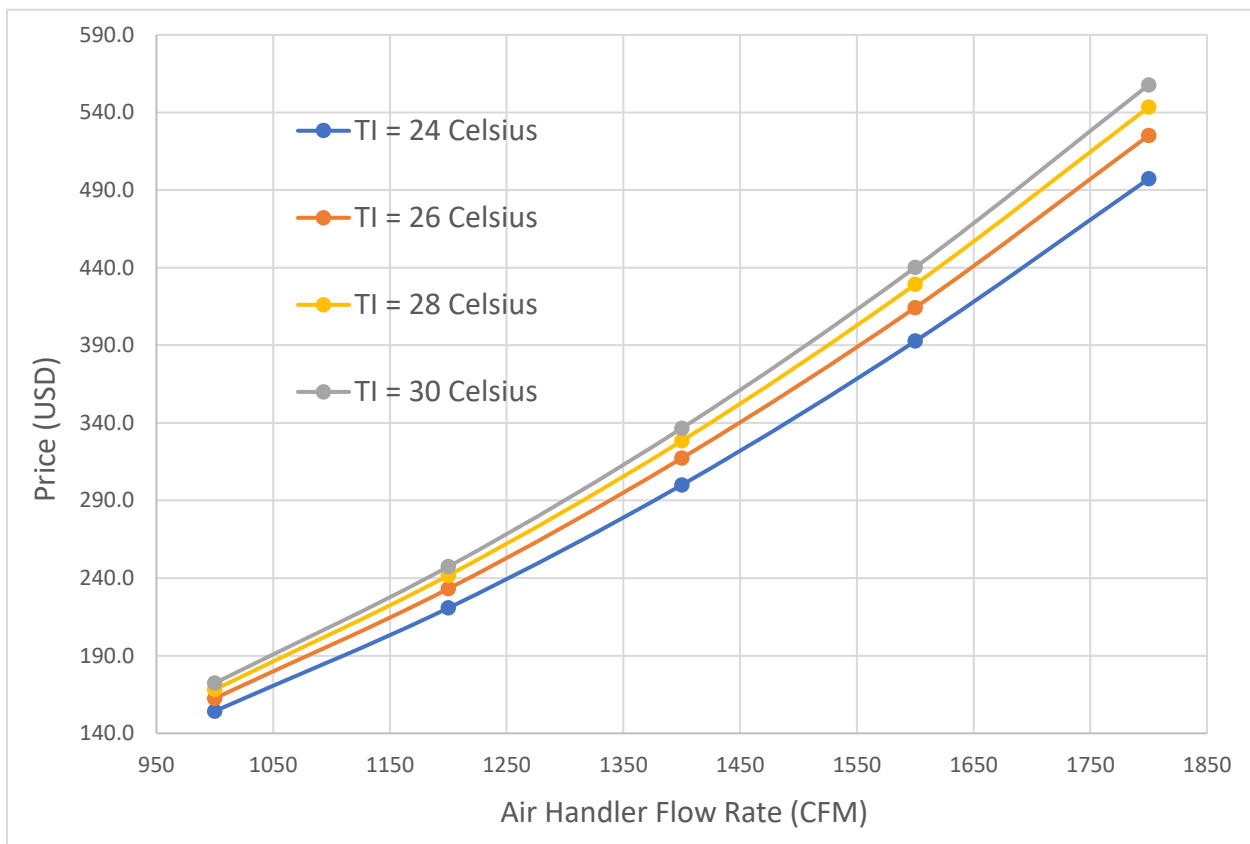


Figure 13.1.1: Yearly prices for air handler operation based on flow rate and initial room temperature T_i .

The most notable difference in this figure (13.1.1) is the slight exponential behavior such that a higher air handler flows rate results in a proportionately higher cost. Seemingly, the best option would be to buy the lowest possible CFM model, one that would always run during the day, to save as much money as possible. There are two deceptive drawbacks to this solution and those are the constant noise the system that would make in the middle of the house (living room) as well as the inability to cool fast in extreme situations. A situation where the outside temp is 100 °F and the users decided to turn off the system to save money (say coming back from vacation), allowing the house to heat up during vacancy, can result in a more difficult experience in cooling. Such as system is also prone to not being able to provide adequate cooling during days where temperatures are extremely hot (>110 °F) especially when the system has years of wear and tear. So how important these drawbacks are will be independent to each user. Looking again at Figure 13.1.1, there is a noticeable in divergence between the room temperatures for a given air handler flow rate. One of those differences (CFM = 1400) is graphed below to visualize (Figure 13.1.2):

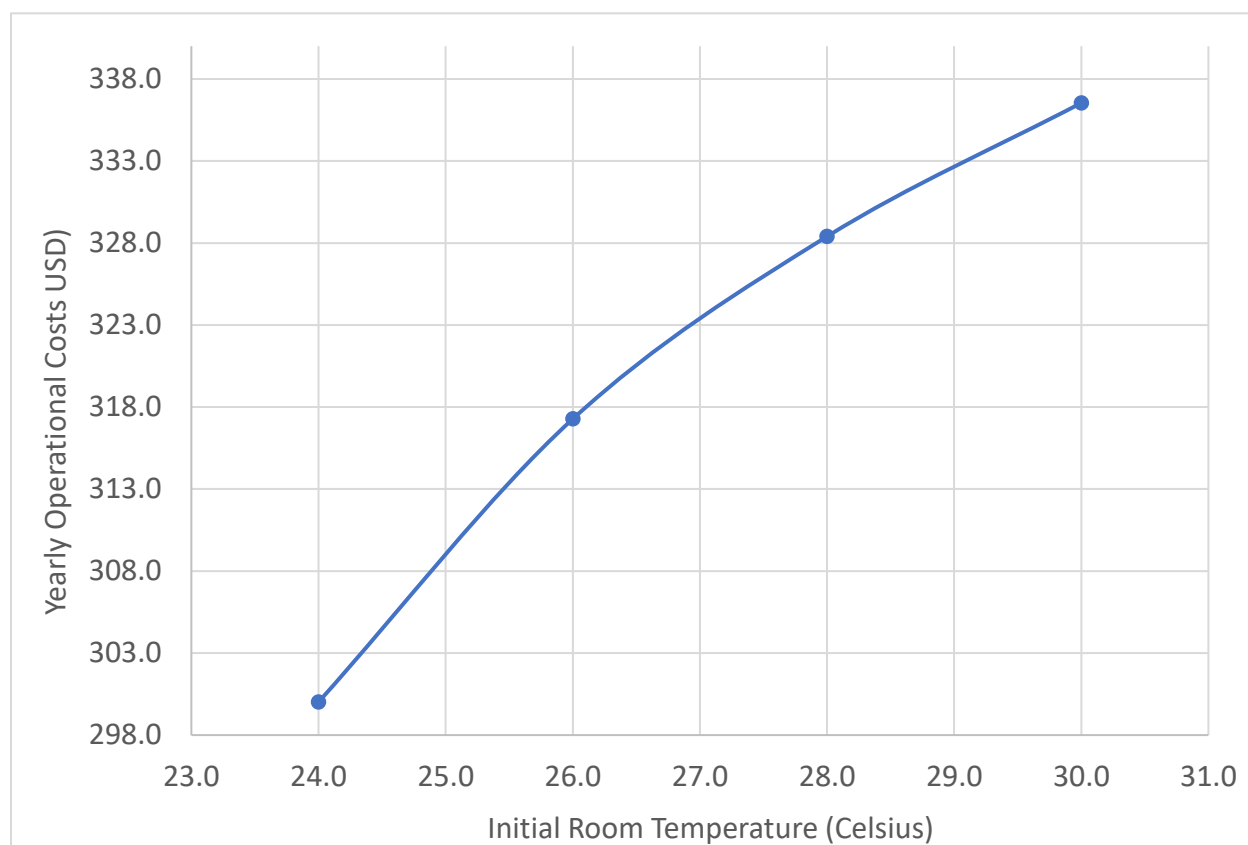


Figure 13.1.2: Yearly operational costs for certain flow rate (CFM = 1400) vs initial inside temperatures (high point)

This figure (13.1.2) shows a logarithmic behavior in that it is favorable to have a higher initial temperature. This is indicative of the reality that cooling from a higher temperature is more efficient than cooling from lower temperatures, as discussed in Figure 12.1.1 and Table 13.1. Lastly for this section, the seasonal to yearly assumption is confirmed by researching temperature data throughout

the entire year. Results show that indeed the hot season will be the only required time of operation throughout the year as temperatures noticeably drop after September (Figure 13.1.3):

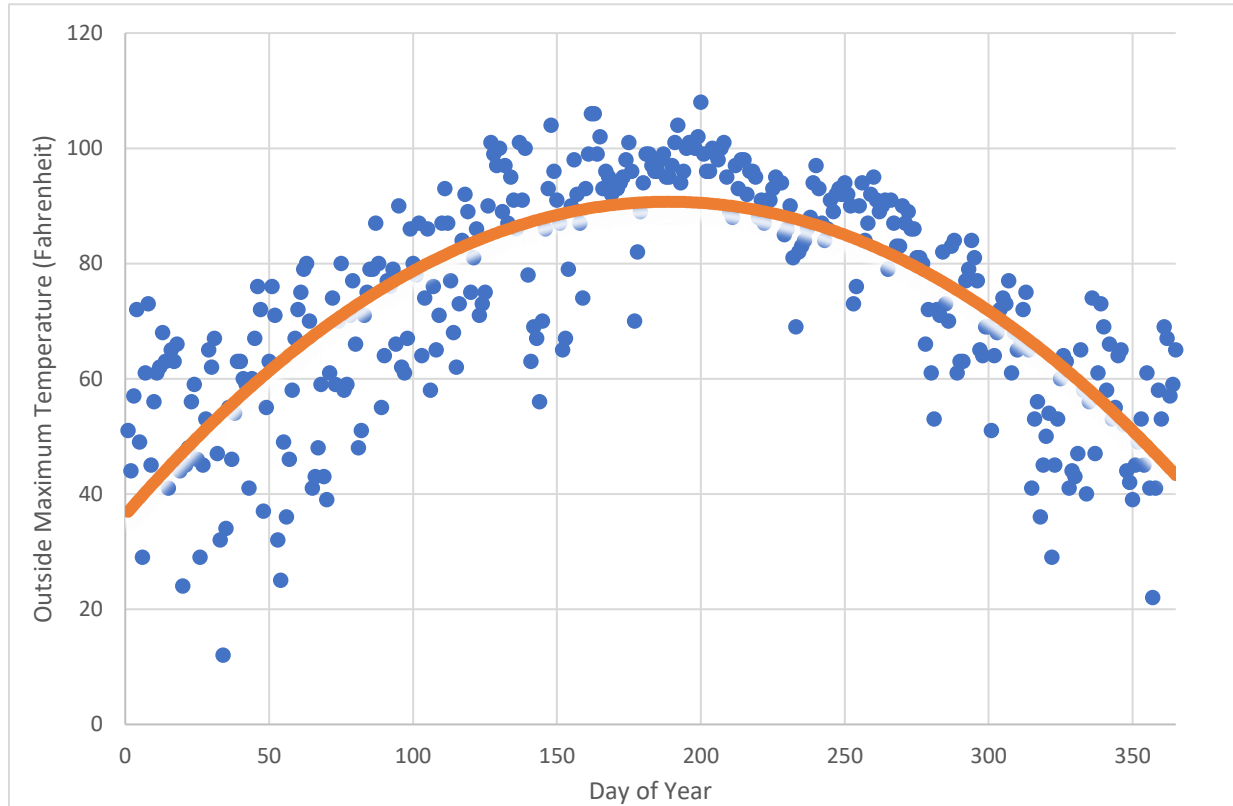


Figure 13.1.3: Temperature vs day of year in northern Texas [13.1.3]

Due to this behavior (Figure 13.1.3), cooling operations during the colder parts of the year are be deemed negligible.

13.2 Duct System Cost

The cost of the duct system will be calculated using typical costs of materials (aluminum, galvanized steel) based on available resources. Knowing the duct system (Figure 9.1) along with duct and pipe dimensions (Tables 9.1, 9.3 and 9.4), the cumulative price of each component was determined using found unit prices (Table 13.2.1):

Table 13.2.1: Duct system component costs

Component	Unit Price (USD)	Unit	Cumulative Units	Cumulative Price (USD)	Source
Pipe Length	16	60" Length	871.4 inches	233	[13.2.1]
Pipe Elbow	7	Single Elbow	12 elbows	84	[13.2.2]
Air Vent	8	Single Vent	6 vents	48	[13.2.3]
Duct	30	60" Length	371.6 inches	186	[13.2.4]

Adding the cumulative prices in Table 13.2.1, the total theoretical cost of the duct system is \$643. The price of duct in Table 13.2.1 did not take into consideration the price of duct fittings as these are individually manufactured unique to demands. There are only two fittings in the main duct (D1F1, J3) that need to be considered as J1, J2, J4, and J5 junctions are the result of cutting holes into the duct and so no equipment is required. The cost of these duct fittings needs to be approximated and so a value of 50 dollars for these two fittings will suffice such that the total cost of this duct system can be estimated to be \$700.

14 Recommendations

This section will summarize behavioral findings of system performance in terms of financial outcomes and suggest potential air handler models for installation. As mentioned in section 13.1, the preferences of not having the system run all the time due to noise as well as the hinderance to cool in extreme scenarios are up to the user. Multiple models will be provided around the optimization of these preferences vs the higher cost, higher flow rate air handler models. To get a model on the cheap side, the minimum CFM to run during expected conditions is found using unperturbed temperature behavior of the house (Figure 12.1.1 (c)) which shows that the maximum cooling time for a day is around 8 hours. Anything significantly above this value will result in accumulation during the heating period that will have to be cooled by means of reverse conduction, that is cooler outside than inside temperatures, in other words, the user will have to wait until night for nature to take its course. Additionally, cooling times for different conditions (Table 13.4) were used for extrapolating trendlines to predict times at lower flow rates (down to 800 CFM). This behavior was compared to the maximum cooling time (8 hours) in the figure below (14.1):

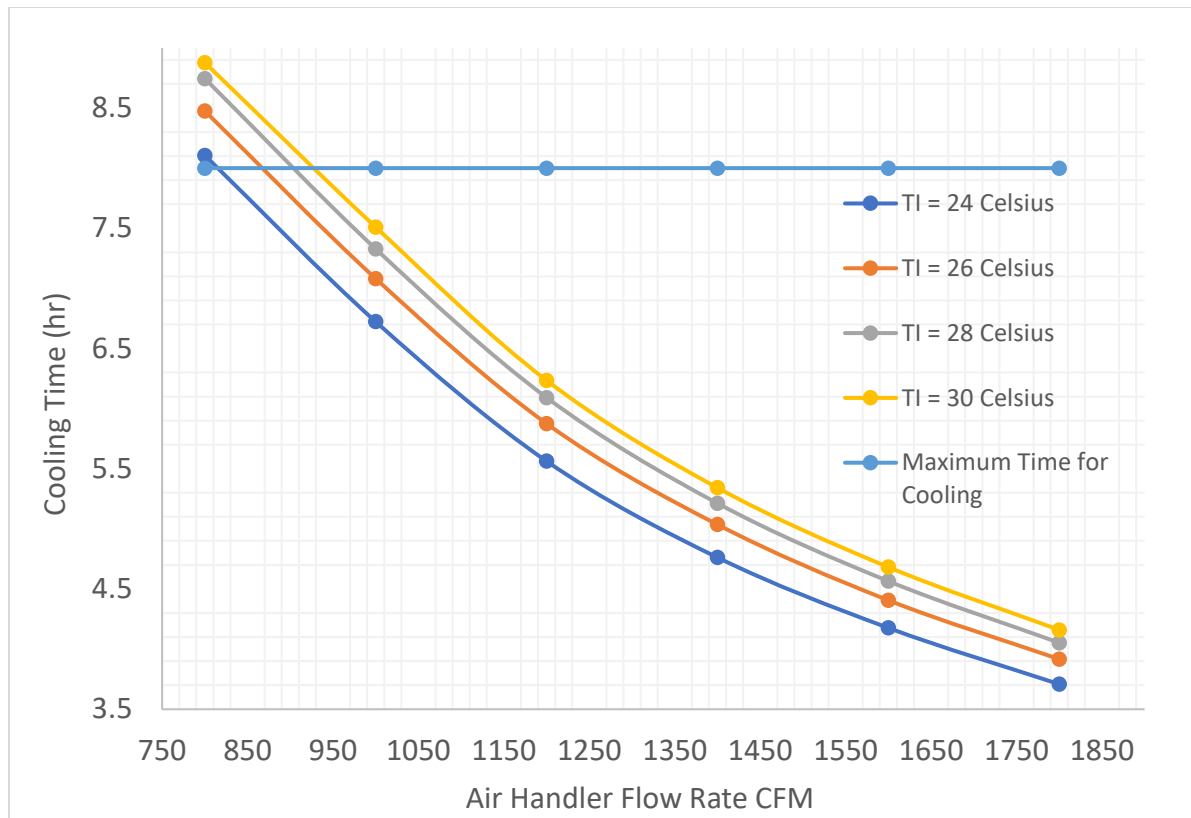


Figure 14.1: Minimum flow rate (air handler) determination using extrapolated cooling times along with max temperature

It is seen in Figure 14.1 that the minimum flow rate is around 950 CFM by the intersection of the two functions. The expected flow rate is around 1400 so this will be considered the medium value and the upper range is around 1800 which will be considered the upper value. On the flip side of the minimum, there is no distinct maximum flowrate for an air handler so long as the duct system does not get worn down due to turbulence and if there is enough electrical supply, but such an option is impractical and would be theoretically expensive. Knowing all this information, 3 air handler models will be recommended from basic research into what the market has available.

A company was found, Goodman, that offers reasonably priced models for residential homes of varying sizes. For the low range, the AVPTC 25B14B* model was selected (Figure 14.2).



Figure 14.2: Low flow rate air handler (AVPTC 25B14B*)[14.1]

The next model presented is a medium flow rate handler also provided by Goodman (Figure 14.3).



Figure 14.3: Medium flow rate air handler (AVPEC 37C14A*) [14.2]

The last model is one that nears the upper flow rate range and is also provided by Goodman (Figure 14.4).



Figure 14.4: High flow rate air handler (AVPEC61 D14A*) [14.3]

A performance-price comparison of the 3 models is shown below in Table 14.1.

Table 14.1: Comparison of air handler models

Model	Producer	Flow Rate Range	Flow Rate (CFM)	Price (USD)	Source
AVPTC 25B14B*	Goodman	Low	1085/610	1330	[14.4]
AVPEC 37C14A*		Medium	1700/800	1550	[14.5]
AVPEC61 D14A*		High	2000/1600	1830	[14.5]

15 Air Flow Simulations

Bernoulli Equation calculations for pressures are only theoretical predictions derived from typical fluid behavior. While the only true empirical model that can be created for this duct system is observing the system itself, observing predictions through a simulation software such as SOLIDWORKS is much closer to an empirical result than textbook equations. The flow simulations use initial and final air pressures, that is the pressure at the air handler (calculated – Section 10.5) and the atmospheric pressure in the rooms. Additionally, the inletting volumetric air flow was required and used for each simulation. A total of 10 simulations were ran, 2 for each flow rate (CFM = 1000, 1200, 1400, 1600, 1800) with a velocity and pressure profile produced for each.

15.1 Duct System Pressure Distribution

The pressure profiles are used to gauge relative pressure differences around junctions to compare and validate head loss coefficients used in Table 10.1.1. Models will be shown in which warmer colors correspond to higher pressures and cooler colors to lower pressures. While the pressure values for a given flow rate at a location in the duct remained constant throughout the upcoming figures, the color scale was changed to visualize discrepancies more feasibly. The 4 figures in this section (15.1.1-15.1.4) are of the same simulation but have different angles and color scales. Figures for all flow rates are shown in Appendix G but only figures for the highest flow rate (1800 CFM) are shown in this section and used for comparison to theoretical values. The properties of this high flow rate are easier to distinguish than the for the lower flow rates because of larger differences across the system. Beginning, the pressure system of the duct system is shown below in Figure 15.1.1:

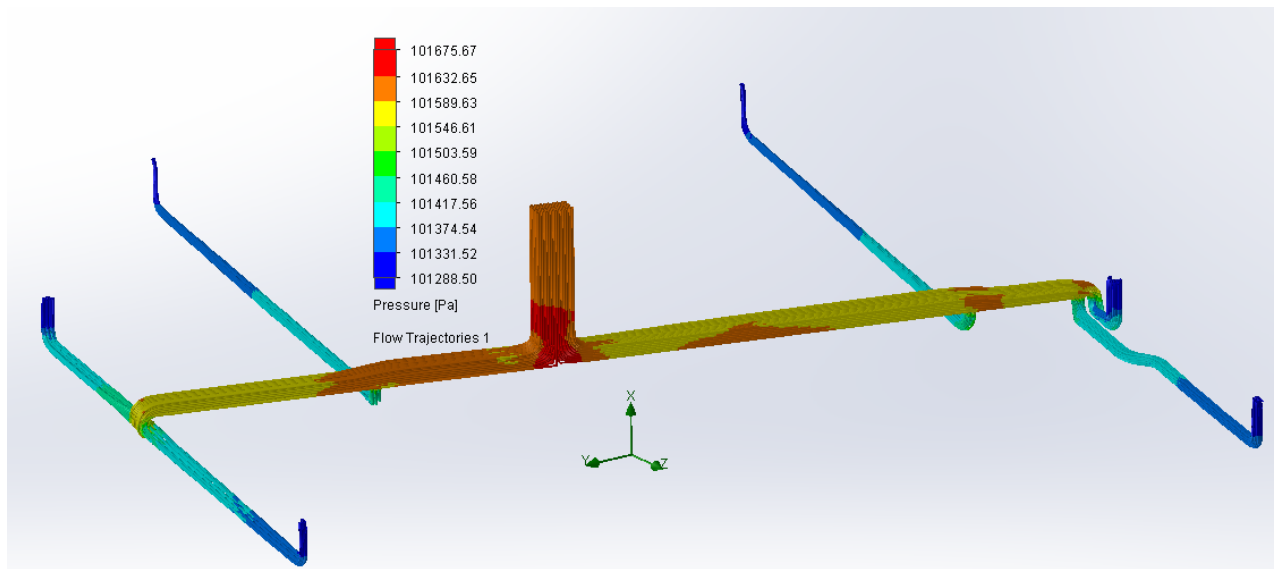


Figure 15.1.1: CFM 1800 overall pressure distribution of duct system

One disclaimer is the transparency mode for the model was not displaying correctly and so the section view was used in which the duct/piping material is invisible such that only the flow trajectories are shown. It is noticed from this figure (15.1.1) that the pressure gets lower and lower as the air progresses from the air handler (rising part) to the pipes (branching parts). This correlates with predictions from the calculations used. Taking closer views at each of the subsections, specifically the fittings, it is observed in the right portion of Figure 15.1.1 that the following pressure behavior takes place (Figure 15.1.2):

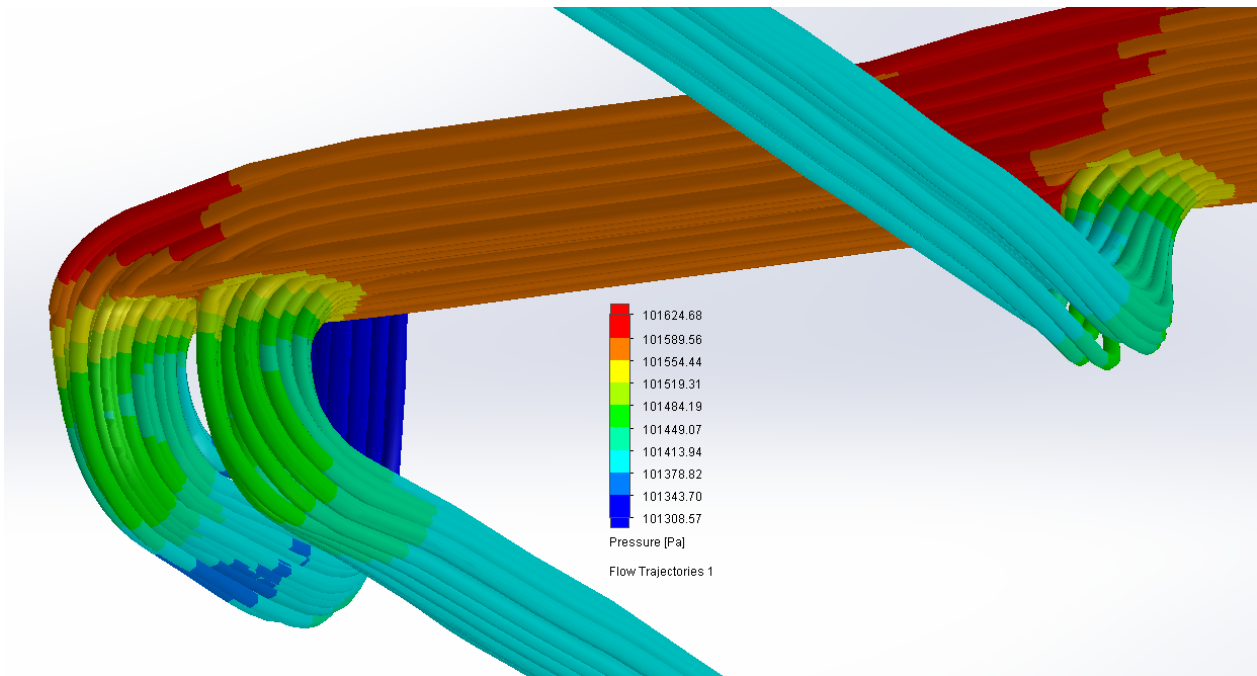


Figure 15.1.2: CFM 1800 pressure distribution of J2 (right), J4 (left)

There is evident pressure buildup in the reduction after J2 and the elbowing portion of J4 shown in Figure 15.1.2. Between the two junctions, it appears as though the head loss due to J2 (red) is greater than that of J4 (yellow). Looking back at the head loss coefficients described in Table 10.1.1, the values for J2 and J4 were 0 and 0.9 respectively. This contradicts behavior observed in the simulation in that reductions (J2) should have a value greater than the 0.9 which estimated would be about 2. This source of error will carry over to the other side of the duct and so head losses due to reductions were mistakenly not considered for portion of the duct system. If these head losses were considered, the pressures of the air handlers would be slightly greater as would the subsequent prices. Decreasing cross-sectional area increases turbulence as air is compressed. Design of this duct was implemented to anticipate volumetric flow distributions at the junction such that a significant amount of flow would branch off warranting a substantially smaller line flow duct. The results of this simulation suggest that installing a duct of uniform size, while slightly more expensive due to the larger amount of material, will save money over time.

Note that the regions of higher pressure correspond to where energy is lost, such that an ideal system would have a more uniform color distribution. What is more so about this illustration (Figure 15.1.2) is that the elbow at the end of the duct (J5), that is the duct cap on the left side, contributes to a significant amount of head loss as indicated by the high pressure with the red color. The air flow is pneumatically unfavorable since air is being compressed up against a wall and then forced to take a hard downward redirection. While still abiding by the criteria in the clarifications section (6), an adjustment can be implemented in which a smooth curve by means of reduction would be more favorable. The air must be inevitably redirected so using a longer turn radius would prove more desirable despite the longer distance of head loss. Next, the other side of the duct system containing pipes 1, 2 and 3 is considered in Figure 15.1.3:

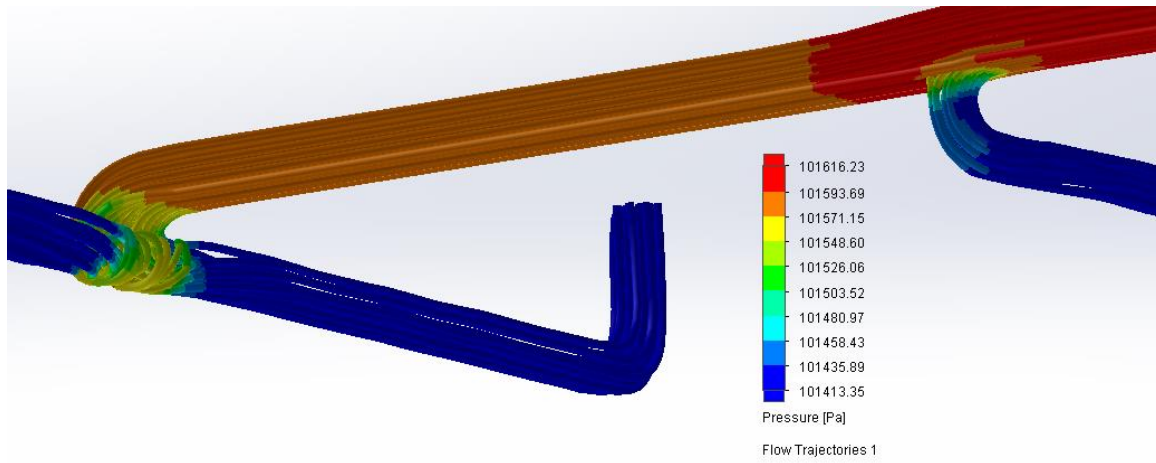


Figure 15.1.3: CFM 1800 pressure distribution of J1, J3

This figure shows more ideal behavior than the other side of the system in terms of pressure distribution. With the exception of the reduction fitting (D1-F2) which has already been discussed, the system shows a gradually decreasing pressure up until the air vents. The results of the ending duct elbow (D1-F4) show a surprising linearity in the progression of the air flow. Like recommendations made about J5, a more rounded corner should prove even more favorable for this apparatus but is certainly not critical. The geometries of D1-F4 and J5 are awfully similar but the pressure distributions are noticeably different. This is because of the orientation difference in branching flows from the two junctions. J5 (Figure 15.1.2) had the two flows branch in series such that the line flow from the first junction had less cross-sectional area to exit out of than D1-F4 (Figure 15.1.3) which had two parallel branch flows. From Drawing 8.6 (b), the alignment and orientation of pipes 5 and 6 prevent them from branching off the main duct in a similar manner as pipes 1 and 2 for J5. A potential compromise for this obstruction is having pipe 5 stem off the bottom of a duct elbow and have pipe 6 branch off the side of the duct elbow, such that pipe 5 travels underneath pipe 6. This would not be too much of a spatial obstruction in the crawl space since this would occur near the wall of the room. The side T-orientation is not as favorable as the symmetric T-orientation as flow will favor pipe 5 over pipe 6 resulting in greater head loss compared to a symmetric stem. The equipment costs of this orientation would be slightly greater due to the extra duct fitting but would be one less pipe elbow required between the pipe 5 and 6 structures. Next, the pressure distribution of the duct entrance (D1-F1, after the air handler) is shown in Figure 15.1.4:

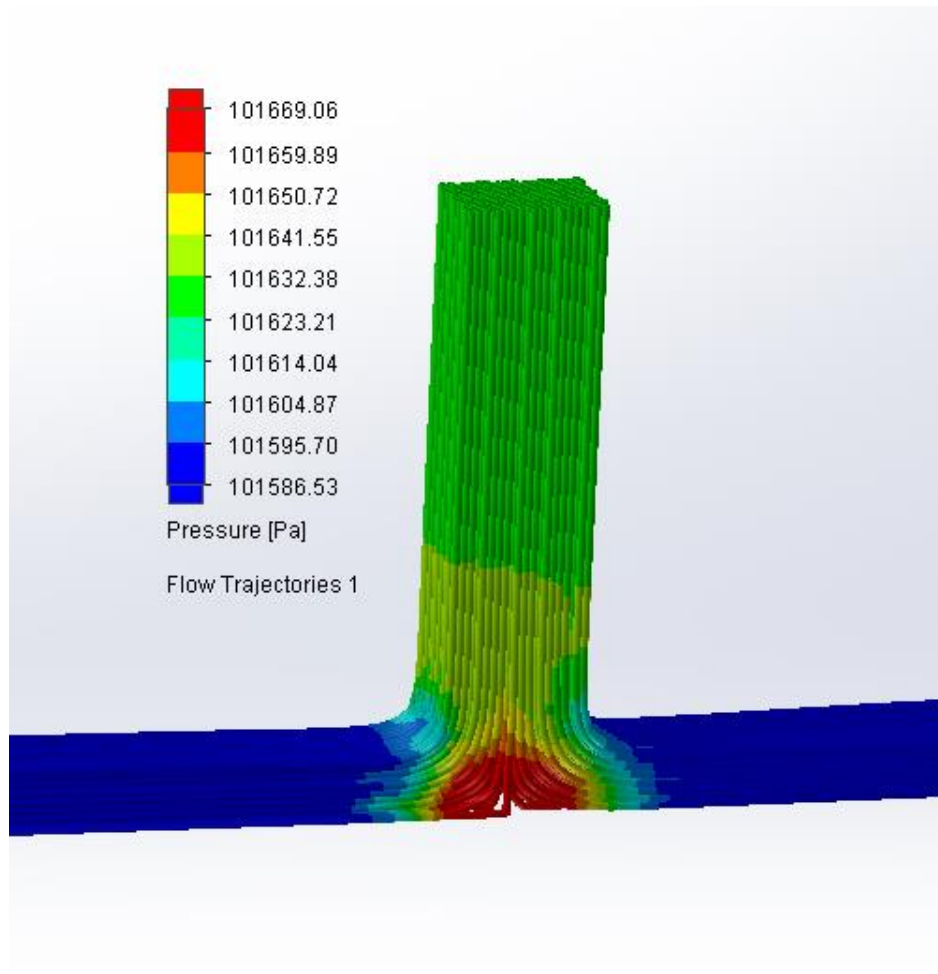


Figure 15.1.4: CFM 1800 pressure distribution of D1F1

Observing the figure (15.1.4), there is an evident buildup in air pressure at the duct fitting that is essentially symmetrical about its geometry. From Table 10.1.1, the head loss coefficient for this fitting is listed at 2. Observing the pressure increase, a proper adjustment would be raising this value to between 3 and 4. This would raise energy costs by a considerable amount. The air handler location with respect to the house as well as the air vents are fixed and so this flow splitting junction is necessary for the system. The only room for improvement in this design (staying on cost-friendly basis) is the to make the fitting more geometrically accommodating to the air flow. Smoothing the inside corners is an option but seems impractical from a production standpoint and considering that most of the pressure buildup is away from these corners, a different approach will be investigated. Changing the angle of the duct system is also not an option as the crawl space needs to be accessible and this would rack up significant duct costs unless a complete revision of the system would be implemented which would still take up room in the crawl space. What is possible is implementing a splitter within the duct that points upward and essentially punctures the incoming airflow into two dividing flows. This splitter would be curved so that the air flow is redirected with before it is able to significantly slow down which will be discussed in the upcoming velocity distribution figures. Such a unique modification would be certainly worth looking into but would increase material costs.

15.2 Duct System Velocity Distribution

In addition to the pressure analysis, models were derived for velocity distributions across the duct system to validate/compare previously derived relationships for flow distributions. The first velocity distribution figure is of the entire system (15.2.1):

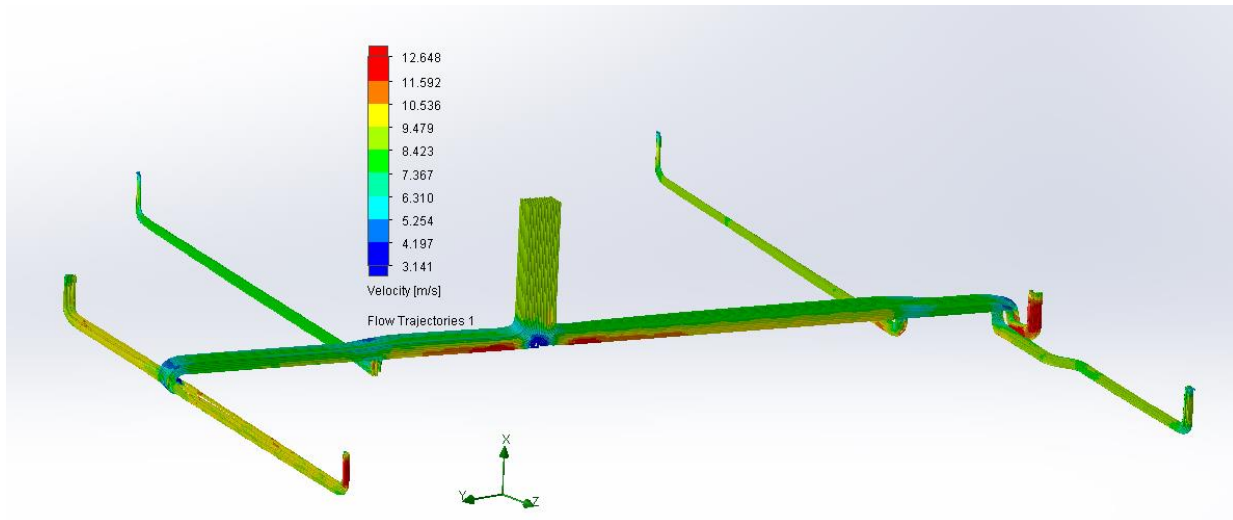


Figure 15.2.1: CFM 1800 overall velocity distribution of duct system

Observing the system initially (Figure 15.2.1), the velocities of the air seem to drop in regions of higher turbulence and remain steady in regions of lower turbulence. Observing more closely, the velocity distribution of air flow through the north side of the system (pipes 4, 5 and 6) is shown in Figure 15.2.2:

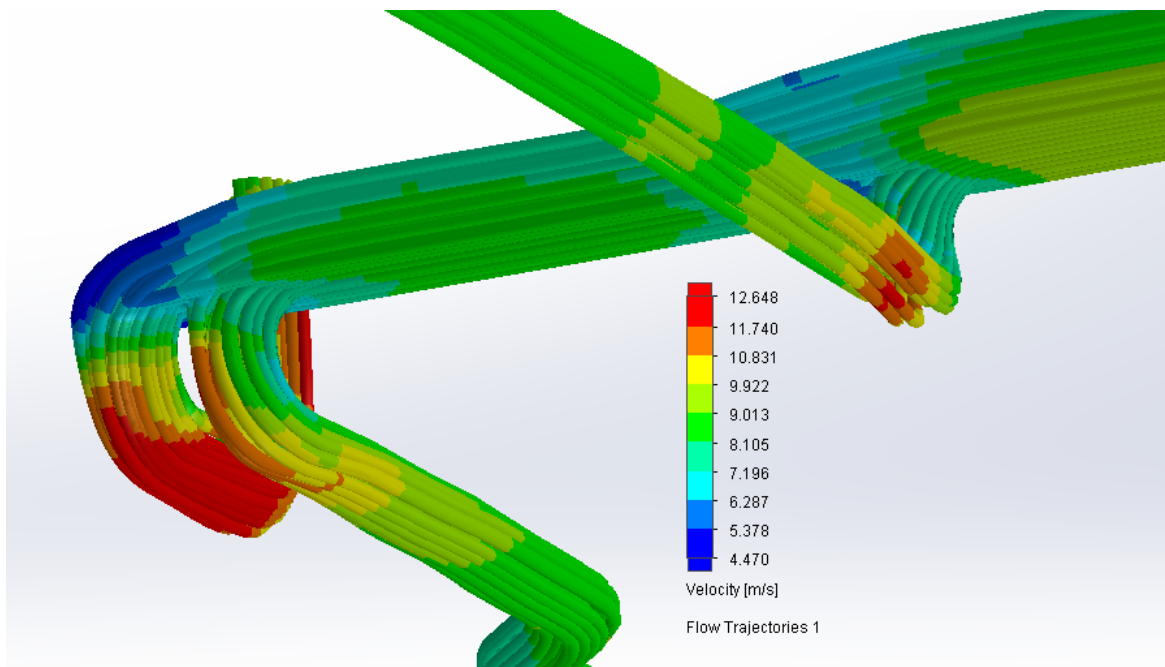


Figure 15.2.2: CFM 1800 velocity distribution of J2, J4

This figure (15.2.2) show that velocity increases in the regions of turbulence (fittings, junctions) such that a pressure buildup initially slows the air flow and then compresses it to move much faster. In assigning a velocity to a particular region (pipe, duct), the average value is taken by assessing the color distribution and subsequent velocity values for that region. These observed values are then compared to the predicted values from Table 10.1.1, as shown in Table 15.2.1:

Table 15.2.1. Observed vs predicted air velocity values for north section of duct system

Region	Observed Velocity (m/s)	Predicted Velocity (m/s) – Table 10.1.1
D1-L2	9.8	8.2
Pipe 4	8.4	3.5
D1-F3	6.3	7.0
D1-L4	8.2	9.3
Pipe 5	8.2	4.0
Pipe 6	13	15.7

These values (Table 15.2.1) are reasonably close for most regions except the branching pipes that are not at the end of the duct (pipes 4 and 5). The predicted velocity flow distributions were too restrictive in delineating flow from the duct to these branching pipes. While it is true that the flows are greater in the pipes that receive the end of the duct flow (Pipe 6 in Figure 15.2.2 and Pipes 1,2 in Figure 15.2.3), this difference is realistically more narrow than predicted. The simulation predicts that a more uniform air distribution takes place and therefore a more uniform temperature distribution in the cooling of each room. An ideal system would have completely uniform flow between these 6 pipes so one potential and while an ideal design is unrealistic, things can be improved with relatively simple adjustments. One of these is to increase the size of the earlier branching pipes (4 and 5 for this side of the duct system). This will allow these branching pipes to capture more air and depending on the room priorities in the house (in terms of air flow) will result in closer to predicted cooling times. Simply reducing the end pipe(s) (6 inches to 4 inches this case) will increase the pressure and velocity at the end of the duct trunk, so this idea is dismissed. Despite the increased up-front material costs via bigger pipes, the long-term savings are respectable since a more uniform heating system will be in place. A more uniform system in terms of flow rates delivered to each room will result in lower cooling times. Additionally, there will be less head loss to frictional forces. Continuing, the other side (south) containing pipes 1, 2 and 3 of the duct system and its respective velocity distribution is shown in Figure 15.2.3:

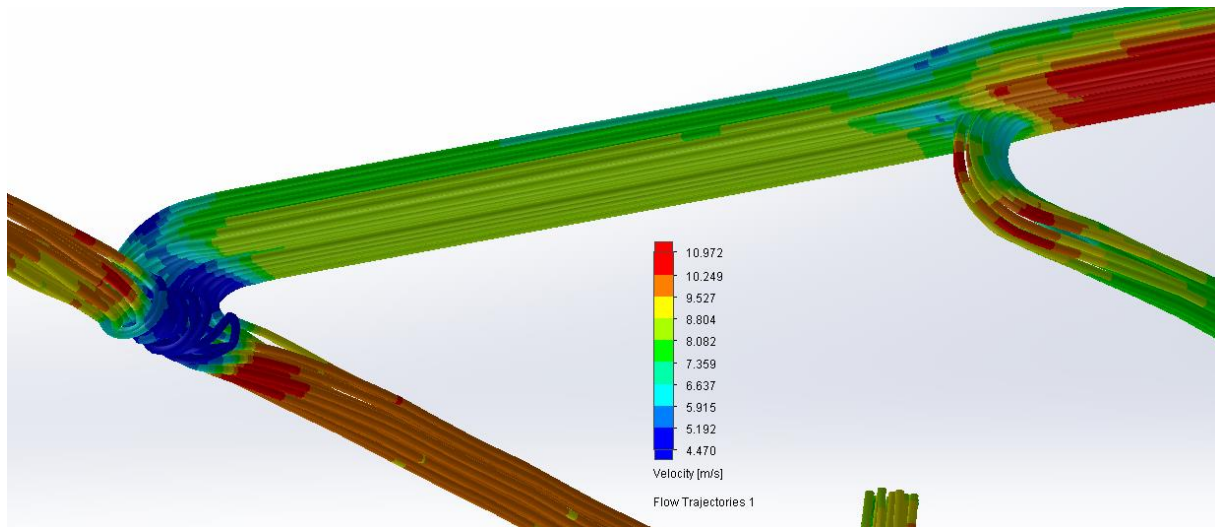


Figure 15.2.3: CFM 1800 velocity distribution of J1, J3

Observing this figure (15.2.3), the theoretical velocities are compared to the observed values as done for the northern section of the duct system. The results are listed below in Table 15.2.2:

Table 15.2.1: Observed vs predicted air velocity values for south section of duct system

Region	Observed Velocity (m/s)	Predicted Velocity (m/s) – Table 10.1.1
D1-L1	9.1	8.2
Pipe 3	7.5	3.5
D1-F2	8.6	7.0
D1-L3	8.1	9.3
Pipe 1	9.8	9.9
Pipe 2	9.8	9.9

Observing these numbers (Table 15.2.1), the only substantial difference is the first branching pipe (3) which follows the concepts discussed previously. Continuing, the velocity distribution around the entrance of the duct system (D1-F1) is shown below in Figure 15.2.4:

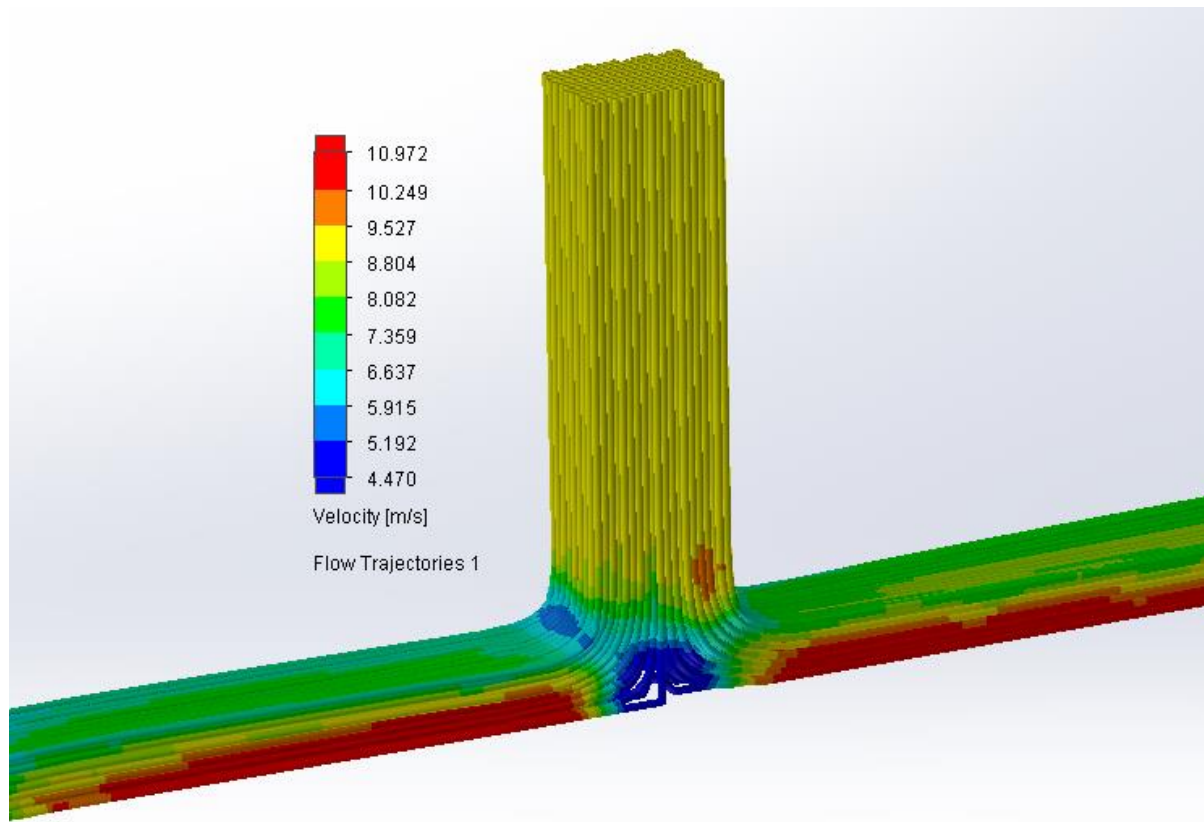


Figure 15.2.4: CFM 1800 velocity distribution of D1F1 (South section on left)

This figure (15.2.4) confirms that the stagnate air flow (blue) is the cause of the increased pressure zone shown in Figure 15.2.4. The most interesting trend of this figure is the difference in velocities from the top to the bottom of the duct, such that the flow is boosted on the bottom of the duct. Observing previous duct flow (Figure 15.2.3) in which the flow is more uniform from top to bottom, the behavior seen here can be attributed to the previous fitting (D1-F1) and how it pressurizes the air flow with respect to the duct geometry. The flow evidently stagnates at the fitting as it is redirected to the perpendicular duct lengths. Because the initial direction of this flow is downward, the projection will carry downwards as it is redirected horizontally. This momentum fades as the flow progresses along the length, as shown by the diminishing red color on the left side (D1-L1).

16 Conclusions

Goals of this project included determining price ranges for different aspects of this cooling system which were met. Prices for the operational costs on a yearly basis were provided as well as the logic that was used to derive them which enables the user to make adjustments as they see fit. The duct system and its materials were clearly defined dimensionally and price wise. Air handler unit recommendations were provided with subsequent prices which combined with the operational and materials costs gives a complete idea towards the cost of the cooling system for this house with the exception of the refrigerant air conditioner.

Another goal of this project was to provide analysis through case studies which implement use-defined variables which in this context were air handler flow rates and set high inside air temperatures (which correspond to intended low temperatures through the thermostat). This provided analysis through tables and figures allows for user to visualize which set or sets of these variables the user would like to use which subsequently defines the economics more clearly.

An additional goal of this project was to provide drawings and 3D dimensional figures that give the user a clear idea towards the suggested specifications. If concepts of this paper are implemented, a guide can be feasibly accessed to aid installation processes. These figures also served as supporting evidence for ideas in this paper as concepts are much more likely to be considered and they can first be feasibly understood which is the aim of these figures.

Simulations were provided to confirm results derived through a theoretical basis. The observed results did not deviate all too much from the predicted results to where adjustments had to be made to the theoretical conclusions. Not accounting for the reduction pieces in the head loss calculations was the most notable mishap as head losses were deemed negligible but pressure increases observed suggest that the pressure losses due to these fittings were indeed significant. Useful recommendations were provided in tandem with these simulations to feasibly improve the system. A goal of this project that was not met was creating a flow simulation through the house. Attempts were made through multiple software applications, but files assembled were either too big to handle for the application or contained unrecognizable mesh errors. These simulations would have served to provide a better indication of the mechanical and thermal effects of air through the house. These simulations would have been able to provide insight as to whether air vents should be moved, removed, or additionally installed.

Overall, most goals of this project were met, and this research was successful.

17 References

7.4 Duct Roughness

[7.4.1] Wpadmin. (2021, May 30). *Absolute pipe roughness*. EnggCyclopedia. Retrieved January 19, 2023, from <https://www.enggcyclopedia.com/2011/09/absolute-roughness/>

8: House Design

[8.1]: [8.1.1 – 8.1.12]

[8.1.1] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/corner-couch-1>

[8.1.2] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/bed-frame-queen-size-2>

- [8.1.3] *Accord 4-in x 12-in 2-Way Steel Brown Floor Register* *Lowes.com*. (n.d.). Retrieved January 20, 2023, from <https://www.lowes.com/pd/Accord-Brown-Floor-Register-Duct-Opening-4-in-x-12-in-Outside-5-5-in-x-13-5-in/3134919>
- [8.1.4] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/dresser-ikea-1>
- [8.1.5] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/bathtub-romance-duroxiet-1>
- [8.1.6] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/bookshelf-22>
- [8.1.7] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/range-stove-ge-jgbs66-1>
- [8.1.8] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/refrigerator-freezer-counter-depth-1>
- [8.1.9] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/kitchen-sink-2-1>
- [8.1.10] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/dining-set-17-1>
- [8.1.11] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/coffee-table-259>
- [8.1.12] *Free CAD designs, Files & 3D models: The grabcad community library*. Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. (n.d.). Retrieved January 19, 2023, from <https://grabcad.com/library/lazyboy-rocker-recliner-1>

10: Duct System Air Distribution

- [10.1] Gajbhiye, B. D., Kulkarni, H. A., Tiwari, S. S., & Mathpati, C. S. (2020). Teaching turbulent flow through pipe fittings using computational fluid dynamics approach. *Engineering Reports*, 2(1). <https://doi.org/10.1002/eng2.12093>

- [10.2] ACHR News. (2019, July 25). *Rules of thumb for troubleshooting*. ACHR News RSS. Retrieved January 19, 2023, from <https://www.achrnews.com/articles/86221-rules-of-thumb-for-troubleshooting#:~:text=One%20cfm%20is%20needed%20per,load%20calculation%20for%20comfort%20cooling>.

10.3: Major Head Loss

- [10.3.1] Dhari, R. (2022, November 7). *Friction factor calculator*. Moody Equation. Retrieved December 28, 2022, from <https://www.omnicalculator.com/physics/friction-factor>

10.4: Minor Head Loss

- [10.4.1] *Pipe and tube system components - minor (dynamic) loss coefficients*. Engineering ToolBox. (n.d.). Retrieved January 19, 2023, from https://www.engineeringtoolbox.com/minor-loss-coefficients-pipes-d_626.html
- [10.4.2] *Air duct components - minor dynamic loss coefficients*. Engineering ToolBox. (n.d.). Retrieved January 19, 2023, from https://www.engineeringtoolbox.com/minor-loss-air-ducts-fittings-d_208.html
- [10.4.3] Munson, B. R. (2013). *Fundamentals of Fluid Mechanics*. Wiley.

10.6: Air Handler Energy Hair Cuts

- [10.6.1] *Improving air handler efficiency in houses - ACEEE*. (n.d.). Retrieved January 20, 2023, from https://www.aceee.org/files/proceedings/2004/data/papers/SS04_Panel1_Paper29.pdf

11: House Heat Transfer

- [11.1] *R-values of insulation and other building materials*. Archtoolbox. (2022, February 27). Retrieved January 19, 2023, from <https://www.archtoolbox.com/r-values/>
- [11.2] Pásztor, Z., Fehér, S., & Börcsök, Z. (2019, November 20). *The effect of heat treatment on thermal conductivity of paulownia wood - european journal of wood and wood products*. SpringerLink. Retrieved January 19, 2023, from <https://link.springer.com/article/10.1007/s00107-019-01470-3#:~:text=The%20thermal%20conductivity%20of%20wood,mK%20perpendicular%20to%20the%20grain>

- [11.3] *Metals, metallic elements and alloys - thermal conductivities*. Engineering ToolBox. (n.d.). Retrieved January 19, 2023, from https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html
- [11.4] *Air - thermal conductivity vs. temperature and pressure*. Engineering ToolBox. (n.d.). Retrieved January 19, 2023, from https://www.engineeringtoolbox.com/air-properties-viscosity-conductivity-heat-capacity-d_1509.html

13: Economics

- [13.1] Amarillo weather in 2022. (n.d.). Retrieved January 19, 2023, from <https://www.extremeweatherwatch.com/cities/amarillo/year-2022>

13.1: Electricity Estimates

- [13.1.1] *Improving air handler efficiency in houses - ACEEE*. (n.d.). Retrieved January 20, 2023, from https://www.aceee.org/files/proceedings/2004/data/papers/SS04_Panel1_Paper29.pdf
- [13.1.2] *Compare texas electricity rates & plans*. EnergyBot. (n.d.). Retrieved January 19, 2023, from [https://www.energybot.com/electricity-rates/texas/#:~:text=Last%20updated%20January%202023&text=The%20average%20Texas%20residential%20electricity,lower%20than%20the%20national%20average\).](https://www.energybot.com/electricity-rates/texas/#:~:text=Last%20updated%20January%202023&text=The%20average%20Texas%20residential%20electricity,lower%20than%20the%20national%20average).)
- [13.1.3] Amarillo weather in 2022. (n.d.). Retrieved January 19, 2023, from <https://www.extremeweatherwatch.com/cities/amarillo/year-2022>

14: Recommendations

- [14.1] *Goodman AVPTC25B14 2 ton Air Conditioner Air Handler with smart frame cabinet*. AC Wholesalers. (n.d.). Retrieved January 20, 2023, from https://www.acwholesalers.com/Goodman-AVPTC25B14/p70112.html?gclid=Cj0KCQiAlKmeBhCkARIsAHy7WVv0iV6RzofJxyOf7--EcOsJyp9KJvQ2Ad7X_7rw4OyPsHXupRaZxsAaAqviEALw_wcB
- [14.2] *Goodman AVPTC37C14 AVPTC - 2.5 to 3.5 ton - air handler - multi-position - variable speed ECM Blower*. eComfort. (n.d.). Retrieved January 20, 2023, from <https://www.ecomfort.com/Goodman-AVPTC37C14/p70116.html>
- [14.3] *Goodman AVPTC61D14 AVPTC - 5.0 ton - air handler - multi-position - variable speed ECM Blower*. eComfort. (n.d.). Retrieved January 20, 2023, from <https://www.ecomfort.com/Goodman-AVPTC61D14/p69953.html>

- [14.4] SS-GAVPTCDB07500022FA6258827EFF0C00754798. (n.d.). Retrieved January 20, 2023, from <https://www.goodmanmfg.com/pdfviewer.aspx?pdfurl=docs%2Flibrariesprovider6%2Fdefault-document-library%2Fss-gavptcdb07500022fa6258827eff0c00754798.pdf%3Fview>
- [14.5] SS-GAVPECD456510022FA6258827EFF0C00754798. (n.d.). Retrieved January 20, 2023, from <https://www.goodmanmfg.com/pdfviewer.aspx?pdfurl=docs%2Flibrariesprovider6%2Fdefault-document-library%2Fss-gavpecd456510022fa6258827eff0c00754798.pdf%3Fview>

15.1 Duct System Simulation

- [15.1.1] hawkridgesystems. (2021, April 12). *Internal Pipe Flow with solidworks flow simulation*. YouTube. Retrieved January 19, 2023, from <https://www.youtube.com/watch?v=8R60y9Y9480>

18 Appendices

Appendix A: Nomenclature Table

Variable	Value	Units	Notes
C_A	Volumetric Coefficient (Duct Air)	Unitless	
CFM	Flow Rate	m^3/s	Flow rate into
C_i	Volumetric Coefficient (Inside Air)	Unitless	
C_i	Head loss Coefficient	Unitless	
C_p	Heat Capacity	J/m^2-K	Heat capacity of fluid
CR	Cooling Rate	$^{\circ}C/hr$	
cs	Cross sectional Area	Unitless	Subscript notation
D_H	Hydraulic Diameter	m	Adjusted diameter for non-circular conduits (Duct)
D_i	Inner Diameter	m	Used for pipes but adjusted for con-circular conduits (R_H , D_H)
dL	Length of Material	M	From 2-D view, same as thickness of material
ϵ	Roughness Coefficient	Unitless	Based on material
f	Friction Factor	Unitless	
H	Duct Height	m	
HR	Heating Rate	$^{\circ}C/hr$	
k	Thermal Conductivity	W/m^2-K	
L	Length	m	Length of pipe/duct for major head loss
$\dot{m}$	Mass flow rate	kg/s	
ρ	Density	kg/m^3	
P	Pressure	Pa	
Q	Flow Rate	m^3/s	Volumetric flow rate of fluid
$\dot{q}$	Heat Rate	W	
R	Resistance	K/W	Resistance of material (Area accounted for)
Re	Reynolds Value	Unitless	
R_H	Hydraulic Radius	m	Adjusted radius for

			non-circular conduits (Duct)
R-value	Resistance	$\text{K/m}^2\text{-W}$	Resistance of material
T_A	Temperature of Duct Air	$^{\circ}\text{C}$	
T_I	Temperature of Room Air (Initial)	$^{\circ}\text{C}$	
T_R	Room Temperature	$^{\circ}\text{C}$	
μ	Dynamic Viscosity	$\text{Pa}\cdot\text{s}$	
v	Velocity	m/s	Velocity of fluid
W	Duct Width	m	
W_{rev}	Work	J/s	
V_A	Volume of duct air	m^3	
V_I	Volume of inside air	m^3	
V_R	Volume of Inside Air (Rooms)	m^3	
γ	Specific Weight	N/m^3	
ζ	Zeta Coefficient	Unitless	

Appendix B: Physical Constants Table

Variable	Value	Units	Notes
C_p	700	J/kg-K	Air
ϵ_D	0.15	mm	Duct- galvanized steel roughness coefficient
ϵ_P	0.0014	mm	Pipe- aluminum roughness coefficient
g	9.81	m/s^2	
P_{atm}	101325	Pa	Atmospheric pressure
ρ	1.293	Kg/m^3	Air density
T_A	15	$^{\circ}\text{C}$	Temperature of duct air

Appendix C: House Dimensions

Section/Dimension	Length (m)	Area (m^2)	Volume (m^3)	Notes
Cinder Block Wall Outside Length – Short Side	10.1			
Cinder Block Wall Outside Length – Long Side	12.5			
Drywall Inside Length –	9.6			From one end of house to other

Short Side				
Drywall Inside Length – Long Side	12			From one end of house to other
Cinder Block Wall Outside Height	3.7			From Foundation to roof
Inside Height	2.4			From floor to ceiling
Cinder Block Height	0.2			
Cinder Block Length	0.4			
Cinder Block Width (Large)	0.3			
Cinder Block Width (Small)	0.2			
Roof Length – Short Side	10.7			From corner to corner (includes overhang)
Roof Length – Long Side	13.2			From corner to corner (includes overhang)
Roof Height	1.63			From attic insulation to top of roof
Concrete Foundation Length – Long, Outside	12.8			
Concrete Foundation Length – Short, Outside	4.3			
Concrete Foundation Length – Long, Inside	11.6			
Concrete Foundation Length – Short, Inside	4.6			1 of 2 inner sections that are divided by medium
Concrete Foundation Height	0.6			Includes amount that is buried in dirt
Kitchen (KI), Living Room (LR), Dining Room (DR), Hallway (HW) Floor Area		61.7		
Kitchen (KI), Living Room (LR), Dining Room (DR), Hallway (HW) Air Volume			146	
Guest Bedroom (BR1) Floor Area		11.2		
Guest Bedroom (BR1) Air Volume			26.5	
Guest Bedroom (BR2) Floor Area		12.9		
Guest Bedroom (BR2) Air Volume			30.5	
Master Bedroom (BR3) plus Master Bathroom (BA2) Floor Area		21.6		
Master Bedroom (BR3) plus Master Bathroom (BA2) Floor Area			51	

Appendix D: SOLIDWORKS Models

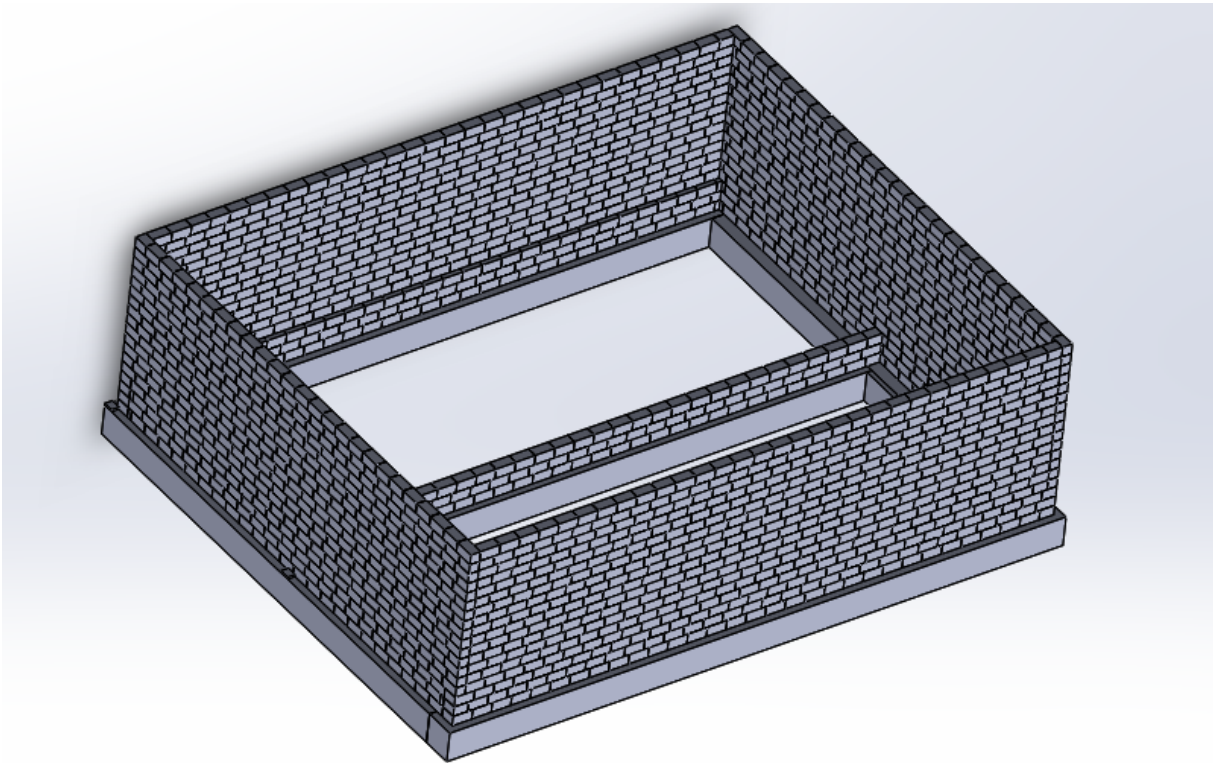


Figure D.1: Concrete foundation and brick wall model

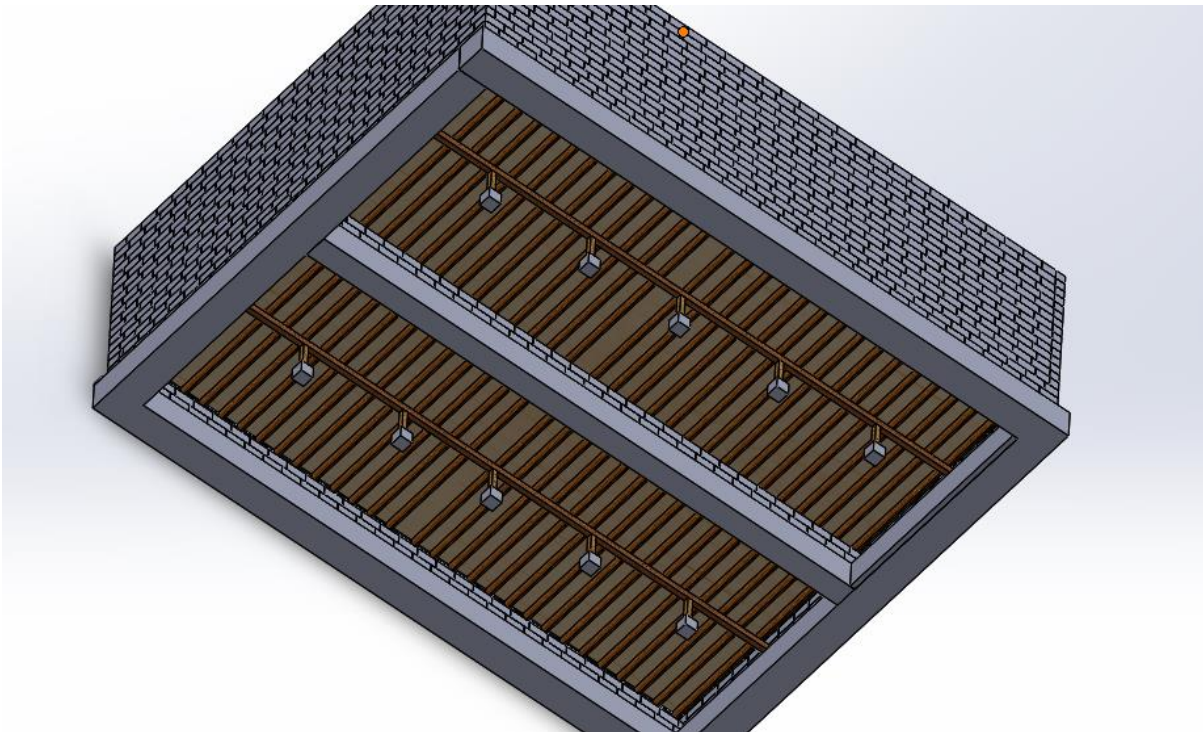


Figure D.2: Brick wall with floor installation

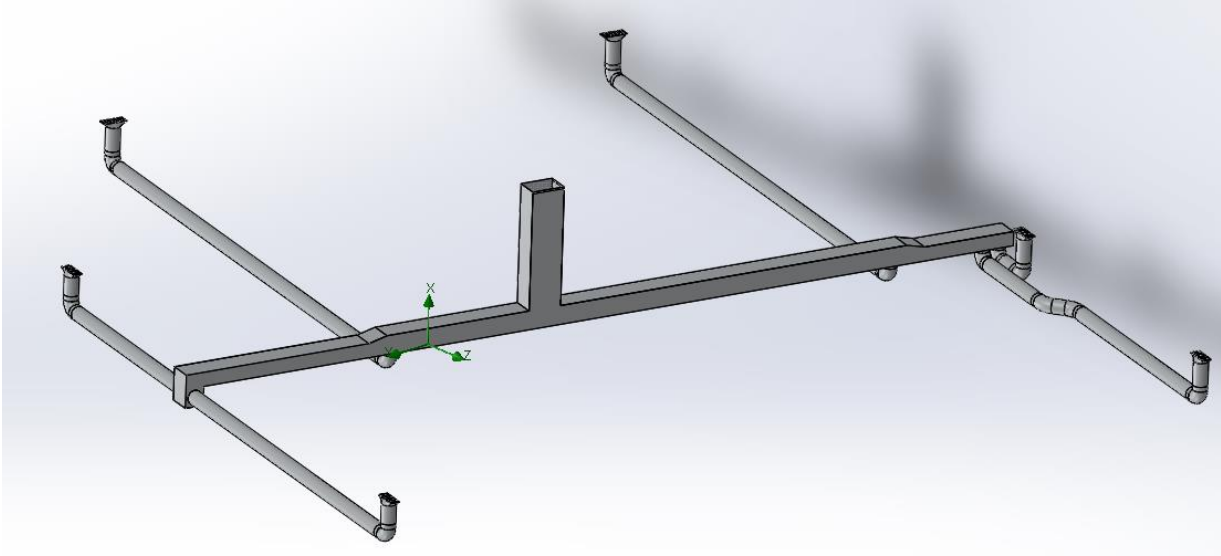


Figure D.3: Duct System

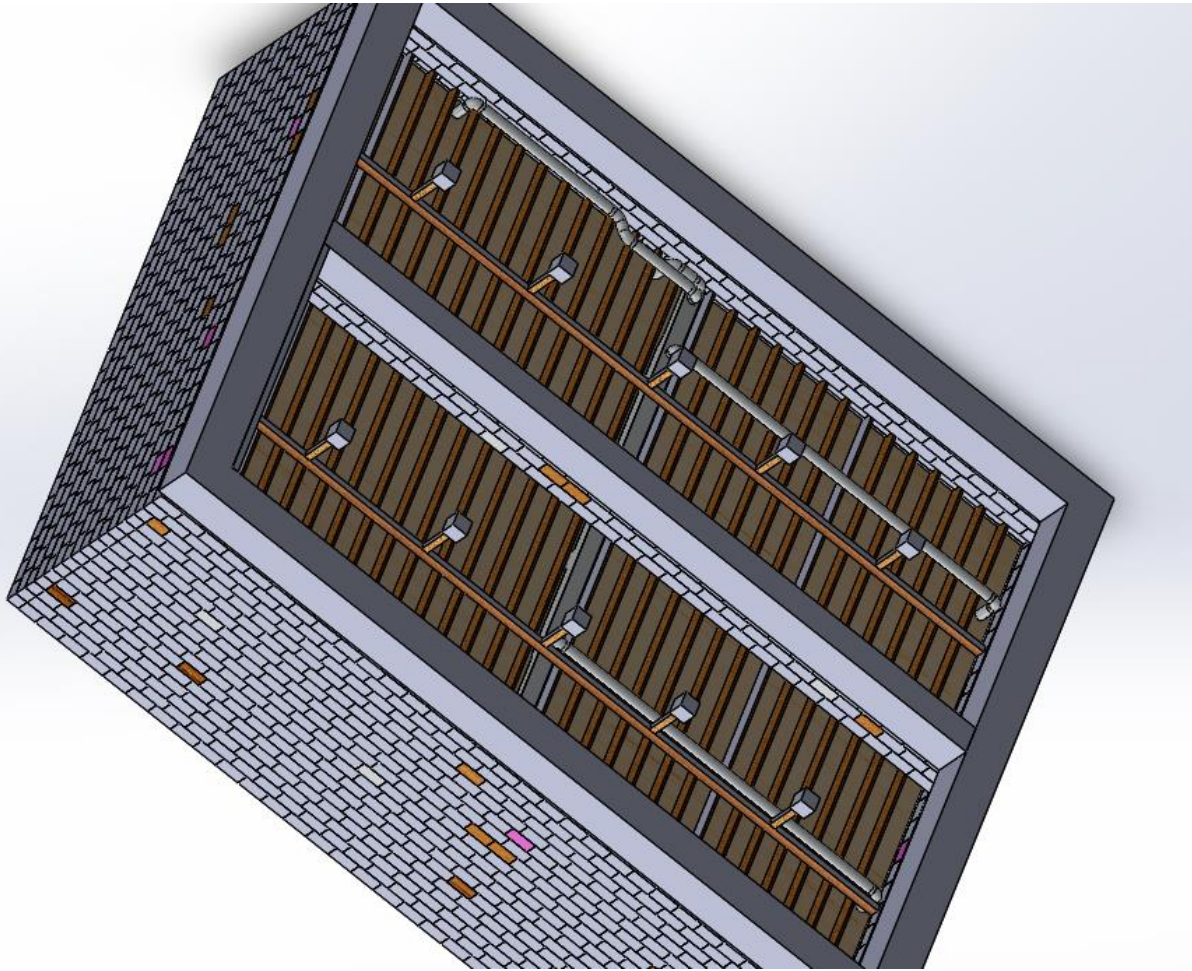


Figure D.4: Brick wall with floor and duct system

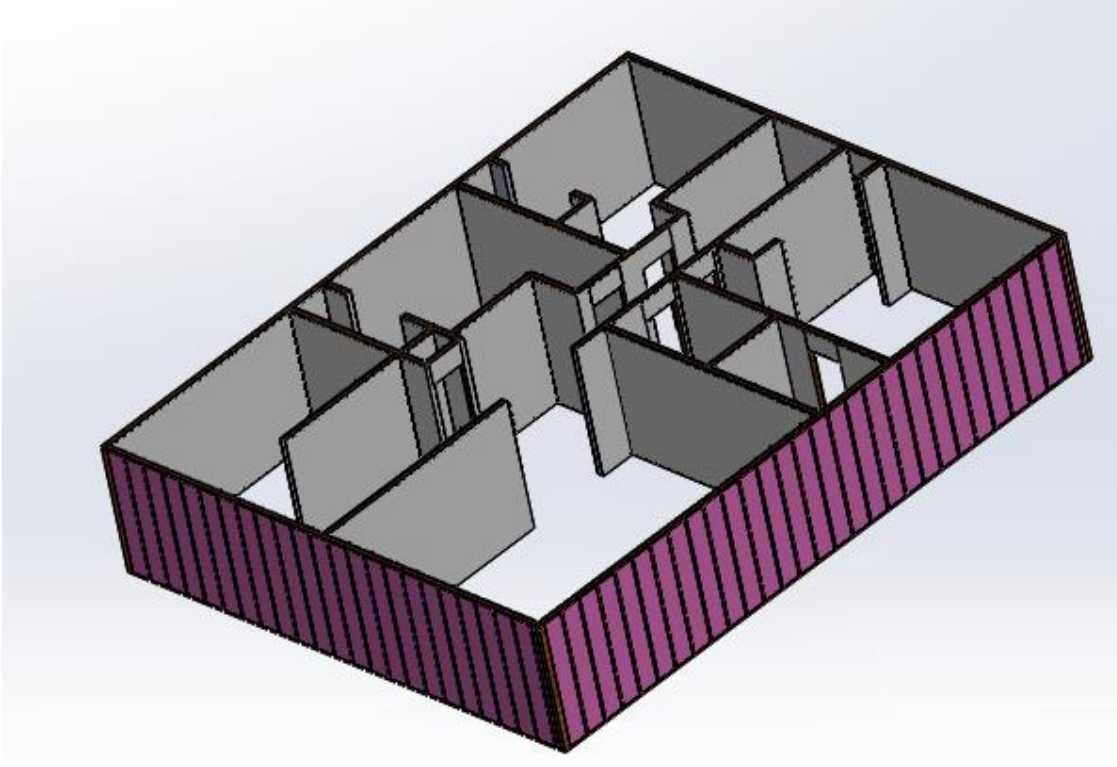


Figure D.5: Insulated walls with drywall (Isolated)

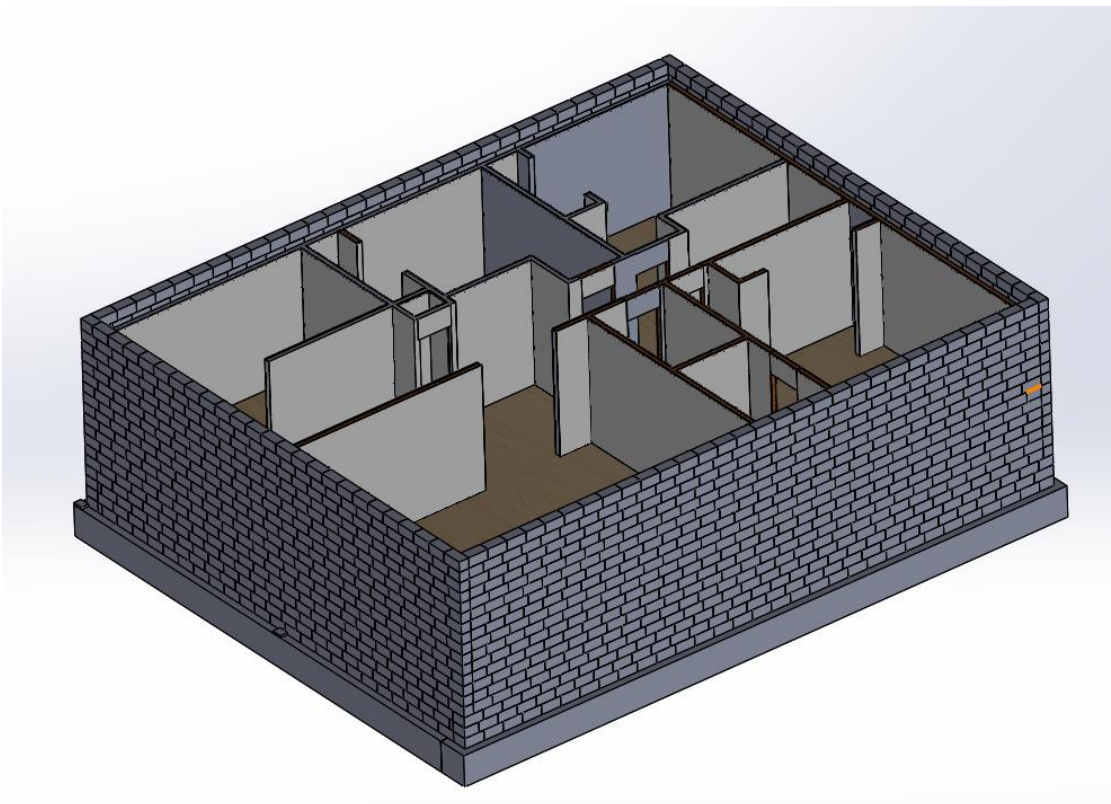


Figure D.6: House with walls

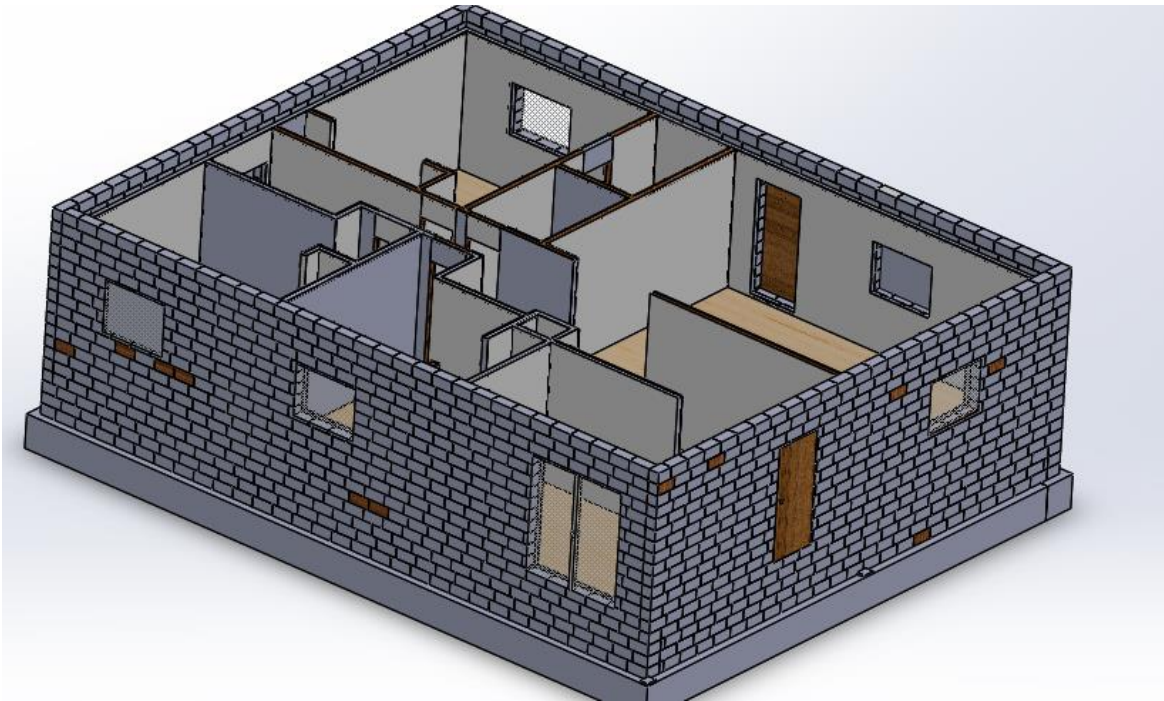


Figure D.7: House with doors and windows

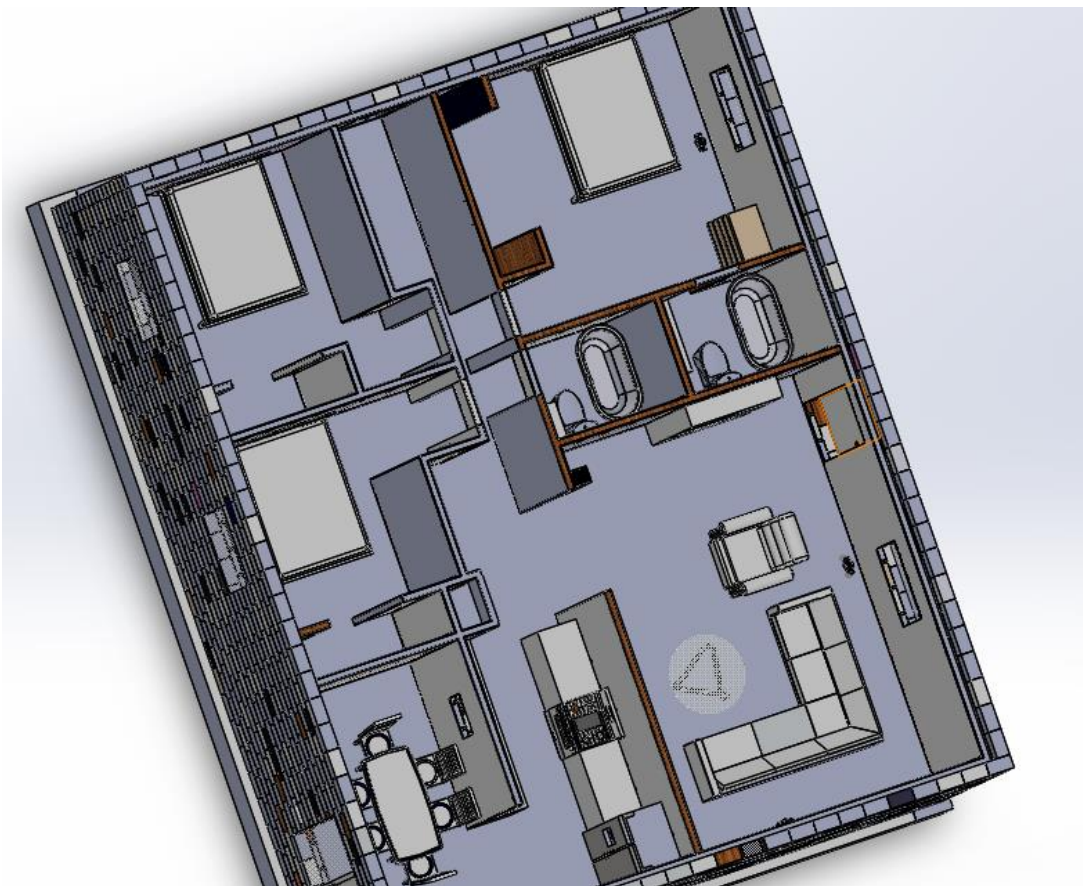


Figure D.8 House with Furniture

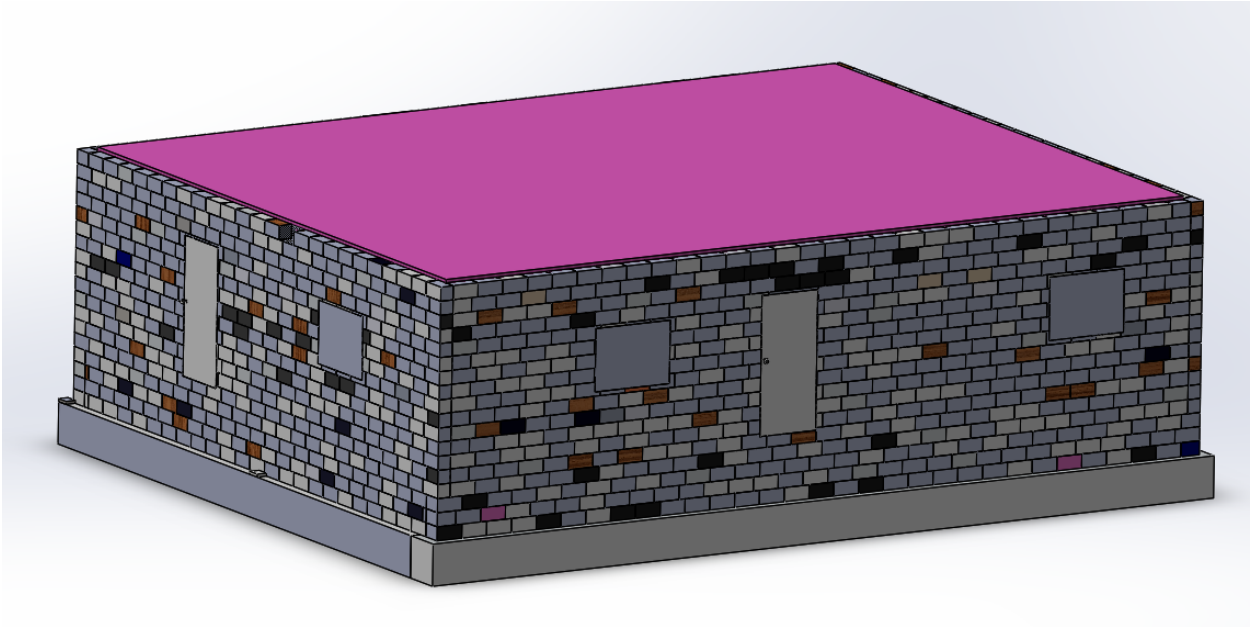


Figure D.9: House with roof insulation

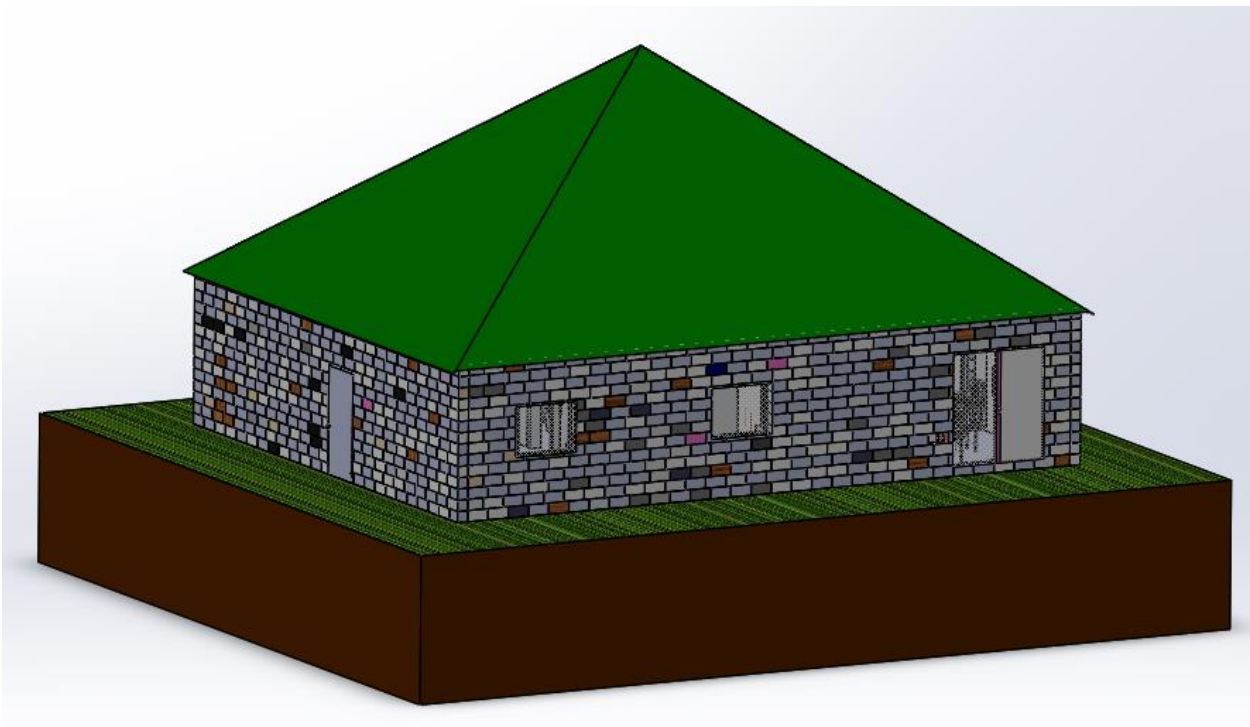


Figure D.10: House with roof and ground environment

Appendix E: MATLAB Code

```

1 function [v1, v2, v3] = D1F1(CFM)
2
3 %Entrance
4 Q1 = CFM*0.0004719471999802417; %ft^3/min to m^3/s,
5 A1 = 14*10*0.0254^2; %m^2, Cross-sectional area of entering duct
6 v1 = Q1/A1; %m/s, velocity of air
7 assignin('base', 'v1', v1)
8
9 %Exit(s)
10 Q2 = Q1/2; %m^3/s, flow rate of air (Equation 10.1)
11 A2 = 10*8*0.0254^2; %m^2, Cross-sectional area of exiting duct
12 v2 = Q2/A2; %m/s
13 assignin('base', 'v2', v2)
14 Q3 = Q1/2; %m^3/s, flow rate of air (Equation 10.1)
15 A3 = 10*8*0.0254^2; %m^2, Cross-sectional area of exiting duct
16 v3 = Q3/A3; %m/s
17 assignin('base', 'v3', v3)
18
19 end

```

Figure E.1: D1F1 Code

```

1 function[v4, v5, v8, v10, v11]= J1(v2)
2
3 Vratio = 0.43; %Velocity ratio of pipe to duct
4 v4 = v2*Vratio; %m/s, Velocity of air flowing out of pipe
5 assignin('base', 'v4', v4)
6
7 %Flow Rate Relationship (Equation ##)
8 A2 = 8*10*0.0254^2; %m^2, Cross-sectional area of duct
9 Q2 = v2*A2; %m^3/s, Flow rate of air through entering duct
10 A4 = pi*(3*0.0254)^2; %m^2, Cross-sectional area of branching pipe
11 Q4 = v4*A4; %m^3/s, Flow rate of air through branching pipe
12 A5 = 8 * 10 * 0.0254^2;%m^2, Cross sectional area of line flow duct (exiting)
13 Q5 = Q2 - Q4; % Flow Rate of line flow exiting duct (Equation 10.2)
14 v5 = Q5/A5; %m^3/s, Velocity of Flow Exiting
15 assignin('base', 'v5', v5)
16
17 %Flow Rate Relationship (Section 10 of paper)
18 A8 = 6 * 10 * 0.0254^2; %m^2, Cross-sectional area of duct after reduction
19 v8 = (A5/A8)*v5; %m/s, Velocity of air after reduction
20 Q8 = A8*v8; %m^3/s, flow rate of air leaving pipe
21 assignin('base', 'v8', v8)
22
23 %Flow Rate Relationship (Section 10 of paper)
24 Q10 = Q8/2; %m^3/s, flow rate of air in pipe
25 A10 = pi*(3*0.0254)^2; %m^2, Cross-sectional area of branching pipe
26 v10 = Q10/A10; %m/s, velocity of air leaving pipe
27 assignin('base', 'v10', v10)
28 Q11 = Q10; %m^3/s, flow rate of air in pipe (Equation 10.6)
29 A11 = pi*(3*0.0254)^2; %m^2, Cross-sectional area of branching pipe
30 v11 = Q11/A11; %m/s, velocity of air leaving pipe
31 assignin('base', 'v11', v11)
32
33
34 end

```

Figure E.2: J1 Code

```

1 function[v6, v7, v9]= J2(v3)
2
3 Vratio = 0.43; %Velocity ratio of pipe to duct
4 v6 = v3*Vratio; %m/s, Velocity of air flowing out of pipe
5 assignin('base', 'v6', v6)
6
7 %Flow Rate Relationship (Section 10 of paper)
8 A3 = 8*10*0.0254^2; %m^2, Cross-sectional area of duct
9 Q3 = v3*A3; %m^3/s, Flow rate of air through entering duct
10 A6 = pi*(3*0.0254)^2; %m^2, Cross-sectional area of branching pipe
11 Q6 = v6*A6; %m^3/s, Flow rate of air through branching pipe
12 A7 = 8 * 10 * 0.0254^2;%m^2, Cross sectional area of line flow duct (exiting)
13 Q7 = Q3 - Q6; % Flow Rate of line flow exiting duct (Equation 10.3)
14 v7 = Q7/A7; %m^3/s, Velocity of Flow Exiting
15 assignin('base', 'v7', v7)
16
17 %Flow Rate Relationship (Section 10 of paper)
18 A9 = 6 * 10 * 0.0254^2; %m^2, Cross-sectional area of duct after reduction
19 v9 = (A7/A9)*v7; %m/s, Velocity of air after reduction
20 assignin('base', 'v9', v9)
21
22
23 end

```

Figure E.3: J2 Code

```

1 function[v12, v13]= J4(v9)
2
3 Vratio = 0.43; %Velocity ratio of pipe to duct
4 v12 = v9*Vratio; %m/s, Velocity of air flowing out of pipe
5 assignin('base', 'v12', v12)
6
7 %Flow Rate Relationship (Section 10 of paper)
8 A9 = 6*10*0.0254^2; %m^2, Cross-sectional area of duct
9 Q9 = v9*A9; %m^3/s, Flow rate of air through entering duct
10 A12 = pi*(3*0.0254)^2; %m^2, Cross-sectional area of branching pipe
11 Q12 = v12*A12; %m^3/s, Flow rate of air through branching pipe
12 A13 = pi*(3*0.0254)^2;%m^2, Cross sectional area of line flow duct (exiting)
13 Q13 = Q9 - Q12; % Flow Rate of line flow exiting duct (Equation 10.7)
14 v13 = Q13/A13; %m^3/s, Velocity of Flow Exiting
15 assignin('base', 'v13', v13)
16
17 end

```

Figure E.4: J4 Code

```

1 function[f1, f2, f3, f4, f5, f6, f7, f8, f9, f10, f11, f12, f13] = moody(v1, v2, v3, v4, v5, v6, v7, v8, v9, v10, v11, v12, v13)
2
3 %Constants
4 T = 15; %Room Temperature minus HVAC air temp
5 eD = 0.15 * 10^-3; %m, Roughness factor of duct (galvanized steel)
6 eP = 0.0014 * 10^-3; %m, Roughness factor of pipe (Aluminum-new)
7 W = 10*0.0254; %m, Width of duct, constant
8
9 %%Duct Dimensions
10 %Air Handler Entrance
11 H1 = 14 * 0.0254; %m, Height
12 A1 = H1 * W; %m^2, Cross-sectional Area
13 P1 = 2*W + 2*H1; %m, Perimeter
14 RH1 = A1/P1; %m, Adjusted Radius (Non-circular conduit)
15 DH1 = 4*RH1; %m, Adjusted Diameter
16 %Main Duct first portion
17 H2 = 8 * 0.0254; %m, First Height of Duct, reduces after first branch to H2
18 A2 = W * H2; %m^2, Cross-sectional area of main duct (1)
19 P2 = 2*W + 2*H2; %m, Perimeter
20 RH2 = A2/P2; %m, Adjusted Radius
21 DH2 = 4*RH2; %m, Adjusted Diameter
22 %Main Duct Reductions
23 H3 = 7 * 0.0254; %m, Average height of reduction ((8+6)/2)in
24 A3 = W * H3; %m^2, Cross-sectional area of main duct (1)
25 P3 = 2*W + 2*H3; %m, Perimeter
26 RH3 = A3/P3; %m, Adjusted Radius
27 DH3 = 4*RH3; %m, Adjusted Diameter
28 %Main Duct Second Portion
29 H4 = 6 * 0.0254; %m, Reduced height of duct
30 A4 = W * H4; %m^2, Cross-sectional area of main duct (2)
31 P4 = 2*W + 2*H4; %m, Perimeter
32 RH4 = A4/P4; %m, Adjusted Radius
33 DH4 = 4*RH4; %m, Adjusted Diameter
34
35 %Pipe Diameter
36 Dp = 6 * 0.0254; %m, Pipe Diameter
37
38 %Relative Roughness
39 RR1 = eD/DH1; %Unitless, Relative Roughness: Y-axis of Moody chart
40 RR2 = eD/DH2; %Unitless, Relative Roughness: Y-axis of Moody chart
41 RR3 = eD/DH2; %Unitless, Relative Roughness: Y-axis of Moody chart
42 RR4 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
43 RR5 = eD/DH3; %Unitless, Relative Roughness: Y-axis of Moody chart
44 RR6 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
45 RR7 = eD/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
46 RR8 = eD/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
47 RR9 = eD/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
48 RR10 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
49 RR11 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
50 RR12 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
51 RR13 = eP/Dp; %Unitless, Relative Roughness: Y-axis of Moody chart
52
53 %Reynolds Values
54 rho = -0.0043*T + 1.2944; %kg/m^3, Density of Air as a function of temperature (C)
55 mu = 5*10^-8*T + 2*10^-5; %Pa*s, Dynamic viscosity of air as a function of temperature (C)
56 Re1 = rho * DH1 * v1/mu; %Unitless, Reynolds value - Flow 1
57 Re2 = rho * DH2 * v2/mu; %Unitless, Reynolds value - Flow 2
58 Re3 = rho * DH2 * v3/mu; %Unitless, Reynolds value - Flow 3
59 Re4 = rho * Dp * v4/mu; %Unitless, Reynolds value - Flow 4
60 Re5 = rho * DH3 * v5/mu; %Unitless, Reynolds value - Flow 1
61 Re6 = rho * Dp * v6/mu; %Unitless, Reynolds value - Flow 2
62 Re7 = rho * DH3 * v7/mu; %Unitless, Reynolds value - Flow 3
63 Re8 = rho * DH4 * v8/mu; %Unitless, Reynolds value - Flow 4
64 Re9 = rho * DH4 * v9/mu; %Unitless, Reynolds value - Flow 1
65 Re10 = rho * Dp * v10/mu; %Unitless, Reynolds value - Flow 2
66 Re11 = rho * Dp * v11/mu; %Unitless, Reynolds value - Flow 3
67 Re12 = rho * Dp * v12/mu; %Unitless, Reynolds value - Flow 4
68 Re13 = rho * Dp * v13/mu; %Unitless, Reynolds value - Flow 4

```

```

70 %friction factors (Equation 10.3.1)
71 f1 = 0.0055*(1+(2*10^4*RR1 + 10^6/(Re1))^(1/3)); %Unitless, Friction factor of duct (entrance)
72 assignin('base', 'f1', f1)
73 f2 = 0.0055*(1+(2*10^4*RR2 + 10^6/(Re2))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
74 assignin('base', 'f2', f2)
75 f3 = 0.0055*(1+(2*10^4*RR3 + 10^6/(Re3))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
76 assignin('base', 'f3', f3)
77 f4 = 0.0055*(1+(2*10^4*RR4 + 10^6/(Re4))^(1/3)); %Unitless, Friction factor of pipe (D1-L1)
78 assignin('base', 'f4', f4)
79 f5 = 0.0055*(1+(2*10^4*RR5 + 10^6/(Re5))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
80 assignin('base', 'f5', f5)
81 f6 = 0.0055*(1+(2*10^4*RR6 + 10^6/(Re6))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
82 assignin('base', 'f6', f6)
83 f7 = 0.0055*(1+(2*10^4*RR7 + 10^6/(Re7))^(1/3)); %Unitless, Friction factor of pipe (D1-L1)
84 assignin('base', 'f7', f7)
85 f8 = 0.0055*(1+(2*10^4*RR8 + 10^6/(Re8))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
86 assignin('base', 'f8', f8)
87 f9 = 0.0055*(1+(2*10^4*RR9 + 10^6/(Re9))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
88 assignin('base', 'f9', f9)
89 f10 = 0.0055*(1+(2*10^4*RR10 + 10^6/(Re10))^(1/3)); %Unitless, Friction factor of pipe (D1-L1)
90 assignin('base', 'f10', f10)
91 f11 = 0.0055*(1+(2*10^4*RR11 + 10^6/(Re11))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
92 assignin('base', 'f11', f11)
93 f12 = 0.0055*(1+(2*10^4*RR12 + 10^6/(Re12))^(1/3)); %Unitless, Friction factor of duct (D1-L1)
94 assignin('base', 'f12', f12)
95 f13 = 0.0055*(1+(2*10^4*RR13 + 10^6/(Re13))^(1/3)); %Unitless, Friction factor of pipe (D1-L1)
96 assignin('base', 'f13', f13)
97
98
99 end

```

Figure E.5: Moody Code

```

1 function[P1pa] = P1B3(v11)
2 %This is furthest section of Pipe 1 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 1 - before vent)
11 v1 = v11; %m/s, velocity of air entering air vent (Solved for in Flow Rate code (J1))
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmposheric pressure
17 z2 = Z*0.0254; %m, Height of fluid
18
19 %Major head loss
20 hf = 0; %no legnth of pipe travled, wall/furniture effects ignored
21
22 %Minor Head loss
23 C1 = 1; %Duct to room
24 C2 = 3; %Air vent to room
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P1pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P1pa', P1pa)
31
32 end

```

Figure E.6: P1B3 Code

```

1 function[P1pb] = P1B2(v8, v11, P1pa, f11)
2 %This is closest section of Pipe 1 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (153 + 8) * 0.0254; %m, Length of Pipe (Table 9.3)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J3)
12 v1 = v8; %m/s, velocity of air in duct (D1-L3) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (P1)
16 v2 = v11; %m/s, Velocity of air in Pipe 1
17 p2 = P1pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 8*0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f11; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.5; %Elbow
26 C2 = 0.5; %Air vent to room
27 C = C1 + C2; %Combined Coefficient
28 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
29
30 %Pressure
31 P1pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
32 assignin('base', 'P1pb', P1pb)
33
34 end

```

Figure E.7: P1B2 Code

```

1 function[P2pa] = P2B3(v10)
2 %This is furthest section of Pipe 2 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 2 - before vent)
11 v1 = v10; %Solved for
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmospheric pressure
17 z2 = Z*0.0254; %m, Height of fluid in room
18
19 %Major head loss
20 hf = 0; %No length of pipe/duct is being ran across since start of section is just below air vent)
21
22 %Minor Head loss
23 C1 = 1; %Air expansion to room (coefficient)
24 C2 = 3; %Air vent (grill)
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P2pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P2pa', P2pa)
31
32 end

```

Figure E.8: P2B3 Code

```

1 function[P2pb] = P2B2(v8, v10, P2pa, f10)
2 %This is closest section of Pipe 2 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (86 + 8) * 0.0254; %m, Length of Pipe (Table 9.3)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J3)
12 v1 = v8; %m/s, velocity of air in duct (D1-L3) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (Pipe 2)
16 v2 = v10; % m/s, Solved for Flow Rate Code
17 p2 = P2pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 8 * 0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f10; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.3; %T-split (J3)
26 C2 = 0.5; %Elbow (P2-F1)
27 C = C1 + C2; %Coefficient
28 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
29
30 %Pressure
31 P2pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
32 assignin('base', 'P2pb', P2pb)
33
34 end

```

Figure E.9: P2B2 Code

```

1 function[P3pa] = P3B3(v4)
2 %This is furthest section of Pipe 3 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 3 - before vent)
11 v1 = v4; %m/s, velocity of air in pipe (Solved for in code)
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmospheric pressure
17 z2 = Z*0.0254; %m, Height of fluid
18
19 %Major head loss
20 hf = 0; %(No length of pipe/duct is being ran across since start of section is just below air vent)
21
22 %Minor Head loss
23 C1 = 1; %Air expansion to room (coefficient)
24 C2 = 3; %Air vent (grill)
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P3pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P3pa', P3pa)
31
32 end

```

Figure E.10: P3B3 Code

```

1 function[P3pb] = P3B2(v2, v4, P3pa, f4)
2 %This is closest section of Pipe 3 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (216 + 10) * 0.0254; %m, Length of Pipe (Table 9.3)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J1)
12 v1 = v2; %m/s, velocity of air in duct (D1-L1) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (Pipe 3)
16 v2 = v4; %m/s, velocity of air in pipe (Solved for in code)
17 p2 = P3pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 10 * 0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f4; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.5; %Elbow
26 C2 = 0.5; %2nd Elbow
27 C = C1 + C2; %Coefficient
28 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
29
30 %Pressure
31 P3pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
32 assignin('base', 'P3pb', P3pb)
33
34 end

```

Figure E.11: P3B2 Code

```

1 function[P4pa] = P4B3(v6)
2 %This is furthest section of Pipe 4 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 4 - before vent)
11 v1 = v6; %m/s, velocity of air in pipe
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmospheric pressure
17 z2 = Z*0.0254; %m, Height of fluid
18
19 %Major head loss
20 hf = 0; %No length of pipe/duct is being ran across since start of section is just below air vent)
21
22 %Minor Head loss
23 C1 = 1; %Air expansion to room (coefficient)
24 C2 = 3; %Air vent (grill)
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P4pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P4pa', P4pa)
31
32 end

```

Figure E.12: P4B3 Code

```

1 function[P4pb] = P4B2(v3, v6, P4pa, f6)
2 %This is closest section of Pipe 4 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (215 + 10) * 0.0254; %m, Length of Pipe (Table 9.4)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J2)
12 v1 = v3; %m/s, velocity of air in duct (D1-L2) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (Pipe 4)
16 v2 = v6; %m/s, velocity of air in pipe
17 p2 = P4pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 10 * 0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f6; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.9; %Stem off pipe (J2)
26 C2 = 0.5; %Elbow (P4-F1)
27 C3 = 0.5; %2nd Elbow (P4-F2)
28 C = C1 + C2 + C3; %Coefficient
29 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
30
31 %Pressure
32 P4pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
33 assignin('base', 'P4pb', P4pb)
34
35 end

```

Figure E.13: P4B2 Code

```

1 function[P5pa] = P5B3(v12)
2 %This is furthest section of Pipe 5 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 5 - before vent)
11 v1 = v12; %m/s, velocity of air in pipe
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmospheric pressure
17 z2 = Z * 0.0254; %m, Height of fluid
18
19 %Major head loss
20 hf = 0; %No length of pipe/duct is being ran accross since start of section is just below air vent)
21
22 %Minor Head loss
23 C1 = 1; %Air expansion to room (coefficient)
24 C2 = 3; %Air vent (grill) (P5-F5)
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P5pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P5pa', P5pa)
31
32 end

```

Figure E.14: P5B3 Code

```

1 function[P5pb] = P5B2(v9, v12, P5pa, f12)
2 %This is closest section of Pipe 5 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (40 + 5.43 + 91 + 10) * 0.0254; %m, Length of Pipe (Table 9.4)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J4)
12 v1 = v9; %m/s, velocity of air in duct (D1-L4) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (Pipe 5)
16 v2 = v12; %m/s, velocity of air in pipe
17 p2 = P5pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 10 * 0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f12; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.9; %Stem-off pipe (J4)
26 C2 = 0.5; %90-degree elbow (P5-F1)
27 C3 = 0.3; %45-degree elbow (P5-F2)
28 C4 = 0.3; %45-degree elbow (P5-F3)
29 C5 = 0.5; %90-degree elbow (P5-F4)
30 C = C1 + C2 + C3 + C4 + C5; %Coefficient
31 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
32
33 %Pressure
34 P5pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
35 assignin('base', 'P5pb', P5pb)
36
37 end

```

Figure E.15: P5B2 Code

```

1 function[P6pa] = P6B3(v13)
2 %This is furthest section of Pipe 6 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 Z = 6 * 12 * 0.0254; %height of air in room
9
10 %Entrance (Pipe 6 - before vent)
11 v1 = v13; %m/s, velocity of air in pipe
12 z1 = 0; %m, ground level
13
14 %Exit (Room)
15 v2 = 0; %m/s, velocity of air in room - assumed to be stationary
16 p2 = 101325; %Pascals, atmospheric pressure
17 z2 = Z * 0.0254; %m, Height of fluid
18
19 %Major head loss
20 hf = 0; %(No length of pipe/duct is being ran across since start of section is just below air vent)
21
22 %Minor Head loss
23 C1 = 1; %Air expansion to room (coefficient)
24 C2 = 3; %Air vent (grill)
25 C = C1 + C2; %Combined Coefficient
26 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 P6pa = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'P6pa', P6pa)
31
32 end

```

Figure E.16: P6B3 Code

```

1 function[P6pb] = P6B2(v9, v12, P5pa, f13)
2 %This is closest section of Pipe 6 from air handler
3
4 %Constants
5 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
6 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
7 g = 9.81; %m/s^2, gravity
8 L = (9 + 10) * 0.0254; %m, Length of Pipe (Table 9.4)
9 Dp = 6 * 0.0254; %m, Diameter of Pipe
10
11 %Entrance (J5)
12 v1 = v9; %m/s, velocity of air in duct (D1-L4) (Solved for in Flow Rate Code)
13 z1 = 0; %m, Pipe Level
14
15 %Exit (Pipe 6)
16 v2 = v12; %m/s, velocity of air in pipe
17 p2 = P5pa; %Pascals, Pressure of Fluid at end of section
18 z2 = 10 * 0.0254; %m, Height of fluid exiting air vent (from pipe to floor)
19
20 %Major head loss
21 f = f13; %Friction factor from another code
22 hf = f * L/Dp * v1^2/2/g; %Head loss from pipe friction
23
24 %Minor Head loss
25 C1 = 0.9; %Stem off from duct (J5)
26 C2 = 0.5; %Elbow (P6-F1)
27 C3 = 0.5; %2nd Elbow (P6-F2)
28 C = C1 + C2 + C3; %Coefficient
29 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
30
31 %Pressure
32 P6pb = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
33 assignin('base', 'P6pb', P6pb)
34
35 end

```

Figure E.17: P6B2 Code

```

1 function[D1L3p1] = P12C1(v8, v10, P1pb, P2pb, f8)
2
3 %Constants
4 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (81) * 0.0254; %m, Length of Duct (Table ##)
8 H = 6 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Diameter (adjustment for duct)
11
12 %Entrance (Duct)
13 v1 = v8; % m/s, Solved for Flow Rate Code
14 z1 = 8 * 0.0254; %m, Duct Level with respect to piping material
15
16 %Exit (Pipe)
17 v2 = v10; %m/s, velocity of air going through pipes (two pipe conditions (P1 and P2) are identical)
18 p2 = (P1pb + P2pb)/2; %Pascals, Pressure of Fluid at end of section
19 z2 = 0; %m, Height of pipe with respect to pipe
20
21 %Major head loss
22 f = f8; %Friction factor from moody code
23 hf = f * L/Dh * v1^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 C = 1.3; %Duct Elbow
27 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
28
29 %Pressure
30 D1L3p1 = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
31 assignin('base', 'D1L3p1', D1L3p1)
32
33 end

```

Figure E.18: P12C1 Code

```

1 function[J1p1] = P12C2(v5, v8, D1L3p1, f5)
2
3 %Constants
4 T = 25-20; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (8.25) * 0.0254; %m, Length of Duct (Table 9.1)
8 H = 8 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Dimater (adjustment for duct)
11
12 %Entrance (Duct)
13 v1 = v5; % m/s, Solved for Flow Rate Code
14 z1 = 0; %m, Duct Level with respect to duct
15
16 %Exit (Pipe)
17 v2 = v8; %m/s, velocity of air going entering duct system
18 p2 = D1L3p1; %Pascals, Pressure of Fluid at end of section
19 z2 = 0; %m, Height of pipe with respect to pipe
20
21 %Major head loss
22 f = f5; %Friction factor from another code
23 hf = f * L/Dh * v1^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 C = 0.9; %Line flow through T-Junction
27 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
28
29 %Pressure
30 J1p1 = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
31 assignin('base', 'J1p1', J1p1)
32
33 end

```

Figure E.19: P12C2 Code

```

1 function[D1L4p1] = P56C1(v9, v13, P5pb, P6pb, f9)
2
3 %Constants
4 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (39.5) * 0.0254; %m, Length of Duct (Table 9.1)
8 H = 6 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Dimater (adjustment for duct)
11
12 %Entrance (Duct)
13 v1 = v9; % m/s, velocity of air flowing through duct (D1-L2) (Solved for in Flow Rate Code)
14 z1 = 0; %m, Duct Level with respect to duct
15
16 %Exit (Pipe)
17 v2 = v13; %m/s, velocity of air through pipe (Both pipes (P5 and P6) are identical
18 p2 = (P5pb + P6pb)/2; %Pascals, Pressure of Fluid at end of section
19 z2 = 0; %m, Height of pipe with respect to duct
20
21 %Major head loss
22 f = f9; %Friction factor from another code
23 hf = f * L/Dh * v1^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 hff = 0; %Minor Head Loss Values - Pressure loss due to fittings
27
28 %Pressure
29 D1L4p1 = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
30 assignin('base', 'D1L4p1', D1L4p1)
31
32 end

```

Figure E.20: P56C1 Code

```

1 function[J2p1] = P56C2(v7, v9, D1L4p1, f7)
2
3 %Constants
4 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (8.25) * 0.0254; %m, Length of Duct (Table 9.1)
8 H = 8 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Dimater (adjustment for duct)
11
12 %Entrance (Duct)
13 v1 = v7; % m/s, velocity of air flowing before reductionv(Solved for in Flow Rate Code)
14 z1 = 0; %m, Duct Level with respect to duct
15
16 %Exit (Pipe)
17 v2 = v9; %m/s, velocity of air flowing after reduction
18 p2 = D1L4p1; %Pascals, Pressure of Fluid at end of section
19 z2 = 0; %m, Height of pipe with respect to pipe
20
21 %Major head loss
22 f = f7; %Friction factor from another code
23 hf = f * L/Dh * v1^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 C = 0.9; %Line flow through T-Junction
27 hff = C * v1^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
28
29 %Pressure
30 J2p1 = gamma * (p2/gamma + z2 - z1 + v2^2/2/g - v1^2/2/g + hf + hff);
31 assignin('base', 'J2p1', J2p1)
32
33 end

```

Figure E.21: P56C2 Code

```

1 function[D1L1p1] = P123C1(v1, v2, J1p1, P3pb, f2)
2
3 %Constants
4 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (63) * 0.0254; %m, Length of Pipe (Table 9.1)
8 H = 8 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Dimater (adjustment for duct)
11
12 %Entrance (Duct)
13 v1a = v1; % m/s, veloctiy of air going out of air handlerSolved for Flow Rate Code
14 z1 = 0 * 0.0254; %m, Duct Level with respect to duct
15
16 %Exit (Pipe)
17 v2a = v2; %m/s, velocity of air going out to J1 junction
18 p2 = (J1p1 + P3pb)/2; %Pascals, Pressure of fluid going into juncntion (equals sum of pressures leaving junction)
19 z2 = 0; %m, Height of pipe with respect to pipe
20
21 %Major head loss
22 f = f2; %Friction factor from another code
23 hf = f * L/Dh * v1a^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 C = 2; %Duct Split (D1-F1)
27 hff = C * v1a^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
28
29 %Pressure
30 D1L1p1 = gamma * (p2/gamma + z2 - z1 + v2a^2/2/g - v1a^2/2/g + hf + hff);
31 assignin('base', 'D1L1p1', D1L1p1)
32
33 end

```

Figure E.22: P123C1 Code

```

1 function[D1L2p1] = P456C1(v1, v3, J2p1, P4pb, f3)
2
3 %Constants
4 T = 15; %Celsius, Temperature of fluid adjusted from room temperature based on heuristic
5 gamma = -0.0447*T + 12.686; %N/m^3, specific weight of air as a function of T
6 g = 9.81; %m/s^2, gravity
7 L = (154) * 0.0254; %m, Length of Pipe (Table 9.1)
8 H = 8 * 0.0254; %m, Duct Height
9 W = 10 * 0.0254; %m, Duct Width
10 Dh = (H*W)/(2*H + 2*W); %m, Hydraulic Diameter (adjustment for duct)
11
12 %Entrance (Duct: D1-L2)
13 v1a = v1; % m/s, velocity of air flowing through duct (Solved for Flow Rate Code)
14 z1 = 0; %m, Height of Duct with respect to duct
15
16 %Exit (Pipe)
17 v2a = v3; % m/s, velocity of air flowing through duct
18 p2 = (J2p1 + P4pb)/2; %Pascals, Pressure of fluid going into junction (equals sum of pressures leaving junction)
19 z2 = 0; %m, Height of Duct with respect to duct
20
21 %Major head loss
22 f = f3; %Friction factor from another code
23 hf = f * L/Dh * v1a^2/2/g; %Head loss from Duct friction
24
25 %Minor Head loss
26 C = 2; %Duct Split (D1-F1)
27 hff = C * v1a^2/2/g; %Minor Head Loss Values - Pressure loss due to fittings
28
29 %Pressure
30 D1L2p1 = gamma * (p2/gamma + z2 - z1 + v2a^2/2/g - v1a^2/2/g + hf + hff);
31 assignin('base', 'D1L2p1', D1L2p1)
32
33 end

```

Figure E.23: P456C1 Code

```

1 function [Pt] = totalpressure(D1L1p1, D1L2p1)
2
3 Pt = (D1L1p1 + D1L2p1)/2; %Pa, total pressure in air handler
4
5 end

```

Figure E.24: totalpressure Code

Appendix F: Physical Constants Table – MATLAB Code

Notation	Variable	Notes
A1	Entering Duct: Cross-sectional area	
A2	Duct Length (D1-L1): Cross-sectional area	
A3	Duct Length (D1-L2): Cross-sectional area	
A4	3 rd Pipe: Cross-sectional area	
A5	Duct Reduction Fitting (F1-F2): Cross-sectional area	
A6	4 th Pipe: Cross-sectional area	
A7	Duct Reduction Fitting (F1-F3): Cross-sectional area	
A8	Duct Length (D1-L3): Cross-sectional area	
A9	Duct Length (D1-L4): Cross-sectional area	
A10	2 nd Pipe: Cross-sectional area	
A11	1 st Pipe: Cross-sectional area	
A12	5 th Pipe: Cross-sectional area	
A13	6 th Pipe: Cross-sectional area	
C	Head Loss coefficient due to fitting	Varies by fitting
DH1	Hydraulic Diameter of duct (Entrance)	
DH2	Hydraulic Diameter of duct (D1-L1, D1-L2)	
DH3	Hydraulic Diameter of duct reduction fittings (D1-F1, D1-F2)	
DH4	Hydraulic Diameter of duct (D1-L3, D1-L4)	
Dp	Diameter of Pipe	All pipes (1-6) have the same diameter
D1L1p1	Pressure of fluid entering D1-F1	Bottom side (Pipes 1-3) iteration
D1L2p1	Pressure of fluid entering D1-F1	Top side (Pipes 4-6) iteration
D1L3p1	Pressure of fluid entering D1-L3	
D1L4p1	Pressure of fluid entering D1-L4	
eD	Roughness coefficient of duct	Galvanized Steel
eP	Roughness coefficient of pipe	Alumnium
f1	Entering Duct: Friction Factor	
f2	Duct Length (D1-L1): Friction Factor	
f3	Duct Length (D1-L2): Friction Factor	
f4	3 rd Pipe: Friction Factor	
f5	Duct Reduction Fitting (F1-F2): Friction Factor	
f6	4 th Pipe: Friction Factor	
f7	Duct Reduction Fitting (F1-F3): Friction Factor	
f8	Duct Length (D1-L3): Friction Factor	
f9	Duct Length (D1-L4): Friction Factor	
f10	2 nd Pipe: Friction Factor	
f11	1 st Pipe: Friction Factor	
f12	5 th Pipe: Friction Factor	
f13	6 th Pipe: Friction Factor	
g	Gravitational acceleration	
gamma	Specific gravity of fluid	
H1	Height of duct (Entrance)	

H2	Height of duct (D1-L1, D1-L2)	
H3	Height of duct reduction fittings (D1-F1, D1-F2)	
H4	Height of duct (D1-L3, D1-L4)	
hf	Major head loss	Due to lengths
hff	Minor head loss	Due to fittings
J1p1	Pressure of fluid entering J1	
J2p1	Pressure of fluid entering J2	
L	Length	
mu	Viscosity	
Pt	Total Pressure	
P1	Perimeter of duct (Entrance)	
P2	Perimeter of duct (D1-L1, D1-L2)	
P3	Perimeter of duct reduction fittings (D1-F1, D1-F2)	
P4	Perimeter of duct (D1-L3, D1-L4)	
P1pa	Pressure of fluid going out of pipe 1 into house	
P1pb	Pressure of fluid going into pipe 1	
P2pa	Pressure of fluid going out of pipe 2 into house	
P2pb	Pressure of fluid going into pipe 2	
P3pa	Pressure of fluid going out of pipe 3 into house	
P3pb	Pressure of fluid going into pipe 3	
P4pa	Pressure of fluid going out of pipe 4 into house	
P4pb	Pressure of fluid going into pipe 4	
P5pa	Pressure of fluid going out of pipe 5 into house	
P5pb	Pressure of fluid going into pipe 5	
P6pa	Pressure of fluid going out of pipe 6 into house	
P6pb	Pressure of fluid going into pipe 6	
Re1	Entering Duct	
Re2	Duct Length (D1-L1)	
Re3	Duct Length (D1-L2)	
Re4	3 rd Pipe	
Re5	Duct Reduction Fitting (F1-F2)	
Re6	4 th Pipe	
Re7	Duct Reduction Fitting (F1-F3)	
Re8	Duct Length (D1-L3)	
Re9	Duct Length (D1-L4)	
Re10	2 nd Pipe	
Re11	1 st Pipe	
Re12	5 th Pipe	
Re13	6 th Pipe	
rho	Density of fluid	air
RR1	Entering Duct: Roughness Ratio	
RR2	Duct Length (D1-L1): Roughness Ratio	
RR3	Duct Length (D1-L2): Roughness Ratio	
RR4	3 rd Pipe: Roughness Ratio	
RR5	Duct Reduction Fitting (F1-F2): Roughness Ratio	
RR6	4 th Pipe: Roughness Ratio	

RR7	Duct Reduction Fitting (F1-F3): Roughness Ratio	
RR8	Duct Length (D1-L3): Roughness Ratio	
RR9	Duct Length (D1-L4): Roughness Ratio	
RR10	2 nd Pipe: Roughness Ratio	
RR11	1 st Pipe: Roughness Ratio	
RR12	5 th Pipe: Roughness Ratio	
RR13	6 th Pipe: Roughness Ratio	
Q1	Entering Duct: Fluid Flow Rate	
Q2	Duct Length (D1-L1): Fluid Flow Rate	
Q3	Duct Length (D1-L2): Fluid Flow Rate	
Q4	3 rd Pipe: Fluid Flow Rate	
Q5	Duct Reduction Fitting (F1-F2): Fluid Flow Rate	
Q6	4 th Pipe: Fluid Flow Rate	
Q7	Duct Reduction Fitting (F1-F3): Fluid Flow Rate	
Q8	Duct Length (D1-L3): Fluid Flow Rate	
Q9	Duct Length (D1-L4): Fluid Flow Rate	
Q10	2 nd Pipe: Fluid Flow Rate	
Q11	1 st Pipe: Fluid Flow Rate	
Q12	5 th Pipe: Fluid Flow Rate	
Q13	6 th Pipe: Fluid Flow Rate	
T	Temperature of fluid	
Vratio	Fluid velocity ratio of branch exit to line entrance	
v1	Entering Duct: Fluid Velocity	
v2	Duct Length (D1-L1): Fluid Velocity	
v3	Duct Length (D1-L2): Fluid Velocity	
v4	3 rd Pipe: Fluid Velocity	
v5	Duct Reduction Fitting (F1-F2): Fluid Velocity	
v6	4 th Pipe: Fluid Velocity	
v7	Duct Reduction Fitting (F1-F3): Fluid Velocity	
v8	Duct Length (D1-L3): Fluid Velocity	
v9	Duct Length (D1-L4): Fluid Velocity	
v10	2 nd Pipe: Fluid Velocity	
v11	1 st Pipe: Fluid Velocity	
v12	5 th Pipe: Fluid Velocity	
v13	6 th Pipe: Fluid Velocity	
W	Duct Width	Constant throughout system
Z	Height of fluid	Varies with scenario

Appendix G: Duct System Flow Simulations

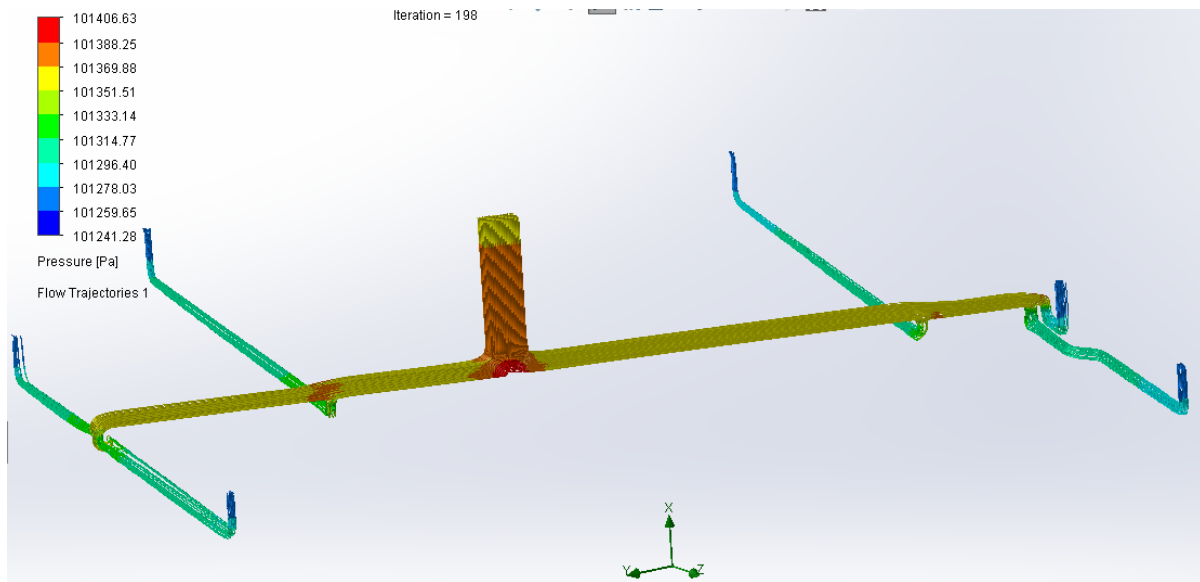


Figure G.1: CFM 1000 overall pressure distribution of duct system

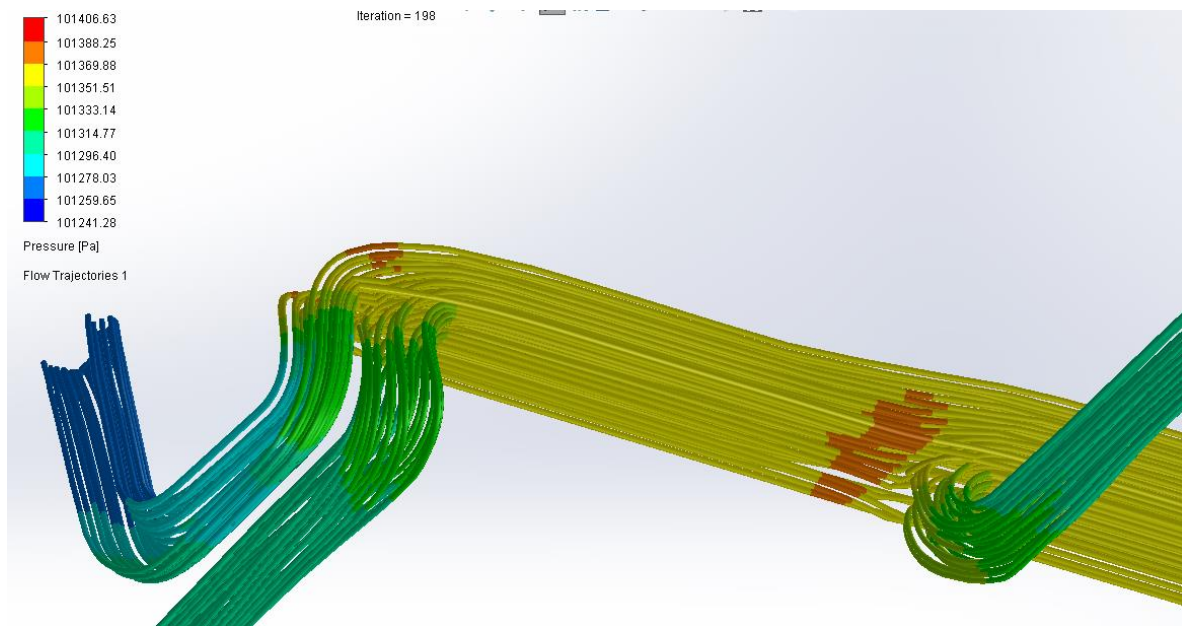


Figure G.2: CFM 1000 J2, J4 pressure distribution

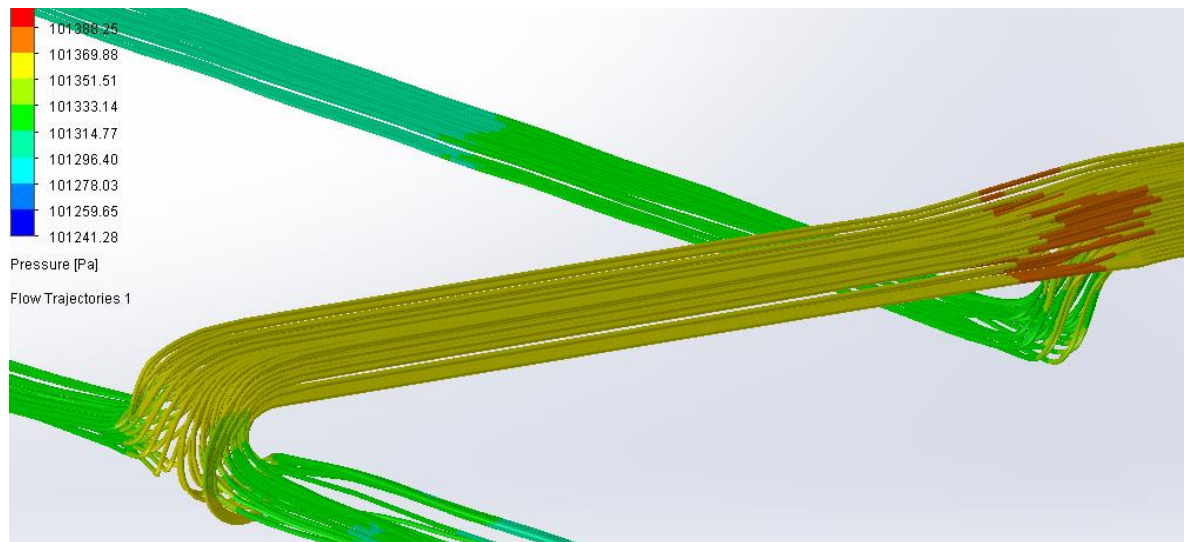


Figure G.3: CFM 1000 J1, J3 pressure distribution

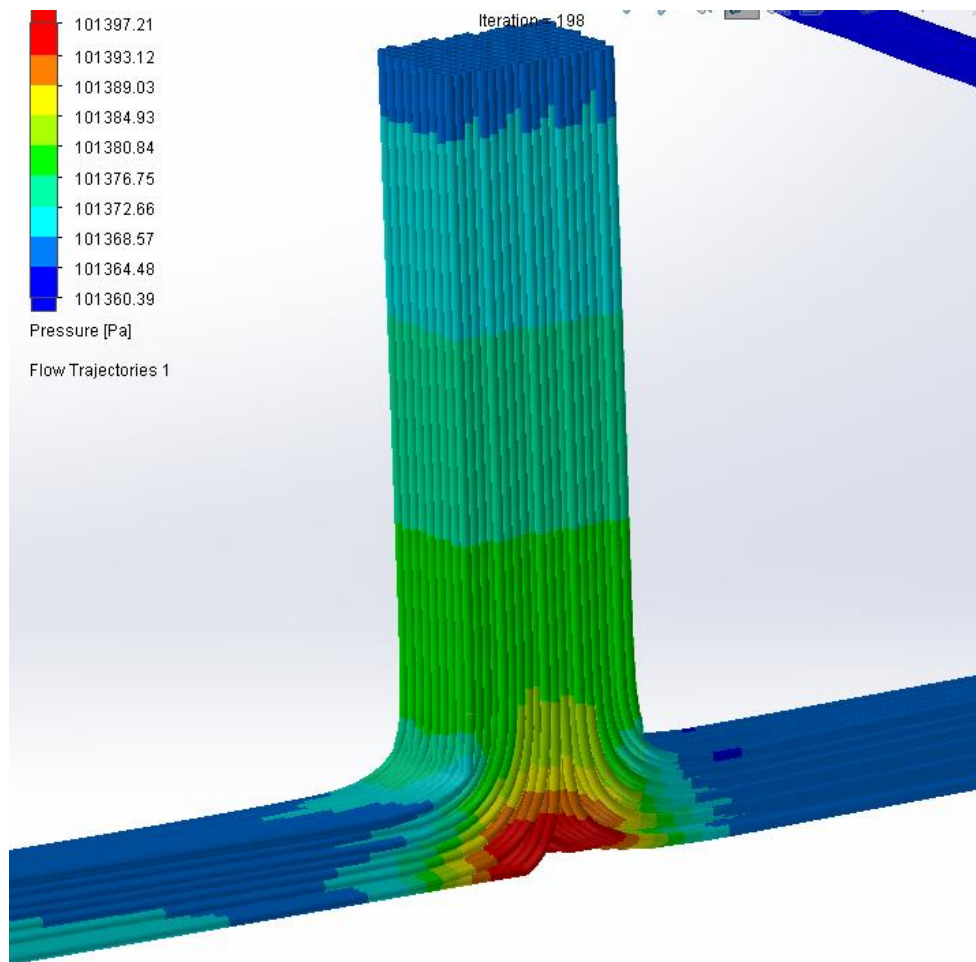


Figure G.4: CFM 1000 D1F1 pressure distribution (South section on left)

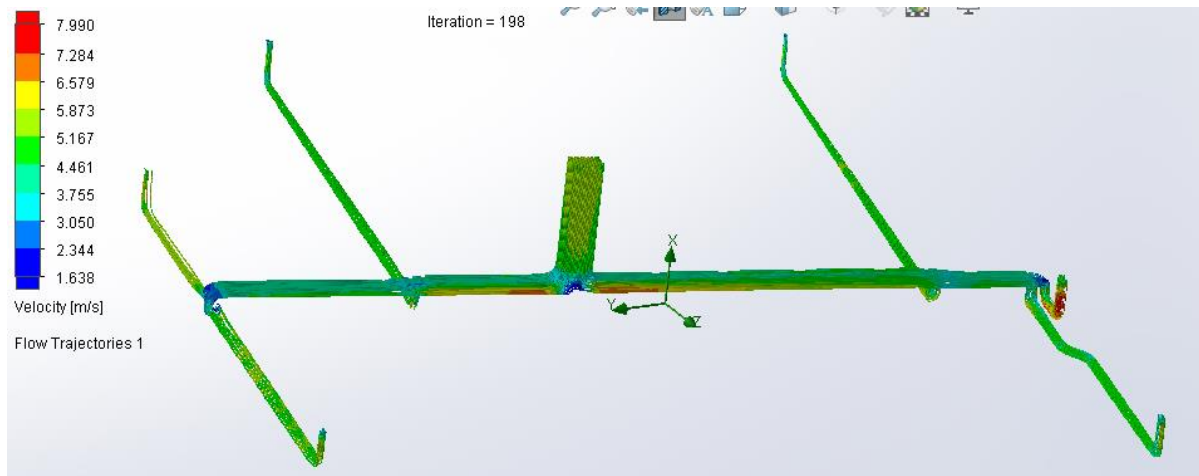


Figure G.5: CFM 1000 overall velocity distribution of duct system

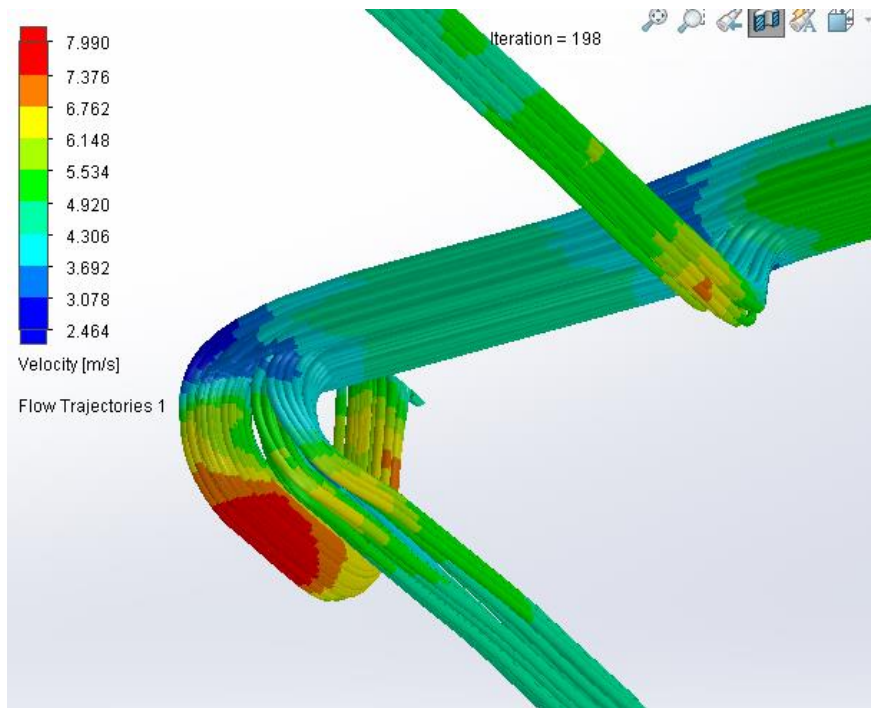


Figure G.6: CFM 1000 J2, J4 Velocity distribution

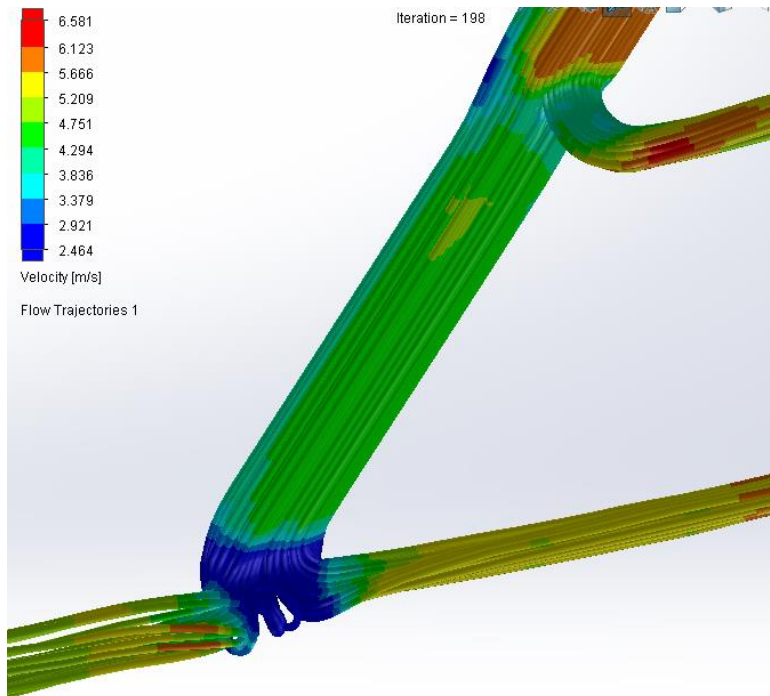


Figure G.7: CFM 1000 J1, J3 Velocity distribution

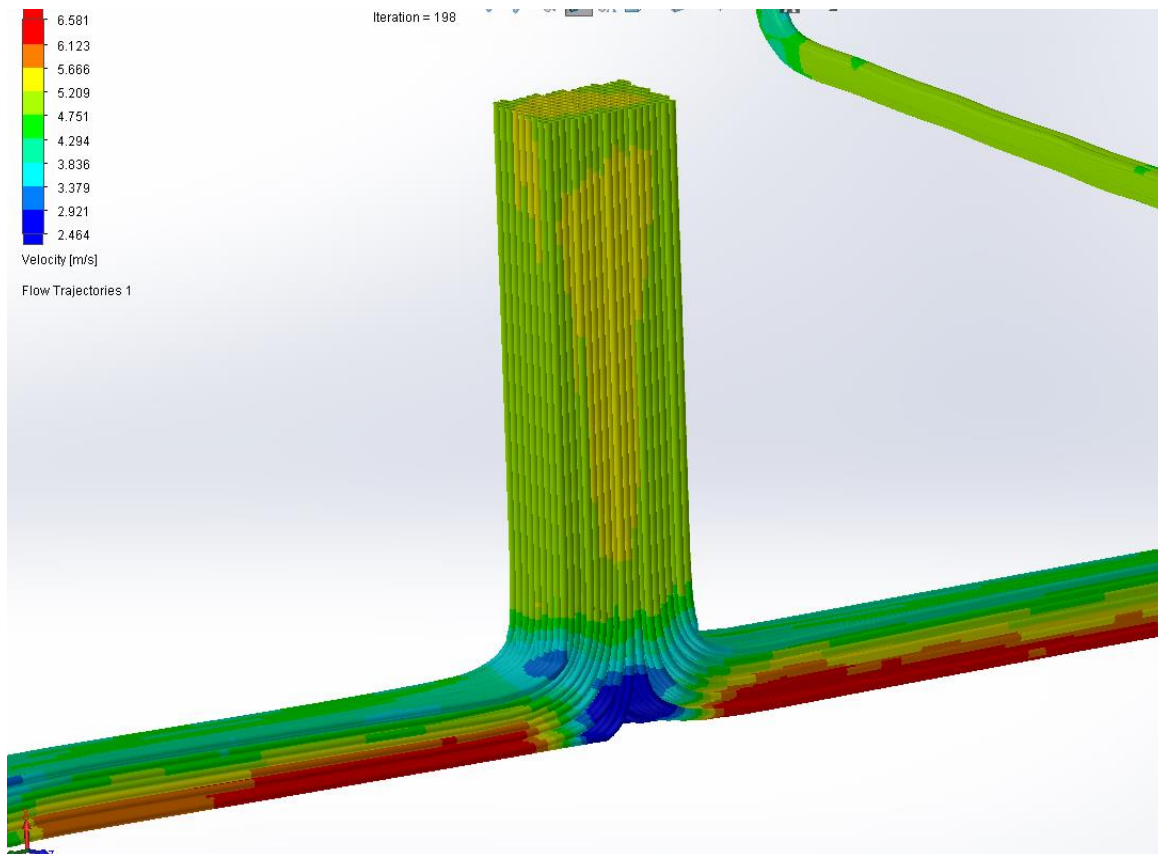


Figure G.8: CFM 1000 D1F1 Velocity distribution (South section on left)

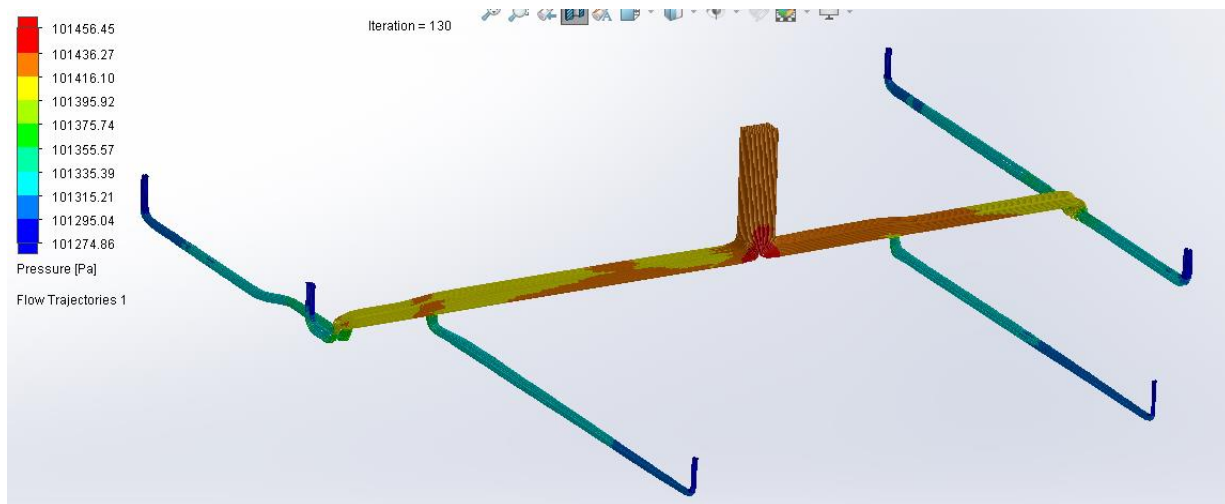


Figure G.9: CFM 1200 overall pressure distribution of duct system

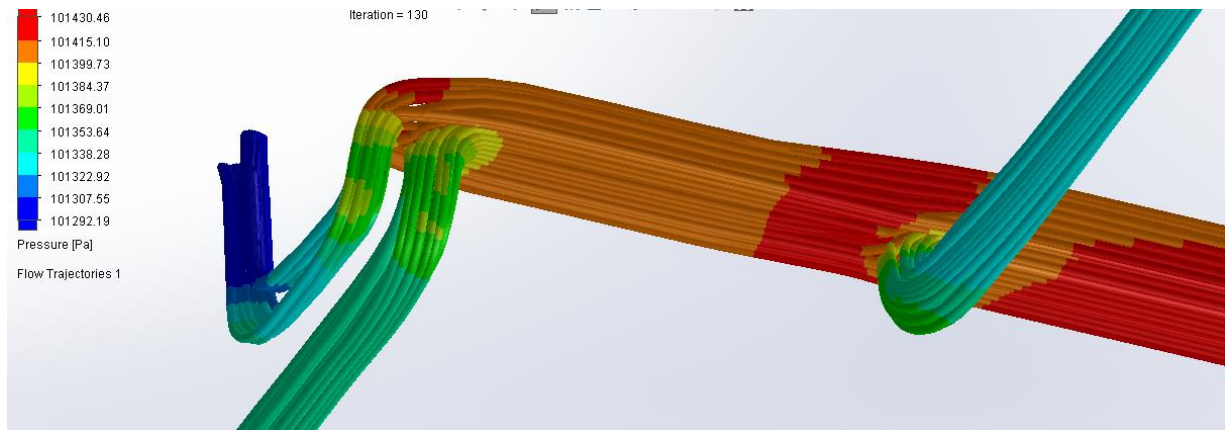


Figure G.10: CFM 1200 J2, J4 pressure distribution

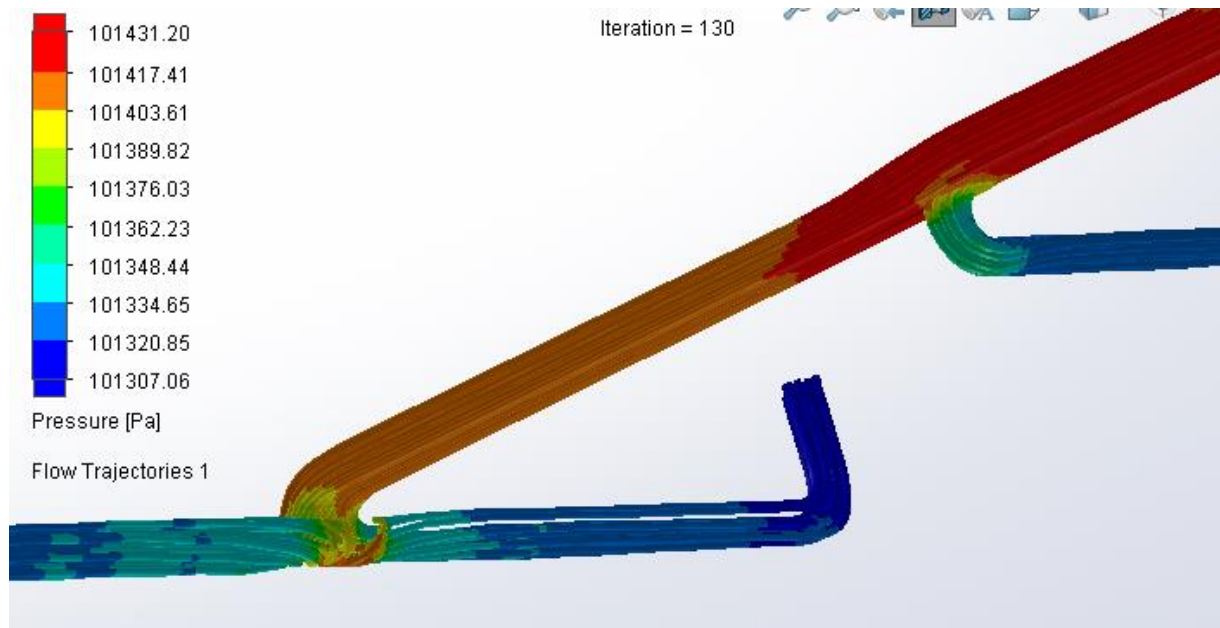


Figure G.11: CFM 1200 J1, J3 pressure distribution

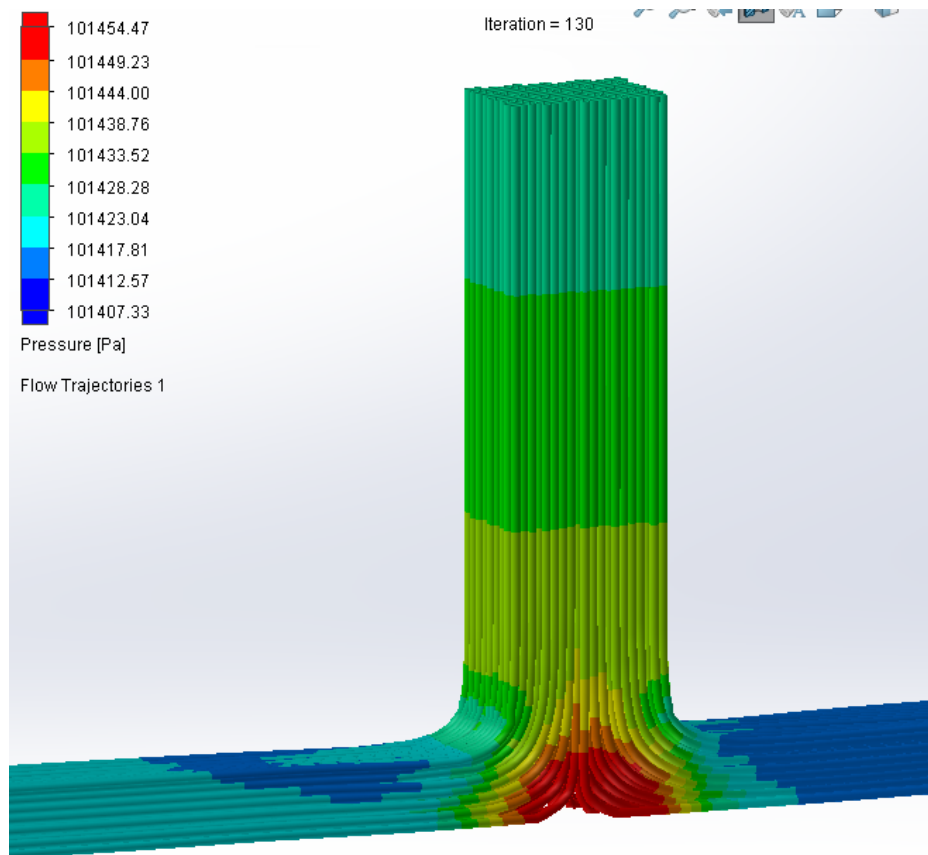


Figure G.12: CFM 1200 D1F1 pressure distribution (South section on left)

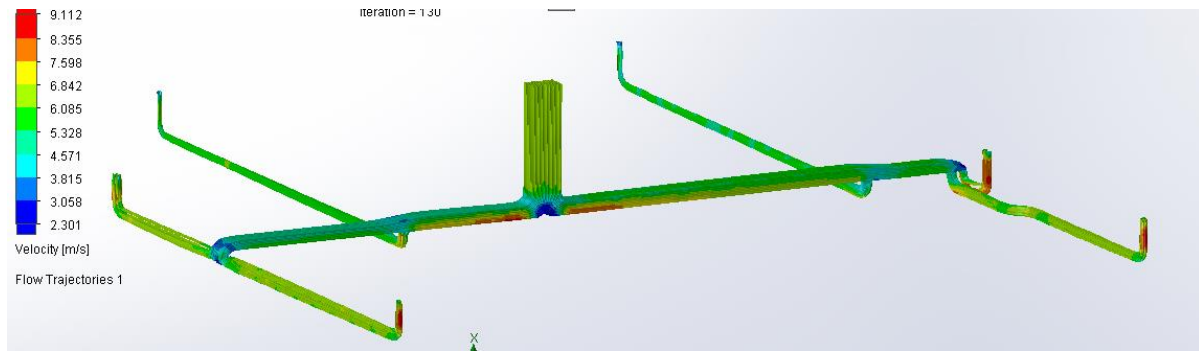


Figure G.13: CFM 1200 overall velocity distribution of duct system

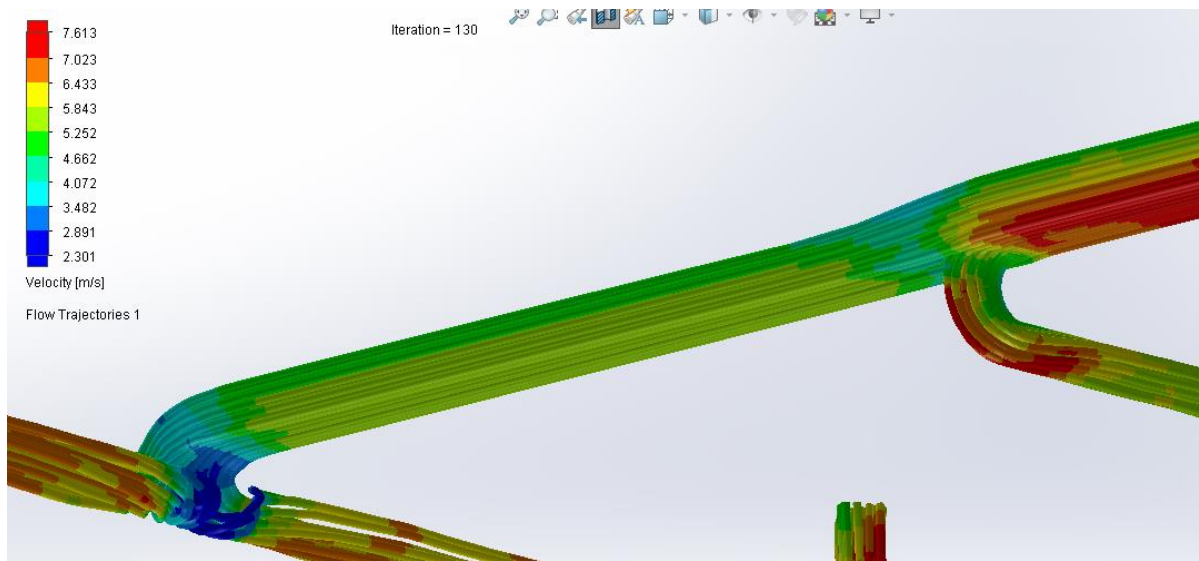


Figure G.14: CFM 1200 J2, J4 velocity distribution

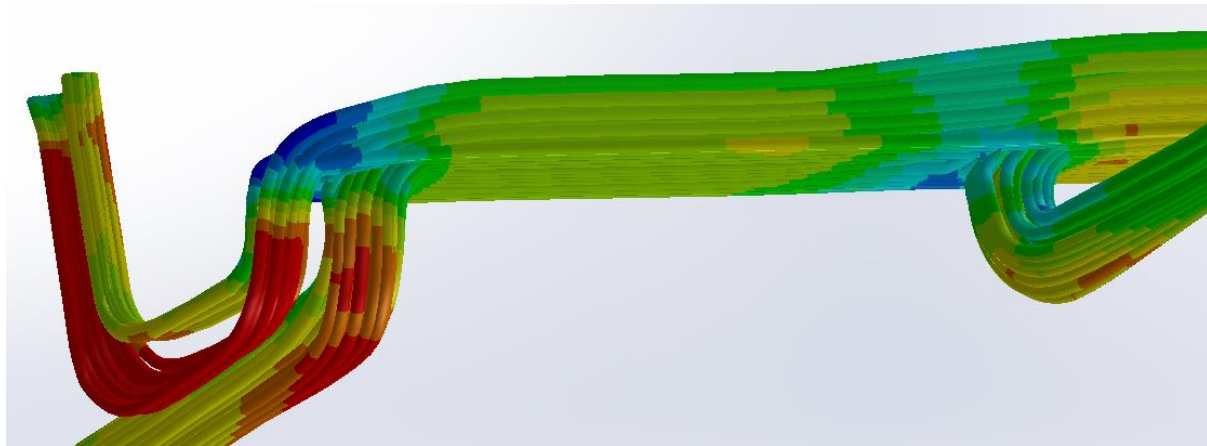


Figure G.15: CFM 1200 J1, J3 velocity distribution

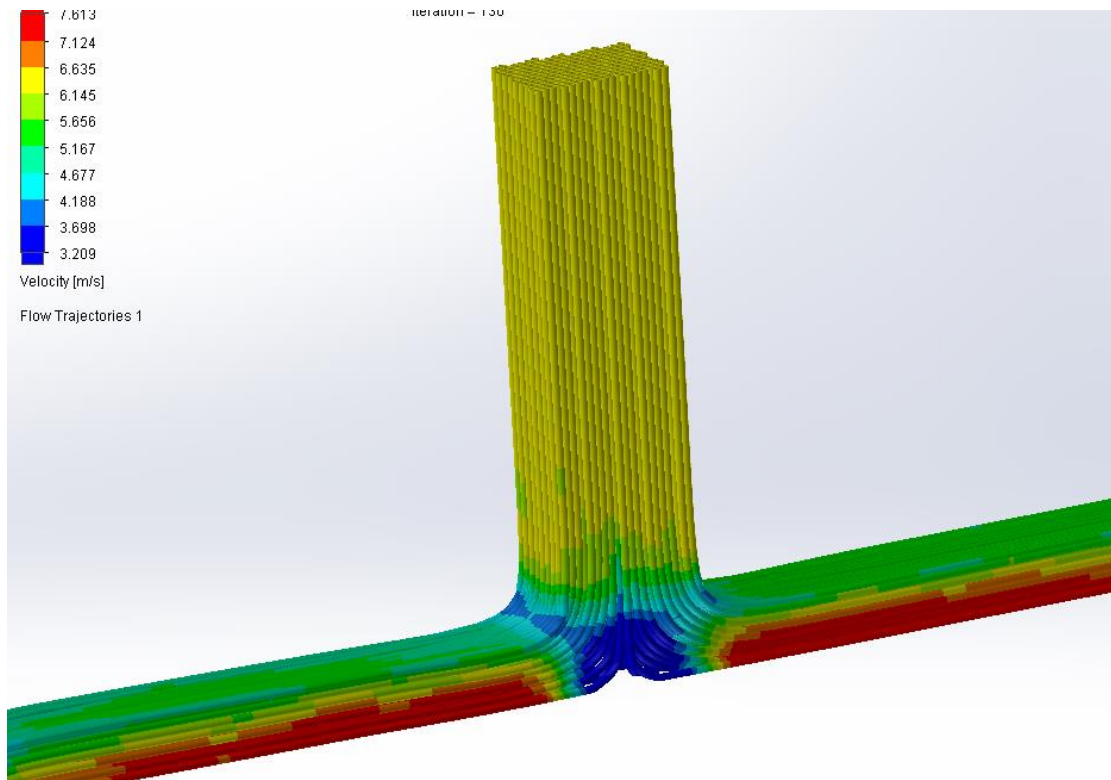


Figure G.16: CFM 1200 D1F1 pressure distribution (South section on left)

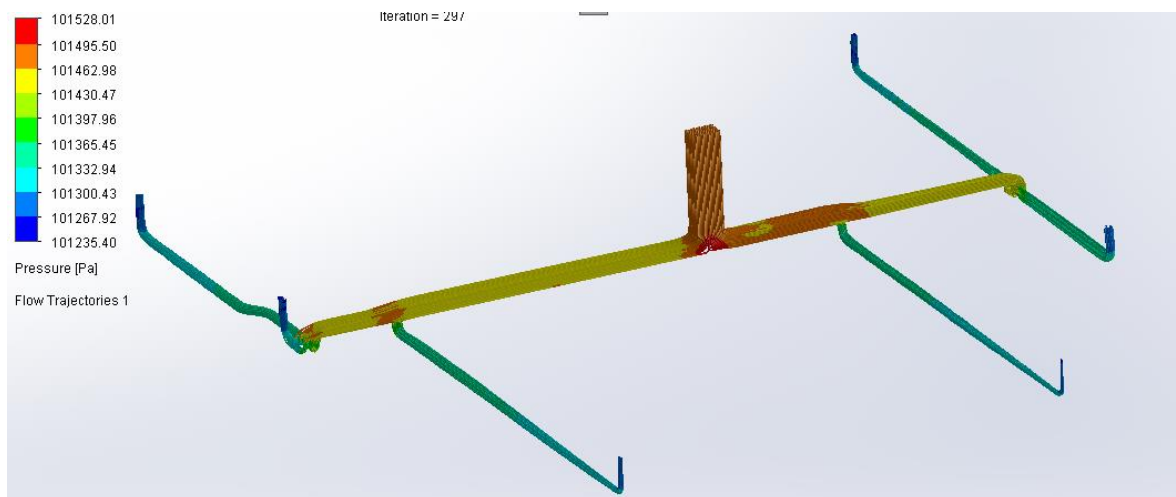


Figure G.17: CFM 1400 overall pressure distribution of duct system

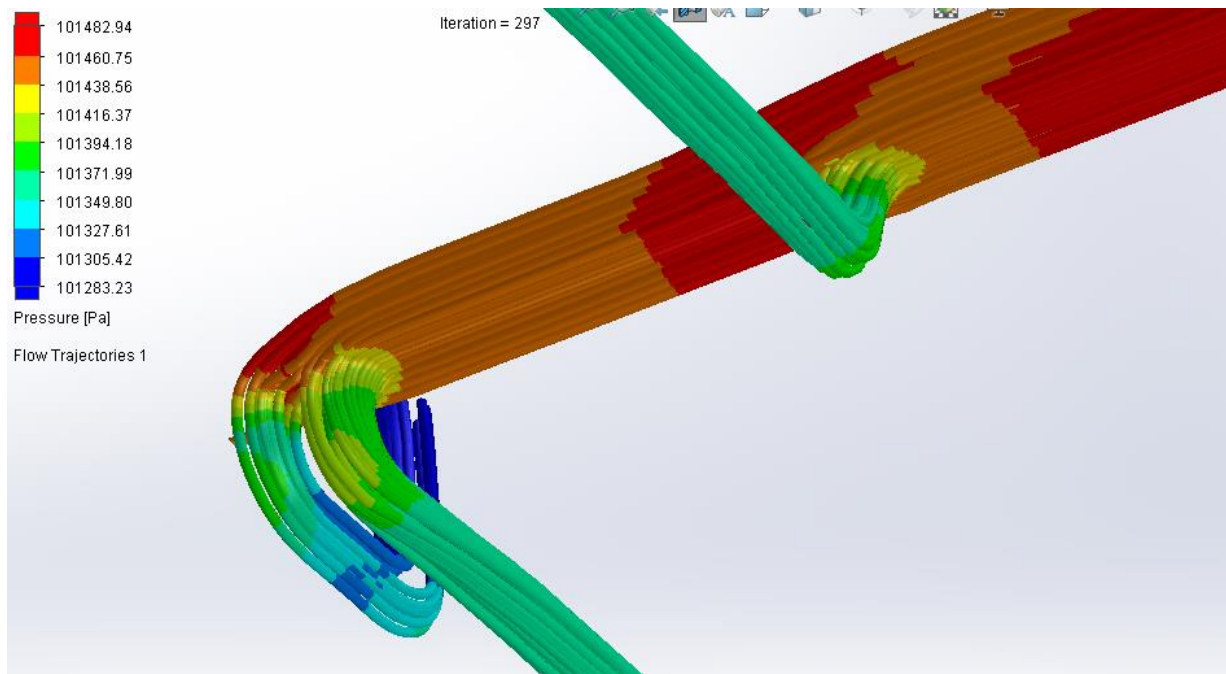


Figure G.18: CFM 1400 J2, J4 pressure distribution

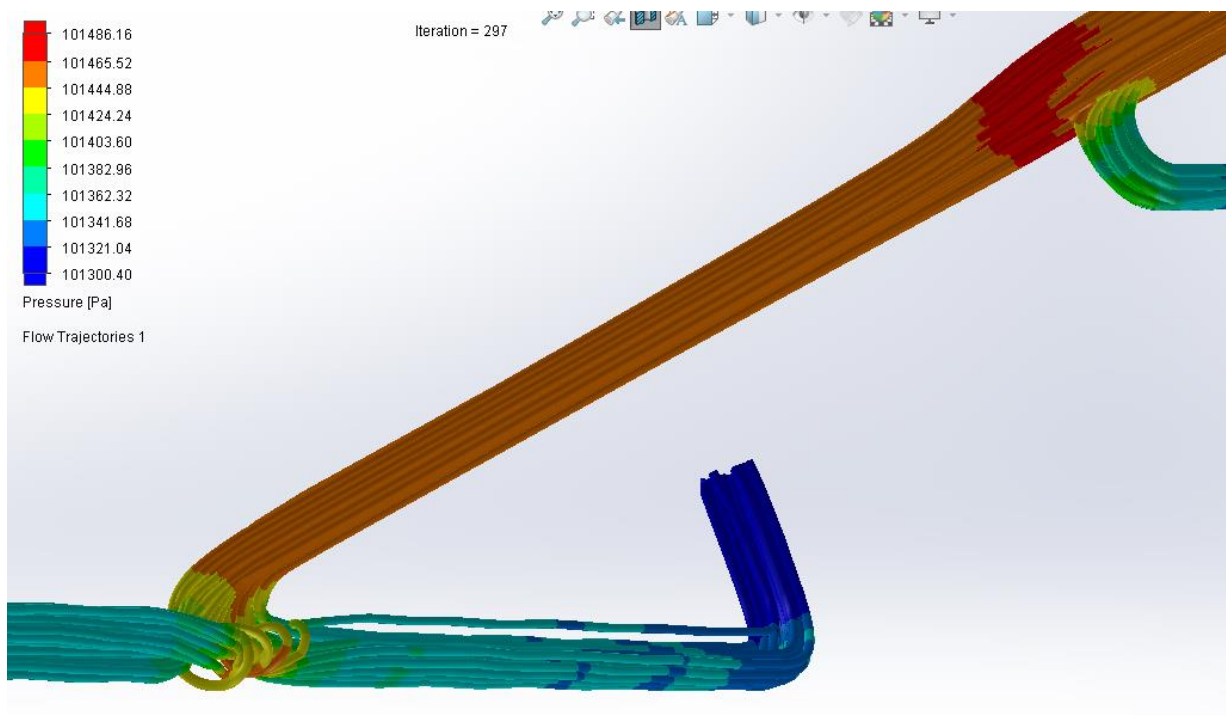


Figure G.19: CFM 1400 J1, J3 pressure distribution

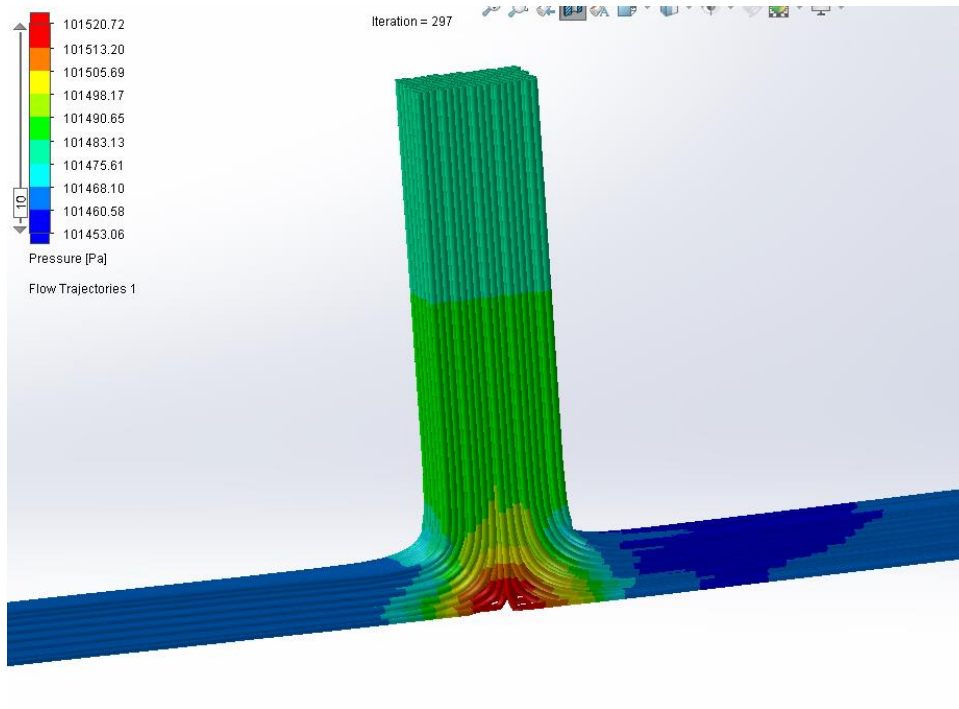


Figure G.20: CFM 1400 D1F1 pressure distribution (South section on left)

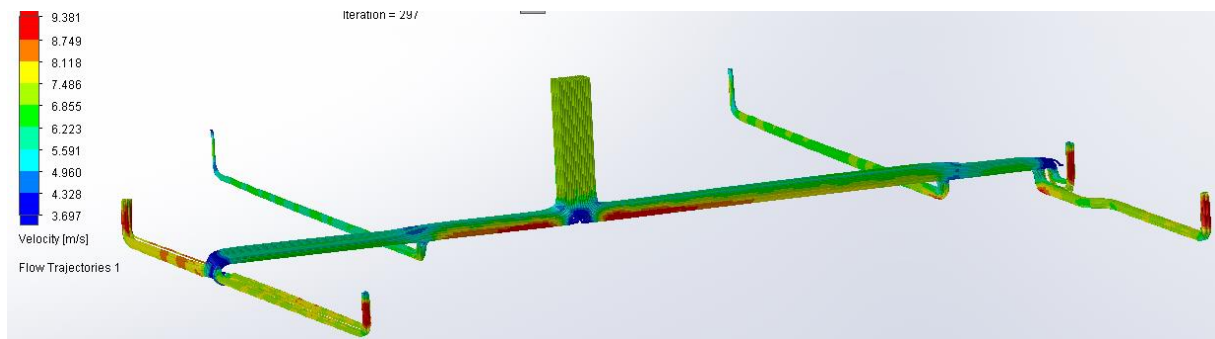


Figure G.21: CFM 1400 overall velocity distribution of duct system

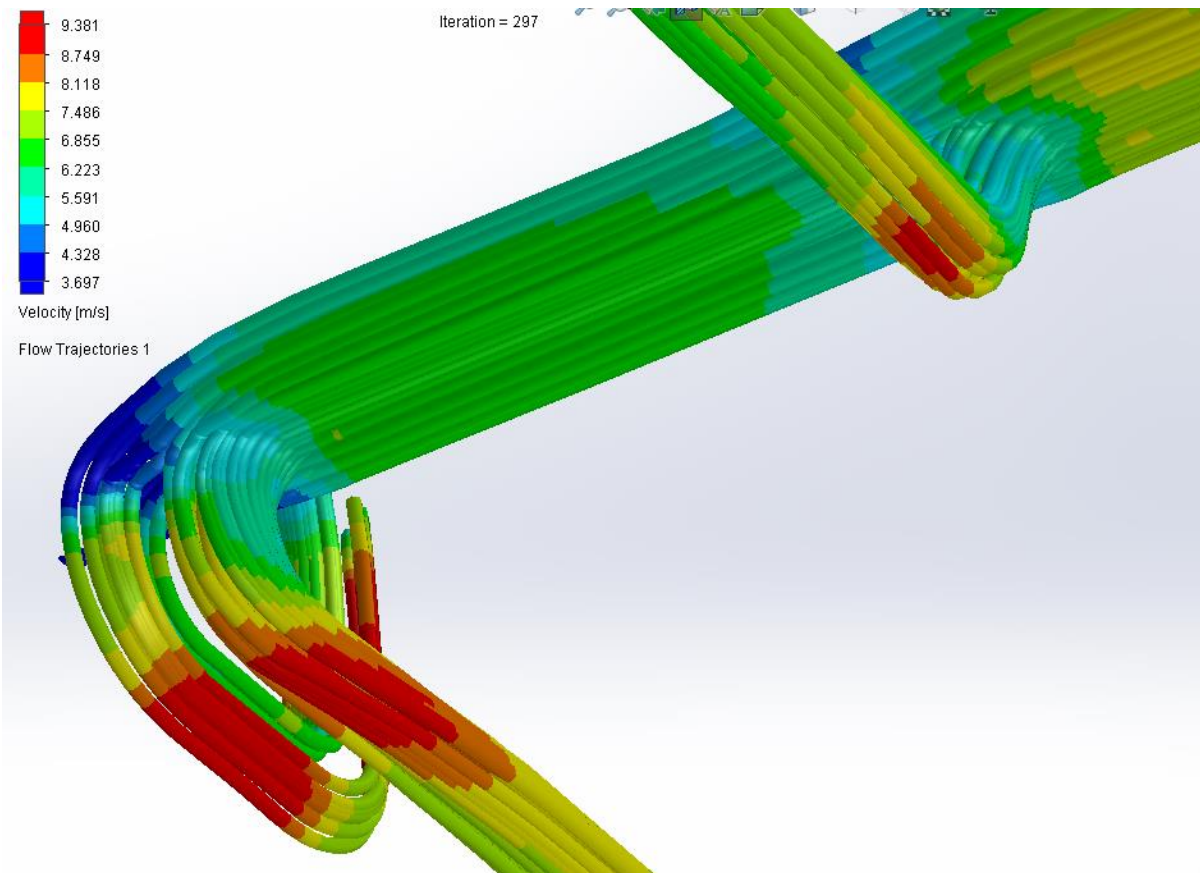


Figure G.22: CFM 1400 J2, J4 velocity distribution

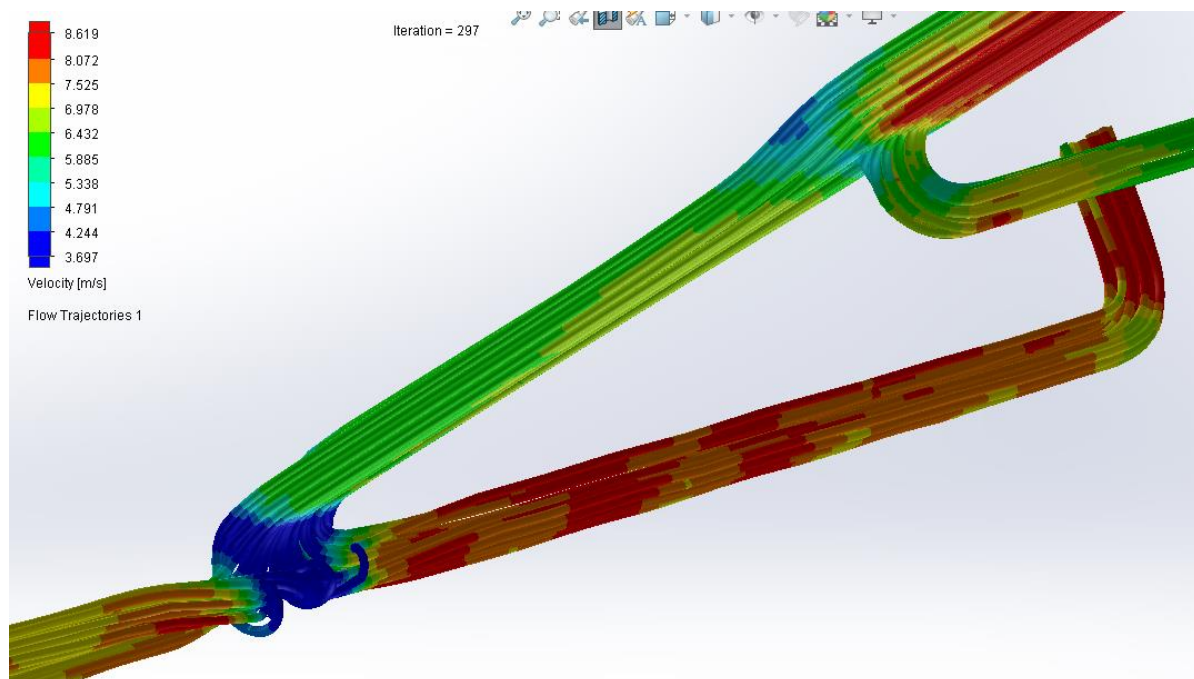


Figure G.23: CFM 1400 J1, J3 velocity distribution

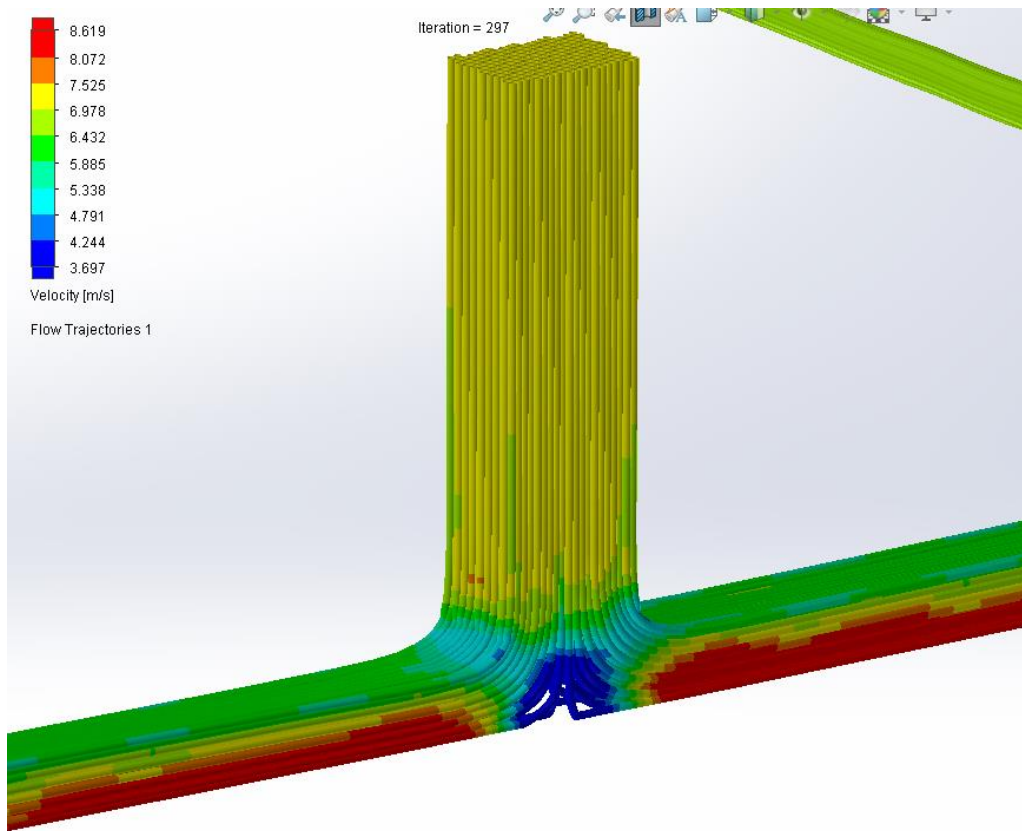


Figure G.24: CFM 1400 D1F1 velocity distribution (South section on left)

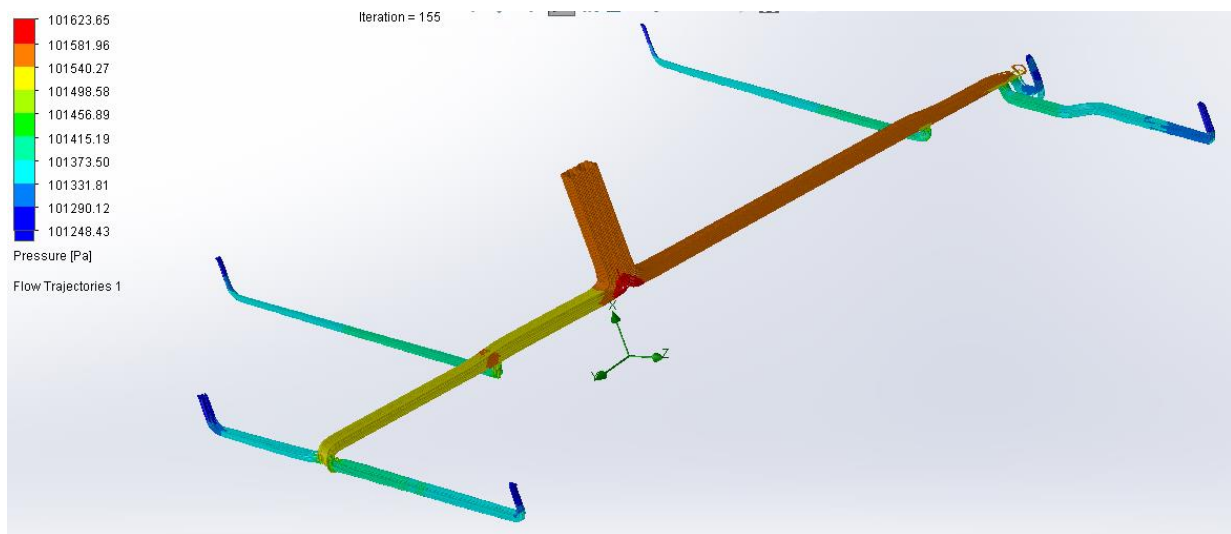


Figure G.25: CFM 1600 overall pressure distribution of duct system

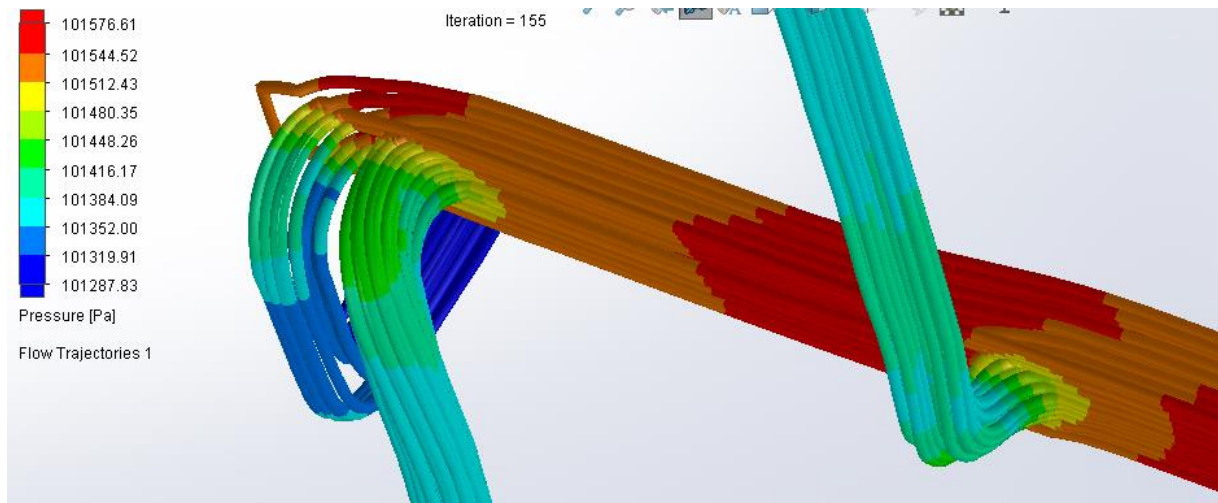


Figure G.26: CFM 1600 J2, J4 pressure distribution

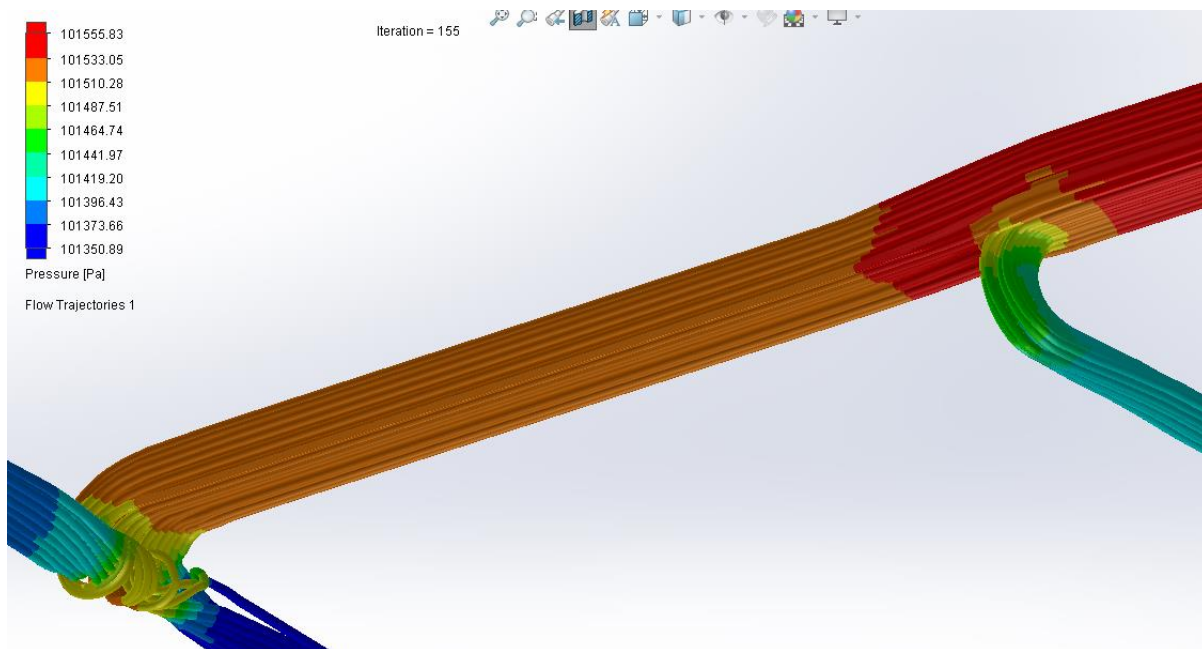


Figure G.27: CFM 1600 J1, J3 pressure distribution

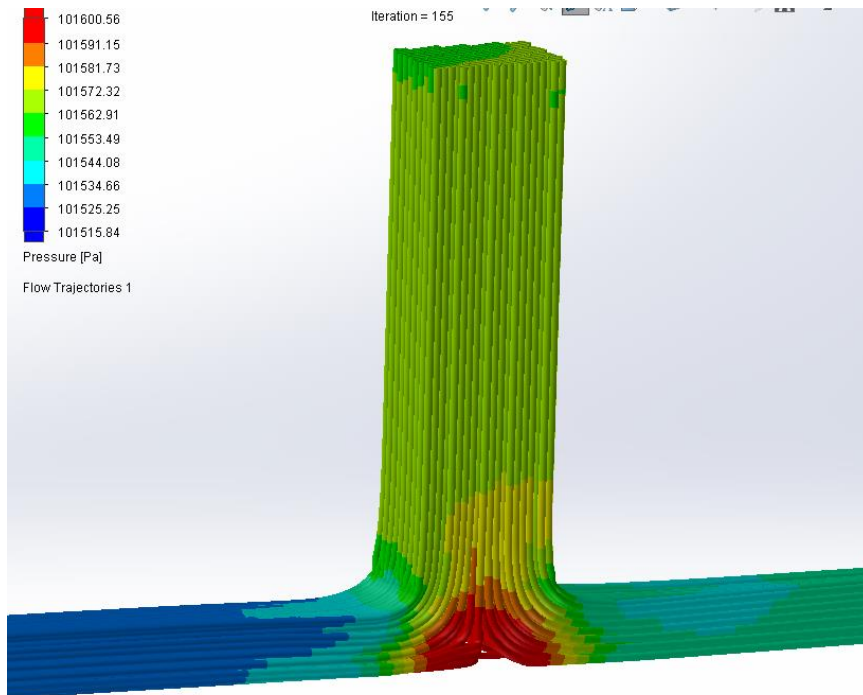


Figure G.28: CFM 1600 D1F1 pressure distribution (South section on left)

CFM 1600: Velocities

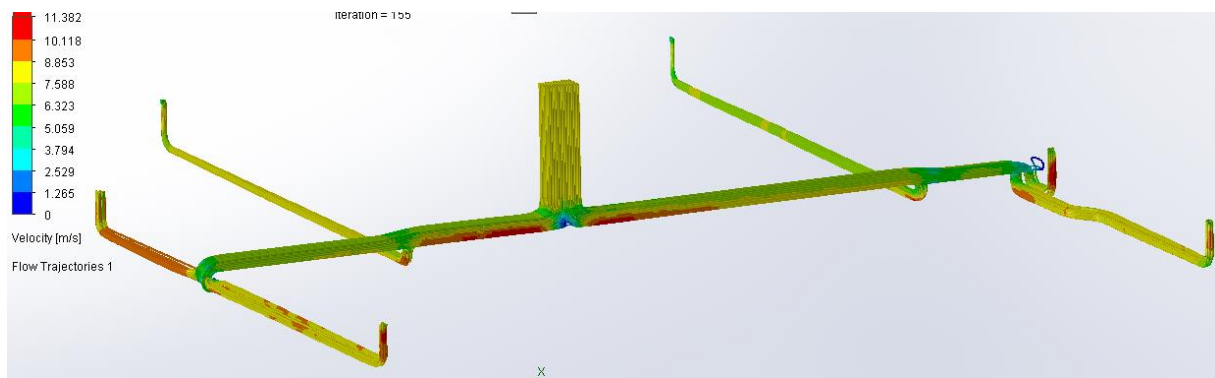


Figure G.29: CFM 1600 overall velocity distribution of duct system

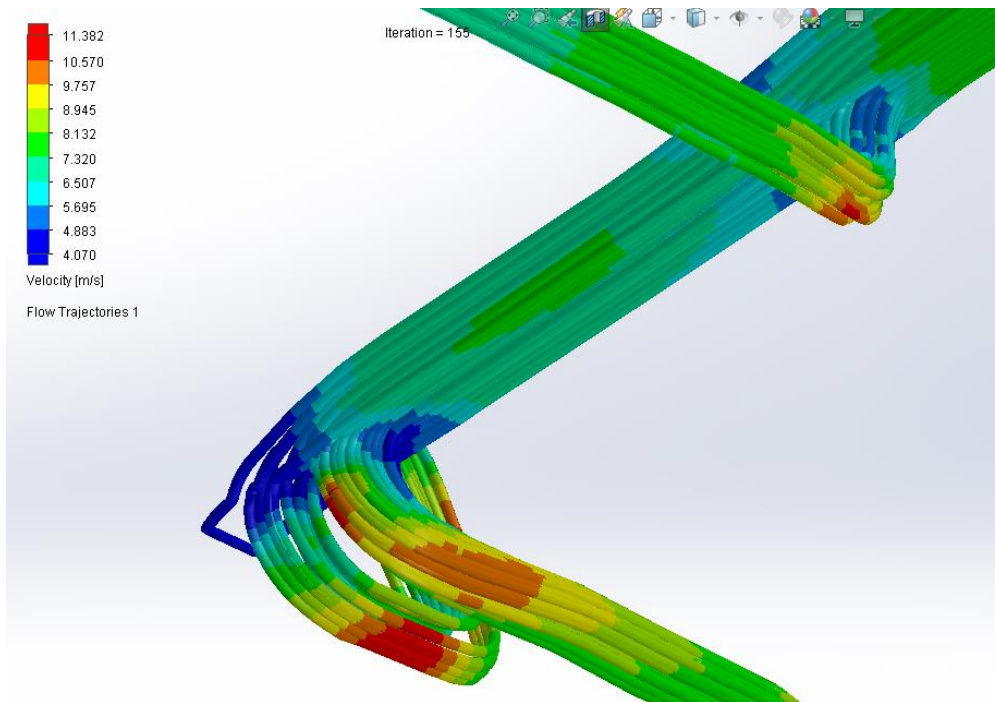


Figure G.30: CFM 1600 J2, J4 velocity distribution

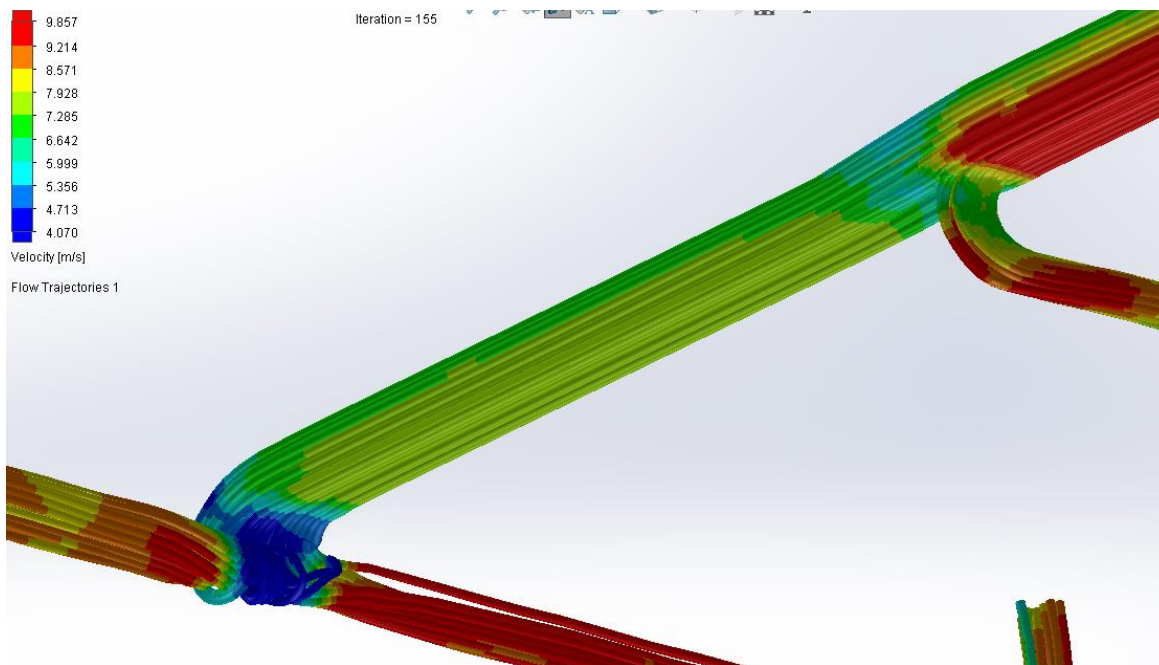


Figure G.31: CFM 1600 J1, J3 velocity distribution

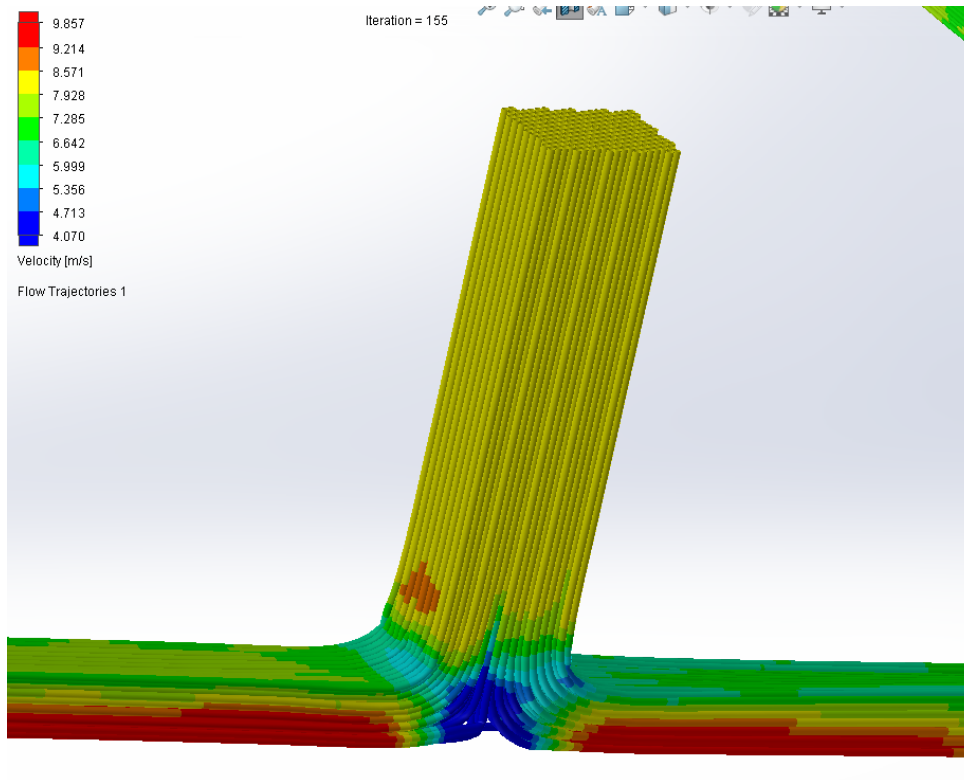


Figure G.32: CFM 1600 D1F1 velocity distribution (South section on left)

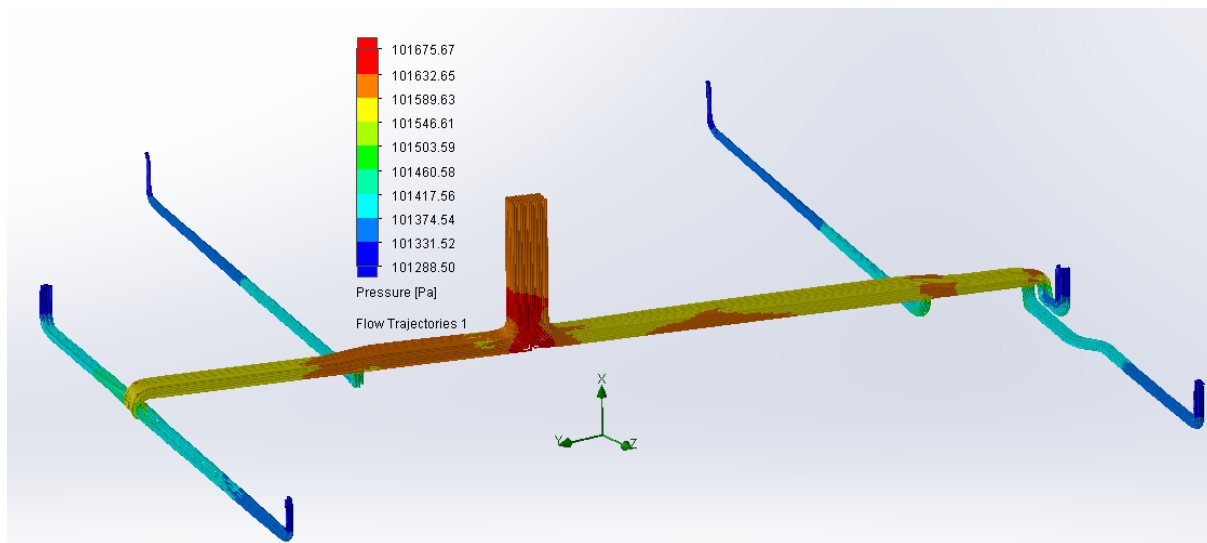


Figure G.33: CFM 1800 overall pressure distribution of duct system

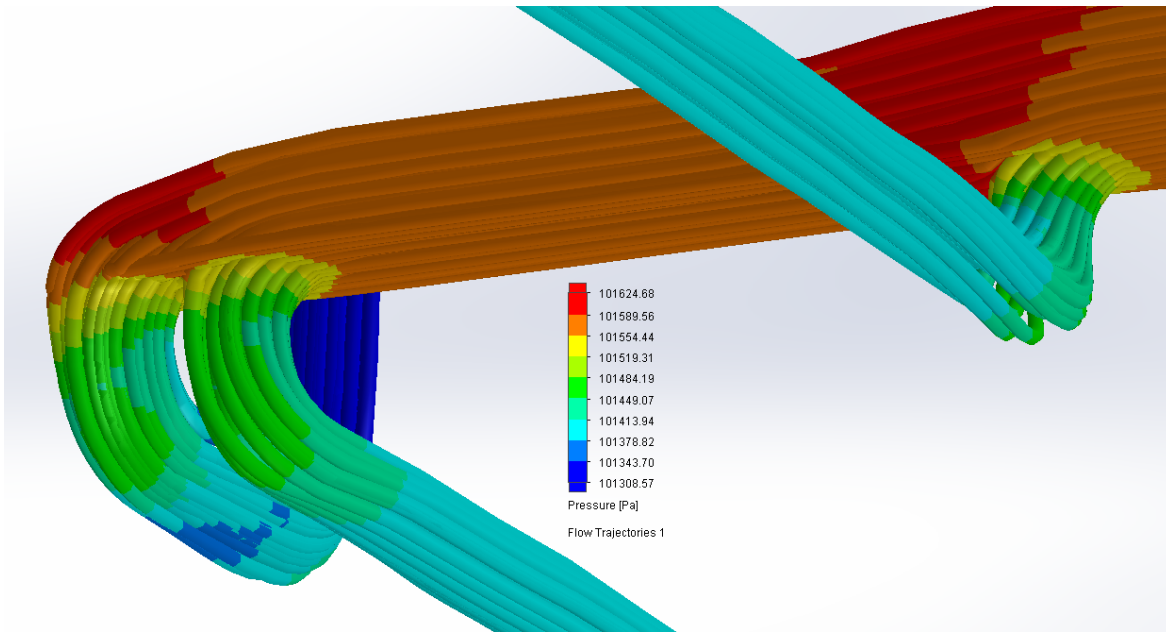


Figure G.34: CFM 1800 J2, J4 pressure distribution

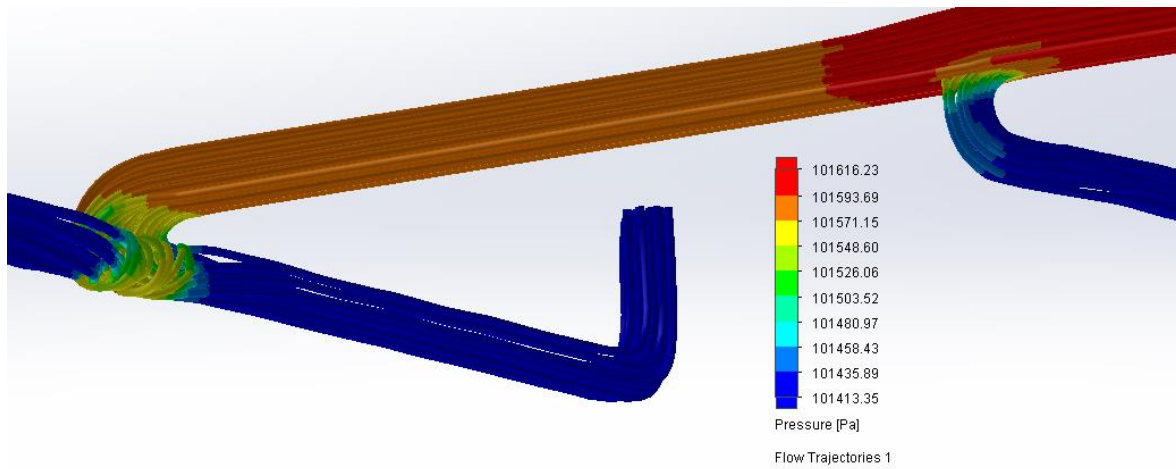


Figure G.35: CFM 1800 J1, J3 pressure distribution

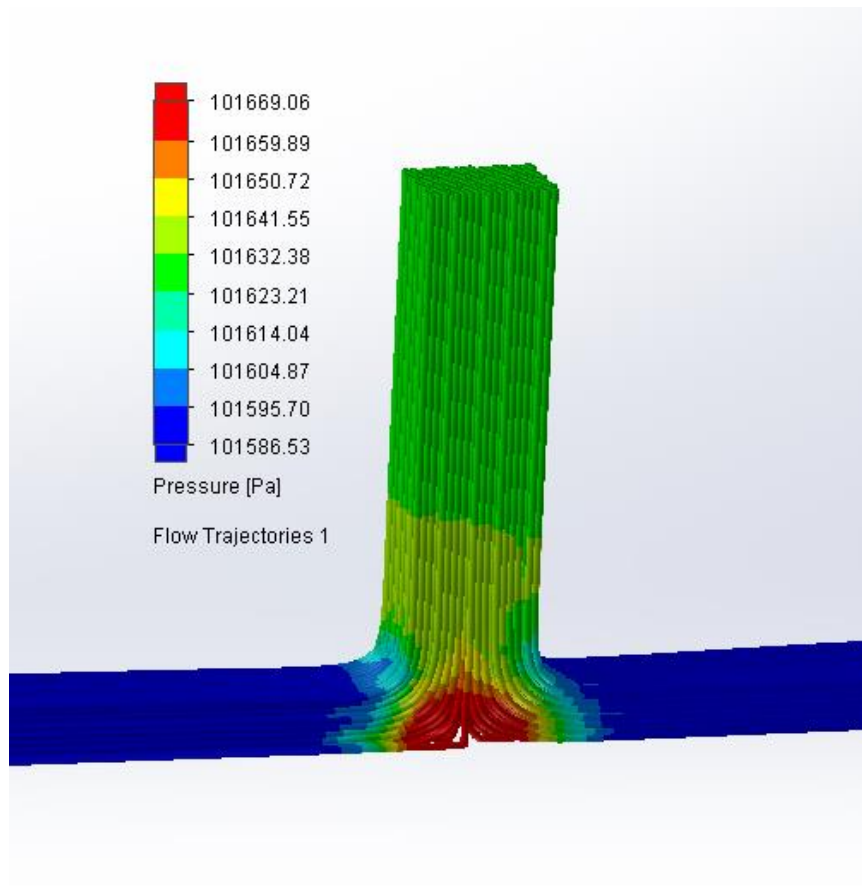


Figure G.36: CFM 1800 D1F1 pressure distribution (South section on left)

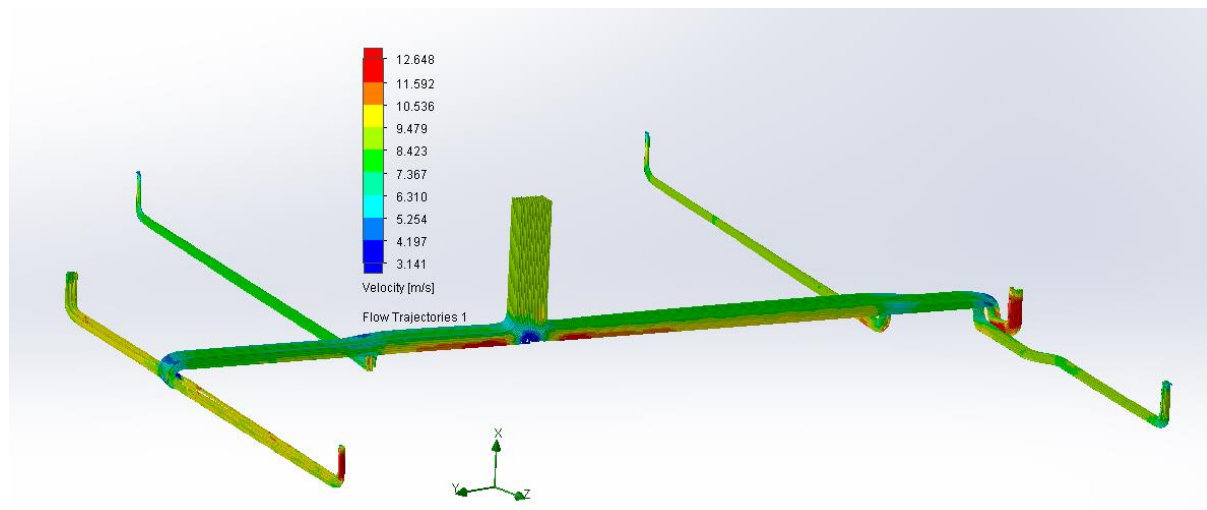


Figure G.37: CFM 1800 overall velocity distribution of duct system

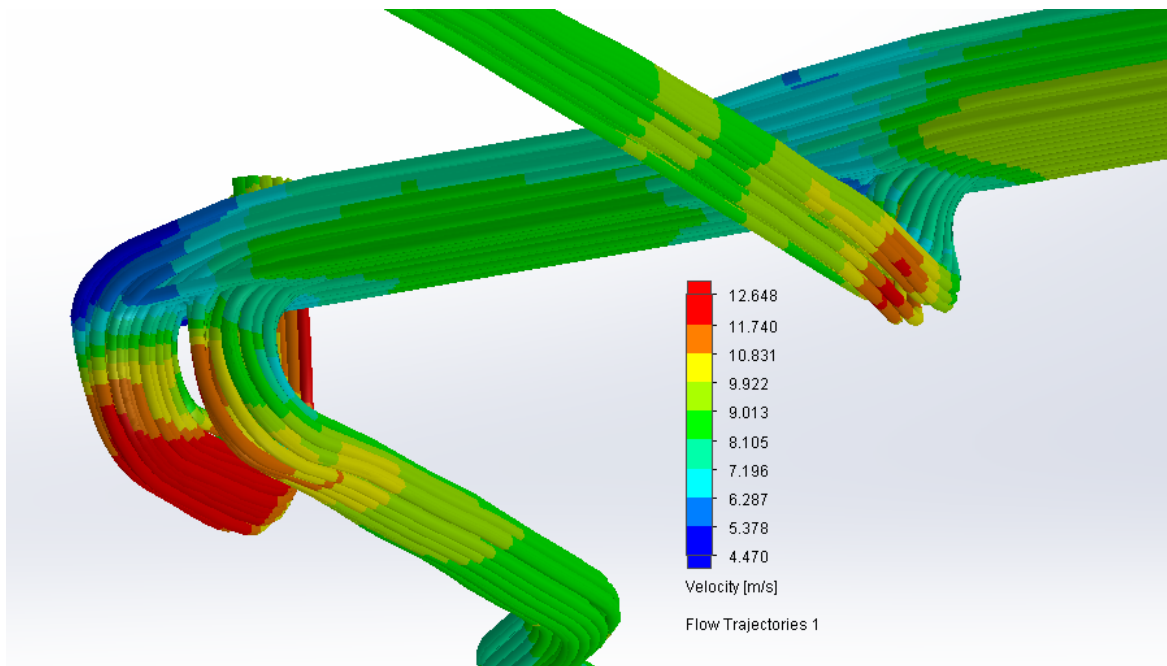


Figure G.38: CFM 1800 J2, J4 velocity distribution

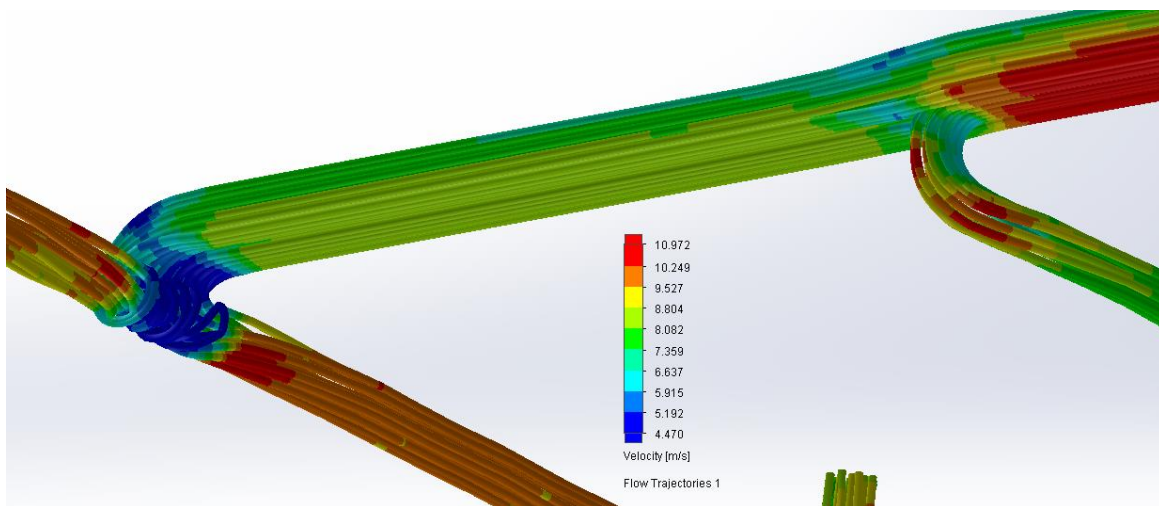


Figure G.39: CFM 1800 J1, J3 velocity distribution

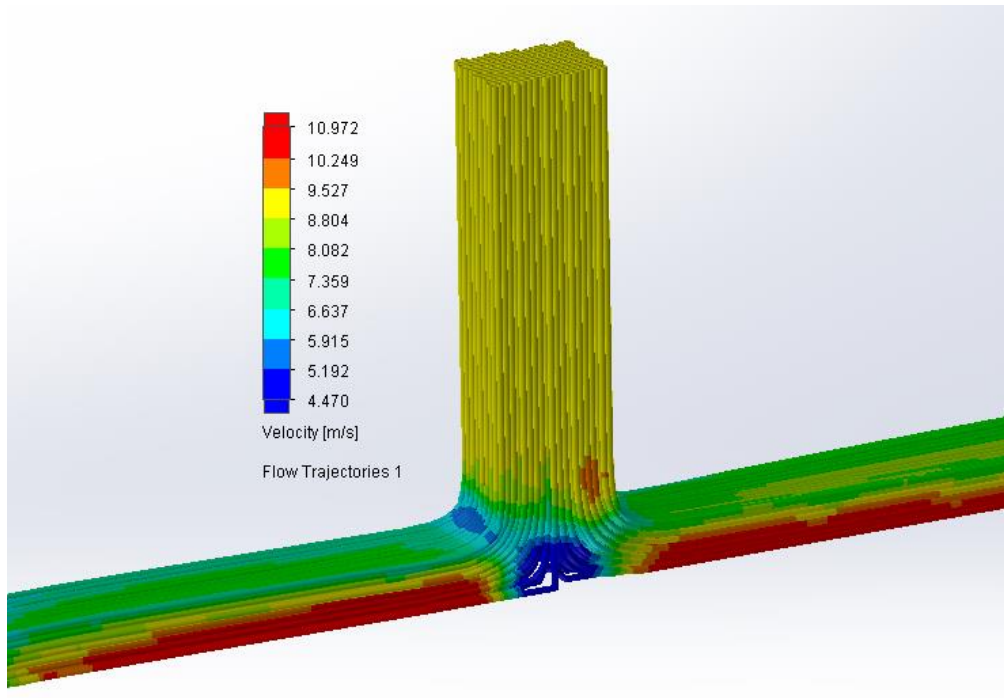


Figure G.40: CFM 1800 D1F1 velocity distribution (South section on left)

Appendix H: Additional Construction Images