NASA Exploration Systems & Habitation (X-Hab) Academic Innovation Challenge 2020

Microgravity Gas/Liquid Separator for the CO_2 Revitalization System

The University of North Texas

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Final Report

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Nomenclature

$v_{li} = velocity\ at\ liquid\ inlet$

$Q_{li} = flow\ rate\ at\ liquid\ inlet$

$A_{li} = area\ of\ liquid\ inlet\ nozzle$

$v_{lo} = velocity\ at\ liquid\ outlet$

$Q_{lo} = flow\ rate\ at\ liquid\ outlet$

$A_{lo} = area\ of\ liquid\ outlet$

$Re = Reynolds\ number$

$\rho_l = density\ of\ liquid\ at\ inlet$

$R = inner\ radius\ of\ separator$

$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet$

$a_b = acceleration\ of\ a\ bubble$

$\sigma = surface\ tension\ of\ liquid$

$C_D = drag\ coefficient\ of\ a\ bubble$

$r = bubble\ radius$

$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator$

$L_N = characteristic\ length\ of\ the\ nozzle\ outlet$

$v = liquid\ kinematic\ viscosity\ at\ liquid\ outlet$

$L_{water} = volume\ of\ water\ in\ separator$ *(L)*

$\rho_l = density\ of\ liquid$

$\rho_g = density\ of\ gas$

$v_{zr} =$ *resultant axial velocity between a bubble and the liquid*

$a_z = axial\ acceleration\ of\ a\ bubble$

$t = time$

$v_z = axial\ velocity\ of\ a\ bubble$

$r_1 = final\ position\ of\ a\ bubble$

$r_2 = initial\ position\ of\ a\ bubble$

$D_z = axial\ distance\ from\ the\ inlet\ nozzle\ to\ the\ baffle\ plate$

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Executive Summary

This report outlines the efforts of UNT X-Hab Team on a project titled, Microgravity Gas/Liquid Separator for the CO_2 Revitalization System. The project is executed as a senior design project during academic year 2019-2020. The X-Hab 2020 Academic Innovation Challenge has selected eleven senior design teams from colleges across the US to demonstrate working prototypes for exploration systems and habitation. UNT has been tasked with the creation of a gas-liquid separator for an air revitalization system. Air revitalization technology has been used to support spaceflight by removing CO_2 from enclosed systems in order to maintain breathable air[1]. Solid sorbents such as zeolites or lithium hydroxide have been used in the past for these systems but are difficult to handle in microgravity environments and require a large amount of energy[1]. This challenge aims to demonstrate vortex phase separator (VPS) technology for removing H_2O from a CO_2 stream. However, VPS technology also has the capability of using liquid sorbents for removing CO_2 from an air stream. Further research could be done on liquid sorbents, such as liquid amine, in use with VPS systems. This would potentially be an alternative technology in replacing use of solid sorbents in CO_2 removal systems. In 2019, NASA proposed a design that uses a gas/liquid contactor to allow for efficient contact between the two fluid phases[1]. This was integrated into an overall CO_2 removal system[1]. The subsystems for gas-liquid separation and storage in NASA's previous models for CO_2 removal system could be replaced with a VPS. Innovative vortex separator technology is expected to allow for high throughput flow and highly efficient CO_2 removal compared to other gas-liquid separation technologies. VPS relies on centripetal driven buoyancy forces to form a gas-liquid vortex within a fixed, right circular cylinder. The gas stream enters the separator through a tangential nozzle and breaks into very small bubbles (<<1 mm) resulting in a very large contact surface area for interaction with the liquid stream via energy and mass exchange. VPS technology can handle mismatches in inlet and outlet flow rates and system volume changes through the range of liquid thickness held in the separator (i.e., buffering and accumulating capability), and requires low pressure differences (<5-10 in H_2O in most cases) for operation. The X-Hab 2020 team leverages these characteristics to investigate VPS technology as an alternative CO_2 removal technology.

Section 1: Introduction

1.1 Objective

As NASA ventures to the Moon and Mars, resupply of oxygen to the crew is crucial in sustaining their lives in space[1]. Since space is a microgravity environment and the cabin of the spacecraft is closed to the space atmosphere, CO_2 and water vapor can build up in the atmosphere, causing hypercapnia to affect the crew[1]. The UNT X-Hab 2020 team's vision is to develop an innovative, reliable, compact, and energy efficient phase separator to be used in air revitalization systems for microgravity manned exploration. In particular, the X-Hab team is designing a multiphase vortex phase separator (VPS) subsystem to separate CO_2 gas and water vapor after cabin air with high levels of CO_2 has been pulled into NASA's existing air revitalization system. This multiphase vortex phase separator subsystem can recirculate H_2O back into the system to continue separation of CO_2 from cabin air, while also purging CO_2 to space or storing it to be used in another system. Implementing VPS technology to NASA's existing air revitalization system could allow for higher efficiency of CO_2 removal, energy conservation, and easier maintenance.

1.2 Motivation

Separating CO_2 from enclosed environments in space application is extremely important. If CO_2 levels in the enclosed cabin exceed 5.2 mmHg per 180 days, death by hypercapnia can occur[2]. This value for CO_2 grows smaller as the days in space increase. Hypercapnia can cause shallow breathing, disorientation, cognitive deficiencies, reduced vision, and headaches, leading to decreased performance amongst crew members and eventually death[2]. As NASA ventures farther into space with the intent of one day allowing humans to inhabit other planets, CO_2 separation technology becomes vital. The VPS system's performance will be compared to NASA guidelines given in Evaluation Criteria for CO_2 Removal System[3], ensuring safe amounts of CO_2 will be removed if this prototype were to be scaled and implemented into a spacecraft.

1.3 Approach

On Earth, vortex separator systems use gravity to aid in gas/liquid separation. When used in space application, vortex phase separators must artificially replicate forces like gravity to produce phase separation in low gravity environments[4]. To do this, the microgravity gas/liquid vortex separator uses centrifugal buoyancy force to separate gas and liquid[4]. As a thin layer of water rotates around the inner diameter of a hollow cylinder, a stream of humidified CO_2 is introduced via tangential injection. These streams coalesce and drive the CO_2 separation from H_2O. Using specially designed injection nozzles, the gas stream breaks into minuscule bubbles upon contact with the water stream. These bubbles are then forced to the center of the cylinder due to density difference in gas and liquid, creating a gas column in the center of the vortex. Gas and liquid outlets are present on the top and bottom of the separator at the centers of the cylinder's faces, with a baffle plate located on the liquid outlet to prevent gas from entering it. Water is led through a liquid outlet where it is chilled through a chiller and heat exchanger and then directed back to the liquid tangential inlet nozzle by a gear pump. A sparger is used to introduce CO_2 gas to a heated tank of water where the gas will be humidified. This humidified CO_2 stream is combined with the chilled H_2O from the liquid outlet and directed back into the gas tangential inlet nozzle by an ejector.

Section 2: Project Timeline

The timeline for this project is described in a chart format in Figure 1 below. Tasks for each team member are also shown in the timeline. These tasks are listed in more detail in Section 7: Team Personal Responsibilities. Table 1 shows the milestones and their corresponding due dates. Figure 2 illustrates the work breakdown structure.

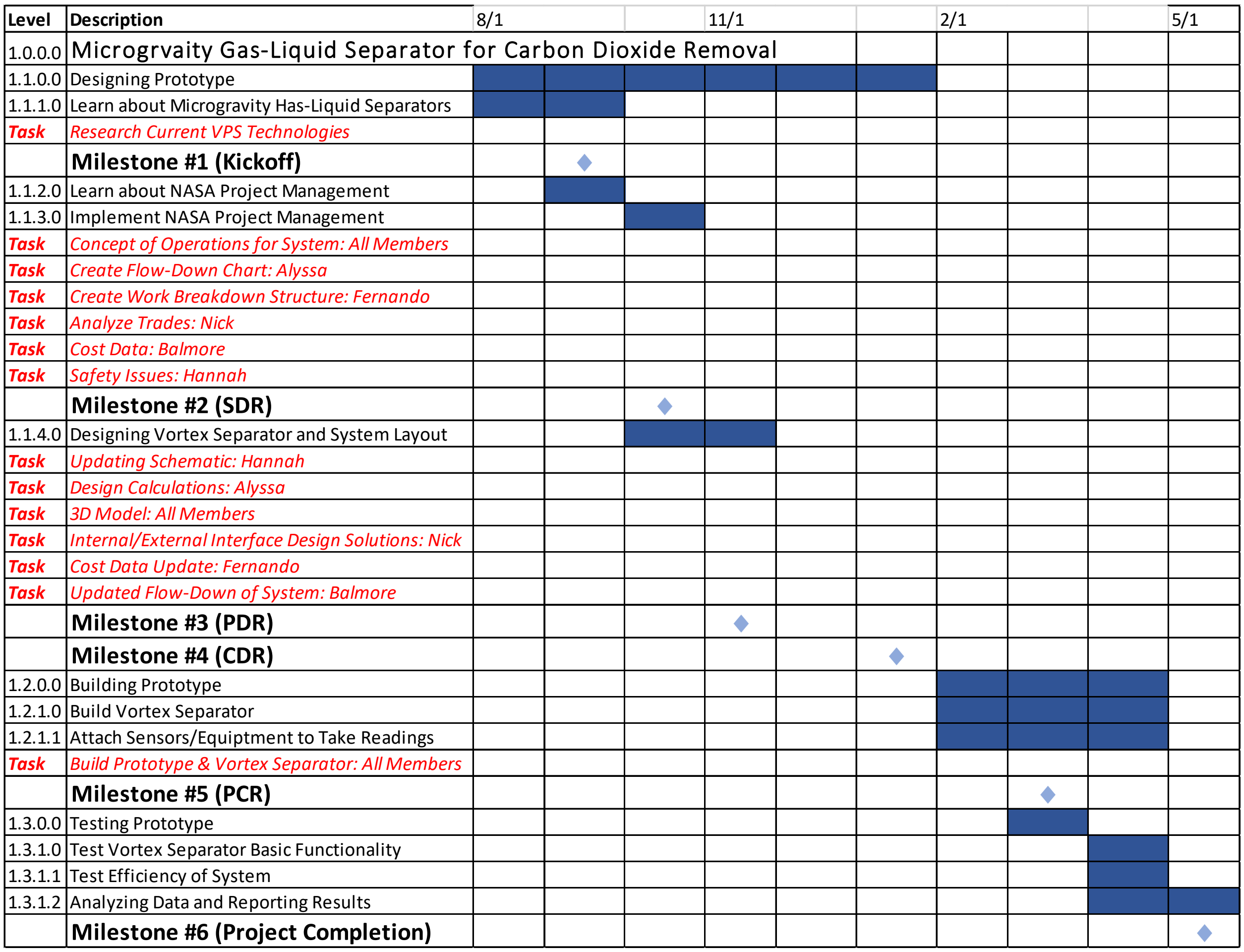

Figure 1: Gantt Chart

Table 1: Milestones and Dates

Milestone	Date
1. Kickoff Meeting	Sept 2019
2. Requirements and System Definition Review (SDR)	08 Oct 2019
3. Preliminary Design Review (PDR)	12 Nov 2019
4. Critical Design Review (CDR)	21 Jan 2020
5. Progress Checkpoint Review (PCR)	11 March 2020
6. Project Completion and Evaluation by NASA	06 May 2020

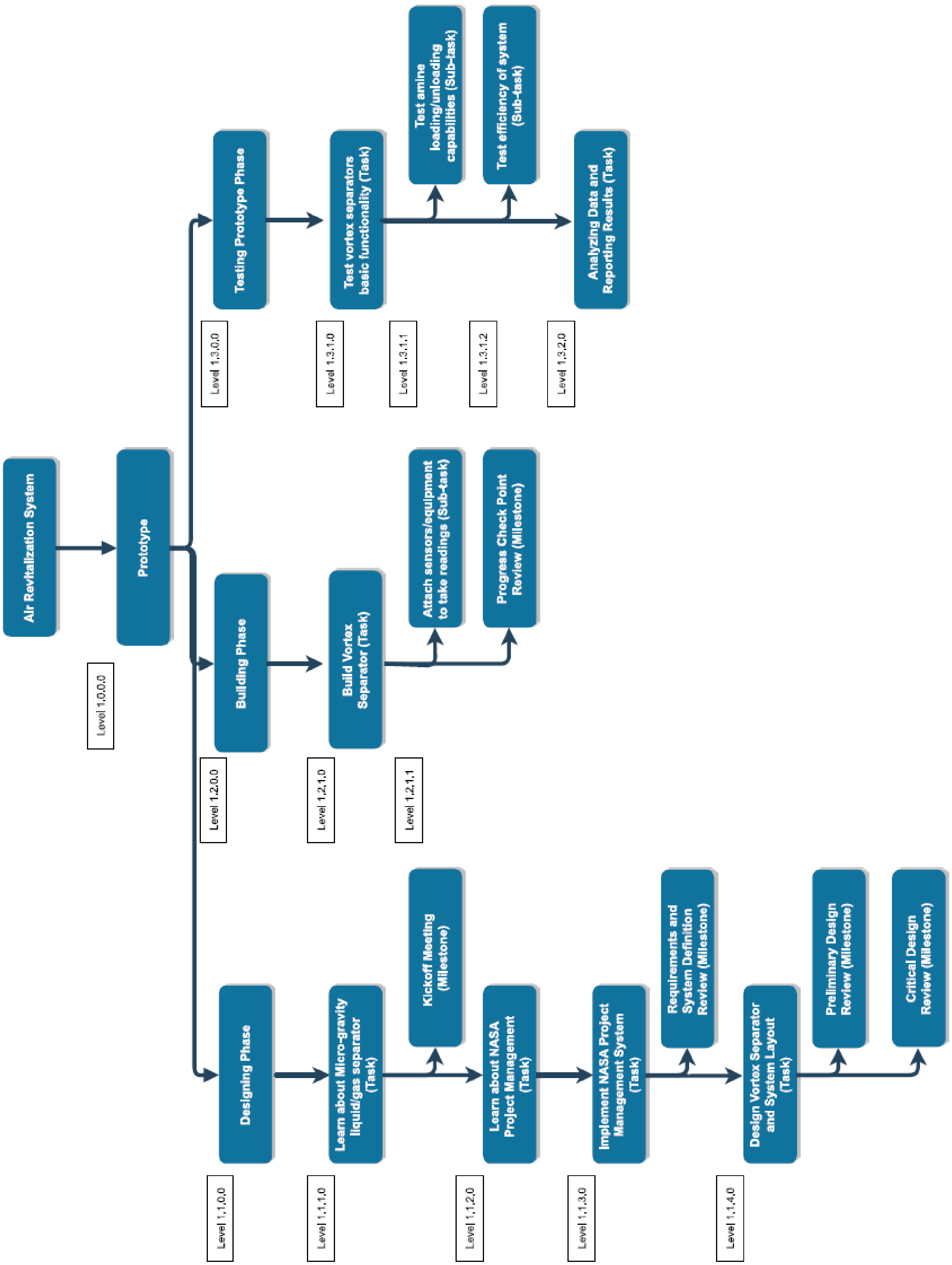

Figure 2: Work Breakdown Structure

Section 3: Design Evolution

3.1 Summary of Competitive Developments

This section discusses developments done on air revitalization technology by NASA.

NASA is currently using a solid sorbent system which utilizes zeolite granules to remove CO_2 from cabin air on the ISS[5]. Failure analysis of a returned flight desiccant/adsorbent bed revealed that there was a failure in the seal of the design and allowed some zeolite particles to be circulated with the movement of process air in the cabin[5]. This decreases the efficiency of CO_2 removal by the system and requires more power usage of the system[5]. The long-term modification plan for this system is to find a system that improves system operability and reliability[5]. Therefore NASA redesigned the sorbent retainment system and is now looking to use liquid amine instead of zeolite granules to aid in CO_2 removal[5]. To mitigate CO_2 toxicity, NASA presented experimental data and modeling results for a liquid amine chemisorbet CO_2 removal system in July, 2019[1]. This system uses a gas-liquid contactor that passes cabin air over groove trays filled with liquid amine sorbent which is regenerated thermally, and a degasser unit that also uses a grooved structure to transport fluid[1]. This system is further discussed in Section 3.2: Phases of Project Design when explaining how the vortex separator subsystem may be integrated into this system.

3.2 Phases of Project Design

Three major design evolutions occurred for the full system, one including liquid amine which the X-Hab team decided to completely remove from the system to simplify the design. This changed the project's scope from removing CO_2 from a humidified CO_2 –rich air stream, to removing only H_2O from a humidified CO_2 stream. The schematics for the system iterations are shown in Figures 3-5. The integration of the final subsystem into NASA's air revitalization system is shown in Figure 6. Three major designs for the vortex separator body also occurred, shown in Figures 7- 9. Figure 10 shows the CO_2 humidifying tank design for the system. The overall housing design for the system is shown in Figure 11.

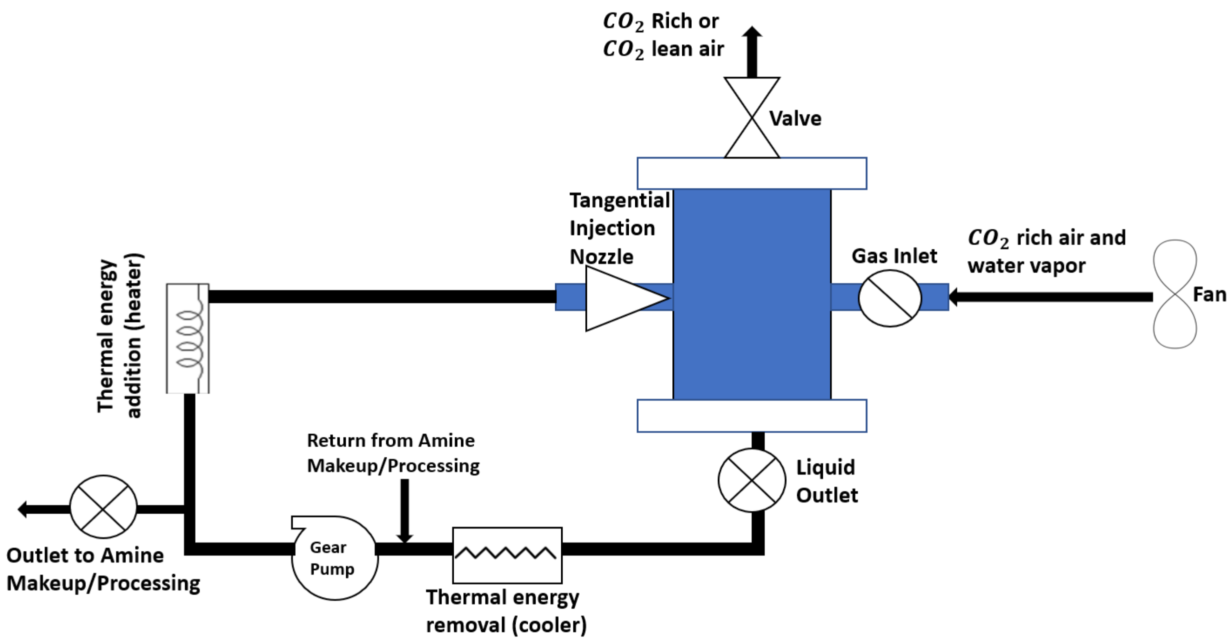

Figure 3: First Design Iteration of System

The first design iteration, shown in Figure 3, used liquid amine which the X-Hab team decided to completely remove from the system to simplify the design, as previously stated. Cabin air with high CO_2 levels and water vapor is fed into the gas inlet at the vortex separator wall. This cabin air then breaks into very small bubbles and moves through the rotating liquid amine solution that's purpose is to absorb CO_2 and condense water vapor before air bubbles combine with the gas vortex and exit from the gas outlet as CO_2 lean air. Liquid amine with an increasing amount of CO_2 exits the vortex separator through its liquid outlet and is cooled by the heat exchanger before being pumped back into the separator through the tangential injection nozzle, aiding in rotational flow and driving the separator process. To recondition liquid amine, cabin air is isolated from the separator and the liquid amine temperature is increased via rope heaters. This heating is what causes CO_2 to be released from the amine collected in the separator. The separator is used to vent excess CO_2 gas from the gas outlet valve and is controlled by a three-way valve. A gear pump is used to recirculate the liquid stream in the system.

The design iteration shown in Figure 3 was not used due to the X-Hab team deciding to remove liquid amine from the system and to focus on H_2O removal from a humidified CO_2 stream. The purpose of this removal was to integrate this subsystem focusing on removing H_2O from a humidified CO_2 stream into NASA's current system that utilizes a liquid amine sorbent in a CO_2 removal system[1]. This is discussed later in this section and shows how the final iteration is utilized in NASA's subsystem. This design iteration is a batch-processing system, meaning CO_2 concentration in VPS increases over time and needs to be released through a regeneration process that involves heating the circulating liquid stream. In the second and third design iterations, water level in the VPS increases over time due to condensation and some of it needs to be drained to maintain proper operation.

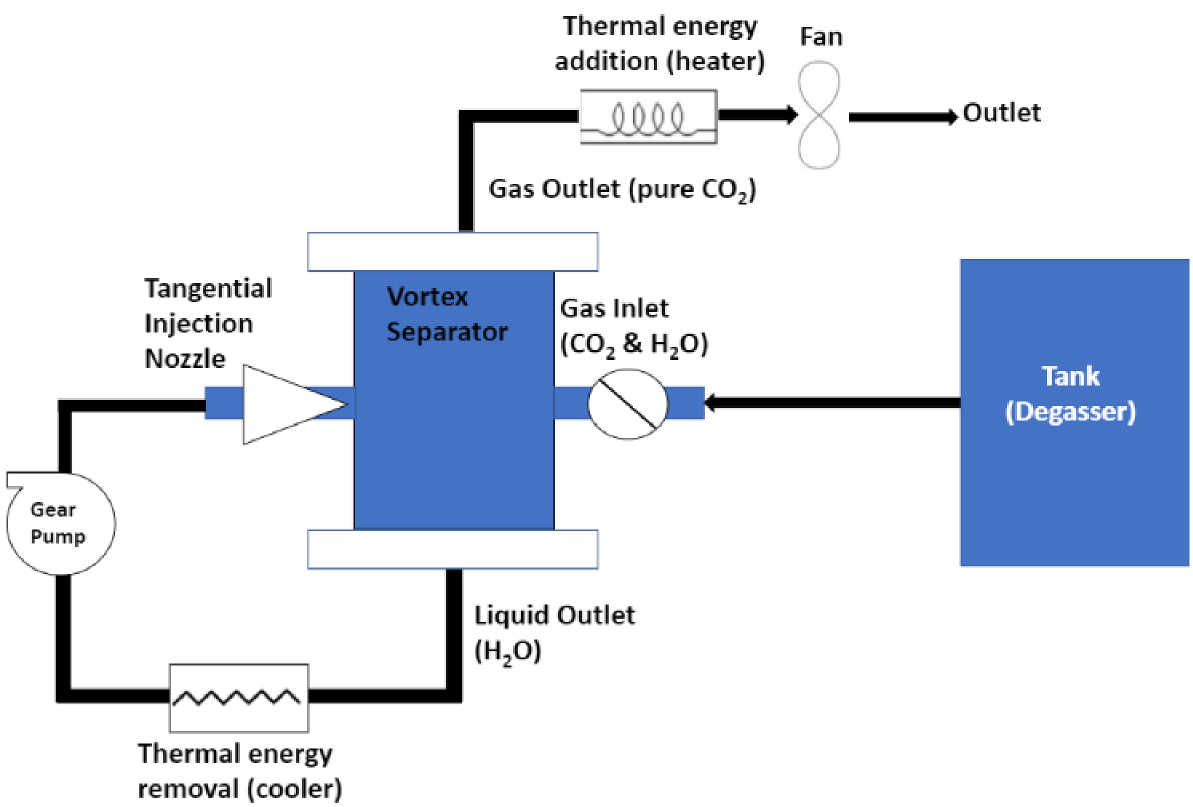

Figure 4: Second Design Iteration of System

Figure 4 shows the second design iteration in which liquid amine was removed from the system. This system operates as a continuous process. Liquid H_2O exits the separator through the liquid outlet and is cooled by the chiller before being pumped back into the separator. This produces a rotational flow that drives the separation process and regulates the temperature of the system. A heater is used to regulate the temperature of CO_2 as needed. The CO_2 with a much lower water content is collected in the gas portion of the vortex separator and vented out through the gas outlet.

The design iteration shown in Figure 4 was not used due to the tank (degasser) not providing an efficient water-laden, heated CO_2 stream. The pressure at the gas inlet was also predicted to be too high. Control of flow into the liquid inlet and gas inlet was also not able to be controlled in this iteration. The fan was found to consume too much power and was removed in the final iteration of the system.

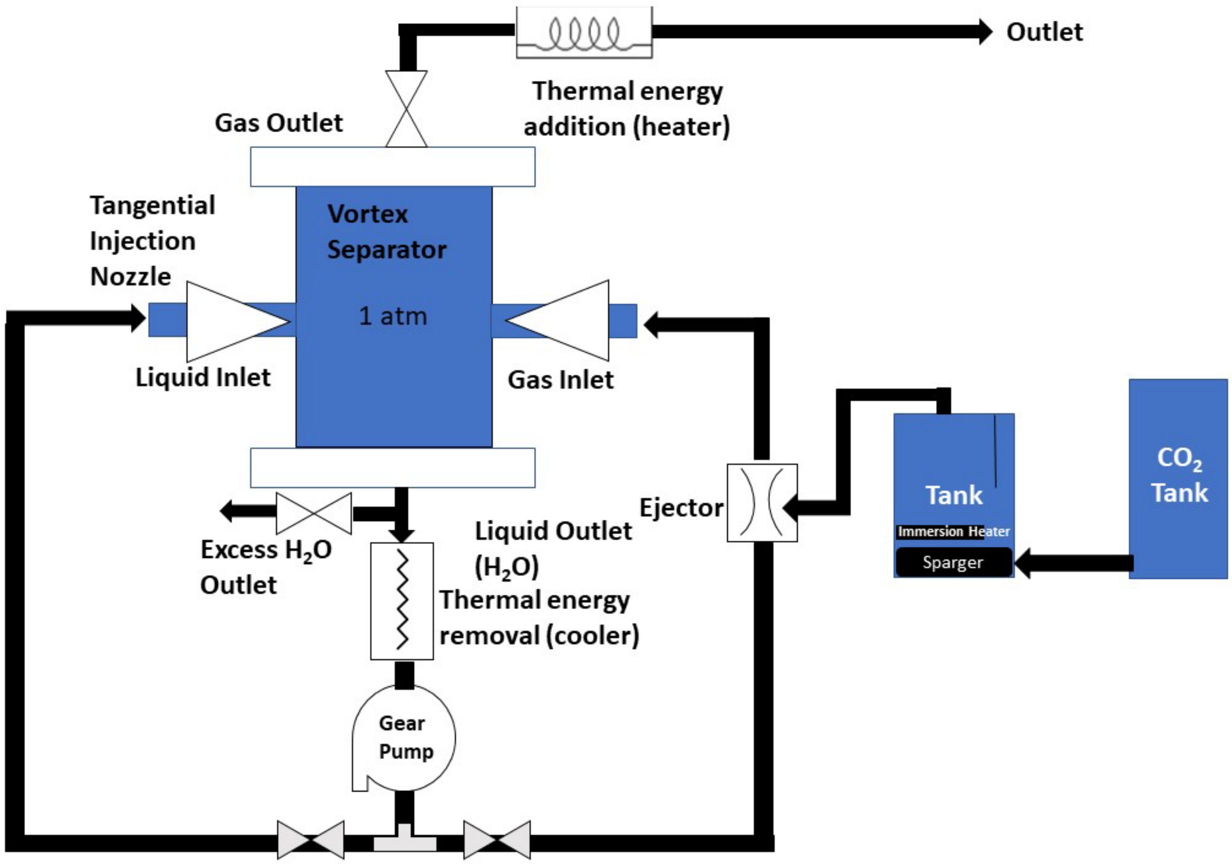

Figure 5: Final Design Iteration of System

Figure 5 shows the final design iteration. CO_2 is pulled into the tank with an ejector. The sparger is used to bubble CO_2 through hot liquid water, which is then passed through the tangential injection nozzle and into the vortex separator body after mixing with cold liquid water from the liquid outlet on the separator by the ejector. The ejector is used along with a gear pump for this driving process. This iteration implemented an ejector as it allows for a low-pressure zone before water-laden CO_2 reaches the mixing chamber in the ejector. This causes a low (~1 atm) pressure to exist at the gas inlet. This low-pressure zone allows for more mixing time to occur, which means flow through the tubing will allow for CO_2 stream to be in contact with cold water longer. The liquid inlet (tangential injection nozzle) aids in driving the separator to remove H_2O from the humidified CO_2 stream. A heat exchanger and chiller are used to cool the liquid from the liquid outlet on the vortex separator before it enters the vortex body via liquid tangential injection nozzle, and before it mixes with the humidified CO_2 stream in the ejector. The heater before the outlet is used to warm the CO_2 air. This CO_2 air could then either be vented to space or used in another system if the vortex separator system were implemented into NASA's current air revitalization system.

The gear pump from the previous iteration was moved near the liquid outlet and a tee junction with two needle valves was also added to this iteration to control flow directed towards the ejector and the flow going to the liquid inlet. At the liquid outlet, a ball valve was added as to maintain thickness of water layer on the separator wall. This iteration also includes an immersion heater as to achieve elevated temperatures in the CO_2 humidifying tank. As previously stated, this subsystem is to be used in NASA's current air revitalization system. This integration is shown in Figure 6.

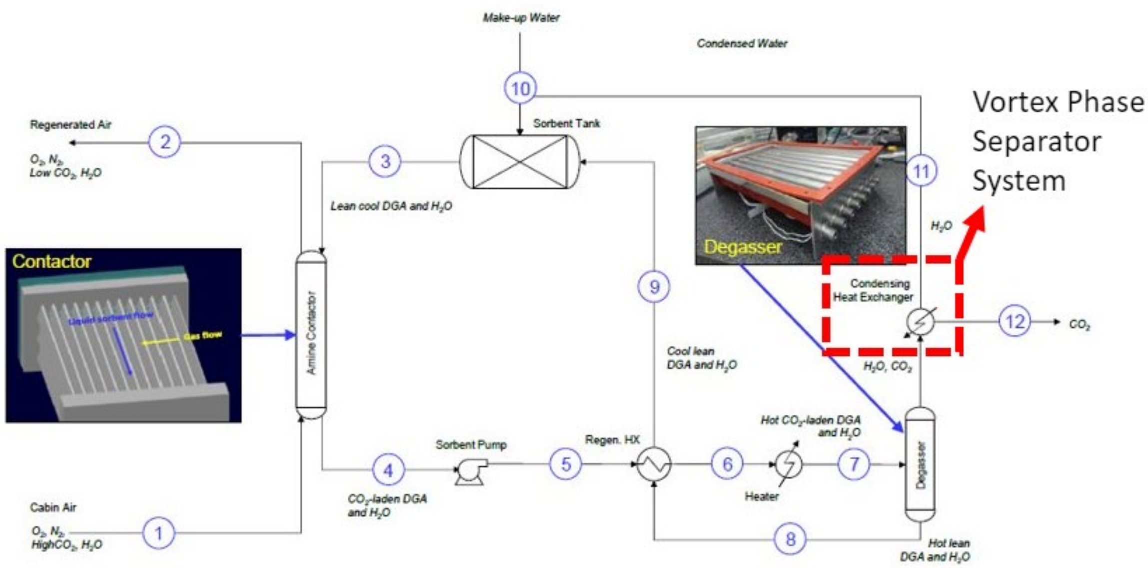

Figure 6: Integration of Subsystem into NASA's System[1]

NASA's air revitilization system works by first pulling CO_2 rich cabin air into a contactor where a liquid film of amine sorbent exists[1]. The liquid sorbent and cabin air flow perpendicularly to each other as to allow CO_2 in the cabin air to be introduced into the liquid amine sorbent. Liquid amine sorbent is held in the sorbent tank[1]. The amine contactor allows for some of the CO_2 in the vapor phase to physically absorb into the liquid amine sorbent[1]. After this, CO_2 is converted to a number of other products[1]. This step is important as it ensures any physically absorbed CO_2 converts to another product before reaching CO_2 saturation in the sorbent which would otherwise end the absorption process[1]. This is done through the regen. HX, which is a regenerative heat exchanger[1]. After this, thermal regeneration then drives products created previously back to the formation of physically absorbed CO_2 via heating[1]. Finally, phase exchange of CO_2 between liquid/gas occurs once again[1]. The condensing heat exchanger reclaims water vapor lost from amine sorbent at high temperatures during regeneration and adds it back into the system[1]. This is important as if the sorbent doesn't have enough water it will not effectively aid in the CO_2 removal process[1]. As can be seen, the X-Hab team's vortex phase separator system could act as the condensing heat exchanger in NASA's existing air revitilization system. Liquid from the liquid outlet in the vortex separator system represents number 11 in the above Figure and gas from the gas outlet in the vortex separator system represents number 12 in the above Figure.

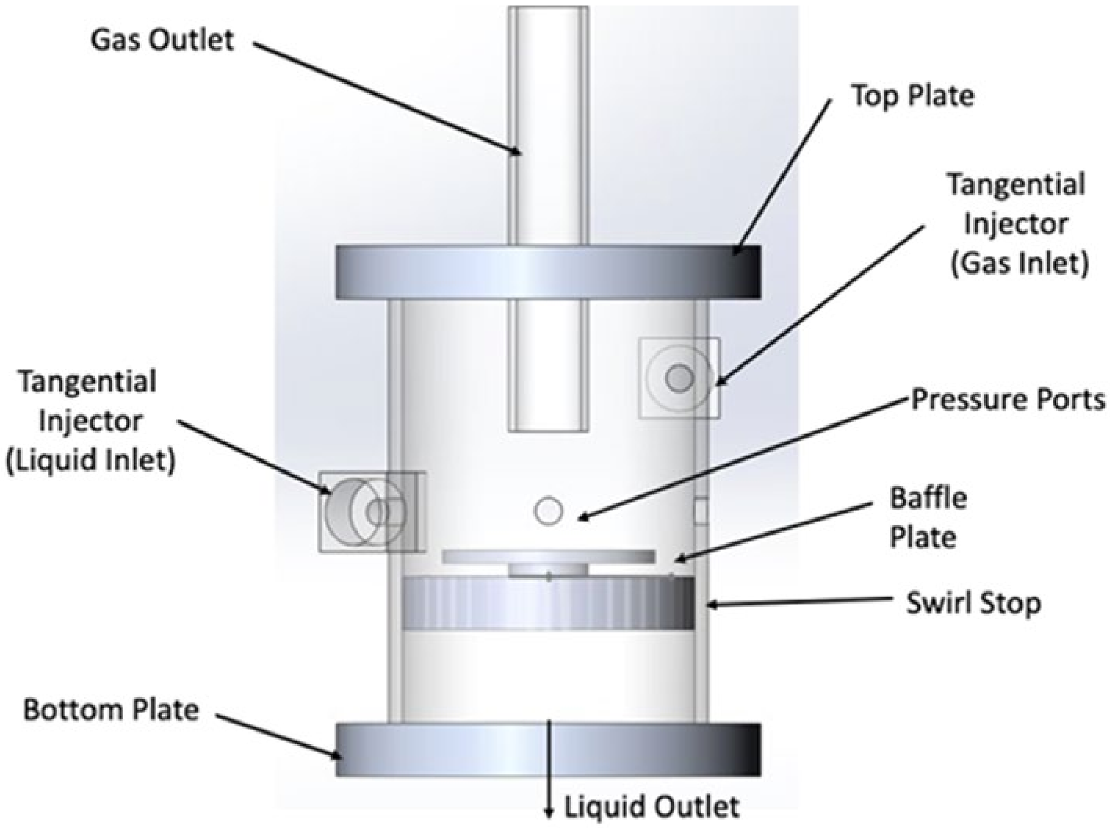

Figure 7: 1st 3D Model of Vortex Separator

Figure 7 shows the first 3D model of the vortex separator. This separator was designed when liquid amine was still going to be used in the system. The gas and liquid inlets can be seen near the top of the separator. The gas inlet pulls cabin air into the separator and the liquid inlet directs the liquid amine and water mixture into the separator. Four pressure ports exist around the body of the separator. These ports are where pressure transducers are to be placed to measure the pressure inside of the separator. The swirl stop was added to further break down the bubbles created in the separator, which increases CO_2 removal rate but was removed later in the next 3D design as it causes a small pressure-drop in the vortex separator. The baffle plate is used to keep gas in the center of the vortex core and direct liquid to the liquid outlet. The next iteration of this design included symmetrical liquid and gas inlets near the center of the vortex separator.

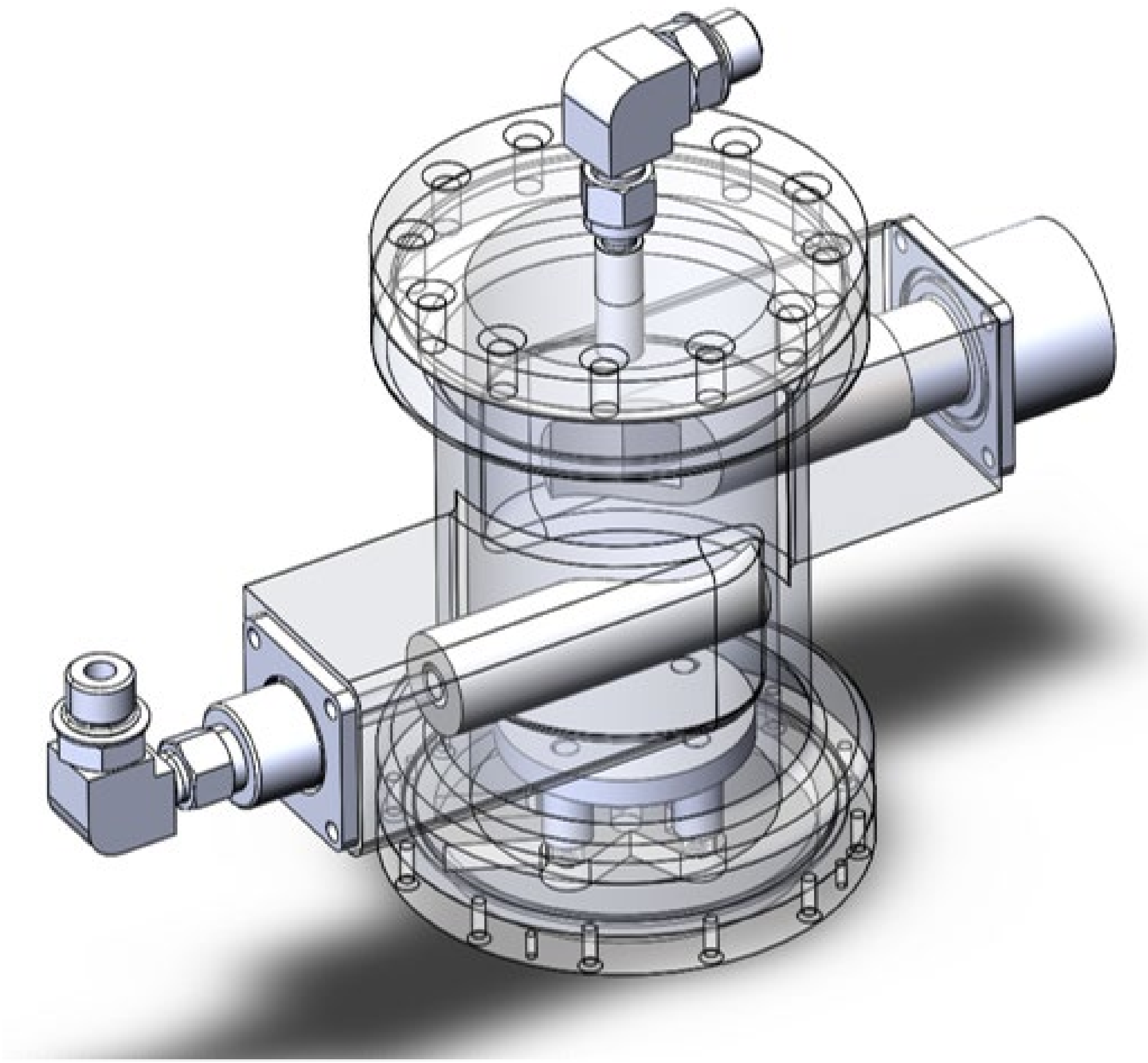

Figure 8: 2nd 3D Model of Vortex Separator

Figure 8 shows the second design iteration for the vortex separator body. A more detailed injector system was implemented, ensuring the size of the nozzles were ideal to aid in separation of water from the CO_2 stream. The pressure ports in the previous model were removed, as pressure is now measured by sensors at liquid inlet and gas outlet. Places for assembly of the separator were added, including creating a design for the baffle plate which allows it to be screwed directly into the bottom plate of the separator. The separator body was also scaled to be 1.25” inner diameter radius, and 5.5” in height. The swirl stop was removed to increase pressure at the wall of the vortex separator. The gas outlet is now smaller in diameter for this model, and its connection to a modified elbow is shown. This allows for control of gas release at the outlet.

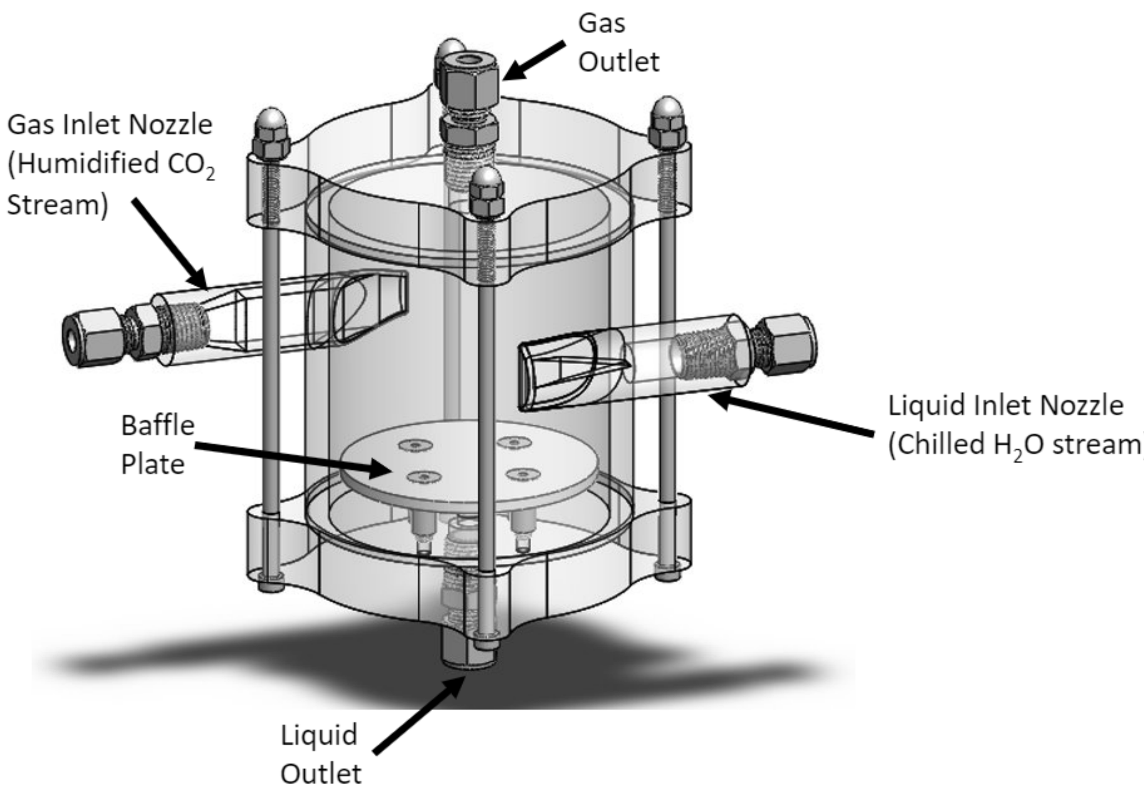

Figure 9: Final 3D Model of Vortex Separator

Figure 9 shows the final design iteration of the vortex phase separator. The design of the nozzles was further refined: they are now slotted into holes in the wall of the main separator body and secured using polycarbonate adhesive. The elbow attachments used in the previous iteration were removed as the nozzles were redesigned. Instead of using elbow attachments, this iteration uses compression (i.e., Yor-Lok) fittings directly attached to the nozzle bodies. Similar fitting are also used at the gas and liquid outlets. The top and bottom plates are now secured to the body using four external, partially threaded rods. The baffle plate has been reworked to be more easily secured to the bottom plate, and its measurements were adjusted to better acclimate the flow of water through the system. The separator was resized to have a 3” ID and is 5” tall from the top to bottom plate. Finally, all the components in the system were changed to polycarbonate material except for the pipe fittings and fasteners, which are made of stainless steel.

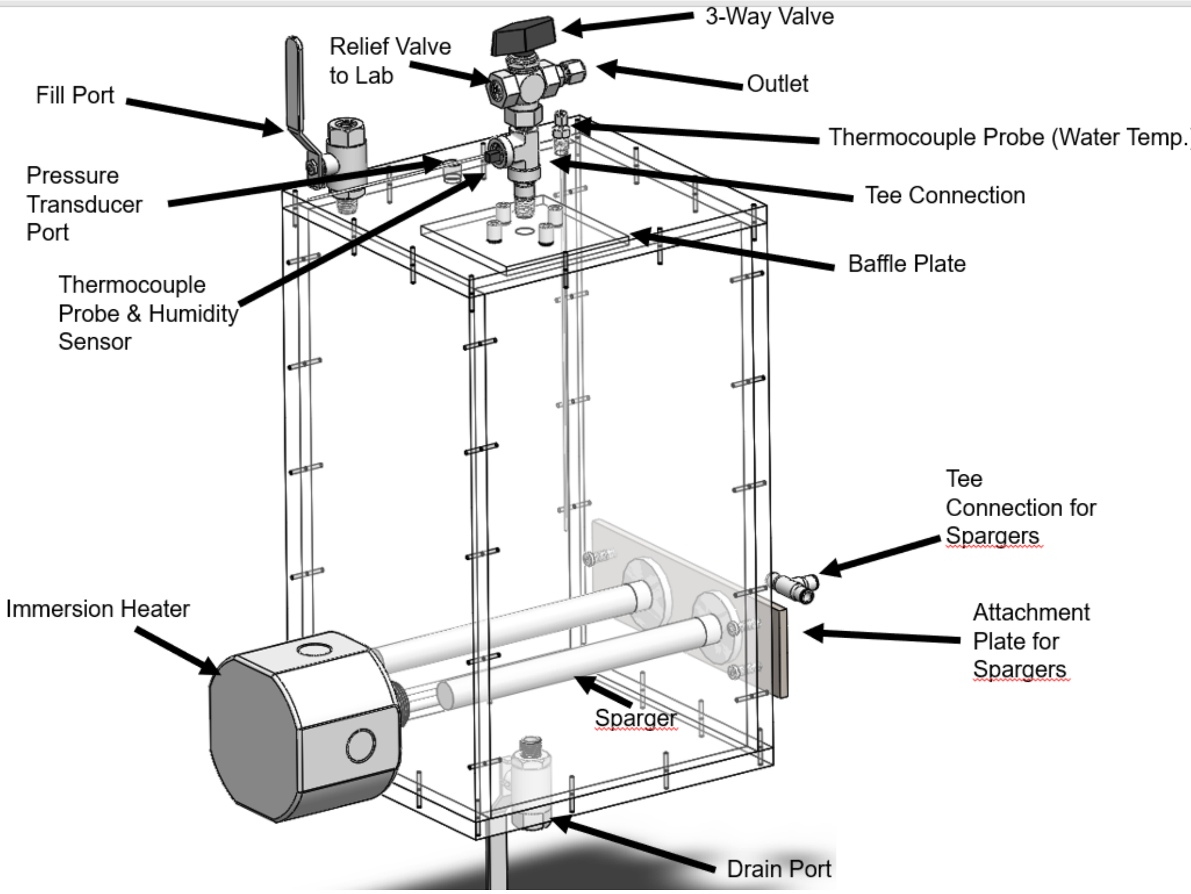

Figure 10: 3D Model of CO_2 Humidifying Tank

Figure 10 shows the CO_2 humidifying tank design iteration used in the system. CO_2 is brought into the spargers which bubbles it through hot water heated by the immersion heater. A drainage port is used to drain water when needed and the fill port is used to fill the tank. A baffle plate is used to ensure no water splashes into the outlet valve and affects the humid stream. Two thermocouple probes, a humidity sensor, and a pressure transducer are used for measurement purposes. This was the final design iteration for the CO_2 heating/humidifying tank, however the first iteration used metal bars around the body of the tank. These metal bars were to ensure safety while the tank was being pressurized. After analysis, it was found that these metal bars were not needed. The tank is secured with screws that attach the six plates that make up its body. These plates are reinforced with polycarbonate glue to prevent leakage of gas from the pressurized tank. Silicone sealant is also used on the internal edges of the assembled tank. An attachment plate is used to hold the spargers in place and the immersion heater is threaded on the opposite side of the tank. Additionally, a 3-way valve is used to control the flow of the hot and humidified CO_2 stream and to release excess pressure that may build up in the tank.

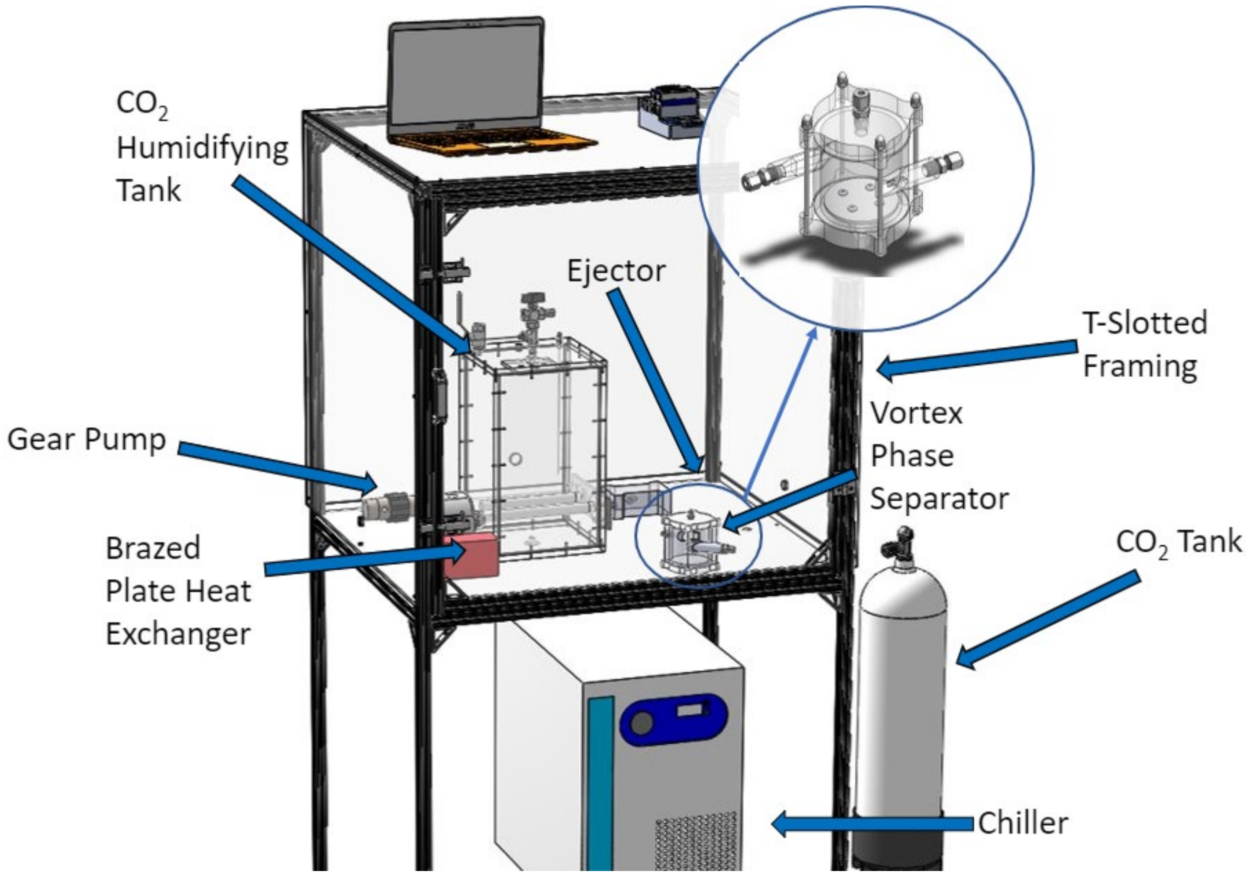

Figure 11: 3D Model of Housing for System

Figure 11 shows the housing of the entire system. T-slotted framing was used to build the base of this structure and polycarbonate sheets were used as the windows and door. Wheels were used on the legs of this housing so that it can be transported easily. Machining was done with drills, mills, and a bandsaw, and is further discussed in Section 4: Fabrication. This housing was designed so that a laptop and DAQ module chassis could be set on the top of it and all instrumentation could be connected to both the DAQ modules and computer. This allows for relevant values obtained from the system to be displayed on the laptop screen.

3.3 Analysis

3.3.1 Prediction of Humidity Levels at the Inlet and Outlet of Vortex Separator

The humidity at the gas outlet of the CO_2 humidifying tank was predicted with use of "Psychometric Properties of a Moist Carbon Dioxide Atmosphere" paper (G. L. Vaughan & C. G. Carrington, 1998)[6]. Equation derivations were performed for moist CO_2 at low temperatures (0-60°C) and at high temperatures (60°C-100°C). Using the psychometric charts given in this paper, multiple points were plotted to find equations for the humidity ratio of g H_2O/kg CO_2 for various relative humidity percentages. These graphs are shown in Figures 12, 13, and 14. The equations obtained from these graphs were then integrated into a MatLab program to predict the g H_2O/kg CO_2 at areas of interest shown in Figure 15.

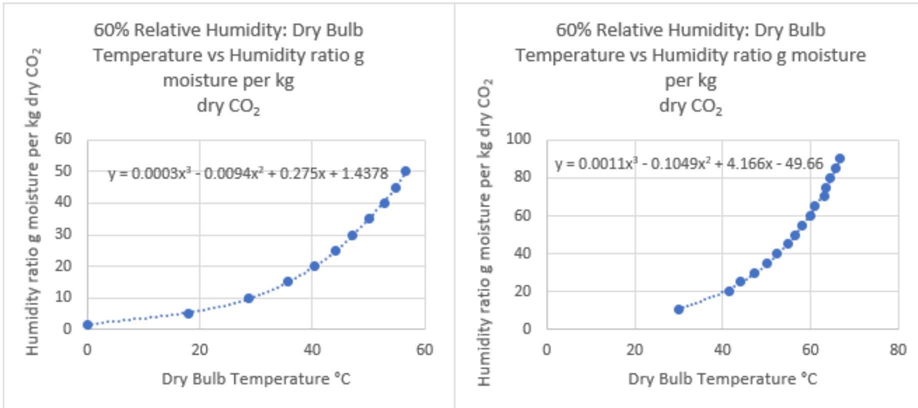

Figure 12: 60% Relative Humidity-Dry Bulb Temperature vs Humidity ratio g moisture per kg dry CO_2 for Low Temperatures (0-60°C) (left) and High Temperatures (60°C-100°C) (right)

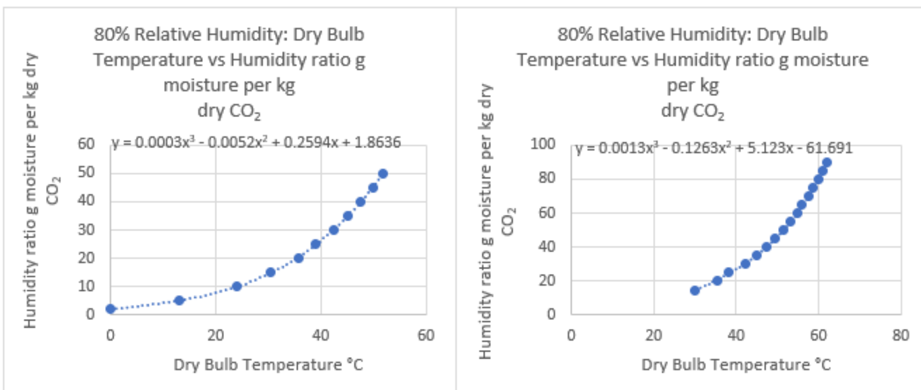

Figure 13: 80% Relative Humidity-Dry Bulb Temperature vs Humidity ratio g moisture per kg dry CO_2 for Low Temperatures (0-60°C) (left) and High Temperatures (60°C-100°C) (right)

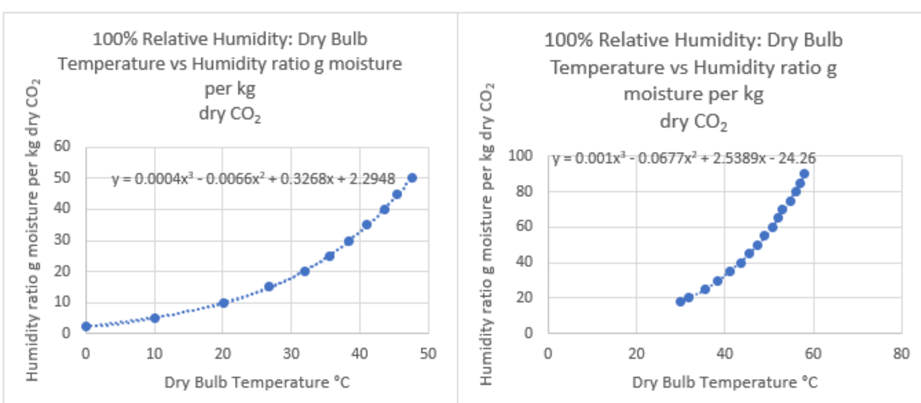

Figure 14: 100% Relative Humidity-Dry Bulb Temperature vs Humidity ratio g moisture per kg dry CO_2 for Low Temperatures (0-60°C) (left) and High Temperatures (60°C-100°C) (right)

Using the equations from these graphs, the following MatLab code was written.

Figure 15: MatLab Code to Predict Humidity at the Gas Outlet of the CO_2 Humidifying Tank

The schematic in Figure 16 was created using data from the previous MatLab code and graphs to demonstrate temperature vs humidity ratio in the vortex phase separator system. The 100% relative humidity at the gas inlet and gas outlet is worst-case scenario, which is why this percentage was used. 115℃ at the gas inlet is the highest expected temperature and 10℃ at the gas outlet is based on the highest coolant temperature in the low temperature loop. This schematic assumes perfect heat exchange in the vortex separator.

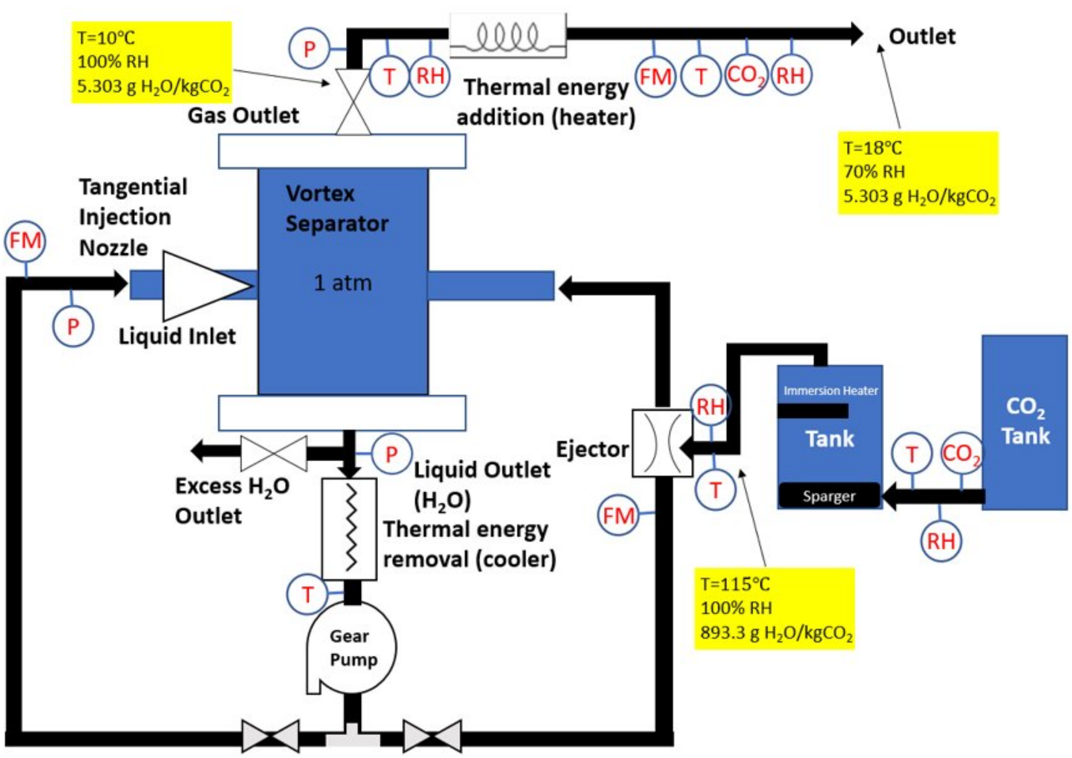

Figure 16: Temperature vs. Humidity Ratio Example

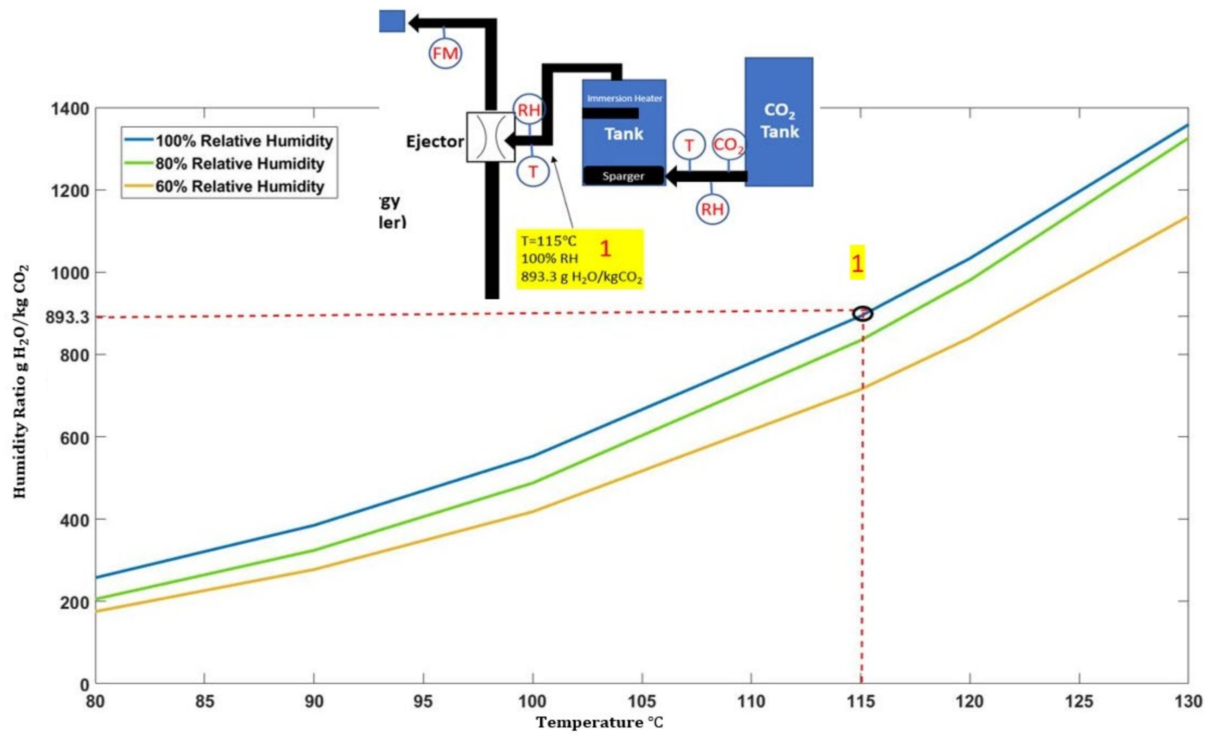

Figure 17: Temperature vs. Humidity Ratio Graph for Point 1

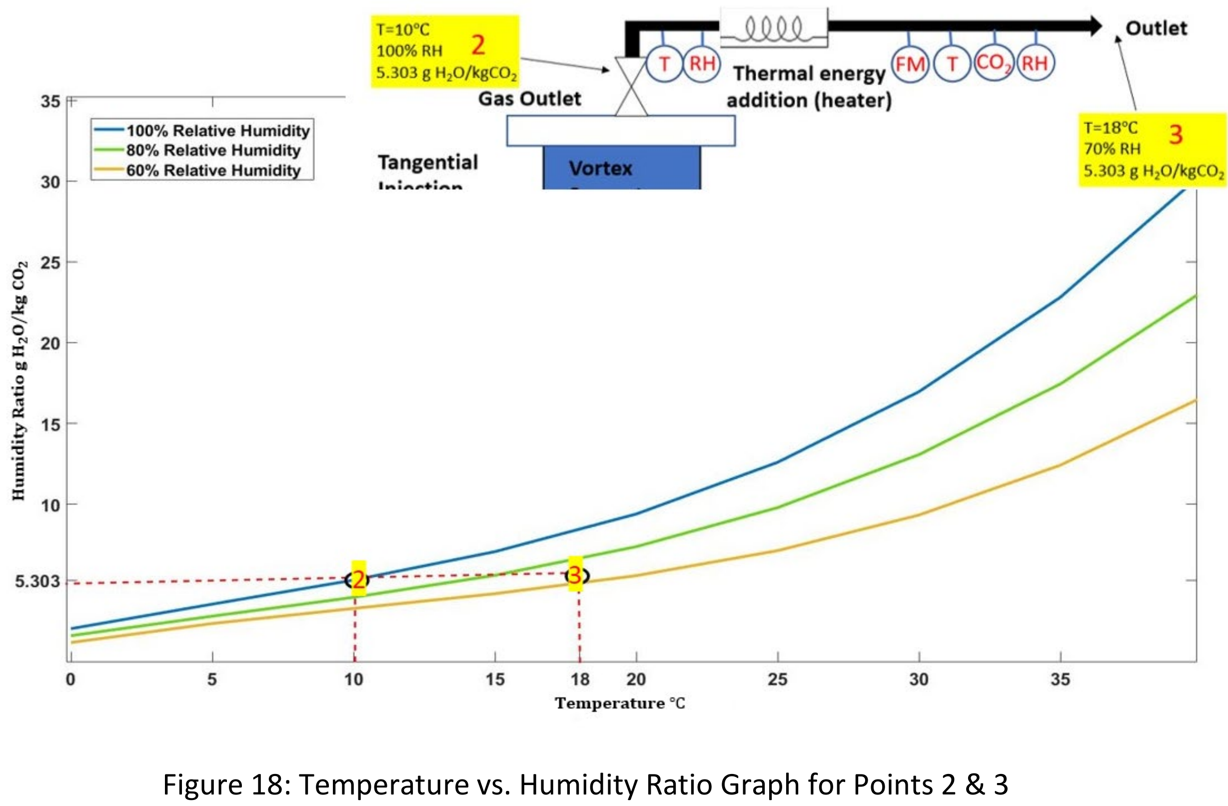

Figure 18: Temperature vs. Humidity Ratio Graph for Points 2 & 3

3.3.2 Theoretical Background on Sizing of Vortex Separator

The following calculations were used to aid in design of the system. The following equations result in radial and axial transit times for bubbles, comparing various variables against them. They also demonstrate equations used in calculation of drag force on bubbles, radial acceleration of bubbles, and the Reynolds and Morton numbers for flow into the separator at the liquid inlet. These predicted values are important in the design process, as if radial time is greater than axial time, bubbles may escape through the liquid outlet of the vortex separator, decreasing the efficiency of CO_2 removal[7]. They will also allow for design parameters to be implemented that ensure bubbles overcome the forces acting against them. Other values are also obtained through the discussed equations to analyze the vortex separator system parameters.

Liquid inlet and outlet velocities for the vortex separator can be found by dividing the liquid inlet area by the liquid inlet flow rate, and the liquid outlet area by the liquid outlet flow rate, respectively:

$$v_{li} = \frac{Q_{li}}{A_{li}}$$ ***Equation 1***

$$v_{lo} = \frac{Q_{lo}}{A_{lo}}$$ ***Equation 2***

Reynolds number and Morton number must be found for the bubbles flowing around a spherical body (the inner separator body) to find the drag coefficient on the bubbles. The drag coefficient must be known in order to overcome the bubbles resistance to flow[7]. Calculation of Reynolds and Morton number can be found using the equations below:

$$Re = \frac{\rho_l v_{li} 2R}{u_l}$$ ***Equation 3***

$$Mo = \frac{a_b u_l^4}{\sigma^4 \rho_l}$$ ***Equation 4***

For drag coefficient calculation, bubbles are assumed to maintain perfect spherical shape. This assumption is verified by the Morton and Reynolds numbers[7].

$$Mo < 10^{-6}, for\ system\ Mo \sim 10^{-11}$$

$$Re < 10^{-3}, for\ system\ 0.1 < Re < 10$$

For low Reynolds numbers as seen in this system, Stokes approximation is valid and drag coefficient is taken as:

$$C_D = \frac{24}{Re}$$ ***Equation 5***

Buckingham Pi Equations may be used to create a relationship between the Reynolds number for the liquid inside of the separator body and the rotational speed of this liquid[7]. When these equations are examined by rearranging their variables, equations are found that represent Reynolds Number vs Rotational Speed in the vortex separator[7].

$$\pi_1 = \frac{R^2\omega}{v_n}$$ ***Equation 6***

$$\pi_2 = \frac{\rho_l R^2\omega}{\mu_l}$$ ***Equation 7***

Equations obtained from graphical analysis of variables in Buckingham Pi equations can then be used to find the rotation of fluid inside of the vortex separator[7]. Graphical analysis is performed by rearranging equations 6 and 7.

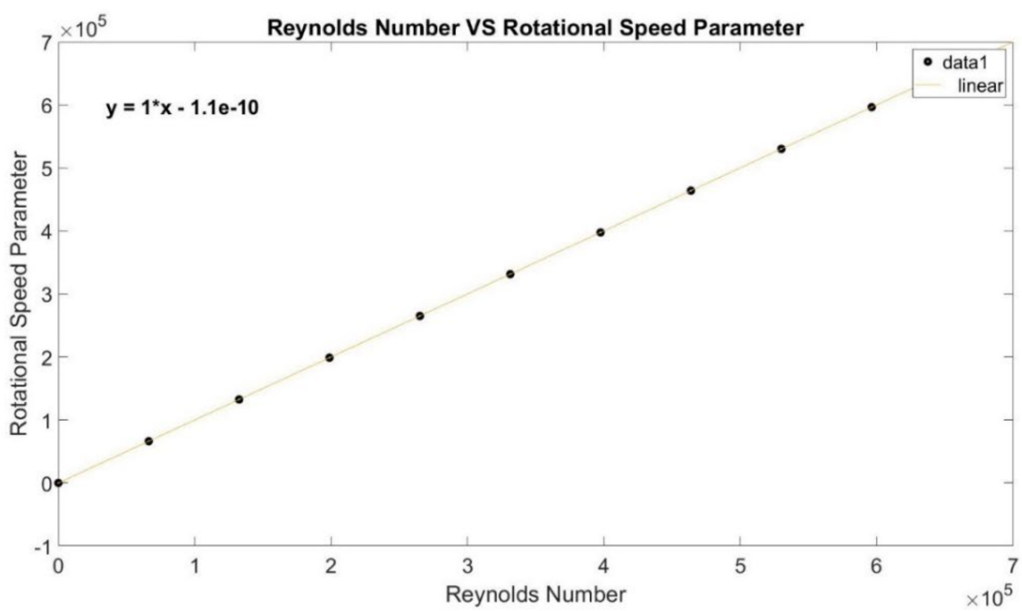

Figure 19: Reynolds Number vs. Rotational Speed Parameter

$$\frac{R^2\omega}{v} = 0.394(Re_N - 2020.0)$$ ***Equation 8***

$$\omega = \frac{0.394L_N v_{lo} - 2020.0v}{R^2}$$ ***Equation 9***

Angular momentum of fluid inside of the separator can then be found knowing the rotation of fluid inside of the vortex separator by:

$$\dot{p} = \frac{\omega}{60} * (2\pi R)^2 * L_{water} * 0.5$$ ***Equation 10***

Bubbles will move in the tangential direction with the same velocity as the fluid. The radial bubble velocity is the result from the balance between both the drag and buoyancy forces. As terminal velocity is achieved by bubbles, the acceleration period will be quickly neglected[7].

Radial transit time for the bubbles is calculated by using the terminal velocity and distance to the gas core of the separator[7]:

$$t_r = \frac{D^2}{\int_D V_r} = \frac{9\mu_l}{r^2\omega^2(\rho_1 - \rho_g)}$$ ***Equation 11***

Axial transit time for a bubble is dependent on the distance it has to travel to reach the liquid outlet, the area of this liquid outlet, and the angular speed of fluid inside of the separator[7]. The equation for axial transit time is therefore given as:

$$t_a = \frac{R}{\frac{\omega}{60} * A_{lo}}$$ ***Equation 12***

Force on the separator wall may also be found by predicting the amount of fluid being driven into the liquid inlet of the separator:

$$F = \left(\frac{\omega * 2 * \pi}{60}\right)^2 * R * L_{water}$$ ***Equation 13***

Bubbles traveling from a position at the vortex inner wall of the separator to the interface between the gas column and liquid film of the separator will have two forces acting against each other. The bubbles will mitigate through the separation volume concerning four forces. The radial buoyancy force results from centrifugal acceleration developed by rotating flow, which produces a radial pressure gradient[7]. Radial, tangential, and axial drag forces also exist and are imposed on each bubble by liquid flow[7]. These forces will be the buoyancy force and the drag force and may be shown mathematically as:

$$F_B = (\rho_l - \rho_g)\frac{4}{3}\pi r^3 * 9.81$$ ***Equation 14***

$$F_D = 0.5C_D\rho_l v_{li}^2\pi r^2$$ ***Equation 15***

Assuming bubble radial acceleration to be homogeneous, radial acceleration may be obtained from the resultant force[7]:

$$F_R = \left[(\rho_g - \rho_1)\omega^2 R\left(\frac{4}{3}\pi r^3\right) + 6\mu_l v_{li}\pi R\right]$$ ***Equation 16***

Axial acceleration of a bubble will therefore be[7]:

$$a_b = \frac{F_R}{\rho_g v_{lo} R}$$ ***Equation 17***

Introducing Stokes approximation and bubble mass, acceleration of a bubble with respect to its axial position may be found by[7]:

$$a_z = \frac{3}{8}C_D\frac{\rho_l}{\rho_g}\frac{v_{zr}^2}{r}$$ ***Equation 18***

When the above equation is integrated with respect to time, resultant axial velocity between a bubble and the liquid may be found[7]:

$$v_{zr} = v_z e^{-\frac{9}{2}\frac{\mu_l}{\rho_g r^2}t}$$ ***Equation 19***

When time = 0, the resultant velocity of bubbles will be equal to the liquid velocity, v_z. Solving for time using above equation, axial bubble transit time can also be found as[7]:

$$t_a = -\frac{2}{9}\frac{\rho_g r^2}{\mu_l}\ln\left(\frac{v_{zr}}{v_z}\right)$$ ***Equation 20***

Minimum averaged rotational speed needed for separation can then be found by equating radial and axial transit times[7]:

$$t_r = t_a$$

The minimum averaged rotational speed necessary for separation then is[7]:

$$\omega = \left[\frac{9\mu_l}{R^2\omega^2(\rho_l - \rho_g)} \frac{(r_1 - r_2)^2}{(r_1{}^2 - r_2{}^2)} \frac{v_z}{D_z}\right]^{\frac{1}{2}}$$ ***Equation 21***

3.3.3 Calculations for Sizing Vortex Separator

Inputs used for all calculations are shown in Table 2. These values represent design parameters for nozzles on the vortex separator, as well as conservative values for liters of water used and flow rate at the liquid inlet on the vortex separator. Figure 20 shows the pump used in the system to aid in directing liquid from the liquid outlet on the vortex separator to both the gas and liquid inlets.

Table 2: Inputs Used for Calculations

Inputs		
Outlet Area Width =	0.12500	in
Outlet Area Height =	0.15000	in
Liquid Outlet Area =	0.01875	in^2
Inlet Area Width =	0.01799	in
Inlet Area Height =	0.17992	in
Liquid Inlet Area =	0.003237167	in^2
Lpm =	2.40000	
Liters of water used =	0.10000	

Figure 20: Clark MG200 Gear Pump with DC Motor; Used for Calculations [8]

Liquid Inlet Velocity

$$v_{li} = \frac{Q_{li}}{A_{li}} = \frac{4 * 10^{-5}\ m^3/s}{2.088 * 10^{-6} m^2} = 19.5\frac{m}{s}$$ ***Equation 1***

Where:

$v_{li} = velocity\ at\ liquid\ inlet$
$Q_{li} = flow\ rate\ at\ liquid\ inlet = 4 * 10^{-5} m^3/s$
$A_{li} = liquid\ inlet\ area = 2.088 * 10^{-6} m^2$

Liquid Outlet Velocity

$$v_{lo} = \frac{Q_{lo}}{A_{lo}} = \frac{4 * 10^{-1}\ m^3/s}{1.209 * 10^{-5} m^2} = 3.31\frac{m}{s}$$ ***Equation 2***

Where:

$v_{lo} =\ velocity\ at\ liquid\ outlet$
$Q_{lo} = flow\ rate\ at\ liquid\ inlet = 1 * 10^{-5} m^3/s$
$A_{lo} = liquid\ inlet\ area = 1.209 * 10^{-5} m^2$

Reynolds Number of Fluid at Liquid Inlet

$$Re = \frac{\rho_l v_n 2R}{\mu_l} = \frac{997.76\frac{kg}{m^3} * 19.15\frac{m}{s} * 2 * .001m}{0.0009532\frac{kg}{m * s}} = 40095$$ ***Equation 3***

Where:

$Re =\ Reynolds\ number$
$\rho_l = density\ of\ liquid\ at\ inlet = 997.76\ kg/m^3$
$v_n = velocity\ at\ liquid\ inlet = 19.15\ m/s$
$R = bubble\ radius = .001m$
$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet = 0.0009532\frac{kg}{m*s}$

Morton Number of Fluid at Liquid Inlet

$$Mo = \frac{a_b u_l^4}{\sigma^4 \rho_l} = \frac{\left(0.00144\,\frac{m}{s^2}\right)\left(0.0009532\,\frac{kg}{m*s}\right)^4}{\left(0.06\,\frac{N}{m}\right)^4 (999.65\,\frac{kg}{m^3})} = 9.17 * 10^{-14} \quad \textbf{\textit{Equation 4}}$$

Where:

$\mathrm{F_R} = resultant\ force\ on\ a\ bubble = 0.009N\ (equation\ 16)$
$a_b = acceleration\ of\ a\ bubble = 0.00144\ m/s^2$
$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet = 0.0009532\,\frac{kg}{m*s}$
$\sigma = surface\ tension\ of\ liquid = 0.06\ N/m$
$density\ of\ liquid\ at\ 10℃ = 999.65 kg/m^3$

Drag Coefficient of a Bubble

$$C_D = \frac{24}{Re} = \frac{24}{40095} = 5.98 * 10^{-4} \quad \textbf{\textit{Equation 5}}$$

Where:

$C_D = drag\ coefficient\ of\ a\ bubble$
$Re = Reynolds\ Number$

Buckingham Pi Calculations

$$\pi_1 = \frac{R^2\omega}{v_n} \quad \textbf{\textit{Equation 6}}$$

$$\pi_2 = \frac{\rho_l R^2 \omega}{\mu_l} \quad \textbf{\textit{Equation 7}}$$

Where:

$\rho_l = density\ of\ injected\ fluid$
$v_{li} = velocity\ at\ liquid\ inlet$
$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet$
$R = inner\ radius\ of\ separator$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator$

Equations obtained from graphical analysis and rearranging of variables in Buckingham Pi equations:

Predicted Rotation of Fluid inside Vortex Separator

$$\frac{R^2\omega}{v} = 0.394(Re_N - 2020.0)$$ ***Equation 8***

$$\omega = \frac{0.394L_N v_{lo} - 2020.0v}{R^2}$$ ***Equation 9***

$$= \frac{0.394(\sqrt{0.00898})(3.3067\ m/s) - 2020.0(1.3081 * 10^{-6}\ m^2/s\ )}{(0.0381m)^2} * 60 \quad = 374.3\ rpm$$

Where:

$L_N = characteristic\ length\ of\ outlet\ area = \sqrt{outlet}\ area\ of\ separator = 0.00898$
$v_{lo} = liquid\ outlet\ velocity = 3.3067\ m/s$
$v = liquid\ kinematic\ viscosity\ at\ liquid\ outlet = \ 1.3081 * 10^{-6}\ m^2/s$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$

Angular Momentum of Fluid in Separator

$$\dot{p} = \frac{\omega}{60} * (2\pi R)^2 * L_{water} * 0.5$$ ***Equation 10***

$$= \frac{374.3rpm}{60} * (2\pi * 0.0381m)^2 * 0.1L * 0.5$$
$$= 0.0028\ kg/s$$

Where:

$\omega = \ predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$
$L_{water} = liters\ of\ water\ in\ separator = 0.1\ L$

Radial Transit Time

$$t_r = \frac{D^2}{\int_D V_r} = \frac{9\mu_l}{r^2\omega^2(\rho_1 - \rho_g)} \qquad \textbf{\textit{Equation 11}}$$

$$= \frac{9\left(.0013076\ N * \frac{s}{m}\right)}{(0.001m)^2(6.2383\ rps)^2\left(999.65\frac{kg}{m^3} - 1.881kg/m^3\right)}$$

$$= 0.303\ seconds$$

Where:

$u_l = Liquid\ Viscosity\ of\ Water\ at\ 5°C =\ .0013076\ N * \frac{s}{m}$
$r_1 = final\ radial\ position\ of\ bubble = 0.0381m$
$r_2 = initial\ radial\ position\ of\ bubble = 0m\ (conservative)$
$r = bubble\ radius =\ .001m$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.2383\ rps$
$\rho_l = density\ of\ liquid\ at\ 10°C = 999.65kg/m^3$
$\rho_g = density\ of\ gas\ at\ 10°C = 1.881kg/m^3$

Axial Transit Time

$$t_a = \frac{R}{\frac{\omega}{60} * A_{liquid\ outlet}} = \frac{0.0381m}{\frac{374.3rpm}{60} * 0.01875\ in^2} \qquad \textbf{\textit{Equation 12}}$$

$$= 0.3257\ seconds$$

Where:
$t_a = axial\ transit\ time$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm$
$A_{liquid\ outlet} = 0.01875\ in^2$

Force at Vortex Separator Wall

$$F = \left(\frac{\omega * 2 * \pi}{60}\right)^2 * R * L_{system} = \left(\frac{374.3rpm * 2 * \pi}{60}\right)^2 * 0.0381m * 0.1L \qquad \textbf{\textit{Equation 13}}$$

$$= 5.85N$$

Where:
$F = force\ on\ separator\ wall$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm$
$L_{water} = amount\ of\ water\ used\ in\ system =\ 0.1\ L$

Drag & Buoyancy Forces on a Bubble

$$F_B = (\rho_l - \rho_g)\frac{4}{3}\pi r^3 = \left(999.65\frac{kg}{m^3} - 1.881\frac{kg}{m^3}\right)\left(\frac{4}{3}\pi(0.001m)^3\right) * 9.81 = 4.1 * 10^{-5}N$$ ***Equation 14***

$$F_D = \frac{1}{2}C_D\rho_l v_{li}^2\pi r^2 = \frac{1}{2} * (5.98 * 10^{-4}) * 999.65\frac{kg}{m^3} * \left(19.15\frac{m}{s}\right)^2 * \pi * (0.001)^2 = 3.44 * 10^{-4}N$$ ***Equation 15***

Where:

$F_B = buoyancy\ Force$
$F_D = drag\ Force$
$\rho_l = liquid\ density\ at\ liquid\ inlet = 999.65 kg/m^3$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.23\frac{1}{s}$
$v_{li} = velocity\ at\ liquid\ inlet = 19.15\ m/s$
$r = bubble\ radius = 0.001m$

$C_D = drag\ coefficient\ for\ bubble = \frac{24}{Re} = 5.98 * 10^{-4}$

Resultant Force on a Bubble & Radial Acceleration

$$F_R = (\rho_g - \rho_l)\omega^2 R\left(\frac{4}{3}\pi r^3\right) + 6u_l v_{li}\pi R = \left(1.881\frac{kg}{m^3} - 999.65\frac{kg}{m^3}\right)\left(6.23\frac{1}{s}\right)^2 .0381m\left(\frac{4}{3}\pi(0.001)^3\right) + (6 * 0.0013076\ N * \frac{s}{m^2} * 19.15\frac{m}{s} * \pi * 0.0381m) = 0.0179N$$ ***Equation 16***

$$a_b = \frac{F_R}{\rho_g v_{lo} R} = \frac{0.009N}{\left(1.881\frac{kg}{m^3}\right)\left(3.3067\frac{m}{s}\right)} = 0.076\ m^2/sec$$ ***Equation 17***

Where:

$F_R = resultant\ force\ on\ a\ bubble$
$a_b = radial\ acceleration\ of\ a\ bubble$

$\rho_l = density\ of\ liquid\ at\ 10°C = 999.65 kg/m^3$
$\rho_g = density\ of\ gas\ at\ 10°C = 1.881 kg/m^3$

$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.23\frac{1}{s}$
$r = bubble\ radius = 0.001m$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$
$u_l = Liquid\ Viscosity\ of\ Water\ at\ 10°C = .0013076\ \frac{N*s}{m^2}$
$v_{li} = velocity\ at\ liquid\ inlet = 19.15\ m/s$
$v_{lo} = liquid\ outlet\ velocity = 3.3067\ m/s$

Axial Acceleration of a Bubble

$$a_z = \frac{3}{8}C_D\frac{\rho_l}{\rho_g}\frac{v_{zr}^2}{r} = \frac{3}{8}*5.98*10^{-4}*\frac{999.65\frac{kg}{m^3}}{1.881\frac{kg}{m^3}}\frac{(0.00878)^2}{0.001m}$$
$$= 0.0092\ m^2/s$$

Equation 18

Where:
$v_{zr} = resultant\ axial\ velocity\ bubble\ and\ the\ liquid = 0.00143\ m/s$
$\rho_l = density\ of\ liquid\ at\ 10°C = 999.65kg/m^3$
$\rho_g = density\ of\ gas\ at\ 10°C = 1.881kg/m^3$
$r = bubble\ radius = 0.001m$
$C_D = drag\ coefficient\ for\ bubble = \frac{24}{Re} = 5.98*10^{-4}$

Resultant Axial Velocity Between a Bubble & the Liquid

$$v_{zr} = v_z e^{-\frac{9}{2}\frac{\mu_l}{\rho_g R^2}t} = v_z e^{-\frac{9}{2}*\frac{0.0013076\frac{N*s}{m}}{\left(1.881\frac{kg}{m^3}\right)0.001^2}1*10^{-4}\ second}$$
$$= 0.00878\ m/s$$

Equation 19

Where:
$v_{zr} = resultant\ axial\ velocity\ bubble\ and\ the\ liquid$
$v_z = axial\ velocity\ of\ a\ bubble = 0.012\ m/s$
$u_l = Liquid\ Viscosity\ of\ Water\ at\ 10°C = .0013076\ \frac{N*s}{m^2}$
$\rho_g = density\ of\ gas\ at\ 10°C = 1.881kg/m^3$
$r = bubble\ radius = 0.001m$
$t = time\ of\ interest = 1*10^{-4}\ second$

Axial Transit Time of Bubble at Specific Time

Equation 20

$$t_a = -\frac{2}{9}\frac{\rho_g r^2}{\mu_l}\ln\left(\frac{v_{zr}}{v_z}\right)$$
$$= -\frac{2}{9} * \frac{1.881\frac{kg}{m^3} * (0.001m)^2}{0.0013079\frac{N * s}{m}} * \ln\left(\frac{0.00878\frac{m}{s}}{0.012\frac{m}{s}}\right)$$
$$= 9.985 * 10^{-5} s$$

Where:

$\rho_g = density\ of\ gas\ at\ 10°C = 1.881 kg/m^3$

$r = bubble\ radius = 0.001m$

$u_l = Liquid\ Viscosity\ of\ Water\ at\ 10°C = .0013076\ \frac{N * s}{m^2}$

$v_{zr} = resultant\ axial\ velocity\ bubble\ and\ the\ liquid = 0.00878\ m/s$

$v_z = axial\ velocity\ of\ a\ bubble = 0.012\ m/s$

$t = time\ of\ interest = 1 * 10^{-4}\ second$

Required Angular Rotation of Fluid for Separation

Equation 21

$$\omega = \left[\frac{9\mu_l}{r^2\omega^2(\rho_l - \rho_g)}\frac{(r_1 - r_2)^2}{(r_1{}^2 - r_2{}^2)}\frac{v_z}{D_z}\right]^{\frac{1}{2}} * 2 * \pi * 60$$
$$= \left[\frac{9\left(0.0013076\frac{N * s}{m}\right)}{(0.001m)^2\left(6.23\frac{1}{s}\right)\left(999.65\frac{kg}{m^3} - \frac{1.881kg}{m^3}\right)}\frac{\left(0.012\frac{m}{s}\right)}{(0.0381\ m)}\right]^{\frac{1}{2}} * 2 * \pi * 60$$
$$= 116.6\ rpm$$

Where:

$u_l = Liquid\ Viscosity\ of\ Water\ at\ 10°C = .0013076\ \frac{N * s}{m^2}$

$r_1 = final\ position\ of\ a\ bubble = 0.0381m$

$r_2 = initial\ position\ of\ a\ bubble = 0m$

$v_z = axial\ velocity\ of\ a\ bubble = 0.012\ m/s$

$r = bubble\ radius = 0.001m$

$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.23\frac{1}{s}$

$\rho_l = density\ of\ liquid\ at\ 10°C = 999.65 kg/m^3$

$\rho_g = density\ of\ gas\ at\ 10°C = 1.881 kg/m^3$

$D_z = Axial\ Distance\ from\ the\ Inlet\ Nozzle\ to\ the\ Baffle\ Plate = 0.0381\ m$

3.4 Safety Considerations

All aspects of the life cycle will be considered, including design decisions that affect training, operations resource management, human factors, safety, habitability and environment, and maintainability and supportability. This section explains various safety issues that may arise during operation of the VPS system. Startup for the VPS system has minimal issues; however, water should first be run through the entire system to prime it before use. This allows for more gradual heating and cooling of fluid flowing through it. If this is not done, tubes may become unnecessarily hot and burn the user. During shut down, problems with the chiller and heater shutting off may arise. If this happens, there will be a breaker attached to the system to immediately shut down the entire system. Table 3 outlines risk management for this project and Figure 21 demonstrates a flow down of the impact of safety issues for this project.

Table 3: Risk, Consequence, and Mitigation Chart

Risk	Consequence	Mitigation Approach
Pump failure	System flow and gas liquid separation will stall	Have a breaker to shut the whole system down.
Piping leakage (Pressure system failure)	Pressure drop in system	Leak test before charging the system.
Uncontrolled heating	Parts start melting, tube expansion, water boiling/water vapor in the system.	At a certain temperature, the system will shut off.
Chiller failure	H20 vapor does not condense into liquid	Have a breaker to shut the whole system down.
Uncontrolled cooling	Chiller is too cold (frostbite)	Insulate cold refrigerant lines.
Excessive pump speed / Insufficient pump speed	Nonoptimal flow rate/pressure	Relief valve / Breaker turns off system.
Excessive pressure	Structural failure	Hydrostatic test before testing full system.
Gas getting mixed with liquid H2O outlet (carry-under)	Separation efficiency is affected	Implementation of baffle plate and design of nozzles.
Water mixing with the gas outlet (carry-over)	Separation efficiency is affected	Constantly monitor water level through clear separator wall and drain as needed.
Noncompatible material selection	Material is corrosive or wears out fast.	Choosing compatible materials
CO2 Leakage	Risk of Hypercapnia (or mild effects)	Leak test before charging the system.
Liquid outlet buildup of fluid	Dangerous increase in pressure	Two valves will be adjusted to control flow rate to nozzles. Breaker system automatically shuts down the whole system in case of high pressure.
Gas outlet buildup of fluid	Dangerous increase in pressure	Valve will be adjusted to control flow rate. Breaker system automatically shuts down the whole system in case of high pressure.

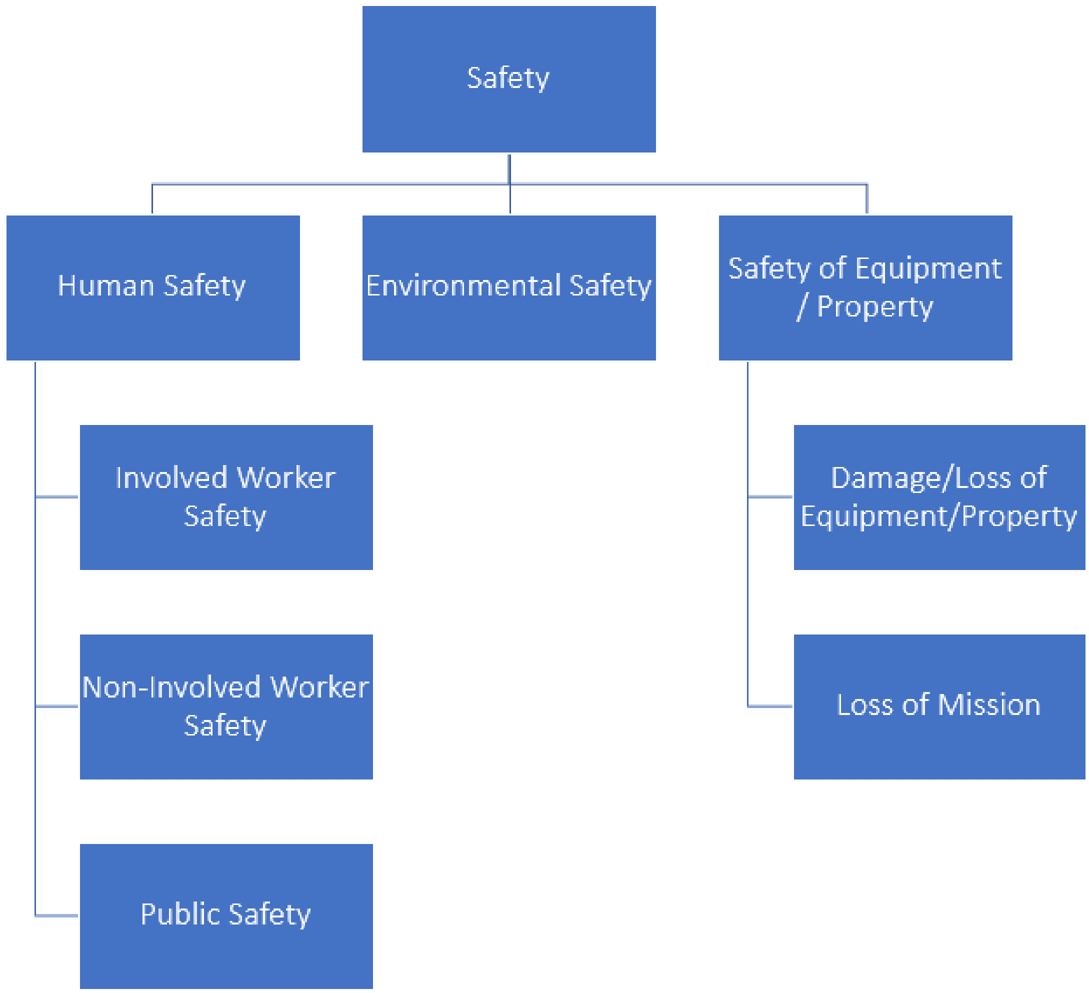

Figure 21: Safety Impact Flow-Down

Human Safety

There are many factors to consider when it comes to human safety. For this prototype, involved worker safety will be the focus since there will not be any non-involved worker or public safety concerns. Below is a Table listing the potential issues and consequences that may be faced during operation and testing. Additionally, it specifies what measures will be taken to prevent or discourage those issues.

Table 4: Human Safety Chart

Potential Issues	Consequence	Preventative Measure
Uncontrolled heat up	Parts start melting, tube expansion, thermal burns, and boiling water.	At a certain temperature, the system will shut off.
Chiller/Refrigerant leakage	Liquid refrigerant is harmful for skin; large amounts of vapor refrigerant is harmful for lungs.	Refrigerant leak test and insulation on cooling lines.
Excessive pressure / Pressure system failure	Structural failure	Hydrostatic test before testing full system.
Water leakage	Hot water can cause burns on skin.	Leak testing prior to running full system.
CO_2 leakage	Pure CO_2 in lab atmosphere (mildly harmful)	Ventilated lab environment. Decrease pressure in system, or immediate shut down.

Start Up / Shutdown Procedures:

The below procedures help ensure safety and maintain the system.

- Start up

1. Initiate LabView VI, turn on sensors, check readings
2. Turn on pump to run water through separator body without heating/cooling to prime system
3. Introduce gas into heating/humidifying tank and separator body
4. Turn on heaters and chiller; wait to reach steady operating conditions
5. Ensure sensors at gas outlet are measuring expected data (discussed in calculation section)

- Shut down

1. Turn off heaters and chiller
2. Cut off gas into heating/humidifying tank and separator body
3. Turn off pump
4. Stop LabView VI, turn off sensors
5. Drain liquid from vortex separator body

Environmental Safety

Since this system implements CO_2, there are environmental considerations to be aware of; however, the amount of CO_2 used to test the system is not large enough to cause hypercapnia within the testing environment. Nevertheless, below is a Table representing the evaluation of potential environmental issues.

Table 5: Environmental Safety Chart

Potential Issues	Consequence	Preventative Measure
Uncontrolled heat up	Parts start melting, tube expansion, thermal burns, and boiling water.	At a certain temperature, the system will shut off.
Chiller/Refrigerant leakage	Liquid refrigerant is harmful for skin; large amounts of vapor refrigerant is harmful for lungs.	Refrigerant leak test and insulation on cooling lines.
Excessive pressure / Pressure system failure	Structural failure	Hydrostatic test before testing full system.
Water leakage	Hot water can cause burns on skin.	Leak testing prior to running full system.
CO_2 leakage	Pure CO_2 in lab atmosphere (mildly harmful)	Ventilated lab environment. Decrease pressure in system, or immediate shut down.

3.5 Ethical/Professional Considerations

The ethics of this project includes holding human safety at the highest standard. The VPS system will ensure enough CO_2 removal so that hypercapnia will not occur, and crew health is at its best. NASA's best interests come first in this project, to ensure their safety standards and procedures are met. Extensive testing will be done on this system before it would ever be considered for space flight. Software will be used to constantly monitor the system and ensure it is removing required amounts of CO_2, ensuring a healthy environment for the crew. The X-Hab team will only report results that have been tested to be true both numerically and by experimental data. All data received from the VPS system will be taken through a software called LabView. Sensors used in the system will be carefully calibrated to ensure accurate measurements.

3.6 Estimated Life Cycle of Development

This section discusses the estimated life cycle of the vortex separator system and various components.

The gear pump being used in this system is the MG 200 Series Magnet Drive Gear pump which offers compact precision and performance and is designed for high technology systems[8]. Based on the MG 200 Series Magnet Drive Gear Pump handbook, to increase pump life, the fluid being pumped must not contain solid particles and the gear pump should operate under wetted conditions[9]. Assuming these parameters are met when the pump is used in the system, the lifetime for this pump is above 8000 hours[9]. For the polycarbonate material that both the vortex separator and CO_2 humidifying tank is made of, an average life span of about 5-10 years is expected assuming the polycarbonate glue used to seal the CO_2 humidifying tank and secure nozzles to the vortex separator body does not crack or peel[10]. The polycarbonate glue used reaches its full strength in 21 days and has the chemical composition of cement after this[11]. Its lifespan and temperature rating are not given, however if assumed it will maintain itself like cement its life span will be many decades[12]. The vortex separator will need to be drained through its liquid outlet due to the film on the separator walls building up. This will need to be done manually and a valve is implemented in the design to perform this. The CO_2 humidifying tank will need to both be filled and drained manually. If there are any small leaks in the CO_2 humidifying tank this will cause the liquid level to slowly decrease and it will need to be added back into the tank via the fill port. Draining of the tank will need to be performed for maintenance of the spargers and immersion heater. The thermocouple probes used in the system do not have a given lifespan but based on other research they are expected to maintain accurate readings for 6-12 months [13]. Pressure transducers used in this system have a pressure cycles rating of 10 million and long-term stability of 1 year[14]. Because pressure is a very important safety measure of this system, pressure transducers should be replaced every year to maintain accurate readings. Relative humidity sensors are also used in this system and have a life span of 15 years[15]. The CO_2 sensor being used in this system is a multi-gas sampling data logger and can measure CO_2 as well as other gas concentrations such as CO, O_2, and CH_4[16]. If this system were to eventually be used with other substances to aid in separation, O_2 could also be measured with the CO_2 multi-gas sampling data logger. Overall, the gear pump in the system is projected to fail first but this may differ based on results found during experimental procedure. For example, the gear pump may not need to run at full power depending on data obtained from experimental analysis. The experimental procedure for running the system is discussed in depth in Section 5: Testing.

3.7 Cost Breakdown of Development

The Bill of Materials for this project is shown in Table 6.

Table 6: Bill of Materials

Item	Quantity	Unit Cost	Total Cost	Cost after discount/shipping	Vendor
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	1				Allied Plastic Supply
PC Top and Bottom Plates- 3.6" x 3.6" x .75"	2				Allied Plastic Supply
PC Baffle Plate- 2.75" x 2.75" x .615" x.25"	2				Allied Plastic Supply
PC Sheet- 32.75 X 35 X .25 thick	1			$	Allied Plastic Supply
PC Sheet- 31.75 X 33.5 X .25 thick	2				Allied Plastic Supply
PC Sheet- 34.5 X 37.5 X .25 thick	1				Allied Plastic Supply
PC Sheet-31.75 X 37 X .25 thick	1				Allied Plastic Supply
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	5				Allied Plastic Supply
Polycarbonate Sheet 9.75" x 8.75" x 1/2"	3			$	Allied Plastic Supply
Polycarbonate Sheet 4" x 4" x 1/4"	2	$			Allied Plastic Supply
Sparger , Carbonation stone	2	$		$	Amazon
Ball-Valve	2	$			Amazon
Brazed Plate Heat Exchanger	1	$		$	Amazon
3-Way Valve	1	$			Amazon
Ball Valve	2	$		$	Amazon
Drill 1" Carbon Steel NPT Piper Tap and 1-5/32" HSS Drill Bit Set	1	$			Amazon
Immersion Heater	1				McMaster Carr
Adapter	3	$			McMaster Carr
Spacers	4	$			McMaster Carr
Screws for Body	3				McMaster Carr
Teflon Tubing (25 ft) 3/16" ID, 1/4" OD	1				McMaster Carr
Yor-Lok Fitting, straight adapter, 1/16" T x 1/8" MNPT	3				McMaster Carr
Yor-Lok Fitting, straight adapter, 1/4" T x 1/4" MNPT	3				McMaster Carr
Yor-Lok Fitting, tee, (1/4" T x 1/4" T x 1/4" T) 1/4" Tube OD	1			$	McMaster Carr
Tee Fitting for 3-Way Valve	1				McMaster Carr
High Temperature Silicone Rubber Sheet (Gasket Sheet)	1				McMaster Carr
Screws for Sparger Bracket	1				McMaster Carr
Nuts for Sparger Bracket	1				McMaster Carr
Silicone Sealent	2				McMaster Carr
Extreme temperature Teflon PTFE Semi- Clear (Item number : 5239K24)	1				McMaster Carr
Extreme temperature Teflon PTFE Semi- Clear (Item number : 5239K23)	1				McMaster Carr
T-Slotted Framing, Single 4-slot rail 1" high x 1 " wide, 10' long	6				McMaster Carr
Corner Brace, 2" long 1" high rail	20	$			McMaster Carr
Slide Bolt	2	$			McMaster Carr
Handle	1	$		$	McMaster Carr
Hinge, 1" high rail	2	$			McMaster Carr
Drop Pins, spring tab nut, 1/4"-20 Thread Size	50	$			McMaster Carr
Casters, swivel mount , 70 lbs	4	$			McMaster Carr
Adapters for Heat Exchanger , Stainless Steel Threaded Pipe Fitting	4	$			McMaster Carr
1/4" Tube OD X 1/4 NPT Male Fitting, Straight Adapter	36	$			McMaster Carr
Tee Connector all Female 1/4" Yor-Lock Fitting	3	$			McMaster Carr
Tee Connector, 1/4 NPT Female	5	$			McMaster Carr
Tee Connector, 1/4 NPT Male	1				McMaster Carr

Adapter Male-Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD X 1/8 NPT Male	2				McMaster Carr
Needle Valves	2			$	McMaster Carr
Metal Tubing for Outlet	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/8 NPT Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/4 NPT Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/8 NPT Male	5	$			McMaster Carr
Plastic quick disconnect tube coupling for air and water (Item number : 5012K76)	2	$			McMaster Carr
Plastic quick disconnect tube coupling for air and water (Item number : 5012K926)	2	$			McMaster Carr
Flexible Rubber Foam Pipe Insulation Tube (Item number:4463K23)	3	$	$		McMaster Carr
316 Stainless Steel Threaded Pipe Fitting (Item number: 4452K165)	2	$	$		McMaster Carr
Sealing Pan Head Screws (Item Number: 90825A172)	1	$	$		McMaster Carr
Spacers (Item Number: 92320A345)	4	$	$		McMaster Carr
Water Flow Meter (Item number: 5079K17)	2	$	$		McMaster Carr
Air Flow Meter (Itme Number: 5079K23)	1	$	$		McMaster Carr
Washers (Itme Number: 90107A007)	1	$	$	$	McMaster Carr
PC Tube (Item Number: 8585K44)	1				McMaster Carr
PC Rod (Item Number:8571K16)	1				McMaster Carr
Acrylic Cement (Item number: 7517A5)	1				McMaster Carr
Cement for plastic (Item number:7515A11)	1				McMaster Carr
Push lock fitting 1/4" bottom	4				McMaster Carr
PC Cylinder for Body- 3" ID, 3.5" OD, 3.25" long	1				McMaster Carr
Nozzle Material	1				McMaster Carr
Rods	4			$	McMaster Carr
Nuts for Rods	1	$			McMaster Carr
Cap Nuts for Rods	1	$			McMaster Carr
Screws for Baffle	1	$			McMaster Carr
Board mount humidity sensors and temperature sensor	10	$			Sensirion
Multiple function sensor development teols sensirion evaluation	1			$	Sensirion
Multiple Function Sensor Development Tools Contains 3x SHTC3 on FPCB and Adapter Cable	1				Sensirion
Ejector	1			$	Fox Venturi Products
Gear Pump +12 VDC motor	1			$	ClarkSol
12 VDC Motor for MG Series Pump	1				ClarkSol
Thermocouple Probe 2 Inch	6				Omega
Pressure Transducers	4				Omega
Temperature Controller	1			$	Omega
Rope Heater	1				Omega
Thermocouple Probe 12 Inch	1				Omega
CO2 Sensor, CM-1000 Series	1			$	CO2 Meter
Metal for Sparger Bracket	1				Metal Supermarket
Aluminum Plate	1			$	Metal Supermarket
Aluminum Sheet	1				Metal Supermarket
Total				$	

Section 4: Fabrication

The fabrication process was interrupted and canceled abruptly due to the 2020 COVID-19 pandemic. All components were being machined at UNT Discovery Park, however it closed on March 23rd, 2020. The plan detailed to fabricate and assemble the system and consisted of taking the raw material ordered and using different machines such as mills, drill presses, and vertical and horizontal band saws, to further refine the polycarbonate to the specifications needed for assembly of the CO_2 tank and vortex separator. To elucidate, the process involved machining polycarbonate plates using drills and end mills to machine holes, using taps to thread them as needed, for both the CO_2 tank and the enclosure. Additionally, vertical and horizontal bandsaws were used to cut t-slot aluminum framing to build an enclosure for the system and a CNC machine was to be used to create the nozzles of the separator out of polycarbonate.

At the beginning of the fabrication phase, Sania Shaik, a graduate student at UNT Mechanical and Energy Engineering, joined the team and supported the fabrication and testing related tasks.

4.1 Fabrication Methods

Fabrication phase of the prototype until the COVID-19 related closures involved the use of following equipment:

- Mill
- Lathe
- Drill Press
- Band Saws
- CNC
- Tap and die set

4.2 Fabrication Stages

Fabrication of the prototype was broken up by individually assembling each subsystem and included an enclosure designed to hold all components to ensure safety and practicality of the system. It was planned to be done in four stages – some done concurrently with others.

Gas Inlet Subsystem

Fabrication for this subsystem primarily consisted of machining and assembling the CO_2 tank with the sparger and the immersion heater openings. Figure 22 shows the CO_2 humidifying tank. Polycarbonate plates with half-inch thickness were first marked and drilled. Threads were added to holes that needed screws and a small chamfer was given to these holes to ensure a snug fit. Next, larger holes for various components such as the pressure transducer, two thermocouple probes, two spargers, the gas outlet, drain port, immersion heater, and fill port were created and threaded. Some larger holes required use of a milling machine for accuracy of hole placement. This was done with a drill attachment and can be seen in Figure 23. The sparger plate on the tank was also drilled and then threaded. The tank was then assembled to ensure all components would fit together and that threads were accurate. The final stage of fabrication for the CO_2 humidifying tank would be to use a silicone sealant to seal all edges, however Discovery Park closed before the team could finish this step.

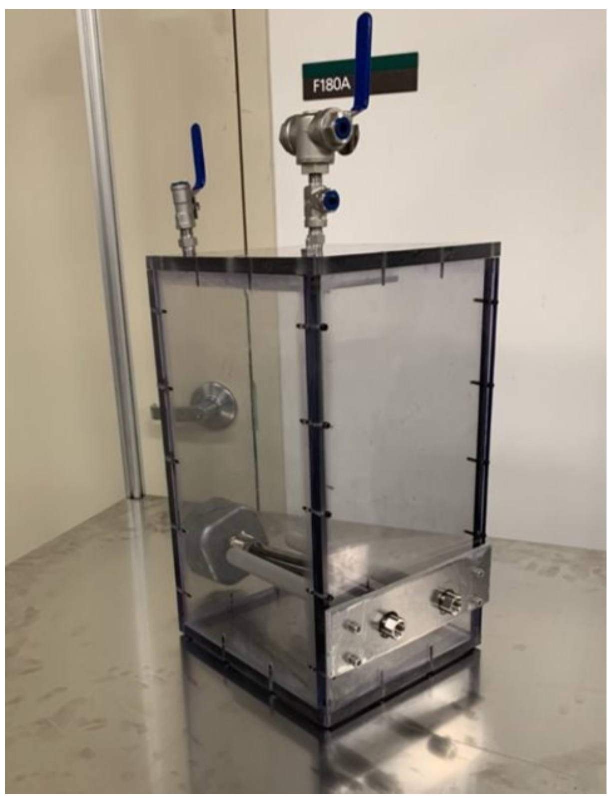

Figure 22: CO_2 Humidifying Tank Assembly

Figure 23: Using a Milling Machine for Drilling Accuracy

Figure 24: Threading Holes with a Drill for the CO_2 Humidifying Tank Walls

System Enclosure

The full system enclosure involves large polycarbonate plates that are secured to 1-inch inch T-slot framing. For the framing, the t-slotted bars were cut to size with a horizontal bandsaw and holes were drilled to place wheels on all four supports. This enclosure was first designed in Solidworks, as discussed in Section 3.2: Phases of Project Design and assembled with reference to this design. The assembled system enclosure without polycarbonate windows is shown in Figure 25. A door was also built from t-slotted framing by using hinges and locks. All attachments used were drop-in fasteners. The next step in the fabrication of this system was to add the polycarbonate windows and attach them using more fasteners via drilled holes in the plates (done using drill press or mill for accuracy).

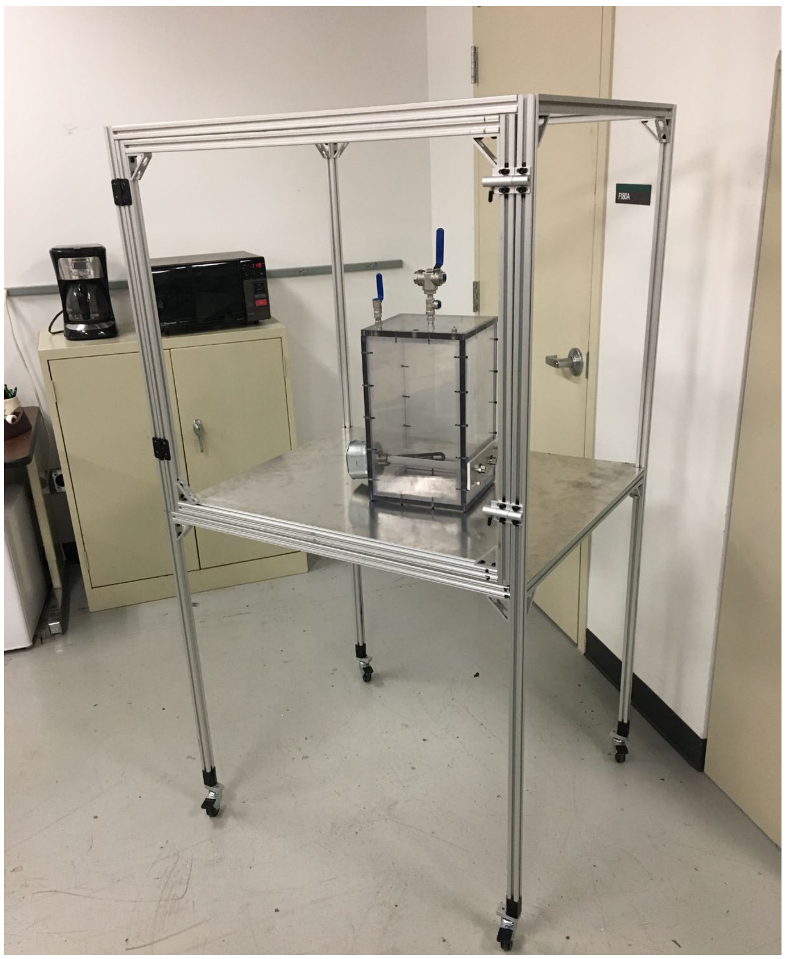

Figure 25: Assembled Framing

Separator Loop Subsystem

The vortex separator is the main component in this subsystem that needed to be fabricated. Mr. Bobby Grimes, a lead machinist at UNT, began working on the vortex separator machining for the X-Hab team as its components are intricate and difficult to machine. Mr. Grimes planned on using a mill and CNC machine for the manufacturing of the vortex separator. He unfortunately could not finish it due to the COVID-19 pandemic. The X-Hab team did print a mock vortex separator out of PLA to see how the components would fit together. This is shown in Figure 26. It should be stated that this design was slightly modified and is not the final version of the vortex separator.

Figure 26: Vortex Separator 3D Printed Model

Gas Outlet Subsystem

This subsystem mainly involves metal (stainless steel) tubing, various sensors, and a rope heater. This subsystem was unable to be completed due to the Discovery Park closure. Metal tubing was to be used with insulation material and a rope heater wrapped around it. This would allow for the CO_2 at the gas outlet to be brought to optimum temperature and relative humidity values given to the X-Hab team by NASA. The heating performed with the rope heater allows for relative humidity of the outlet stream to be decreased. Temperature and relative humidity before and after the rope heater is monitored. The flow and CO_2 amount after the heater is also monitored.

Section 5: Testing

Testing of the system was unfortunately unable to be completed due to the COVID-19 pandemic. The UNT Discovery Park closed on March 23rd, 2020, and instruction moved online to protect the health and safety of UNT students and staff. This section discusses the plans for testing procedures. Test matrices for the CO_2 humidifying tank and vortex separator are shown and discussed in Tables 7 and 8. The instrumentation of the system is shown in Figure 27 and is further described in Table 9. Figure 28 shows the overall system and how instrumentation is connected to the system with various fittings. Data acquisition and analysis is also discussed, which was to be performed with use of the software LabView and Sensirion Evaluation Kit.

5.1 Testing Plan

The X-Hab 2020 team worked closely with a Texas Academy of Mathematics and Science (TAMS) student at the UNT throughout this project. TAMS allows gifted high-school students to attend UNT and start college classes early. Charlie Wang, a TAMS student at UNT, worked with the X-Hab team and was going to perform initial testing for the CO_2 humidifying tank to analyze the effects of gas flow rate, fill level, liquid temperature, and pressure levels inside of the tank. This would allow for further insight on the effects of CO_2 loading and unloading for the system. Effective humidification is crucial to the system as this is how CO_2 enters the vortex separator and is what drives the H_2O removal from CO_2 separation process[4]. If humidification is not effective, the loading of CO_2 upon the humidified H_2O stream will decrease and H_2O will not be able to be removed from it effectively through use of vortex separator technology. The goal for initial testing on the CO_2 humidifying tank was to find ideal temperatures and flow rates in the system to reach 100% relative humidity for the humidified CO_2 gas stream entering the vortex separator at its gas inlet. As previously stated, this would allow for the highest efficiency of H_2O removal from the humidified CO_2 stream through use of the vortex separator.

Table 7 demonstrates the planned test matrix for initial analysis of the CO_2 humidifying tank. Predicted theoretical values are shown and were planned to be tested against through use of instrumentation, LabView software, and Sensirion Evaluation software. Runs 10, 11 and 12 have a temperature of water inside of the tank set to 388.15K which was calculated theoretically and is used as a baseline for all other tests. This temperature value of 388.15K was chosen as it was shown previously in theoretical calculations to cause the system to reach requirements given to the X-Hab team by NASA for H_2O removal rate from the CO_2 stream at the gas outlet of the system[3]. The 388.15K temperature was used as a conservative value, as this is the highest expected temperature at the gas inlet for the vortex separator. Assuming this temperature causes humidified CO_2 stream to be also at 388.15K at the ejector, it was predicted theoretically that 283.15K would be the temperature at the gas outlet on the vortex separator. This temperature is based on the highest coolant temperature in the low temperature loop of the system. It also assumes perfect heat exchange in the separator. This initial test matrix, shown in Table 7, will not only provide insight for CO_2 loading and unloading and to what parameters the CO_2 humidifying tank should be set to for a successful overall system, but it will also allow analysis on how conservative the initial predicted values for temperature and H_2O removal rate were.

Table 7: Test Matrix (Broken Up) for CO_2 Humidifying Tank

Carbon Dioxide Humidifying Tank

	CO_2 Flow Rate (m^3/sec)	Water in Tank (kg)	Temp. of Water in Tank (K)
Run 1	8.1935E-06	3.88	313.15
Run 2	1.22902E-05	4.44	313.15
Run 3	1.6387E-05	5.55	313.15
Run 4	1.6387E-05	4.44	343.15
Run 5	3.2774E-05	5.55	343.15
Run 6	4.9161E-05	6.67	343.15
Run 7	1.6387E-05	5.55	363.15
Run 8	3.2774E-05	6.67	363.15
Run 9	4.9161E-05	7.78	363.15
Run 10	3.2774E-05	6.67	388.15
Run 11	4.09675E-05	7.78	388.15
Run 12	4.9161E-05	8.33	388.15

	Center Line of Sparger to Water Surface (m)	Partial Pressure of Water Vapor (kPa)	Total Volume of Tank (m^3)
Run 1	0.022860046	7.37765	0.000033
Run 2	0.035560071	7.37765	0.000033
Run 3	0.060960122	7.37765	0.000033
Run 4	0.035560071	31.23435	0.000168
Run 5	0.060960122	31.23435	0.000168
Run 6	0.086360173	31.23435	0.000168
Run 7	0.060960122	70.1911	0.000399
Run 8	0.086360173	70.1911	0.000399
Run 9	0.111760224	70.1911	0.000399
Run 10	0.086360173	169.2033	0.000943
Run 11	0.111760224	169.2033	0.000943
Run 12	0.124460249	169.2033	0.000943

	Humidity at Outlet (g H20/kg CO_2)	Temp. of CO_2 at Outlet (K)
Run 1	32.98	
Run 2	32.98	
Run 3	32.98	
Run 4	164.7	
Run 5	164.7	
Run 6	164.7	
Run 7	384.9	
Run 8	384.9	
Run 9	384.9	
Run 10	893.3	
Run 11	893.3	
Run 12	893.3	

CO_2 flow rate for all runs was based off theoretical calculations previously discussed in 3.3.1 Prediction of Humidity Levels at the Inlet and Outlet of Vortex Separator. It was theoretically predicted that for a temperature of water in the CO_2 humidifying tank at 388.15K, a CO_2 flow rate of $4.9161*10^{-5}$ m^3/s at the inlet to the sparger is necessary to remove maximum required levels of H_2O from the humidified CO_2 stream given to the X-Hab team by NASA[3]. These values were predicted to cause 100% relative humidity to occur at the gas outlet of the CO_2 humidifying tank. The CO_2 flow rate is to be varied with temperature of water in the tank, as seen in Table 7. Varying both CO_2 flow rate and the temperature of water in the tank will allow conditions to be verified for 100% relative humidity to occur at the gas outlet of the humidifying tank.

The water levels were chosen carefully for all runs because if the water level were to be below 0.0762 m, it would not cover the spargers in the tank completely. This would decrease the amount of CO_2 being bubbled into the water and cause bubbles to simply fizzle outwards instead of causing them to rise upwards. An upwards motion is needed for the bubbles to ensure adequate flow of humidified gas to the outlet on the humidified tank, where it is directed into the ejector and then combined with chilled liquid from the liquid outlet on the vortex separator. This gas-liquid stream is what enters the gas inlet on the vortex separator and drives separation of H_2O from CO_2. Water levels to be tested were also chosen so that they would not affect the baffle plate in the humidifying tank. This is crucial as water splashing and mixing with the gas stream could cause separation failure. These water levels correspond to the center line of the sparger to the water surface (m).

The humidity at the gas outlet was predicted with use of "3.3.1 Prediction of Humidity Levels at the Inlet and Outlet of Vortex Separator" (G. L. Vaughan & C. G. Carrington, 1998)[6]. This is further discussed in Section 3.3.1: Calculation of Humidity at the Gas Outlet of the CO_2 Humidifying Tank. The humidity ratio for H_2O/CO_2 varies with considered parameters such as temperature of water in the tank, pressure in the tank, and fill level (water height) in the tank. The temperature of CO_2 at the outlet of the humidifying tank could not be predicted and would need to be found strictly by experimental procedure.

Table 8: Test Matrix for Vortex Separator

Vortex Separator			
	Water Temperature (K)	**CO_2 Temperature (K)**	**Water Flow Rate (m^3/sec)**
Run 1			
Run 2			
Run 3			
Run 4			
Run 5			
Run 6			
Run 7			
Run 8			
Run 9			
Run 10			

Table 8 demonstrates the test matrix for the vortex separator system. Once the proper oeparting conditions are found, including temperature of water inside of the CO_2 humidifying tank, center line of sparger to water surface distance, and the CO_2 flow rate to the CO_2 humidifying tank, from the previous test matrix, they will be used to ensure 100% relative humidity occurs in CO_2 stream near the ejector and gas inlet for the vortex separator and will no longer need to be varied. The chiller temperature at the liquid outlet on the vortex separator will be varied depending on the temperature of water in the CO_2 humidifying tank which will affect the water temperature as shown in the above matrix. The lower the temperature of the water in the CO_2 humidifying tank, the colder this chiller temperature must be set to. This is to ensure an optimal humidified stream being directed into the gas inlet of the vortex separator by the ejector. Heater temperature at the gas outlet of the separator will also be varied to ensure the purified CO_2 is around room temperature, a parameter given to the X-Hab team by NASA[3]. This value is represented by CO_2 temperature in Table 8. The water flow rate at the liquid outlet of the vortex separator, after the chiller, will also be varied to find a flow rate that demonstrates efficient H_2O removal.

5.2 Instrumentation

Figure 27 shows the system instrumentation and Table 9 shows images and description of this instrumentation. All instrumentation is to be connected to LabView, a software that is used for data acquisition, monitoring, and recording. CO_2 sensors are used with a software provided by Sensirion called “Sensirion Evaluation Kit.” Figure 28 shows the instrumentation more in depth with all fittings implemented into the system.

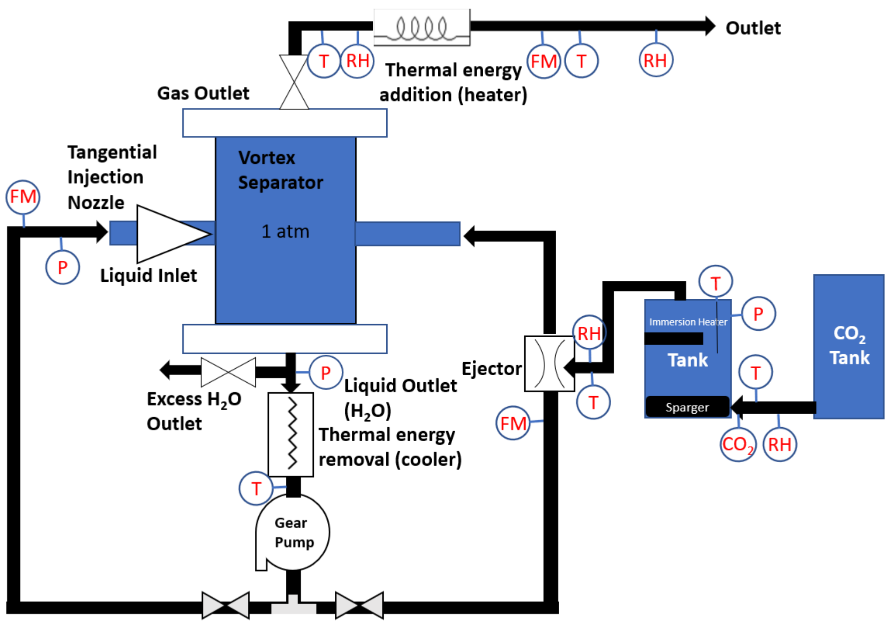

Figure 27: Instrumentation of System

Table 9: Instrumentation Description

Label	Instrumentation	Image	Measurement
RH	Digital Humidity Sensor by Sensirion		**Relative Humidity**
CO_2	Multi Gas Sampling Data Logger by CO_2meter.com		**Carbon Dioxide Level**
P	Pressure Transducers by Omega		**Pressure**
T	Thermocouple Probes by Omega		**Temperature**
FM	Flowmeter by McMaster Carr		**Flow Rate**

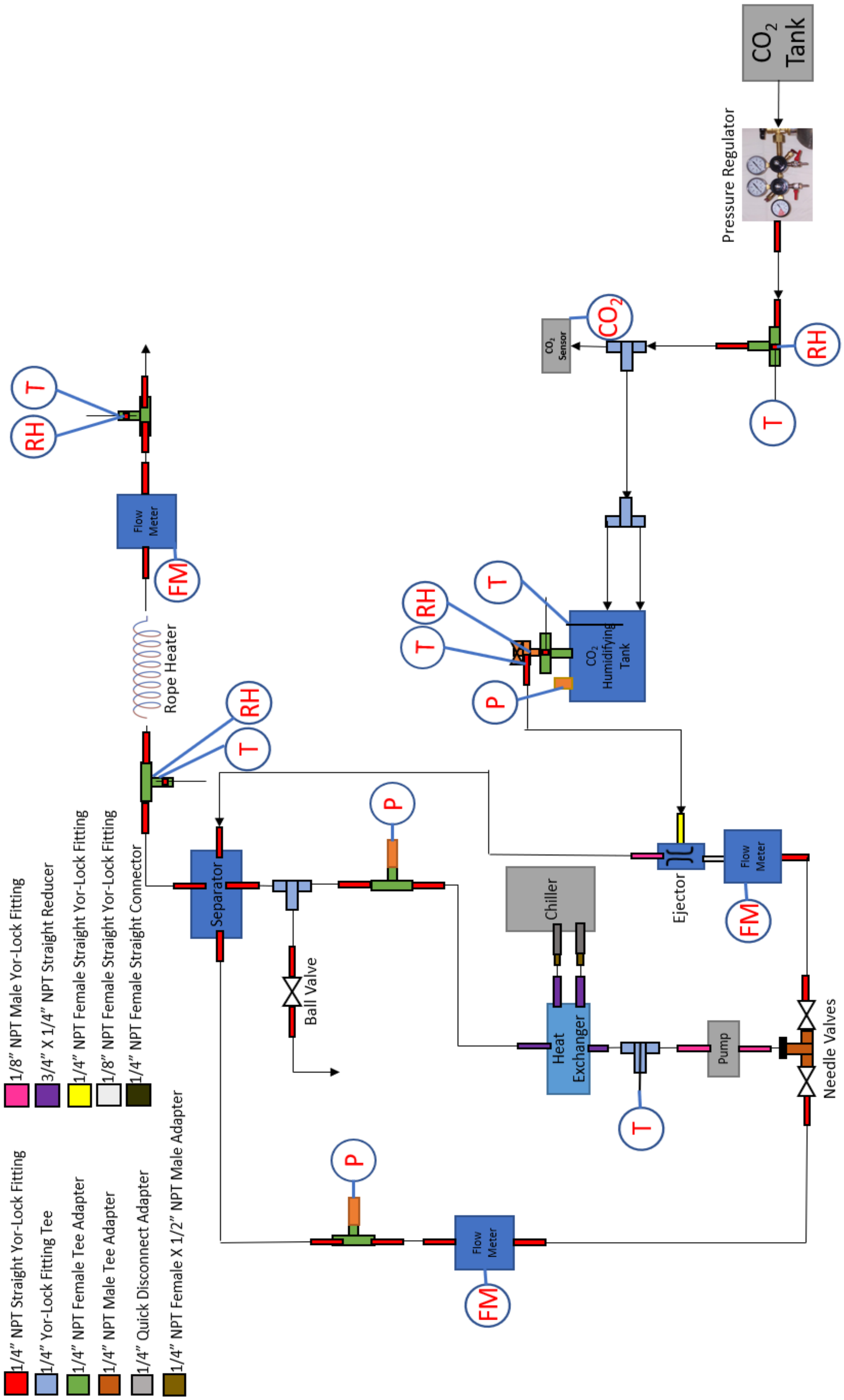

Figure 28: Overall Setup and Instrumentation of the System

5.3 Data Acquisition & Analysis

LabView (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language by NI that uses graphical representations rather than lines of code. LabView was used for simulating, modeling, and monitoring the signal from the thermocouple sensors, pressure transducers, relative humidity sensor and the CO_2 sensor. The LabView configuration is seen in Figure 29 and Figure 30.

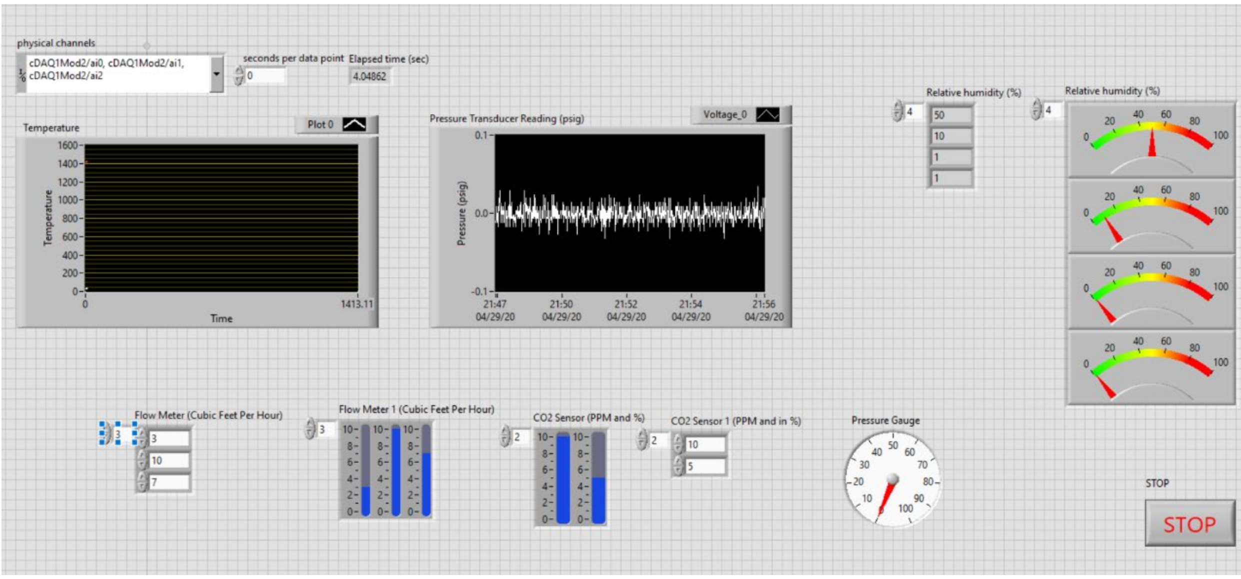

Figure 29: Front Panel of the Configuration to Acquire Various Sensor Data on Labview

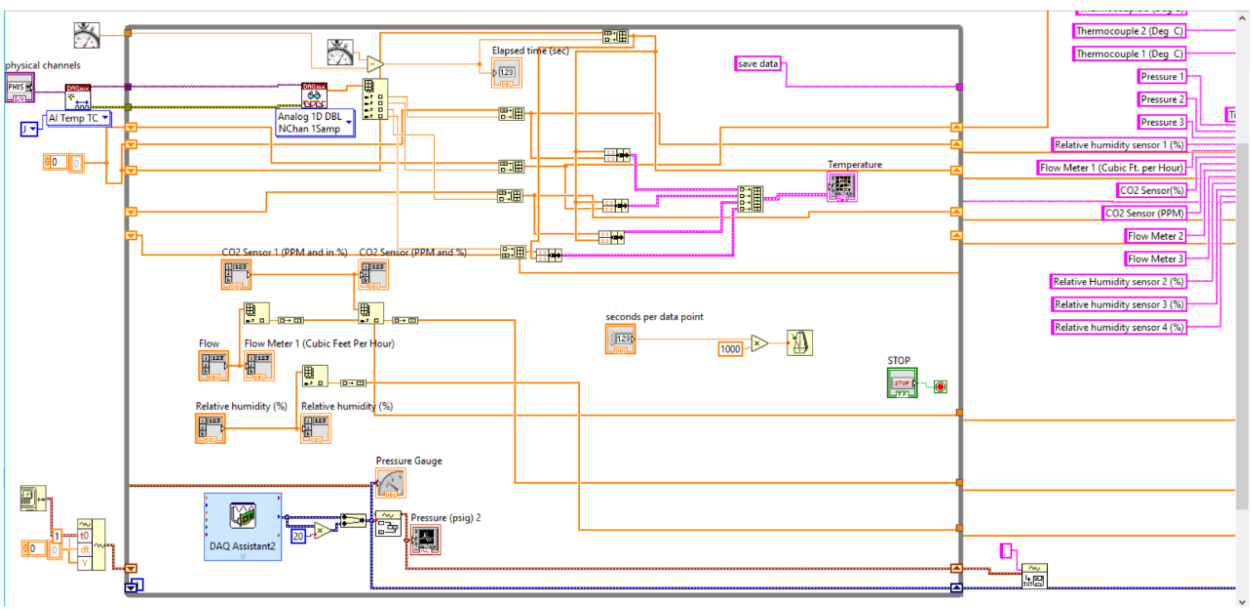

Figure 30: Block Diagram the Configuration to Acquire Various Sensor Data on Labview

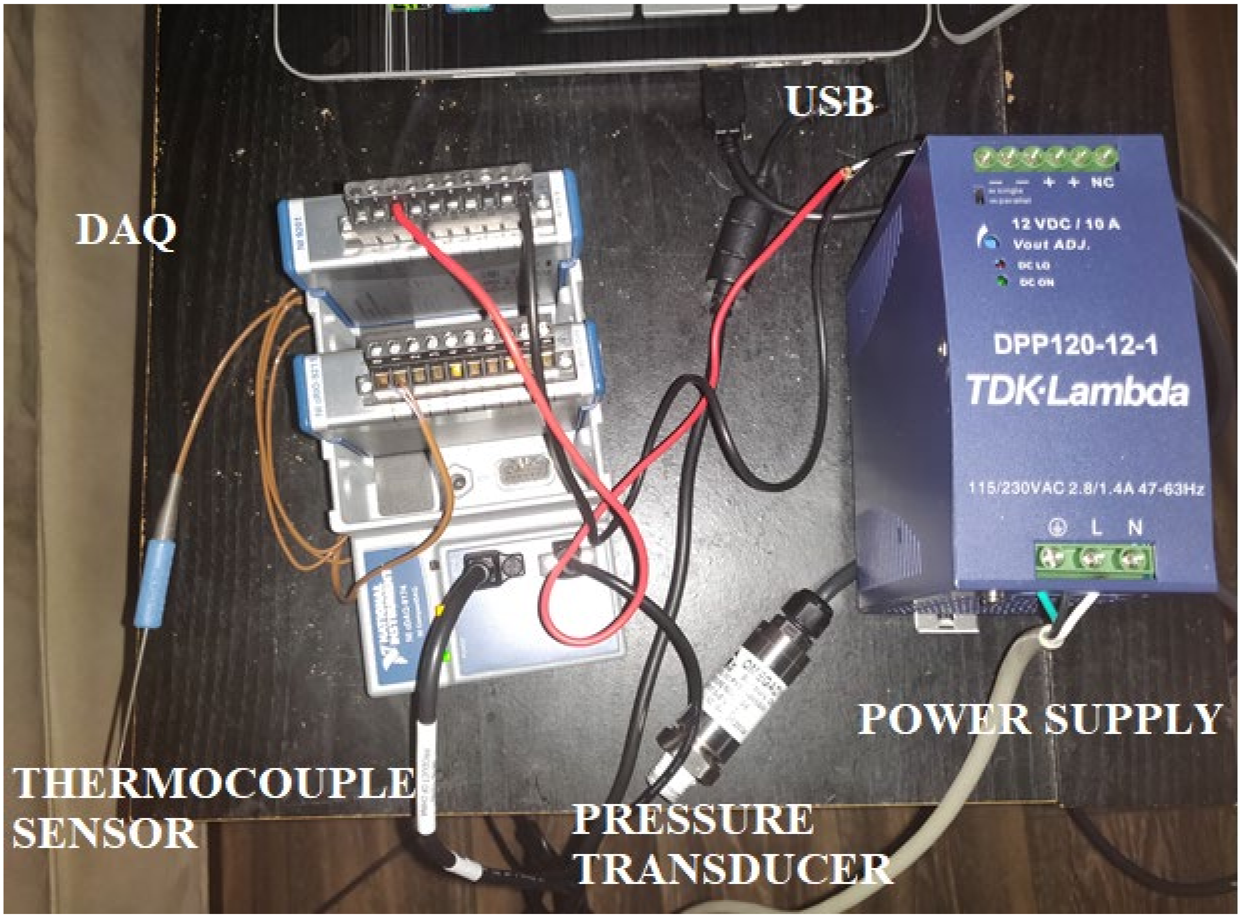

Figure 31: Experimental Setup for Thermocouple Sensor and Pressure Transducer

Temperature Data Acquisition

Thermocouple sensors can measure wide temperature ranges and are inexpensive devices. In order to measure the temperature output of the thermocouples, an NI Data Acquisition device connected to LabView was used. The configuration of the setup is described as follows.

The system hardware mainly consists of NI cRIO-9211, cDAQ-9174 Compact DAQ Chassis and the Omega T- type thermocouples and USB connector cable. The thermocouples output the signal in the millivolt range, a signal conditioning, and as the thermocouple can only measure the temperature difference a cold junction compensation is required. The signal conditioning and cold junction compensation are provided by the National Instruments (NI) cRIO-9211 that measures the temperature signal from the thermocouple and is transferred to the cDAQ-9174 Compact DAQ Chassis which in turn is connected to LabView, a real-time interface system.

In Figure 30 the DAQ assistant is shown. DAQ Assistant is a step by step wizard to set up the measurement. The setting of the thermocouple is to be chosen from analog input modules. Here, the number of supported physical channels can be selected as required. The signal input range can be varied to be 0-100°C. The type of thermocouple being measured can be chosen and the unit for temperature was set to °C. The module is set to have a built-in cold junction compensation. Each time the DAQ assistant is called it will output one signal, so to continually acquire an output a while loop set up. The time delay was kept at 1 second so one sample can be received every second. To obtain the temperature data, the output is wired to a numeric thermometer in the front panel. This outputs the current temperature reading. Currently, the reading shows ambient room temperature.

Pressure Data Acquisition

The system consists of a power supply TDK Lambda 12 VDC/10 A, an Omegadyne pressure transducer of voltage output 0-5 VDC, 0-100 psig range and 10-30 VDC excitation, an NI DAQ 9201 module, cDAQ-9174 Compact DAQ Chassis and a USB connector cable.

The pressure transducer is conFigured using NI DAQ assistant. On LabView, the configuration of signal input range in voltage input setup is done in order to measure the pressure output. The pressure transducer used has and 0-5 VDC signal output. The voltage signal output from the transducer is being conFigured by LabView, and it is linearly proportional to the pressure output range. Thus, through the linearity of the voltage reading the pressure reading is acquired.

To measure the voltage output the NI DAQ was connected to the pressure transducer as shown in the circuit diagram below:

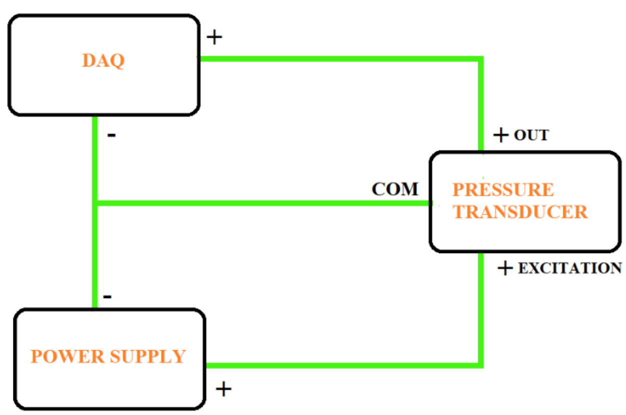

Figure 32: Circuit Diagram for Pressure Transducer

The DAQ assistant was set up to conFigure the analog signal input of voltage from the supported physical channels connected to the DAQ across the resistor channels. In the configuration: the voltage range is set from 10V to -10V range; the units are chosen as volts and the timing is set to 1 sample on demand. The VI is now built according to the set parameters. Like the thermocouple module, this case also uses a while loop to continually acquire signals. The output is graphed using the waveform graph whose input is wired from the data acquisition output in the block diagram. The output in voltage linearly varies with the pressure applied. The pressure output is 20 times the voltage output value hence the output is wired to be multiplied by 20 to give pressure output. To be able to export the data to a spreadsheet in an excel file the waveform to spreadsheet option is used and the file can be saved as a .csv file.

CO_2 Concentration Data Acquisition

A multi gas sampling data logger (CM-1000 series) is being used to obtain the CO_2 amounts in the set up before entering the CO_2 humidifying tank. The sensor outputs the data in parts per million and shows in terms of %. This sensor is represented in Labview as a gauge meter.

Relative Humidity Data Acquisition

The relative humidity sensor used is from Sensirion SEK SHTC3. This is a plug and play type sensor which works with Control Center and does not connect to Labview. The sensor outputs are shown from Control Center in Figure 33. The sensor is reading relative humidity levels in ambient air.

The CO_2 sensor and the relative humidity sensor have been included on Labview as numerical controls, so user can input these values for recording purposes. They were not connected to the setup to measure data.

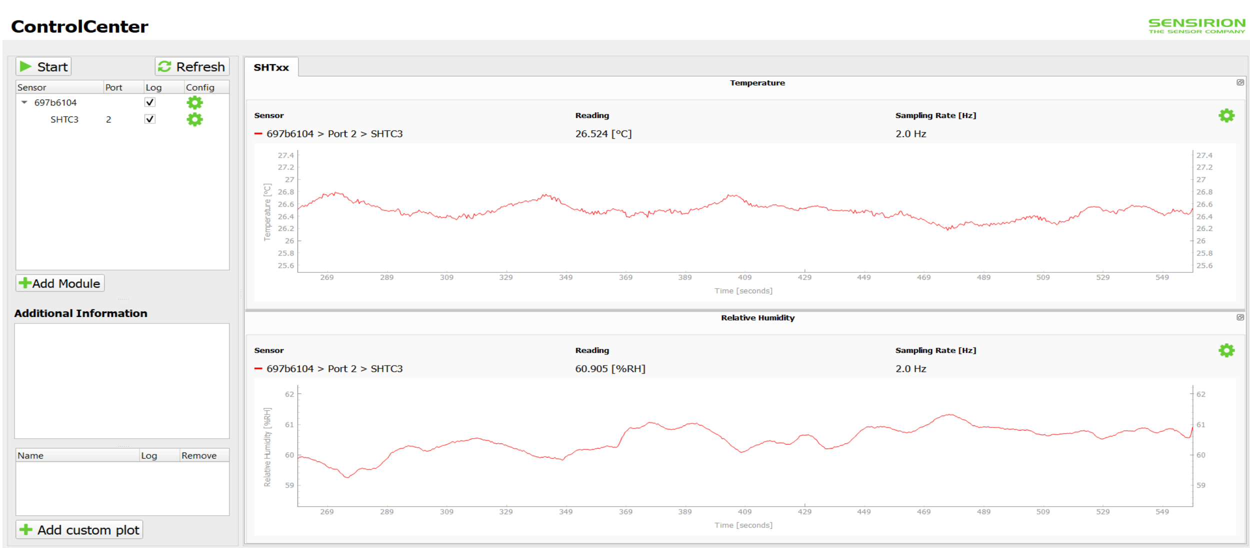

Figure 33: Relative Humidity Data Using Control Sensor

Section 6: Marketing Plan

This section introduces the X-Hab project logo, outlines the target market, and describes means of accessing the target market.

6.1 Project Logo

Figure 34: Project Logo

6.2 Target Market

The target market for the air revitalization system is a very niche group due to the function of the system, but the device can be applied to multiple industries through differentiated applications. The vortex separator can be implemented in air revitalization systems as a continual flow separator to recycle water and isolate CO_2[9]. The market for a gravity independent gas/liquid separator for CO_2 can be used in the space industry and can be applied to numerous systems such as space shuttles, rockets, and other space exploration vehicles. It can also be used to separate other chemicals for dual phase applications, such as submarine systems[17]. Companies that may have an interest in the current product would include SpaceX, Reliable Robotics, NASA, Boeing, Lockheed Martin, etc.

6.3 Means of Accessing the Target Market

In order to reach the desired target market, a website, as well as commercial advertising can be used. However, many of the companies interested may desire confidentiality and military contracts, which would have to be accessible as well. According to the chart below, more than a quarter of the aerospace industry sales are due to DOD contracts[18]. Civil contracts do, however, make up a decent portion of the rest of the market. In addition, the growing interest in space exploration will contribute to an increased interested in a product that can separate two phase fluids due to the need of air revitalization systems and the compact size and efficiency of this particular vortex style apparatus[19]. Additionally, there has recently been a jump of commercial businesses getting contracts with NASA and other government agencies that may have interest in an important subsystem of an air-revitalization system[18-19]. As many more companies are developing capsules and other space crafts, the need for such a subsystem will increase dramatically.

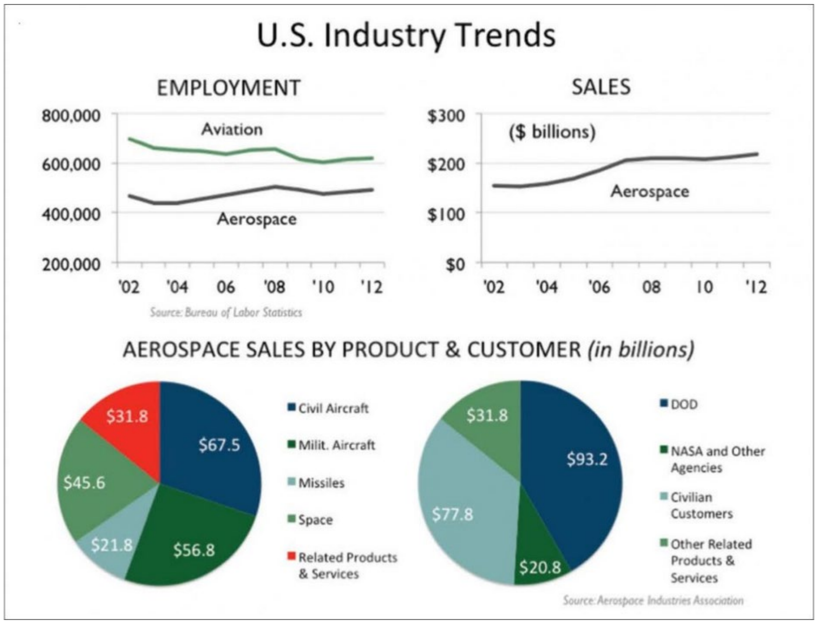

Figure 35: Industry Trends (2013)[17]

Section 7: Team Personnel

This section introduces responsibilities of team members in the project. Resumes of team members are also included following this section.

Table 10: Team Member Responsibilities

Team Member	Task
All Members	Concept of Operations, Fabrication, 3D Modeling
Alyssa Sarvadi	Gantt Chart, Design Calculations, 3D Model, Cost Data, Full System Schematic & Instrumentation, Testing Plan
Nick Frease	3D Model, Implementing Calculations to Design, Fabrication & Assembly
Balmore Giron	Design Calculations, Cost Data, Flow-Down of System, Order Placement, Fabrication
Hannah Whitehead	Safety considerations, Market Plan, Fabrication, Full System Schematic
Fernando Primo	Fabrication, Work Breakdown Structure

Hannah Whitehead

EDUCATION

University of North Texas, Denton, TX

Bachelor of Science in Mechanical Engineering,

Major: Mechanical Engineering Technology; Minor: Management; Certifications: Lean Sigma White Belt, Manufacturing Engineering

Alyssa Sarvadi

EDUCATION
University of North Texas, Denton, TX
Bachelor of Science in Mechanical Engineering, Major: Mechanical Engineering Technology; Certifications: Lean Sigma White Belt

Nicholas Frease

EDUCATION

University of North Texas, Denton, TX

Bachelor of Science in Mechanical Engineering,

Major: Mechanical Engineering Technology

Balmore Giron

EDUCATION
University of North Texas, Denton, TX
Bachelor of Science in Mechanical Engineering,
Major: Mechanical Engineering Technology;

Fernando Primo

EDUCATION
University of North Texas, Denton, TX
Bachelor of Science in Mechanical Engineering,
Major: Mechanical Engineering Technology;

Appendices

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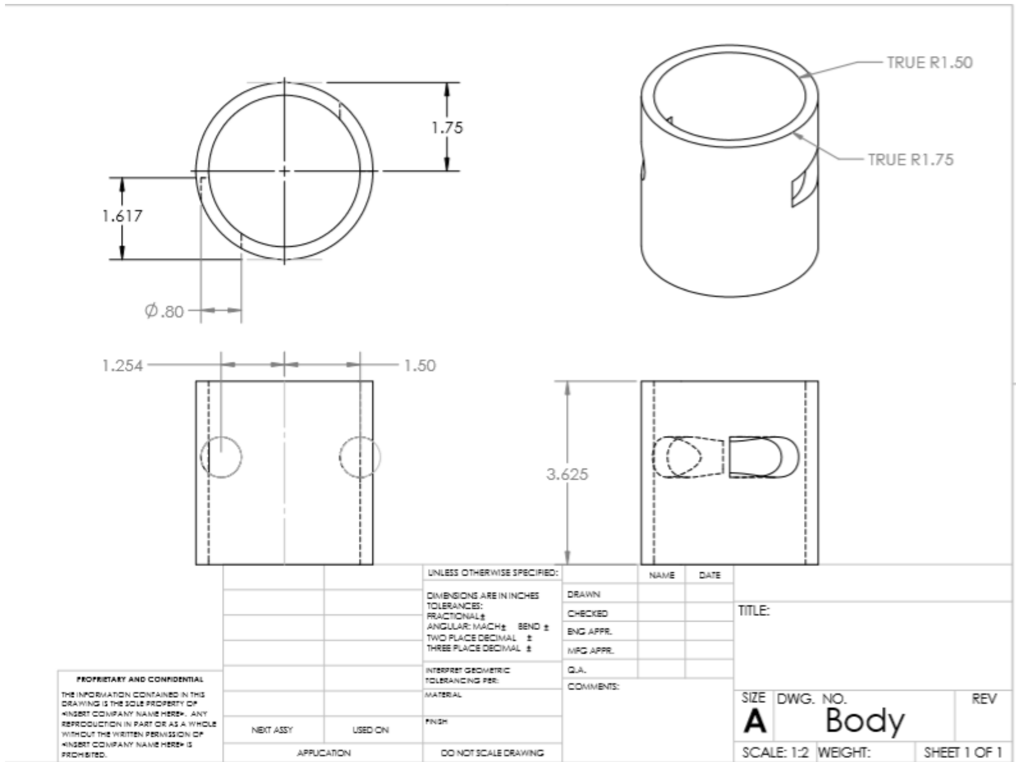
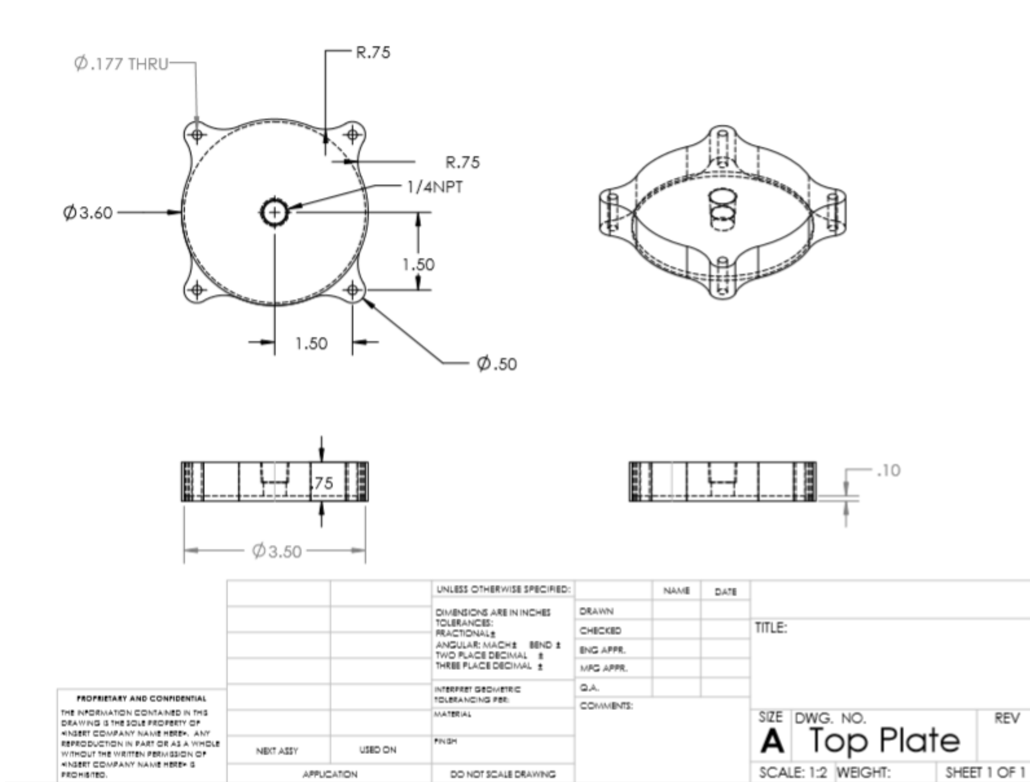
Complete Specifications for Major Purchased Parts/Components

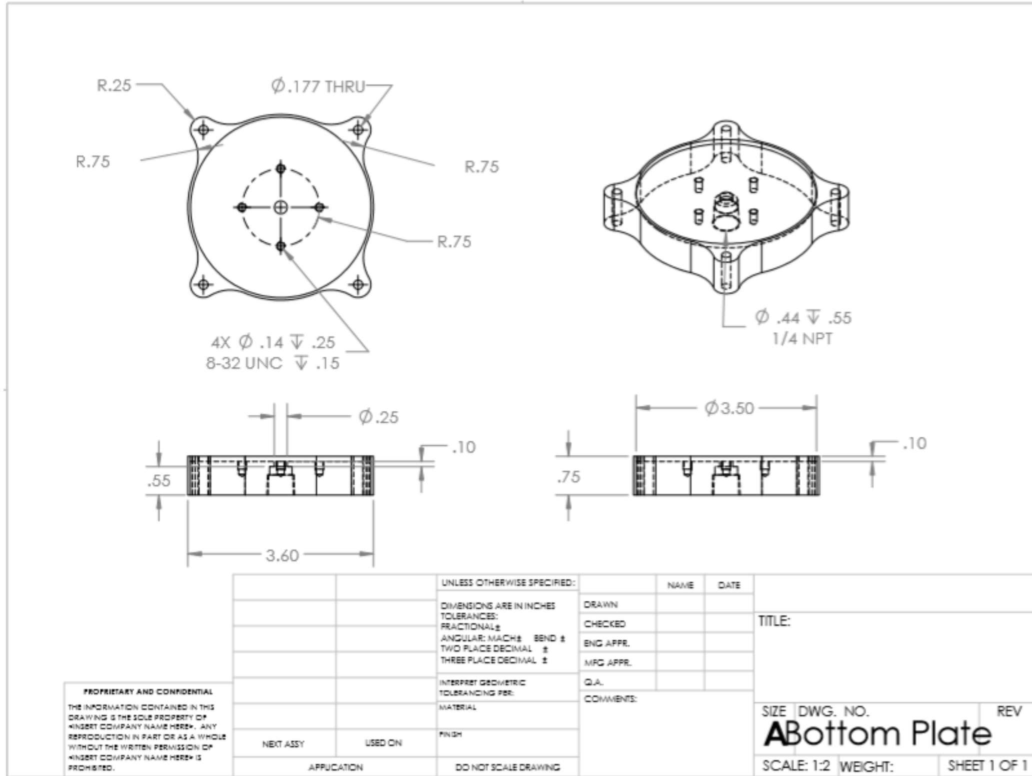
Table 11: Specifications for Major Purchased Parts/Components

Item	Quantity	Unit Cost	Total Cost	Cost after discount/shipping	Vendor
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	1	$	$		Allied Plastic Supply
PC Top and Bottom Plates- 3.6" x 3.6" x .75"	2	$	$		Allied Plastic Supply
PC Baffle Plate- 2.75" x 2.75" x .615" x.25"	2	$	$		Allied Plastic Supply
PC Sheet- 32.75 X 35 X .25 thick	1	$	$	$	Allied Plastic Supply
PC Sheet- 31.75 X 33.5 X .25 thick	2	$	$		Allied Plastic Supply
PC Sheet- 34.5 X 37.5 X .25 thick	1	$	$		Allied Plastic Supply
PC Sheet-31.75 X 37 X .25 thick	1	$	$		Allied Plastic Supply
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	5	$	$		Allied Plastic Supply
Polycarbonate Sheet 9.75" x 8.75" x 1/2"	3	$	$	$	Allied Plastic Supply
Polycarbonate Sheet 4" x 4" x 1/4"	2	$	$		Allied Plastic Supply
Brazed Plate Heat Exchanger	1	$	$	$	Amazon
Screws for Body	3	$	$		McMaster Carr
Teflon Tubing (25 ft) 3/16" ID, 1/4" OD	1	$	$		McMaster Carr
PC Tube (Item Number: 8585K44)	1	$	$		McMaster Carr
PC Rod (Item Number:8571K16)	1	$	$		McMaster Carr
Nozzle Material	1	$			McMaster Carr
Gear Pump +12 VDC motor	1	$		$	ClarkSol
Thermocouple Probe 2 Inch	6	$			Omega
Pressure Transducers	4	$			Omega
Temperature Controller	1	$		$	Omega
Rope Heater	1	$	$		Omega
Thermocouple Probe 12 Inch	1	$	$		Omega
CO2 Sensor, CM-1000 Series	1			$	CO2 Meter
Metal for Sparger Bracket	1	$	$		Metal Supermarket
Aluminum Plate	1	$	$	$	Metal Supermarket
Aluminum Sheet	1				Metal Supermarket

Drawings for Custom-Built Parts






R.25
⌀.177 THRU
R.75
R.75
R.75
4X ⌀ .14 ↧ .25
8-32 UNC ↧ .15
⌀ .44 ↧ .55
1/4 NPT
⌀.25
.10
.55
3.60
⌀3.50
.10
.75
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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NEXT ASSY
USED ON
APPLICATION
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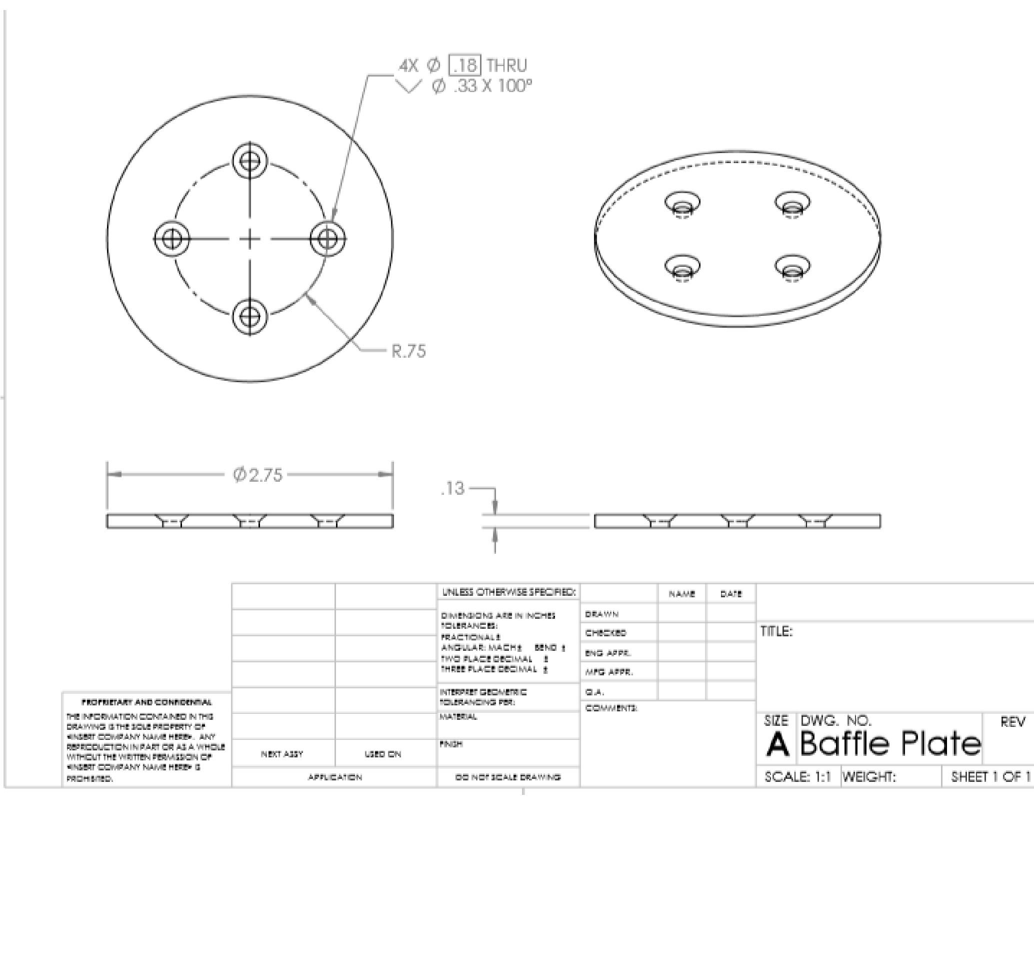
PROPRIETARY AND CONFIDENTIAL
TITLE:
SIZE DWG. NO.
REV
A Bottom Plate
SCALE: 1:2 WEIGHT:
SHEET 1 OF 1


4X ⌀ .18 THRU
⌵ ⌀ .33 X 100°
R.75
⌀2.75
.13
UNLESS OTHERWISE SPECIFIED:
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DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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CHECKED
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MFG APPR.
Q.A.
COMMENTS:
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APPLICATION
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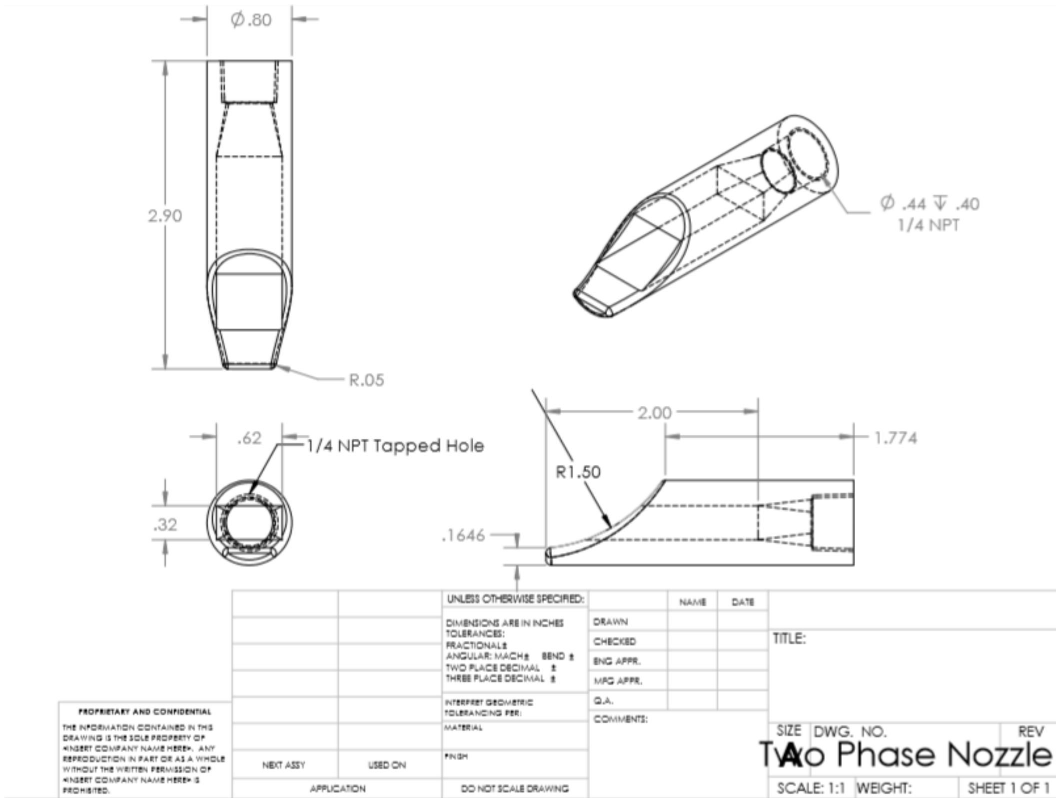
A Baffle Plate
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1


Ø.80
2.90
R.05
Ø .44 ↧ .40
1/4 NPT
.62
1/4 NPT Tapped Hole
.32
2.00
1.774
R1.50
.1646
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
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USED ON
APPLICATION
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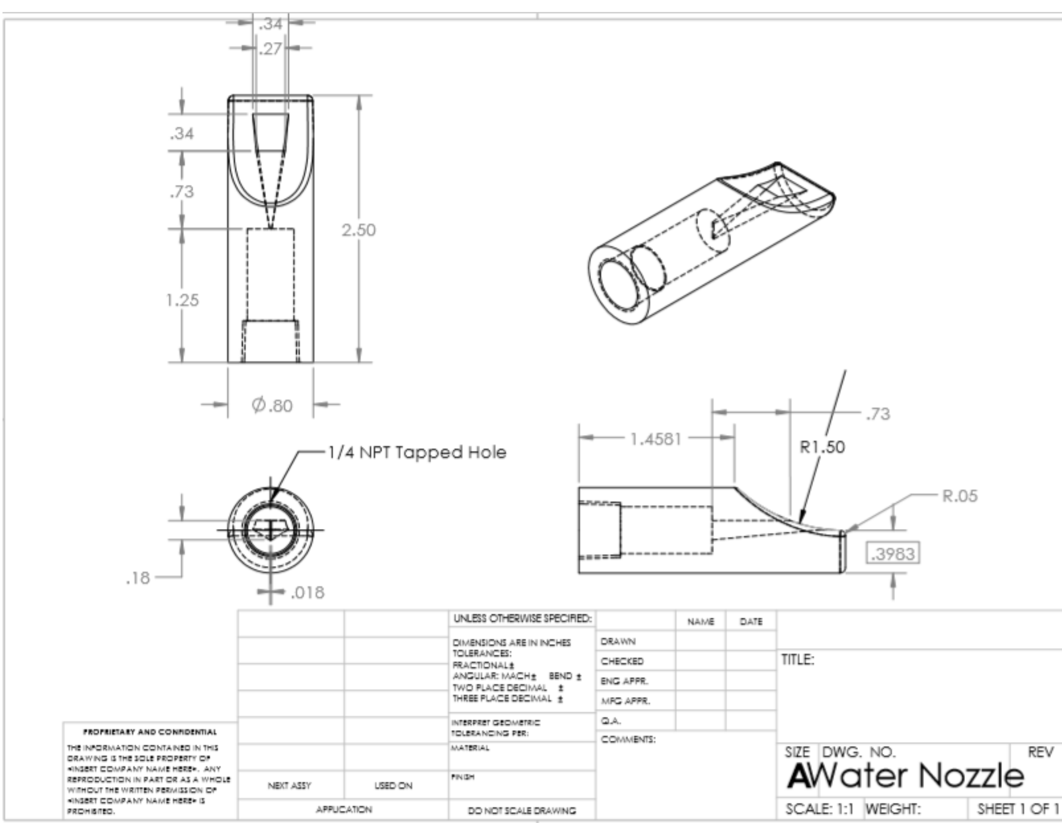
TAo Phase Nozzle
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1


.34
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1/4 NPT Tapped Hole
.18
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R1.50
R.05
.3983
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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COMMENTS:
TITLE:
INTERPRET GEOMETRIC TOLERANCING PER:
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USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SIZE DWG. NO.
REV
AWater Nozzle
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1

Bill of Materials

Item	Quantity	Unit Cost	Total Cost	Cost after discount/shipping	Vendor
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	1				Allied Plastic Supply
PC Top and Bottom Plates- 3.6" x 3.6" x .75"	2				Allied Plastic Supply
PC Baffle Plate- 2.75" x 2.75" x .615" x.25"	2				Allied Plastic Supply
PC Sheet- 32.75 X 35 X .25 thick	1			$	Allied Plastic Supply
PC Sheet- 31.75 X 33.5 X .25 thick	2				Allied Plastic Supply
PC Sheet- 34.5 X 37.5 X .25 thick	1				Allied Plastic Supply
PC Sheet-31.75 X 37 X .25 thick	1				Allied Plastic Supply
Polycarbonate Sheet 8.75" x 15" x 1/2 " thick	5				Allied Plastic Supply
Polycarbonate Sheet 9.75" x 8.75" x 1/2"	3			$	Allied Plastic Supply
Polycarbonate Sheet 4" x 4" x 1/4"	2	$			Allied Plastic Supply
Sparger , Carbonation stone	2	$		$	Amazon
Ball-Valve	2	$			Amazon
Brazed Plate Heat Exchanger	1	$		$	Amazon
3-Way Valve	1	$			Amazon
Ball Valve	2	$		$	Amazon
Drill 1" Carbon Steel NPT Piper Tap and 1-5/32" HSS Drill Bit Set	1	$			Amazon
Immersion Heater	1				McMaster Carr
Adapter	3	$			McMaster Carr
Spacers	4	$			McMaster Carr
Screws for Body	3				McMaster Carr
Teflon Tubing (25 ft) 3/16" ID, 1/4" OD	1				McMaster Carr
Yor-Lok Fitting, straight adapter, 1/16" T x 1/8" MNPT	3				McMaster Carr
Yor-Lok Fitting, straight adapter, 1/4" T x 1/4" MNPT	3				McMaster Carr
Yor-Lok Fitting, tee, (1/4" T x 1/4" T x 1/4" T) 1/4" Tube OD	1			$	McMaster Carr
Tee Fitting for 3-Way Valve	1				McMaster Carr
High Temperature Silicone Rubber Sheet (Gasket Sheet)	1				McMaster Carr
Screws for Sparger Bracket	1				McMaster Carr
Nuts for Sparger Bracket	1				McMaster Carr
Silicone Sealent	2				McMaster Carr
Extreme temperature Teflon PTFE Semi- Clear (Item number : 5239K24)	1				McMaster Carr
Extreme temperature Teflon PTFE Semi- Clear (Item number : 5239K23)	1				McMaster Carr
T-Slotted Framing, Single 4-slot rail 1" high x 1 " wide, 10' long	6				McMaster Carr
Corner Brace, 2" long 1" high rail	20	$			McMaster Carr
Slide Bolt	2	$			McMaster Carr
Handle	1	$		$	McMaster Carr
Hinge, 1" high rail	2	$			McMaster Carr
Drop Pins, spring tab nut, 1/4"-20 Thread Size	50	$			McMaster Carr
Casters, swivel mount , 70 lbs	4	$			McMaster Carr
Adapters for Heat Exchanger , Stainless Steel Threaded Pipe Fitting	4	$			McMaster Carr
1/4" Tube OD X 1/4 NPT Male Fitting, Straight Adapter	36	$			McMaster Carr
Tee Connector all Female 1/4" Yor-Lock Fitting	3	$			McMaster Carr
Tee Connector, 1/4 NPT Female	5	$			McMaster Carr
Tee Connector, 1/4 NPT Male	1				McMaster Carr

Adapter Male-Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD X 1/8 NPT Male	2				McMaster Carr
Needle Valves	2			$	McMaster Carr
Metal Tubing for Outlet	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/8 NPT Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/4 NPT Female	1				McMaster Carr
Straight Adapter for 1/4" Tube OD x 1/8 NPT Male	5	$			McMaster Carr
Plastic quick disconnect tube coupling for air and water (Item number : 5012K76)	2	$			McMaster Carr
Plastic quick disconnect tube coupling for air and water (Item number : 5012K926)	2	$			McMaster Carr
Flexible Rubber Foam Pipe Insulation Tube (Item number:4463K23)	3	$	$		McMaster Carr
316 Stainless Steel Threaded Pipe Fitting (Item number: 4452K165)	2	$	$		McMaster Carr
Sealing Pan Head Screws (Item Number: 90825A172)	1	$	$		McMaster Carr
Spacers (Item Number: 92320A345)	4	$	$		McMaster Carr
Water Flow Meter (Item number: 5079K17)	2	$	$		McMaster Carr
Air Flow Meter (Itme Number: 5079K23)	1	$	$		McMaster Carr
Washers (Itme Number: 90107A007)	1	$	$	$	McMaster Carr
PC Tube (Item Number: 8585K44)	1				McMaster Carr
PC Rod (Item Number:8571K16)	1				McMaster Carr
Acrylic Cement (Item number: 7517A5)	1				McMaster Carr
Cement for plastic (Item number:7515A11)	1				McMaster Carr
Push lock fitting 1/4" bottom	4				McMaster Carr
PC Cylinder for Body- 3" ID, 3.5" OD, 3.25" long	1				McMaster Carr
Nozzle Material	1				McMaster Carr
Rods	4			$	McMaster Carr
Nuts for Rods	1	$			McMaster Carr
Cap Nuts for Rods	1	$			McMaster Carr
Screws for Baffle	1	$			McMaster Carr
Board mount humidity sensors and temperature sensor	10	$			Sensirion
Multiple function sensor development teols sensirion evaluation	1			$	Sensirion
Multiple Function Sensor Development Tools Contains 3x SHTC3 on FPCB and Adapter Cable	1				Sensirion
Ejector	1			$	Fox Venturi Products
Gear Pump +12 VDC motor	1			$	ClarkSol
12 VDC Motor for MG Series Pump	1				ClarkSol
Thermocouple Probe 2 Inch	6				Omega
Pressure Transducers	4				Omega
Temperature Controller	1			$	Omega
Rope Heater	1				Omega
Thermocouple Probe 12 Inch	1				Omega
CO2 Sensor, CM-1000 Series	1			$	CO2 Meter
Metal for Sparger Bracket	1				Metal Supermarket
Aluminum Plate	1			$	Metal Supermarket
Aluminum Sheet	1				Metal Supermarket
Total				**$**	

University of North Texas
Microgravity Gas/Liquid Separator for the CO_2 Revitalization System
Team #3

Alyssa Sarvadi, Hannah Whitehead, Nicholas Frease, Balmore Giron, Fernando Primo

Faculty Mentor: Dr. Huseyin Bostanci

External Mentor: Dr. Cable Kurwitz (A&M)

Introduction: Vision, Mission, Goal and Objectives of Project

- **Vision:** Develop an innovative, reliable, compact, and energy efficient air revitalization system for gravity independent manned exploration.
- **Mission:** Investigate an alternative gravity independent gas-liquid separator solution for H_2O removal from a heated, humid CO_2 system.
- **Goal:** Develop modeling capabilities for a gravity independent vortex separator and direct contact heat exchanger system and provide design points that will be verified in a lab-based setting.
- **Objectives:** Design, build, and test a prototype gravity independent gas-liquid separator for removing H_2O from CO_2.

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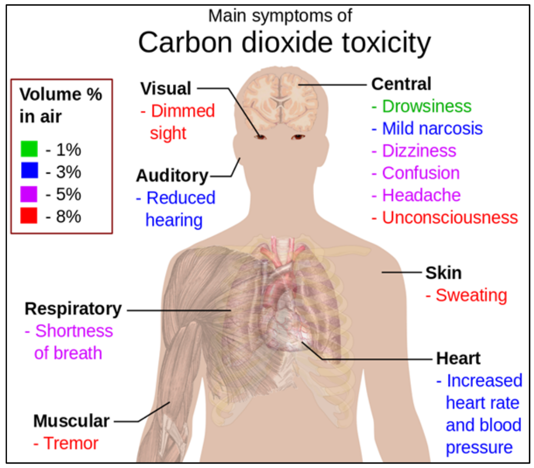
Introduction: Motivation for Project

- As NASA ventures to the Moon and Mars, resupply of clean oxygen to the crew is crucial in sustaining their lives in space.
- Since space is a microgravity environment and the cabin of the spacecraft is closed to the external space, CO_2 can build up in the cabin, causing hypercapnia to affect the crew.
- On the ISS, NASA currently uses granules of a synthetic rock called zeolite as a solid sorbent in their CO_2 removal system. These require high power usage and experience long-term reliability issues.



[1]

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Project Timeline

Level	Description
1.0.0.0	Microgrvaity Gas-Liquid Separator for Carbon Dioxide Removal
1.1.0.0	Designing Prototype
1.1.1.0	Learn about Microgravity Has-Liquid Separators
Task	*Research Current VPS Technologies*
	Milestone #1 (Kickoff)
1.1.2.0	Learn about NASA Project Management
1.1.3.0	Implement NASA Project Management
Task	*Concept of Operations for System: All Members*
Task	*Create Flow-Down Chart: Alyssa*
Task	*Create Work Breakdown Structure: Fernando*
Task	*Analyze Trades: Nick*
Task	*Cost Data: Balmore*
Task	*Safety Issues: Hannah*
	Milestone #2 (SDR)
1.1.4.0	Designing Vortex Separator and System Layout
Task	*Updating Schematic: Hannah*
Task	*Design Calculations: Alyssa*
Task	*3D Model: All Members*
Task	*Internal/External Interface Design Solutions: Nick*
Task	*Cost Data Update: Fernando*
Task	*Updated Flow-Down of System: Balmore*
	Milestone #3 (PDR)
	Milestone #4 (CDR)
1.2.0.0	Building Prototype
1.2.1.0	Build Vortex Separator
1.2.1.1	Attach Sensors/Equiptment to Take Readings
Task	*Build Prototype & Vortex Separator: All Members*
	Milestone #5 (PCR)
1.3.0.0	Testing Prototype
1.3.1.0	Test Vortex Separator Basic Functionality
1.3.1.1	Test Efficiency of System
1.3.1.2	Analyzing Data and Reporting Results
	Milestone #6 (Project Completion)

Milestone	Date
1. Kickoff Meeting	Sept 2019
2. Requirements and System Definition Review (SDR)	08 Oct 2019
3. Preliminary Design Review (PDR)	12 Nov 2019
4. Critical Design Review (CDR)	21 Jan 2020
5. Progress Checkpoint Review (PCR)	11 March 2020
6. Project Completion and Evaluation by NASA	06 May 2020

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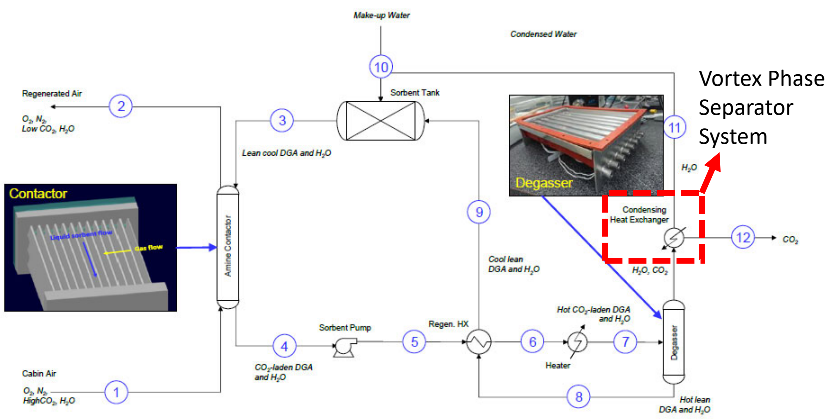
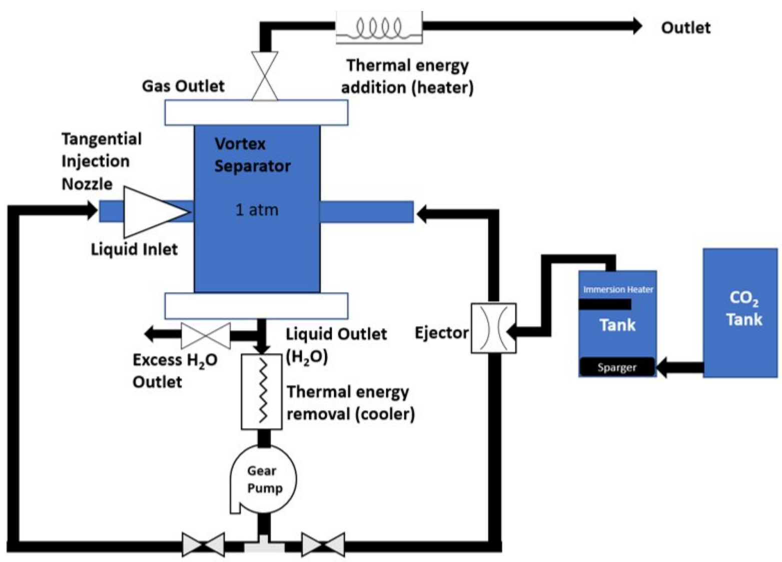
Overview of NASA’s System



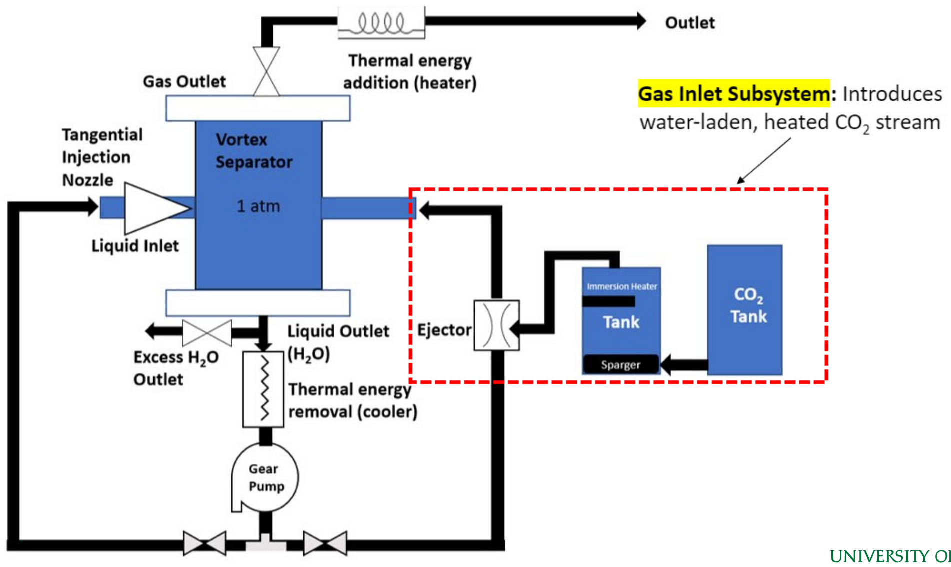
Giraldo Akvarez, Geoff Degraff, Micheal J. Swickrath, Grace Belancik. Jeffery J. Sweterlisch. “Continued Development of a Liquid Amine Carbon Dioxide Removal System for a Microgravity Application.” (2019)

[2]

Design: Vortex Separator System



Design: Gas Inlet Subsystem



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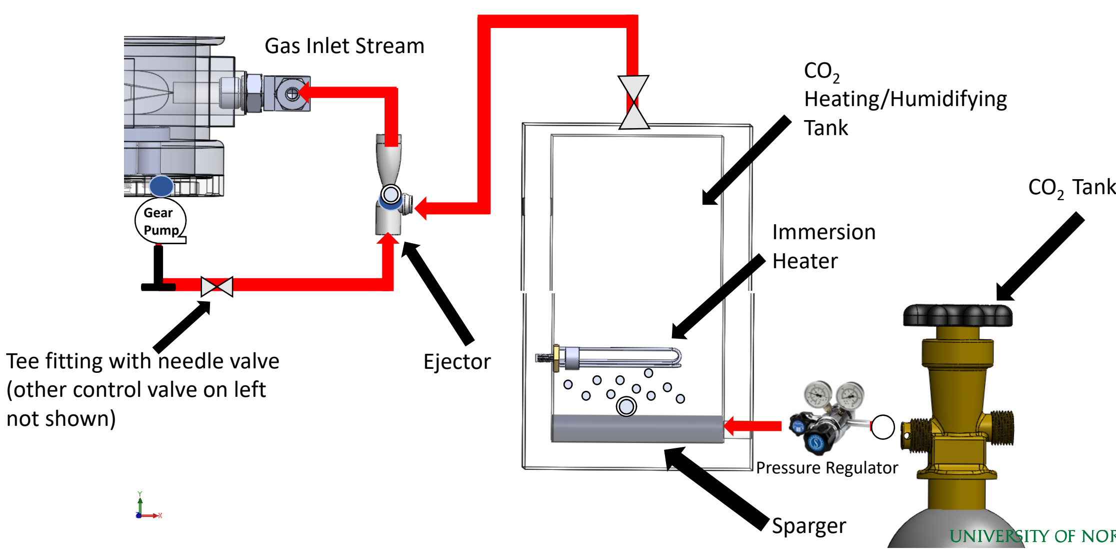
Design: 3D Model Gas Inlet Subsystem



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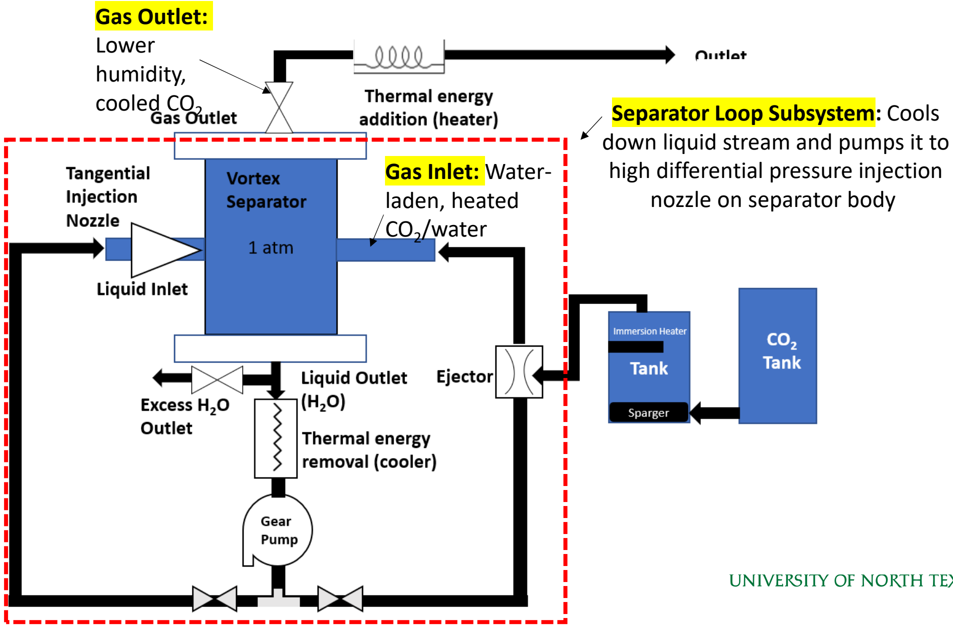
Design: Separator Loop Subsystem



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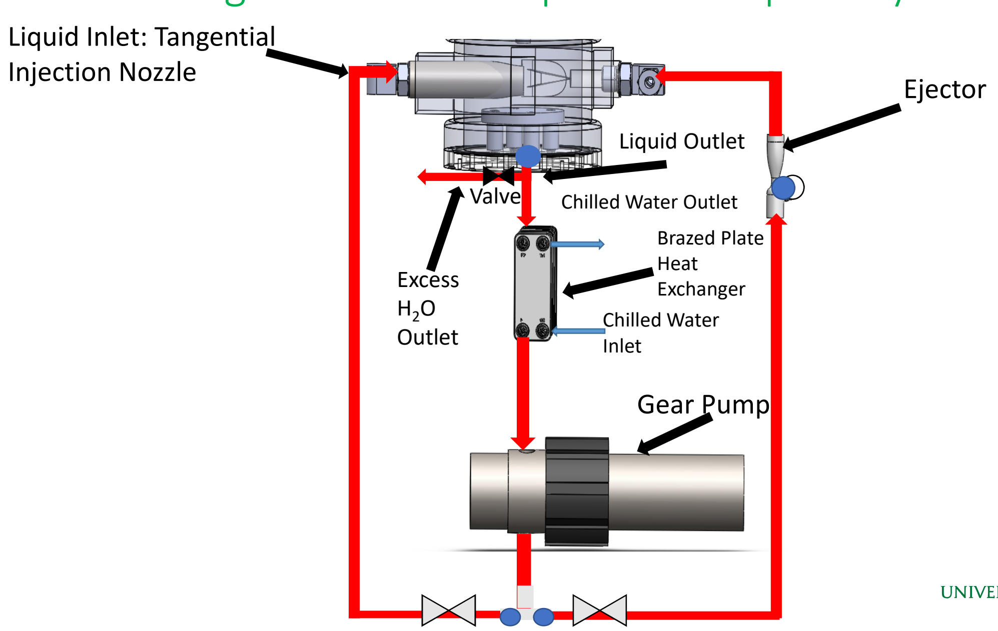
Design: 3D Model Separator Loop Subsystem



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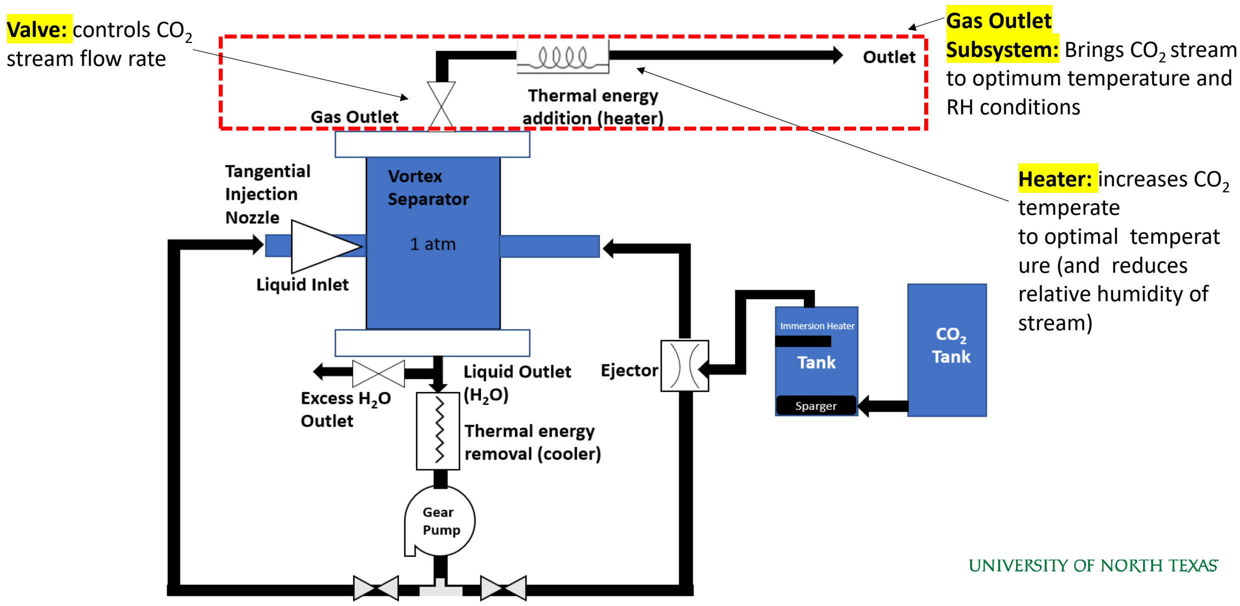
Design: Gas Outlet Subsystem



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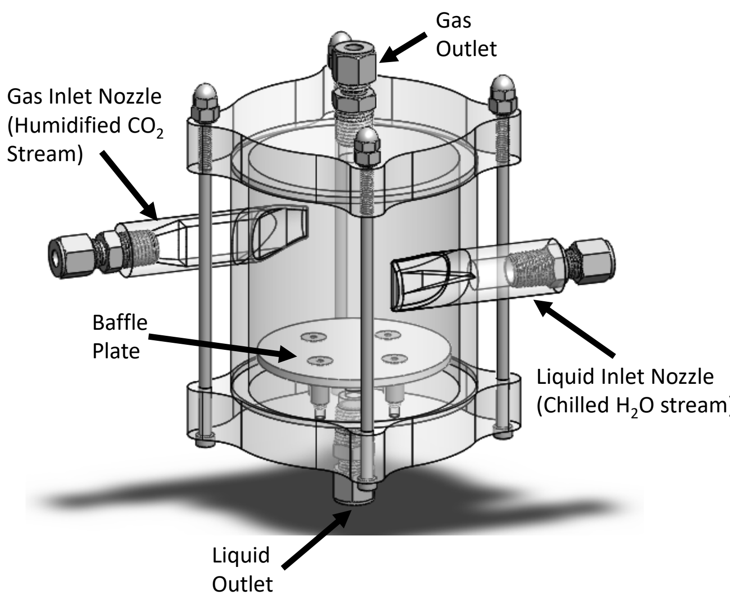
Design: 3D Model of the Vortex Separator



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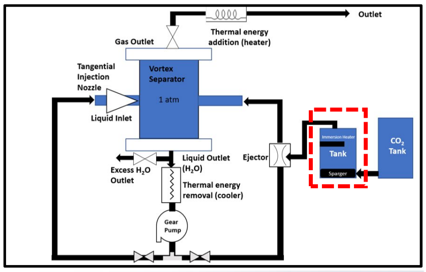
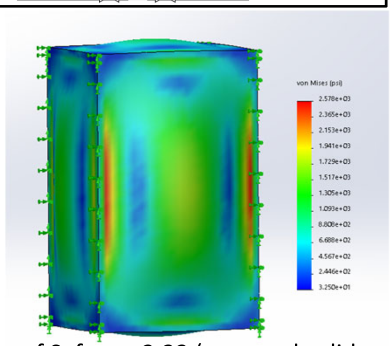
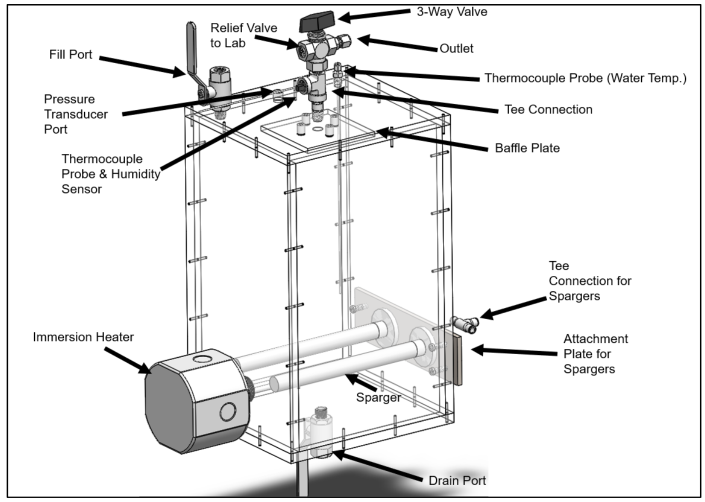
Design: 3D Model of the CO_2 Heating/Humidifying Tank

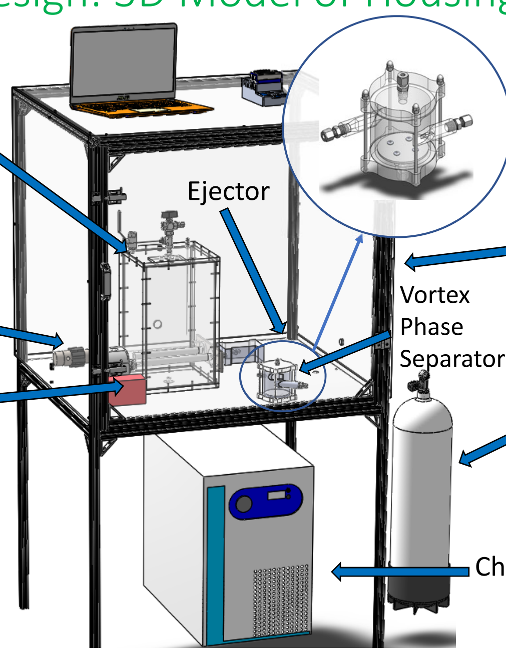






Factor of Safety = 2.32 (assumed solid polycarbonate body)

Design: 3D Model of Housing



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Fabrication: Vortex Separator 3D Printed Model

- Older version of VPS, 3-D printed using ABS Plastic.
- Model to scale.
- Used to see how pieces would fit together/if they are machinable.
- Manufacturing of final separator was halted due to the COVID-19 pandemic.

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Calculations: Sample of Calculations Used During Design

Radial Transit Time

$$t_r = \frac{D^2}{\int_D V_r} = \frac{9\mu_l}{r^2\omega^2(\rho_1 - \rho_g)}$$

$$= \frac{9\left(.0013076\ N * \frac{s}{m}\right)}{(0.001m)^2(6.2383\ rps)^2\left(999.65\frac{kg}{m^3} - 1.881kg/m^3\right)}$$

$$= 0.303\ seconds$$

Where:

$u_l = Liquid\ Viscosity\ of\ Water\ at\ 5°C = .0013076\ N * \frac{s}{m}$
$r_1 = final\ radial\ position\ of\ bubble = 0.0381m$
$r_2 = initial\ radial\ position\ of\ bubble = 0m\ (conservative)$
$r = bubble\ radius = .001m$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.2383\ rps$
$\rho_l = density\ of\ liquid\ at\ 10°C = 999.65kg/m^3$
$\rho_g = density\ of\ gas\ at\ 10°C = 1.881kg/m^3$

Predicted Rotation of Fluid Inside Vortex Separator

$$\frac{R^2\omega}{v} = 0.394(Re_N - 2020.0)$$

$$\omega = \frac{0.394L_N v_{lo} - 2020.0v}{R^2}$$

$$= \frac{0.394(\sqrt{0.00898})(3.3067\ m/s) - 2020.0(1.3081 * 10^{-6}\ m^2/s)}{(0.0381m)^2} * 60 = 374.3\ rpm$$

Where:

$L_N = characteristic\ length\ of\ outlet\ area = \sqrt{outlet}\ area\ of\ separator = 0.00898$
$v_{lo} = liquid\ outlet\ velocity = 3.3067\ m/s$
$v = liquid\ kinematic\ viscosity\ at\ liquid\ outlet = 1.3081 * 10^{-6}\ m^2/s$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$

Axial Transit Time

$$t_a = \frac{R}{\frac{\omega}{60} * A_{liquid\ outlet}} = \frac{0.0381m}{\frac{374.3rpm}{60} * 0.01875\ in^2}$$

$$= 0.3257\ seconds$$

Where:

$t_a = axial\ transit\ time$
$R = inner\ radius\ of\ the\ vortex\ separator = 0.0381m$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm$
$A_{liquid\ outlet} = 0.01875\ in^2$

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Calculations: Vortex Separator Liquid Inlet Nozzle

Liquid Inlet Velocity

$$v_{li} = \frac{Q_{li}}{A_{li}} = \frac{4 * 10^{-5}\ m^3/s}{2.088 * 10^{-6} m^2} = 19.5 \frac{m}{s}$$

Where:

$v_{li} = velocity\ at\ liquid\ inlet$
$Q_{li} = flow\ rate\ at\ liquid\ inlet = 4 * 10^{-5} m^3/s$
$A_{li} = liquid\ inlet\ area = 2.088 * 10^{-6} m^2$

Reynolds Number of Fluid at Liquid Inlet

$$Re = \frac{\rho_l v_n 2R}{\mu_l} = \frac{997.76 \frac{kg}{m^3} * 19.15 \frac{m}{s} * 2 * .001m}{0.0009532 \frac{kg}{m * s}} = 40095$$

Where:

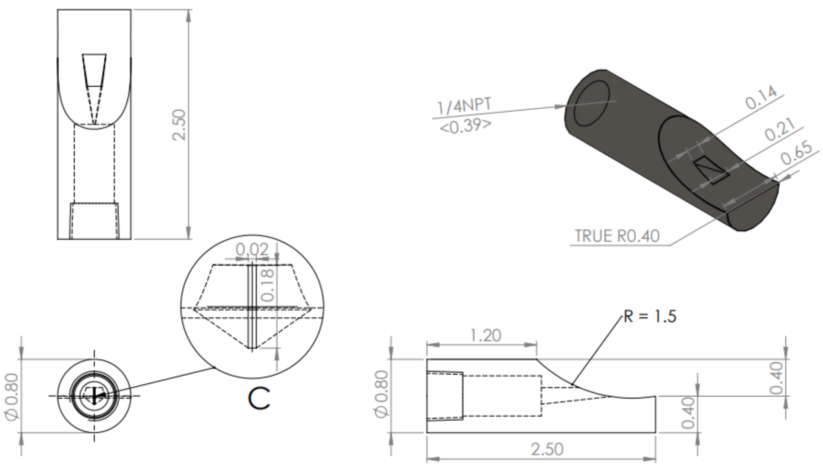
$Re =\ Reynolds\ number$
$\rho_l = density\ of\ liquid\ at\ inlet = 997.76\ kg/m^3$
$v_n = velocity\ at\ liquid\ inlet = 19.15\ m/s$
$R = bubble\ radius = .001m$
$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet = 0.0009532 \frac{kg}{m*s}$

Morton's Number of Fluid at Liquid Inlet

$$Mo = \frac{a_b u_l^4}{\sigma^4 \rho_l} = \frac{\left(0.00144 \frac{m}{s^2}\right)\left(0.0009532 \frac{kg}{m * s}\right)^4}{\left(0.06 \frac{N}{m}\right)^4 \left(999.65 \frac{kg}{m^3}\right)}$$
$$= 9.17 * 10^{-14}$$

Where:

$F_R = resultant\ force\ on\ a\ bubble = 0.009N\ (equation\ 16)$
$a_b = acceleration\ of\ a\ bubble = 0.00144\ m/s^2$
$\mu_l = dynamic\ viscosity\ of\ fluid\ at\ liquid\ inlet = 0.0009532 \frac{kg}{m * s}$
$\sigma = surface\ tension\ of\ liquid = 0.06\ N/m$
$density\ of\ liquid\ at\ 10°C = 999.65 kg/m^3$



Calculations: Vortex Separator Gas Inlet Nozzle

Drag Coefficient of a Bubble

$$C_D = \frac{24}{Re} = \frac{24}{40095} = 5.98 * 10^{-4}$$

Where:

$C_D = drag\ coefficient\ of\ a\ bubble$
$Re = Reynolds\ Number$

Drag & Buoyancy Forces on a Bubble

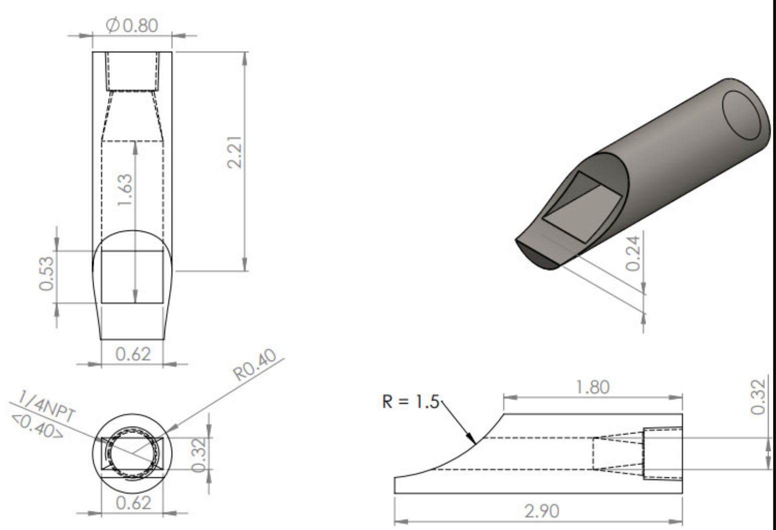
$$F_B = (\rho_l - \rho_g)\frac{4}{3}\pi r^3 = \left(999.65 \frac{kg}{m^3} - 1.881 \frac{kg}{m^3}\right)\left(\frac{4}{3}\pi (0.001m)^3\right) * 9.81$$
$$= 4.1 * 10^{-5} N$$

$$F_D = \frac{1}{2} C_D \rho_l v_{li}^2 \pi r^2$$
$$= \frac{1}{2} * (5.98 * 10^{-4}) * 999.65 \frac{kg}{m^3} * \left(19.15 \frac{m}{s}\right)^2 * \pi * (0.001)^2$$
$$= 3.44 * 10^{-4} N$$

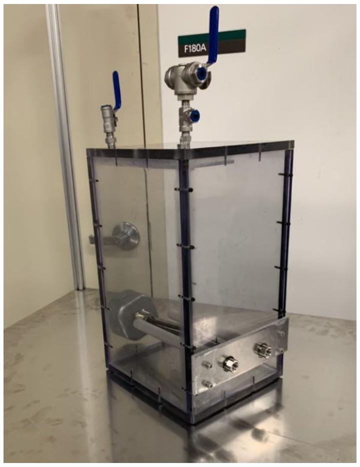
Where:

$F_B = buoyancy\ Force$
$F_D = drag\ Force$
$\rho_l = liquid\ density\ at\ liquid\ inlet =\ 999.65 kg/m^3$
$\omega = predicted\ rotation\ of\ fluid\ inside\ vortex\ separator = 374.3\ rpm = 6.23 \frac{1}{s}$
$v_{li} =\ velocity\ at\ liquid\ inlet = 19.15\ m/s$
$r = bubble\ radius = 0.001m$

$C_D = drag\ coefficient\ for\ bubble = \frac{24}{Re} = 5.98 * 10^{-4}$



Fabrication: CO_2 Heating/Humidifying Tank and Housing



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Testing: Testing Plan Matrices

Carbon Dioxide Humidifying Tank

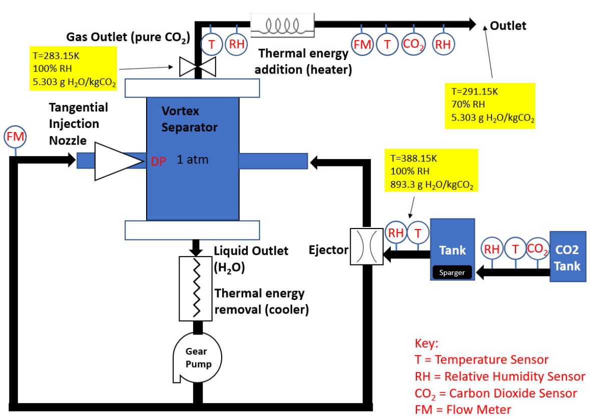
	CO_2 Flow Rate (m^3/sec)	Water in Tank (kg)	Temp. of Water in Tank (K)
Run 1	8.1935E-06	3.88	313.15
Run 2	1.22902E-05	4.44	313.15
Run 3	1.6387E-05	5.55	313.15
Run 4	1.6387E-05	4.44	343.15
Run 5	3.2774E-05	5.55	343.15
Run 6	4.9161E-05	6.67	343.15
Run 7	1.6387E-05	5.55	363.15
Run 8	3.2774E-05	6.67	363.15
Run 9	4.9161E-05	7.78	363.15
Run 10	3.2774E-05	6.67	388.15
Run 11	4.09675E-05	7.78	388.15
Run 12	4.9161E-05	8.33	388.15

	Center Line of Sparger to Water Surface (m)	Total Water Pressure in Box (kPa)	Total Volume of Tank (m^3)
Run 1	0.022860046	7.37765	0.000033
Run 2	0.035560071	7.37765	0.000033
Run 3	0.060960122	7.37765	0.000033
Run 4	0.035560071	31.23435	0.000168
Run 5	0.060960122	31.23435	0.000168
Run 6	0.086360173	31.23435	0.000168
Run 7	0.060960122	70.1911	0.000399
Run 8	0.086360173	70.1911	0.000399
Run 9	0.111760224	70.1911	0.000399
Run 10	0.086360173	169.2033	0.000943
Run 11	0.111760224	169.2033	0.000943
Run 12	0.124460249	169.2033	0.000943

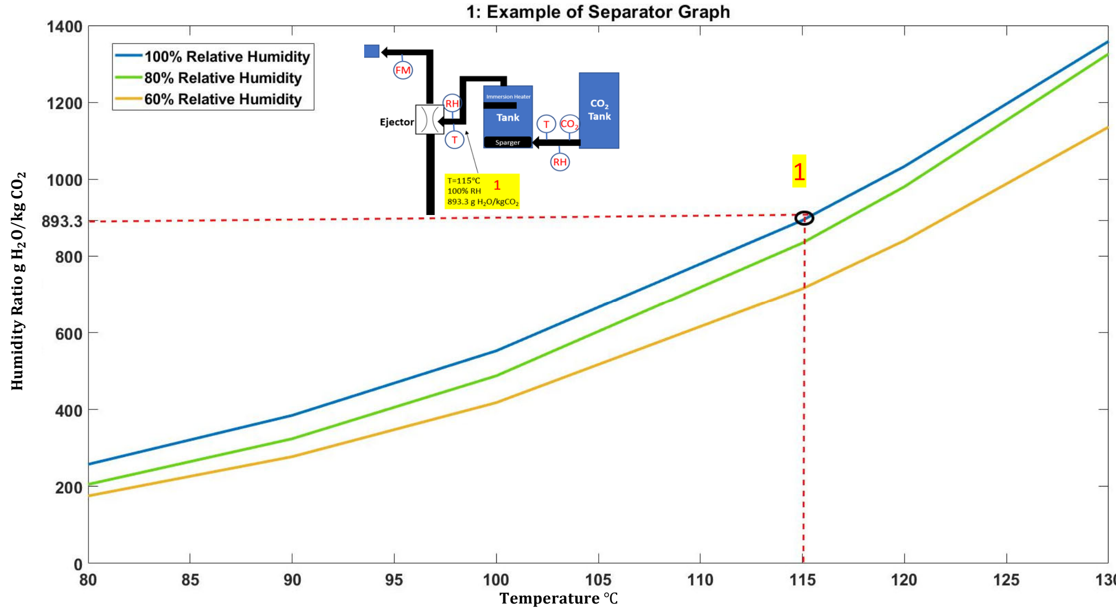
	Humidity at Outlet (g H20/kg CO_2)	Temp. of CO_2 at Outlet (K)
Run 1	32.98	
Run 2	32.98	
Run 3	32.98	
Run 4	164.7	
Run 5	164.7	
Run 6	164.7	
Run 7	384.9	
Run 8	384.9	
Run 9	384.9	
Run 10	893.3	
Run 11	893.3	
Run 12	893.3	

Vortex Separator

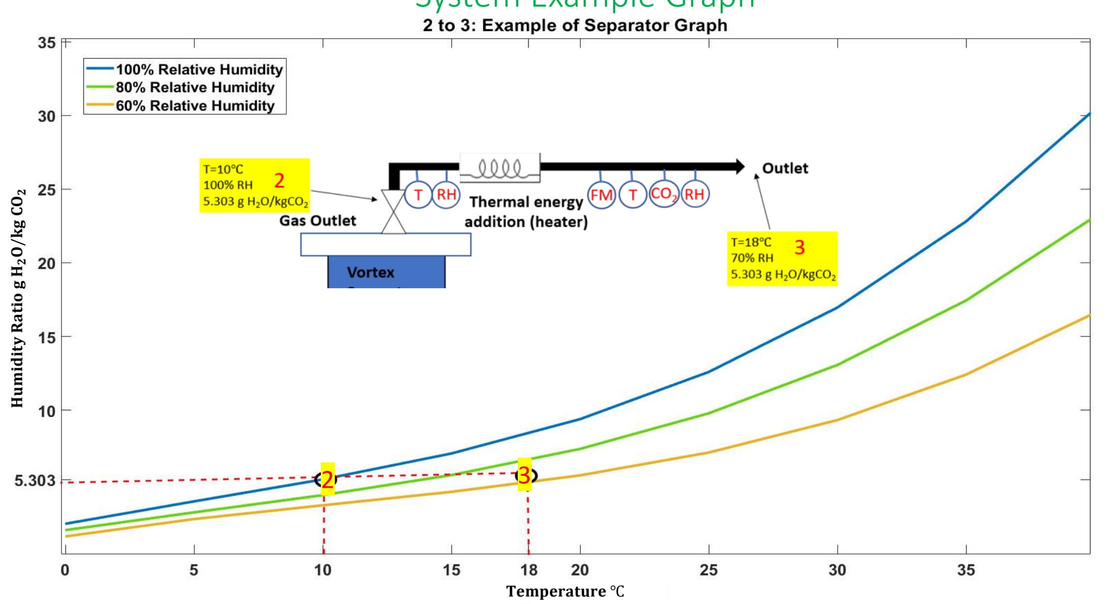
	Water Temperature (K)	CO_2 Temperature (K)	Water Flow Rate (m^3/sec)
Run 1			
Run 2			
Run 3			
Run 4			
Run 5			
Run 6			
Run 7			
Run 8			
Run 9			
Run 10			



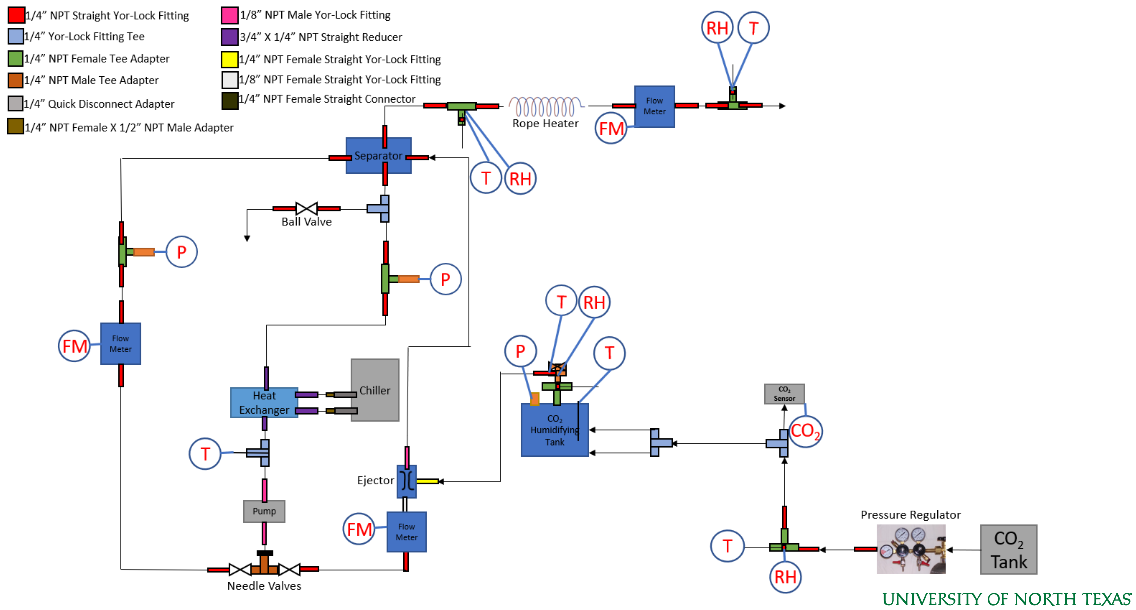
Concept of Operations: Use of Temperature vs Humidity Ratio in System Example Graph



Concept of Operations: Use of Temperature vs Humidity Ratio in System Example Graph



Instrumentation



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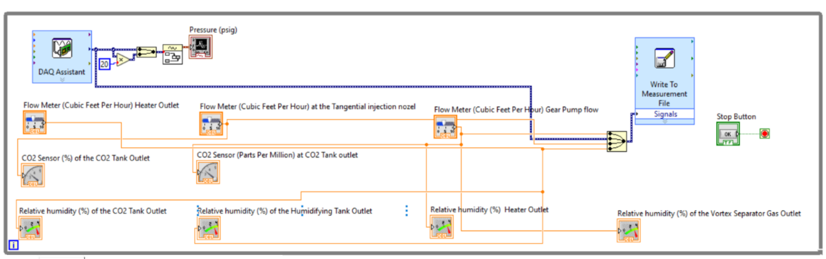
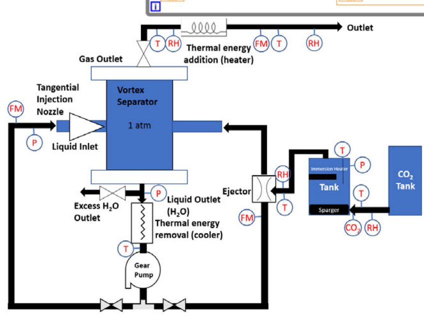
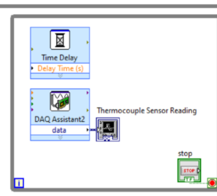
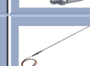
Data Acquisition







Label	Instrumentation	Image	Measurement
RH	Digital Humidity Sensor by Sensirion		Relative Humidity
CO_2	Multi Gas Sampling Data Logger by CO_2meter.com		Carbon Dioxide Level
P	Pressure Transducers by Omega		Pressure
T	Thermocouple Probes by Omega		Temperature
FM	Flowmeter by McMaster Carr		Flow Rate

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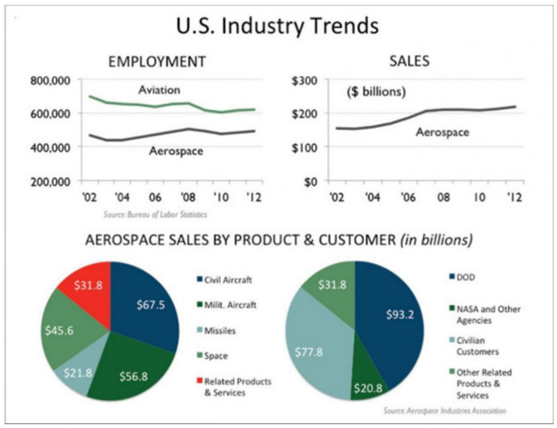
Marketing

- The target market for the revitalization system is a very niche group due to the function of the system, but the device can be applied to multiple industries through differentiated applications.
- The market for a gravity independent gas/liquid separator for CO_2 can be used in the Space Industry and can be applied to numerous systems such as space shuttles, rockets, and other space exploration vehicles.



[3]

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Safety

- All aspects of the life cycle will be considered, including design decisions that affect training, operations resource management, human factors, safety, habitability and environment, and maintainability and supportability.

Risk	Consequence	Mitigation Approach
Pump failure	System flow and gas liquid separation will stall	Have a breaker to shut the whole system down.
Piping leakage (Pressure system failure)	Pressure drop in system	Leak test before charging the system.
Uncontrolled heating	Parts start melting, tube expansion, water boiling/water vapor in the system.	At a certain temperature, the system will shut off.
Chiller failure	H20 vapor does not condense into liquid	Have a breaker to shut the whole system down.
Uncontrolled cooling	Chiller is too cold (frostbite)	Insulate cold refrigerant lines.
Excessive pump speed / Insufficient pump speed	Nonoptimal flow rate/pressure	Relief valve / Breaker turns off system.
Excessive pressure	Structural failure	Hydrostatic test before testing full system.
Gas getting mixed with liquid H2O outlet (carry-under)	Separation efficiency is affected	Implementation of baffle plate and design of nozzles.
Water mixing with the gas outlet (carry-over)	Separation efficiency is affected	Constantly monitor water level through clear separator wall and drain as needed.
Noncompatible material selection	Material is corrosive or wears out fast.	Choosing compatible materials
CO2 Leakage	Risk of Hypercapnia (or mild effects)	Leak test before charging the system.
Liquid outlet buildup of fluid	Dangerous increase in pressure	Two valves will be adjusted to control flow rate to nozzles. Breaker system automatically shuts down the whole system in case of high pressure.
Gas outlet buildup of fluid	Dangerous increase in pressure	Valve will be adjusted to control flow rate. Breaker system automatically shuts down the whole system in case of high pressure.

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We Acknowledge the Support of

Dr. Bostanci and Dr. Kurwitz for being mentors to the X-Hab Team

Mr. Bobby Grimes, graduate student Sania Shaik, and undergraduate student Charlie Wang for their hard work and dedication to the X-Hab project.

X-Hab 2020 Academic Innovation Challenge

NASA Advanced Exploration Systems (AES) Division Life Support Systems

NASA Ames Research Center

Dr. Darrel Jan & Ms. Grace Belancik

References & Photo Sources

1. https://en.wikipedia.org/wiki/Hypercapnia#/media/File:Main_symptoms_of_carbon_dioxide_toxicity.svg
2. Giraldo Akvarez, Geoff Degraff, Micheal J. Swickrath, Grace Belancik. Jeffery J. Sweterlisch. "Continued Development of a Liquid Amine Carbon Dioxide Removal System for a Microgravity Application." (2019)
3. Holloway, A., & McCallum, E. (2018, July 3). About the Author. Retrieved December 2, 2019, from https://www.tradeandindustrydev.com/industry/aerospace-defense/aerospace-and- aviation-finding-opportunities-amid-7846.

Questions?

NASA Exploration Systems & Habitation (X-Hab)
Academic Innovation Challenge 2020

Microgravity Gas/Liquid Separator for the CO_2 Revitalization System

The University of North Texas

X-Hab Team: Alyssa Sarvadi, Hannah Whitehead, Fernando Primo, Balmore Giron, Nicholas Frease
Faculty Mentors: Dr. Huseyin Bostanci (PI),
Dr. Cable Kurwitz (Collaborator, Texas A&M University)

Outreach Report

May 2020

The X-Hab 2020 Academic Innovation Challenge has selected eleven senior design teams from colleges across the US to demonstrate working prototypes for exploration systems and habitation. UNT has been tasked with the creation of a microgravity gas-liquid separator for an air revitalization system.

This report briefly outlines the X-Hab Team's outreach efforts. Although initial plans for outreach activities involved presentations at area high schools and hosting high school teachers in the lab for a demonstration, due to the COVID-19 pandemic, UNT labs closed and fabrication and testing stages of the project were halted. Such circumstances also prevented team to do the original outreach activities. Instead, team decided to reach out to four high schools in the North Texas area and do a live presentation through Zoom video conferencing on April 20th, 2020.
The goal of this presentation was to inspire high school students and to spark their interest in air revitalization and NASA space technology in general.

The team contacted the administrators or science teachers of the following high schools, sent a flier, and invited them to the presentation:

- Emmett J. Conrad High School in Dallas, TX (Temesghen Asmermom, Principal)
- Texas Academy of Math and Science (TAMS) in Denton, TX (Russ Stuckel, Assistant Dean)
- Newman Smith High School in Carrollton, TX (Jan Elmore, Science Teacher)
- Boswell High School in Boswell, TX (Ronny Armstrong, Computer Science Teacher)

Live Zoom presentation had up to 28 participants, including X-Hab Team and Dr. Darrel Jan and two other NASA ARC scientists. Boswell High School students were not allowed to use Zoom. However, Mr. Armstrong showed his class the recorded presentation afterwards, and 28 participants attended the presentation including 25 students from Boswell High School.

Additionally, the X-Hab team made a final presentation during UNT Senior Design Day on April 27th, 2020. This presentation had nearly 60 participants including Industrial Advisory Board members, faculty, as well as other student teams and their family and friends.

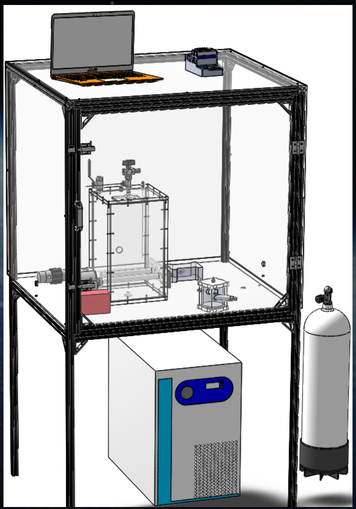
A copy of the flier and the outreach presentation slides are included in the appendix.

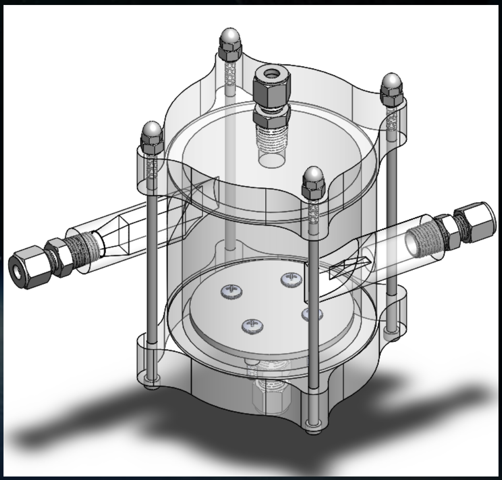
University of North Texas Students on their Partnership With NASA:

Breathing in Space

Undergrad students talk about building an Air Revitalization Subsystem for NASA.

Have you ever wondered how life is supported in space? What technology we will need to potentially inhabit other planets? Join the UNT Senior Design team to learn about space technology and how they are working with NASA to remove CO_2 to maintain breathable air for astronauts! With an open Q&A.





Join us on Zoom: https://unt.zoom.us/j/124496256

Monday, April 20th, 2020

from 1:00 PM to 2:00 PM EST

Air Revitalization for NASA

Alyssa Sarvadi, Hannah Whitehead, Nicholas Frease, Balmore Giron, Fernando Primo

What is This Project About?

- The X-Hab 2020 Academic Innovation Challenge has selected eleven senior design teams from colleges across the US to demonstrate working prototypes for exploration systems and habitation
- UNT has been working on the creation of a gas-liquid separator for an air revitalization system.
- Air revitalization technology is used to support spaceflight by removing CO_2 from enclosed systems to maintain breathable air.

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What is This Project About?

[1]

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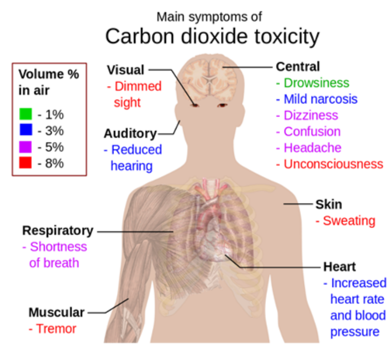
Objectives of Project

- **Objectives of the Project:** Design, build, and test a prototype gravity independent gas-liquid separator for removing H_2O from CO_2
- As NASA ventures to the Moon and Mars, resupply of clean oxygen to the crew is crucial in sustaining their lives in space.
- Humans exhale a mixture of CO_2 and water vapor.
- Since space is a microgravity environment and the cabin of the spacecraft is closed to the external space, CO_2 can build up in the cabin, causing hypercapnia to affect the crew.
- The UNT X-Hab team is designing a multiphase vortex separator system to separate CO_2 gas and water vapor after they have been extracted from the cabin air via NASA's existing air revitalization system.



[2]

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Motivation for Project

- **Motivation:** Separating CO_2 from enclosed environments in space application is extremely important. If CO_2 levels in the cabin exceed 5.2 mmHg per 180 days, death by hypercapnia can occur. Even before that, the symptoms of hypercapnia greatly inhibit an astronaut's performance both physically and mentally.
- This value for CO_2 grows smaller as the days in space increase (important as we venture out to other planets)
- Hypercapnia can cause shallow breathing, disorientation, cognitive deficiencies, reduced vision, and headaches, leading to decreased performance amongst the crew and eventual death.
- The Vortex Phase Separator (VPS) system's performance will be compared to NASA guidelines, ensuring safe amounts of CO_2 will be removed if the prototype were to be scaled and implemented into spacecraft.
- On the ISS, NASA currently uses granules of a synthetic rock called zeolite as a solid sorbent in their CO_2 removal system. These require high power usage and experience long-term reliability issues.

Zeolite Granules

[3]

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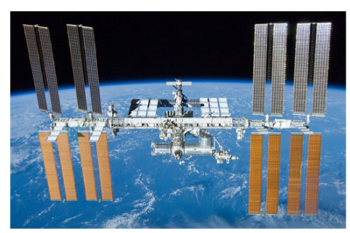
Background on Air Revitalization

- The ISS's current air revitalization system is founded upon the systems found in submarines
  - System uses liquid amine to absorb CO_2 from the cabin air, where it is then ejected into the ocean
  - Amine absorbs CO_2 gas when it is cold, and releases CO_2 as it is heated
- Two key design challenges are ***gravity independence*** and ***recyclability***
  - Submarine air revitalization systems cannot function in microgravity environments, so gravity needs to be simulated
  - Additionally, submarine systems do not filter H_2O out of the system
  - Currently, about 93% of the ISS's wastewater is recycled
  - In best case scenarios, only 50% of waste CO_2 is recycled into oxygen



International Space Station

[4]

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Background on Vortex Separators: Why are we using this technology?

- The Vortex Phase Separator (VPS) in our system is the driving force for separating H_2O from a CO_2 stream
- Innovative vortex separator technology will allow for **high throughput flow** while utilizing maximum efficiency of CO_2 removal and using less energy than gravity dependent tanks used for gas-liquid separation.
- **High throughput flow** means higher amounts of CO_2 rich air is pulled into the system and separated with the same energy consumption
- NASA currently uses a solid sorbent system to aid in CO_2 removal: they have not used VPS technology before
- VPS Technology could potentially offer an alternative air revitalization technology for crewed NASA space exploration and habitat missions.

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Approach for the Project

- **Approach for the project:** Use the theoretical analysis and design a system which allows a vortex phase separator to artificially replicate gravitational force to achieve H_2O removal from a stream of CO_2 gas.
- On Earth, phase separator systems use gravity to aid in gas/liquid separation
  - Most gasses are less dense than liquid, so they naturally separate over time
- When used in extraterrestrial applications, phase separators must artificially replicate gravitational force to achieve separation.
- To do this, the VPS uses centrifugal buoyancy force to separate gas and liquid.

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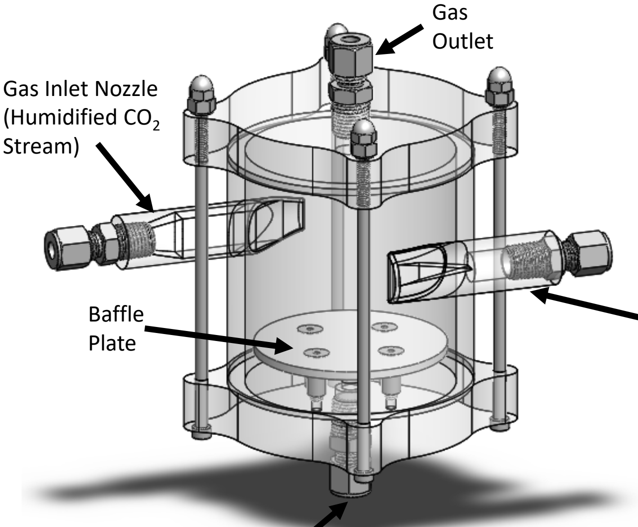
Approach for the Project



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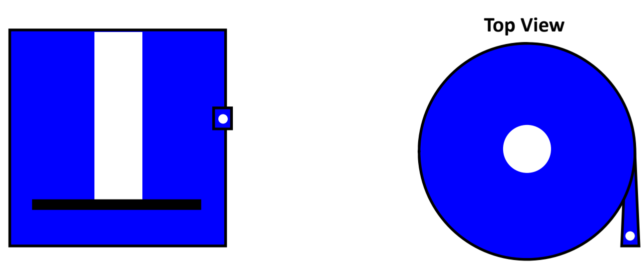
Approach for the Project

How CO_2 bubbles travel in the vortex separator



- As a thin layer of water rotates around the inside of a hollow cylinder, a stream of humidified CO2 is introduced via tangential injection.
- Using specially designed nozzles, the gas stream breaks into minuscule bubbles upon contact with the water layer.
- These bubbles then float to the center of the cylinder due to the density difference, creating a column of gas in the center of the vortex.

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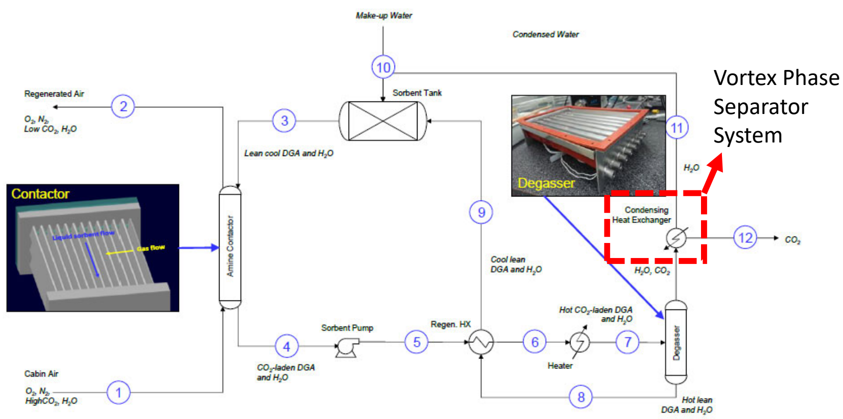
Overview of NASA's System



Giraldo Akvarez, Geoff Degraff, Micheal J. Swickrath, Grace Belancik. Jeffery J. Sweterlisch. "Continued Development of a Liquid Amine Carbon Dioxide Removal System for a Microgravity Application." (2019)

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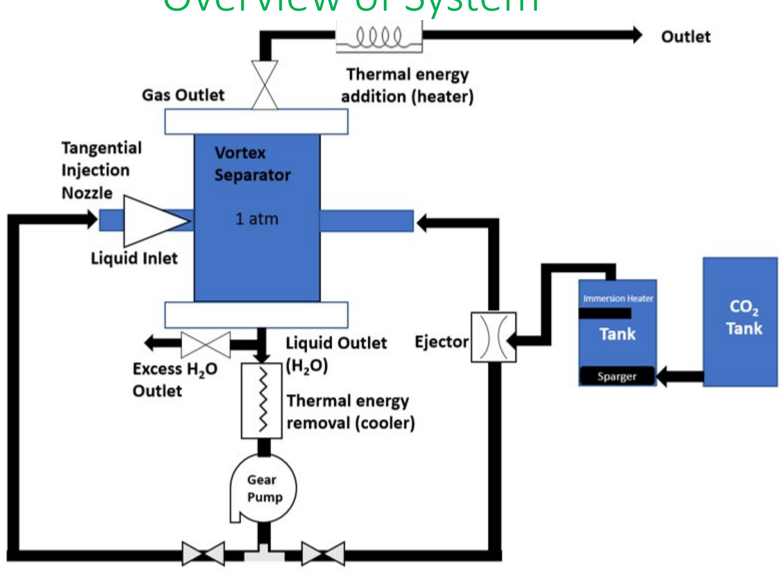
Overview of System



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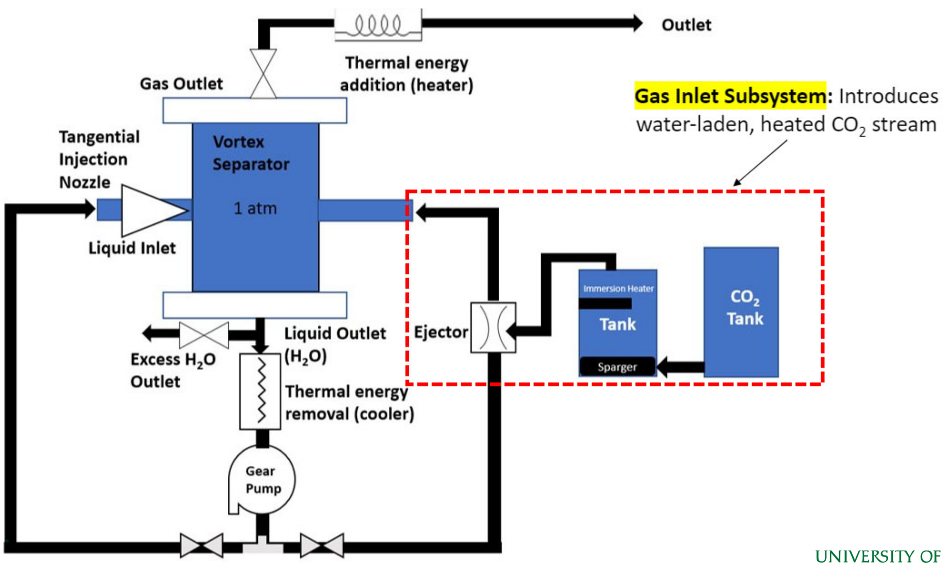
Overview of system: Gas Inlet Subsystem



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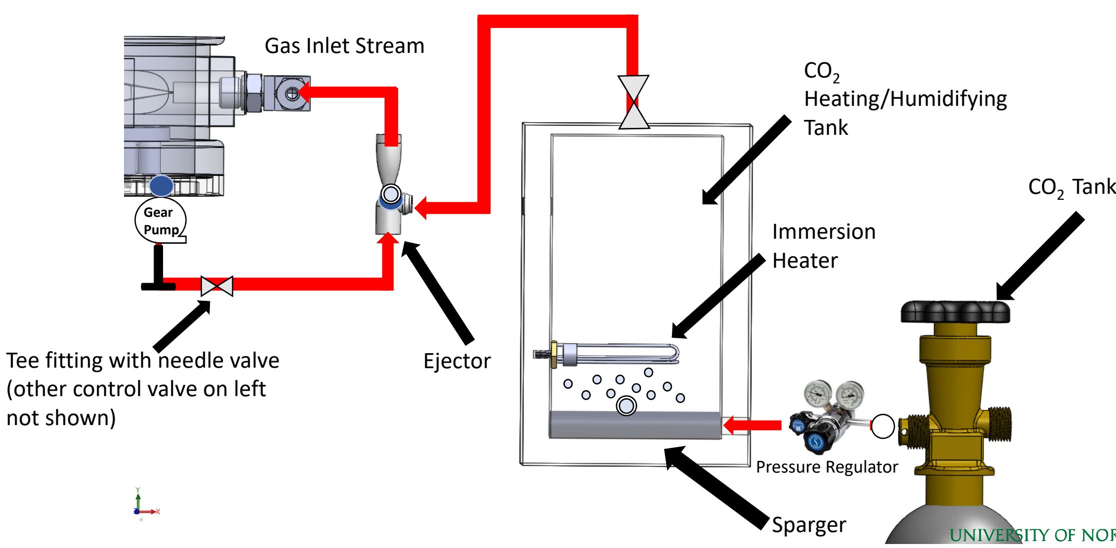
3D Model Gas Inlet Subsystem



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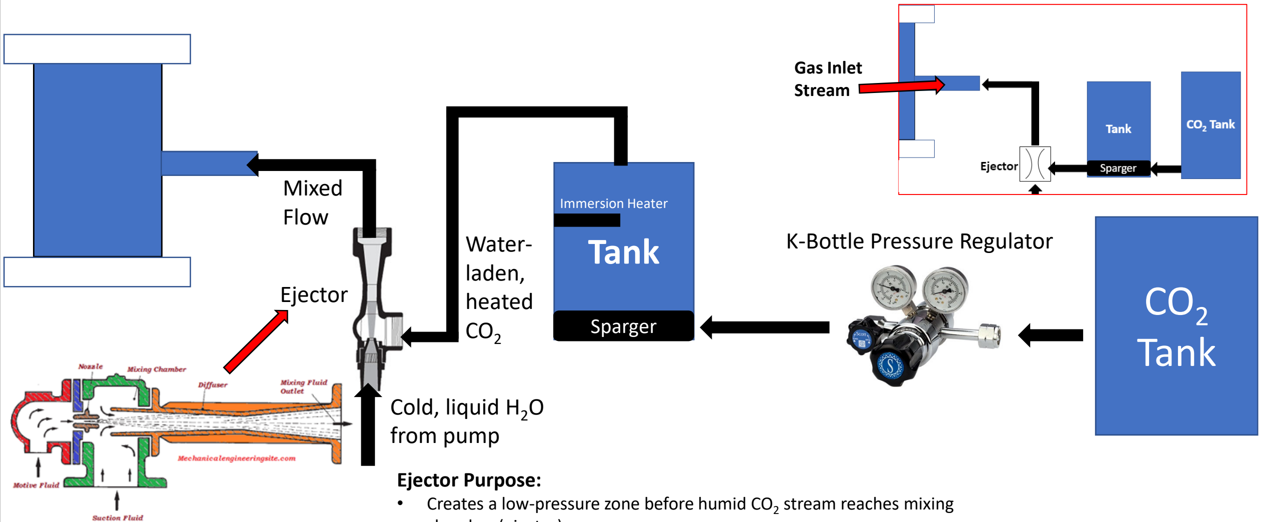
Gas Inlet Instrumentation



Ejector Purpose:

- Creates a low-pressure zone before humid CO_2 stream reaches mixing chamber (ejector)
- More mixing time occurs due to this; flow through pipe allows bubbles to be in contact with cold liquid H_20 longer.
- This is good because it allows the separator to more easily separate the liquid water from the CO_2

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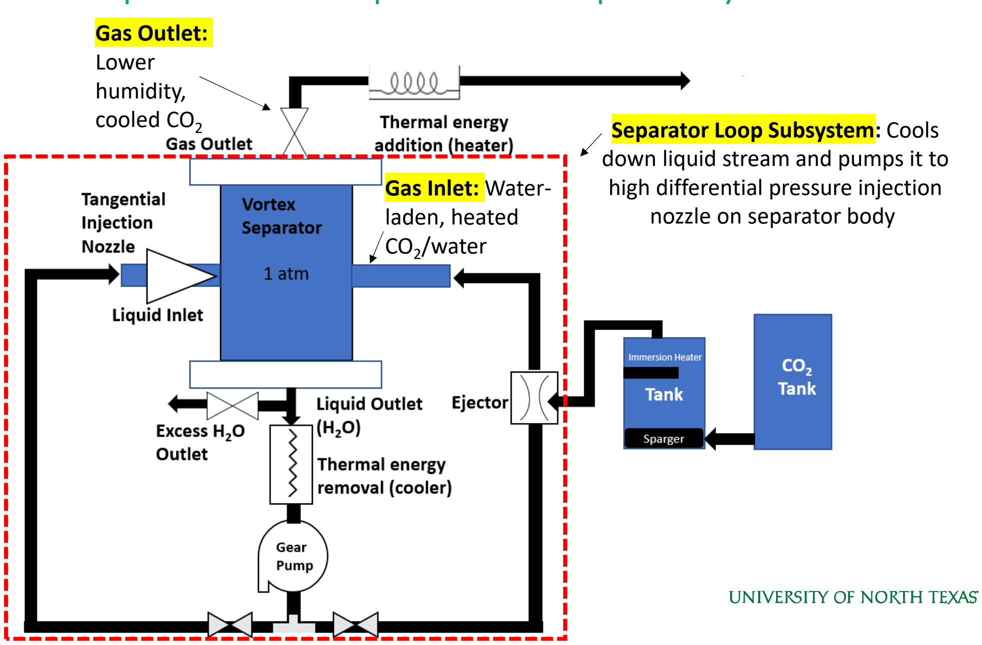
Concept of Operations: Separator Loop Subsystem



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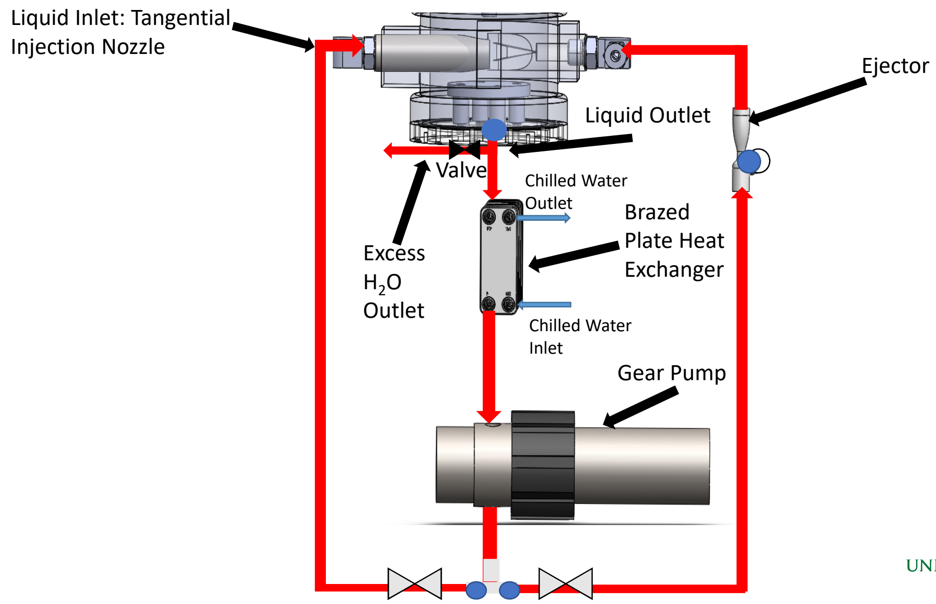
3D Model Separator Loop Subsystem



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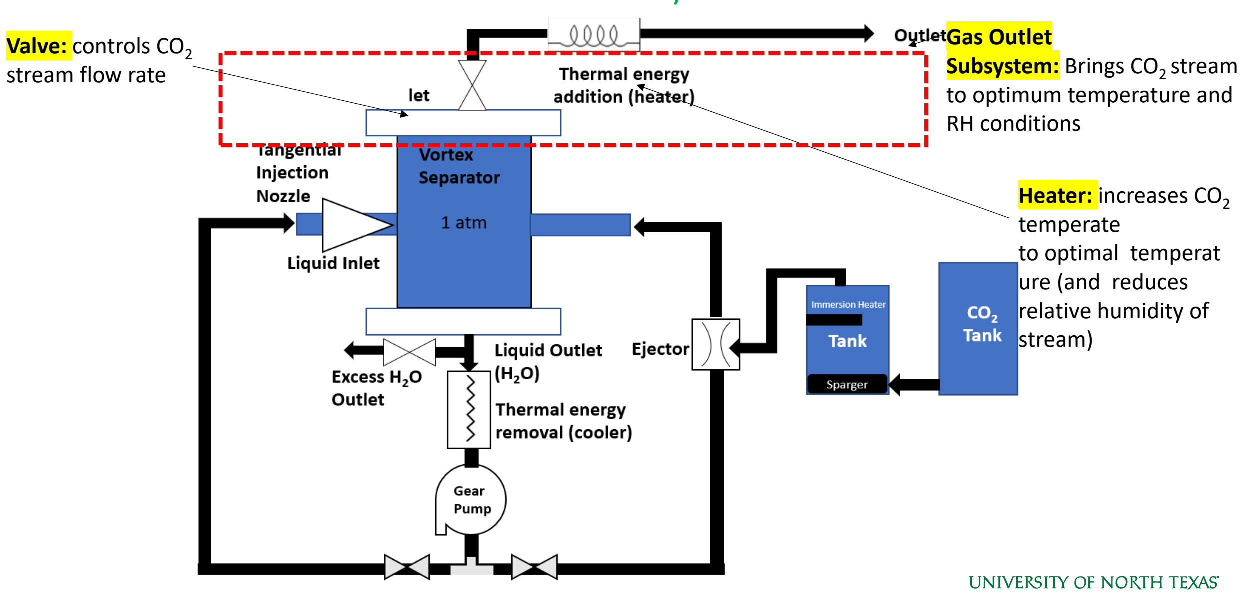
Gas Outlet Subsystem



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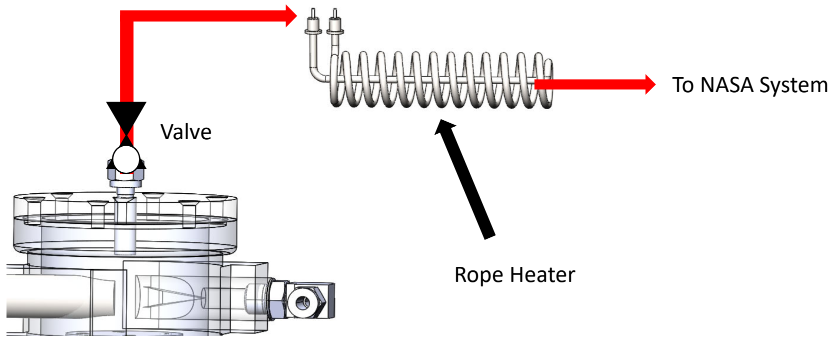
3D Model Gas Outlet Subsystem



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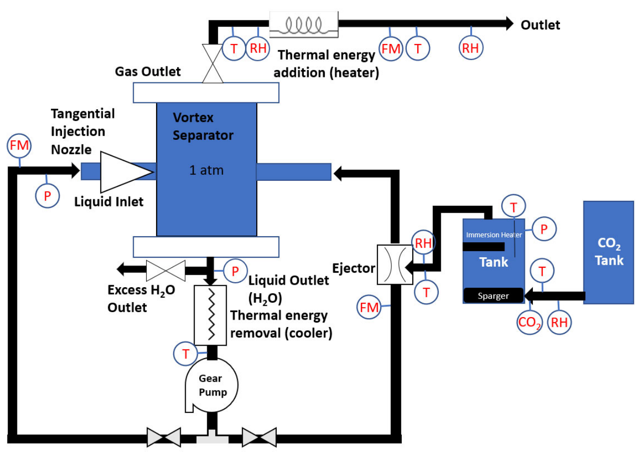
Full System Instrumentation



Label	Instrumentation	Image	Measurement
RH	Digital Humidity Sensor by Sensirion		**Relative Humidity**
CO_2	Multi Gas Sampling Data Logger by CO_2meter.com		**Carbon Dioxide Level**
P	Pressure Transducers by Omega		**Pressure**
T	Thermocouple Probes by Omega		**Temperature**
FM	Flowmeter by McMaster Carr		**Flow Rate**

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Vortex Separator: 3D Printed Model

- Older version of VPS, 3-D printed using ABS Plastic.
- Model to scale.
- Used to see how pieces would fit together/if they are machinable.
- Manufacturing of final separator was halted due to the COVID-19 pandemic.

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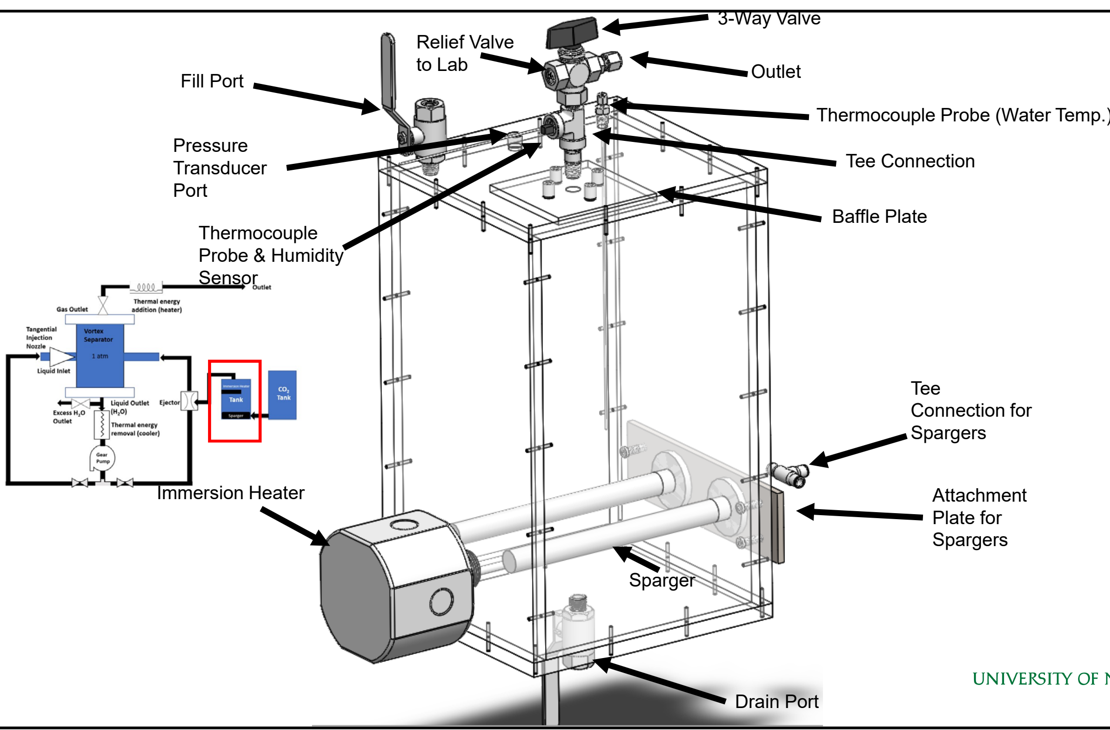

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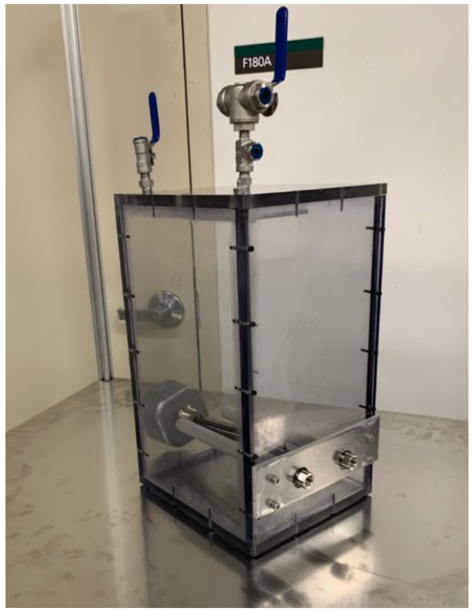
Final Design: CO_2 Heating/Humidifying Tank



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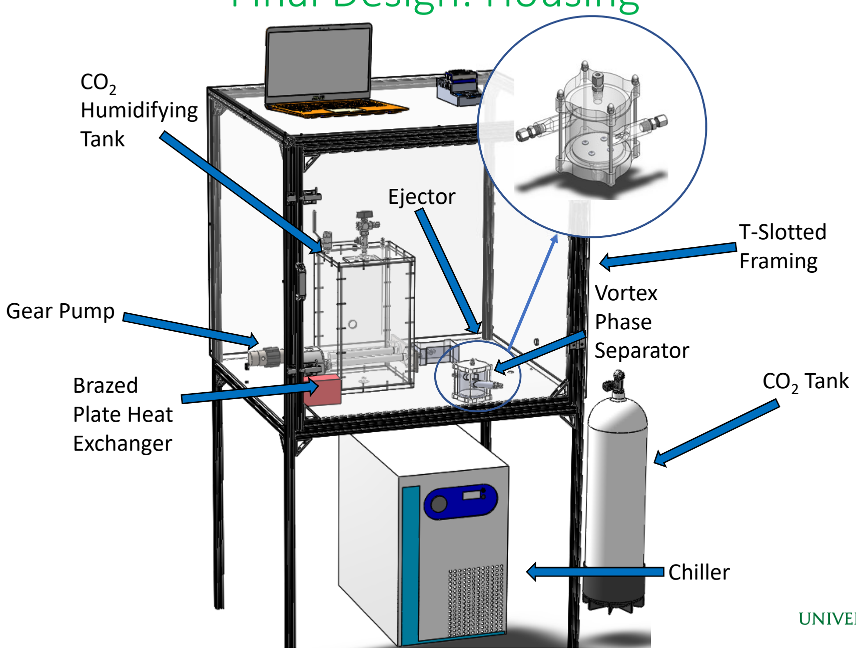
Final Design: Housing



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Final Design: Housing (Without Windows)

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NASA Ames Research Center

Dr. Darrel Jan, Ms. Grace Belancik

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References & Photo Sources

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Questions?

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