Vacuum Moisture Swing

ELI WOOLRIDGE
JUSTIN PATTERSON
RANDY BRIERLEY
BRANDEN WELKER

Project Description

- The purpose of our project is to create a **Direct Air Capture (DAC) Reactor** that uses **Vacuum Moisture Swing** as it's CO_2 collection process.
- This will allow us to pull air (~420 ppm CO_2) through our reactor, react it with the **sorbents to separate the CO_2**, and store that CO_2 product in a large canister.
- This will be comparable to **Point Source Carbon Capture** technology is already in use that collects emissions coming **directly from factories** and will likely be scaled much further with the addition of DAC Reactors.
- This process could be an important technology for **lowering global emissions to reverse climate change.** CO2 emission is the largest contributor to global warming, in addition to causing ocean acidification.

Stakeholders

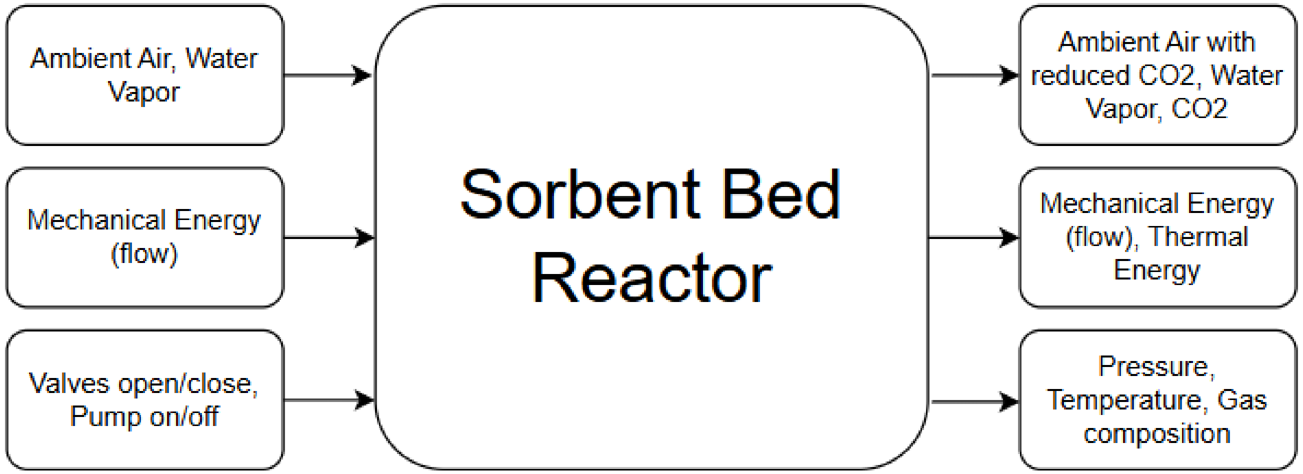
Industry Sponsor: Salt River Project (SRP)

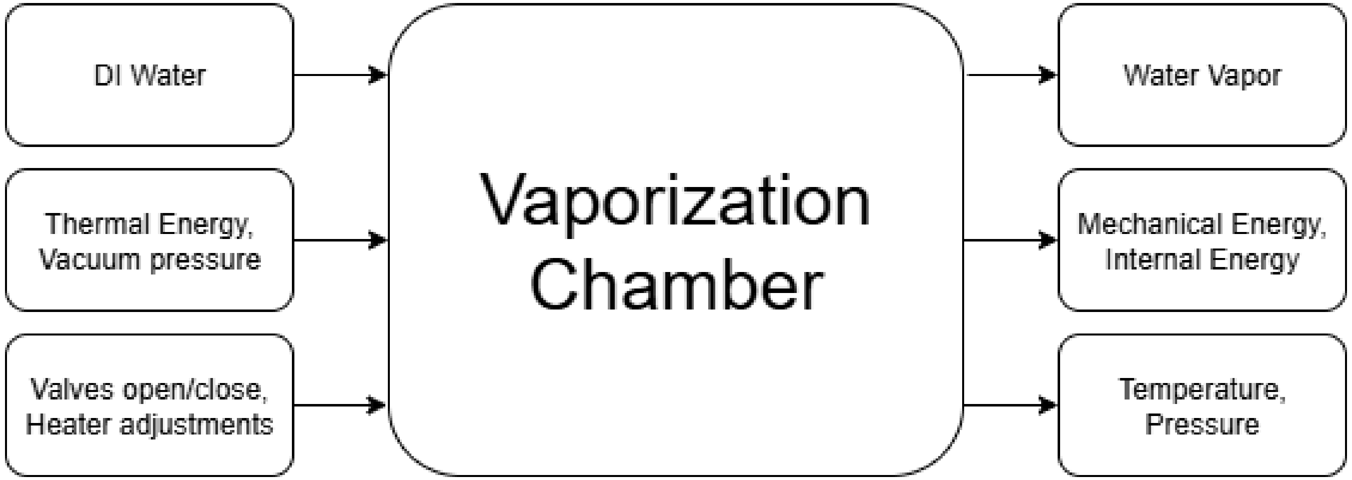
Advisor: Professor Jennifer Wade

Mentor: PhD Candidate Stephano Sinyangwe

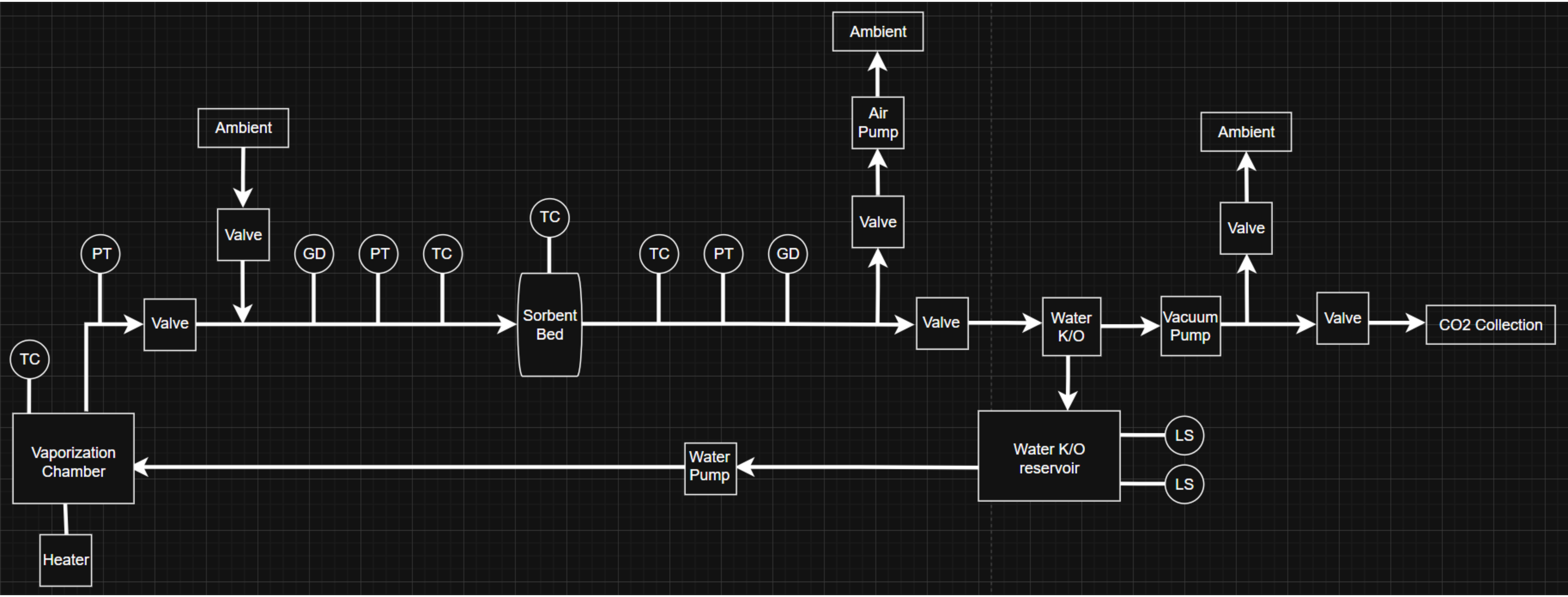
Other Stakeholders: NAU Climate Lab

Black Box Models



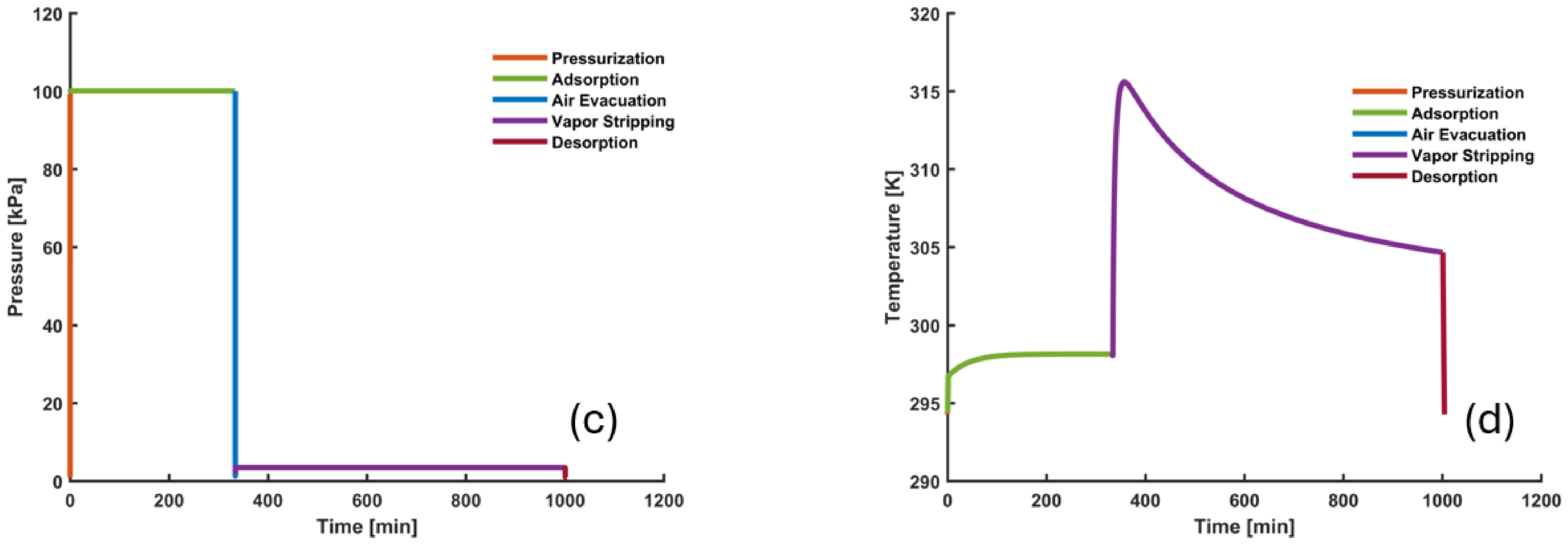


Decomposition:

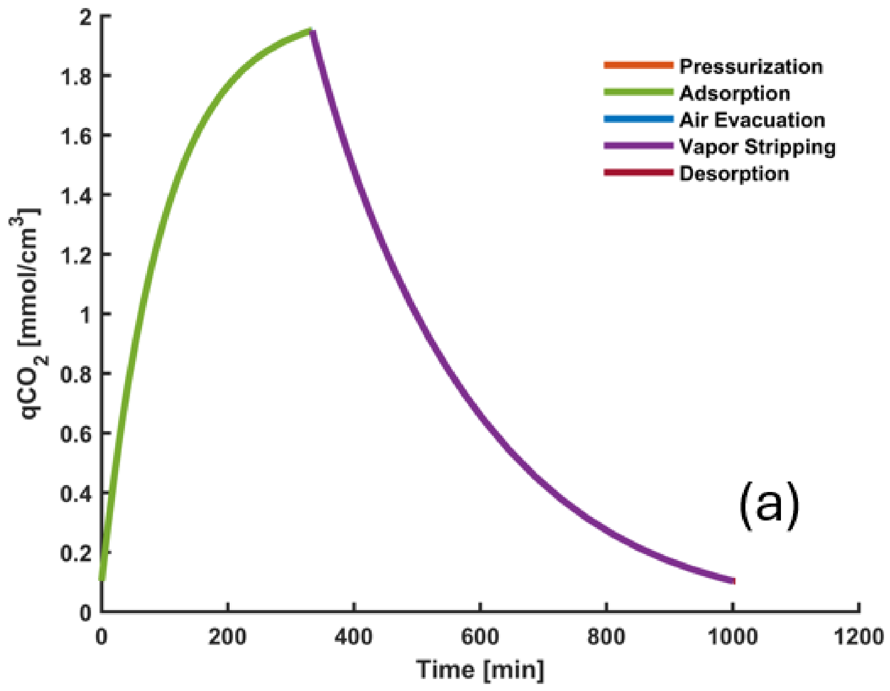


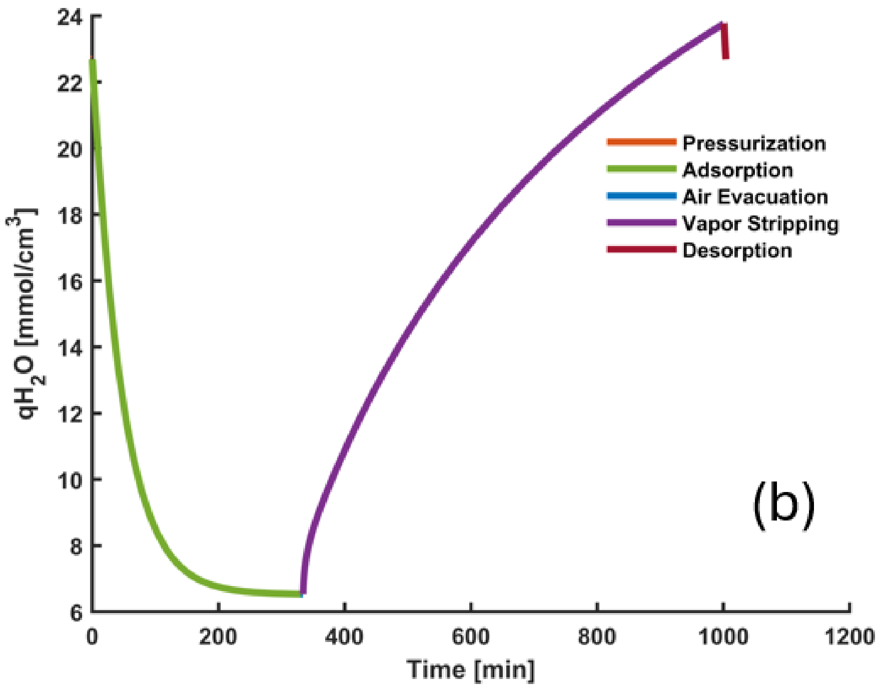
- How it informed: provided clear reference for discussions, helped ensure complete view

Pressure and Temperature Through Each Phase



Concentration Through Each Phase



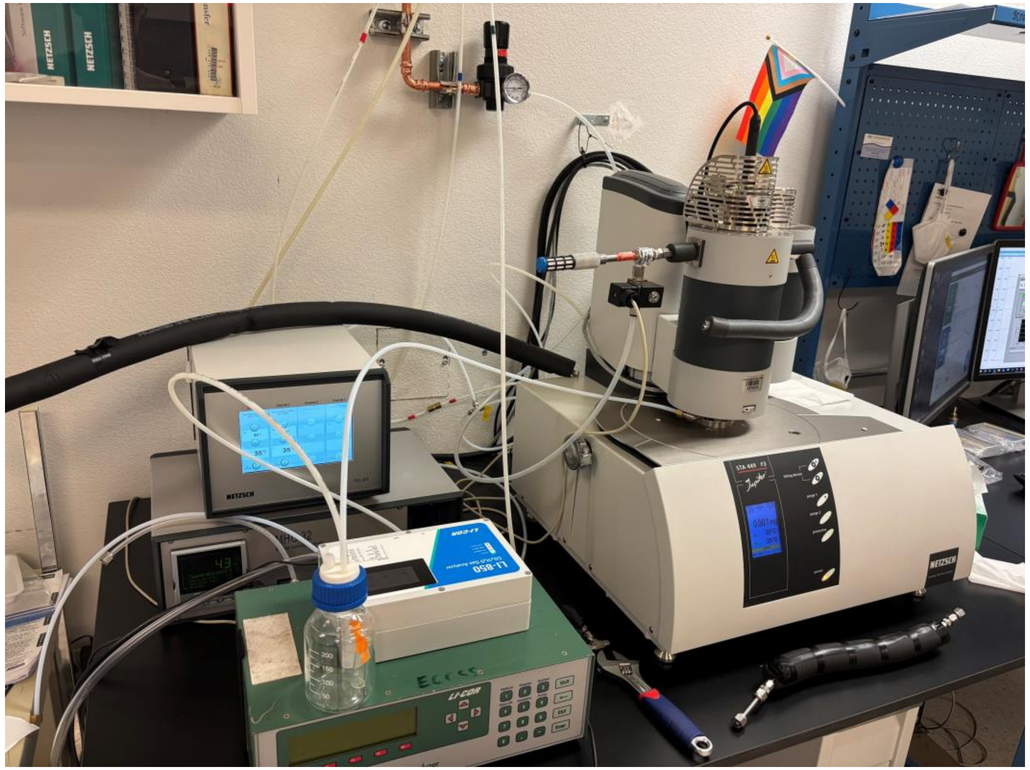


Concept Generation and Selection Process

- Subsystems: Valve Type, Vapor CO2 Separation, Pipe Diameter, Control Architecture, Sorbent Mesh, Air Filters, Vacuum Pump, Sorbent Structure
- Most subsystems In our design are independent of each other
- We decided it would be most effective to select the optimal choice from individual subsystems as opposed to selecting from full concept variants
- Each team member was assigned 2-3 subsystems to research and perform calculations for
- As a team this data was used to select the optimal design for each subsystem

Sorbent Size Calculation

	Diameter (mm)	Volume (mm^3)	Density (kg/m^3)
Pre-Absorption (Dry)	0.568	0.1105	1227
Post-Absorption (Wet)	0.596	0.1212	1159



The same machine that Post doctorate researcher Golnaz has been using to test sorbent capacities was used to control an exact 95% humidity to simulate real reactor conditions

A 9.68% volume increase was calculated with a 5.87% decrease in density. This is due to the density of water vapor/liquid water being lower than the dry density of the sorbents.

$$V = \frac{4}{3}\pi r^3$$

Subsystem: Pipe Diameter

- To save on costs and manufacturing our advisor requested we use standard KF vacuum tubing
  - Withstand Vacuum pressures less then 1 Pascal
  - Inner Diameters: 16mm, 25mm, 40mm, 50mm
  - Stainless steel was requested to avoid corrosion
  - Many lengths and fitting available
- Influencing Factors
  - Head loss per unit length at each diameter
  - Flow rate for practical velocity
  - Average Sorbent Diameter: 0.568mm
  - Expected Tolerance of 3D printer: 0.1 mm +.05

Pipe Calcs And Evaluation

- Darcy-Weisbach equation for major head loss: $h_{L,major} = f\frac{L}{D}\frac{V^2}{2g}$
  - Friction factor, f, based on Reynolds number: $Re = \frac{\rho V d}{\mu}$
  - For laminar Flow: $f = 64/Re$

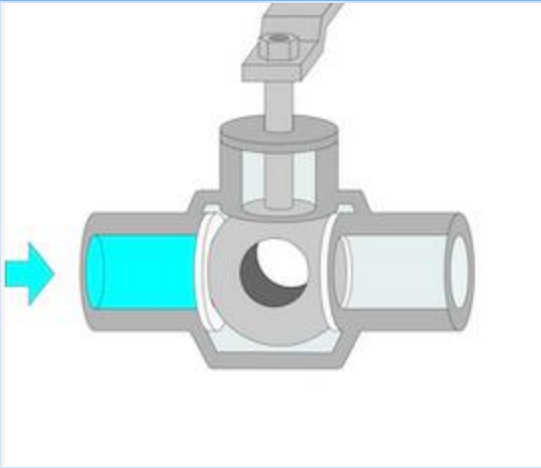
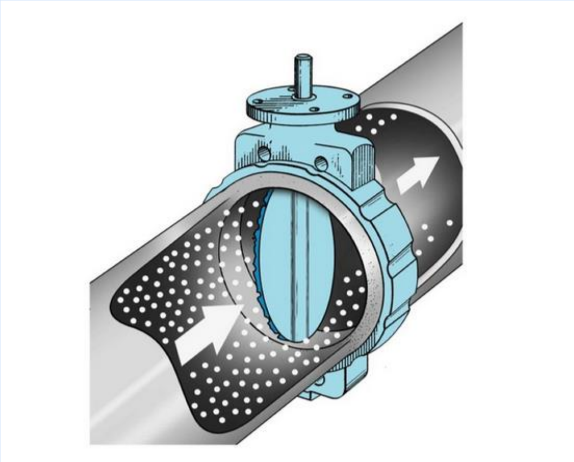
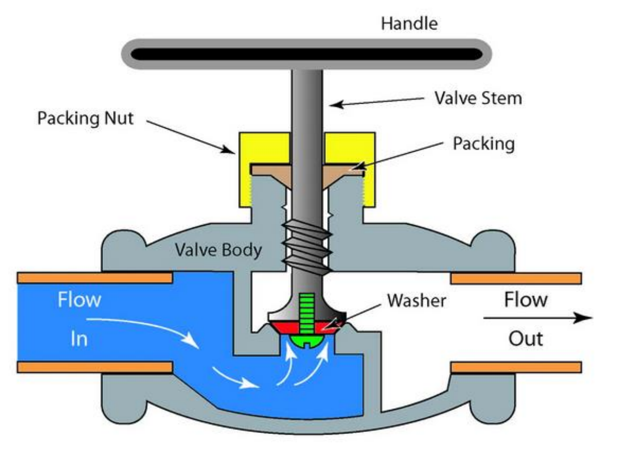
Dia (mm)	16	25	40	50
h/L (Pa/m)	0.622	0.255	0.099	0.064
Q (cm^3/s)	151	368	942	1472.6

- Assuming practical velocity of 0.75m/s
- Vapor properties for 2kPa, 24°C
- To Find Flowrate: $Q = A_c V$

Selected Diameter: 40mm (KF40)

Minimizes major head loss without requiring excessive pumping capabilities, keeps pipe size reasonably higher than sorbent size and printer tolerances, slightly cheaper then KF50

Subsystem: Valve Type

Ball Valve	Butterfly Valve	Globe Valve
		
• Inexpensive • Reliable • Low pressure drop • Limited throttling	• Inexpensive • Small • Low pressure drop • Excellent throttling • Poor sealing	• Excellent throttling • Excellent sealing • High pressure drop • Large size • Usually pneumatically actuated

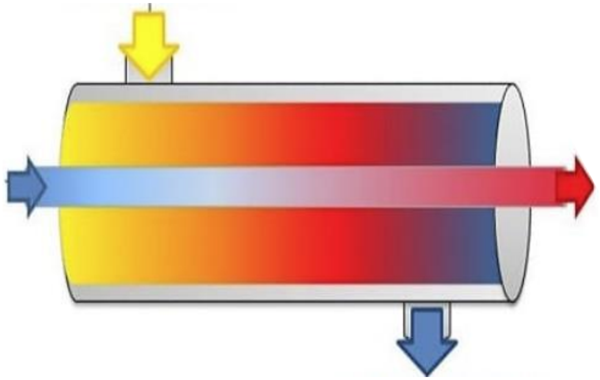
Valve type evaluation

Engineering Requirements	2a. Minimize pressure drop	2b. Keep air velocity within 1m/s	3a. Vacuum pressure below 3 kpa	6b. Incorporate control logic	Customer Requirement: Low Cost	
Ball Valve	+	0	+	+	+	4
Butterfly Valve	+	+	-	+	+	3
Globe Valve	-	+	+	0	-	0

Subsystem: Vapor and CO2 Separation

- Water must be separated from CO2 after leaving the sorbent bed during desorption
  - Pressurization: increased pressure > saturation temp above operating temp
    - Vapor would have to be pulled through pump which could be very destructive
  - Adsorption: additional adsorption process after leaving primary sorbent bed
    - Would require additional phases and components to then remove this water
  - Cooling: decreased temperature > saturation pressure below system pressure
    - Requires heat exchanger
    - Liquids and gasses are significantly easier to separate then a gas mixture

Condenser Calcs and Evaluation



- Considerations for cooling with condenser
  - If vapor is condensed into liquid some C02 may be trapped within and would require a freeze thaw cycle to remove
  - H2O does not have a liquid phase below 0.6kPa and gas would directly turn into ice through deposition
  - Increased contact between fluid and cooled surface would increase heat transfer but would also increase pressure drop
- Refrigeration Requirements
  - Using the first law of thermodynamics we can estimate that 17 Watts of refrigeration will be required to saturate water

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

Subsystem: Control architecture

Comparison	OPC UA	PC (MATLAB)	MODBUS & PC
Advantages	Works on nearly all equipment Complex data and metadata Secure Scalable	Simplified architecture Low cost Quick to prototype	Simplicity Deterministic Low cost Easy to debug
Disadvantages	Complex Higher processor demand Learning curve	Non-deterministic Not scalable for many I/O Not physically robust	Basic data (register, coil, discrete) Scalability Security Not as universal

Considerations:

- Multiple sensors, multiple pumps, multiple valves – many I/Os
- Could be exposed to water
- Need stability for accurate measurements
- Client wants Matlab for lab integration
- Skill / time constraints: new topics, short timeframe to implement

- Choice: Modbus + PC

Subsystem: Sorbent Mesh

- Our smallest measured particle size has a diameter of .35mm
- To be safe, we want our mesh to be near .2mm in case for any other smaller particles
- This corresponds to a mesh size of 70 (.21mm)

Centering Ring

Subsystem: Ambient Air and Pump Filters

The inlet ambient air filtration system will need 3 stages, with each one making the next filter in line more efficient and last longer.

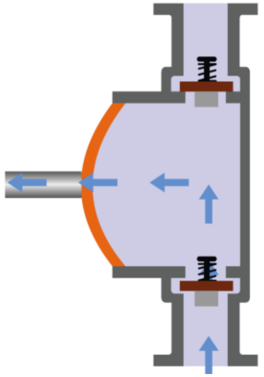
The pump filtration system doesn't need the largest filter due to the large filter on the ambient air.

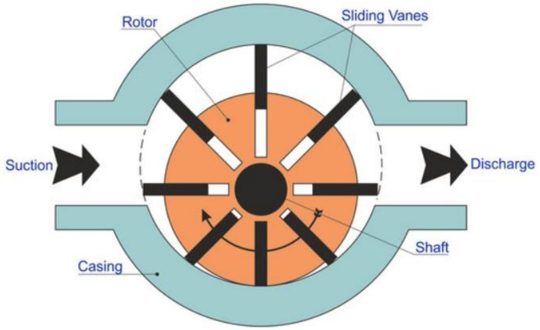
The HEPA filters are the industry standard for protecting sensitive equipment such as sensors. ULPA filters were decided against due to there vastly restricted airflow.

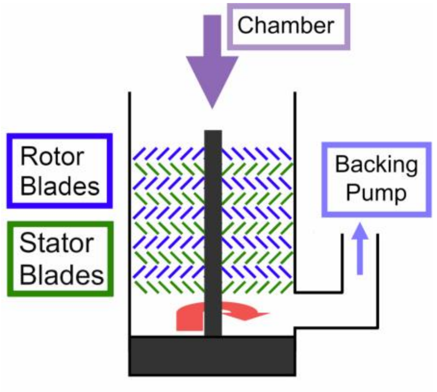
Filter Stage	Micron Size	MERV Rating	Purpose for Ambient Air Filtration	Purpose for Pump Air Filtration
Stage 1: Mesh Screens	50 to 100+ microns	1–4	Captures the **largest particles** such as sand or coarse debris	Not needed
Stage 2: Polyester or Cartridge Filter	1 to 10 microns	8–11	Captures dust, pollen and mold. Key for **protecting lifespan** of the **final, more expensive filter**	Will capture larger sorbent particles. These will be from possible breakdown due to water absorption.
Stage 3: HEPA Filter	0.3 microns	17–20	**Removes 99.97%** of particles with **diameters of .3 microns**. Crucial for **protecting sensors and the vacuum pump**	Will capture the finest particles generated by the rubbing of the sorbents in a fluidized bed

Subsystem: Vacuum pump

- Diaphragm pump: 0.0017 – 0.1 L/s
- Rotary vane pump: 0.3 – 28 L/s
- Turbomolecular pump: 50 – 3000 L/s







Vacuum pump calcs and evaluation

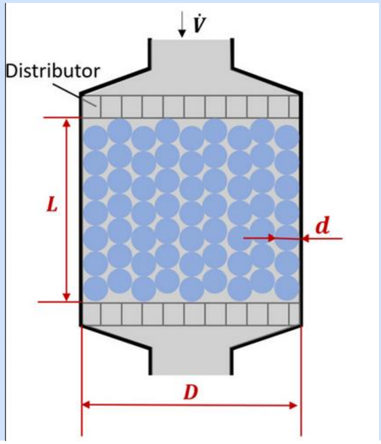
S_{eff}: effective pumping speed
$\dot{m}_v$: vapor mass flow rate
ρ_v: vapor density
M_w: molar mass
P : pressure
R: universal gas constant
T: temperature
$\dot{Q}_{max}$: heat transfer rate
h_{fg}: specific enthalpy of vapor

- $S_{eff} = (S_{pump} * C_{total})/(S_{pump} + C_{total})$
- $\dot{m}_v = \rho_v S_{eff} = (M_w P_{target})/(RT) * S_{eff}$
- $\dot{m}_v^{max} = \dot{Q}_{max}/h_{fg}(T)$
- $S_{eff} = \frac{RT}{M_w P_{target}} \dot{Q}_{max}/h_{fg}(T)$
- $\mathrm{Q_{max}} = 120\mathrm{V} * 15\mathrm{a} * 0.8 = 1.44\mathrm{kW} = 1440\mathrm{J/s}$
- R=8.314 J/molK, Mw=0.018015 kg/mol, hfg=2.454E6 J/kg, T=293K, P=1000 Pa
- S_{eff} = 0.079 m^3/s=79 L/s

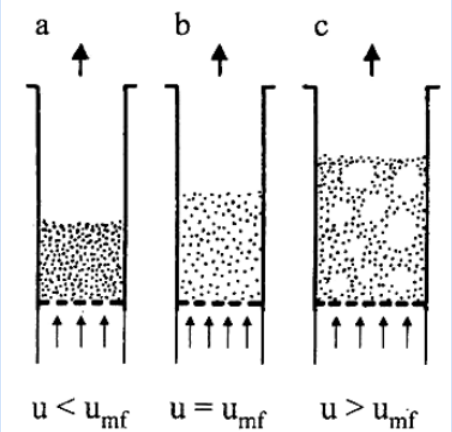
- Evaluation: Rotary vane pump is best fit (next step is to talk with client about desired cycle time)
  - Note: This S_{eff} is an upper max if a standard 120v outlet sized heating element is considered a max. Given the overly high flow rate, the conclusion here is that the heating element will not be a limiting factor.

Subsystem: Sorbent structure

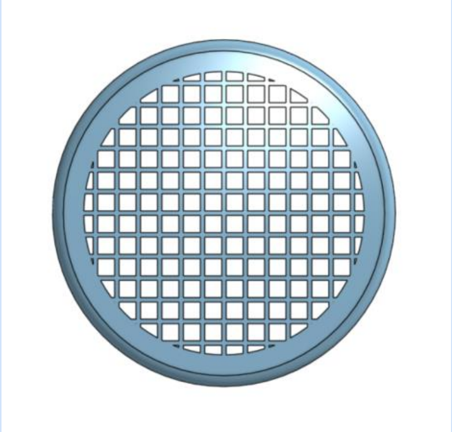
Packed Bed



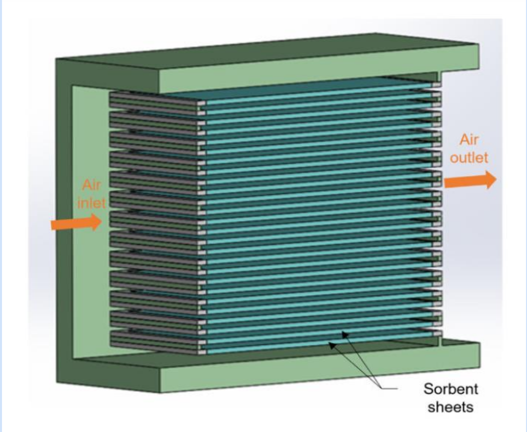
Fluidized Bed



Monolith structure



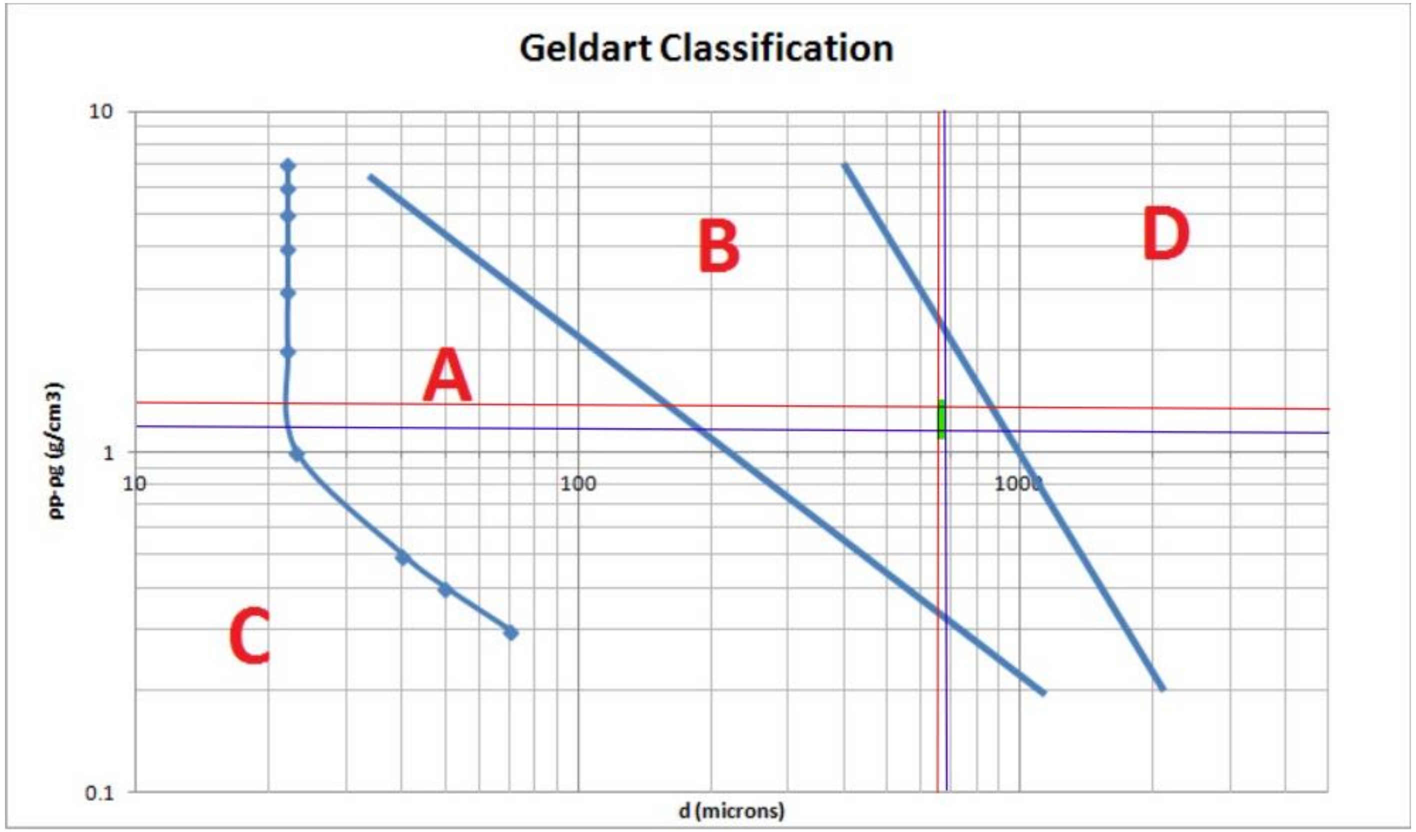
Laminate structure



Sorbent structure calcs and evaluation: Packed Bed

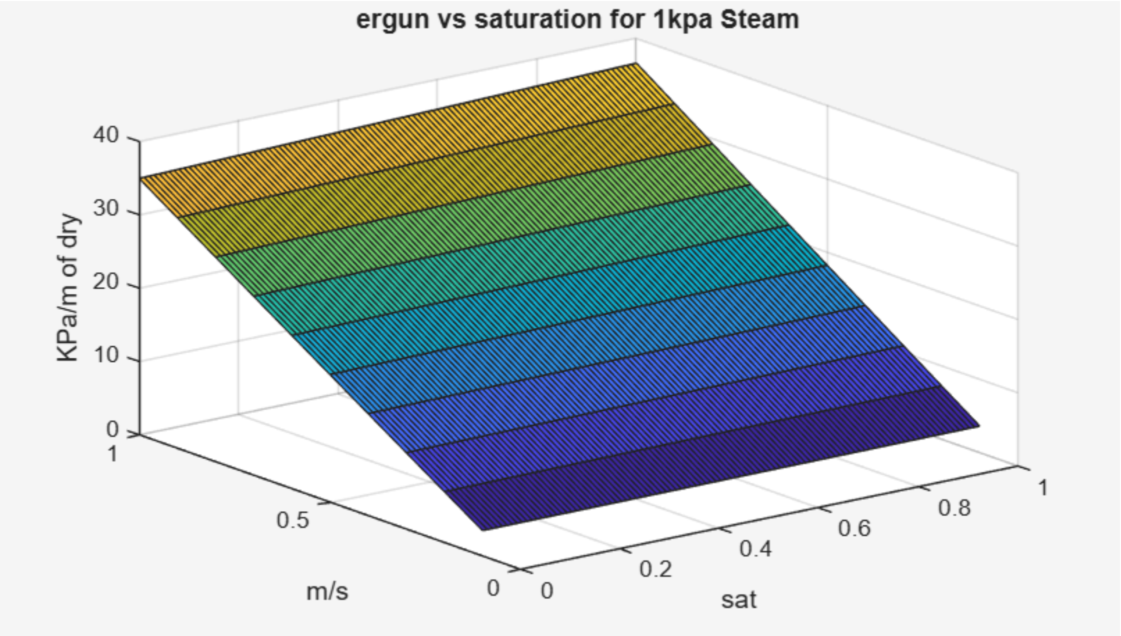
- Behavior range verified through Geldart classification
- Fluid assumptions
  - Air at standard atmospheric conditions
    - μ= .00001846 pa*s ρ=1.225 kg/m^3
  - Steam @ 5 Kpa & 33 deg C
    - μ= .000001 pa*s ρ=.035 kg/m^3
- Particle assumptions
  - d_{dry} = .5694 mm = .0005694 m d_{wet}=.596 mm = .000596 m
  - ρ_{dry}= 1.2273 g/cm^3 ρ_{wet}= 1.11587 g/cm^3
- Packed bed ΔP

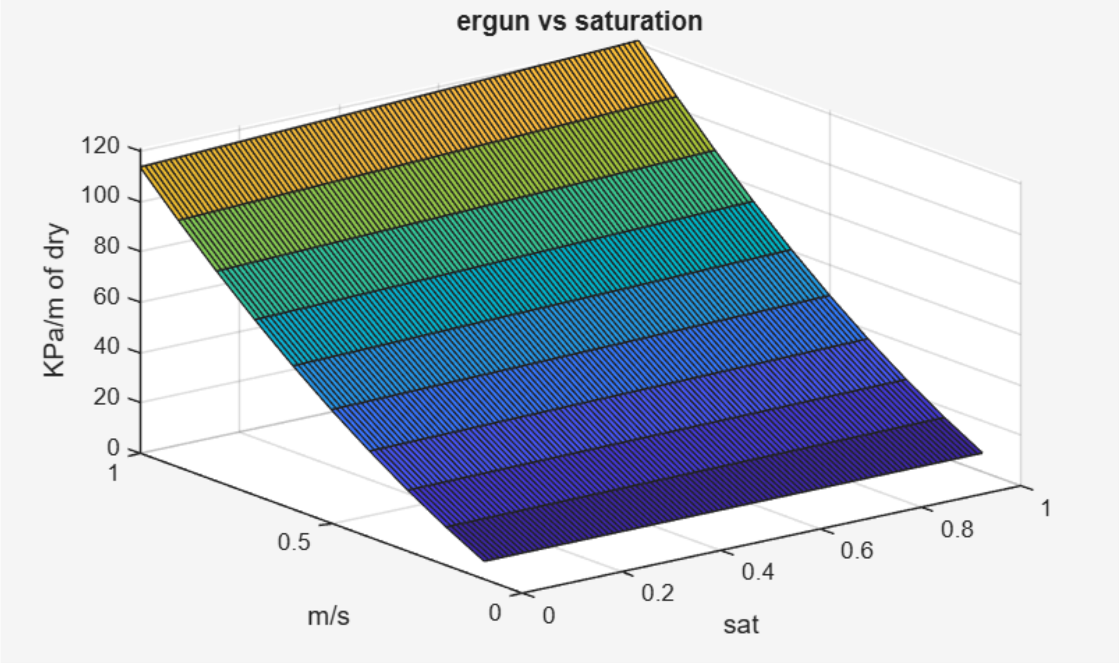
$$\frac{\Delta P}{L} = \frac{\left(150 \cdot \mu \cdot (1-\varepsilon)^2 \cdot U_0\right)}{\varepsilon^3 \cdot d^2} + \frac{\left(1.75 \cdot (1-\varepsilon) \cdot \rho \cdot U_0^2\right)}{\varepsilon^3 \cdot d}$$



Packed bed

- High pressure drop at speed
- Very high sorbent capacity
- dP dry, air = 113.748 Kpa/m @1 m/s
- dP wet, air = 121.351 Kpa/m
- dP dry, steam= 34.91 Kpa/m
- dP wet, steam= 36.54 Kpa/m





Sorbent structure calcs and evaluation: Fluidized bed

- Ergun > bed weight > drag
- Like indoor skydiving

$$g \cdot (\rho_s - \rho) = \frac{\left(150 \cdot \mu \cdot (1-\varepsilon)^2 \cdot U_0\right)}{\varepsilon^3 \cdot d^2} + \frac{\left(1.75 \cdot (1-\varepsilon) \cdot \rho \cdot U_0^2\right)}{\varepsilon^3 \cdot d}$$

$$Re = \frac{\rho u d_p}{\mu}$$; variables defined above except C_D

$$Re < 1 \quad \Rightarrow \quad u_t = \frac{(\rho_s - \rho) g d_p^2}{18\mu}$$

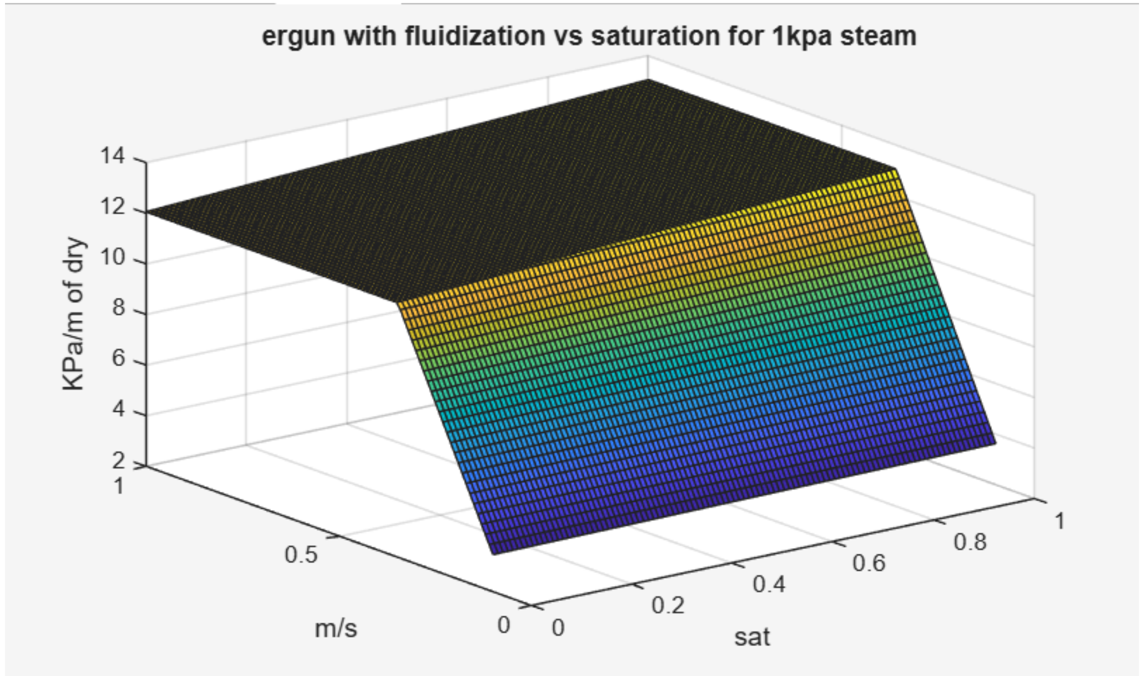
$$1 < Re < 500 \quad \Rightarrow \quad u_t = \left[\frac{4(\rho_s - \rho) g d_p}{3\rho C_D}\right]^{\frac{1}{2}}$$

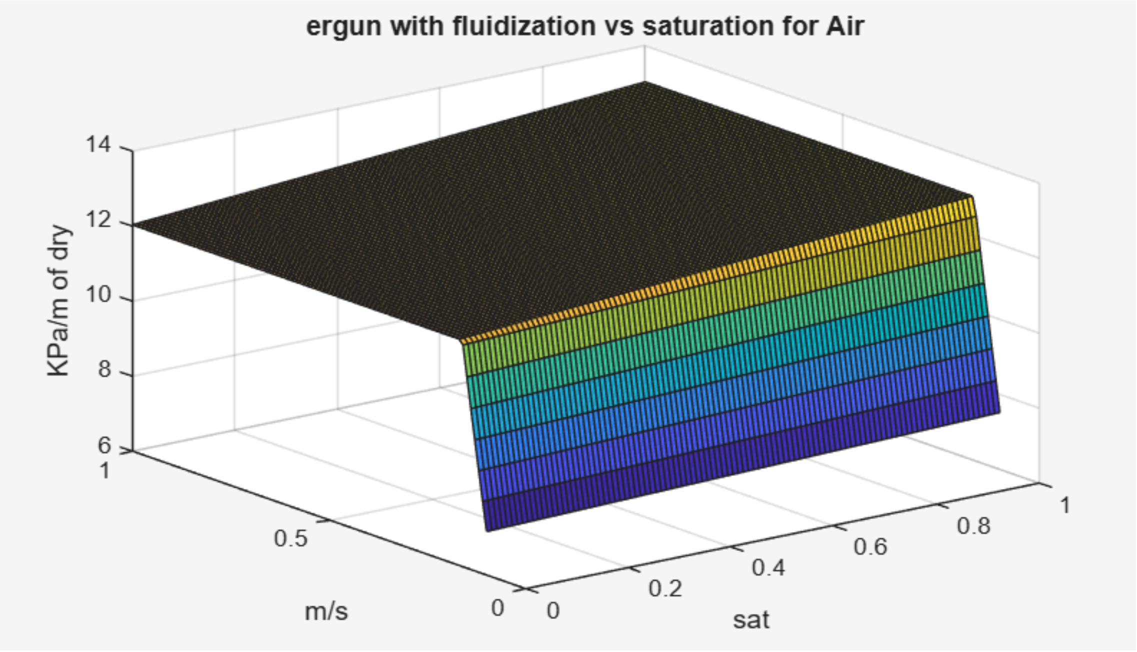
where $C_D = \frac{18}{Re^{\frac{3}{5}}}$,

$$500 < Re < 2 * 10^5 \quad \Rightarrow \quad u_t = \left[\frac{3(\rho_s - \rho) g d_p}{\rho}\right]^{\frac{1}{2}}$$

Fluidized bed

- Air @ atm
  - Dry U_{crit}= .17 m/s dP= 12.03 kPa/m
  - Wet U_{crit}= .17 m/s dP= 12.77 kPa/m
- Steam @ 1kpa
  - Dry U_{crit}= .35 m/s dP= 12.04 kPa/m
  - Wet U_{crit}= .37 m/s dP= 13.02 kPa/m
- Excellent pressure drop
- High sorbent capacity
- High wear on sorbent potentially producing dust and sorbent degradation





Sorbent structure calcs and evaluation: Monolith and Laminate structures

DARCY-WEISBACH EQUATION

$$\frac{\Delta p}{L} = f_D \cdot \frac{\rho}{2} \cdot \frac{\langle v \rangle^2}{D_H},$$

- Darcy friction factor
  - Bellos-Nalbantis-Tsakiris approximation

$$f = \left(\frac{64}{\mathrm{Re}}\right)^a \left[0.75 \ln\left(\frac{\mathrm{Re}}{5.37}\right)\right]^{2(a-1)b} \left[0.88 \ln\left(3.41 \frac{D}{\epsilon}\right)\right]^{2(a-1)(1-b)}$$

where

$$a = \frac{1}{1 + \left(\frac{\mathrm{Re}}{2712}\right)^{8.4}}$$

$$b = \frac{1}{1 + \left(\frac{\mathrm{Re}}{150 \frac{D}{\epsilon}}\right)^{1.8}}$$

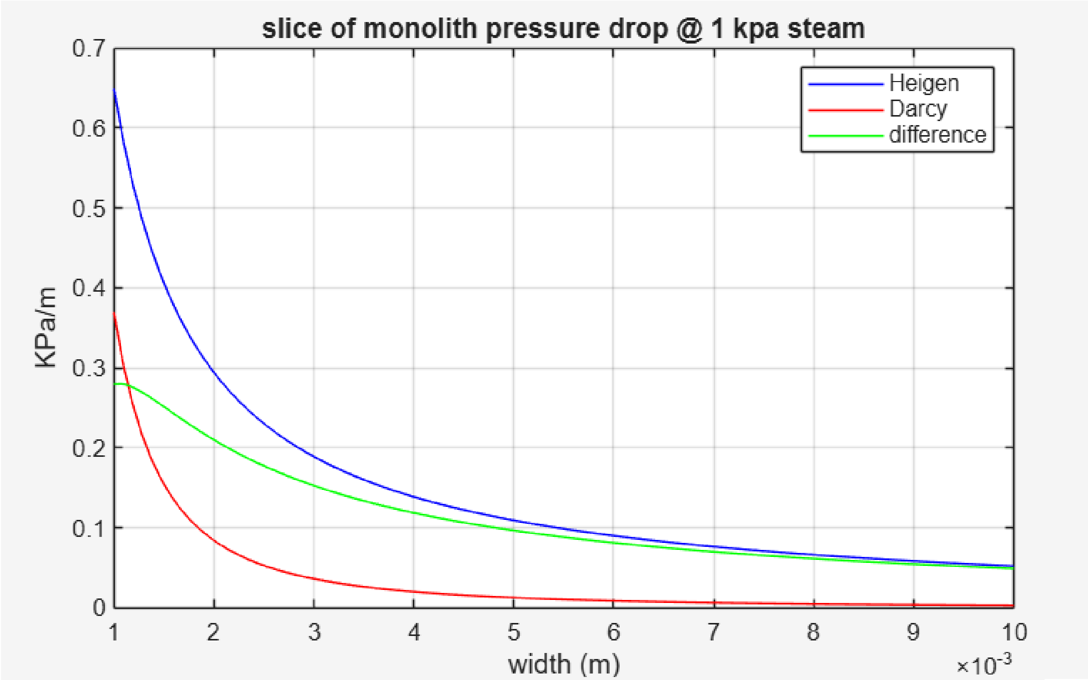
HEIGEN-POISEULLE

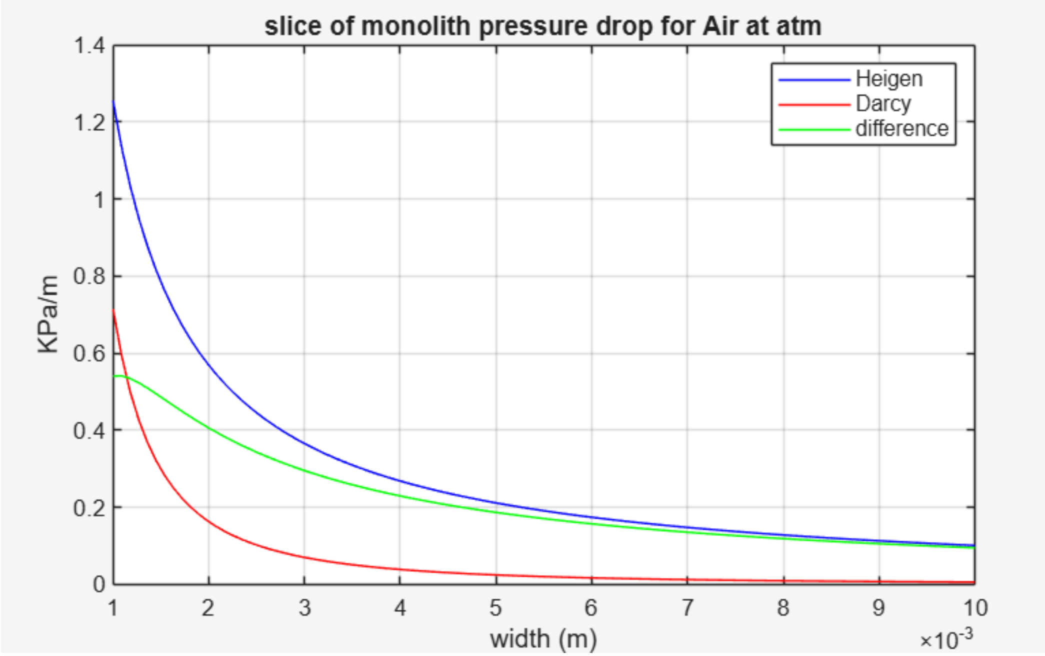
$$\Delta p = \frac{8 \mu L Q}{\pi R^4} = \frac{8 \pi \mu L Q}{A^2},$$

.1mm wall thickness assumed

Sorbent structure calcs and evaluation: Monolith structure

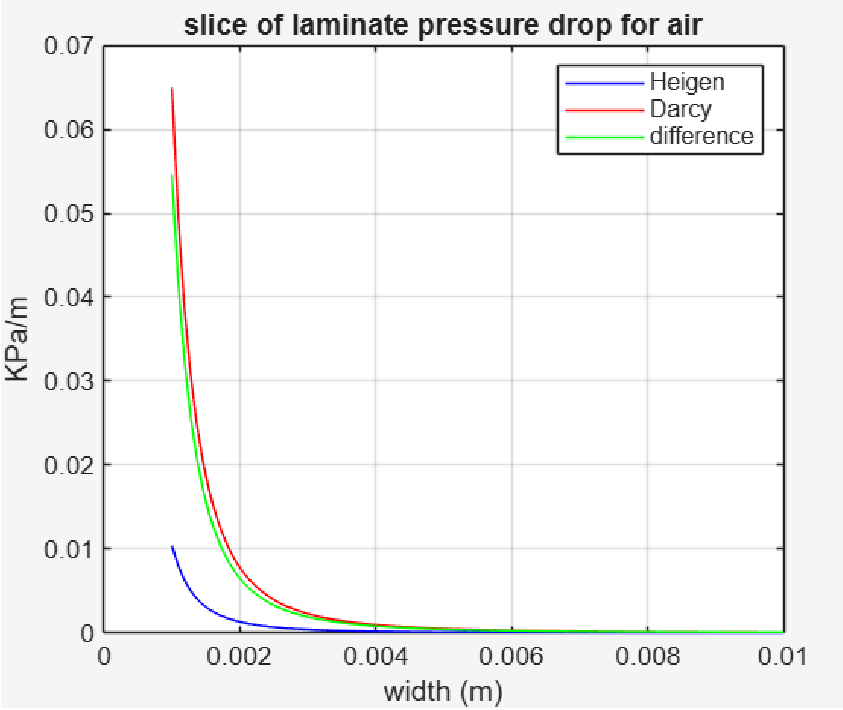
- Medium sorbent density
- Low pressure drop
- Good performance at fast flow rates

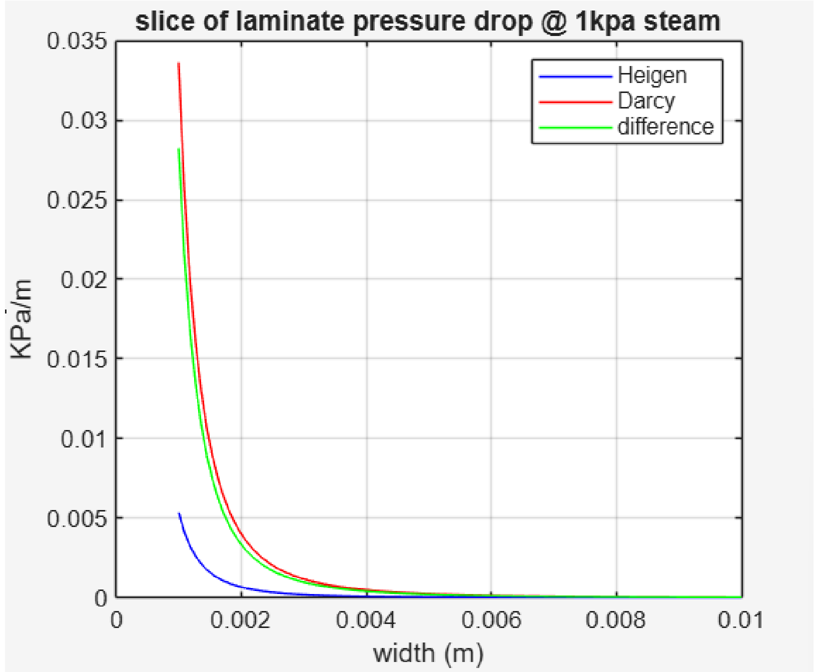




Sorbent structure calcs and evaluation: Laminate structure

- Low sorbent density
- Low pressure drop
- Excellent performance at fast flow rates

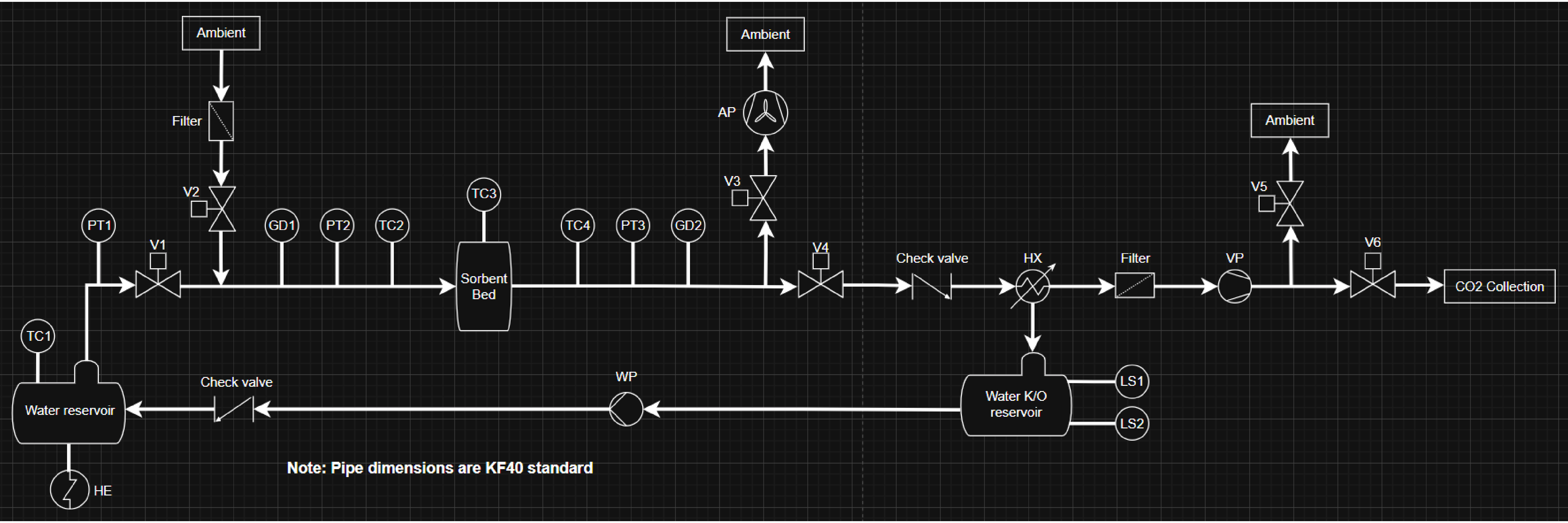




Sorbent structure evaluation

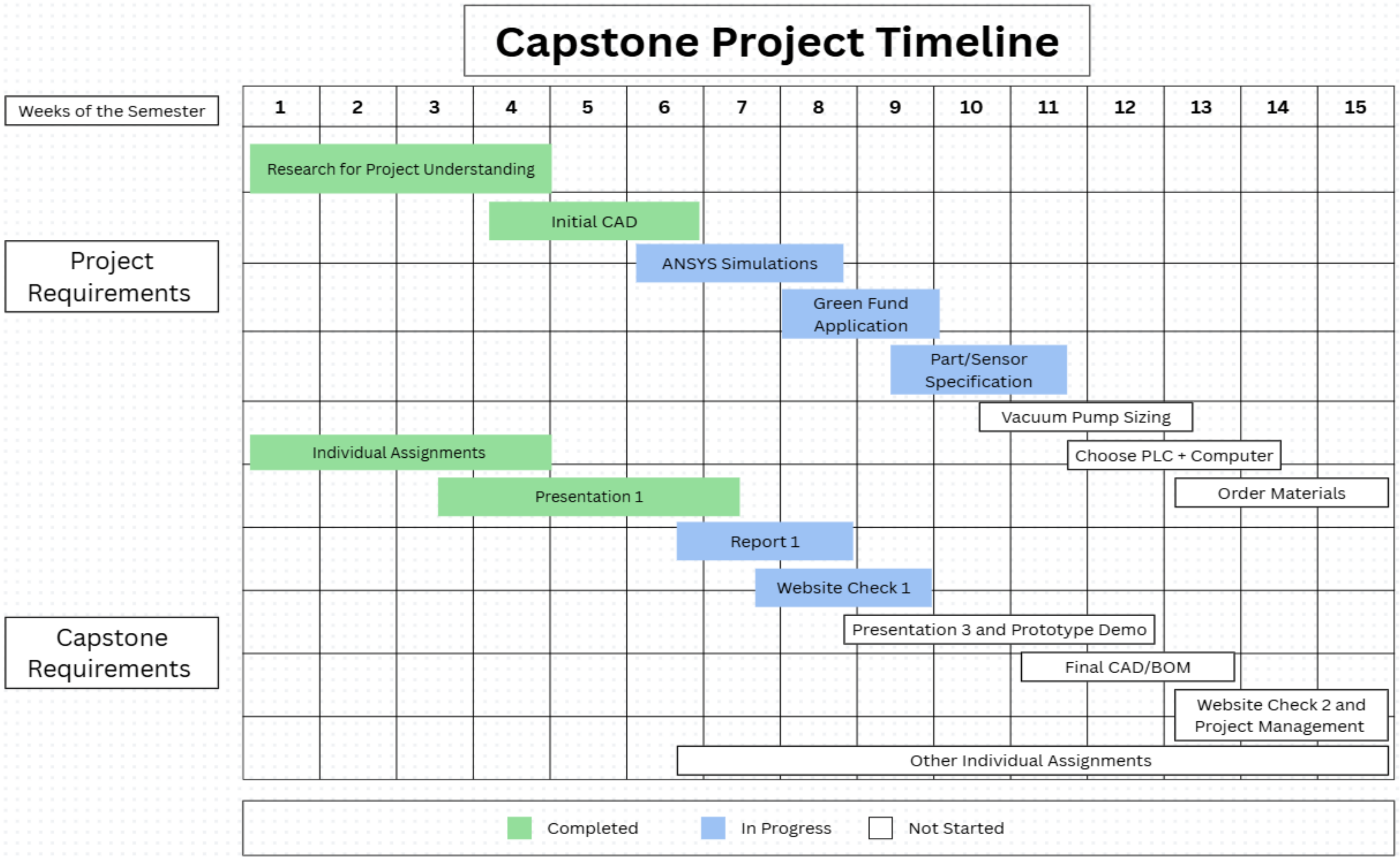
- Because of our flow rate restriction, we are likely to use a packed bed
- It is to be determined if fluidization is too harsh for the sorbent
- All processes will be tested

Concept Selection: Process Diagram



- Specified part types from subsystems, added detail parts

Gantt Chart



Capstone Project Timeline
Weeks of the Semester
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Project Requirements
Capstone Requirements
Research for Project Understanding
Initial CAD
ANSYS Simulations
Green Fund Application
Part/Sensor Specification
Vacuum Pump Sizing
Choose PLC + Computer
Order Materials
Individual Assignments
Presentation 1
Report 1
Website Check 1
Presentation 3 and Prototype Demo
Final CAD/BOM
Website Check 2 and Project Management
Other Individual Assignments
Completed
In Progress
Not Started

BOM

BoM Level	Part Legend	Description	Qty
1	Water Reservoir	Vacuum-rated tank, ~3 liters	2
2	V1...6	Actated ball valves	6
3	Filter	Hepa rated filter, 0.3 micron	2
4	Check valve	Liquid rated check valve	1
5	Check valve	Gas rated check valve	1
6	WP	Water pump	1
7	VP	Vacuum Pump	1
8	AP	Air Pump	1
9	HE	Heating Elements	1
10	HX	Heat Exchanger	1
11	Sorbent Bed	Custom made sorbent holder	1
12	IRA900CL	Sorbent bead bottle	1
13	CO2 Collection	CO2 cannister + hardware	1
14	KF40 Tee	Tee pipe fitting, KF40	10
15	KF40 Clamp	KF40 rated connection clamps	32
16	PT	Pressure transducer	3
17	TC	Thermocouple	4
18	GD	Gas detector	2
19	LS	Level Sensor	2
20	PLC	Programmable logic controller	1
21	PC	Desktop computer	1
22	Wire	Insulated electrical wire roll	1
23	Ethernet	Ethernet cable	1
24	Enclosure	Electrical enclosure, waterproof	1

Budget

- Salt River Project provided a $50,000 grant for the construction of our DAC system
- Fundraising: Green Fund
  - We are looking to purchase a 3D printer to experiment with printed sorbent structures that maximize contact with minimal pressure drop
  - Estimated cost: $900 to $1400
  - Application currently in progress

	Low Estimate	High Estimate
INCOME		
Budget Grant from SRP	+$50,000	+$50,000
Possible Green Fund Grant	+$5,000	+$8,000
EXPENSES		
Oil Free Vacuum Pump (1mBar, 10 LPM)	-$6,000	-$15,000
Variable Frequency Drive	-$500	-$1,000
Cold Trap & Chiller	-$2,500	-$5,000
Water Vessel w/ Thermal Jacket & Temp Control	-$3,000	-$5,000
KF40 Vessel	-$100	-$200
KF25/40 Adapters & Sorbent Bed Supports	-$5,000	-$10,000
Instrumentation (pressure transducers, thermocouples)	-$4,000	-$12,000
Welding 316 stainless steel	-$1,500	-$3,000
Experimental 3D Printer (Green Fund)	-$5,000	-$8,000
TOTALS		
Total Income	+$55,000	+$58,000
Total Expenses	-$27,600	-$59,200
Net Balance	+$27,400	-$1,200

3D Printer

- Eazao Bio
    - Ceramic 3D printer for lab application
    - Nozzle allows printing of viscous materials
    - Low tolerance: 0.1 mm +.05
    - $900 base price
    - Additional $500 for pressure control

Thank You

Questions?

References

- [1] V. Bellos, I. Nalbantis, and G. Tsakiris , "Friction modeling of flood flow simulations | Journal of Hydraulic Engineering | Vol 144, no 12," ASCE library, https://ascelibrary.org/doi/10.1061/%28ASCE%29HY.1943-7900.0001540 (accessed Oct. 9, 2025).
- [2] "Darcy–Weisbach equation," Wikipedia, https://en.wikipedia.org/wiki/Darcy%E2%80%93Weisbach_equation (accessed Oct. 9, 2025).
- [3] D. Thornhill, "Fluid Mechanics for Fluidized Beds," FBR Fluid Mechanics, https://faculty.washington.edu/finlayso/Fluidized_Bed/FBR_Fluid_Mech/fluid_bed_scroll.htm (accessed Oct. 9, 2025).
- [4] D. Thornhill, "Flow Through Packed Beds," Packed beds, https://faculty.washington.edu/finlayso/Fluidized_Bed/FBR_Fluid_Mech/packed_beds_fbr.htm#ergun (accessed Oct. 9, 2025).
- [5] A. Sinha, L. Darunte, C. Jones, M. Realff, and Y. Kawajiri, "Systems design and economic analysis of direct air capture of CO2 through temperature vacuum swing adsorption using MIL-101(CR)-PEI-800 and mmen-mg2(dobpdc) MOF adsorbents | Industrial & Engineering Chemistry Research," Systems Design and Economic Analysis of Direct Air Capture of CO2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg2(dobpdc) MOF Adsorbents, https://pubs.acs.org/doi/10.1021/acs.iecr.6b03887 (accessed Oct. 9, 2025).
- [6] R. Cocco and J. W. Chew, "50 years of Geldart classification - sciencedirect," 50 years of Geldart classification, https://www.sciencedirect.com/science/article/pii/S0032591023006459 (accessed Oct. 9, 2025).
- [7] "Eazao Bio," Eazao, https://www.eazao.com/product/eazao-bio/ (accessed Oct. 9, 2025).

References (continued)

- [8] Agilent Technologies, "Vacuum Made Simple: Q = P × S Explains Everything," *Agilent*, [Online]. Available: Vacuum Made Simple: Q = P x S Explains Everything | Agilent. [Accessed: 9-Oct-2025].
- [9] Pfeiffer Vacuum, "2.2 Calculations," *Pfeiffer Vacuum Knowledge Book – Basic Calculations*, [Online]. Available: Vacuum Calculations: Basic Formulas - Pfeiffer Know-How | Pfeiffer Global. [Accessed: 9-Oct-2025].
- [10] J. Laswell et al., "Chapter 3: An Introduction to Vacuum Systems," *Introduction to Vacuum Technology*, Milne Publishing / SUNY Geneseo, [Online]. Available: CHAPTER 3: An Introduction to Vacuum Systems – Introduction to Vacuum Technology. [Accessed: 9-Oct-2025].
- [11] Kenya Agri, "Vacuum Pumps," *Kenya Agri Products*, [Online]. Available: Vacuum Pumps - Kenya Agri. [Accessed: 9-Oct-2025].
- [12] "What is a MERV rating? | US EPA," *US EPA*, Feb. 19, 2019. https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating [Accessed: 9-Oct-2025].
- [13] SKI GmbH, "Steam Tools," SKI GmbH, [Online]. Available: https://www.ski-gmbh.com/swa/tools/steam
- [14] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, *Fundamentals of Engineering Thermodynamics*, 8th ed. Hoboken, NJ, USA: Wiley, 2015
- [15] P. J. Pritchard, *Fox and McDonald's Introduction to Fluid Mechanics*, 10th ed. Hoboken, NJ, USA: John Wiley & Sons, 2019