Vacuum Moisture Swing

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Design Handout

Presentation 3 handout1.docx

- Above is a link to the handout in case anyone wants it

Project Description

- The purpose of our project is to design, build and test a **Direct Air Capture (DAC) Reactor** that uses **Vacuum Moisture Swing** as it's CO_2 collection process. This process draws a vacuum on room temperature water to utilize low energy vapor to strip CO2 from the sorbent.
- 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.
- The sorbent bed will be optimized for increasing surface area (for reaction extent) and decreasing pressure drop (to save energy). This will likely be done using an experimental 3D printer so we can test a wide variety of sorbent structures

Stakeholders

Industry Sponsor: Salt River Project (SRP)

Advisor: Professor Jennifer Wade

Mentor: PhD Candidate Stephano Sinyangwe

Other Stakeholders: NAU Climate Lab

Design Requirements: QFD

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0	0						
0	0	+					
0	0	0	+				
+	0	0	0	+			
0	-	0	0	0	+		
-	-	-	0	0	+	+	
+	-	-	+	-	+	+	+

weight	Customer Requirements / Engineering Requirements	Sorbent Efficiency	Packing Density	Pressure Drop	Practical Velocity Range	Vacuum Pressures	Condensor	Sensor Integration	PLC	VFD	Packed Bed	Monolithic	Laminate
25	C02 Capture Effeciency	5	3.5	2	2.5	3	2	3	3	2	5	2	3
22.5	Minimal Power Input	1.5	2.5	4.5	3	3.5	2	2.5	3	4	1	5	4
7.5	Vaporization Without Heating	1	1.5	2	2	4.5	1.5	1.5	1.5	2	2	5	3
32.5	Measurable Results	1.5	1.5	1	2	1.5	1.5	5	2.5	1.5	2	5	4
12.5	Controllable Flow Rate	1	1.5	2	2.5	2	1.5	5	5	4.5	2	5	4
	Units	mmol/g	m^3/m^	kPa	m/s	kPa	QTY	QTY	QTY	QTY			
	Target Score	>1.5	>0.6	<0.5	<1	<3	1	6	1	1			
	Relative Importance Weight	2.275	2.225	2.2375	2.4125	2.6125	1.7375	3.675	2.975	2.6			
	Packed Bed	2	4	2	3	3	3	4	4	4			
	Monolithic	3	3	3	3	3	3	3	3	3			
	Laminate	4	4	4	3	3	3	3	3	3			

Design Requirements: CR/ER Description & Relation

CR	ER
1. Capture as much co2 as possible	1a. Maximize sorbent productivity [(mmol CO2/g sorbent)/hour] 1b. Maximize surface area (cm^2/cm^3) 1c. Find ideal void fraction (cm^3/cm^3)
2. Minimize power requirement	2a. Minimize pressure drop (ΔkPa/cm) 2b. Keep air velocity within practical range, <1m/s
3. Utilize moisture swing	3a. Vacuum pressure below water vaporization pressure at ambient temperature, <~3kPa

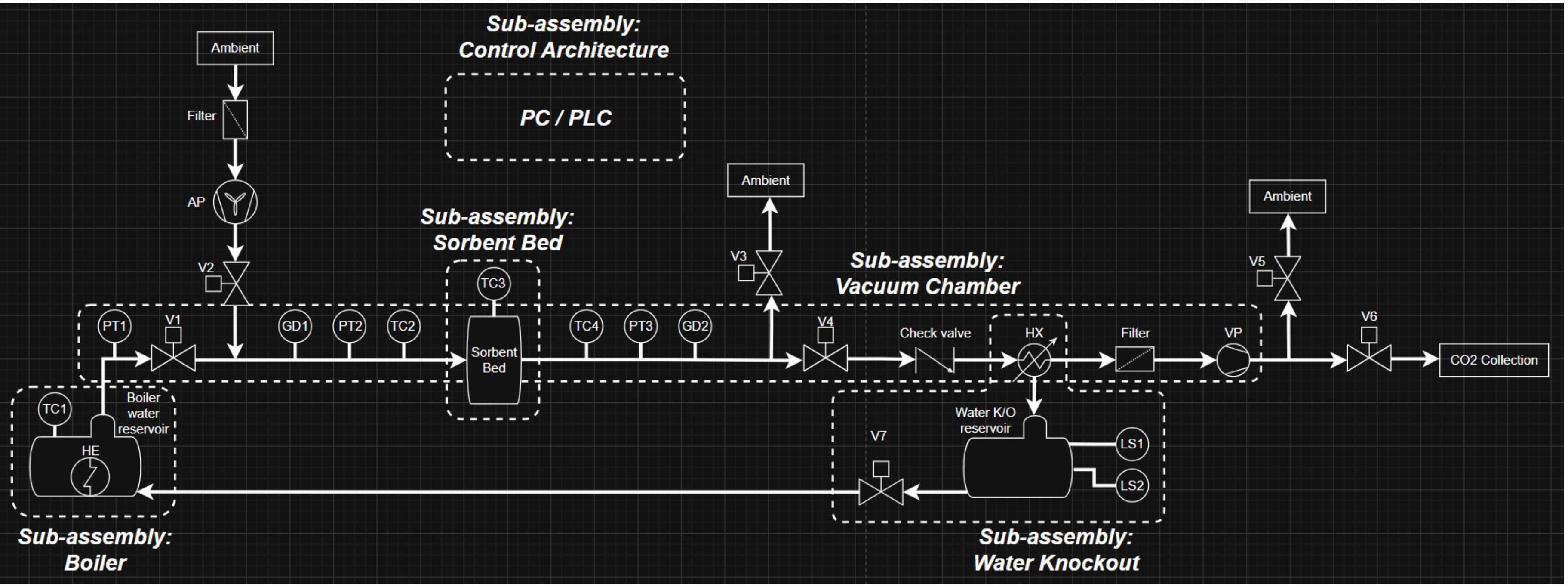
Design Requirements: CR/ER Description & Relation

CR	ER
4. Minimize water loss	4a. Reuse water by condensing water vapor (°C) 4b. Heat water reservoir to offset evaporative cooling to maintain ambient temperature (~15 °C)
5. Track the metrics of the apparatus as it runs	5a. Incorporate pressure transducers before and after reactor chamber (kPa) 5b. Incorporate thermocouples before and after reactor chamber (°C)

Design Requirements: CR/ER Description & Relation

CR	ER
6. Be able to control flow rate and pressure.	6a. Incorporate a VFD (matched to vacuum pump, rated by kW) 6b. Utilize a PLC with PID loops for the vacuum pressure, water temperature, and reservoir levels
7. Maintain a clean lab environment	7a. Utilize an oil free pump
8. Keep design compact	8a. Less than 1 meter in the longest direction
9. Utilize existing common vacuum parts	9a. All parts must be standard KF40 and KF25 fittings.
10. Remain under budget	10a. Less than 50K spent

Design Description: Top-level

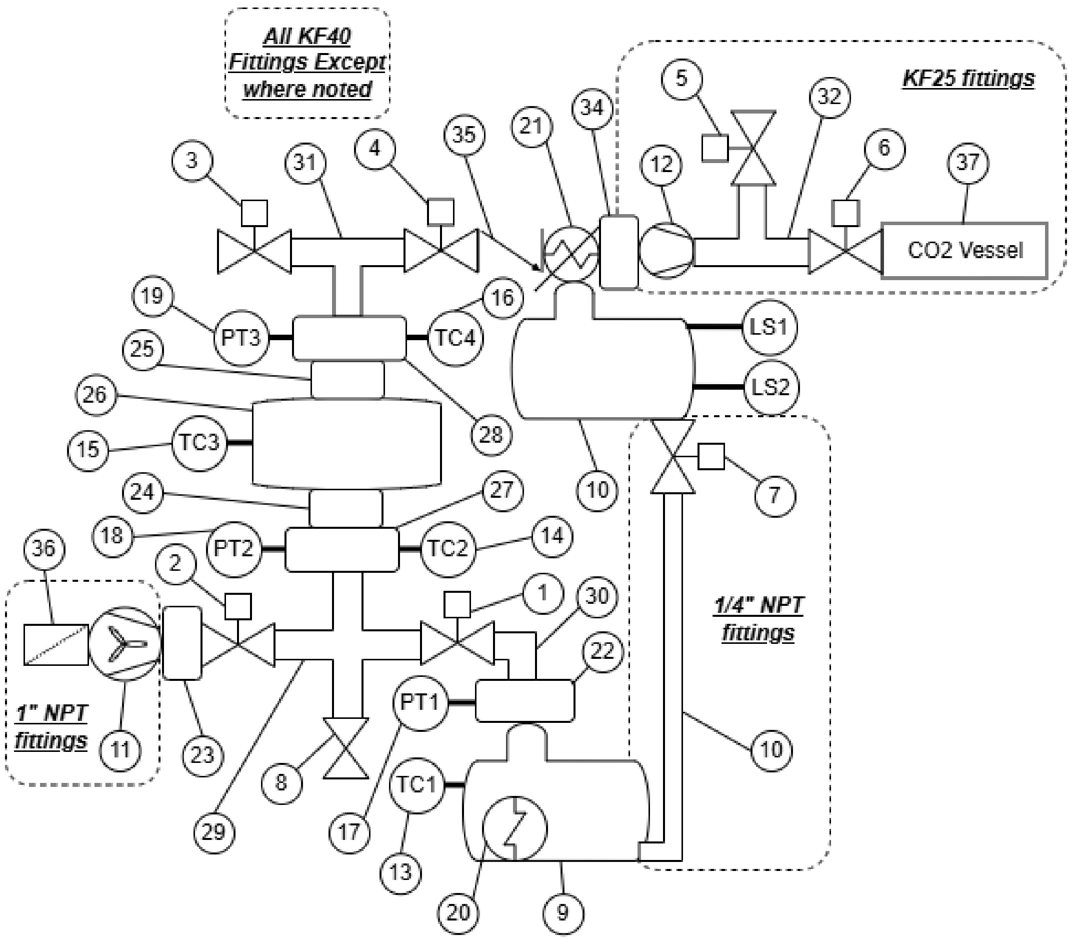


States:

Part	Adsorption	Air Evacuation	Vapor Stripping	Final Desorption	Pressurization
V1	closed	closed	open	closed	closed
V2	open	closed	closed	closed	open
V3	open	closed	closed	closed	closed
V4	closed	open	open	open	closed
V5	closed	open	closed	closed	closed
V6	closed	closed	open	open	closed
AP	on	off	off	off	off
VP	off	on	on	on	off
V7	off	off	active	active	off
HE	off	off	active	off	off
HX	off	off	on	on	off

- Top-level design function:
- Phase 1: Adsorption Air is pushed through the sorbent bed, adsorbing CO2 and returning the cleaned air to environment.
- Phase 2: Air Evacuation The vacuum pump pulls a vacuum, evacuating remaining cleaned air to environment.
- Phase 3: Vapor Stripping The water reservoir is exposed to vacuum, causing it to vaporize. Vapor desorbs the CO2, and the CO2 is pushed to a collection canister.
- Phase 4: Final Desorption The water reservoir is isolated, and the vacuum pressure is pulled lower for a final desorption and warming of sorbent.
- Phase 5: Repressurize All pumps are off, and the sorbent chamber is exposed to environment to repressurize to ambient.

Design Description: Assembly

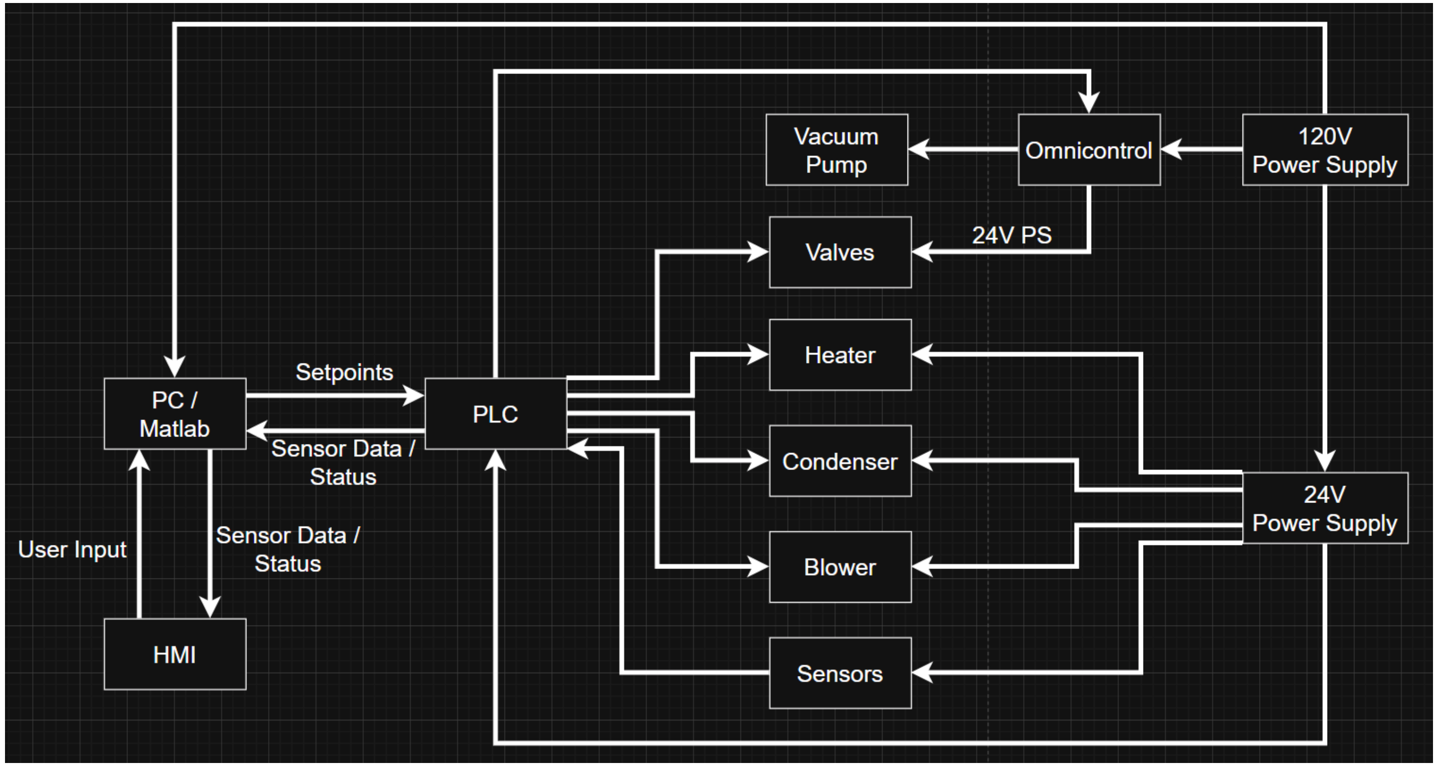


BOM	
ID	Description
1	Valve 1
2	Valve 2
3	Valve 3
4	Valve 4
5	Valve 5
6	Valve 6
7	Valve 7
8	Manual Valve
9	Boiler Reservoir
10	Water K/O Reservoir
11	Air Blower
12	Vacuum Pump
13-16	Temperature Thermocouples
17-19	Pressure Transducers
20	Heating Element
21	Condenser
22	1xNPT adapter
23	KF40 to NPT adapter
24-25	Mesh Centering Rings
26	Sorbent Bed
27-28	3xNPT adapter
29	KF40 Cross
30	KF40 90 Elbow
31	KF40 Tee
32	KF25 Tee
33	1/4" Tubing
34	KF40-KF25 adapter
35	Check Valve
36	Filter
37	CO2 Vessel

- Assembly diagram of top-level design
- Doesn't include automation/ control hardware

Design Description: Block Diagram

- Control system block diagram
  - Overarching control architecture



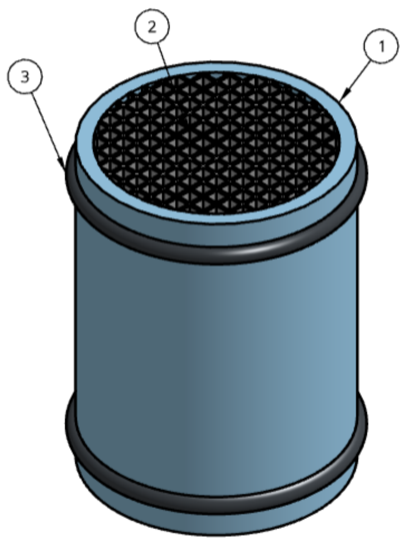
	Adsorption	Air Evacuation	Vapor Stripping	Final Desorption	Pressurization
Start Conditions	Previous state complete or Start command	Previous state complete	Previous state complete	Previous state complete	Previous state complete
Control (Note: HE and V7 control loop latched on)	Blower speedbased on pressure drop	None	Flow rate* and pressure setpoint (based on optimized data)**	Pressure setpoint (PT1) (based on optimization data)	None
Stop Conditions	Time = setpoint (based on optimized data)	Pressure ≤ setpoint (PT3) (based on optimized data)	Time = setpoint (20% of adsorption time setpoint)	Temperature ≥ setpoint (TC3) (based on optimization data)	Complete or cycle count Stop

*backed out from pump curve and pressure drop

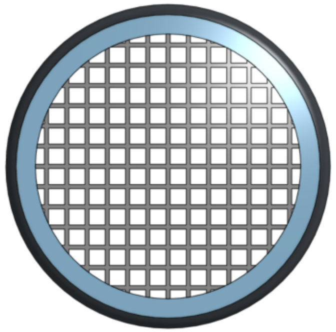
**calculated by Ergun eqn using velocity which is based on optimized data which is dependent on humidity and duration of stripping (based on duration of adsorption)

Design Description: Sub-assembly: Sorbent Bed

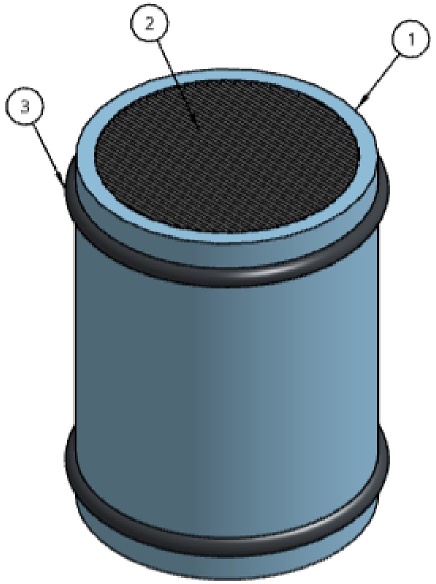
Monolithic Structure:



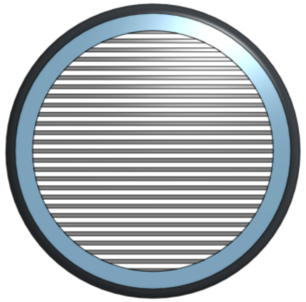
Part	Quantity	Description
1	1	Structural cylinder
2	1	Monolith structure
3	2	O-Rings



Laminate Structure:

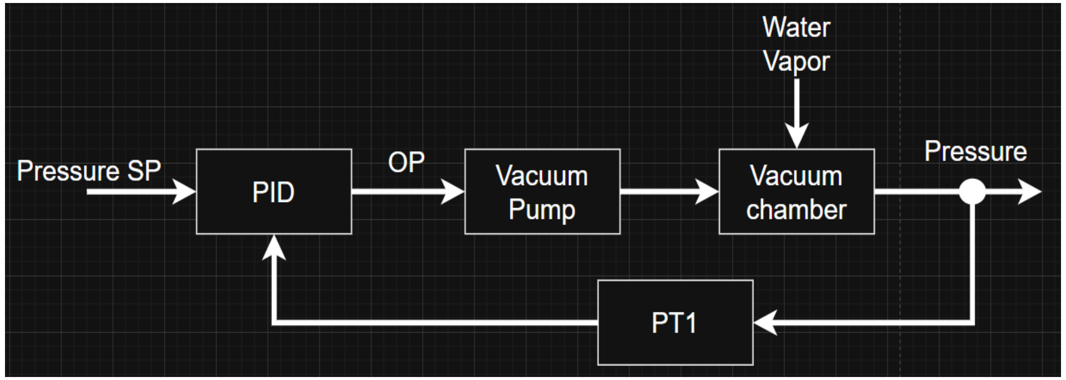


Part	Quantity	Description
1	1	Structural cylinder
2	1	Laminate structure
3	2	O-Rings



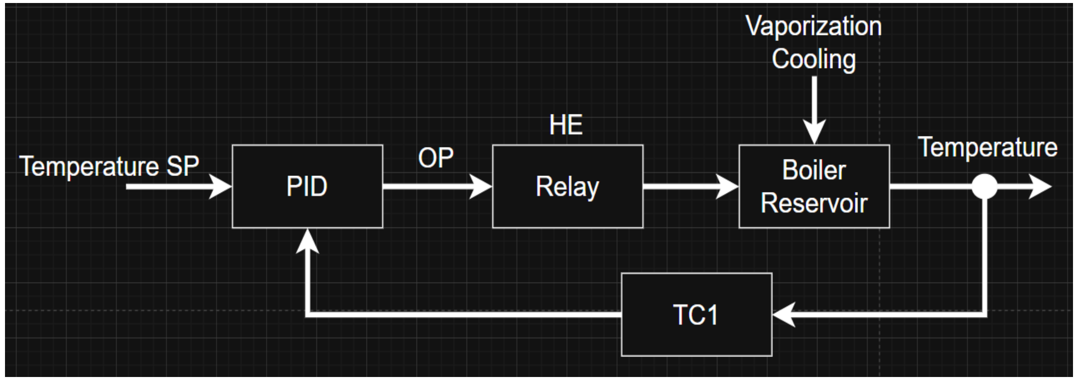
- Structured sorbents are 3d printed as inserts for round KF pipes.
- Two O-rings are used to seal and hold each in place within the sorbent tube

Design Description: Sub-assembly: Vacuum Chamber



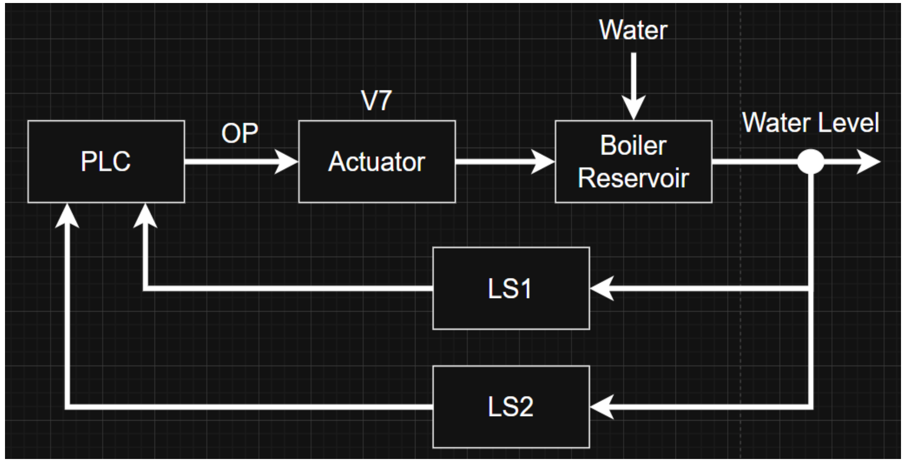
- Vacuum pump on a PID loop
  - Process variable is pressure, from the pressure transducer right above the boiler reservoir
  - Will maintain a pressure setpoint issued by the user

Design Description: Subassembly: Boiler



- Heating element in the boiler reservoir on a PID loop
  - Process variable is temperature of the water
  - Will maintain a water temperature setpoint issued by the user

Design Description: Sub-assembly: Water Knockout

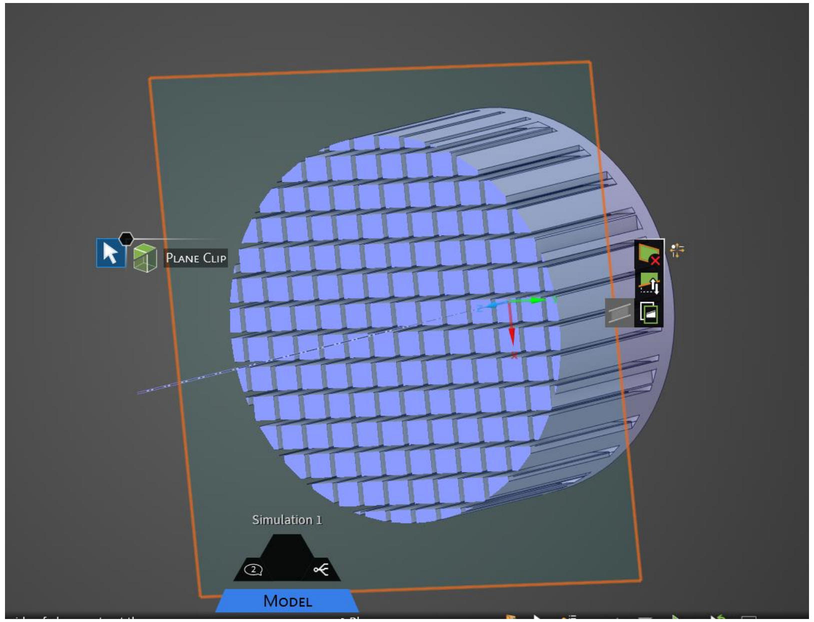


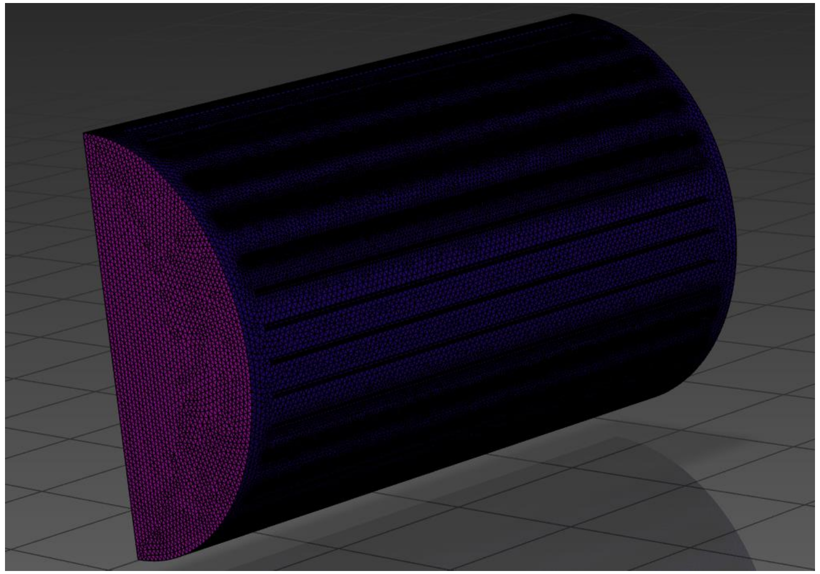
- The Water K/O Reservoir needs to never be empty, but drain so it doesn't overflow
- High and low level sensors, open drain valve when high and close when low

Sorbent Bed ANSYS Analysis

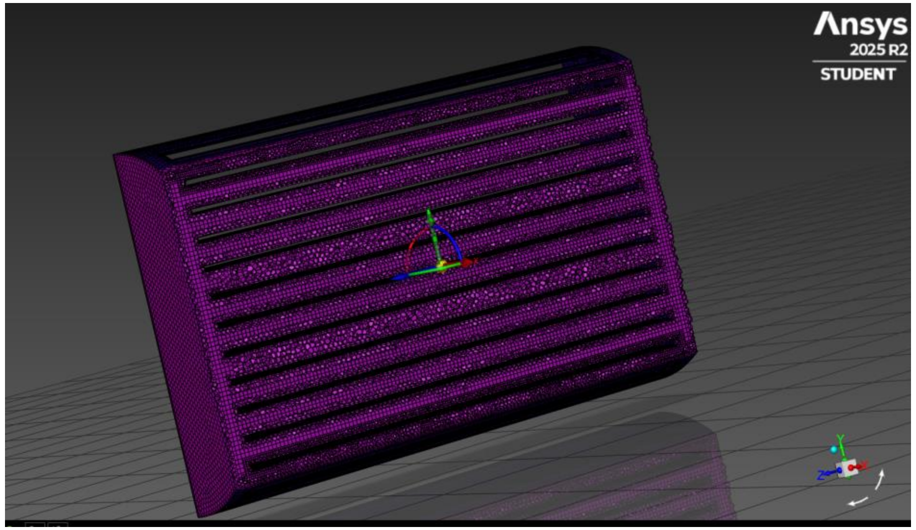
Steps for a Successful Mesh

- **Extract the volume** in between the channels as one solid piece
- **Less than 1,048,576 total cells** for mesh to be usable
- **Maximum size = .5mm** (width of channel walls)
- **Cells per Gap = 1** (to avoid having "too much detail in too little space.)
- V_{inlet}, P_{outlet} (mesher knows **not** to build boundary layers on them)
- **Boundary layers = 1 layer**, smooth transition (no slip condition, focus areas)
- **Fill with = Poly-hexcore** (uses larger hex cells and flexible/smaller polyhedral cells





Sorbent Bed ANSYS Analysis



The volume mesh has been generated with a **minimum orthogonal quality of .06** (average of .85)

Anything above a .05 can be used to converge to a solution

Ways to Improve Meshing

- After our first solution, we can calculate our y+ parameter
- This will provide a boundary layer with a much higher accuracy
- If possible, we will use a Multizone mesher that can reach mesh qualities of above .9

A solution for our pressure drop across the structure will be found in the future, along with mass transfer between sorbents

Heat Exchanger Analysis.

- @ 21 deg C

  P_sat = 2.505 kPa h_{steam} = 2539.492 kj/kg h_{liquid} = 88.57 kj/kg

  h cond = 2450.922 kj/kg   p=.0018 kg/m^3

  Power = 1 [m/s] * pi*(.04/2)^2 [m^2] * .018 [kg/m^3] * 2450.922 [kj/kg] = 55.438 [W]

  A min @ 21 deg C = q*L/(k*(dT)) = .00001789 m^2 = 17.89 mm^2

- @ 1 Kpa

  T_sat = 6.67 deg C h_{steam} = 2513.683 kj/kg h_{liquid} = 29.258 kj/kg

  h cond =2484.425 kj/kg   p=.008 kg/m^3

  Power = 1 [m/s] * pi*(.04/2)^2 [m^2] * .008 [kg/m^3] * 2484.425 [kj/kg] = 24.976 [W]

  A min @ 6.67 deg C= q*L/(k*(dT)) = .0001805 m^2 = **180.5 mm^2**

Given a fast-flowing coolant (6 deg C) with high heat capacity, and a phase change in the steam, constant temperature boundary conditions are assumed for this estimate. 2mm copper plates, k= 413 w/mk

Vacuum Chamber Flow Rates

- Hertz-Knudsen equation for evaporative flux: $\varphi = \alpha \frac{\sqrt{M}}{(2\pi RT)}(P_{(sat)} - P)$
- Ideal gas – mass flow relation: $\dot{m} = \dot{v}\frac{(PM)}{(RT)}$
- Flux continuity: $\varphi = \frac{\dot{m}}{A}$
- Phase change energy balance: $\dot{Q} = \dot{m}h_{fg}$
- Area of a circle: $A = \pi r^2$

- Φ= evaporative flux
- M= molar weight
- R= ideal gas constant
- T= temperature
- P= pressure
- $\dot{m}$= mass flow rate
- A= area
- $\dot{Q}$= heat power
- H_{fg}= enthalpy of vaporization
- R=radius

Vacuum Chamber Flow Rates (cont.)

$T = 300K$
$P = 1kPa$
$v = 1m/s$
$D_{sb} = 40mm$
$R = 8.314 J/mol*K$
$M_w = 18E-3\ kg/mol$
$hfg = 2.44E6\ J/kg$
$P_{sat} = 3.53x10^3\ Pa$

- Client requested 1m/s flow velocity in sorbent bed
- Converted to flow rate
- Converted to mass transfer: $\dot{m} = 9.06E-6\ kg/s$
- Converted Hertz-Knudsen eqn from flux to mass transfer
- Plugged in mass transfer to find surface area needed for correct evaporative mass transfer rate
- Also plugged in mass transfer to phase change eqn to find heat power
- CONCLUSION: to maintain a flow of 1 m/s in the sorbent bed at T=27C and P=1kPa
  - The boiler surface area must be 112 mm^2
  - The heating element must be able to sustain a power output average of 22.1 W

Engineering Calculations: ERs to be Quantified

- Minimize power requirement: need to benchmark current DAC devices to quantify what kW / gram CO_2 is considered efficient.
- Efficient CO_2 capture: benchmark current DAC devices to quantify grams CO_2 / volume air
- Ideal packing density and void fraction: Calculate power draw of vacuum pump at different pressure drops due to packing density and void fraction
- Compact size: need to finish sizing all parts, then sum dimensions in each axis

Design Validation: FMEA

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)
Control hardware	Malfunction	Unable to control pump, heating, etc	10	Poor Monitoring/Calibration	Medium
1-8, Valves	Corrosion/Wear	Unable to control cycle steps	5	Poor Maintenance	Low
9, Bolier Reservoir	Overheating	High Pressure (possible explosion)	8	Poor Maintenance	Low
10, Water K/O reservoir	Carbonic Acid Buildup	Corrosion in entire system as water flows	5	Poor Maintenance	Low
12, Vacuum Pump	Overheating	Pump breaks, pressure rises	7	Poor Maintenance	Low
20, Heating Element	Control Malfunction	Overheats Boiler Reservoir	8	Poor Maintenance	Low
21, Condenser	Over-freezing	Pipes freeze or vapor contamination	5	Poor Monitoring/Calibration	Low
26, Sorbent Bed	Sorbent Rubbing/Reaction	Heating and Microparticle infiltration	6	Poor Maintenance	Medium
36, Filter	Particle Wear	Vacuum pump and sensor damage	7	Poor Maintenance	Low
37, CO_2 Vessel	Overpressurization	Explosion/Concentrated CO_2 leaking	9	Poor Maintenance/Safety	Medium
KF25/40 tubing and adapters	Corrosion/Wear	Leaking and ruined experiment	5	Poor Maintenance	Low

- Almost every problem can be avoided with regular maintenance and monitoring.
- After our initial reactor is assembled we will be testing, calibrating, and troubleshooting the heating element, condenser, and CO2 pressurization

Design Validation: Testing Procedures (Short Term)

- Test subsystems individually to verify efficient PID loops:
  - Run vacuum pump PID loop on simple throttled chamber
  - Test boiler heating PID loop for temperature control
  - Test water K/O reservoir high/low drain logic
- Test pressure drop across sorbent structure for CFD validation
  - Test pressure drop across structure with ambient air
  - Test pressure drop across structure with air at vacuum pressure
  - Test pressure drop across structure with water vapor at vacuum pressure
  - Compare all experimental data to Mathematical CFD data

Design Validation: Testing Procedures (Long Term)

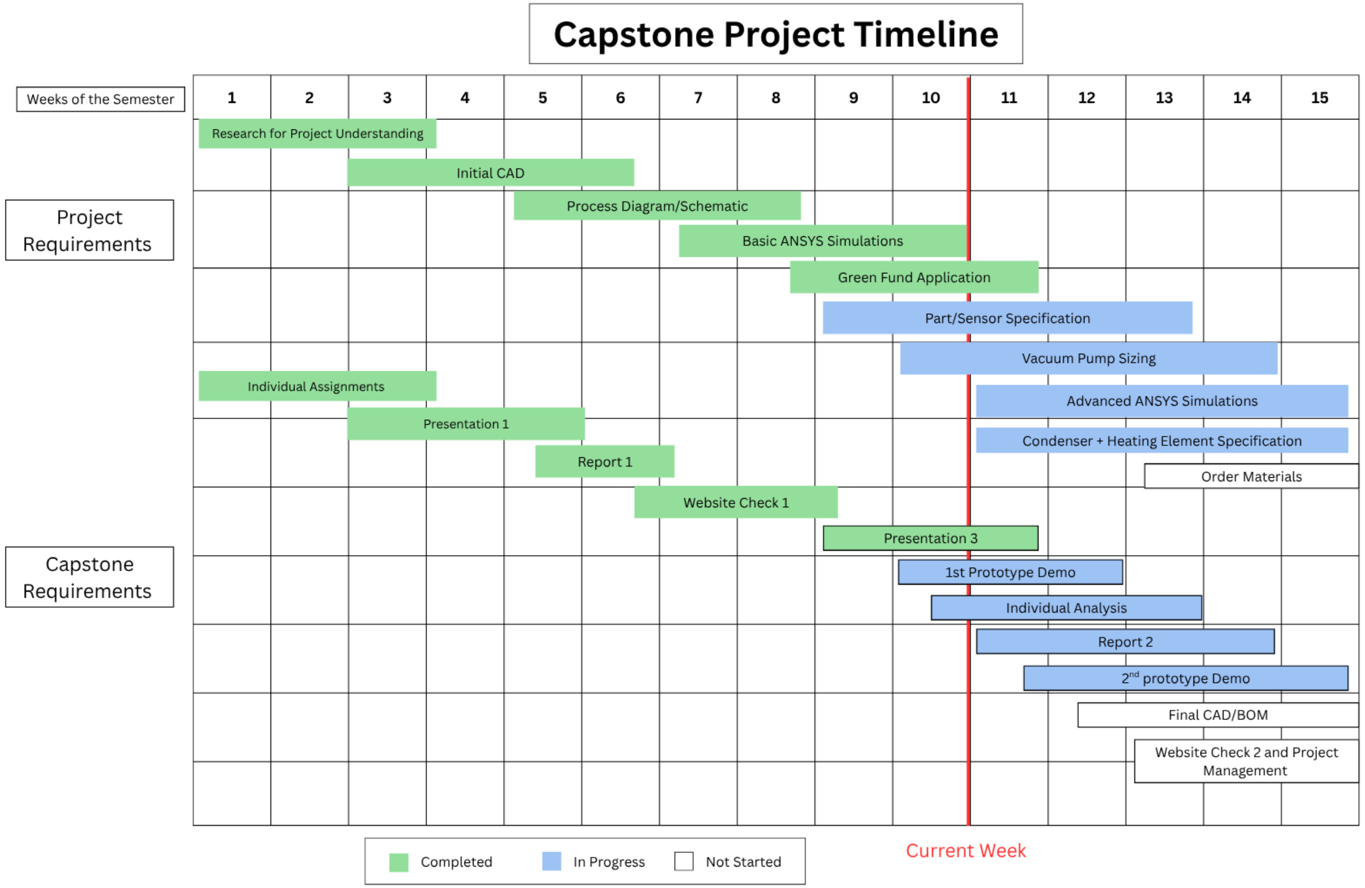
- Test full build with extra sensors:
  - Run cycles with power meter connected to track power consumption
  - Run cycles with weight scales under water reservoirs to track mass transfer and water recycle efficiency
  - Run cycles comparing flow rate of air and volume/time of CO_2 canister fill to analyze CO_2 capture efficiency
  - Run cycles with different 3D printed sorbent bed designs and compare pressure drop and power consumption
  - Run repeated cycles to confirm ability to run long-term without overheating, over-cooling, or imbalance of water reservoirs.

Design Validation: Resources Needed

- Lab space – open workbenches in Climate Solutions Lab
- Power source – lab has variety of power outlets with suitable voltages and phases
- Water source – deionized water
- Sensors - Thermocouples, pressure transducers, weight scales, power meters, DMM for validation
- Time - cycle times will be long (single cycle ~ 1-2 hours, multiple cycles)

Schedule

- We are mostly on time
  - slightly behind on purchasing due to a bottle neck in the pump selection process
  - Ready to begin purchasing parts next week



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
  - Application currently in progress
- We have yet to purchase because the system must be fully designed for parts to fit.

	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

Budget: Anticipated expenses

- Before the pump, mounting hardware, electronics, and extra fittings the total cost is $8146.00
- The heat exchanger is the greatest expense.
- An additional $1648.43 will be required for sensors

Designation	Price	Quantity	Total Price
PT	$420.73	3	$1,262.19
TC	$96.56	3	$289.68
TC3	96.56	1	$96.56
LS		2	$0.00
		sum =	**1648.43**

BOM Level	Designation	Manufacturer	Unit Price	Quantity	Total Price
1	Boiler reservoir	Ideal vaccum	516.8	1	516.8
2	K/O reservoir			1	0
3	NPT single adaper	Ideal vaccum	86.27	1	86.27
4	Elbow	Ideal vaccum	94.9	1	94.9
5	1" Npt Ball Valve	U.S. Solid	64.99	4	259.96
6	1" NPT adapter	Ideal vaccum	143.78	8	1150.24
7	Cross	Ideal vaccum	242.62	1	242.62
8	Manual valve	Ideal vaccum	19.43	1	19.43
9	KF40 to ? Adapter	Ideal vaccum	64.57	1	64.57
10	Filter			1	0
11	NPT triple adapter	Ideal vaccum	130.07	2	260.14
12	Mesh centering ring	Ideal vaccum	59.27	2	118.54
13	Sorbent bed	Ideal vaccum	86.27	1	86.27
14	KF40 tee	Ideal vaccum	133.37	1	133.37
15	Gas check valve	Ideal vaccum	417.96	1	417.96
16	HX	Yamato Scientific	3752.29	1	3752.29
17	Pipe			0	0
18	Water valve	U.S. Solid	64.99	1	64.99
19	KF40-KF25 adapter	Ideal vaccum	64.57	1	64.57
20	Vacuum pump	Pfeiffer		1	0
21	KF25 tee	Ideal vaccum	120.01	1	120.01
22	KF25 valve	Pfeiffer		2	0
23	CO2 collection			1	0
24	KF40 Clamp	Ideal vaccum	20.26	17	344.42
25	KF40 centering ring	Ideal vaccum	15.25	15	228.75
26	KF25 clamp	Ideal vaccum	12.25	5	61.25
27	KF25 centering ring	Ideal vaccum	9.93	5	49.65
28	Plug	Joywayus	9	1	9

Budget: Green Fund

- Green Fund donation will cover:
  - Experimental ceramic 3D printer
    - Allows for printing of viscous and grainy materials which will allow sorbent to be printed into complex structures.
  - Air compressor and fittings to feed nozzle
  - Spare parts known to commonly brake
  - Clay to begin commissioning printer
- Green Fund will review proposal 11/7/2025

Incomes	
Green Fund Donation	+$2,049.65
Expenses	
Eazao Bio printer (E)	-$899
Air control box (E)	-$500
x2 30mL cartridges (E)	-$16
x3 55mL cartridges (E)	-$36
x5 Print release films (E)	-$25
x2 Eazao nozzles 4pk (E)	-$10
x2 Eazao nozzle adapters (E)	-$10
Eazao tax and shipping (E)	-$189.38
1gal air compressor (HD)	-$149
Husky air hose kit (HD)	-$20.98
Husky air filter (HD)	-$16.48
PTFE tape (HD)	-$0.98
Home Depot tax (HD)	-$18.94
x3 NPT to pneumatic adpater	-$14.83
5lb Clay	-$26.69
24pc Nozzle kit	-$18.77
%5 Contingency	-$97.60
Net Balance	$0

Thank You

Questions?