Thermal Storage Device
Group 17

JHAMAL HOLLIDAY

BELAL NABULSI

CORY NELSON

BRUCE OROZCO

Verdicorp, Inc.

- Organic Rankine Cycle Power systems
- Builds Modular Vapor Power cycles
- Runs from waste or low temperature heat sources
- Uses environmentally friendly fluids (R245a)

Figure 1. Image of Verdicorp ORC System

Need & Solution

Depending on waste or renewable heat sources causes:

1. unreliable power output
2. Limits running time to that of the fuel source
3. Decreases system efficiency

Solved by inclusion of Thermal Energy Storage

Goal: To produce a commercially viable thermal storage solution for Verdicorp's Rankine Cycle utilizing environmentally friendly materials.

System overview

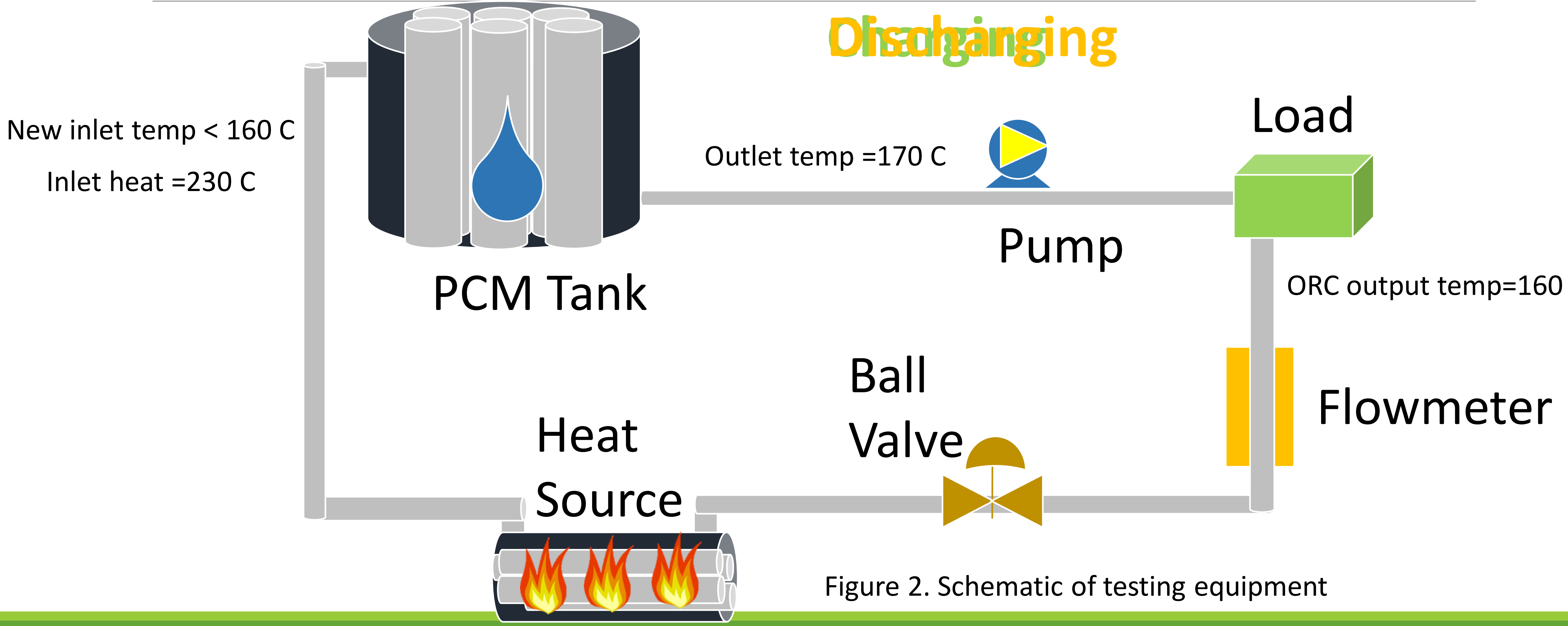


Figure 2. Schematic of testing equipment

Thermal Energy Storage

Forms of storage:

- Sensible
- Latent

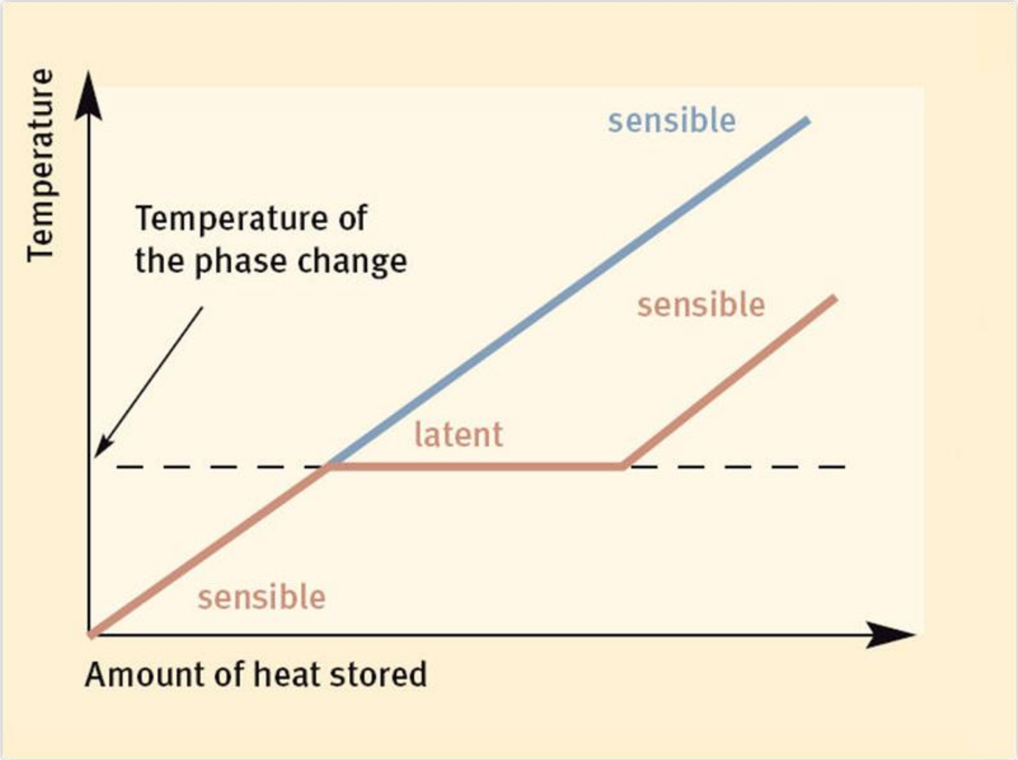


Figure 3. Heat Storage Forms

Latent heat storage

- Based on Shell-and-tube heat exchanger
- Tubes are 12 inch long Schedule 10
- Transfer fluid transfers heat to/from phase change material
- Full size: 37.8GJ Model: 8.8MJ
- Energy Scale: 1/4000th
- Capsule Length Scale: 1/20th

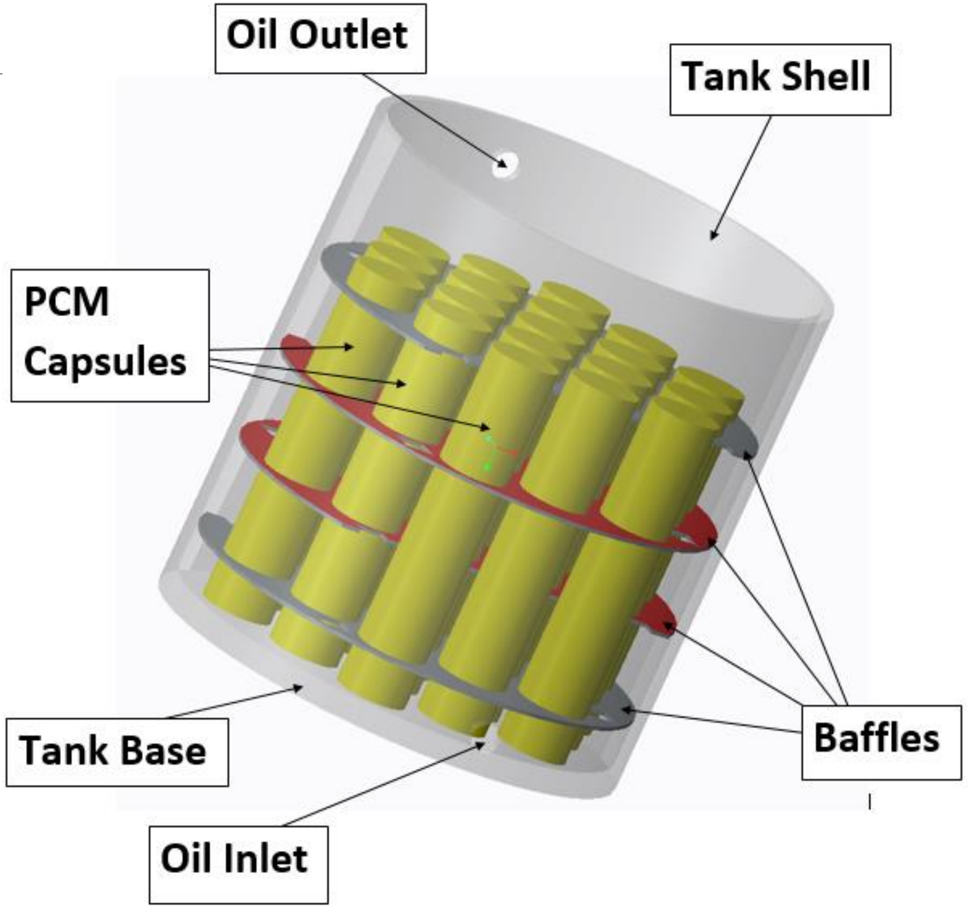


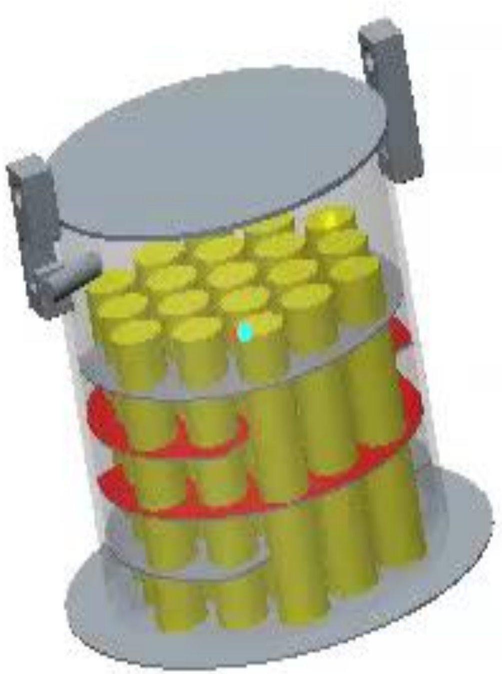
Figure 4. Model of Latent Heat Storage Device

Fluid Flow: Single Segmental

- Fluid flow is dictated by baffles
- Baffle cuts are 30% of tank inside diameter
- Spacing is 1/5 the tank inside diameter
  - 3.05 in apart
- Tube Pitch is the center-to-center distance of each tube
  - 1.25 times outside diameter of tube

Figure 5. Animation of Fluid Flow in Shell

Single Segmental Configuration



Fluid Flow:
Disk and Doughnut

Annular area between disk and shell is same as area of ring

Spacing is 1/5 the tank inside diameter

- 3.05 in apart

Tube Pitch is the center-to-center distance of each tube

- 1.25 times outside diameter of tube

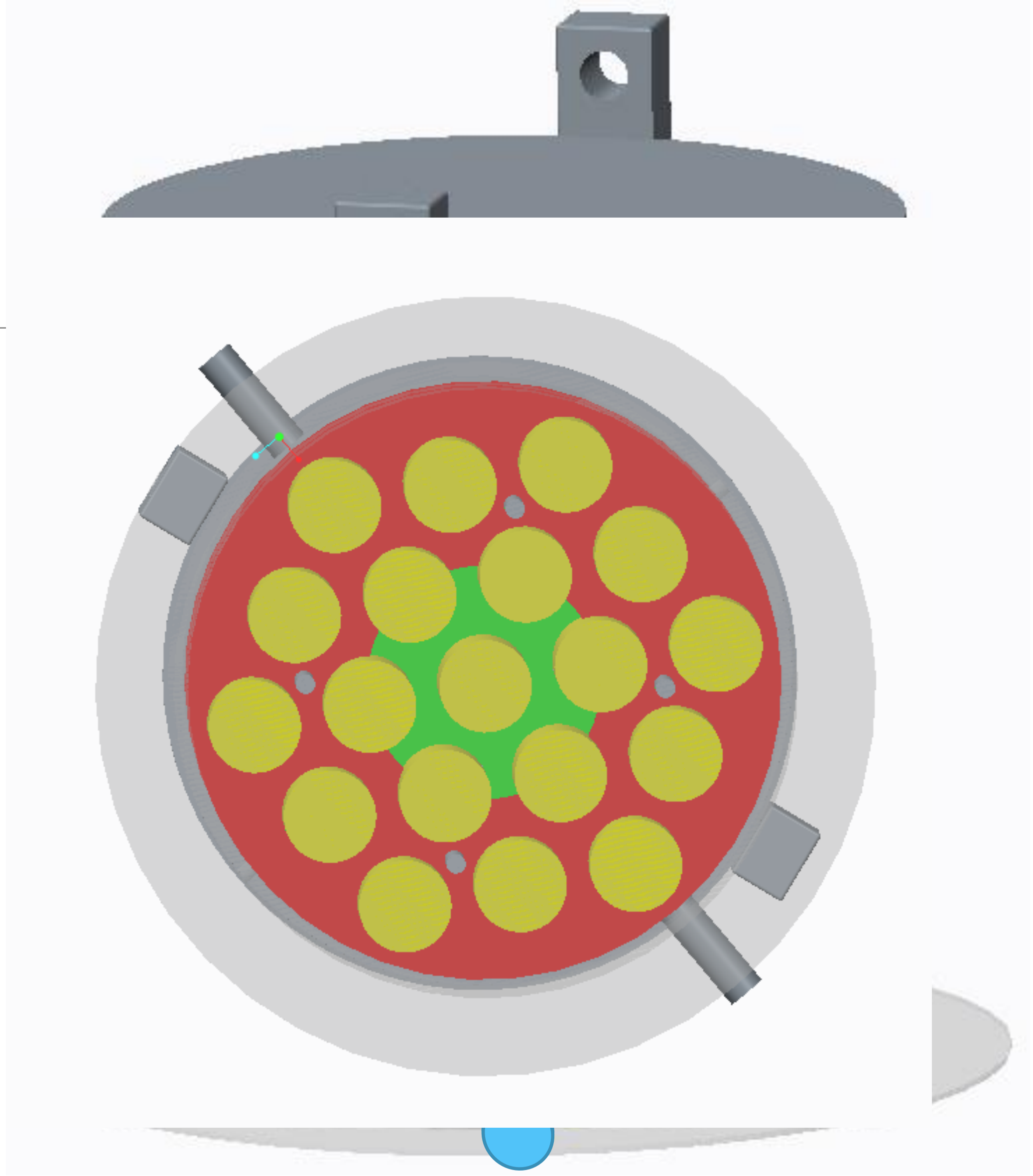
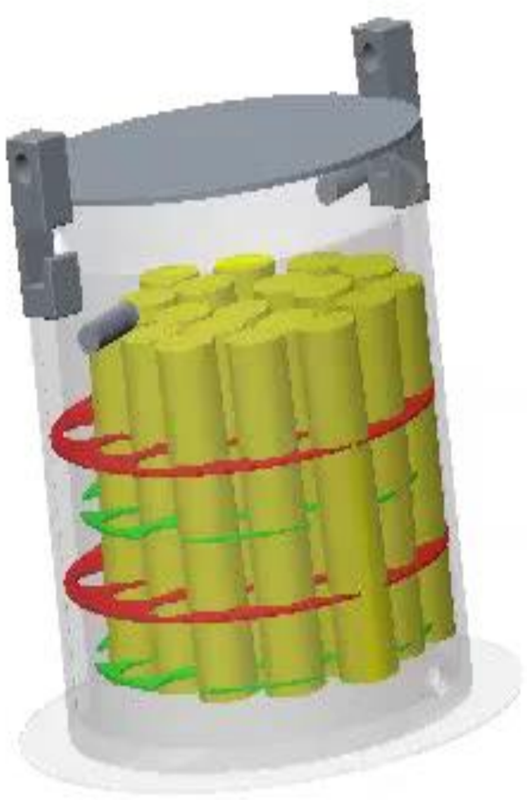


Figure 6. Animation of Fluid Flow in Shell

Disk and Doughnut Configuration



Which Do We Choose?

Table 1 Pros and cons of the two configurations

Single Segmental Configuration		**Disk and Doughnut Configuration**	
Pros	**Cons**	**Pros**	**Cons**
Easy to assemble	Sharp bends cause Higher pressure drop	Gradual bends cause Less pressure drop	Harder to assemble
Proven and used extensively	Not ideal in high vibration situations	Less Likely to have dead zones	More likely to produce laminar flow patterns
More likely to produce turbulent flow & enhance heat transfer	Likely to produce dead zones if not careful resulting in increased fouling	Great for high vibration	Fouling is a greater concern for this type

Storage Medium & Transfer Fluid

DYNALENE MS-1 (PHASE CHANGE MATERIAL)

- Molten Salt with minimal corrosion to stainless steel
- Stable thermal properties throughout operation temperature range
- 3% expansion allows for higher power density per capsule
- Melting Point of 225°C

DURATHERM HF (HEAT TRANSFER FLUID)

- Petroleum based
- High oxidation resistance
- Low viscosity
- Available at the price of synthetic car oil
- Flash point of 275°C
- Compatible with steels and aluminum

Table of Material Properties

Table 2 Properties for tank materials including oil and salt

Property	Dynalene, MS-1	Duratherm HF	304 Stainless Steel
Specific Heat kJ/kg*K	C_{PD} = 1.4	C_{PL} = 2.587	-
Thermal Conductivity W/m*K	k_D = 0.5 (200)	k_L =0.225 (260)	k_S = 16.2
Density kg/m^3	ρ_D= 1900	ρ_L= 700	-
Viscosity m^2/s	-	$10.45*10^{-6}$	-

Simulation: What we expect

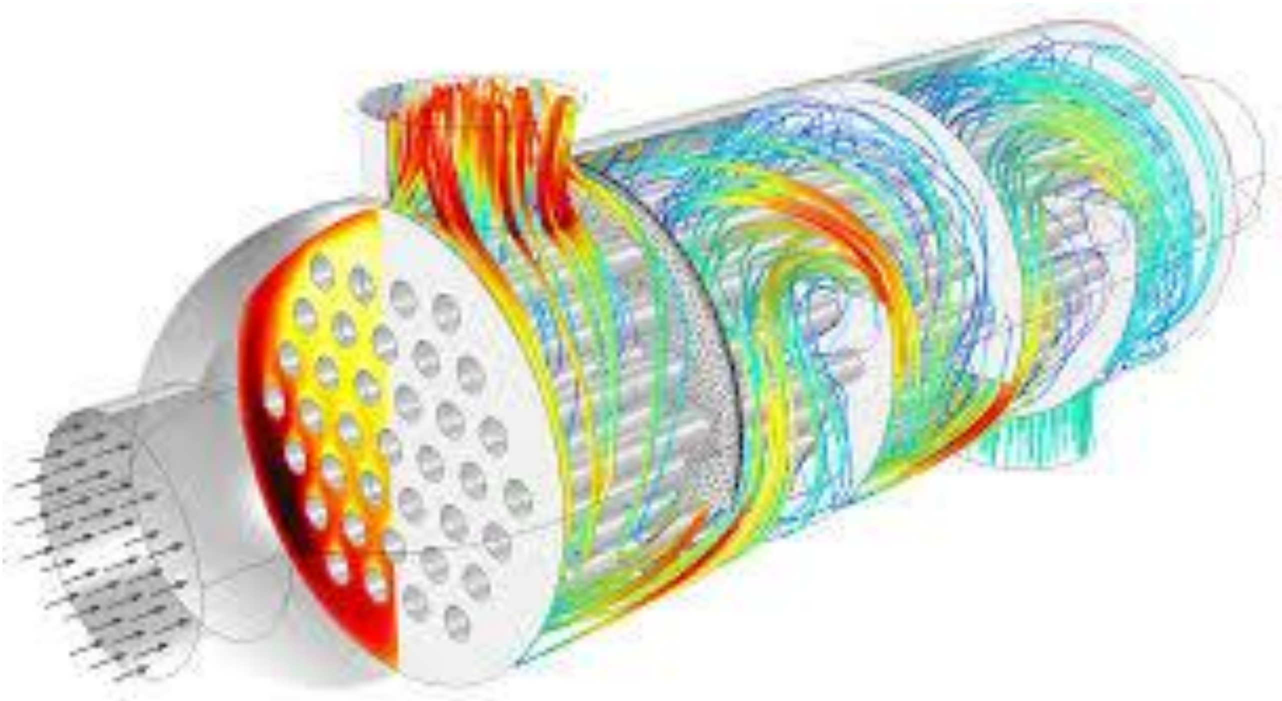


Figure 6. Generic Example of Flow in Shell-and-tube Exchanger

Simulation Method

Methodology

1. Take the inlet temp. and calculate the heat lost per level
2. Record energy stored per level
3. Recalculate the Duratherm temp. and use as T_{inf} for adjacent level
4. Record total energy stored
5. Repeat over 15min intervals

Assumptions

- Flow rate of 0.27gpm
- Ambient temperature for each level is constant
- Initial Duratherm Inlet temperature of 240°C
- losses of 205W based on tank held at 240°C in room temp. conditions

Charging Time - Simulation Results

CHARGING TIME OF 2.25HRS

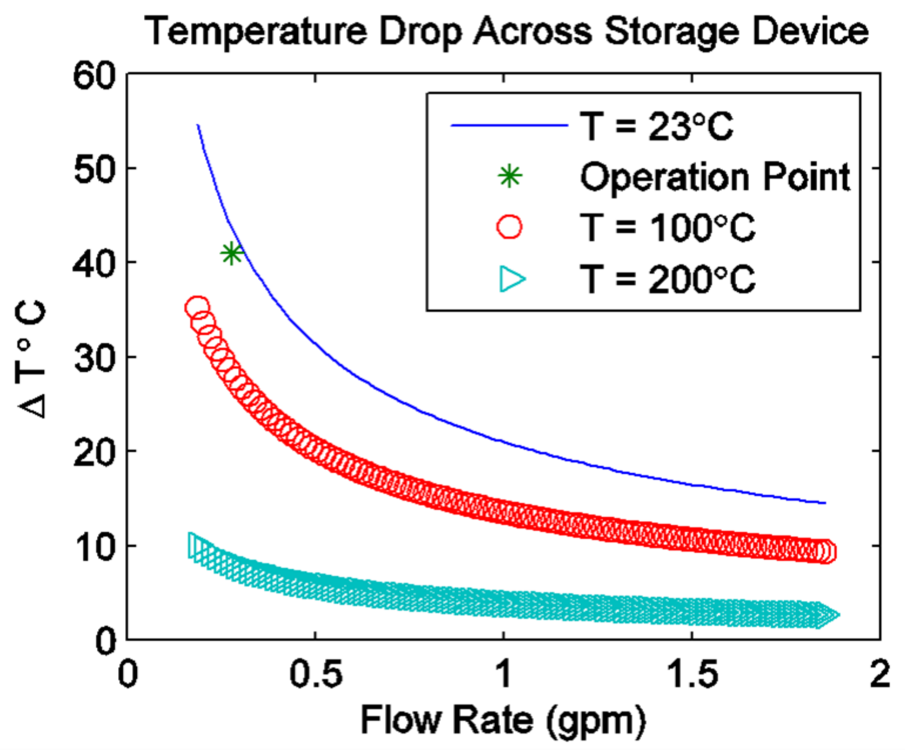


Figure 7. Energy stored vs. Time

EFFICIENCY

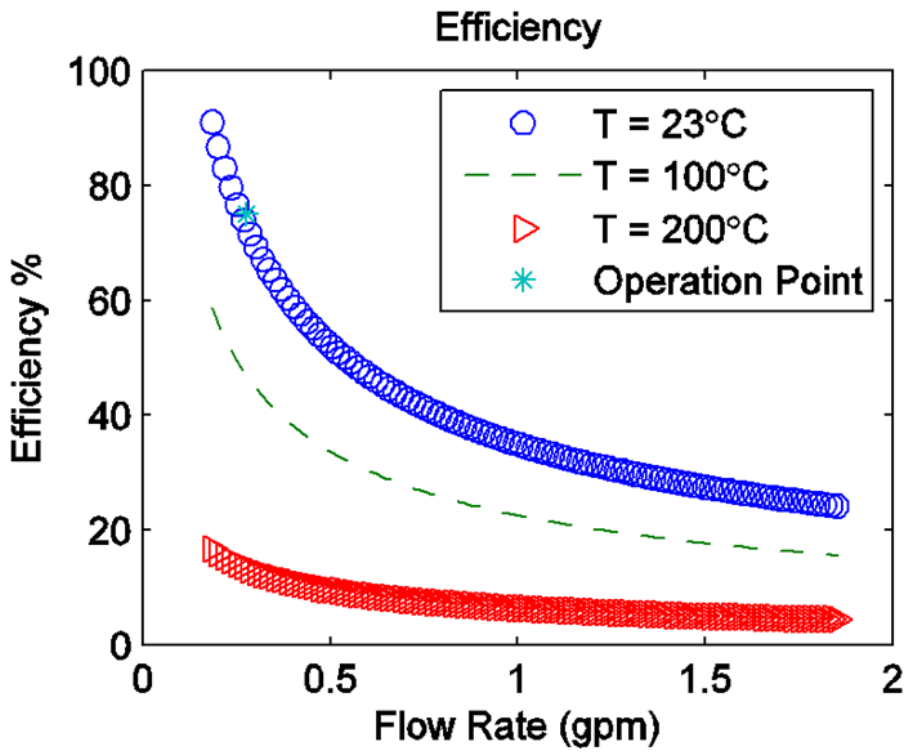


Figure 8. Temperature vs. Time

Charging Time Cont. – Simulation Results

THERMAL TANK OUTPUT TEMPERATURE

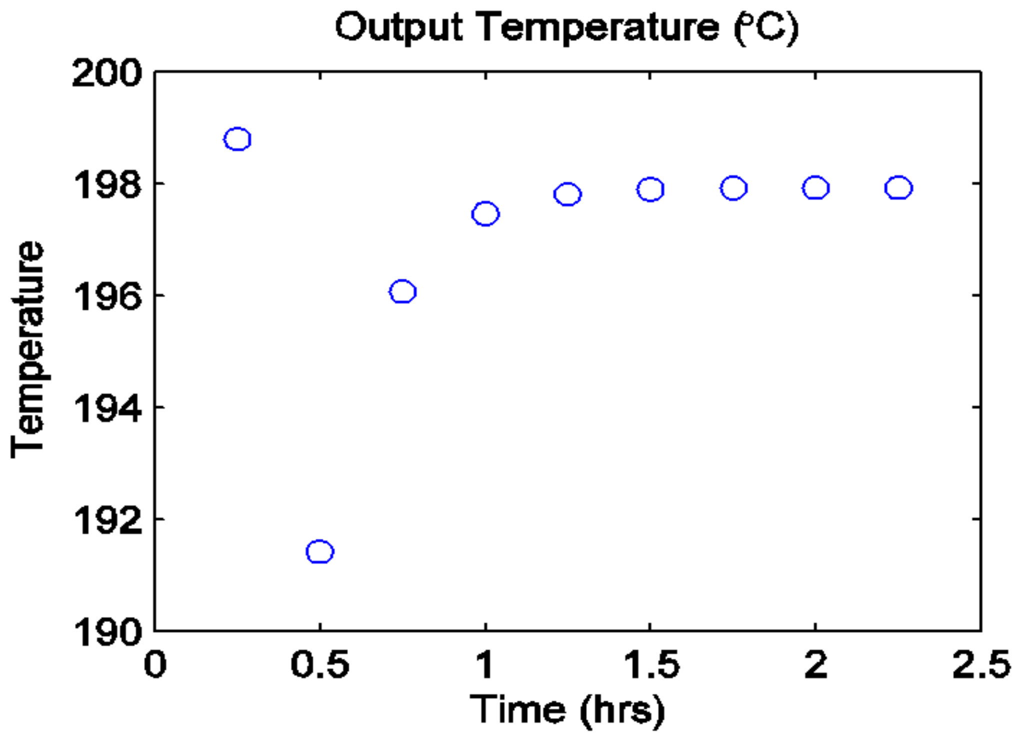


Figure 9. Output Temperature vs. Time

ANALYSIS SUMMARY

- ✓Charges in 2.25 hours
- ✓Output temperature is stabilizes at 200°C
- ✓Operates at an efficiency of 70%
- ✓7Pa pressure drop

Operation Time - Simulation Results

At the end of charging:

- Energy stored is 8.8MJ
- However the useful Stored above 170°C is 4.9MJ
- 44% of the energy stored can not be used to produce electricity
- 34mins On full load, 2274W (70°C drop at 0.27gpm)

- Found by using the energy balance equation below:

$$Energy_{useful} = time * (load + losses)$$

How Does It Work?

System overview

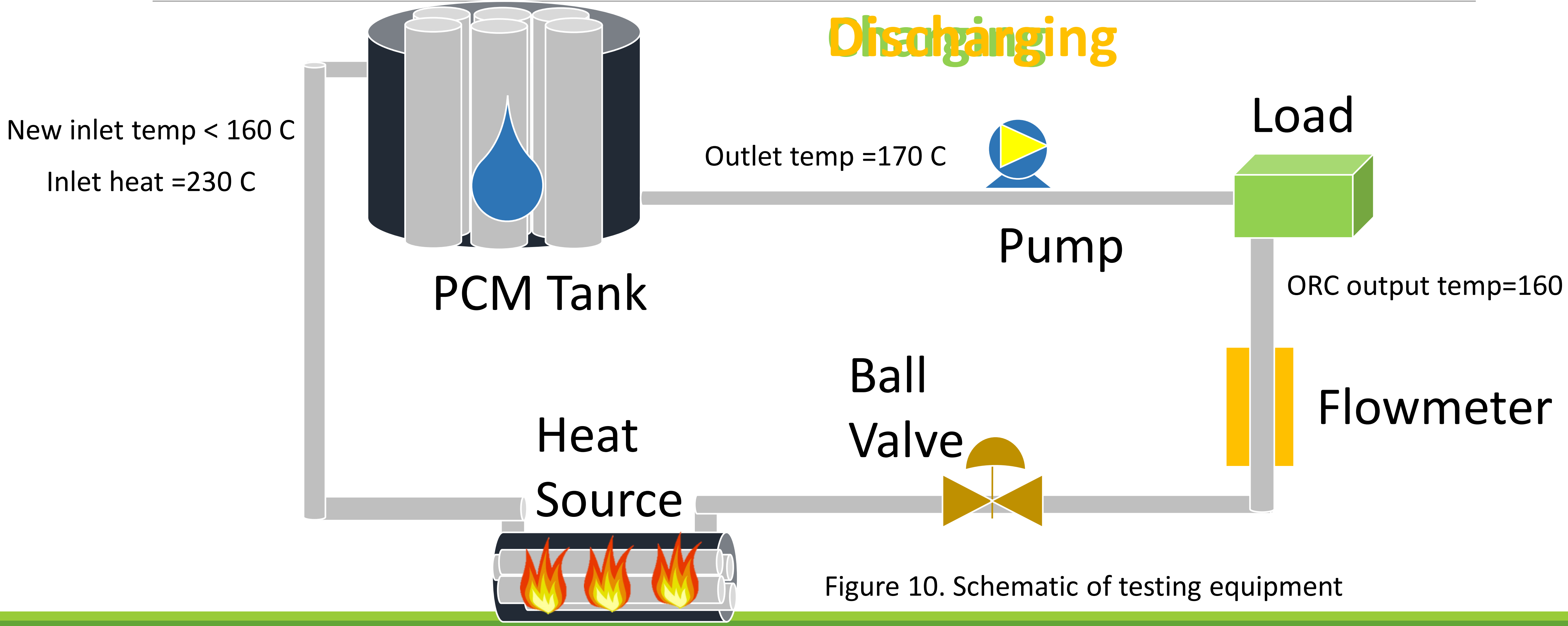


Figure 10. Schematic of testing equipment

PCM Tank

- Base
  - Diameter: 18”
  - Height: ¼”
- Tank
  - Outer Diameter: 16”
  - Inner Diameter: 15-1/4”
  - Height: 17”
- Top
  - Diameter: 16-1/4”
  - Overall Height: 2-1/4”

Figure 11. Final tank assembly

PCM Tank Lid

Figure 12. Tank caps

- Water tight welds were used to secure the base to the bottom of the tank
- A 1/4” tall ring with a diameter of 15” was welded to the top to prevent it from slipping off
- A handle was then welded to the top for easier mobility
- The inlet and outlet holes were drilled in the tank at the desired locations and caps were added

Baffles

Figure 13. Baffles

- Fabricated at the college of engineering in the machine shop using the water jet
- Fourth baffle had small defect but will be fixed by the end of the day today
- Next step is to build baffle frame with threaded rod and insert into the tank
- Excess threaded rod will be used to lock frame of baffles in place to prevent movement caused by the oil flow

Heat Exchanger Load

Hayden #1260 Liquid-to-air Heat Exchanger

- Provided by Verdicorp
- Coupled with 2 60/75W fans
  Mechatronics® Model:UF25GCA12
- Requires 115V
- ¾" pipe diameter
- Finned
- 6 levels

Figure 14. Heat Exchanger and Fan Assembly

Heat Source

Cartridge Heater

Provided by Verdicorp

Rated at 1500W each Only 1 is Needed at steady state

Using Q = $\dot{m}C_p(230^{\circ}\text{C}) \approx 6{,}000W$

Need up to 6 cartridges to have speedy start up time at0.27gpm

Figure 15. Generic Cartridge Heaters

Heat Source

Figure 16. Proposed Heat Source & Final Design

Manufacturing / Budget Bar

<u>Table 3 Manufacturing Purchases</u>

What was provided?	What was bought?
Tank	Flowmeter
Baffles	PCM Salt
PCM Capsules	Heat Transfer Oil
Heat Source	Piping/Fittings

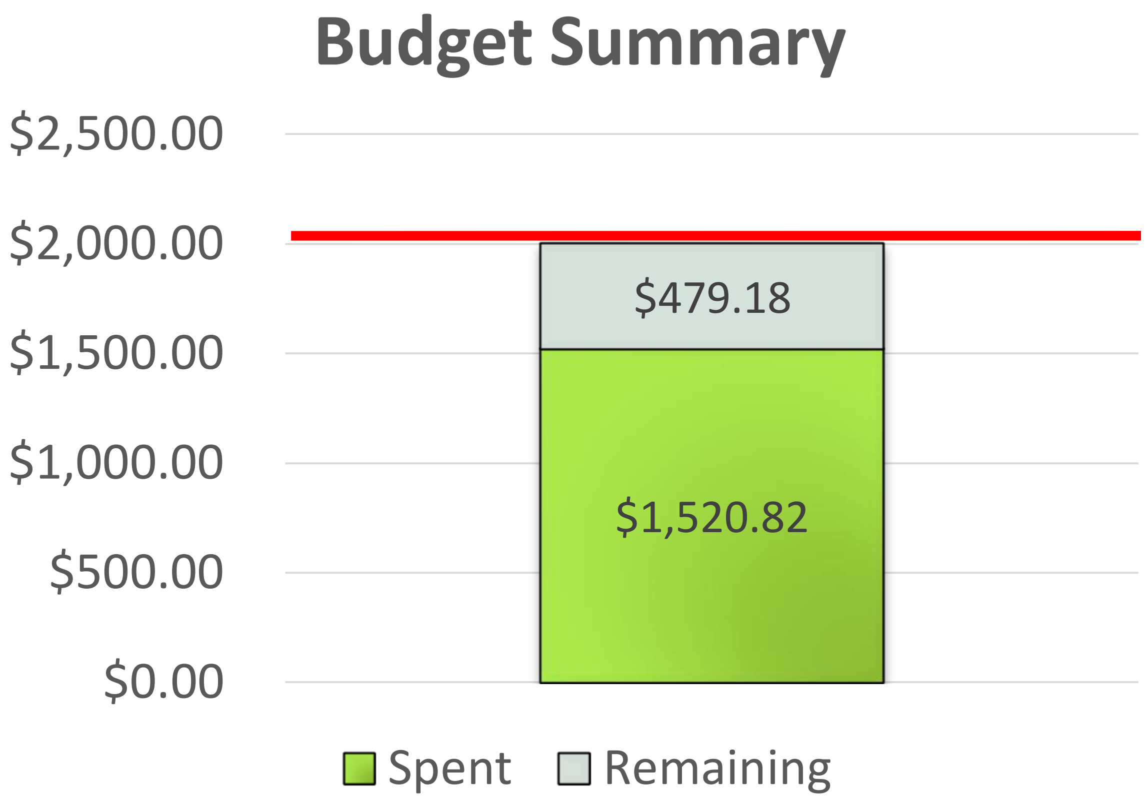


Figure 17. Final budget

Testing: What We Actually Found

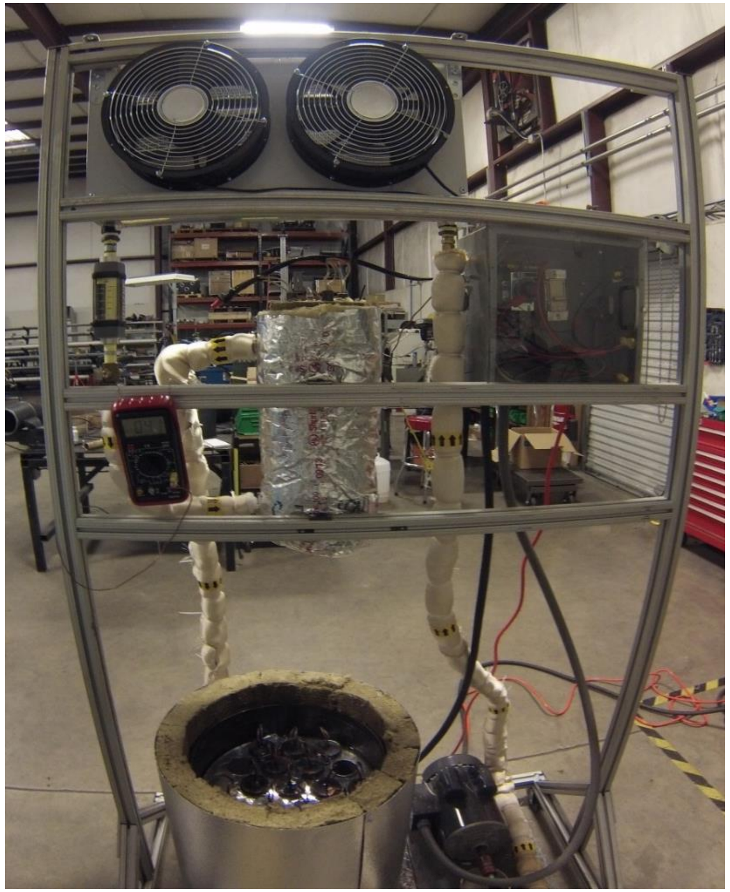


Figure 18. Assembled System

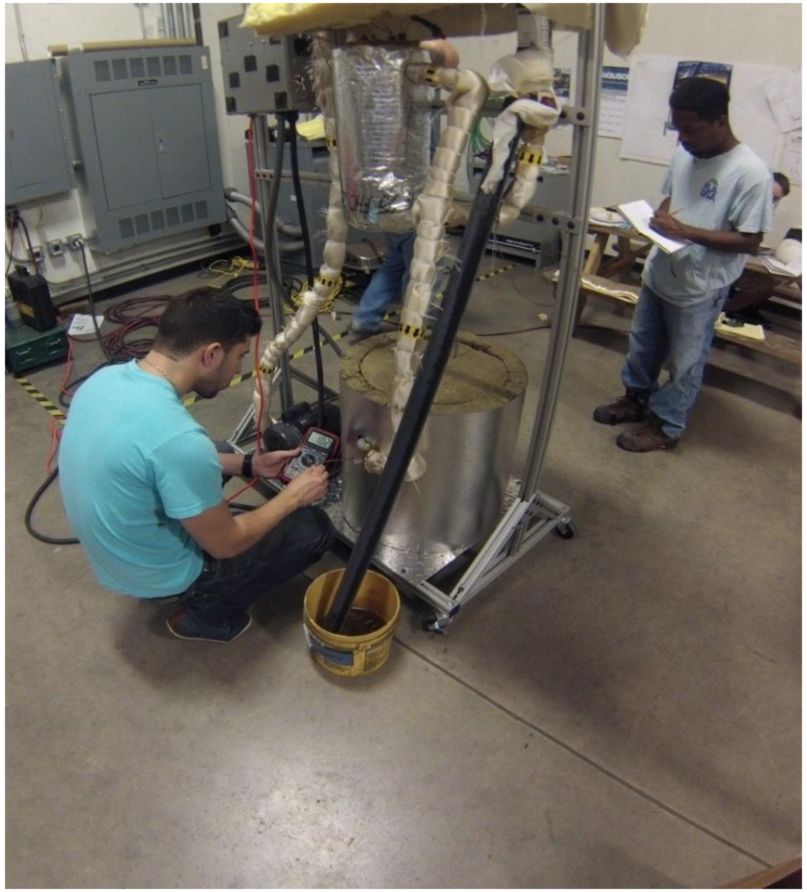


Figure 19. Group Measuring Temperatures

Assembly variations

Verdicorp unable to complete the design of a new manufacturing process to vacuum seal capsules

- ❑PCM capsules were given an air gap
- ❑Allowed to expand during phase change by displacing air
- ❑Outlet at the top of the tank became the inlet

Figure 20. Capsules with attached pigtails

Testing

1. Recorded ambient temperature conditions
2. Pulled emergency stop to deliver power to the system
3. Turn pump on
4. Turn heater on with Temperature controller

Include video

Testing Results

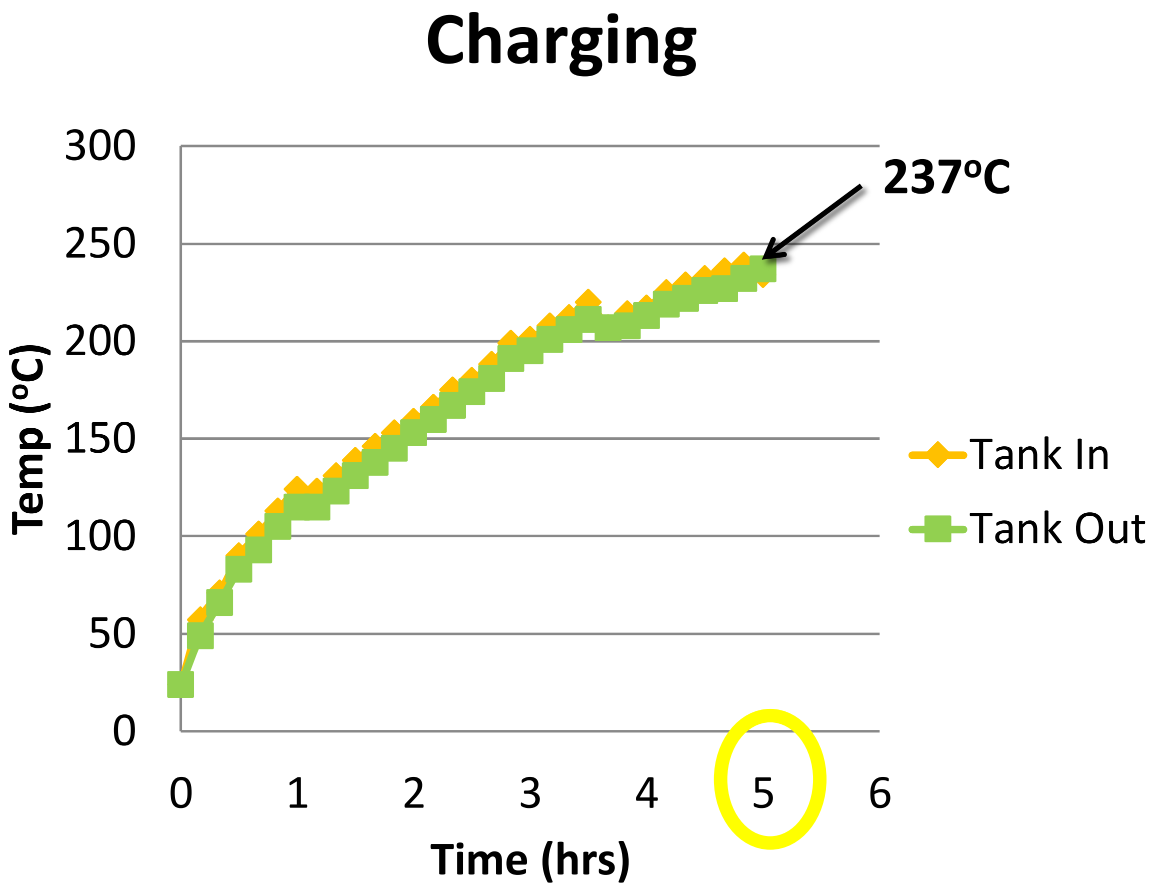


Figure 21. Animation of Fluid Flow in Shell

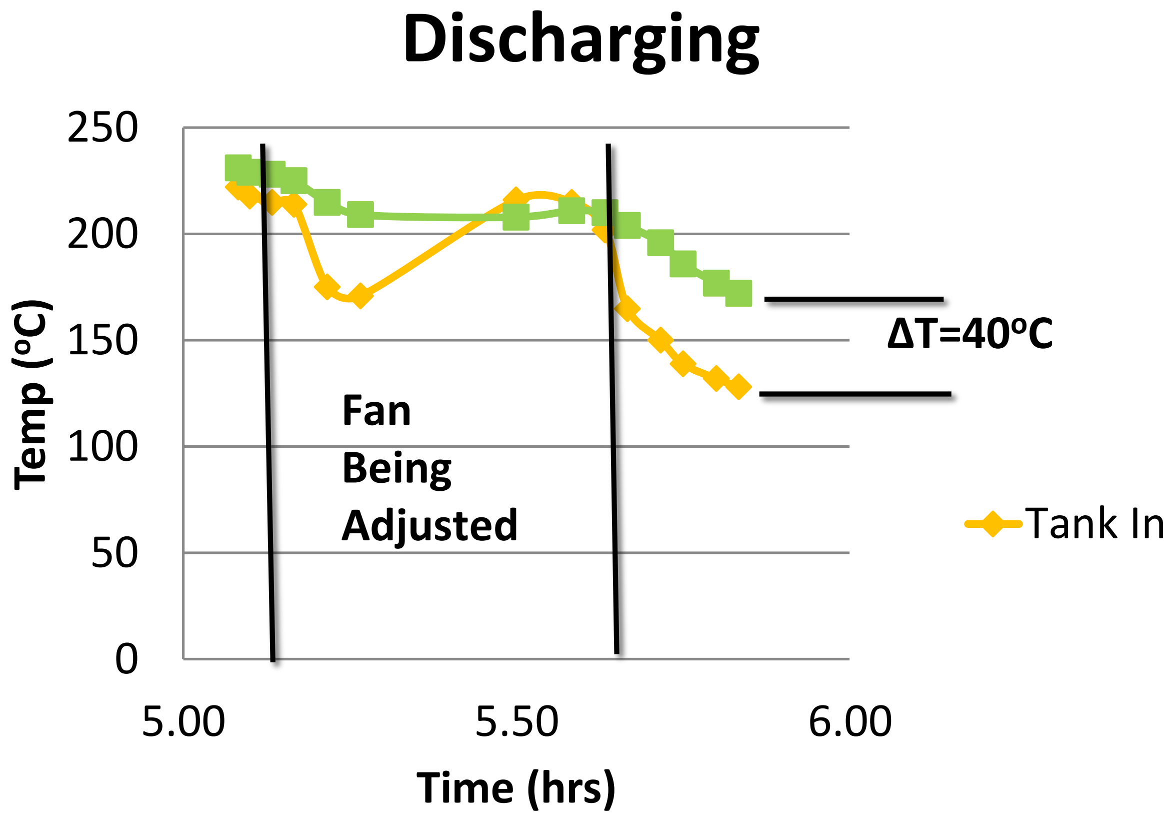


Figure 22. Animation of Fluid Flow in Shell

Issues Encountered

1. Flowmeter failed during testing due to excessive heat
2. Fans mounted to the load failed due to excessive heat
3. Increased flow rate to 1.12gpm during charging cycle to keep Resistance heaters from over heating drastically increased charging time

Figure 23. Damaged Flow Meter

Overcoming obstacles

Problem	Solution
Burnt out load fans	Replace fan with on hand fan that blew air across the load from a distance
Flow meter failure	1. Heat source was turned off 2. Pump remained on with the setup/ unknown flow rate 3. After system cooled, recorded the time it took to fill a cup of known volume 3 times

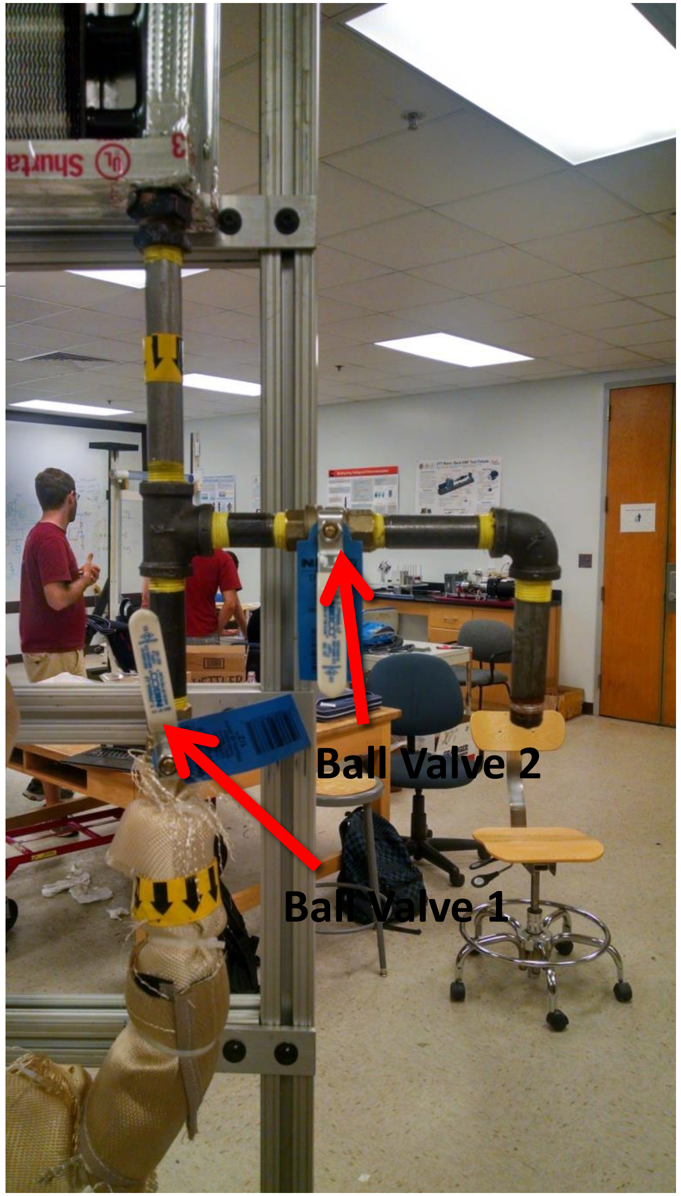


Figure 24. Flow meter work around

Lessons Learned

- Check parts for consistency between those delivered and those specified
- Real world international projects are dynamic and subject to change abruptly
- Confirm components can be delivered on time.
- Take into consideration minor details. You will be surprised how much knowledge it takes to seal a pipe, fasten a screw, or weld two pieces of metal.
- Take into consideration machine shop time and assembly. It’s never as easy as it sounds.
- Be professional. Respect each other and the sponsor.

Business Case

Full Scale Model (For 14hours and Assuming Safety Factor of 1.5):

Need approximately 6,121capsules (2” inner diameter and 20ft tall)

Tank would need to be 22.5ft wide and 22.5ft tall

Price of Materials

Totaling over $3.7

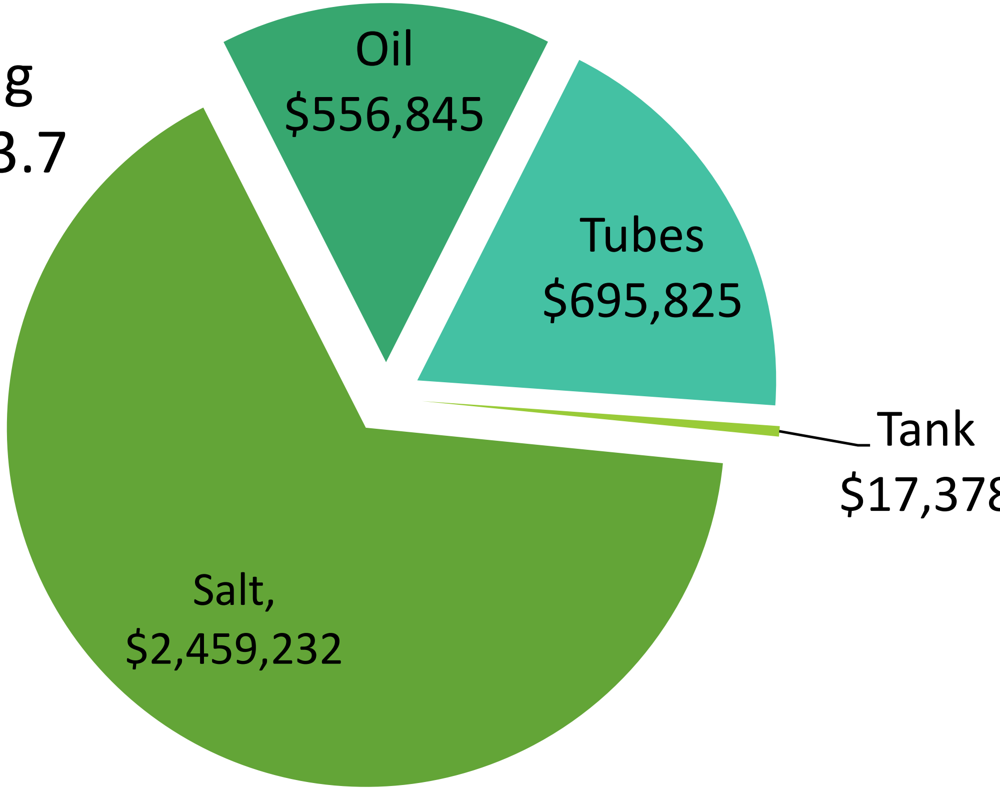


Figure 25. Cost Breakdown for full scale Project

Thanks!!

Verdicorp

Dr. Gupta

Dr. Shih

Figure 26. Group 17

Resources

Hasnain, S.M., "Review on Sustainable Thermal Energy Storage Technologies, Part 1: Heat Storage Materials And Techniques," Energy Conversion Mgmt., Vol. 39 No. 11 pp1127-1138, 1997.

Sharma, Atul, Tyagi, V.V., Chen, C.R., Buddhi, D., "Review on Thermal Energy Storage with Phase Change materials and applications," Renewable and Sustainable Energy Reviews 13, pp318-345, 2009.

Cengel, Yunus, and Cimbala, John M., and Turner, Robert, *Fundamentals of Thermal Fluid Sciences*, 4th ed., New York, New York, 2011

Mukherjee, R , (2014, December 20) *Effectively Design Shell-and-Tube Heat Exchangers*. *(1st ed.)* [Online] Available: http://www.mie.uth.gr/ekp_yliko/CEP_Shell_and_Tube_HX.pdf

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Appendix Follows

Convection Coefficient Single Segmental

Determining h, the convective heat transfer coefficient

$h = \frac{Nu * K_L}{D}$, where D (2.375in) diameter of the capsule

Nusselt's Number, Nu, for flow across a cylinder defined as:

$$Nu = 0.3 + \frac{0.62 * Re^{0.5} * Pr^{\frac{1}{3}} * \left(1 + \frac{Re}{282000}^{\frac{5}{8}}\right)\hat{}\left(\frac{4}{5}\right)}{(1+(0.4/Pr)^{2/3})^{1/4}}$$

Prandtl's Number, Pr = $(viscosity * \rho_L * C_{PL})/k_L$

Reynold's Number, Re = $(v * D_h)/viscosity$

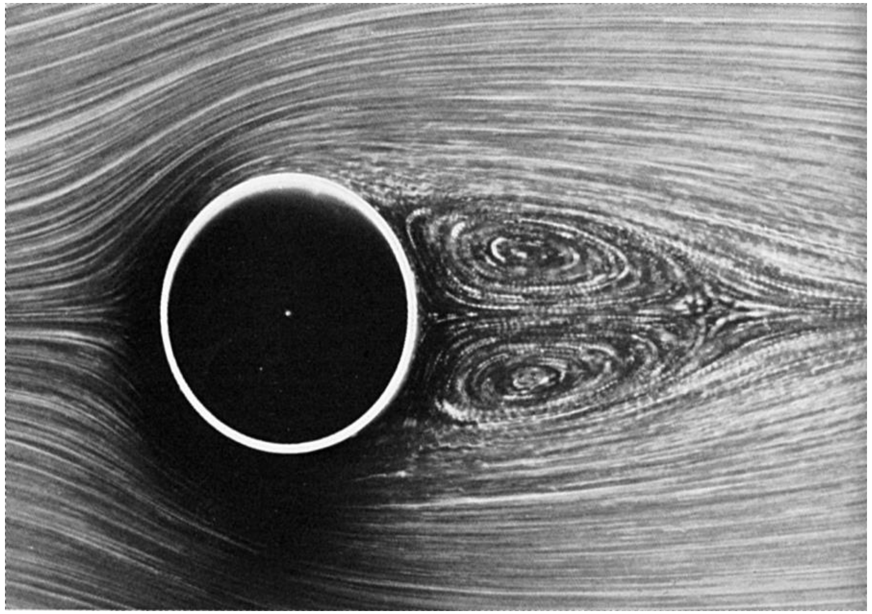

Figure 27. Example of external flow around a cylinder

Convection Coefficient Disc & Doughnut

Determining h, the convective heat transfer coefficient

$h = \frac{Nu * K_L}{D}$, where D (2.375in) diameter of the capsule

Nusselt's Number, Nu, for flow in a rectangular pipe:

$Nu = 0.664 * Re_L^{0.5} * Pr^{1/3}$

Prandtl's Number remains the same

Reynold's Number, Re = $(v * D_h)/viscosity$ = 21.4

Changing hydraulic diameter to

$D_h = 4 * \text{Area}_{\text{UA}}/(\text{pi} * r_o)$

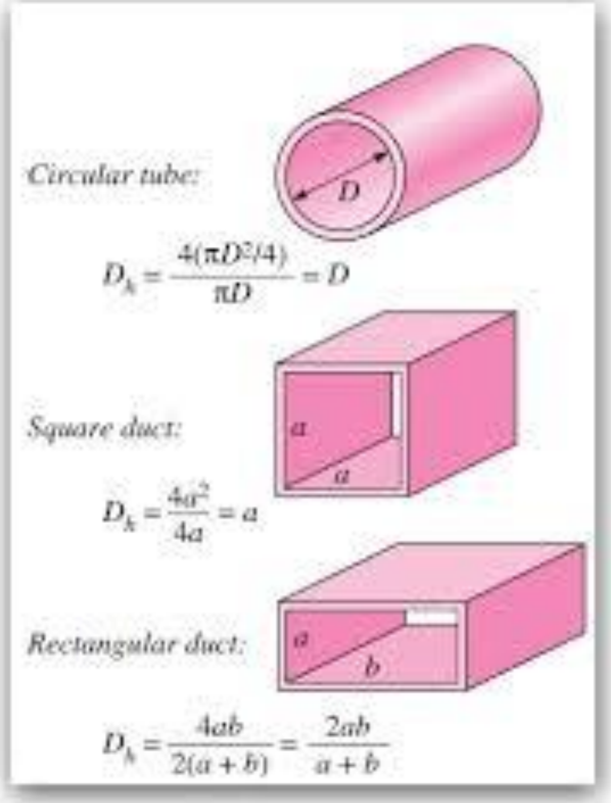

Figure 28. Characteristic diameter of various shapes

Transient Heat Conduction, T_{origin}

Need Origin temperature to find the heat added to storage per cycle

$$\frac{\partial^2 y}{\partial^2 x} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad | \qquad \frac{\partial^2 \theta}{\partial X^2} = \frac{\partial \theta}{\partial \tau}$$

Taking the boundary & initial conditions to be:

1. $\theta(X,0) = 1$
2. $\frac{\partial \theta(0,\tau)}{\partial X} = 0$
3. $\frac{\partial \theta(1,\tau)}{\partial X} = -Bi\theta(1,\tau), \qquad Bi = \frac{h * r_o}{k_D}$

A numerical solution for simple geometries can be found and the origin Temperature can be determined

Transient heat conduction, T_{origin} cont.

Our problem specific geometry is a short cylinder

Introduces multidimensional heat conduction radially and vertically

Solution: $\theta_{short\ cylinder} = \frac{T(r,x,t)-T_\infty}{T_i - T_\infty} = \theta_{plane\ Wall} * \theta_{long\ cylinder}$, T_i = 23°C

$\theta_{plane\ Wall} = A_w e^{-\lambda^2\tau} * \cos(\frac{\lambda x}{L})$, L = height of cylinder and x is vertical displacement

$\theta_{long\ Cylinder} = A_{cyl} e^{-\lambda_{cyl}^2\tau} * J_0(\frac{\lambda_{cyl} * r}{r_0})$, r_0 = 2.375in

Making a mesh of temperature points within the capsule (1.55x 1.21cm cells) the average temperature at the origin was found

Capsule Thermal Resistance Analysis

Convection

Varies with average flow velocity, v

- $R_{convection} = \frac{1}{2*\pi*r_{outer}*Height*h}$

  - h depends on the Nusselt # specific to the flow velocity

  - Assume a Hydraulic Diameter:

$$D_h = \frac{4 * tubepitch * baffleSpacing}{2 * (tubepitch + baffleSpacing)}$$

Conduction

- Thermal properties remain constant
- Outer/Inner Diameters for schedule 10 pipe (2.375in)/(2.157in)
- Height of 12in

- $R_{304\ Steel} = \frac{ln(r_{outer}/r_{inner})}{2*\pi*Height*k_s}$
- $R_{Dynalene} = \frac{r_{inner}}{2*\pi*Height*k_D}$

Pressure Drop

$$\Delta P = \Delta P_{tank} + f * \frac{L*\rho}{D*2} * v^2 + 8 * K_L * v^2 + 2 * K_r * v^2$$

Assuming

- L =15ft of D= 0.5inch pipe
- K_L = 1.1 90 degree turn minor loss coefficient (8)
- K_r = 0.1 for reduction fittings (2)
- V = 0.0149m/s for mass flow rate of 0.0123kg/s or lower

Heat transfer

Transfer to and from Storage defined as Q

$$Q = \frac{\Delta T}{R_{total}} = \frac{T_{inf} - T_{origin}}{R_{Dynalene} + R_{304\ Steel} + R_{convection}},\ T_{inf} = 240°\text{C inlet temperature}$$

- Define T_{origin} as average temperature in the center of the PCM capsules

Assumptions

- Dynalene and 304 Steel resistance can be modeled as conduction
- Convective heat transfer from Duratherm to capsule walls
- Radiative resistance is negligible

What's the total Resistance?

Thermal Resistance Components

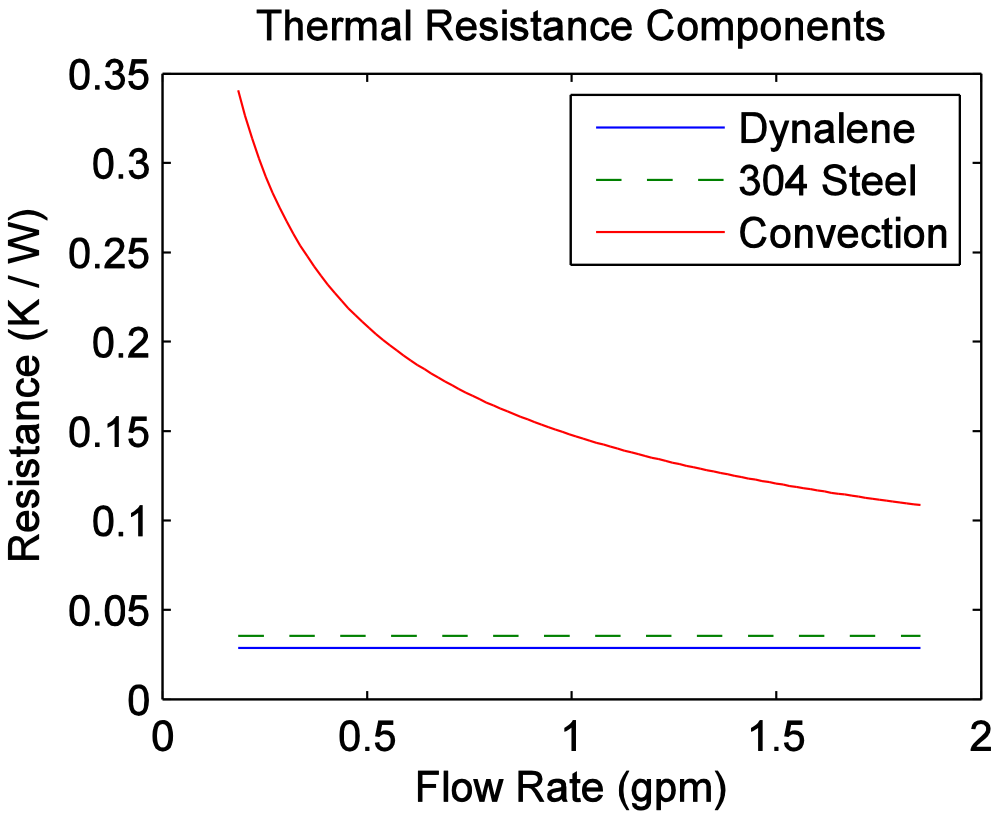

Figure 29. Thermal resistance estimation based on model

Efficiency

Taken as the ratio of energy stored to energy available for storage

$Q_{available} = \dot{m}C_{PL}(240°\text{C} - 170°\text{C})$, energy available to be stored

$Q_{stored} = \frac{\Delta T}{R_{total}}$, Energy transferred or stored in PCM capsules

$$\eta = \frac{Q_{stored}}{Q_{available}} * 100$$

Operation Point

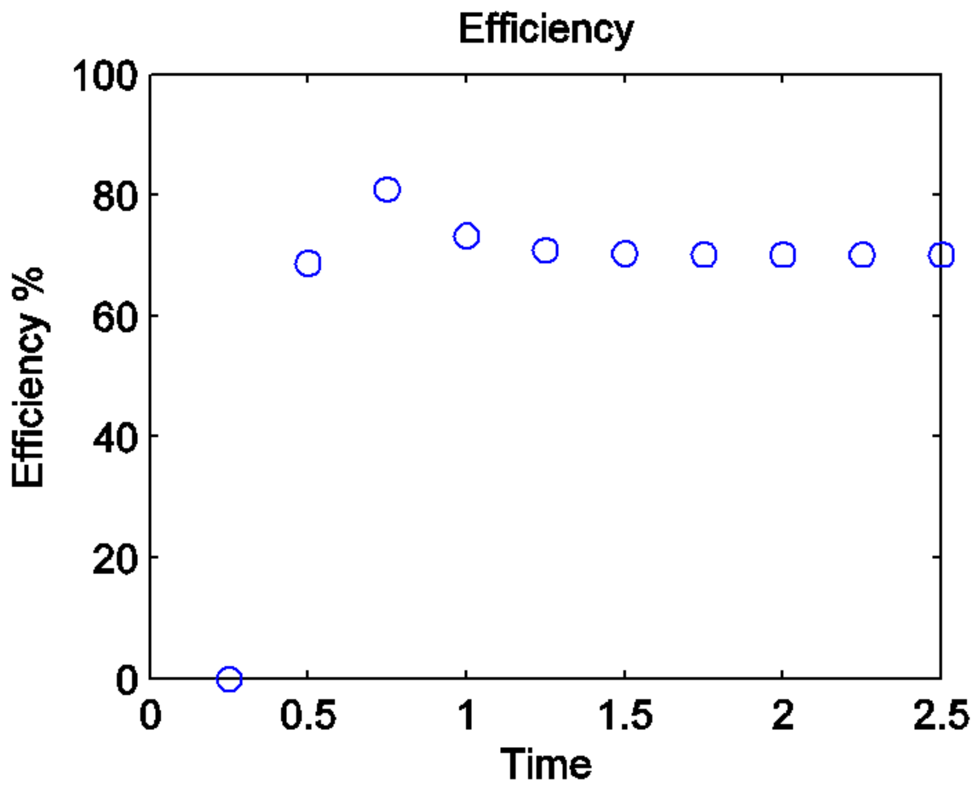

Figure 30. Temperature drop estimation

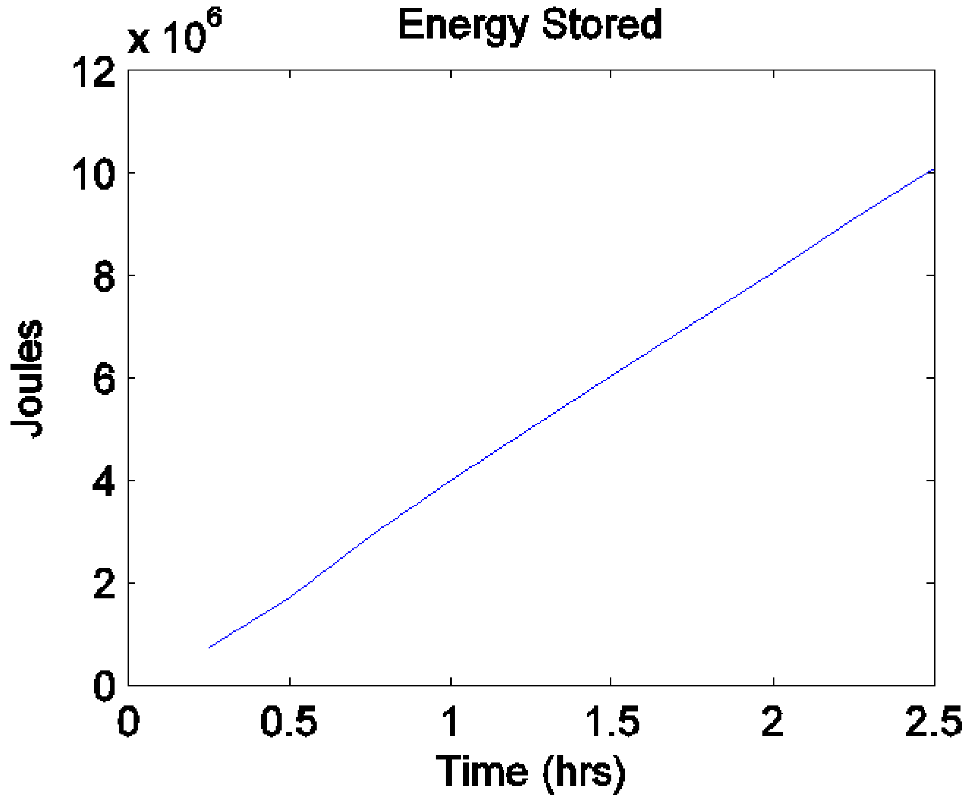

Figure 31. Efficiency estimation of system

Gantt Chart

	Task Name	Duration	Start	Finish
1	**Purchases**	**20 days**	**Mon 1/5/15**	**Fri 1/30/15**
14	**Simulation & Modeling**	**26 days**	**Mon 1/5/15**	**Mon 2/9/15**
19	**Building**	**15 days**	**Mon 2/16/15**	**Fri 3/6/15**
20	Create Capsules	14 days	Mon 2/16/15	Thu 3/5/15
21	Create Heat Exchanger	14 days	Mon 2/16/15	Thu 3/5/15
22	Weld bottom to tank	1 day	Mon 2/16/15	Mon 2/16/15
23	Cut Baffels	1 day	Mon 2/16/15	Mon 2/16/15
24	Frame for baffels	3 days	Mon 2/16/15	Wed 2/18/15
25	Connect pipes	1 day	Thu 3/5/15	Thu 3/5/15
26	Place capsules/oil in tank	1 day	Thu 3/5/15	Thu 3/5/15
27	Screw top on tank	1 day	Thu 3/5/15	Thu 3/5/15
28	**Testing**	**21 days**	**Mon 3/9/15**	**Mon 4/6/15**
29	**First configuration**	**10 days**	**Mon 3/9/15**	**Fri 3/20/15**
30	Test 1	2 days	Mon 3/9/15	Tue 3/10/15
31	Test 2	2 days	Fri 3/13/15	Mon 3/16/15
32	Test 3	2 days	Mon 3/16/15	Tue 3/17/15
33	**Second configuration**	**10 days**	**Mon 3/23/15**	**Fri 4/3/15**
37	**Evaluation on tests**	**7 days**	**Wed 4/1/15**	**Thu 4/9/15**
40	**Future Suggestions**	**7 days**	**Sat 4/11/15**	**Mon 4/20/15**
43	**Presentation Prep**	**5 days**	**Mon 4/20/15**	**Fri 4/24/15**

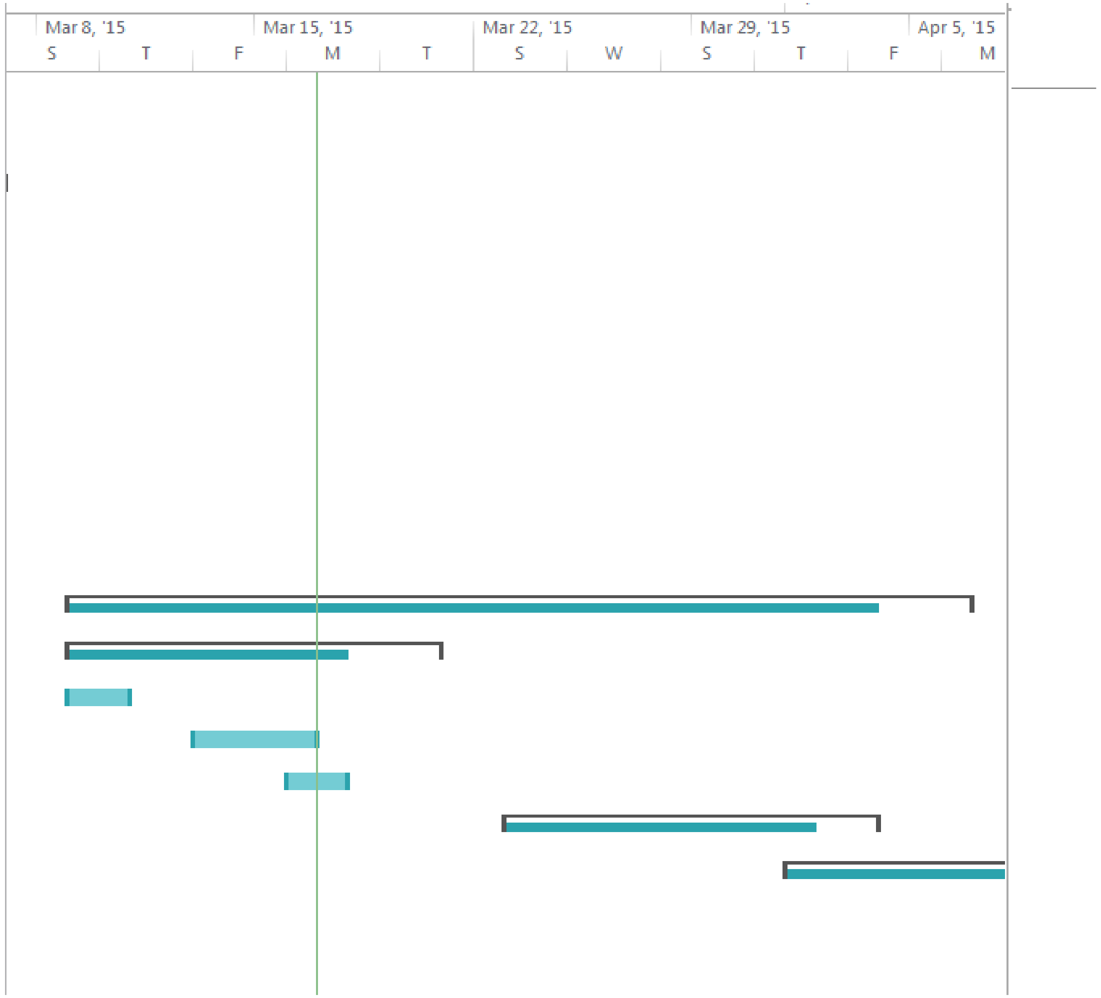

Figure 32. Gantt Chart

Testing Results