Pumped Fluid Loop Thermal Management Design Proposal for Stirling Power Conversion System

School of Engineering + Technology

Problem Statement

Design a scalable pumped liquid cooling system proposal that maintains optimal temperature for the cold side of the Stirling Conversion System as part of NASA's Kilopower Reactor design. Stirling Conversion Systems generate electricity through a heat motor that is heated on one end and cooled on the other. The new design needs to reject 3kW of heat and be able to scale to 30kW producing a power output of approximately 50% of Carnot. The system will have to be able to function in a lunar environment while maintaining a heat rejector surface temperature between 30℃ and 100℃.

Original Objectives

- Research cooling methods used in designs that have similar boundary conditions and requirements.
- Research and evaluate the thermodynamic properties of different fluids used in cooling processes in order to make a selection that meets the design criteria. Cooling liquid will be researched and chosen based on the properties, characteristics, and applications as these relate to the moon's atmospheric conditions.
- Research and select a pump compatible with chosen fluid, capable of space travel, and able to pump coolant throughout system at a specified flow rate.
- After selection of fluid and pump, design a program within MATLAB that is capable of calculating the necessary radiator size and flow rates depending on necessary heat dissipation.
- Simulate calculated properties in a multi-physics simulation platform such as ANSYS to confirm the numerical analysis performed.
- If time permits a small scale experiment confirming the initiation of fluid flow.

Concepts

- Initial concept was to use a pumped single phase liquid ammonia cooling loop. This concept was rejected in favor of a two phase liquid-gas pumped cooling loop utilizing a boiling curve.
- Boiling curves measure the heat flux absorbed by a fluid while turning to a gas at varying differences between the saturation temperature of the fluid and temperature of the surface heating the surface or being cooled[1].
- By reaching a steady state with an optimal difference in surface and saturation temperature an optimized heat transfer coefficient can be reached that is orders of magnitude higher than otherwise achievable.
- Figure 1 to the right shows the optimized heat transfer coefficient as a function of interpolated boiling curve data[1].

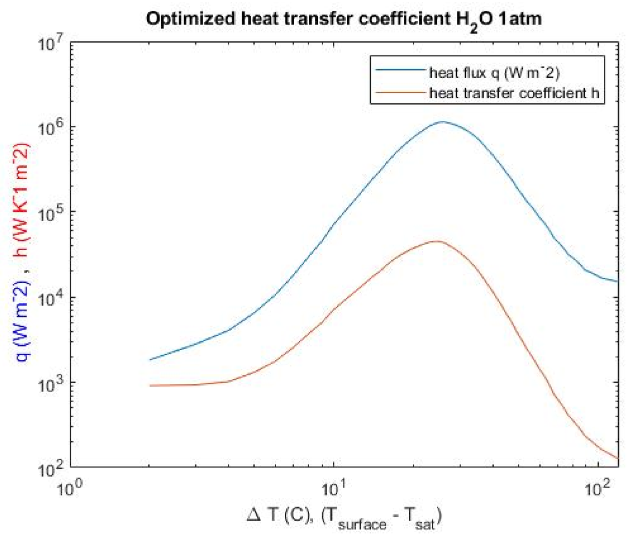


Figure 1: Optimized heat transfer coefficient as a function of interpolated boiling curve data.

Requirements

Table 1: Final Design Requirements

Req #	Requirement	Description	Achieved?	If no, why?
1	Temp. close to 30C	Achieve a range between 30 and 100 C	No	Change of scope, unable to simulate vacuum conditions.
2	3kW of heat rejection	System radiates 30kW of heat energy	Yes	-
3	Fluid cannot freeze	The fluid must remain liquid below -173C	No	Change of scope, no longer applicable.
4	Pump maintains dynamic stability	Vibration is dampened or mitigated	Yes	-
5	Fluid is chemically stable	Compound cannot cause structural failure or self-ignite	Yes	-
6	Pump able to operate from -30C to 100C	Mechanical portion must continually function	Yes	-
7	Boiling reaches optimized Heat Transfer coeffieicnt	Maximum usage of phase change of fluid	No	Need to modify geometry and utilize vacuum to decrease Tsat

Final Design/Results *

- The objective was to create a design proposal that was scalable of dissipating 3kW-30kW of heat.
- To simplify simulation 3kW of heat dissipation was used, knowing it is scalable with surface area.
- The proposed Stirling Conversion Systems regardless of size utilize 8 units, as seen in Image 1[4].
- Per unit this setup requires 200W of heat dissipation with the next step being 600W per unit[6], the individual unit can be seen in Image 2 with the orange flange being the current passive heat sink[4].
- The heat stink that is the current passive cooling method is replaced with a solid-liquid pumped fluid heat exchanger as shown in Image 3.
- A 2D cut-out of the center of the cylinder is used to create the simulation boundary conditions in Image 4.
- The fluid used in the current simulation is water at 1 atm pressure. This is to form a baseline for comparing other fluids and pressures.

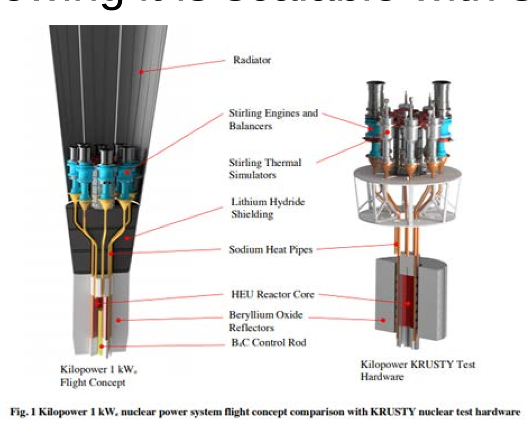


Image 1: Kilopower proposed set-up

Image 2: Individual Stirling Converters with heat sink

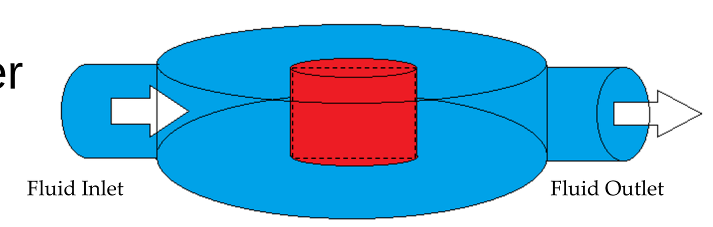


Image 3: Visualization of cooling liquid

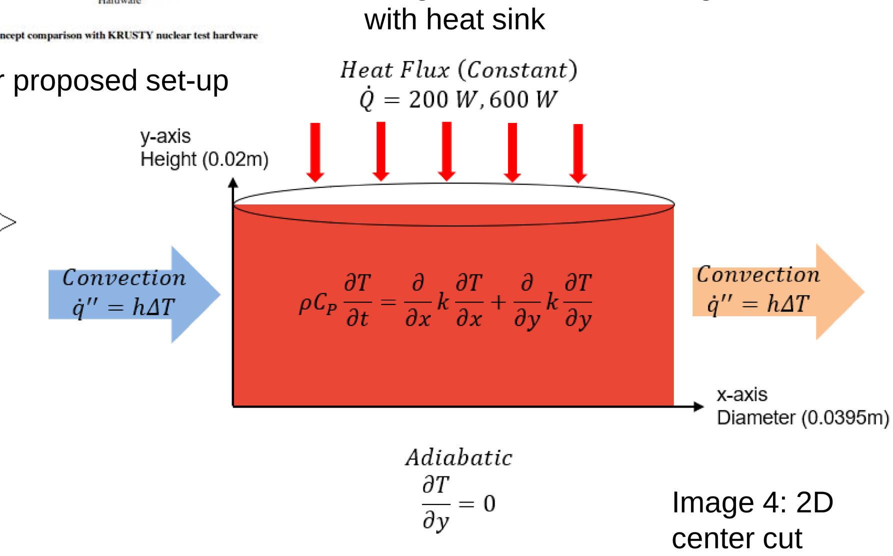
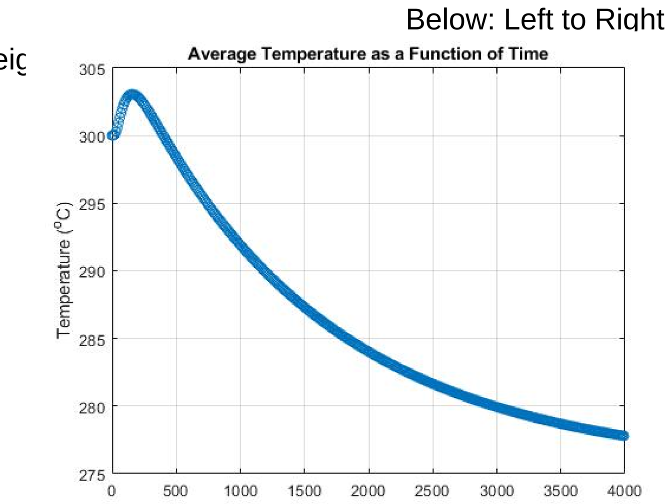
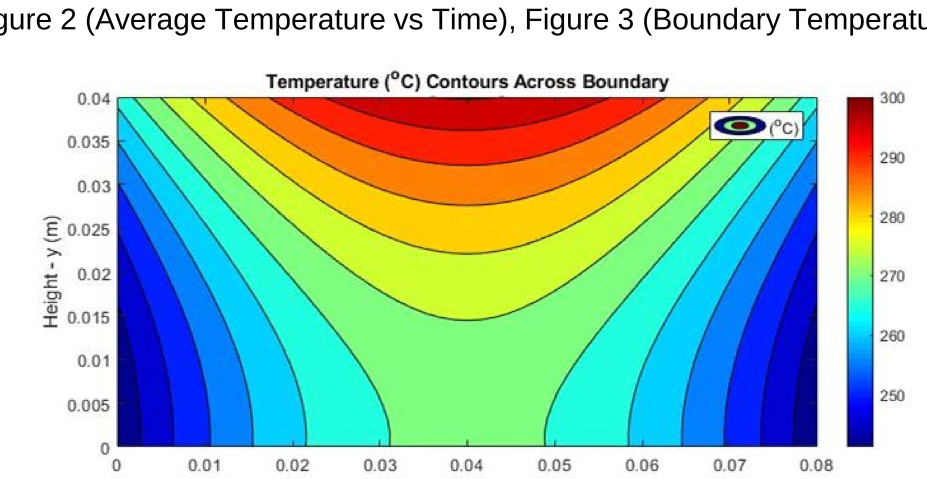


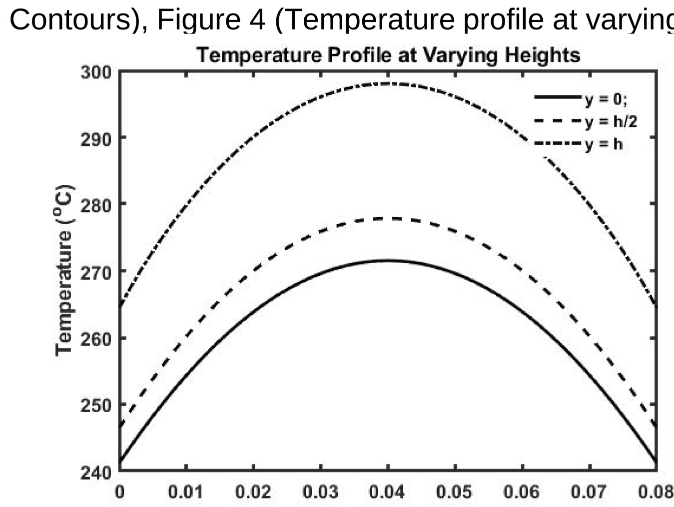
Image 4: 2D center cut boundary conditions

- A heat exchanger geometry was discovered that reduces the surface startup temperature to a steady state. Below in Figure 1 this slope into steady state can be seen, the temperature it reaches is above the required temperature, around 277 ℃, however shows promise.
- The temperature contour and profile at different heights in Figure 2 and Figure 3 show expected results with the hottest region being the center top and cooling towards the bottom outer region. The temperature profile at varying heights further demonstrates the cooling towards the bottom region in a nonlinear fashion.
- In order to reduce the temperature further investigation into other geometries and reducing the pressure in order to lower the fluid saturation temperature is necessary.

Below: Left to Right Figure 2 (Average Temperature vs Time), Figure 3 (Boundary Temperature Contours), Figure 4 (Temperature profile at varying heig







Pump Selection:
Additionally to simulating and designing a heat exchanger it is necessary to determine the proper pump type and size for moving the fluid. The requirements[7] for the pump are:

- Hermetically sealed
- Rugged and reliable
- Low noise
- Small size
- Vibration resistant

Canned motor pumps feature a range of unique attributes which compare well against conventional pumps[7]. An optimal canned motor pump is found, manufactured by the company Nikkiso.

- The bearings and motor are self lubricating, the same fluid also cools the physical components.
- There is no mechanical seal, meaning the whole housing itself hermetically seals the system from surroundings.
- The pump and motor function as one unit, reducing weight and complexity.
- Axial balancing reduces the bearing wear, the displacer is kept close to the center of mass upon any vertical deviation.
- Foundation is not required as the motor is self-contained.
- Already used in space application on the ISS.
- Wide range of operating conditions as found to the right in Table 2.

Table 2: NIKKISO Specifications[3]

Max. Capacity	3,430 gpm (780 m^3/h)
Max. Head	670ft (300m) single stage
Fluid Temp. Range	-76 to 662 F (-60 to 350 C)
Specific Gravity Range	0.3 to 2.0
Max. Viscosity	200 cP (200 mPas)
Design pressure	Max. 600 psig (4Mpa)
Motor Power Range	0.5 to 268 hp (0.4 to 200W)
Liquid End Material	316SS, 304SS

* On March 16, 2020 classes and labs were closed to students due to the COVID-19 Pandemic. Without access to fabrication and testing equipment, Objectives and Deliverables were modified accordingly.

Modified Objectives*

- During the semester switch the problem solution changed to a more efficient and robust system. This change coincided with the outbreak of COVID-19 and therefore progress was stagnated.
- Unable to perform due to COVID-19:
  - Investigate vacuum pressure boiling curve.
  - Testing various coolants other than water.
  - Testing boiling curves with different flow rates.
  - Cool system below the maximum temperature of 100 ℃.
  - Researching and choosing material with a higher thermal conductivity.

Summary

Findings from the team show a working model to simulate the cooling of the cold end of a Stirling Conversion System utilizing a two-phase pumped cooling loop. A maximum heat flux was not reached and therefore the steady state temperature was well above the threshold. The next step for investigation would be to examine boiling curves at reduced pressure to operate with a lower saturation temperature and more effective geometries.

Team & Acknowledgements

Student Team Members:
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- Jarid Williams - Engineering Technology
- Nick Kropelnicki - Engineering Technology

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