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Entropy Optimization of an Additively Manufactured Heat Exchanger with a Dual Stage Gifford-McMahon Cryogenic Refrigerator for Hydrogen Liquefaction

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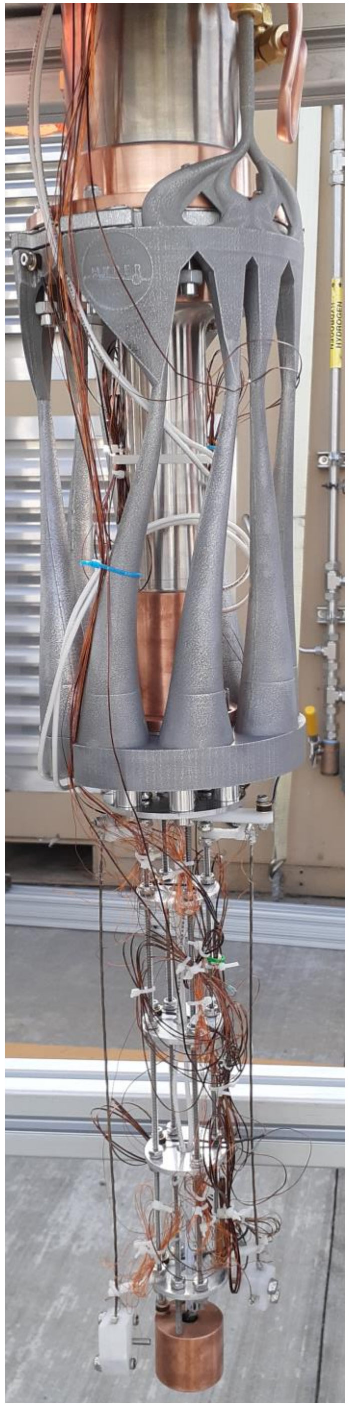
WASHINGTON STATE UNIVERSITY

[1] Raymond J 2021 Entropy Optimization of an Additively Manufactured Heat Exchanger with a Dual Stage Gifford-McMahon Cryogenic Refrigerator for Hydrogen Liquefaction. In: *School of Mechanical and Materials Engineering*: Washington State University) p 171

Outline



1. Introduction
   - The Opportunity for Hydrogen
2. Background
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1. Limited Accessibility of Hydrogen

Small-scale liquefaction is being employed as a method of refueling small aircraft using fuel cells.

Liquefiers are expensive and inefficient.
- Small scale systems operate around 20% of second law efficiency.
- Large scale systems cost $3 million for each tonne per day capacity [2].

To improve system feasibility, the system efficiency must be improved. The three lowest efficiency components are the:
- Heat exchanger,
- Cycle compressor,
- And nitrogen refrigerator [3].

Heat exchangers experience thermodynamic losses of almost 13% and represent the largest opportunity for improvement in small-scale systems.

InSitu’s ScanEagle 3 [4].

Take-Aways:
- To make small-scale liquefiers cost-effective the system efficiency must be improved.
- Heat exchangers represent one of the largest opportunities for improvement.

[2] 2019 Air Liquide committed to producing renewable hydrogen for the West Coast mobility market with new liquid hydrogen plant. In: *Air Liquide*, (airliquide.com)
[3] Baker C and Shaner R 1978 A study of the efficiency of hydrogen liquefaction *International Journal of Hydrogen Energy* **3** 321-34
[4] ScanEagle 3 Unmanned Aircraft System. (Aerospace-Technology.com: Aerospace Technology)

Outline

Introduction Summary:

- Small-scale liquefier efficiency must be improved so that they can be effectively implemented in industry.
- Heat exchangers are one of the most inefficient components.

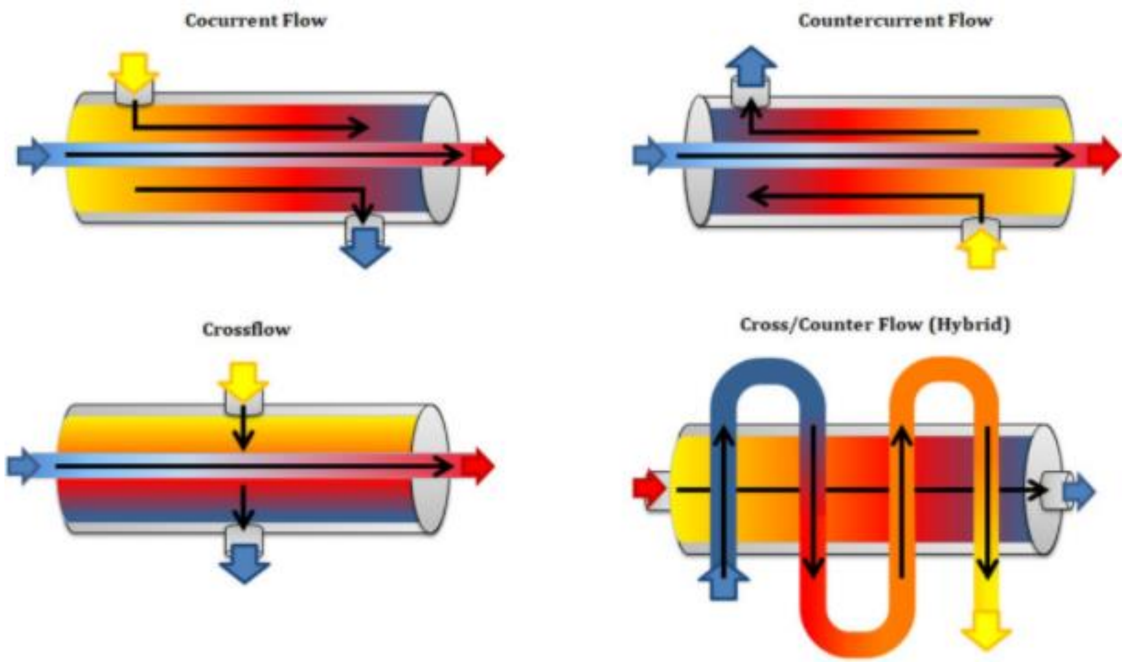
2. Heat Exchanger Optimization

Goal: Minimize the pressure drop while maximizing the heat transfer between fluids to minimize the temperature gradient. The ideal temperature profile is linear.

Varying Geometry
- Increasing tube diameter
- Selecting fluids with low viscosities
- Ensuring smooth surfaces
- Increasing the surface-area to volume ratio
- Modifying fluid inlet temperatures
- Flow configuration
- Axial conduction

Fins
- Increase surface area to volume ratio
- Increase pressure drop
- Increase system complexity and difficulty of manufacture

Precooling
- Staged cooling decreases temperature gradients
- Systems are theoretical or small scale
- Can achieve unique thermal properties



[5]

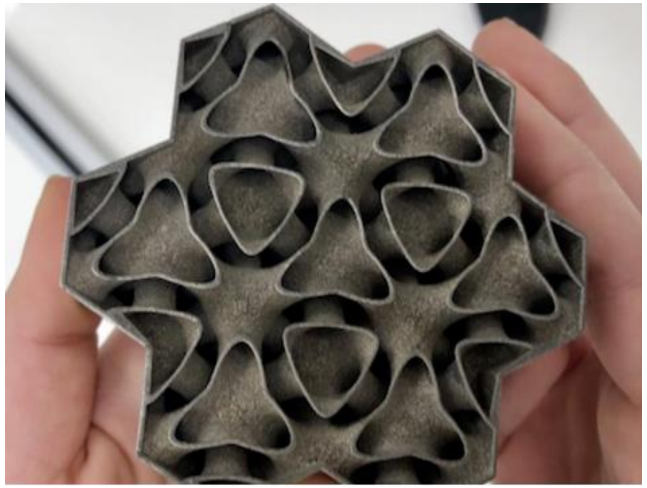
Take-Aways:
- Heat exchangers are optimized for specific flow scenarios by varying geometry and incorporating fins, and/or precooling.

[5] Ronquillo R Understanding Heat Exchangers. (Thomasnet.com)

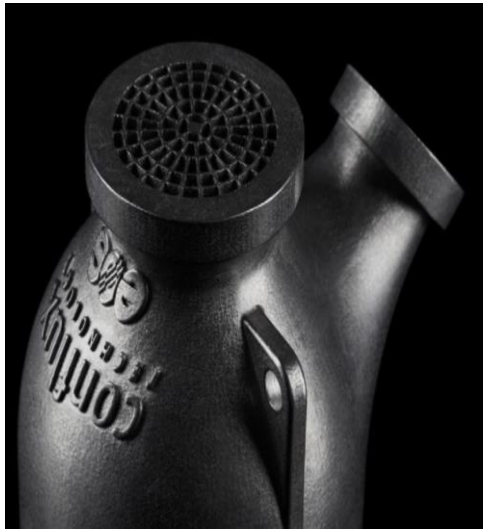
2. The Potential of Additive Manufacturing

Heat exchanger technology has co-evolved with leading methods of manufacturing.

Additive manufacturing has emerged as a method for creating previously un-manufacturable parts.



Heat exchanger designed by GE modeled after the human lung.



[6]

Heat exchanger designed by Conflux Core with a novel internal structure.

Additive manufacturing now includes metals and enables the creation of free-form parts. The technology has not yet been used to create a freeform heat exchanger for cryogenics.

Take-Aways:

- The advancements in metal additive manufacturing represent an opportunity to create the next-generation freeform heat exchanger for cryogenics. This has yet to be attempted.

[6] 2019 Application Spotlight: 3D Printing for Heat Exchangers. (amfg.ai: AMFG)

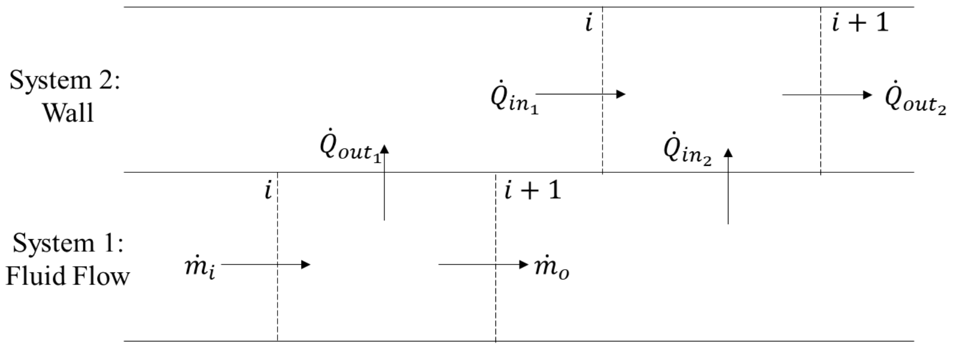
Outline

Background Summary:

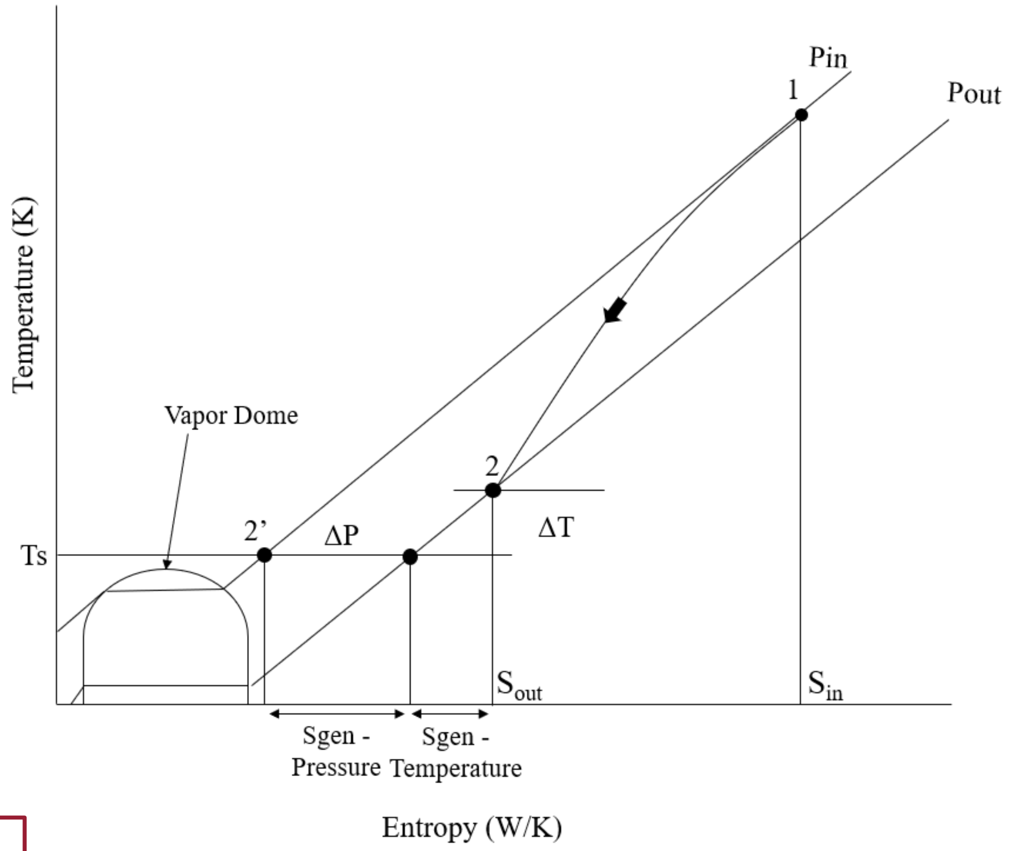
- Current methods to customize heat exchangers include modifying geometry and including fins, and/or precooling.
  - Modifying geometry can lead to designs with increased complexity and difficulty to manufacture.
  - Fins increase the surface area to volume ratio, as well as the pressure drop.
  - Precooling for large-scale hydrogen liquefiers is a promising, but theoretical option.
- Additive manufacturing could be used to design the next-generation heat exchanger.

3. Entropy Generation in a Tube

- Entropy is generated as a result of system inefficiencies.
- A system with no excess entropy generation is ideal, and the efficiency of a system is inversely proportional to the rate of entropy generation.
- In a tube, entropy is generated as a result of pressure and temperature differentials.



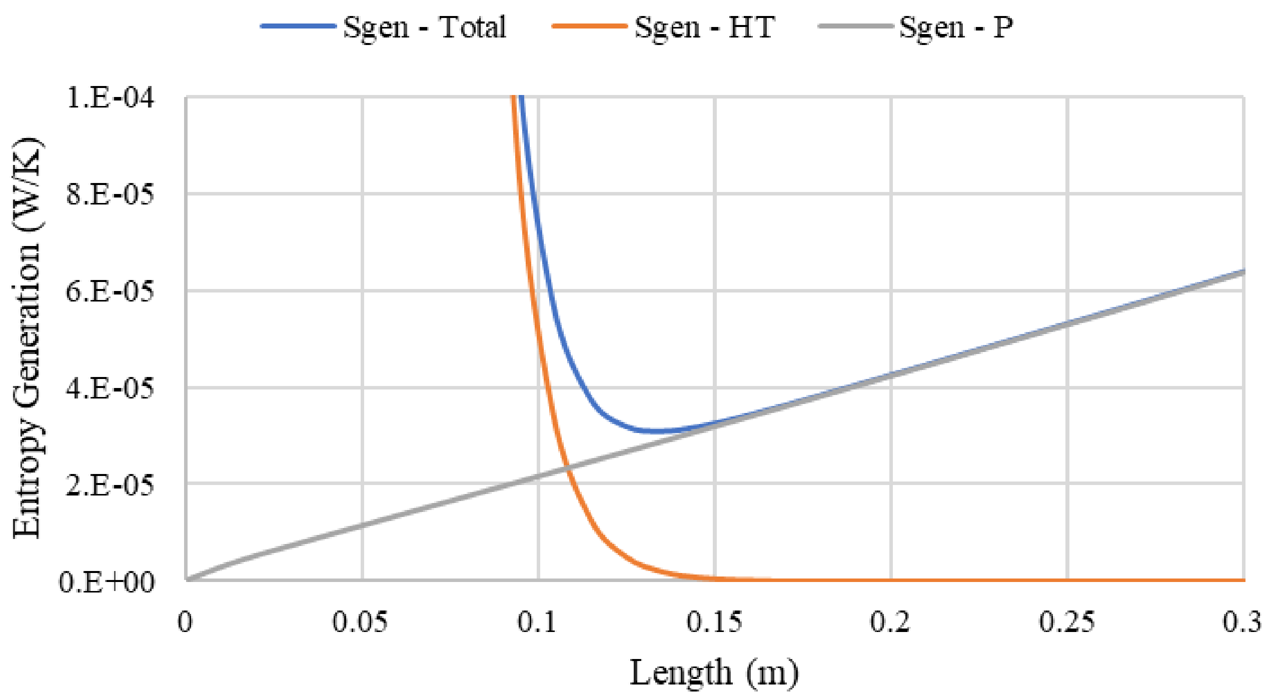
- $|\dot{Q}_{out_1}| = |\dot{Q}_{in_2}|$
- $|\dot{m}_i| = |\dot{m}_o|$



$$\dot{S}_{gen_{HT}} = \dot{m}\, C_p \frac{T_{out} - T_s}{T_s} \qquad \dot{S}_{gen_P} = \dot{m}\, R \frac{P_{in} - P_{out}}{P_{in}}$$

Take-Aways:
- An ideal system is one with no entropy generation.
- Round tubes yield minimal rates of entropy generation.
- In a tube, entropy is generated as a result of pressure and temperature differentials.

3. Entropy Generation from Pressure and Temperature Differentials



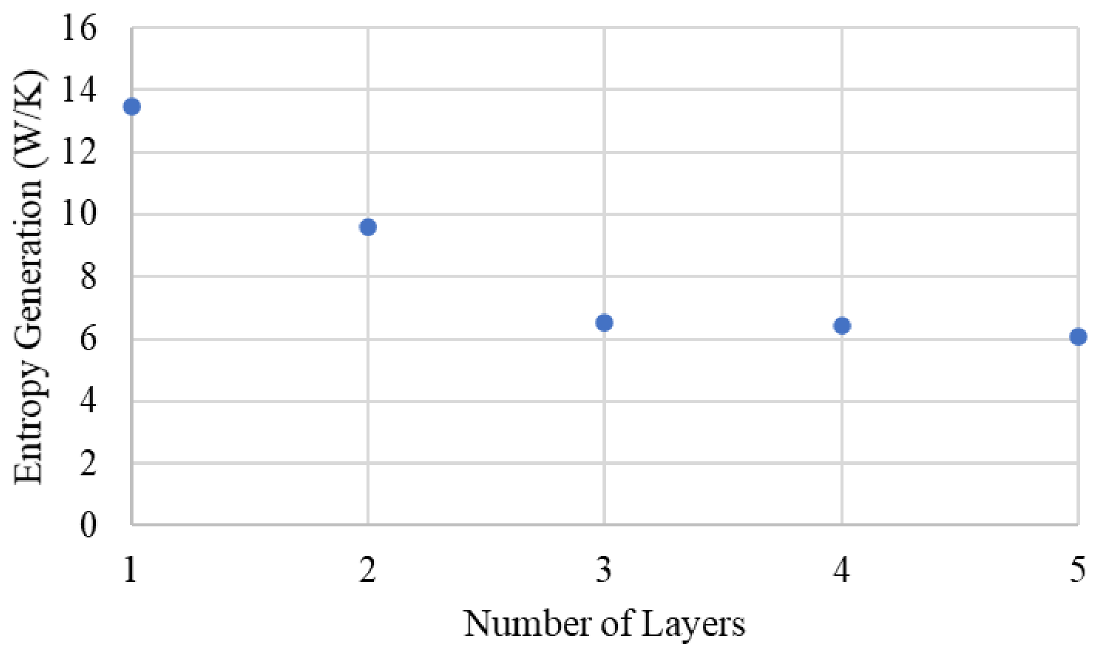
The Hess-Murray rule describes small-scale fluid system optimization through bifurcation.

Once the ideal aspect ratio is obtained, to reach a new optimum the system must be allowed bifurcate, generating a new mass flow rate and a new ideal aspect ratio. This pattern then continues until a physical limitation is reached to obtain a minimum entropy generation system.

Take-Aways:

- Entropy generation from heat transfer decreases with increasing length.
- Entropy generation from pressure drop increases with increasing length.
- For a given diameter, there exists an ideal length where a point of minimum entropy generation occurs.
- To obtain a minimum entropy system, the tubes must be allowed to bifurcate.

3. Geometry Optimization of a Tube with a Linear Temperature Gradient



Number of Layers	Total Entropy Generation (W/K)	Final Pressure (Pa)	Final Temperature (K)
1	13.500	648095	156
2	9.614	647640	118.7
3	6.533	648091	87.82
4	6.403	646962	65.57
5	6.064	646970	51.04

Total Number of Layers		Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
1	Length (m)	0.142				
	Diameter (m)	0.009525				
2	Length (m)	0.001	0.0141			
	Diameter (m)	0.003195	0.003175			
3	Length (m)	0.001	0.001	0.14		
	Diameter (m)	0.006747	0.009525	0.006038		
4	Length (m)	0.001	0.01013	0.01035	0.1205	
	Diameter (m)	0.0018	0.0022	0.003	0.0035	
5	Length (m)	0.001	0.01011	0.01046	0.01019	0.1102
	Diameter (m)	0.0018	0.0022	0.003	0.0035	0.003175

Take-Aways:

- Entropy generation and outlet temperature decrease with increasing layers.
- Later layers are longer than layers prior.
- Diameters are fairly consistent between layers.

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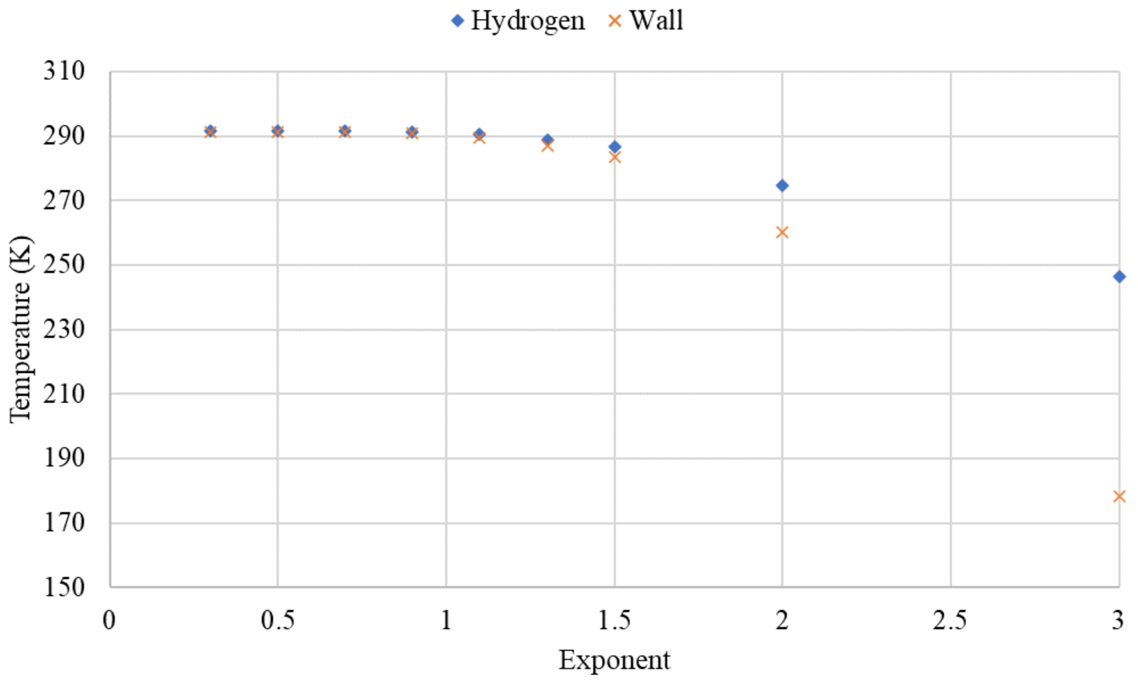
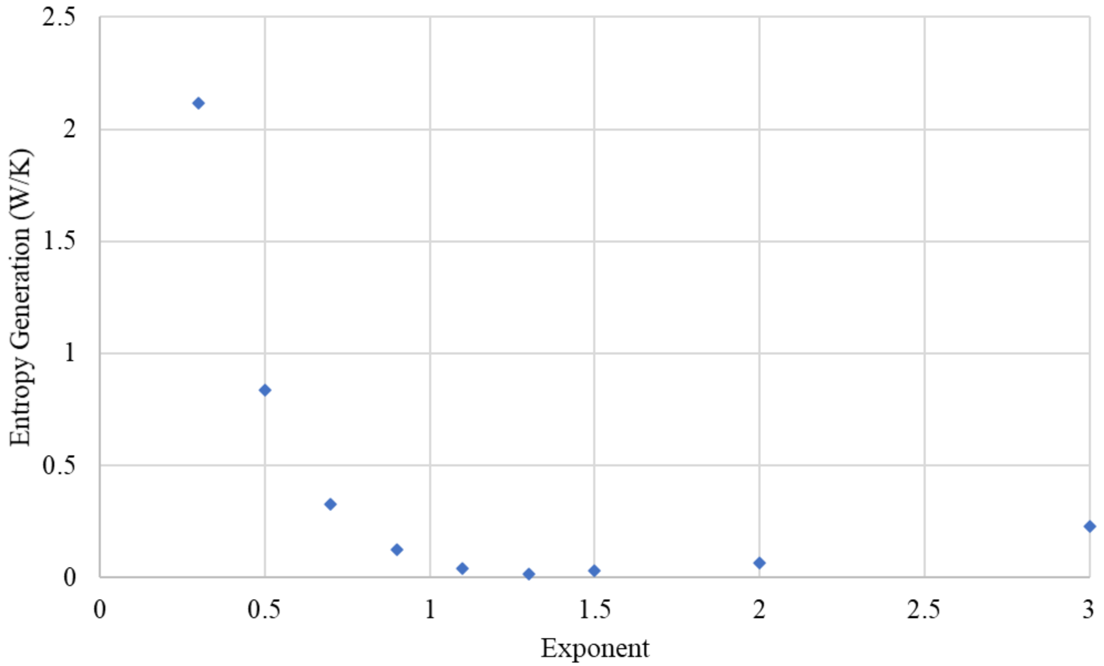
3. Varying Wall Thickness Using Al 6061





x	y	Total Entropy Generation (W/K)	Hydrogen Outlet Temperature (K)	Wall Outlet Temperature (K)
3	0.003	0.2283	246.4	178.5
2	0.003	0.06269	274.6	260.1
1.5	0.0032	0.03101	286.6	283.6
1.3	0.0032	0.01449	288.8	287.2
1.1	0.0033	0.04193	290.4	289.6
0.9	0.0033	0.1221	291.2	290.9
0.7	0.0028	0.3265	291.5	291.3
0.5	0.0026	0.8385	291.6	291.4
0.3	0.0026	2.116	291.6	291.4

$$th = x[i]^x + y$$

Take-Aways:

- The outlet temperature decreases as the exponent increases.
- Minimum entropy generation occurs when the exponent is 1.3.

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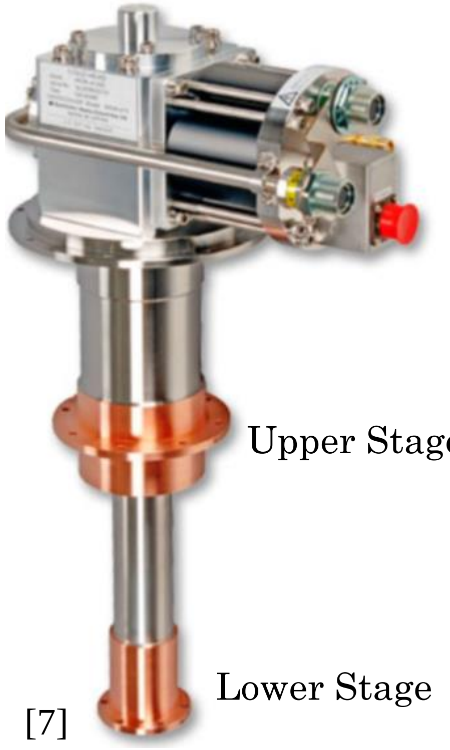
Outline

Theory Summary:

- In a tube, entropy generation from pressure drop increases as length increases, and that from heat transfer decreases.
- For a tube with a given diameter, there exists an ideal length where minimum entropy generation occurs.
- Branching represents a way to optimize fluid flow systems.
- When varying wall thickness according to a function, there is an ideal exponent which produces minimum entropy generation and almost linear temperature profiles.

4. Experimental Constraints

- Thermal contraction of the heat exchanger and cryogenic refrigerator.
- Minimum wall thickness to prevent bursting.
- Resistance from indium foil.
- Lengths and Diameters
  - Maximum print bed height: 0.325 m
    - 0.0525 m of the total length of the cryogenic refrigerator cannot be printed
    - The lower portion of the heat exchanger must be 0.239 m and the upper portion must be 0.0795 m
  - Minimum allowable inner diameter: 0.003175 m
  - Maximum allowable inner diameter: 0.009525 m
- Mass Flow Rate
  - Maximum electrolyzer output
  - Total load capacity of cryogenic refrigerator
- Assume:
  - Hydrogen is always equilibrium, rather than normal.



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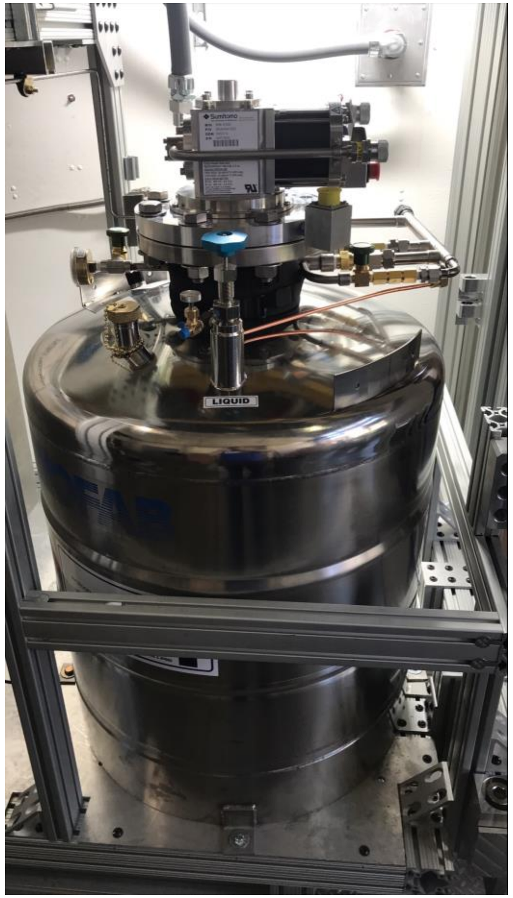


Limited Space

- The inner diameter of the dewar neck is 6”, and the outer diameter of the upper stage is 4.9”.
- The heat exchanger must wrap around the upper stage but still be able to fit inside the dewar neck without making contact.

[7] Group S C RDK-415D 4K Cryocooler Series.

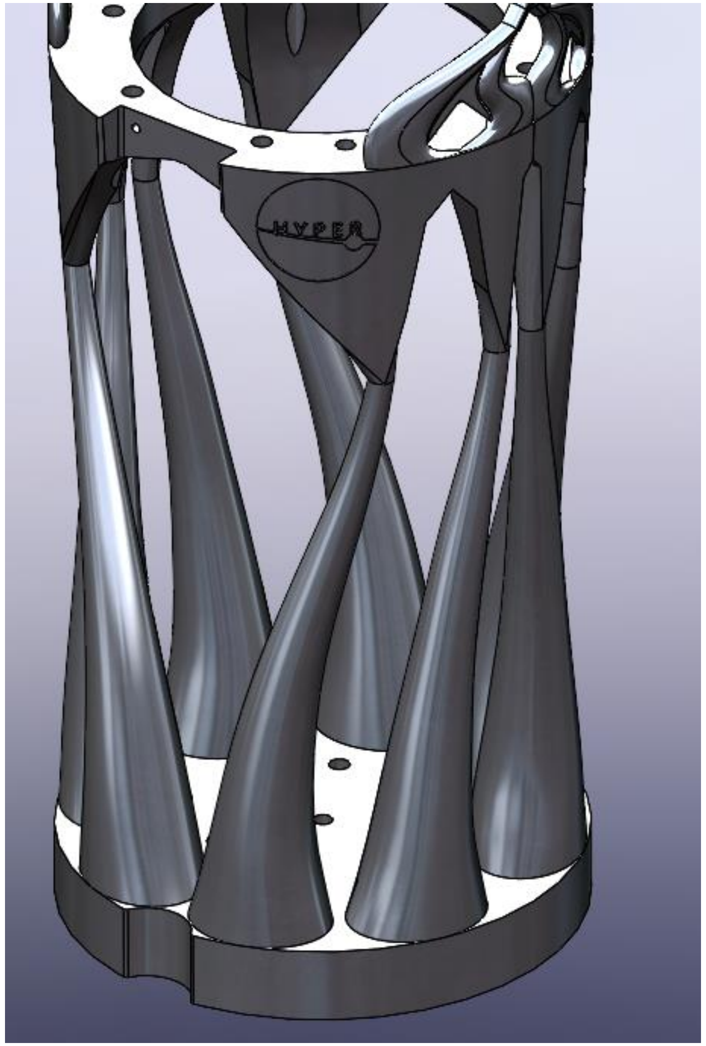
4. Upper Stage to Lower Stage Design

Goal: Maximize the inlet temperature into the section and output hydrogen at the saturation temperature. This will maximize the upper stage temperature and the possible heat lift. Do so while minimizing entropy generation during liquefaction.

Assume: Inner diameter of 3.175 mm, wall thickness of 1 cm.

Result: The lower section of the heat exchanger contains eight tubes.

Parameter	Value
Hydrogen Inlet Temperature	100 K
Wall Inlet Temperature	95 K
Mass Flow Rate	0.008 g/s
Hydrogen Outlet Temperature	24.39 K
Wall Outlet Temperature	20.18 K
Wall Thickness Equation	th[i] = 0.3*x[i]^2.1 + 0.0009
Inner Diameter	0.003175 m
Length	0.239
Rate of Entropy Generation	0.7087 W/K



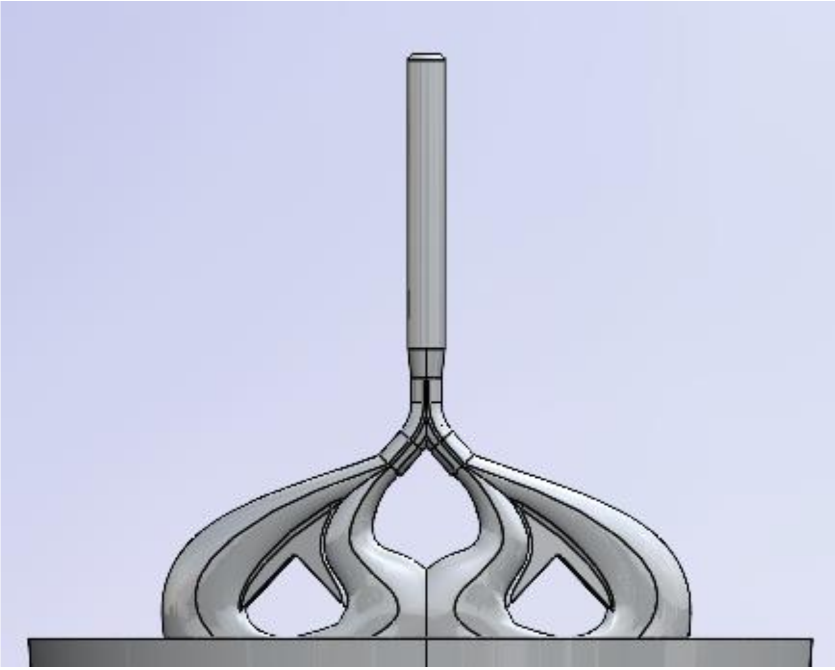
Take-Aways:

- The lower section contains eight tubes. The inner diameter is 3.175 mm and the maximum wall thickness is 1 cm.

4. Flange to Upper Stage Design

Goal: Accept hydrogen at ambient temperature and output hydrogen near 100 K.

Result: The upper section of the heat exchanger begins with one tube and ends with eight.



Parameter	Value
Hydrogen Inlet Temperature	293 K
Wall Inlet Temperature	292 K
Mass Flow Rate	0.008 g/s
Hydrogen Outlet Temperature	102 K
Wall Outlet Temperature	84.63 K
Wall Thickness Equation	th[i] = x[i]^2.15 + 0.00043
Rate of Entropy Generation	0.6886 W/K

	Layer 1	Layer 2	Layer 3	Layer 4
Length (m)	0.01	0.01	0.01	0.0495
Diameter (m)	0.003175	0.003175	0.003175	0.003175

Take-Aways:
- The top section of the heat exchanger begins with one tube and ends with eight.
- The lengths of all layers are 1 cm, except for the last.
- The diameter is constant at 3.175 mm.

4. Quantifying Heat Exchanger Effectiveness

The LMTD and NTU-ε methods cannot be used to assess performance. These metrics compare the actual and ideal rates of heat transfer. The temperature of the helium in the cryocooler, as well as the overall temperature profile of the hydrogen stream, are unknown. Therefore, the ideal rate of entropy generation is unknown. A new metric is defined:

$$\mu = \frac{\dot{Q}_{ideal}}{\dot{Q}_{real}}$$

$$\dot{Q}_{ideal} = \dot{Q}_{H2} + \dot{Q}_{HEX} + \dot{Q}_{OP}$$

$$\dot{Q}_{real} = \dot{S}_{gen} T_f + \dot{Q}_{ideal}$$

$$\dot{Q}_{H2} = \dot{m}(h_i - h_f)$$

$$\dot{Q}_{OP} = \dot{m} h_c f$$

$$\dot{Q}_{HEX} = \frac{mC_p(T_i - T_f)}{t}$$

Final Design (with Equilibrium Hydrogen): μ = 0.6645

Take-Aways:
- A new metric is defined to quantify performance.
- The effectiveness of the final design is 0.6645.

4. Comparing to a Single Tube Heat Exchanger

Single Tube Parameters:

- Total Entropy Generation: 2.3372 W/K
- Effectiveness Metric: μ = 0.5392
- Mass: 3.15 kg
- Length: 3.70 m
- Cost: $4,200

Printed design:

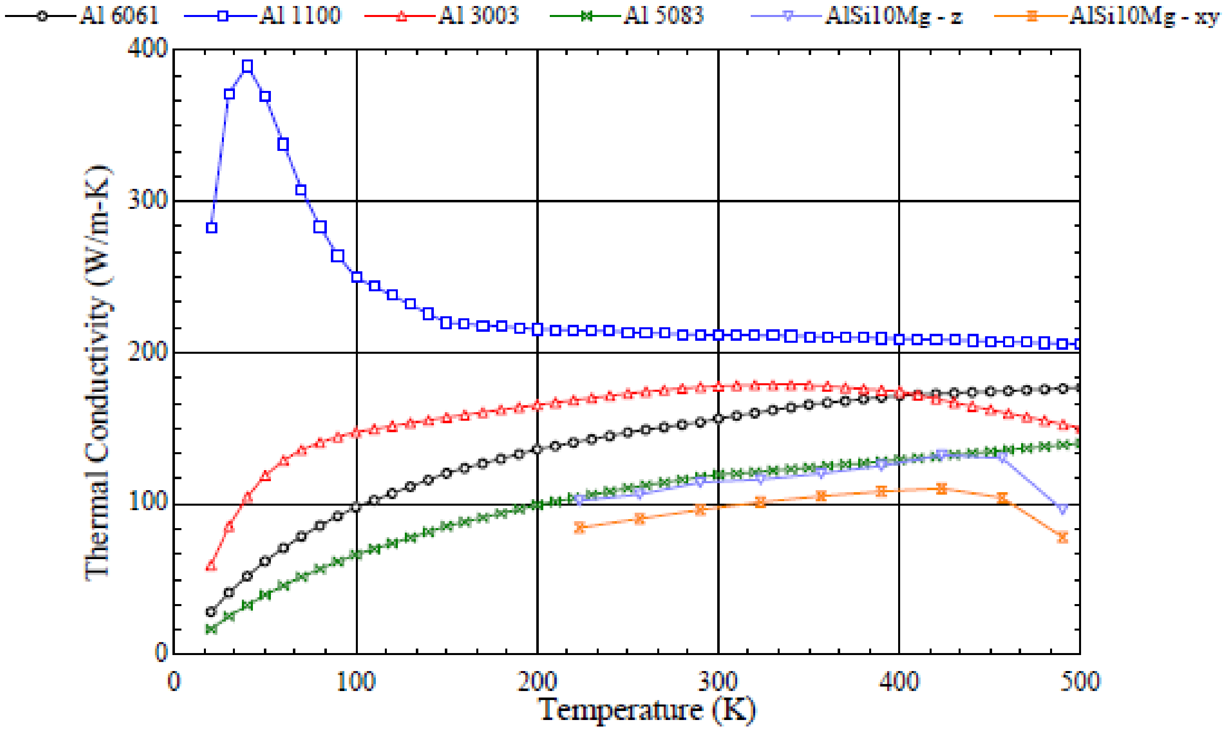
- Total Entropy Generation: 1.3973 W/K
- Effectiveness Metric: μ = 0.6645
- Mass: 2.19 kg
- Length: 0.3185 m
- Cost: $8,633

Take-Aways:

- μ of the printed design is 23.23% larger than that of the single tube design
- The thermal mass of the printed design is 43.82% less than that of the single tube design
- The length of the printed design is 8.61% of the length of the single tube design
- The printed design costs 206% more than the single tube design.

4. Printing in AlSi10Mg

- The part was designed in Al 6061.
- Additive manufacturers were not comfortable printing in this material due to the part complexity.
- The part was printed in AlSi10Mg, an aluminum composite common to additive manufacturing
- The thermal properties of AlSi10Mg are unknown below 230 K.
- The system is estimated to have a 30% decrease in performance based on information about the known thermal properties.



Take-Aways:

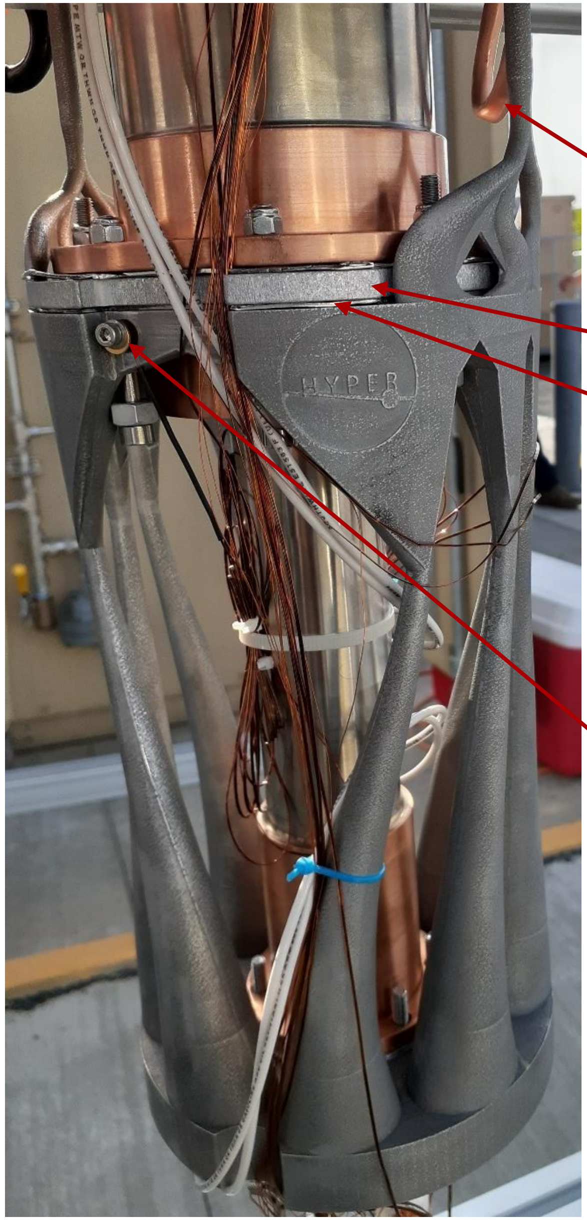
- The part was designed in Al 6061 but printed in AlSi10Mg.
- AlSi10Mg has lower thermal conductivity than Al 6061 and the performance is expected to decrease by about 30%.

Outline

Experimental Design Summary:

- The upper section of the heat exchanger contains one tube that branches into eight.
- The lower section of the heat exchanger contains eight tubes.
- The printed heat exchanger has a higher efficiency, a lower thermal mass, and a shorter length than the single tube design. However, it costs over twice as much to manufacture.

5. Mounting the Heat Exchanger



System Components:

- 122 copper tubing
- 6061 aluminum spacer plate
- Indium foil
- 316 stainless steel socket headed cap screws
  - M5 for the cryocooler and M3 for the temperature sensors
- Belleville washers
- Brass Swagelok fittings
- Lakeshore XDT-670-CU-1.4L temperature sensors
- Ruthenium(iii) chloride

5. Quantifying System Performance

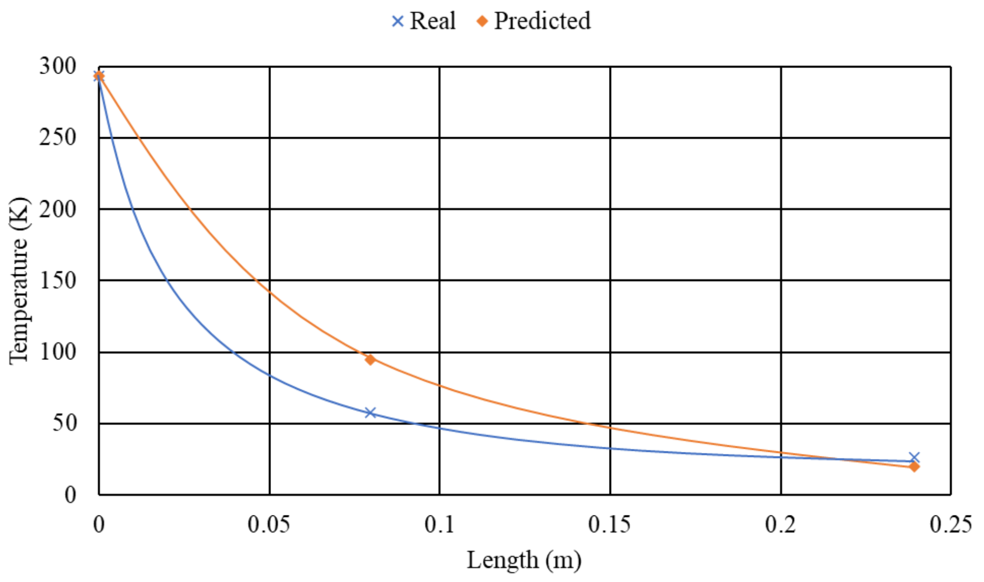
Mass Flow Rate

- A buffer tank is installed prior to the heat exchanger. The change is pressure over time is used to determine the rate of liquefaction.
- Average rate of liquefaction: 0.003535 g/s
  - Standard deviation: 0.0002375 g/s
- The calculated value is 44.19% of the predicted value.

	Rate of Liquefaction (g/s)
Charge 1	0.003770
	0.003819
	0.003718
Charge 2	0.003374
	0.003534
	0.003433
Charge 3	0.003100

Temperature Profile

- The inlet temperature is assumed to be ambient.
- The upper flange maintains an average temperature of 58.0523 K.
- The lower flange maintains an average temperature of 26.1631 K.



5. Discussion of Results and Suggested Improvements

Discussion

The mass flow rate and the temperature of the upper stage of the cryocooler are lower than expected. Possible causes include:

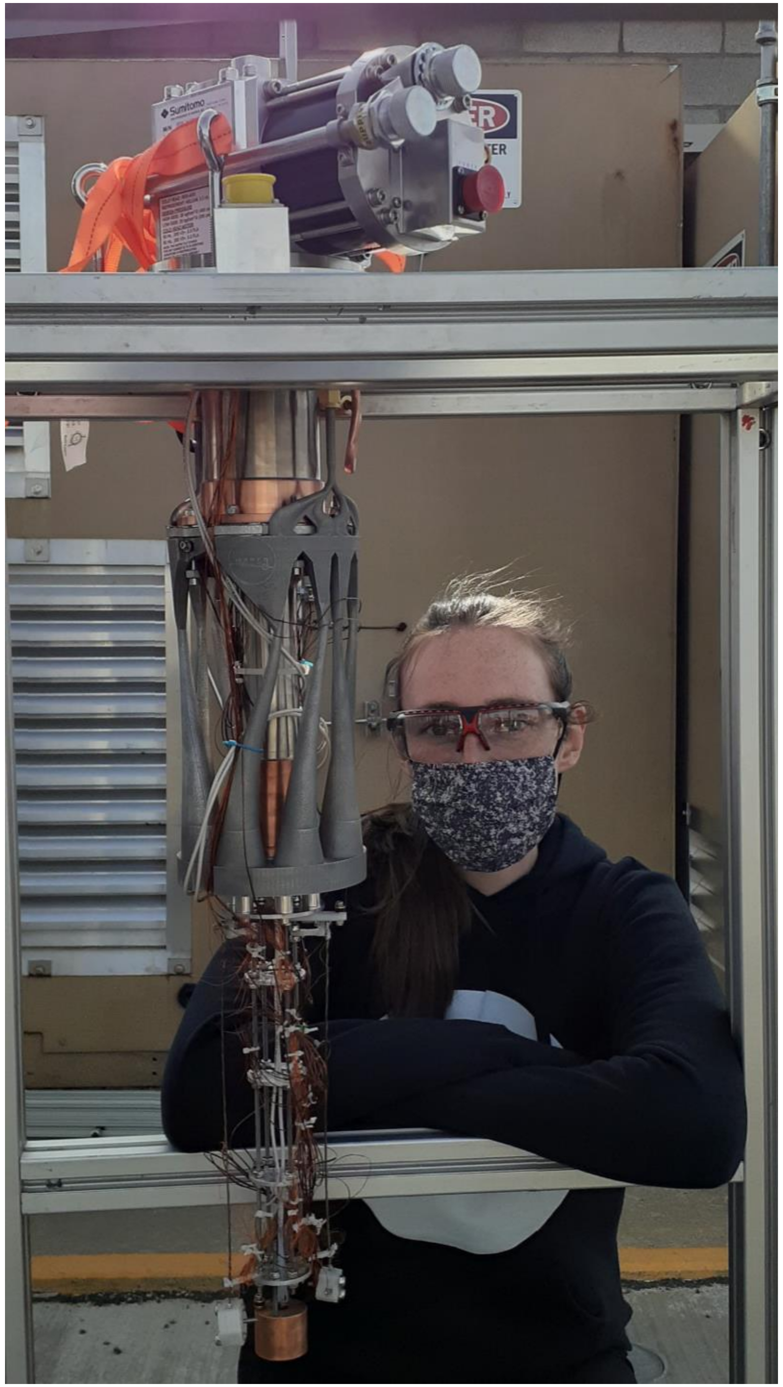
- Unknown thermal properties of the heat exchanger material.
- The addition of the spacer plate.
- Unknown properties of the ruthenium catalyst including the resistance and thermal conductivity.
- The assumption that each stage of the cryocooler only pulls heat from the portion of the heat exchanger prior may be incorrect.
- The lower stage of the cryogenic refrigerator may be lifting less heat than anticipated.
- There may not be adequate pressure applied to the indium foil.

Suggested Improvements

- Print in a more optimal material (high thermal conductivity, low heat capacity, and low density).
- Investigate then thermal contraction that occurs during printing.
- Remove support material when possible.

5. Summary

- This work is a proof of concept of an additively manufactured optimized heat exchanger for hydrogen liquefaction. It represents an opportunity to improve a historically inefficient part in a more compact form factor, improving overall system efficiency and increasing accessibility.
- A Crank-Nicolson model was used to optimize a heat exchanger form factor to minimize entropy generation.
- The printed heat exchanger has an effectiveness metric 23.23% larger than that of a single tube design.
- The printed heat exchanger has a thermal mass 43.82% less and is 91.39% shorter than the single tube design.
- The printed heat exchanger successfully liquefied hydrogen at a mass flow rate of 0.003535 g/s with an outlet temperature of 26 K.



5. Acknowledgements

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Thank You!