Design of Heat Exchanger in a Hybrid Cascaded Refrigeration Cycle for Venus Lander Electronics Cooling Applications

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Kellogg Honors College Capstone Project

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Abstract:

A heat exchanger within a proposed Venus Lander's cascaded refrigeration cycle was designed using a discretized enthalpy analysis with variable heat transfer coefficient capabilities. This method of heat exchanger analysis was used due to its higher accuracy than other methods such as Log Mean Temperature Difference (LMTD) and Number of Transfer Units (NTU). The discretized enthalpy method uses iteration which analyzes each unit length individually. This makes it more accurate than LMDT and NTU methods which analyze the entire heat exchanger in a more general fashion.

This heat exchanger's design constraints included the requirement of corrosion-resistant materials, low weight, low physical footprint, high performance, and high thermal creep resistance. Different heat exchanger types were considered such as Shell and Tube, Spiral, and Plate in order to find the most space-efficient design. All analysis and computation was completed in Excel and MATLAB where temperature, heat transfer coefficient, and other values were calculated and recorded.

With this method, a more accurate analysis was performed resulting in a heat exchanger specification that more closely matched the system's actual performance. Designing closer to actual behavior allowed for lower weight and size, both of which are extremely significant in spacecraft payload design.

LMTD Analysis of Heat Exchanger:

$$q_C = U * A * \Delta T_{LM}$$

$$\Delta T_{LM} = \frac{(T_{H,Out} - T_{C,In}) - (T_{H,In} - T_{C,Out})}{\ln\left(\frac{T_{H,Out} - T_{C,In}}{T_{H,In} - T_{C,Out}}\right)}$$

$$U = 300\frac{W}{m^2 * K}, A = 64.7\ mm^2 * 90\ nodes$$

$$T_{H,Out} = 122.3°C, T_{C,In} = 117°C, T_{H,In} = 154.8°C, T_{C,Out} = 138.56°C$$

$$\Delta T_{LM} = \frac{(122.3°C - 117°C) - (154.8°C - 138.56°C)}{\ln\left(\frac{122.3°C - 117°C}{154.8°C - 138.56°C}\right)} = 9.7699\ K$$

$$q_{LMDT} = \left(300\frac{W}{m^2 * K}\right) * \left(64.7\ mm^2 * 90\ nodes * \frac{1\ m^2}{1000000\ mm^2}\right) * (9.7699\ K) = \boxed{17.067\ W}$$

E-NTU Analysis of Heat Exchanger: (Assumed Shell and Tube One Pass)

$$NTU = \frac{U * A}{C_{min}}, C_{min} = c_{p,min} * \dot{m}_{cp,min}$$

$$c_{p,min} = 2.36\frac{kJ}{kg * K}, \dot{m}_{cp,min} = 0.624\frac{kg}{hr}, U = 300\frac{W}{m^2 * K}, A = 64.7\ mm^2 * 90\ nodes$$

$$NTU = \frac{\left(300\frac{W}{m^2 * K} * \frac{1\ kJ}{1000\ J}\right) * \left(64.7\ mm^2 * 90\ nodes * \frac{1\ m^2}{1000000\ mm^2}\right)}{\left(2.36\frac{kJ}{kg * K}\right) * \left(0.624\frac{kg}{hr} * \frac{1\ hr}{3600\ s}\right)} = 4.270$$

$$\varepsilon = 2\left(1 + C_r + (1 + C_r^2)^{\frac{1}{2}} * \frac{1 + e^{-NTU(1+C_r^2)^{\frac{1}{2}}}}{1 - e^{-NTU(1+C_r^2)^{\frac{1}{2}}}}\right)^{-1}, C_r = \frac{C_{min}}{C_{Max}} = \frac{c_{p,min} * \dot{m}_{cp,min}}{c_{p,max} * \dot{m}_{cp,max}}$$

$$C_r = \frac{\left(2.36\frac{kJ}{kg * K}\right) * \left(0.624\frac{kg}{hr} * \frac{1\ hr}{3600\ s}\right)}{\left(20.56\frac{kJ}{kg * K}\right) * \left(0.095\frac{kg}{hr} * \frac{1\ hr}{3600\ s}\right)} = 0.5748$$

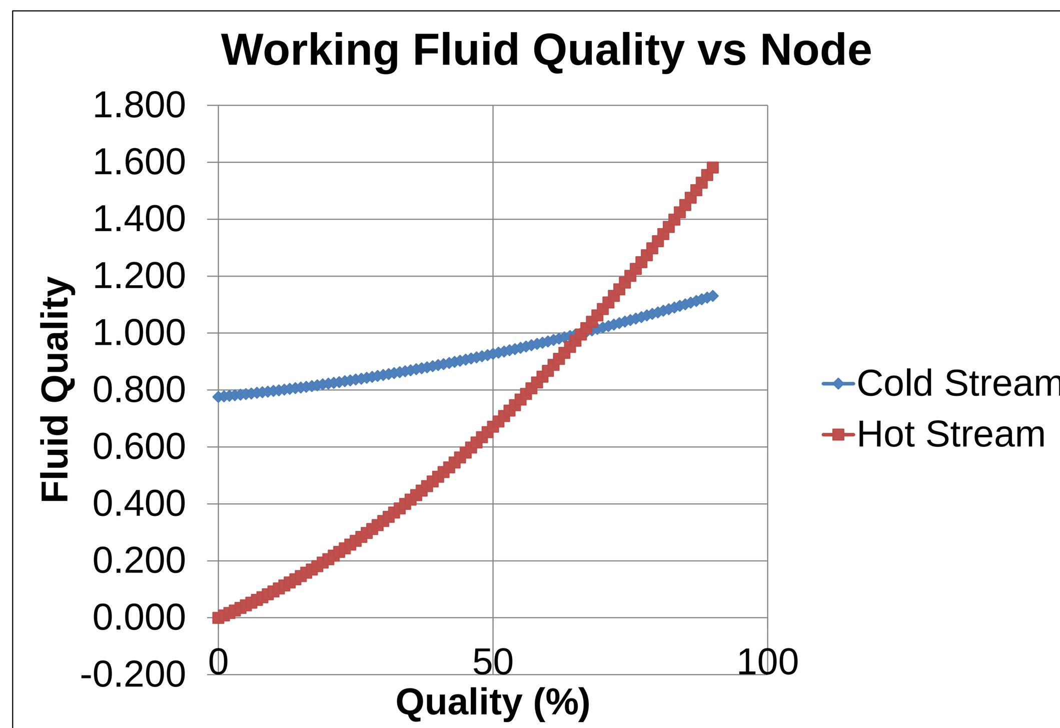
$$\varepsilon = 2\left(1 + (0.5748) + (1 + (0.5748)^2)^{\frac{1}{2}} * \frac{1 + e^{-(4.270)(1+(0.5748)^2)^{\frac{1}{2}}}}{1 - e^{-(4.270)(1+(0.5748)^2)^{\frac{1}{2}}}}\right)^{-1} = 0.7286$$

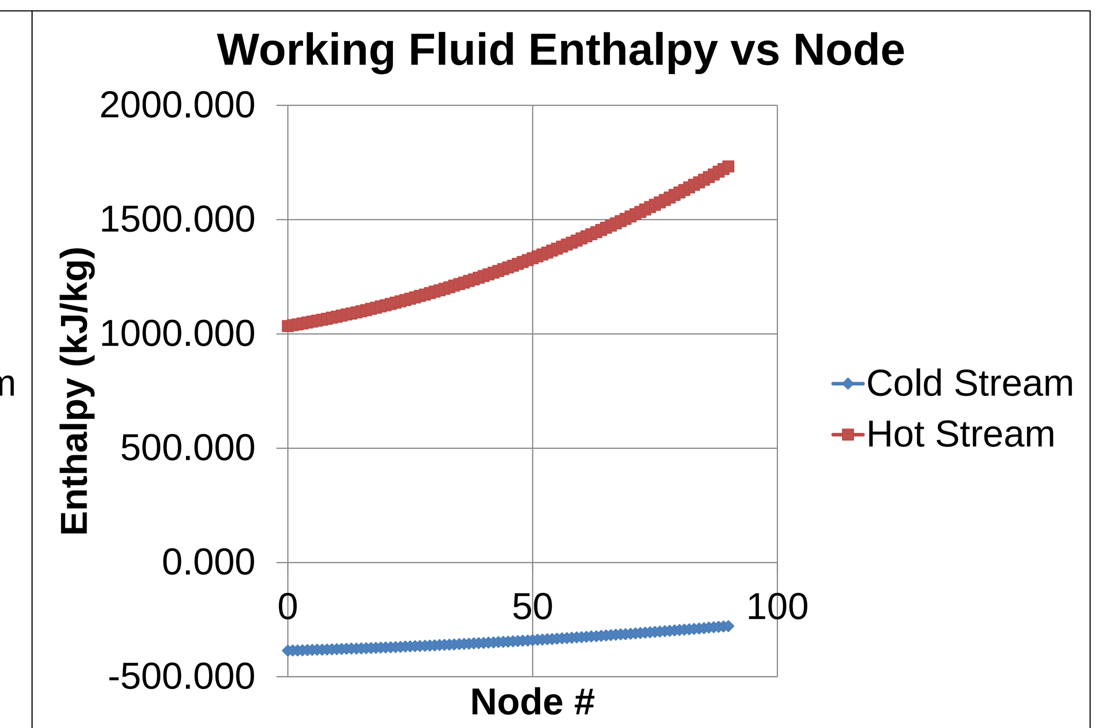
$$q_{NTU} = \varepsilon * C_{min} * (T_{h,in} - T_{c,in})$$

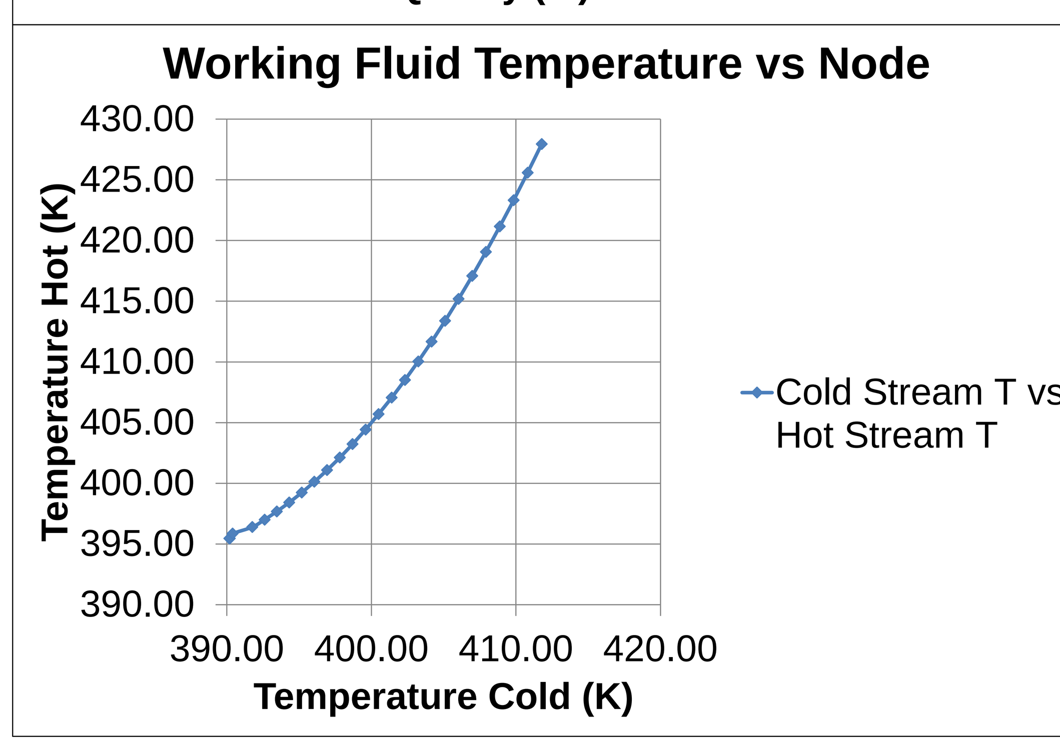
$$T_{h,in} = 154.8°C, T_{c,in} = 117.0°C$$

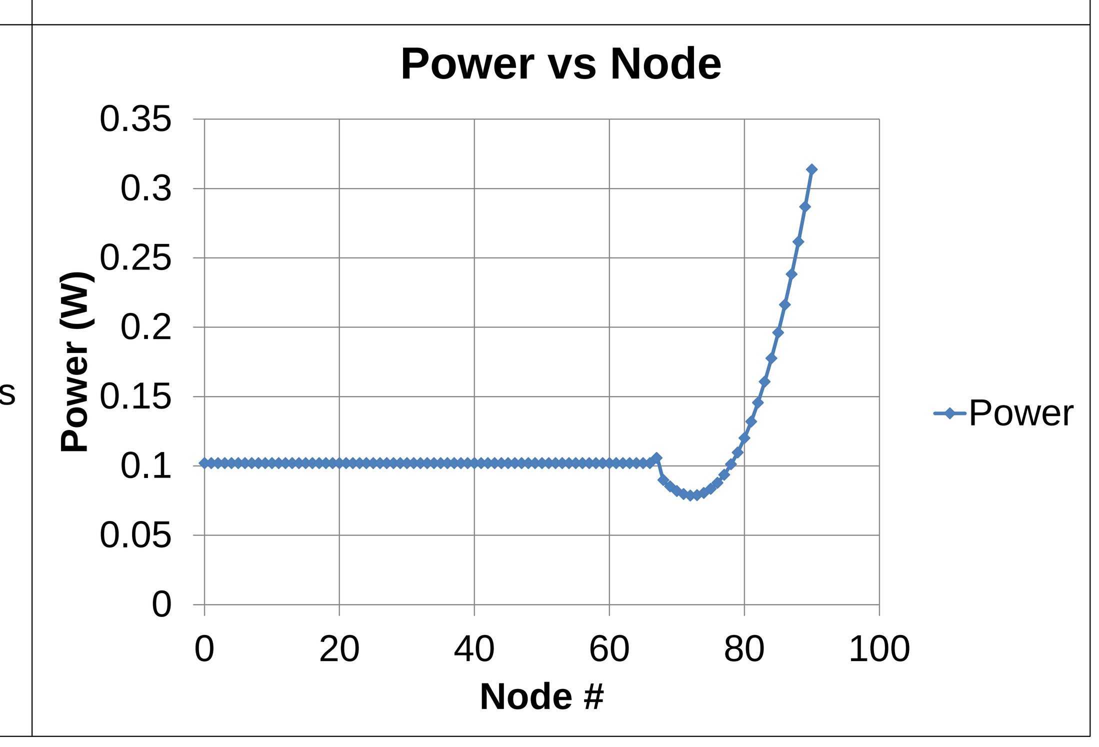
$$q_{NTU} = (0.7286) * \left(2.36\frac{kJ}{kg * K}\right) * \left(0.624\frac{kg}{hr} * \frac{1\ hr}{3600\ s}\right) * (154.8°C - 117.0°C) = \boxed{11.266\ W}$$

Simulation Results:







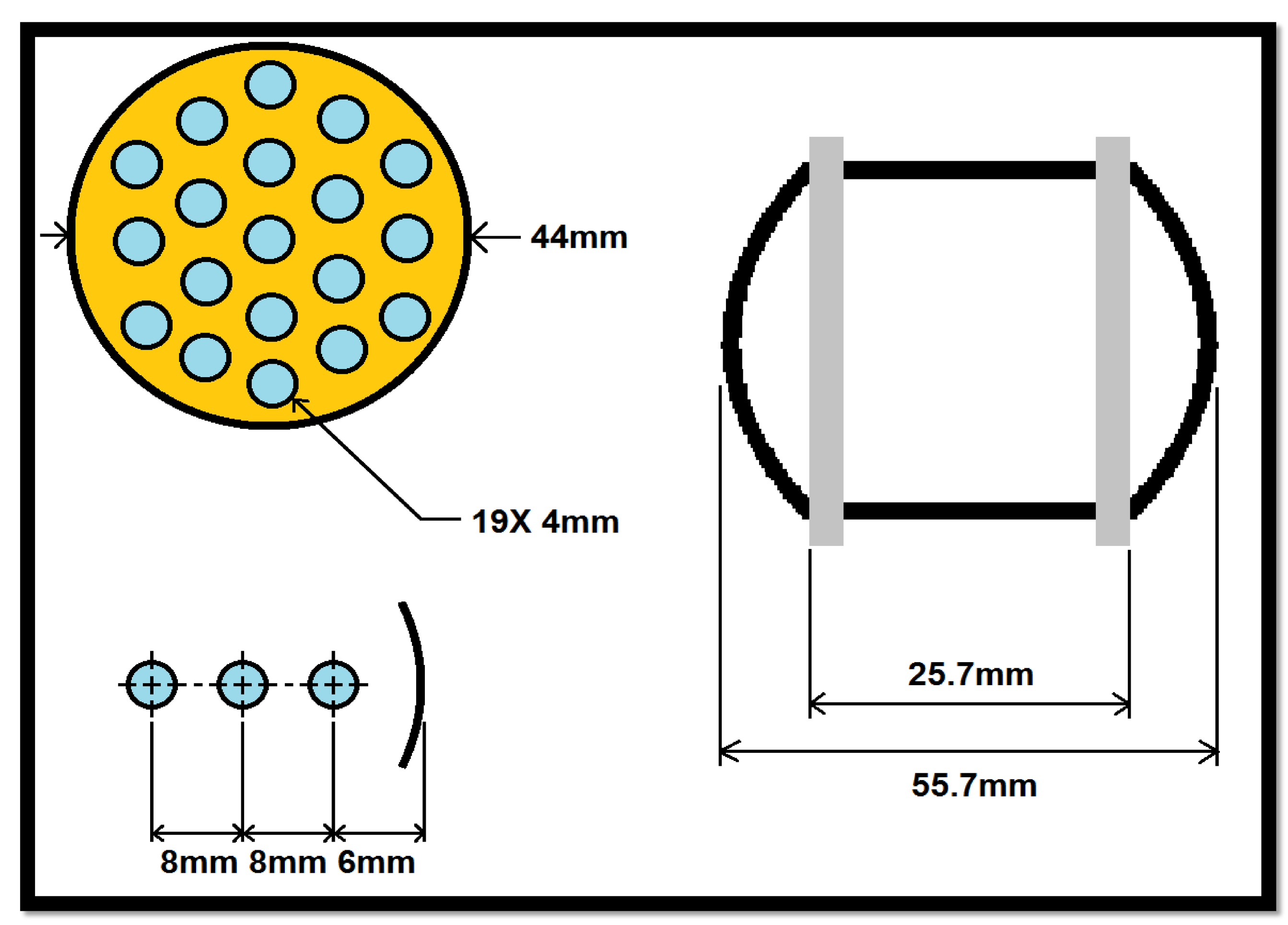


Heat Exchanger Attributes:

Approach Point: 16.24°C
Pinch Point: 126.09°C
Cold Fluid Range: 117°C – 138.56°C
Hot Fluid Range: 122.3°C – 154.8°C

Number of Tubes: 19
Total Tube Length: 463.6 mm
Layout: 2 Rings and Center
Form Factor: 44mm Diam. x 55.7 mm
B Ratio = 0.0067 mm³/mm³

Resulting Heat Exchanger Overview:



Simulation Discussion:

The simulation's resulting power, found from the sum of nodal powers, was 10.246 watts. This is Lower than the NTU analysis by 1.02 watts and lower than the LMTD analysis by 6.821 watts.

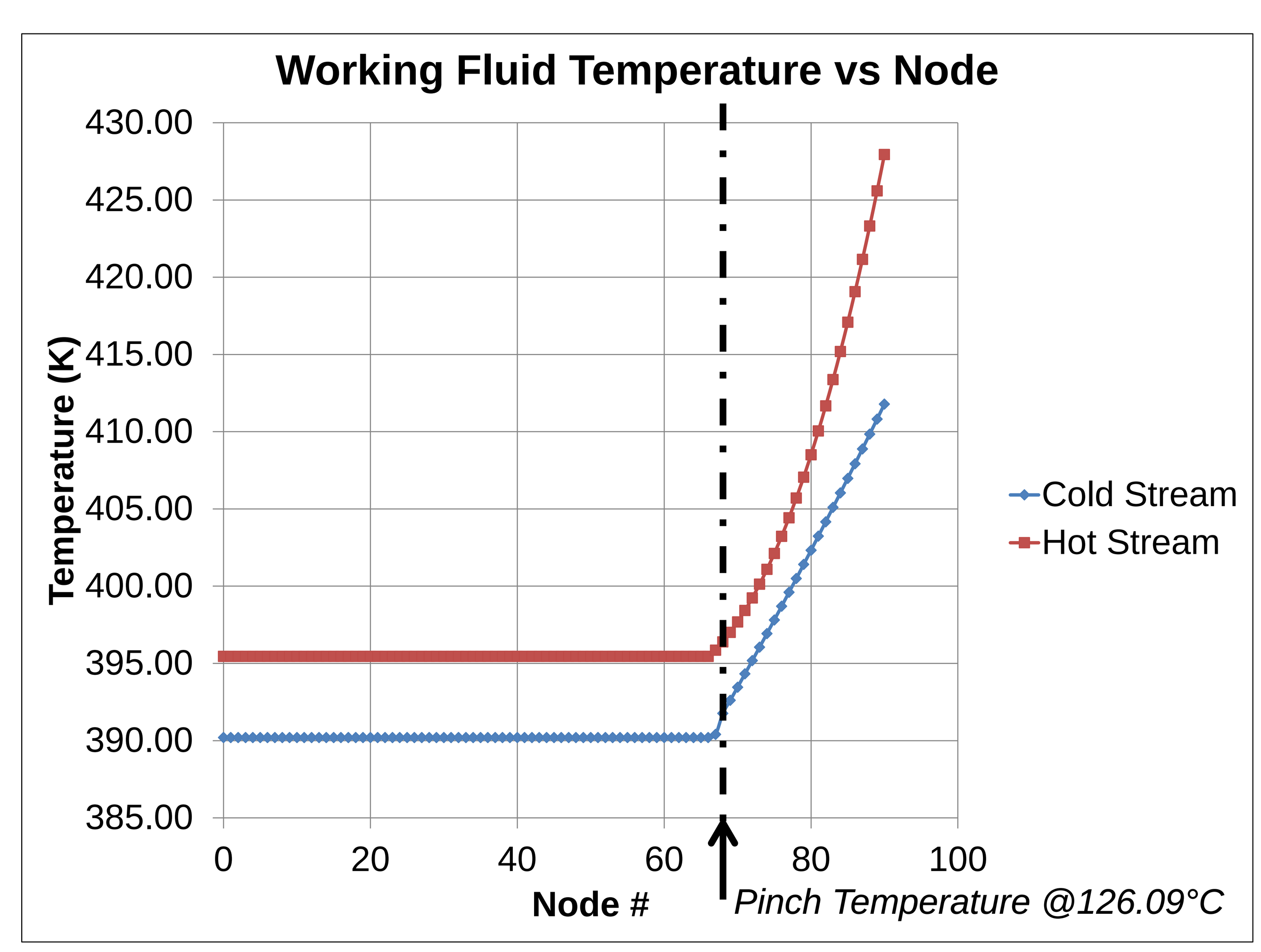
The results of this simulation make sense since the size of the heat exchanger with respect to its duty is reasonable: 10.2 watts within 84 mL.

The material to be used in this heat exchanger is Copper due to its high corrosion resistance and high thermal conductivity.

Conclusion:

The simulation yielded good results; however, other configurations of heat exchangers should be tested such as plate HX, spiral HX, and such.

A potential change in the design may also instead use a lighter Nickel alloy in the heat exchanger, Increasing the size slightly but reducing overall weight of the heat exchanger. More analysis would be needed to decide which material offers better design results.



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