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A biomimetic concept for the design of NASA's deep space-flight radiators

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ABSTRACT

Traditionally, NASA has relied primarily on pumped, single-phase liquid systems to collect, transport, and reject heat via single-phase radiators. The heat-rejection system used on the space shuttle orbiters consists of over 250 small, one-dimensional tubes embedded within a honeycomb structure. Heat is transferred by convection to the tube walls, conduction through the honey-comb structure, and finally, through radiation to space. NASA is currently developing nuclear electric propulsion engines to power next generation spacecrafts to transit to Mars and beyond, and these spacecrafts need heat rejection systems with performance capabilities significantly better than those provided by current systems.

The origins of a heat pipe go back over 60 years, but there is still room for new ideas to grow. Traditional heat pipe consists of an open adiabatic zone, with a mesh wick lining the inside of the tube wall to aid in transportation of condensed liquid from the condenser side to the evaporator side. A biomimetic, multi-function concept developed at New Mexico Tech (NMT) has an architecture consisting of interconnected pores graded radially as well as longitudinally can be implemented for heat pipe to allow heated fluid to flow radially as well as longitudinally. This configuration promotes fast convection of the heat from evaporator end to the tube walls and dissipates heat more evenly throughout the radiator lateral surface.

Past experiments done at NMT using samples with biomimetic design demonstrated that upon localized heating, there can be an induced convective transport of thermal energy as fluid passes through a closed-loop porous layer. The goal of on-going investigation is to highlight how biomimetic architecture may provide the required thermal performance simultaneously reducing heat rejection system mass.

KEY WORDS: Biomimetic Design, Heat Pipe, Deep Space, Wick Layer,

1. INTRODUCTION

Traditionally, NASA has relied primarily on pumped, single-phase liquid systems to collect, transport, and reject heat via single-phase radiators. The heat-rejection system used on the space shuttle orbiters consists of over 250 small, one-dimensional tubes embedded within a honeycomb structure. Heat is transferred from the coolant by convection to the tube walls, conduction through the honey-comb structure, and finally, by radiation to space. NASA is currently developing nuclear fusion engines to power the next generation of spacecrafts to transit to Mars and beyond, and these spacecrafts need heat rejection systems with performance capabilities significantly better than those provided by current systems. Designing innovative radiators is critical to advancing future deep space missions. Figure 1 shows various components of a Nuclear Electric Propulsion (NEP). Radiator manifold carries waste heat from the nuclear reactor to the heat pipe radiator to be rejected into the atmosphere.

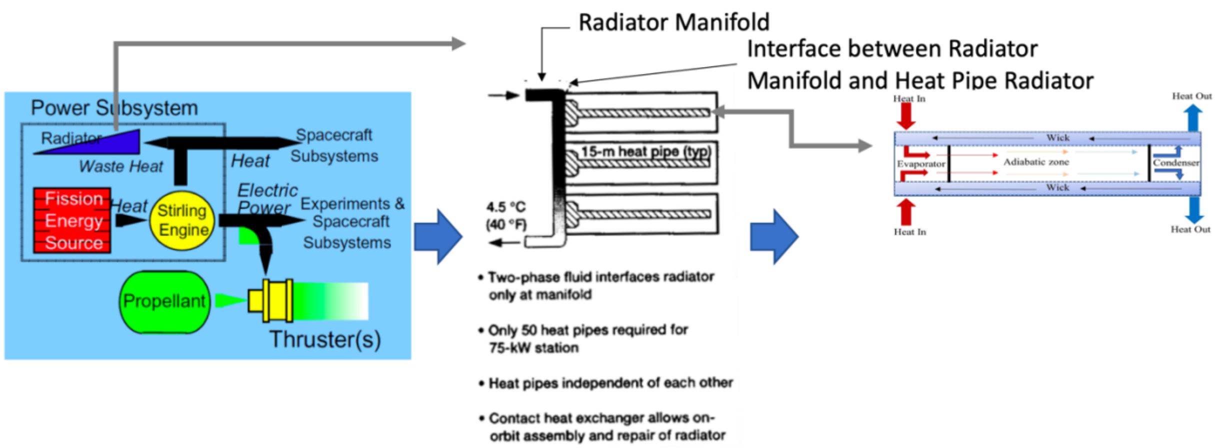


Figure 1: (left) Schematic of Power Subsystem for NEP [taken from figure 1.6 of [1]]; (middle) Waste Heat transport from radiator manifold to heat pipe radiator; (right) Cross-section of a classical (copper/water) heat pipe showing heated region on left and transfer region on right.

1.1 Literature Research on Heat Pipe Technology

Heat pipe (HP) concepts were created first in the early 40's [2], but the theory was not intensely investigated until the late 60's. The first published paper on design of a traditional two-phase heat pipe was shown in "Theory of Heat Pipes" by T.P. Cotter - a scientist at Los Alamos National Laboratory [2]. Many decades later now, there are over 1000 references to his paper. Cotter's publication is the foundation of this large field of study. Heat pipes efficiently dissipate heat passively, reject heat without any external source needed to function properly, i.e. no external power source is required.

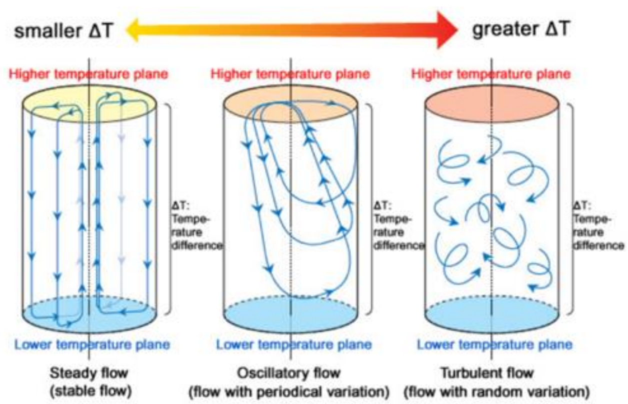
There are 4 main areas of a heat pipe, the evaporator side, the condenser side, the adiabatic zone, and the wick. Heat enters the evaporator section typically through conduction. The working fluid in the evaporator end absorbs the heat and the fluid changes from a liquid to a vapor. As it becomes a vapor, the fluid is transported through the adiabatic zone to the condenser side. On the condenser side, the heat pipe is much cooler. When enough vapor is moved to this side, the vapor changes back into a liquid [3]. The wick then transports the condensed liquid back to the evaporator side. This occurs due to capillary action and pressure differences. A cyclic process will start and will continue to dissipate as long as the heat flux being added to the system is within the specifications of the HP's design. The process is considered adiabatic due to the liquid/vapor being fully contained within the heat pipe. Depending on the fluid type, shape/material of the housing, type/material of wick, and the internal structural architecture, functioning of heat pipe requirements will change accordingly.

1.1.1. Wick of the Heat Pipe

A wick is a type of porous media that is designed to match the length of the tube it is used in, and is responsible for transporting fluid in a single direction. They are typically placed around the outer circumference of the heat pipe, and are directly attached to the casing. Homogeneous wicks, which are composed of various materials, all share a uniform structure throughout. On the other hand, non-homogeneous wicks have varying geometries that depend on the pore size and layering. Furthermore, heat transfer can also affect the wick in several ways. Recent research has revealed that the type of mesh used and their surface finish can significantly impact heat flux amount.

1.1.2 Convection at Micro-gravity

On Earth, convection is dominated by buoyancy due to gravity. In low gravity space environments, buoyance effects will diminish but the surface tension driven “Marangoni Effect” may play an important role in generating similar convective flow inside the porous structure. In the Japanese experiment module “Kibo”, a series of experiments were performed on board International Space Station (ISS) and demonstrated the spatio-temporal flow structure in Marangoni convection. They generated Marangoni convection by applying temperature differential between the ends of a large liquid bridge. As the temperature differential is increased, the initial steady state planer flow turned to oscillatory.



With more temperature differential, flow turned into turbulent flow that no longer is limited to a state of planer (shown in figure 2) [4]. This phenomenon will be implemented in the proposed design of the Biomimetic Hot Pipe.

Figure 2: “Kibo” Experiment on board ISS [4].

1.2 State of the Art (SOA)

Traditionally, copper/water heat pipes are used in advanced spacecraft radiator systems as shown in figure 1(right). Copper is used as the envelop next to a wick layer. Water as the working fluid at temperatures below 150°C. Classical/ Traditional copper/water heat pipe transfers heat with no temperature change from end to end (isothermally). The heat pipe makes use of the phase change features of the fluid as it flows from evaporating end to the condensation end.

1.2.1 Deficiency of the SOA Design

In a traditional heat pipe, the inner face of the wick layer may be permeable or impermeable to the operating fluid in the heat pipe. When it is impermeable, operating fluid cannot flow radially to reach the wall. Thus, lateral surface does not participate directly towards heat rejection to environment through radiation. If the wick face is permeable, then the longitudinal flow will try to reach the wall radially through the wick thickness. This will give rise to two cross currents at 90° to each other. Again, heat rejection amount will decrease.

1.2.2 Hypothesis and the Rationale

Lesson learned from the Kibo program combined with our own experience is implemented in the design and development of the proposed biomimetic radiator system. By filling the inner volume of the heat pipe with open-cell inter-connected porous structure will allow both the longitudinal as well as the radial movement of the operating fluid. This will allow participation of the lateral surface in the dissipation.

2. PROPOSED BIOMIMETIC DESIGN

A biomimetic, multi-function composite is developed at New Mexico Tech (NMT) that has an architecture consisting of interconnected pores graded radially to dissipate heat as fluid travels through it. Past experiments demonstrated that upon localized heating, there can be an induced convective transport of thermal energy as fluid passes through a closed-loop structure. Figure 3 shows the longitudinal cross section of both the designs.

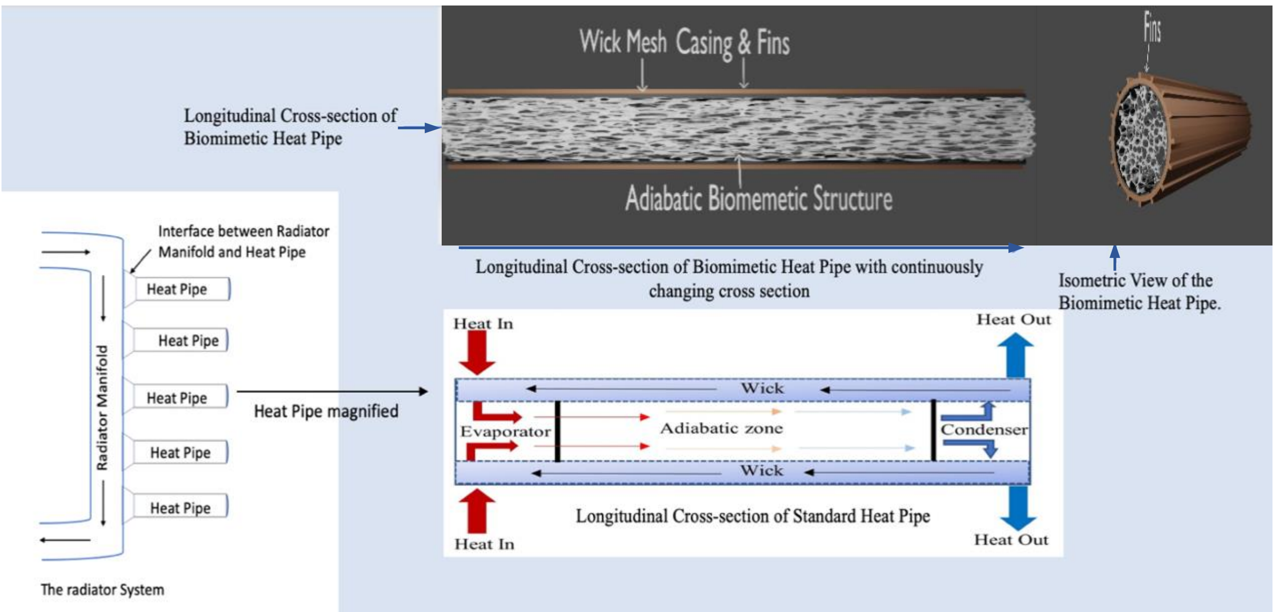


Figure 3: longitudinal cross section of both the designs

2.1 Prior Investigation

Thermal management characteristics of a fluid filled porous composite (FFPC) developed for space application is studied experimentally to determine the adaptability of the composite when exposed to high thermal load. Localized heating will generate an out-flow of fluid in the interstitial pores from the hot region to cooler surroundings, resulting in dissipation of thermal energy and eventually providing a good thermal management capability to the composite. FFPC being a heterogeneous material, there exist no ASTM standards for such material. A new test method is successfully designed, developed and tested to determine the thermal management characteristics of the FFPC.

The objectives of this past study are to experimentally demonstrate the thermal management characteristics of the fluid filled porous composite (FFPC) developed for space application. The objectives also include to development of an acceptable test method for testing such heterogeneous material. Experimental results are presented and published in the Proceedings of the 23rd National Heat and Mass Transfer Conference and 1st International ISHMT-ASTFE heat and Mass Transfer Conference, IHMTC2015, 17-20 December, 2015, Thiruvanthapuram, India (paper No 2233) [5].

2.2 Current Investigation

In current analysis, there will be two types of heat pipes that will be analyzed, a classic wicked heat pipe and a biomimetic heat pipe. The former has the geometry of a traditional heat pipe. There is a wick that is lining the interior walls of the heat pipe throughout. Vapor travels through an open adiabatic zone to the condenser end. As its phases change into a liquid, capillary pressure forces the liquid into the wick and brings it to the evaporator end.

The biomimetic design has a similar geometry in the wick, but the adiabatic zone has changed to a porous media for the vapor to travel through. Instead of heat only being rejected in the condenser end, heat can get dissipated laterally throughout the length of the pipe. This, along with a sectioned wick structure and fin attachments along the length of the pipe is hypothesized to help with heat dissipation throughout the entire heat pipe. As the vapor travels through the modified adiabatic zone, the vapor can interact with the lattice structure. Collisions between vapor molecules and the structure will cause energy transfer between them. This heat can be absorbed through conduction and if enough collisions occur, the vapor will change back into a liquid and condense on the structure. Figure 4 shows a cross-sectional view of the biomimetic heat pipe. The porous media in the wick has a low porosity, while the one in the adiabatic zone has a large porosity. Materials used in their respective meshes are shown. Figure 4 also shows cross-section of 16 longitudinal fins to promote heat dissipation along with a cut wick design to increase internal surface area. Please note that the wick layer is absent at locations where longitudinal fins are located. The following analysis will consider each zone's geometry and calculate the maximum heat transport of each design.

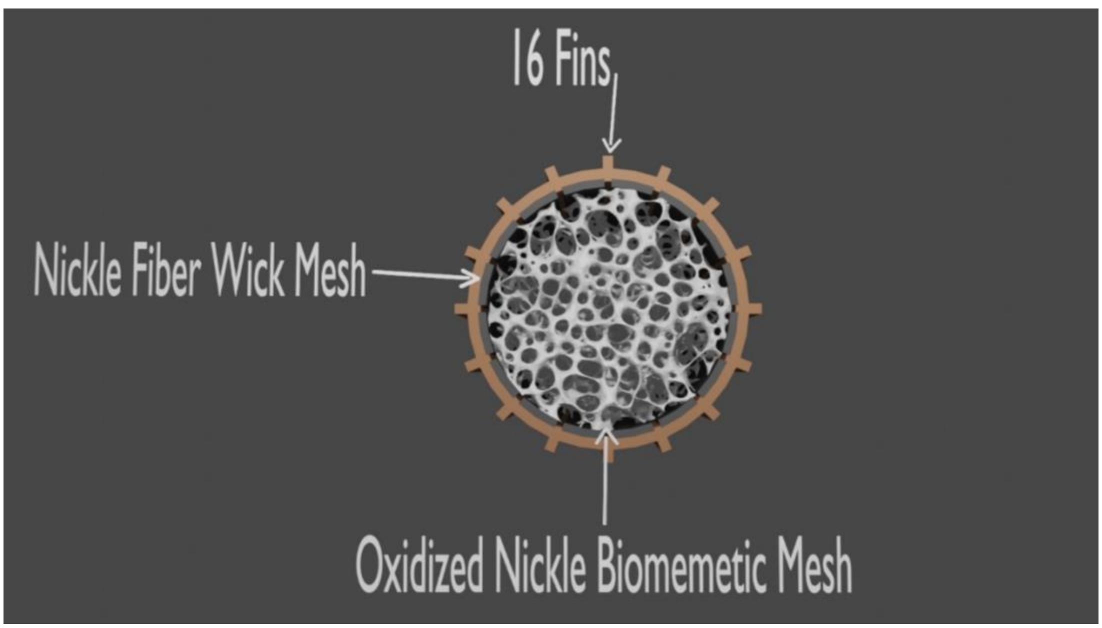


Figure 4: Front View of the Biomimetic Heat Pipe

2.2.1 Method

The two heat pipe designs will be analyzed using water as the working fluid. The heat pipes are assumed to be operating at a temperature of 100 °c, with a length of 0.3m and a diameter of 0.01m. There will be two meshes that are analyzed. The mesh in the wick has two layers of Oxidized Nickle [6] and the adiabatic porous media will have 10 layers of a Nickle fiber [6]. The first selection is made based on the pore radius, which is an average size. The latter selection was chosen because it has the largest permeability in the reference, this ensures that the fluid can flow through the media with ease. Both heat pipes are also assumed to be horizontal.

The maximum heat transport can be found by using a pressure balance equation for a heat pipe.

$$\Delta P_{c,max} = \Delta P_v + \Delta P_g + \Delta P_1 \tag{1}$$

Where ΔP_c is the capillary pressure difference of the heat pipe, ΔP_v is the pressure difference of the vapor in the heat pipe, ΔP_1 is the pressure difference of the wick section and ΔP_g is the pressure difference due to gravity. The three pressures add up to the total capillary pressure change. If the inequality is true, a cycle occurs. It is also assumed that since the adiabatic zone is at the saturation temperature, the phase of the fluid can change in the adiabatic zone before it reaches the condenser. This would cause the fluid to be pulled into the wick lining the wall. Each pressure can be broken down further and is shown below.

$$\Delta P_{c,max} = \frac{2\sigma cos\theta}{r_c} \tag{2}$$

Where σ is the value for the surface tension of water (N/m), θ is the degree of wetting of the wick (in radians), and r_c is the pore radius of the larger mesh.

The value for ΔP_v can be neglected, because, for low temperature (0-227°c), the value becomes negligible [7]. The equation for effect due to gravity is shown below in equation 3.

$$\Delta P_g = \rho_1 g l sin\emptyset \tag{3}$$

Where ρ_1 is the density of the liquid, g is the acceleration due to gravity, l is the length of the pipe, and $\emptyset$ is the incline of the heat pipe. Since the assumption that the heat pipe is horizontal, $\emptyset = 0$ and this, $\Delta P_g = 0$. The equation for ΔP_1 is shown in equation 4.

$$\Delta P_1 = \frac{\mu Q l}{\rho_1 L\, A_w K_1} \tag{4}$$

Where μ is the dynamic viscosity of the fluid (Ns/m^2), Q is the heat transport of the heat pipe (W), ρ_1 is the density of the liquid (kg/m^3), L is the latent heat of water (J/kg). A_{w1} is the area of the wick (m^2

), and K_1 is the permeability of the mesh (m). Since both ΔP_g and $\Delta P_v \approx 0$, equation (1) can now be rewritten.

$$\frac{2\sigma cos\theta}{r_c} = \frac{\mu Q l}{\rho_1 L\, A_w K_1} \tag{5}$$

Since the maximum heat transport needs to be found, Q can be solved for in equation 5 and the maximum heat transport can be found. Equation 6 shows the newly solved equation.

$$Q = \frac{2\sigma cos\theta}{r_{c1}} * \frac{\rho_1 L\, A_w K_1}{\mu l} \tag{6}$$

This is used to find the maximum heat transport of the traditional heat pipe. For the biomimetic heat pipe, the equations need to be considered differently to account for the additional mesh material.

The cross-sectional area can be calculated using equation 7.

$$A_{w,a} = (2 * N)D_w * \pi * D_s \quad (7)$$

Where N is the number of layers of the mesh, D_w is the diameter of the wire of the mesh, and D_s is the diameter of the section being analyzed.

When accounting for the addition of the porous material an additional pressure difference needs to be accounted for. It is assumed that if the vapor in the adiabatic zone partially changes to a liquid, this pressure accounts for. This will be denoted as ΔP_2 the equation for this looks similar to equation 4 but needs to be changed based on the area of the mesh, the permeability, and the density. It is assumed that if the vapor in the adiabatic zone partially changes to a liquid, ΔP_2 accounts for it. This is shown in equation 8.

$$\Delta P_2 = \frac{\mu Q l}{\rho_v L\, A_a K_2} \quad (8)$$

Where ρ_v is the density of the vapor, A_a is the area of the adiabatic zone, and K_2 is the permeability of the second mesh. Now going back to our pressure balance equation, we need to account for this additional pressure difference.

$$\frac{2\sigma cos\theta}{r_{c2sa}} = \frac{\mu Q l}{\rho_1 L\, A_w K_1} + \frac{\mu Q l}{\rho_v L\, A_a K_2} \quad (9)$$

By factoring and solving for Q, we obtain equation 10.

$$Q = \frac{2\sigma cos\theta}{r_{c2}} * \left(\frac{\rho_1 L\, A_w K_1 + \rho_v L\, A_a K_2}{\mu l}\right) \quad (10)$$

Dynamic viscosity is assumed to be constant for this calculation because the operation is at the saturation temperature of the fluid, there can be areas in which the adiabatic section is areas in which the water becomes liquid. This would cause the liquid portions to be pulled into the wick and transported back to the evaporator section. Now that equation 10 has been obtained, the maximum heat transport will be calculated for each of the cases and then compared.

2.2.2 Results

The constant values for each of the variables are shown in table 1.

Table 1: Calculation Parameters [6,7,8]

Parameter	Values
σ	.0589 N/m [6]
θ	0°
μ	.00283Ns/m^2 [6]
l	.3 m
ρ_1	958 kg/m^3 [7]
ρ_v	.5974 kg/m^3 [7]
L	2258000 KJ/kg [8]
A_w	5.7*10^{-6} m^2

A_a	11*10^{-6} m^2
K_1	.302*10^{-10} m^2 [2]
K_2	6.35*10^{-10} m^2 [2]
r_{c1}	0.00002 m [2]
r_{c2}	0.00001 m [2]

The degree of wetting on both meshes are assumed to be perfectly wetted. In this case, Equation 6 is used to find the maximum heat transport of the standard heat pipe using the values that are shown above. Equation 9 finds the maximum heat transport for the biomimetic heat pipe. To distinctly compare the two heat pipes, Q is assumed to be a function of the length of the heat pipe and is iteratively calculated. The heat pipe length is increased to 1 m and incrementally reduced to the target length of 0.3 cm. A MATLAB code was created for this analysis to calculate the iterated heat transport values. Figure 5 shows this analysis.

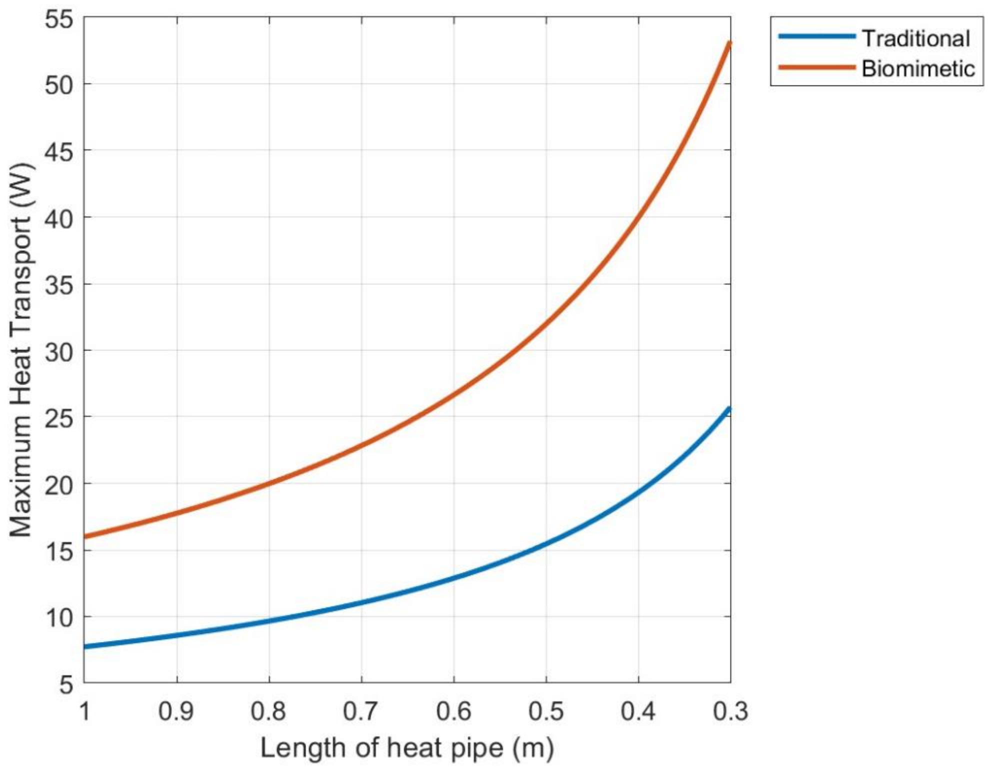


Figure 5: Q values for each Heat Pipe as it reaches the target length.

The maximum value for the traditional heat pipe is 25.72 W and the biomimetic heat pipe has a maximum heat transport value of 53.21 W.

2.2.3 Discussion and Conclusion

This analysis shows that the biomimetic heat pipe can transport more heat as the heat pipe length is reduced. The biomimetic heat pipe value is double throughout. This shows that if the biomimetic heat pipe is reduced to a length half of the target length, it will dissipate just as much as the traditional heat pipe at the current length. This shows that even though the material is being added to the system, and this causes it to have more mass, the biomimetic heat pipe is efficient enough to reduce the length, thus keeping the heat pipe lightweight. The analysis also does not put into consideration the lateral dissipation due to the addition of the wick and fins. Further investigation is on-going to prove the efficacy of the biomimetic design. These would include using simulation software to compare values. Physical testing will also be utilized. Full testing procedure and results of this analysis will be compiled and included in the final presentation. The quantities used for the mesh and geometry constants are subject to change based on further optimization.

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