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Low-Power Water-Vapor Generation using Ultrasonic Atomizer for Use with Microwave Electrothermal Thrusters

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ABSTRACT

Water vapor, as a non-toxic, liquid-storable, and environmentally friendly substance, is a compelling propellant to use with Microwave Electrothermal Thrusters (METs). Due to the power limitations of spacecraft that would utilize METs, such as CubeSats, the vaporization of liquid water must be achieved with as little power as possible. Utilizing an ultrasonic atomizer was investigated as it provides a flow of water with increased surface area by generating small water particles via ultrasonic mechanical vibrations. In order to efficiently heat these particles, the stream was injected into a heated pipe containing copper foam, used to increase the heated surface area with which the flow interacts. Testing of this system found that utilizing copper foam decreased the specific energy of the system by 20%. When compared to existing water vaporizers designed for similar thermoelectric propulsive devices, a 33–79 % decrease in specific energy would be required for this system to be comparable. As no optimization of this system was attempted after proof-of-concept testing, further work to decrease this specific energy could bring the specific energy closer to these existing systems. It was also found that ultrasonic atomizers do not provide as simple of mass flow control as conventional vaporizers do; however, varying propellant pressurization could provide this control capability. Further work will involve pressurization of propellant tanks and changes to the testing apparatus to allow for mass flow control and optimization of the system, with the goal of decreasing specific energy.

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Chapter 1: Introduction

1.1 Introduction to Electric Propulsion

Electric propulsion (EP) comprises propulsive devices that utilize electrical power in the production of thrust, rather than conventional chemical propulsion devices, which utilize the energy stored in chemical bonds to produce thrust. The development of EP dates back to the 1960s, and the technology has steadily matured to the point where hundreds of EP thrusters have operated on satellites and interplanetary probes [1].

The main advantage of electric over chemical propulsion is that the amount of propellant mass consumed can be greatly reduced as, in principle, there is no limit to the amount of electrical energy that can be added to a given quantity of mass. This also means that there is no hard limit to the specific impulse, or I_{sp}, of the thruster [2]. The I_{sp} of a thruster is defined as the impulse delivered per unit of propellant consumed. The I_{sp}, by convention, uses weight at the surface of the Earth in its definition, and is given by

$$I_{\mathrm{sp}} = \frac{\int_0^{t_p} F(t)dt}{g_0 \int_0^{t_p} \dot{m}_p dt} = \frac{I}{g_0 m_p} \tag{1}$$

where I is the impulse delivered, g_0 is the gravitational acceleration on the surface of Earth, and m_p is the mass of the propellant ejected. This equation can be further simplified under the assumption that the thrust is constant, and can be written as a simple relationship with the propellant exit velocity, v_e, as

$$I_{\mathrm{sp}} = \frac{\mathcal{T}}{g_0 \dot{m}_p} = \frac{v_e}{g_0} \tag{2}$$

where $\mathcal{T}$ is the thrust. As this equation shows, an increase in v_e leads to a linear increase in I_{sp}. With EP, adding more electrical power to the system leads to a higher exit velocity, which in turn leads to larger I_{sp}. The efficiency of an electric thruster, defined as the percentage of the input electrical power converted to mechanical power, can also be determined. The lower the efficiency a thruster has, the greater the power loss experienced. Various sources of power loss include fuel ionization and decomposition, velocity spread, beam divergence, and radiative heat transfer.

The main drawback associated with EP is the amount of thrust that can be produced. While EP devices can lead to a very high I_{sp}, their overall thrust output generally does not exceed 1 N and is usually in the range of 10 mN to 220 mN [2]. This makes EP devices infeasible for orbital insertion, but ideal for in-space orbital or interplanetary maneuvers for satellites.

While all EP systems share the same feature of adding energy to a working fluid via an electrical source, EP systems are numerous and diverse. The operation of the system can be steady or pulsed; the gas acceleration can occur via thermal, electrostatic, or electromagnetic means; and the propellant can be a gas, a monopropellant, or even a solid [3]. Of these various configurations, four different, well-established thrusters will be discussed.

1.1.1 Resistojets

Resistojets are electrothermal EP devices that operate on the basic concept of heating up a gas by passing it over an electrically heated material, such as pipes heated radiatively from the outside, and exiting the heated gas through a nozzle to generate thrust. This heating reduces the gas flow rate of a given upstream pressure through a nozzle, with the specific impulse increasing as a function of $\sqrt{T}$, where T is the temperature of the heated gaseous propellant. There are few requirements for the fuel, as any gas that can withstand the high temperature can be used for this type of thruster, with the most prevalent being catalytically decomposed hydrazine. The I_{sp} achieved by hydrazine thrusters is around 300 s with an efficiency of 80%, and is limited by the wall heating temperature, which can reach up to 2000 K based on the material properties.

1.1.2 Arcjets

The arcjet is another type of electrothermal device, but unlike the resistojet it is able to bypass the wall heating limitation by using an electric arc to heat the gas. This is done by using a concentric upstream rod cathode and a downstream anode, which also acts as a supersonic nozzle. The center of the chamber, where the arc is mostly located, can reach temperatures of 10,000–20,000 K, while the walls remain at 2000 K. Though the walls are unable to achieve higher temperatures than the resistojet, the higher temperatures elsewhere lead arcjets to achieve an I_{sp} of 500–600 s. However, arcjets are much less efficient, with no higher than 40% efficiency being achieved. If a spacecraft has the ability to use extra power, an arcjet is superior, whereas spacecraft that are much more power limited may opt for resistojets, if considering electrothermal options.

1.1.3 Hall Thrusters

Unlike resistojets or arcjets, Hall thrusters are electrostatic thrusters that inject a gas, typically xenon, through an anode into a chamber in which counterflowing electrons, injected by a hollow, external cathode, ionize the gas. The now-positively-charged xenon atoms then get accelerated out of the thruster by the cathode. Behind the anode sit magnetic coils that produce a radial magnetic field in the chamber. The xenon atoms are only slightly deflected by this field, whereas the electrons are strongly deflected and execute an azimuthal drift, or Hall current, and get pumped back to the cathode. The cathode also shoots a stream of electrons out into the ionized exhaust in order to neutralize the exhaust. An I_{sp} of 1600 s can be achieved utilizing this method of thrust and occurs with an efficiency of around 50%.

1.2 Microwave Electrothermal Thruster

The microwave electrothermal thruster (MET) is an EP device that uses microwave energy to heat a gaseous propellant. This heating is performed within a microwave resonant cavity in which a free-floating plasma is produced and exhausted out via gasdynamic nozzle expansion to produce thrust [4]. The MET is comparable to the more widely-used arcjet, as it produces similar thrust and specific impulse, but the MET has a higher efficiency and longer lifetime due to the plasma remaining free-floating, causing mush less erosion of the cavity over time. Various propellants, including ammonia, helium, hydrogen, methane, nitrogen, oxygen, and water vapor have been successfully ignited to plasma within METs.

The microwave resonant cavity, a schematic of which is shown in Figure 1, contains two endplates: one containing the nozzle and the other containing a candlestick antenna for microwave energy input. Between these two endplates is a dielectric separation plate, made out of quartz or a similar material, which allows the two halves of the cavity to be maintained at different pressures. The antenna section is maintained at atmospheric pressure to prevent unwanted plasma formation and reduce mechanical stress on the separation plate for when the chamber pressure gets high. The chamber section, containing the nozzle, is kept at low pressure (< 6 kPa) during ignition as plasma ignition can only occur at low pressure. Once ignited, plasma can be maintained at pressures greater than atmospheric through increasing the mass propellant flow.

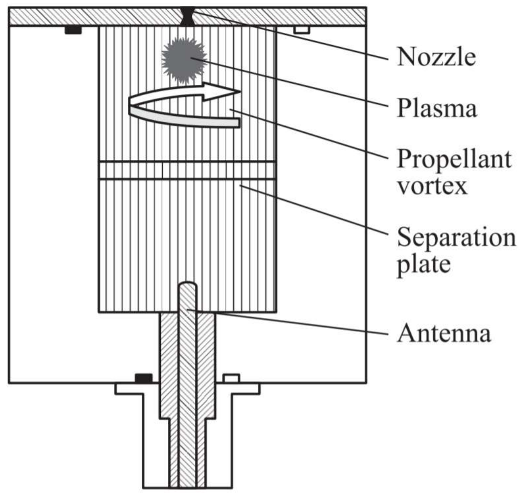

Figure 1: MET cross section schematic [5]

The propellant is injected into the chamber tangentially in order for a vortex to be formed. The introduction of the vortex allows for chamber walls to be cooled and stabilizes the plasma as the radial pressure gradient keeps it centered on the cavity axis. Through the geometry of the cavity, the placement of the antenna, and the frequency of the injected microwave power, a transverse magnetic TM^z_{011} mode is established, which concentrates the electric field along the cavity axis at both the nozzle and antenna ends of the cavity. Figure 2 illustrates the resultant electric and magnetic fields and their locations within the cavity.

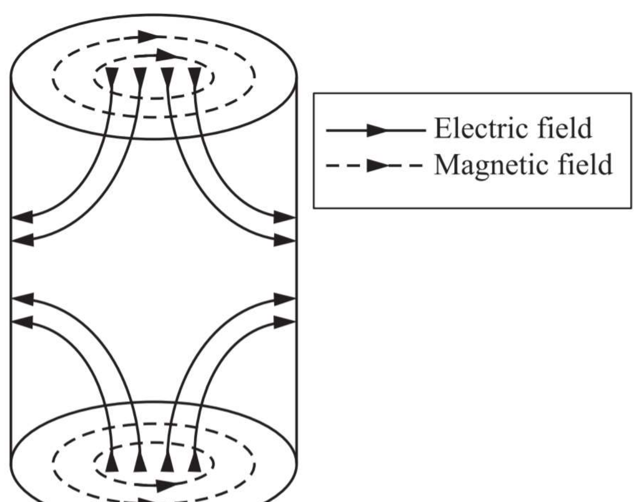

Figure 2: TM^z_{011} mode electromagnetic field in MET cavity [5]

The majority of the microwave power that is fed into the cavity is absorbed by the plasma, while the rest is reflected. The walls of the cavity, made out of aluminum or another conductive material, do not experience any significant ohmic heating. The total amount of microwave power required for a given MET is dependent on the resonant frequency of the MET. METs that have been tested include 2.45 GHz, 7.5 GHz, 14.5 GHz, 17.8 GHz and 30 GHz. As the frequency increases, the overall size of the microwave resonant cavity decreases due to the decrease in wavelength, and the total input power required for plasma ignition decreases [5].

1.3 Contribution of Thesis

The contribution of this thesis to the field of electric propulsion is the design and test of a unique concept for a fuel feed system for METs that generates water vapor and utilizes an ultrasonic atomizer. Water, due to being non-toxic, liquid storable, and environmentally friendly, is a compelling fuel for use in METs. However, water must be in its gaseous form to be heated into plasma within an MET, and due to the inherent power constraints of a satellite that would make use of an MET, must achieve this vaporization at a low specific energy. A system that atomizes prior to vaporization was designed and tested. The results and conclusions of these tests help inform future work into MET water-vaporization systems.

1.4 Overview of Thesis

In Chapter 2, a discussion of water-vapor propellant systems used in resistojets emphasizes the modes of heating that occur in a heated flow channel. Multiple existing water vaporizers, used in resistojets, are described and compared. Boiler systems theorized for use in METs are discussed, and reasons for the divergence from this design are highlighted.

In Chapter 3, the testing apparatus designed to investigate the efficacy of ultrasonic atomizers is described. The various types of data taken, as well as the measurement devices used, are subsequently listed, and the chapter ends with a discussion of the experimental procedure.

In Chapter 4, the results of two tests are discussed. These tests give values for the power required to completely vaporize the water, normalized by the mass flow rate. The chapter continues with a comparison of this system to the resistojet systems described in Chapter 2, and ends with a discussion of system complexities. Chapter 5 concludes the thesis with a summary and discussion of the conclusions drawn from this study.

Chapter 2: Background Information

2.1 Water-Vapor Propellant Systems

Water vapor used as a propellant for EP devices is not a new concept; due to being readily-available, cheap, and clean, water vapor has been studied and used on electrothermal EP devices for decades. Liquid-fed resistojets have been developed since the early 1970s and, more recently, METs using water vapor have been developed. The vaporizer systems proposed or created for these applications are compared and discussed in this section. One quantifiable way to compare the efficiency of the vaporizers is by using the specific energy, which is defined as

$$e = P/\dot{m} \tag{3}$$

where P is the input power and $\dot{m}$ is the mass flow rate of the water. The specific energy of each vaporizer discussed is given in J/mg.

2.1.1 Overview of Water Vaporizers for Resistojets

The development and design of liquid-fed water resistojets can greatly inform this project as the basis of resistojet design is creating a water vaporizer that includes a nozzle at the end in order to produce thrust. Here, the way in which liquid water is heated and converted into vapor is discussed by looking at previously developed resistojets.

Because resistojets utilize once-through boilers, there can be no recycling of liquid water back through the system for vaporization; rather, all water must be fully vaporized in one pass through the system. The heating regime that occurs in typical boiling in a flow channel is shown in Figure 3. In such a system, liquid water gets heated until nucleation occurs, after which nucleation is suppressed and a thin film of liquid forms on the wall of the channel. Heat is added to that film and causes evaporation of the film, until the liquid film breaks down and droplet vaporization and vapor superheating occurs. For a once-through boiler, it is important that the final step, droplet vaporization, effectively vaporizes all of the remaining droplets in the flow channel, as the presence of droplets causes decreased performance in resistojets [6].

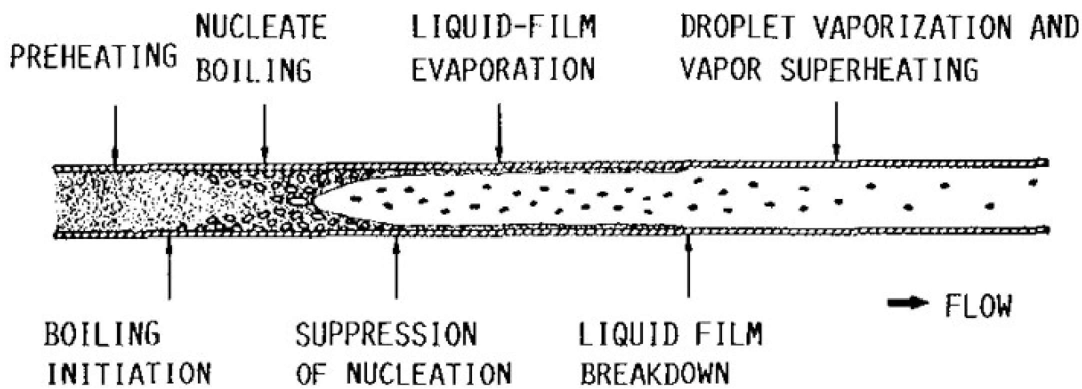

Figure 3: Illustration of water boiling in a heated flow channel [6]

An important aspect of this boiling process that must be examined is the heat-transfer coefficient of the heating from the flow chamber to the water. Shown in Figure 4 is a graph of the normalized heat transfer coefficient, h/h_T, of the heating process illustrated in Figure 3. L_{H} corresponds to the length of the flow channel from boiling initiation to vapor superheating, h_{T} is the heat transfer coefficient of the system with room-temperature subcooled water, and h is the heat transfer coefficient of the system at a point z in the flow channel. As this graph illustrates, the normalized heat transfer coefficient increases significantly as the subcooled liquid reaches boiling temperatures and continues to increase to 100 until the point of the boiling crisis is reached. This point, which corresponds to the point of liquid film breakdown in Figure 3, causes the normalized heat coefficient to begin decreasing dramatically until the heat transfer coefficient reaches around 0.1 during vapor superheating. This shows that vaporization is most efficient during the liquid film phase of flow channel heating, and the boiling crisis must be held off for as long as possible to have continued efficient vaporization.

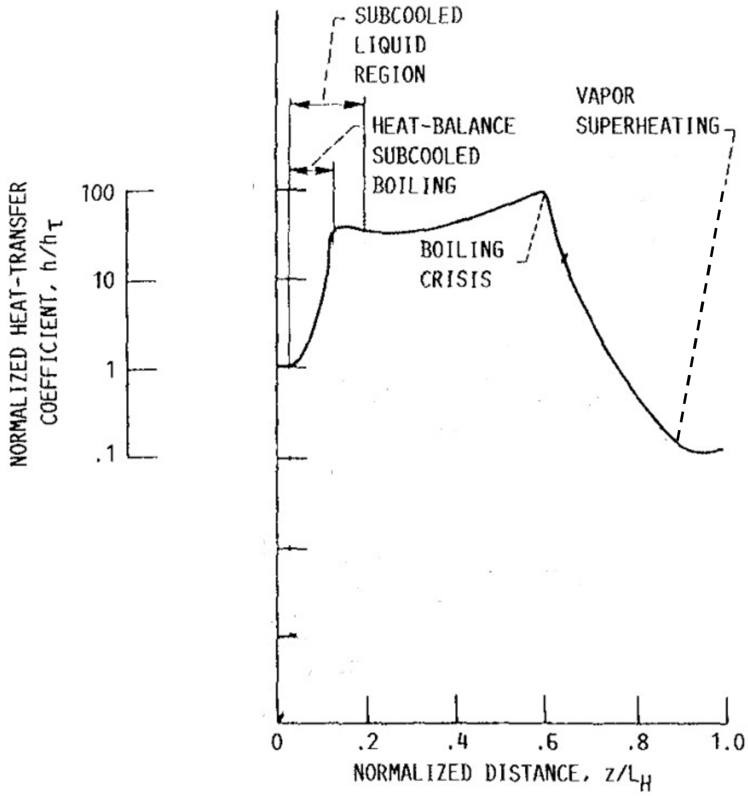

Figure 4: Normalized heat transfer coefficient in a heated flow channel from subcooled liquid to superheated vapor [6]

2.1.2 Applications of Resistojet Water Vaporizers

A resistojet developed by the NASA Glenn Research Center (prior to 1999, this center was named Lewis Research Center) beginning in the late 1980s and continued through the 1990s used a boiler called a cyclone boiler. A cyclone boiler utilizes a heated chamber into which a flow of either liquid- or two-phase water is inserted tangentially, causing a vortex flow to be present in the chamber. This vortex causes the liquid water to be centrifuged against the wall, which causes the heating to remain at the most efficient point, i.e., a liquid film heated against a wall with vapor in the center of the chamber. The chamber itself is heated through a coil of nichrome–Inconel® heater cable that is thermally insulated and provides constant heat addition to the boiler chamber. Figure 5 shows a sectional view of the cyclone vaporizer that was designed, with the tangential liquid inlet, heated chamber wall, and vapor exhaust. The specific energy of this system is approximately 4.5 J/mg [6].

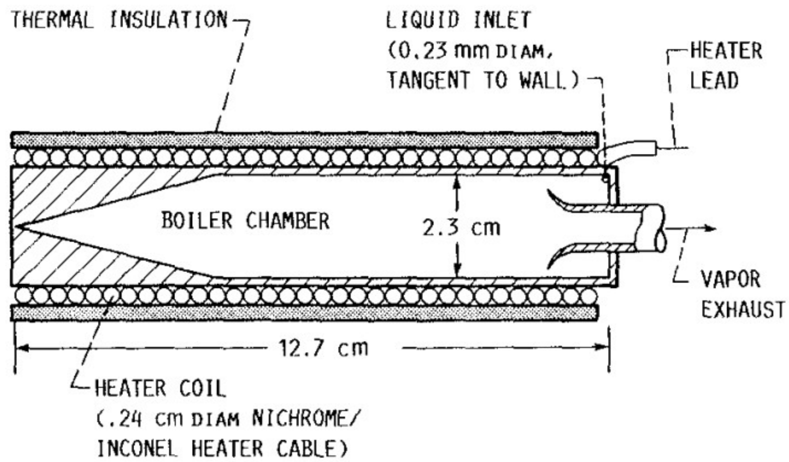

Figure 5: Cyclone boiler concept from NASA Glenn Research Center, 1988 [6]

Later work done at NASA Glenn demonstrated the abilities of a different type of vaporizer that was of the cartridge variety. The vaporizer, a sectional view of which is shown in Figure 6, contains a cartridge heater made of ceramic insulation surrounding a nichrome heater wire, all of which is contained in an Inconel® heater sheath. Surrounding the cartridge is the water propellent line in which liquid water is pumped in and water vapor is pumped out. In this vaporizer, the propellant line made of copper piping is packed with granular silica of maximum grain size 0.8 mm. The granular bed packing provides the water with a much larger surface area to interact with than a simple flow channel, thus avoiding the boiling crisis and maintaining a higher heat transfer coefficient throughout the heating process. The specific energy of this system is 3 J/mg [7].

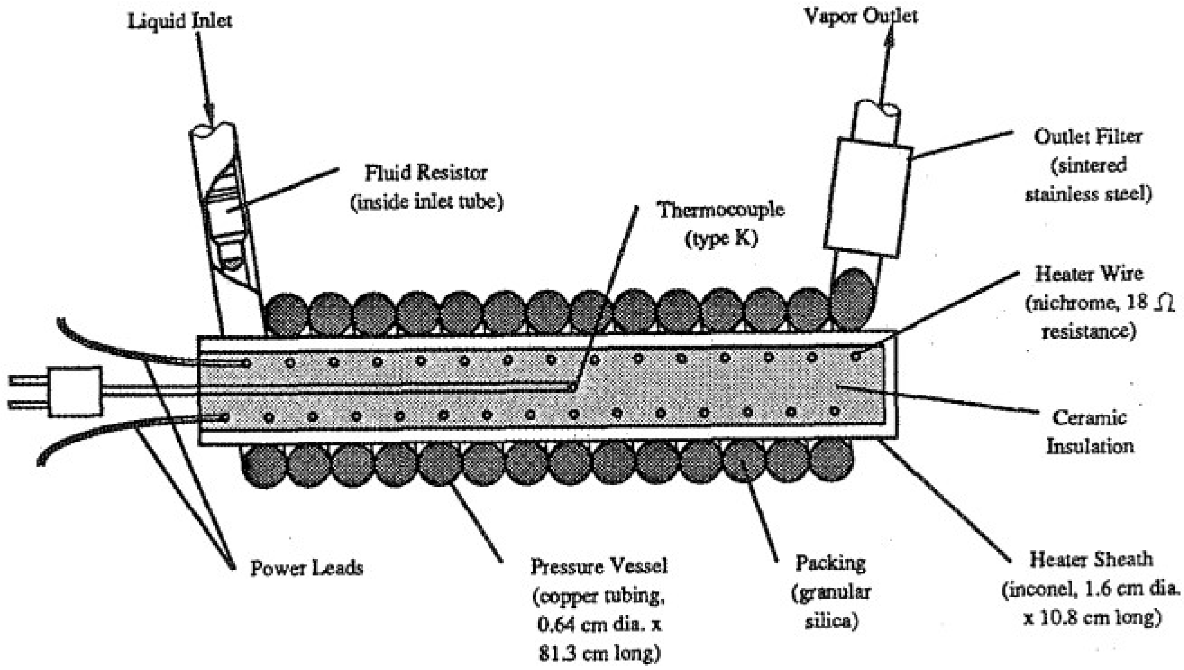

Figure 6: Cartridge vaporizer from NASA Glenn Research Center, 1992 [7]

More recent work on resistojet water vaporizers by researchers at the University of Tokyo uses an aluminum vaporization chamber that vaporizes the water and sends it through flow channels towards the nozzles. Those flow paths, also made of aluminum, experience heating from the same heater and are labyrinthine, which allows any remaining water droplets to interact with a heated wall and completely vaporize. This design takes advantage of additive manufacturing, as labyrinthine aluminum flow channels would not be possible to manufacture through conventional manufacturing methods. The specific energy of this vaporizer is 1.4 J/mg, giving this design the best specific energy of all resistojet vaporizers discussed [8].

2.2 MET Water Vapor Designs

While research on propellants such as helium, ammonia, and other room-temperature gases has been the focus of much of the research into METs, some research has been focused on water vapor as a propellant. This research is of particular importance now, as the private sector is beginning to produce water-vapor powered METs for use in satellite ferrying, with the Santa Clara–based Momentus leading the industry.

Work done by researchers at Research Support Instruments, Inc. (RSI), found that using water vapor with METs required well-regulated pressure, as water's tendency to attach electrons caused maintaining a plasma to be difficult. In order to achieve desired results, RSI needed to keep the MET at a chamber pressure of 500 Torr. Therefore, a conventional boiler was used in order to allow for a large pressure to build up in the boiler, which allowed a quick increase in MET chamber pressure when opened to the boiler. This method is not being considered for this project as a conventional boiler is not a low power method to achieve water vaporization, but rather an easier, high-powered method. RSI noted that the difficulty of maintaining a water plasma can be overcome with a sufficient increase in microwave power [9].

Other work done by researchers at The Pennsylvania State University posited using a pot boiler as well, with the flow connected to a mass flow controller, which in turn is connected to a thruster. It was mentioned that it is difficult to maintain water vapor through all necessary flow lines when using a pot boiler, and that heated flow lines or significant insulation are required to keep the water vapor from condensing. It was also found that a pot boiler cannot produce a consistent enough flow, and does not have functionality beyond a proof-of-concept [10]

2.3 Ultrasonic Atomizers

An ultrasonic atomizer, also known as an ultrasonic nebulizer, is a device that turns a liquid into a fine mist through ultrasonic vibration. This occurs through mechanical vibration of a piezoelectric element, made of a ceramic material, which sits on top of a metallic disk. At the center of the disk is an array of small channels, on the order of magnitude of a few micrometers. As an electrical voltage is applied across the atomizer, the piezoelectric element vibrates longitudinally to the flow of liquid, which causes the entire metallic disk to vibrate. This vibration causes a repeated expansion and contraction of the array of channels, which allows water droplets to be forced through the channels and ejected with velocity downstream. For ultrasonic atomizers, droplet size increases as frequency decreases or channel diameter increases.

Various applications of ultrasonic atomizers include: systems for aerosol-based drug delivery, in which a mixture of a drug and water are atomized and inhaled by the user; small-scale room humidifiers; and scientific research requiring particle atomization. The quality and prices of these systems vary greatly, with cheap, consumer models used for humidifiers and expensive, high-quality atomizers used in scientific research.

Chapter 3: Testing Apparatus

3.1 System Design

The system created for this project produces atomized water that feeds into a heated copper pipe containing copper foam, which outputs fully vaporized water. Figure 7 below shows a basic schematic of the system. Liquid water is gravity-fed from a reservoir through piping to an ultrasonic atomizer. The atomizer itself is housed between two aluminum blocks that secure the atomizer in place. The water, now atomized, passes through the heated copper pipe containing copper foam, allowing the water droplets to vaporize on contact with the foam and pipe walls, as the pipe is heated using a coiled resistive heating element. A gap between the atomizer and the heating element exists to allow for radiative and convective cooling near the atomizer. This reduces the chance of failure of the atomizer due to high temperatures.

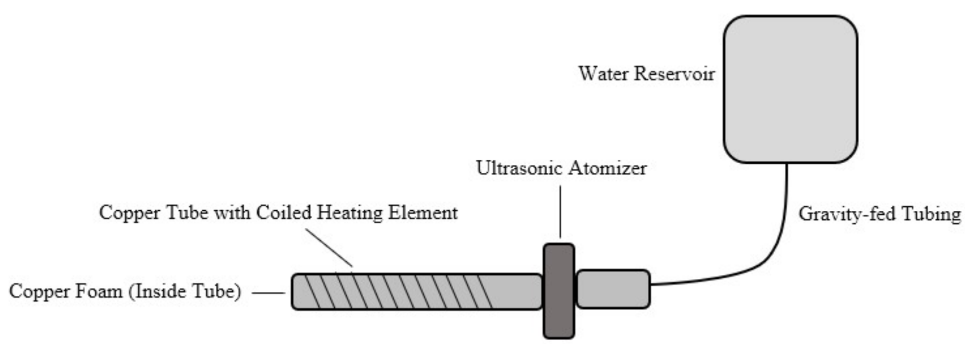

Figure 7: Basic schematic of vaporizer system

The ultrasonic atomizer of this system runs at 2 W, with a voltage of 5 V DC and a current of 300 mA. The diameter of the stainless-steel disk, on which lies a ceramic piezoelectric ring, is 0.63 in (16.0 mm). The piezoelectric mechanically vibrates at an ultrasonic frequency of 110 kHz. This causes the water located at the inlet to the atomizer to be pushed through an array of 740 channels, each 5 micrometers in diameter, and sprayed into the flow channel. The ultrasonic atomizer is the limiting factor behind the mass flow of the system, as no pressurization of the system is attempted. The mass flow through the atomizer varies due to downstream conditions and is between 0.3 and 1.0 g/min.

The spray from the ultrasonic atomizer is directed into a 0.5-in (12.7 mm) diameter copper pipe of length 7 in (177.8 mm). The outlet of the pipe was constricted to approximately 0.1-in (2.54 mm) diameter using aluminum foil of thickness 0.0006 in (0.016 mm). The final 5.5 in (140 mm) of the pipe is wrapped with a coiled heating element of length 24 in (610 mm) and works as a resistive heater, heating the length of the pipe to the temperature required to achieve vaporization. The resistance of this heating element is 146 Ω. In order to reduce radiative and convective heat losses of the pipe, fiberglass thermal insulation of approximately 0.5 in (12.7 mm) is wrapped around the pipe. Within this heated pipe is a length copper foam, which is copper that is manufactured to contain voids through which liquids or gases can flow. Metal foams such as these are defined by their porosity, which is defined as the ratio of the void volume to the total volume of the foam. The copper foam used in this system has a porosity of 0.95. A high porosity was chosen as it allows for atomized water to flow through the system and contact a heated surface, while not greatly restricting the flow. The length of the copper foam used was 4.5 in (114 mm), located 1.5 in (38 mm) from the atomizer and 1 in (25 mm) from the pipe outlet.

The combined design of an ultrasonic atomizer feeding into copper foam was chosen in order to increase the surface area of the water to allow for more efficient vaporization, while also increasing the surface area of heated surface that the water will come into contact with, in order to avoid the boiling crisis discussed previously.

3.2 Data Measurement

The experimental system was instrumented with multiple devices to measure the power, mass flow rate, and temperature of the system. These measurement devices allow for calculation of the specific energy of the system, which is used to compare this system to existing thermoelectric propulsion water-vapor systems.

In order to control the power that is added to the system using the resistive heating element, a variable transformer is used. The resistive heating element is attached to the variable transformer, which is itself connected to a 120-V AC wall outlet. The variable transformer contains a dial that allows the incoming voltage to be modified to a percentage of the original 120 V AC. By way of controlling the voltage, this variable transformer also controls the power, with the AC current measured using an AC clamp-on meter, which was placed around one lead of the resistive heating element to measure AC current. When analyzing the power of the system, the power was numerically calculated using

$$P = I^2R \tag{4}$$

where I is the measured current and R is the resistance of the heating element. It should be noted that this method of controlling the heater was implemented for expediency in building the laboratory setup. Such a system would require redesign to make it relevant for space thrusters, but this implementation is relatively straightforward.

The mass flow through the system is recorded through the use of an electronic mass scale. The entire system is placed on this scale and as atomized or vaporized water exits the system, the mass decreases. In order to determine the flow rate, a stopwatch is used to record time, with the mass of the scale recorded at various time intervals. The resolution of this scale is 0.1 g.

The exit temperature of water was recorded using a K-type thermocouple, placed such that it is held inside of the pipe right before the outlet. This placement allows for as close to an accurate reading of the water temperature at the outlet while removing any cooling on the thermocouple due to being located outside of the pipe in a room-temperature laboratory. The temperature of the copper pipe was also measured using a K-type thermocouple, and was located at the center of the pipe. Figure 8 shows a picture of the setup in experimental mode.

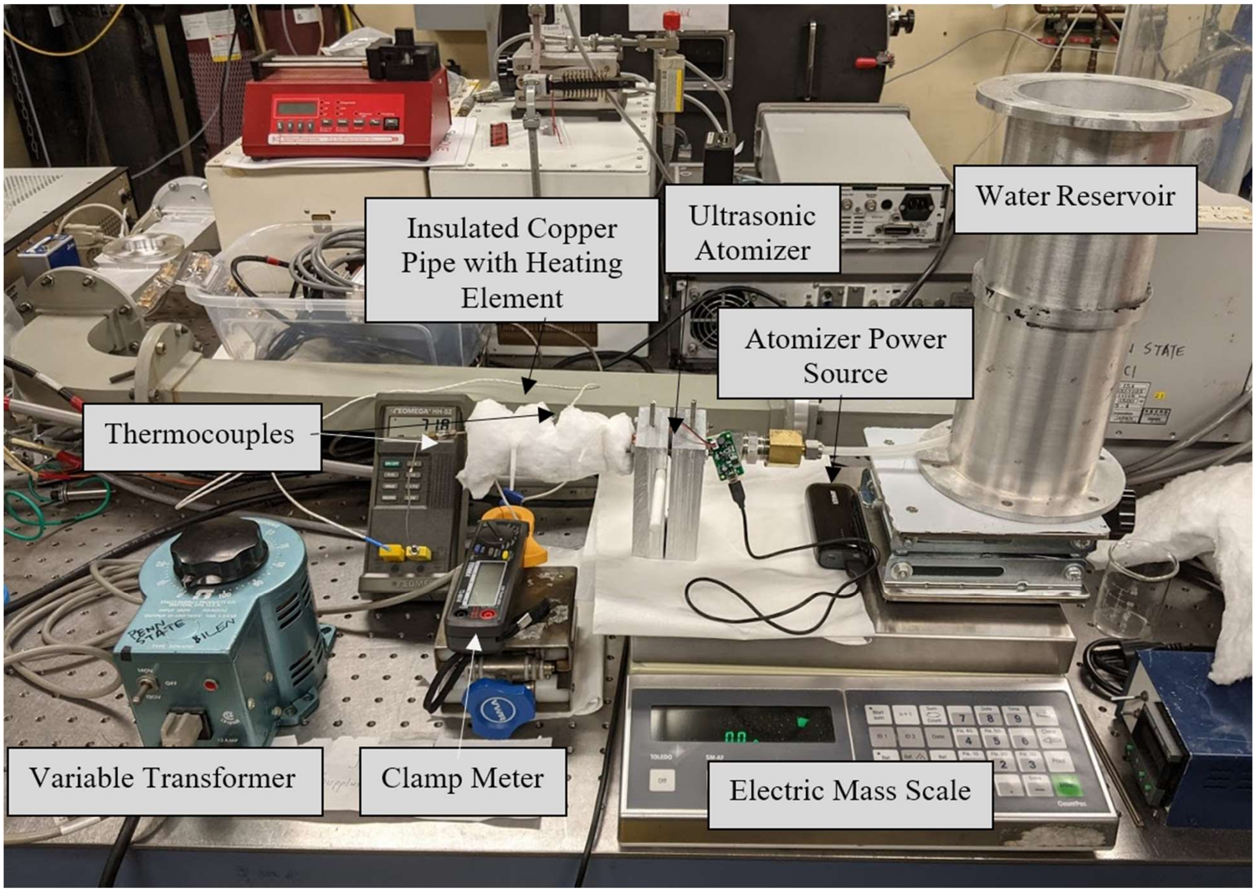

Figure 8: Experimental setup

3.3 Experimental Procedure

Testing of this system occurred in two different configurations: one containing the copper foam and the other without the copper foam. For both configurations, the same procedure is followed, with the exception of mass and time being recorded at every 1-g interval without foam, whereas mass was recorded at every minute interval when foam was present for higher resolution data.

For both configurations, the atomizer is turned on and run continuously throughout the experiment. The variable transformer is then turned on and set to an initial value of 50%, which corresponds to approximately 60 V, and the current is recorded using the clamp meter. Mass, time, and temperatures are recorded at the intervals mentioned above, until the outlet temperature reaches a steady state. The variable transformer is then used to increase the voltage by 5%, with the clamp meter recording the current at each level, and at each level data is recorded until the outlet temperature again reaches a steady state. This process continues until the outlet temperature reaches a temperature greater than boiling, at which point that power level is taken as the power required for complete vaporization to occur.

Further testing, including heating the pipe prior to turning on the atomizer, was planned but was unable to be completed due to failure of the atomizer circuit board. A breakage of the atomizer disk electrical leads caused overheating of an inductor, rendering the atomizer inoperable. The atomizer and circuit board used were low-end, consumer products intended for use in humidifiers, and further investment into ultrasonic atomizers may be used in future work.

Chapter 4: Results

In this chapter, the results of two tests performed on the system are discussed. The first test case, in which no copper foam was present in the system, is discussed and the specific energy is determined. The second case, in which 4.5-in of copper foam is located in the heated pipe, is also discussed. These two cases are compared with each other and the previously-discussed resistojet vaporizers. The complexities of an ultrasonic atomizer system are also discussed.

4.1 Test 1: No Copper Foam

The results of the initial test, in which the 4.5-in copper foam was not placed in the heated copper pipe, are shown in Figure 9.

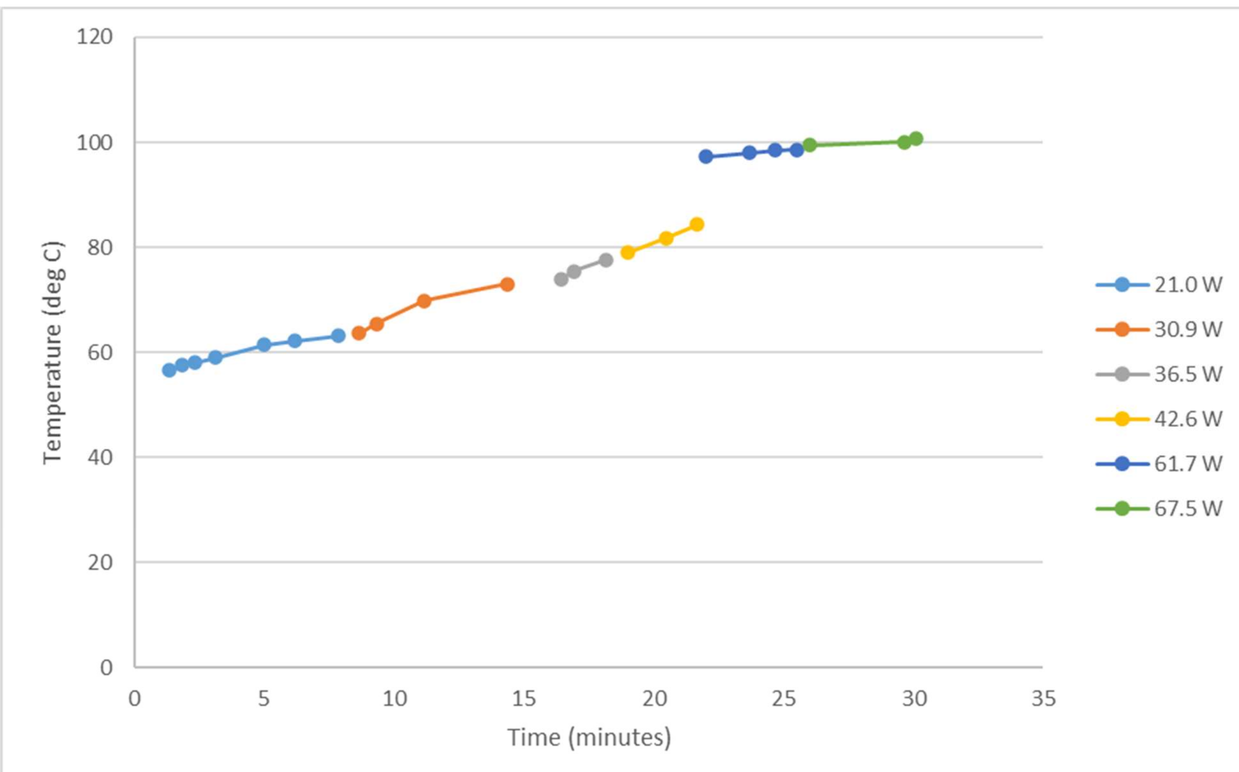

Figure 9: Downstream water temperature at increasing power levels, no copper foam

The temperature in Figure 9 refers to the output temperature of the water vapor, with total liquid vaporization being assumed to occur at a temperature of 98.9 °C, when corrected for the altitude of University Park, Pennsylvania (1,150 ft). Below 61.7 W, the output temperature is well below the temperature of vaporization. At 61.7 W, the temperature reaches 98.5 °C, which indicates that boiling has most likely been initiated; however, the output was observed to not yet be fully vaporized water. At 67.5 W, the output temperature reached 100.7 °C, above the required 98.9 °C. The observable characteristics were found to change at this temperature; atomized water is observed to be opaque, while vaporized water is transparent, and this transition was observed at 67.5 W.

Based on these results, the specific energy of the system, which is defined in Equation 3, is calculated to be 8.34 J/mg. This calculation includes an additional 2 W for the overall power of the atomizer.

4.2 Test 2: Copper Foam

The second test that was performed included the 4.5-in copper foam, located inside the heated copper pipe. The results of this test are shown in Figure 10. The water is again considered to be vaporized once the output temperature reaches 98.9 °C. In this test, the temperature of the water increases in a fairly linear fashion as the power increases until 56.1 W, where the increase in temperature begins to level out. This is most likely due to initiation of boiling inside of the pipe at higher power levels, with the output reaching 92 °C at 56.1 W. Because the center of the pipe is warmer than the outlet of the pipe, it is likely that vaporization and condensation is occurring throughout the pipe at this power level, with the power not yet great enough to produce fully vaporized water.

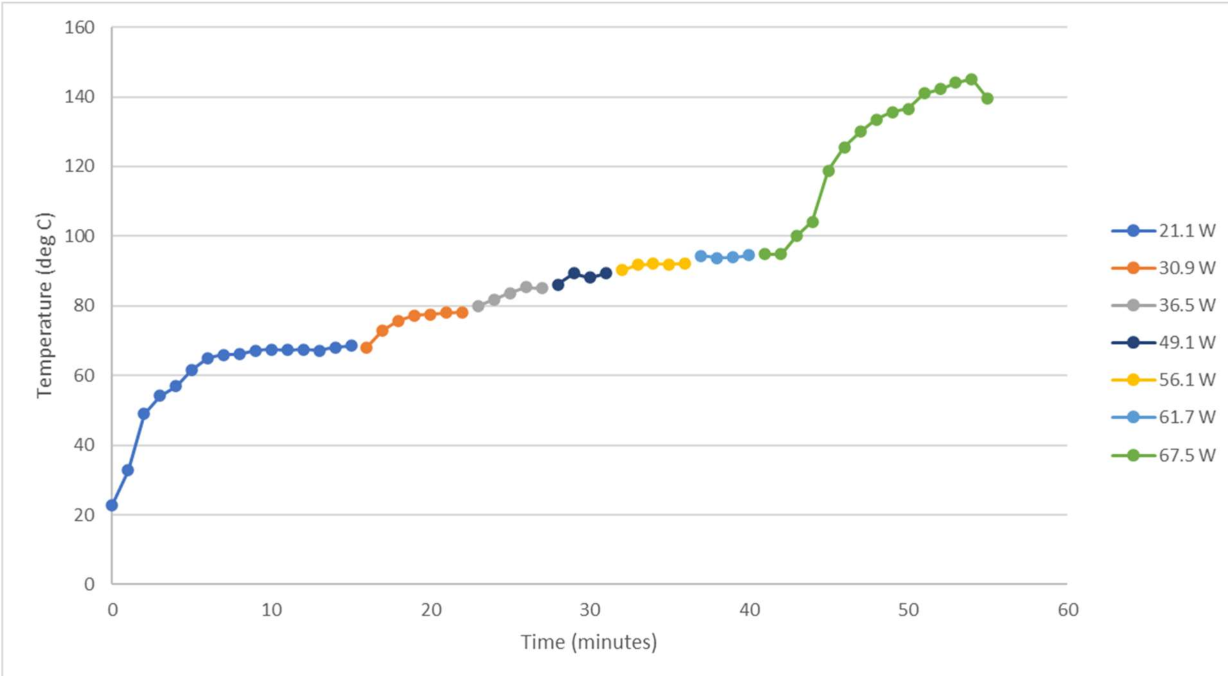

Figure 10: Downstream water temperature at increasing power levels, copper foam

Once the power reached 67.5 W, full vaporization of the water was achieved and superheating of the vapor began. At this power level, the outlet flow temperature reached 145 °C. The reason for this large increase in the superheating of the vapor was because of a change in the mass flow rate after vaporization was achieved, which is discussed in Section 4.4. The mass flow rate at which vaporization took place was determined to be 1.0 g/min. Based on these results, the specific energy of the system was calculated to be 6.67 J/mg. Despite being at the same power level for both the no-copper-foam and copper-foam tests, the copper-foam test had a lower specific energy due to a higher mass flow rate. This shows that copper foam does help in reducing the amount of energy required to heat atomized water, with a decrease in specific energy of 1.67 J/mg. This was expected, as the copper foam provides a higher surface area of heated copper for atomized water particles to interact with. As shown in Figure 4, conductive heating of water is much more efficient than radiative heating, due to the phenomenon known as the boiling crisis.

4.3 Comparisons to Existing Vaporizers

Existing electrothermal water vaporizers, described in Chapter 2, are good comparisons to this system as they perform the same function through alternative means. In order to normalize the differences in mass flow rate, specific energy is used to compare the power efficiency of each system. Table 1 lists each vaporizer being investigated, its specific energy, as well as the initial temperature of the water added to the system. The initial temperature is important because if the water into the system is pre-heated, the specific energy would be lower as less energy would be required to heat the water to its boiling point. For all systems described, the flow is close to or at room temperature (20 °C), with only the 3-D printed flow channel vaporizer starting at above room temperature, at 28 °C.

Table 1: Comparison of various vaporizer specific energies

Thruster	Specific Energy	Difference in Specific Energy from Copper Foam Vaporizer	Initial Water Temperature
Cyclone Vaporizer [6]	4.5 J/mg	−2.17 J/mg	"Room Temperature"
Cartridge Heater Vaporizer [7]	3.0 J/mg	−3.67 J/mg	"Room Temperature"
3-D Printed Flow Channels [8]	1.4 J/mg	−5.27 J/mg	28 °C
No-Copper-Foam Vaporizer	8.34 J/mg	+1.67 J/mg	21.6 °C
Copper-Foam Vaporizer	6.67 J/mg	0.00 J/mg	21.6 °C

Table 1 shows that, while the addition of the copper foam was able to reduce the specific energy of the vaporizer being tested, it still has a higher specific energy than any of the existing vaporizers. The specific energy difference column shows that this vaporizer still requires 2.17–5.27 J/mg more specific energy to vaporize water from room temperature than the other systems. In order to achieve comparable specific energy results, the power of this system would have to decrease 33–79 %. Improvements to this system may have the capability to close this gap in specific energy. Due to the failure of the ultrasonic atomizer, no optimization of the system could be performed after the initial tests. While the first tests resulted in higher specific energies, future optimization may have the capability to bring the specific energy to comparable levels.

4.4 System Complexities

During experimentation, it was found that the mass flow through the atomizer varied with downstream conditions. Figure 11 shows how mass flow varied with the output temperature. As Figure 11 shows, as the downstream temperature of atomized water increased, so did the mass flow rate. This ranged from a flow rate of 0.33 g/min at 75 °C to 1.0 g/min at 94 °C. However, once the flow changed to purely water vapor, the flow rate dropped significantly to 0.61 g/min. This drop allowed for the water vapor to become superheated, as shown in Figure 10, as a power level that could vaporize a flow of 1.0 g/min would have the excess power to not only vaporize but superheat a flow at 0.61 g/min.

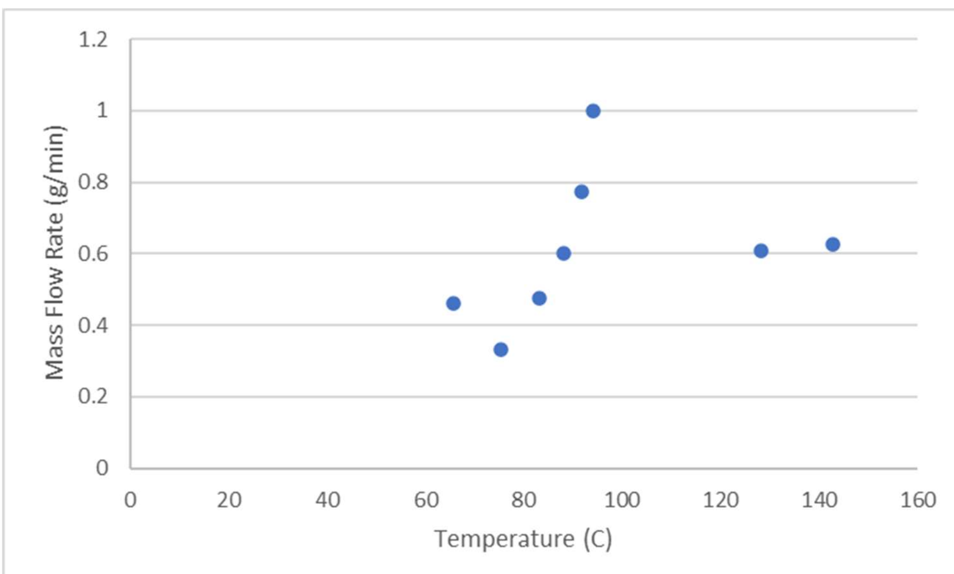

Figure 11: Mass flow rate at various outlet temperatures, with copper foam

This behavior points to one of the challenges of working with ultrasonic atomizers, which is the challenge of controlling mass flow through them. Conventional systems, which have an input of purely liquid water, have the capability to regulate the mass flow through a simple gate or proportional valve.

This provides control over the flow, as closing/constricting the valve will decrease the flow and opening the valve will increase the flow. For a system utilizing a single ultrasonic atomizer, the atomizer is the limiting device and is the bottleneck to the flow. Figure 11 shows that for any application that requires precise control over mass flow, which would include the propellant feed system for an MET, a single ultrasonic atomizer may not provide enough flow control to be usable. However, future work may investigate ways to overcome this, possibly including attempts to pressurize the system and changing the pressure to control mass flow; use of multiple atomizers; and investigation into higher-quality, reliable atomizers that may experience less fluctuation in mass flow during operation.

Another system complexity that was observed was the need for an air-flow channel. During experimentation, the atomizer and copper pipe had to be placed 0.25 in (6.35 mm) apart, which allowed there to be an air channel through which air flowed in from the sides of the atomizer into the heated pipe. This was necessary as it was observed that the atomizer flow would cease when the copper pipe was flush against the atomizer. This raises questions about the ability of an atomizer to perform in space. In spaceflight operating conditions, an air channel would not be possible, nor would it be beneficial as the output of the vaporizer would be required to be pure water vapor for water vapor plasma generation to occur. Instead, there would be a pressure gradient between either side of the nebulizer, the water reservoir and the MET chamber. The water reservoir would be set to a specific pressure, while the MET chamber would be close to vacuum pressure. Future work can be done to determine whether an air flow channel is a requirement for an ultrasonic atomizer, or whether a favorable pressure gradient removes the need for an air channel. This pressure gradient could be created through gas pressurization of the water reservoir, or through utilizing a pressurized bladder propellent tank.

Further work can also be done to determine whether the atomizer can prevent leakage through the atomizer's centrally located array of flow channels when subject to a vacuum. At atmospheric pressure, no water flows through the array of channels due to the surface tension of the water. However, in the presence of a favorable pressure gradient it may be possible for water droplets to flow through these holes, even when the atomizer is turned off. This leakage could be avoided by utilizing a valve when the atomizer is off, cutting the atomizer off from the pressure gradient. When the atomizer is in use, the flow through the atomizer would simply act as additional mass flow, thus giving the ability to toggle mass flow. Determination of this may be done in future work.

Chapter 5: Summary and Conclusions

The use of water vapor as a propellant in METs provides many advantages as it is non-toxic, liquid storable, and environmentally friendly. However, for water vapor to be viable for the types of satellites that utilize METs, the vaporization of water must be accomplished with low specific energy. While no water vaporizers for METs are available in the open literature for quantitative comparison, similar water vaporizers used in resistojets can be used to compare the specific energy of the vaporizers.

Utilizing an ultrasonic atomizer for increased flow surface area and a heated pipe containing a porous copper foam for increased heating surface area, a system with a specific energy of 6.67 J/mg was achieved. This specific energy was lower than that of the same system without copper foam, which had a value of 8.34 J/mg. This reduction shows that the addition of copper foam to the heated copper pipe is able increase the heated surface area over which atomized water flows, thus more efficiently heating the atomized water when compared to a system utilizing only a single flow channel.

This specific energy with the copper foam was higher than the specific energy that existing vaporizers used for resistojets require, with a 33–79 % decrease in specific energy required of this system to be comparable to these existing vaporizers. While this decrease is significant, no optimization of the current system was attempted. Therefore, future optimization, such as decreasing the size of the system, using superior heat retention methods, and pressurization of the propellant could reduce the specific energy to be more comparable to existing water vaporizers.

It was also found that utilizing an ultrasonic atomizer increased the complexity of the system when compared to conventional methods of water vaporization, as there is no easy way to control the mass flow through the system when using a single atomizer. However, the propellant pressurization and the use of multiple, high-quality, and reliable atomizers could produce a system that is able to have superior mass flow control.

Overall, it is recommended that future work be completed to optimize this system, with the goal of reducing the specific energy and obtaining greater control over mass flow.

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Vertical Flight Student Competition, Team Lead

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- Design and submit proposal for vertical lift vehicle to deliver medical supplies 200 km
- Lead team as project manager, assigning tasks and coordinated work
- Conduct Functional Hazard Assessment to determine and prove aircraft safety

Systems Engineering Intern *05/2020 - 07/2020*

Northrop Grumman Aeronautics Systems, Redondo Beach, CA

- Enhance aircraft behaviors to improve survivability in high-threat, deep-strike missions
- Use AFSIM software to create models of aircraft command and control systems
- Build logic in code to create autonomous decision making in simulated environments

Space Propulsion Lab Research Assistant *01/2020 - 05/2021*

The Pennsylvania State University, University Park, PA

- Research thrust capabilities of Microwave Electrothermal Thrusters (METs) through hardware testing
- Write a thesis on minimal heat loss water vapor generation and integration into MET as fuel source
- Machined and built experimental setup for water vapor generation using ultrasonic nebulizers

Engineering Design *Spring 2019*

The Pennsylvania State University, University Park, PA

- With locomotive company Wabtec, innovate train energy and power systems design
- Engineer medical splint with low-cost resources tailored for use in refugee camps
- Solve real-world engineering design problems with groups of peers and formally present outcomes

Engineering Skills

- *Programming*: C++, MATLAB, AFSIM
- *Computer Aided Design*: SolidWorks, AutoCAD
- *Technical Report Composition*
- *Public Speaking*
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Leadership and Involvement

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Penn State Blue Band – Sousaphone

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- Attained leadership position of squad leader second year and section leader fourth year
- Teach entire band basic marching maneuvers in third year after being selected for teaching team
- Practice and perform between 10 and 20 hours every week during fall semesters