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Thermosyphon Flooding in Reduced Gravity Environments Test Results

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July 2013

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Abstract

The condenser flooding phenomenon associated with gravity aided two-phase thermosyphons was studied using parabolic flights to obtain the desired reduced gravity environment (RGE). The experiment was designed and built to test a total of twelve titanium water thermosyphons in multiple gravity environments with the goal of developing a model that would accurately explain the correlation between gravitational forces and the maximum axial heat transfer limit associated with condenser flooding. Results from laboratory testing and parabolic flights are included in this report as part I of a two part series. The data analysis and correlations are included in a follow on paper.

Nomenclature

ρ_L	Density of the liquid
ρ_V	Density of the vapor
D	Thermosyphon inner diameter
g	Acceleration of gravity
σ	Surface tension
B_o	Bond number
A_v	Vapor area
h_{fg}	Heat of vaporization
RGE	Reduced Gravity Environment

1.0 Introduction

Fission power systems have long been recognized as potential multikilowatt power solutions for lunar, Martian, and extended planetary surface missions. These power sources are especially attractive in places where solar intensity is limited by providing uninterrupted power, day or night, for extensive periods of time that can span one to two decades. Typically, 30 to 40 percent of the reactor heat gets converted to electricity and the remaining 60 to 70 percent gets rejected to space through large surface area heat rejection radiators. Current heat rejection technology for fission surface power systems has focused on titanium water thermosyphons embedded in carbon composite radiator panels with the working fluid temperature range of 300 to 450 K (Ref. 1). Figure 1 provides a graphical representation of

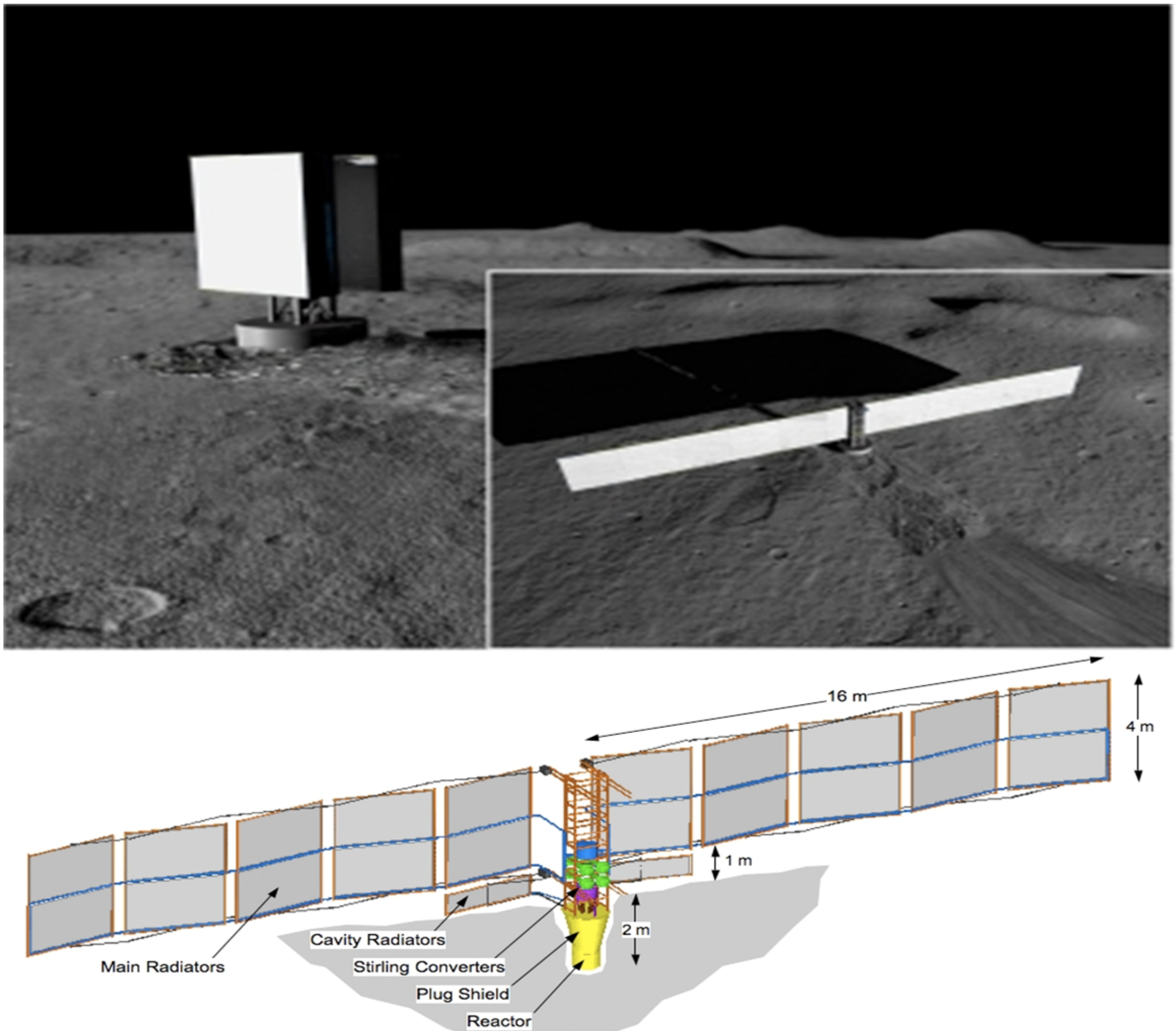

Figure 1.—Notional 40 kWe fission surface power system.

a potential 40-kWe Moon-based fission surface power system that has a total heat rejection surface area of 185 m (Ref. 2) with over 300 thermosyphons. The thermosyphons, or wickless heat pipes, are used as a redundant and efficient way to spread the waste heat from the power conversion unit(s) over large radiator surface areas where it can be rejected to space. It is well known that thermosyphon performance is reliant on gravitational forces to keep the evaporator wetted with the working fluid. One of the performance limits that can be encountered, if not understood, is the phenomenon of condenser flooding. This occurs when the gravity forces acting on the condensed fluid cannot overcome the shear forces created by the vapor escaping the evaporator throat. When this occurs, the heat transfer process is stalled and may not re-stabilize to effective levels without corrective control actions. The flooding limit in Earth’s gravity environment is well understood as experimentation is readily accessible, but when the environment and gravitational forces change relative to other planetary bodies, experimentation becomes difficult. An innovative experiment was designed and flown on a parabolic flight campaign to achieve the reduced-gravity environments (RGE) needed to obtain empirical data for analysis, as none was found during literature searches. The 1-g laboratory and parabolic reduced-gravity results will be compared to existing models to determine if they can accurately predict the flooding limit. If not, new correlations will be established to model the behavior and give new insight into the flooding limit in actual RGEs.

2.0 Experiment Design

Specific design constraints and requirements were developed using input from the parabolic flight provider, heat pipe design codes, literature review, and experienced personnel. Initially, these inputs helped determine the overall power levels of the thermosyphons, which was largely based on aircraft power availability. A baseline of 2 kW at 115 V was used as the maximum electrical constraint for the experiment design while in flight. The next consideration was to determine the number and size of thermosyphons to meet the electrical constraints while still being able to reach the desired flooding limit. Knowing that the flooding limit was going to be extremely difficult to obtain in parabolic flight, it was determined that 12 thermosyphons, if possible, would be a good balance between getting multiple chances at capturing the flooding event while keeping in mind the electrical constraints. Using 12 thermosyphons, each heater would have a total of 165 W of supply power while in reduced gravity.

The length and diameter of the thermosyphon was mainly based on the flooding limits of the thermosyphons as predicted by analytical and empirical heat pipe models, but also took into account the geometric constraints of the intended flight rack. A significant effort was taken to study different correlations from several sources with the intensions of verifying the predictive models or proposing new correlations based on the test results. Initial research led to two models developed by Faghri et al. (Ref. 2) and Tien and Chung (Ref. 3), which took into account the bond number, Equation (3). The bond number is increasingly important as the thermosyphon diameter decreases below 0.5 in. (12.7 mm), and takes into account the densities of the liquid and vapor as well as the surface tension, acceleration of gravity, and the diameter of the thermosyphon. Other sources were investigated (Refs. 4 to 15) but many had limited or no correlations with water, had limited or no test results using small diameter thermosyphons, or had equation variables that could only be determined after testing. Equations (1) to (3) describe Faghri's semi-empirical correlation built from multiple test sources and different working fluids, which has been shown to agree well with water, but has had limited comparisons to diameters less than 0.5 in. Note, none of these flooding models have been proven in RGE.

$$\dot{Q}_{max} = K h_{fg} A_v [g\sigma(\rho_L - \rho_V)]^{1/4} \left[{\rho_V}^{-1/4} + {\rho_L}^{-1/4}\right]^{-2} \tag{1}$$

$$K = \left[\frac{\rho_L}{\rho_V}\right]^{0.14} tanh^2 {B_O}^{1/4} = R\ tanh^2 {B_O}^{1/4} \tag{2}$$

$$B_o = D\left[\frac{g(\rho_L - \rho_V)}{\sigma}\right]^{\frac{1}{2}} \tag{3}$$

Equations (4) and (5) describe Tien and Chung's correlation, which was later modified by Faghri, with slight differences between C_K in Equation (5) and K in Equation (2). Equation (1) was used for early predictions as it represented the more conservative approach to staying within the aircraft electrical budget. The diameter of the thermosyphon would be estimated by graphically evaluating the flooding limit of 165 W and a lunar gravity value of 1.7 m/s^2. Both lunar and Martian gravity environments were analyzed but the lesser lunar gravity was chosen as the desired target because it would allow a wider range of data for the intended correlation as well as require less heater power. The decision to test mostly in lunar gravity, as opposed to half lunar and half Martian, was due to the fact that during the parabolic flights only a limited number of parabolas are dedicated to reduced gravity and the experiment needed as much time as possible to pass through a flooding event.

$$\dot{Q}_{max} = C_K^2 h_{fg} A_v [g\sigma(\rho_L - \rho_V)]^{1/4} \left[{\rho_V}^{-1/4} + {\rho_L}^{-1/4}\right]^{-2} \tag{4}$$

$$C_K = \sqrt{3.2}\tanh(0.5 {Bo}^{1/4}) \tag{5}$$

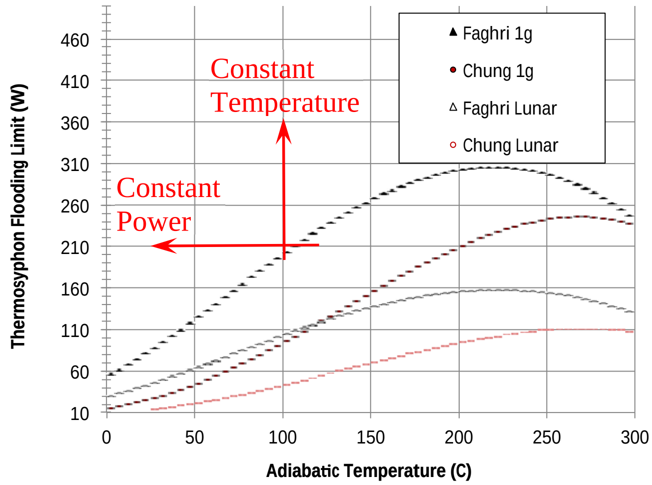

Figure 2.—Predictive models of thermosyphon flooding by Faghri et al. (Ref. 1) and Tien and Chung (Ref. 2) for both Earth and lunar gravity.

After careful examination, the final decision was to design the experiment with a total of 12 thermosyphons made from 0.25 by 0.035 in. (6.35 by 0.889 mm) wall titanium tube using water as the working fluid. The total thermosyphon length of 24 in. (60 cm) was built with a 2.5 in. (6.35 cm) evaporator, a 2.5 in. (6.35 cm) adiabatic section, and a 19 in. (45.7 cm) condenser, providing a length to diameter (L/D) ratio of 130, similar to the thermosyphons designed for the fission surface power system in Figure 1. Two wraps of 100-mesh titanium screen were used in the evaporator section to increase fluid flow during nucleation and prevent dryout. The condenser was designed to be air cooled, using a finned aluminum tube that would enhance heat transfer and allow the internal fluid temperature to be altered via a variable speed fan. Plots of the flooding limit from Equations (1) and (4) are provided in Figure 2 using the above thermosyphon geometry and water properties. The equations show significant differences but provided a good baseline model to compare with test results.

Figure 3.—Experiment flight rack with data acquisition system, 12 thermosyphons, power conditioning, safety interlocks, and variable fans.

Electrically, the experiment also needed extensive preparation for the data acquisition, heater control, power conditioning, and safety interlocks. A National Instruments PXI chassis and real-time controller was employed using customized LabVIEW (National Instruments) programming to provide the system logic and user interface functions. The end product used a laptop computer that was linked to the PXI controller inside the flight rack and let the operator view and collect data signals, control the heater power, view alarms, and record notes. Several revisions of the data acquisition and control (DAC) system were implemented to establish a streamline process that allowed quick communication and control needed during parabolic maneuvers. Pictures of the experiment hardware can be seen in Figure 3.

3.0 Test Results

3.1 Earth Gravity

Testing was conducted in the laboratory well before any flight testing took place to address the functionality of the experiment and determine how the sensors would be used to detect the flooding limit. The thermosyphons were taken to their flooding limit using several procedures, which were eventually down selected into the most appropriate for parabolic flight. During the constant temperature procedure, the heaters were taken up in temperature using a voltage ramping function that would vary the heater voltage at 1 V/min. Using the variable speed fans, the operator adjusted the airflow across the finned condenser to control the adiabatic temperature of the thermosyphon. Using this strategy, the power increases as the adiabatic temperature stays constant and eventually the thermosyphon passes through the flooding limit. This can be seen graphically by the “Constant Temperature” arrow in Figure 2. Another method that was incorporated into the test procedures was to keep the power constant and increase the airflow, thus cooling the adiabatic temperature and ultimately passing through the flood limit from a different angle (see “Constant Power” arrow, Fig. 2). Both methods produced similar results and would be used for parabolic flight.

When the condenser floods, heat transfer is stalled and the heater temperature increases while the condenser temperature decreases. This can be seen in the thermocouple data as a change in slope and is easily visible during testing. An example of a 1-g flooding event can be seen in Figure 4 and depicts the change in slope of both the heater and condenser temperatures. During the laboratory and parabolic testing, 12 thermosyphons would be monitored visually to detect if a flooding event had occurred and would initiate shutdown of the individual heaters. Using this philosophy, all thermosyphons were set and ramped at exactly the same settings, providing a total of 12 flooding data points during an ideal test run. This procedure was used to gather multiple flooding points over a large temperature range providing the needed data to compare to Equations (1) and (2) as shown in Figure 5.

In comparing the 1 g test results with the predictions from Equations (1) and (4) it was evident that neither correlation model fit the data very well. Figuring out what caused the differences was of great interest. Both of these equations came from semi-empirical methods and incorporated the smaller diameter, working fluid properties, and gravitational constants, which should provide a good estimate, but the results are in disagreement.

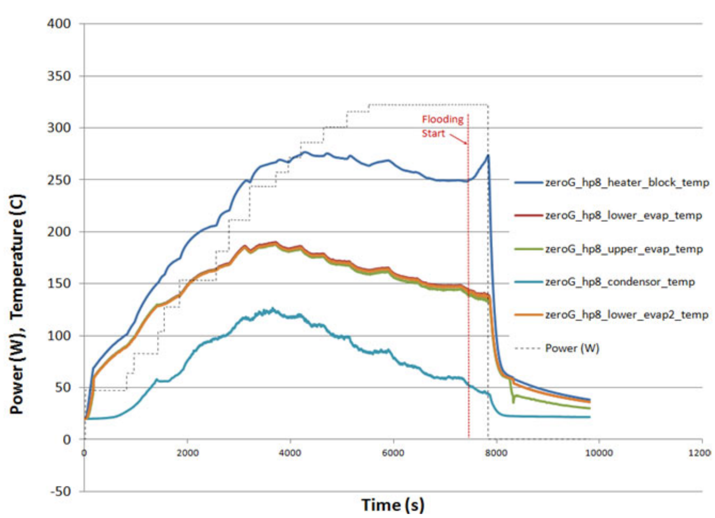

Figure 4.—Typical 1-g flooding event while cooling the condenser.

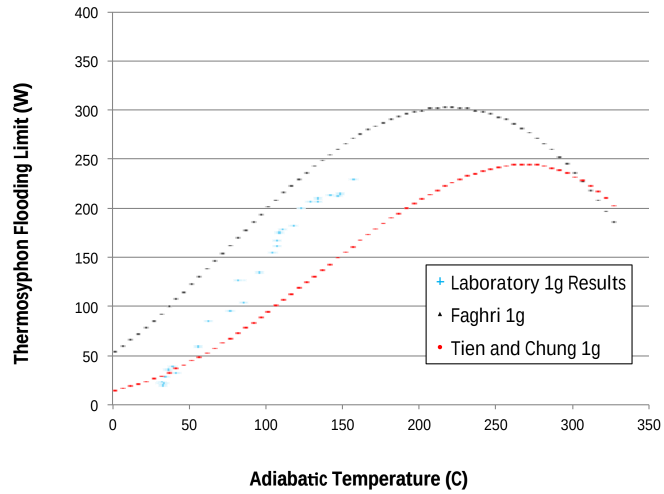

Figure 5.—The 1 g test results using 2 grams of working fluid versus predictions from Equations (1) and (4).

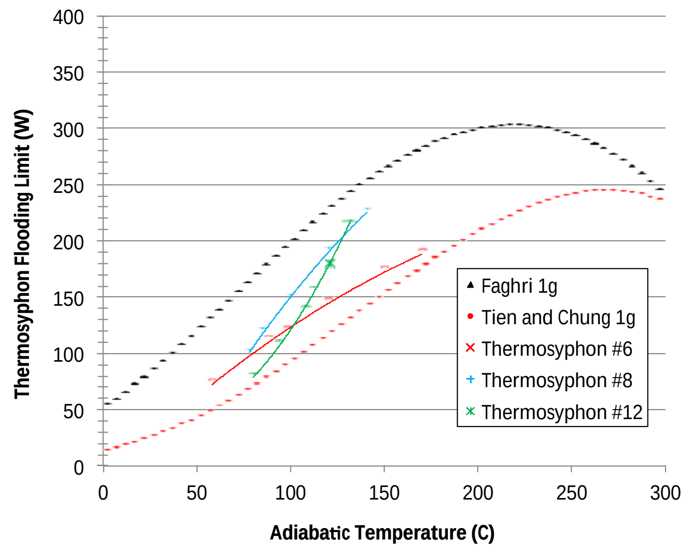

Figure 6.—The 1-g test results of initial thermosyphons 6, 8, and 12 to investigate the affect of fluid charge on test results.

One idea that had surfaced throughout initial 1 g testing, as well as the first parabolic flight campaign, was the exact amount of working fluid in each thermosyphon and how it affected the test results. Throughout the testing, it was noticed that data scatter between individual thermosyphons was more than desirable, so a further investigation was initiated. Of the initial 12 thermosyphons, 3 were tested individually to their flooding limits and are reported in Figure 6. It was thought that these differences were due to the amount of working fluid, but to determine this, the thermosyphons would have to be cut open. After the September 2011 flight week, the thermosyphons were all weighed and cut open so that the water could be baked out of the tubes. The assemblies were reweighed and the difference was known to be the fill charge. The thermosyphons had fluid charges ranging from 0.76 grams to 2.5 grams and could be related to the performance of the individual units with number 6 having 0.76 grams of fluid, 8 with 2.5 grams, and 12 with 2.1 grams. The fluid charge differences in these initial 12 units were attested to filling procedures that worked well with larger diameter thermosyphons but would prove difficult using the 0.125 in. (3.2 mm) fill tube associated with the 0.25 in. (6.35 mm) thermosyphons.

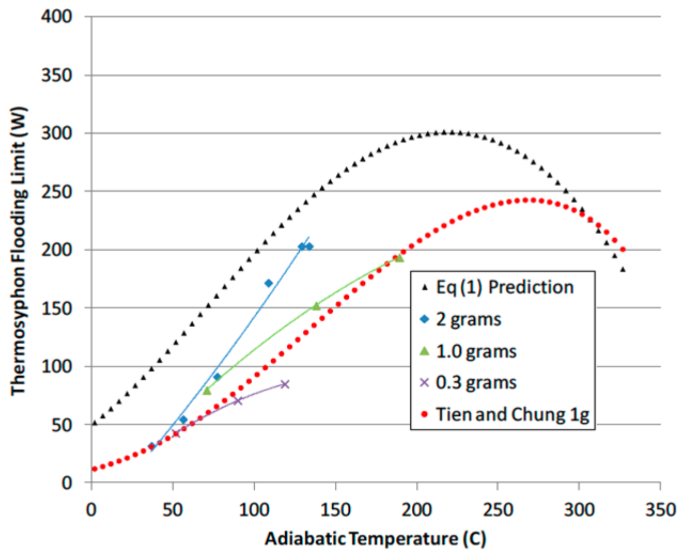

Figure 7.—Dryout and flooding events of thermosyphon number 12 using 2.0, 1.0, and 0.3 grams of water as the fluid charge.

Before the thermosyphons were hermetically sealed, a test was completed to determine, for this specific thermosyphon geometry, what the best fluid charge is, and how the charge affects the flooding limit. Figure 7 reports the results as the charge was changed from 0.3 grams up to 5.0 grams. The results are clear that fluid charge has a significant impact on the heat transfer limit of the thermosyphon. When using too little fluid, the evaporator dries out before ever getting to the flooding limit and when too much fluid was used, the heat pipe would not work at all. Although not reported in the figure, the maximum amount of fluid that could be used was around 3.0 grams. At 3.0 grams and above, the thermosyphons could not be started. Also worth mentioning is the fact that 2.0 grams of fluid took up 5 in. (12.7 cm) of the 24 in. (60 cm) total length. This volume of fluid was needed to achieve the maximum flooding limit, but may not be practical in some design applications. It was determined that 2.0 grams of fluid would be used as the new fluid charge. The 1-g data in Figure 5 was compiled using the newly filled thermosyphons with 2.0 grams of working fluid.

Notice in Figure 6 that thermosyphon number 6 agrees well with Equation (1) and numbers 8 and 12 do not. The data suggests that the differences in Equations (1), (4), and the test data may very well be related to fluid charge and whether or not the flooding limit is actually reached, or if the evaporator is drying out before flooding occurs. It appears that the differences between past and current test results might be explained by fluid charge. Typically, after a flooding event starts, it is quickly followed by evaporator dryout, but knowing that the fluid charge determines which event happens first makes the analysis much more difficult. Through careful temperature measurement, both below, inside, and above the evaporator, it was possible with this experiment to determine whether dryout had occurred before or after flooding. With the use of a wicked evaporator, the dryout limit could be detected in the data when the lower evaporator temperature changed slope and started increasing before condenser temperatures started falling. The lower evaporator can be best described as a 1-in. adiabatic section just below the heater, which served as a fluid reservoir. As the fluid left the reservoir to increase the mass flow needed to transfer the increased heat output, the thermocouple in that section would show an increase in temperature. This signified the start of dryout and depending on the fluid charge, may or may not be close to the flooding limit. After some time, the evaporator section directly under the heater block would also dry out and start the familiar slope increase of the heater block temperature, which would ultimately limit the heat transfer. Conversely, when flooding occurred as shown in Figure 4, the lower evaporator temperatures would initially not show signs of dryout, but the stalled heat transfer due to flooding would suddenly increase the heater block temperature. The timing of these events can be used to help determine whether or not flooding is actually occurring or if the thermosyphon is running out of working fluid as in the dryout case. Understanding this difference is key to finding the maximum heat transfer limit of the thermosyphons in all gravity fields.

The proposed theory that correlations between different sources might be explained by fluid charge and test methods, will be hard to prove without a large test program covering numerous thermosyphon geometries and working fluids, which is not under the scope of this project. As with many heat transfer and fluids experiments, it is important to update existing models to improve the understanding of the engineering and physics associated with the process and hardware. Correlation of the test data resulting from this experiment will be covered in a follow on paper.

3.2 Lunar Gravity

The parabolic flights took place in September of 2011 and May of 2012. Typically, each flight week consists of 4 days of flights with 40 parabolas per day. These 40 parabolas can consist of several different gravity targets and are usually agreed upon between the experiment principal investigators and the flight engineer at the beginning of the flight week. During the September 2011 campaign, each of four flights consisted of 12 lunar, 3 Martian, and 25 zero gravity parabolas. During the May 2012 flight week, each flight consisted of 15 lunar and 25 zero gravity parabolas. The thermosyphons need some gravitational force to send the fluid from the condenser back to the evaporator and therefore will not function in zero gravity environments. In 2011, the experiment was shut down during the zero gravity parabolas. During the May 2012 campaign, four thermosyphons were replaced with four fully wicked heat pipes that would be operated during the zero gravity parabolas to gather additional research data, but results will not be included in this report.

Determining the flooding limit during parabolic flight was more difficult than expected. The reduced gravity portion of the parabola only lasts about 20 to 30 sec depending on the gravity target, leaving little time to decipher the flooding status of 12 thermosyphons. Immediately following the reduced gravity portion of the parabola is hyper-gravity, which occurs during the bottom of the parabola as the aircraft pulls out of the nose down position and begins to climb altitude for the next parabola. Gravity levels are usually between 1.5 and 2 g's during this portion of the parabola and force the fluid back down to the evaporator. The positive side of the sinusoidal occurrence of gravity levels is that it allows the thermosyphons to hydraulically "reset" if they had flooded in the previous parabola, and allows the operator to change power levels or cooling rates to try and "recover" for the remaining parabolas. The down side to the alternating gravity levels is that it requires the thermosyphons to redistribute the working fluid after hyper-gravity and continue functioning near their maximum capacity. Figure 8 shows a data plot from the September 2011 flight campaign of thermosyphon number 8 going through parabolic maneuvers. The graph shows power and temperature on the left axis, gravity levels on the right axis, and

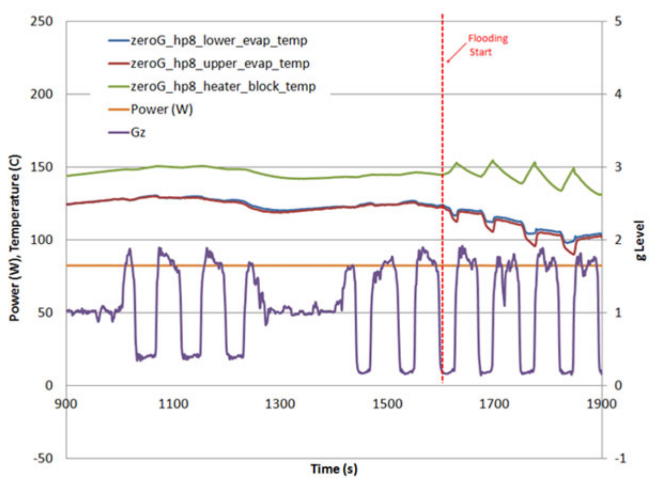

Figure 8.—Flooding event data of thermosyphon number 8 taken during Martian and lunar gravity parabolas in September 2011.

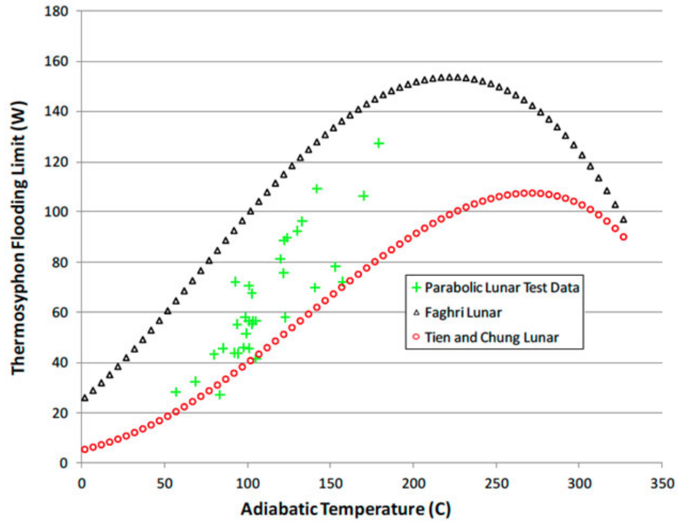

Figure 9.—Lunar gravity flooding data from September 2011 and May 2012 flight campaigns compared to Equation (6) correlation.

time on the horizontal axis. The gravity levels can be seen alternating between reduced gravity and hyper-gravity with the first three parabolas at Martian gravity and the remainder targeted at lunar gravity. At lunar parabola 3, a flooding event can be seen taking place. Notice the change in slope of the heater block temperature as well as the change in the lower and upper evaporator temperatures during reduced and hyper-gravity. This is a good example of what flooding looks like from the captured reduced gravity data.

Thermosyphon flooding Data from both the September 2011 and May 2012 flight weeks have been compiled into Figure 9. This represents all the flooding events that occurred after the first parabola. In many occurrences, one or more of the thermosyphons would flood during the first parabola which meant that the power level and temperature targeted was above the flooding limit and would not allow the heat to transfer axially down the thermosyphon. Each full parabola only lasted about 1 min, meaning that for the 12 or 15 lunar parabolas there was only 12 to 15 min to pass through the flooding limit. This required the initial setting to be as close as possible to the predicted flooding point which ultimately led to many first parabola floods. In total, there were only 4 chances to capture the intended flooding data (once per flight), which was amplified by using 12 thermosyphons for the experiment. Out of the total 96 chances from the 8 flights of September 2011 and May 2012, only 34 data points were captured that would explain the maximum heat transfer limit. The perseverance in building the experiment and gathering the lunar gravity flooding data in parabolic flight will provide the needed information to formulate the required correlations for future thermosyphon designs for reduced gravity environments.

4.0 Conclusions

Thermosyphons can be used in fission surface power applications for the Moon, Mars, or other planetary surfaces as a redundant and efficient way to spread waste heat from the power conversion system. This research effort set out to verify leading semi-empirical models related to the flooding limits of simple cylindrical thermosyphons in reduced gravity environments. Testing was completed in the 1 g laboratory environment as well as in reduced gravity environments using parabolic flights. Equations from Faghri et al. (Ref. 1) and Tien and Chung (Ref. 2) were used as a baseline to study the flooding phenomenon. Early laboratory testing and parabolic flights showed that the fill volume of the thermosyphons could possibly explain some of the differences between the predictive models knowing that evaporator dryout and flooding limits are hard to distinguish. After finding the optimum fill volume, the flooding limit of the current thermosyphons were shown to differ from existing models. Determining new correlating models to explain the test results will be the next step in the research.

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14. ABSTRACT
The condenser flooding phenomenon associated with gravity aided two-phase thermosyphons was studied using parabolic flights to obtain the desired reduced gravity environment (RGE). The experiment was designed and built to test a total of twelve titanium water thermosyphons in multiple gravity environments with the goal of developing a model that would accurately explain the correlation between gravitational forces and the maximum axial heat transfer limit associated with condenser flooding. Results from laboratory testing and parabolic flights are included in this report as part I of a two part series. The data analysis and correlations are included in a follow on paper.

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