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Investigation of two-phase refrigerant behavior upon cycle startup for compressor protection in microgravity applications

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ABSTRACT

Vapor compression cycles (VCCs) are a promising technology for refrigeration needs on future space craft due to their generally high cooling COP. However, due to microgravity there lies a risk of liquid flooding the compressor during start-up. Thus, to better prepare VCCs for microgravity applications, it is significant to understand the dependence of two-phase refrigerant on gravity during start-up. In this work, liquid flooding is evaluated at the start-up of a VCC and a possibility for passive compressor protection is considered. The experimental setup has two configurations. In the first, two-phase phenomena can be observed in a transparent tube and different tube insertions can be tested for their effectiveness as a liquid flooding obstruction. In the second configuration, liquid flooding from a commercial evaporator can be evaluated for different charge levels. The results show a clear effect of tube insertions on liquid flooding in a straight tube and find the felt tube insertion to be most effective at impeding flow. The evaporator test results also present a strong correlation of liquid flooding parameters with the charge level and show only a small dependence on the orientation of the evaporator.

1. INTRODUCTION

As spacecraft technology is developed for long-term missions, refrigeration systems are inevitable for storage of scientific samples and food. Single-phase refrigeration cycles, such as the Reversed-Brayton or Stirling-cycles, have been used for space applications due to their relatively simple microgravity adaptation. One example is the Minus Eighty Degrees Celsius Laboratory Freezer for ISS (MELFI), which is a successful cryocooler utilizing a Reversed-Brayton cycle (Viennot et al., 1994). Vapor Compression Cycles (VCCs) are a particularly energy efficient refrigeration technology in the refrigerator/freezer temperature range commonly used on earth and have been considered for microgravity applications as summarized in Brendel et al. (2021). However, VCCs still have a low technology readiness level for space applications partially attributed to the two-phase fluid dynamics in microgravity.

Several concerns regarding the operation of VCCs in microgravity need to be addressed to increase the confidence in the technology. One concern is the behavior of the liquid refrigerant phase upon cycle start-up in microgravity, which could lead to compressor flooding (liquid entering the compression chamber). While there are numerous challenges unique to the application of VCCs in microgravity, liquid flooding of the compressor has been identified as highly relevant (Brendel et al., 2020). It is essential to avoid liquid slugging, as it can greatly damage a compressor. For example, the amount of liquid refrigerant that floods a reciprocating compressor over time can shorten the life expectancy of the compressor (Foster, 1967). Liquid flooding can often be detected by pressure spikes within the compressor (Singh et al, 1986) and irregularities of the compressor power draw (Laughman et al., 2006). Liu & Soedel (1995) developed a mathematical model for the effect of slugging on different types of compressors and stated that slugging is more likely to occur in reciprocating compressors than other types for their high volume compression gradient with respect to crank angle, $dV/d\alpha$. However, Liu identified that variations in the quality of two-phase refrigerant entering the compressor do not always lead to a slugging problem in compressors (Liu & Soedel, 1995). Lin et al. (2020) provided a numerical model to simulate pressure jumps in two-phase compression of refrigerant with a significant amount of liquid present in the compression chamber of a rotary compressor.

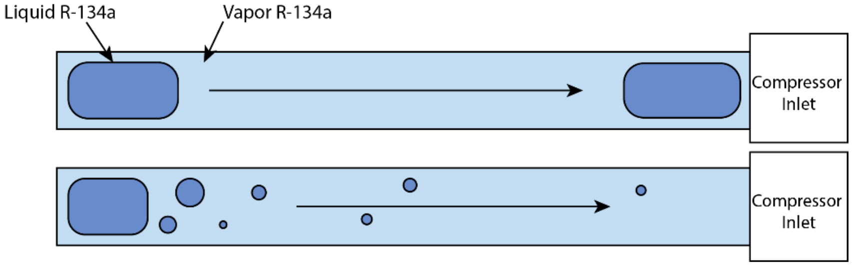

Figure 1: Example of liquid slugging (top) vs liquid flashing (bottom)

Two scenarios of interest are liquid slugging and liquid flashing. The former is characterized by large slugs of liquid refrigerant travelling separately. Generally, slug flow occurs for lower qualities (Lee & Mudawar, 2016). Liquid flashing is here defined as liquid refrigerant evaporating as a result of a drop in external pressure without moving to the compressor inlet. A schematic of the two flow phenomenon can be seen in Figure 1. The fundamental difference between the two phenomenon is that slug flow can bring larger amounts of liquid to the compressor inlet, while liquid flashing will result in mostly vapor reaching the compressor inlet.

While proposals for phase separation methods in microgravity have been made, passive methods have not been experimentally tested in vapor compression systems in microgravity. In order to develop more effective passive phase separation methods, a deeper understanding of two-phase refrigerant behavior in microgravity upon compressor startup should be pursued.

The main goals of the presented research are to understand the transient behavior of liquid refrigerant in a VCC directly after compressor start-up under the influence of gravity. The work will be continued with microgravity testing on parabolic flights. In particular, future work will study how significant of a problem compressor flooding will be in microgravity and what steps can be taken to prevent it.

2. COMPRESSOR PROTECTION

2.1 Need for Compressor Protection

Due to the high likelihood of damage caused by compressor flooding, a number of methods to protect the compressor from flooding have been developed. Typically, these methods are gravity-dependent, such as utilizing the height difference within the cycle to settle the liquid far from the compressor or using an accumulator. These methods will no longer be viable in microgravity due to the lack of buoyancy forces.

To ensure a safe start-up in microgravity, a novel method of compressor protection which does not depend on gravity is desirable. Such a method should be passive because the absence of needed control schemes and actuators will result in fewer possible failure modes during the mission.

2.2 Potential Microgravity-Compliant Passive Compressor Protection

One potential method of a passive, zero-gravity compressor protection would be the presence of a storage tube in the system in parallel to the evaporator. By using a tube insertion within the storage tube, the liquid refrigerant would be wicked into the tube when the cycle is turned off by capillary forces and released slowly upon start-up (patent pending). Concept sketches for such a storage tube are shown in Figure 2. Lowering the temperature in the storage tube compared to the evaporator and suction line would also ensure the migration of liquid refrigerant into the tube due to the difference in vapor pressures, which could be used for terrestrial applications or if the wicking forces are insufficient. During operation, the refrigerant will mainly flow through the evaporator due to the much higher pressure drop in the storage tube. The storage tube is located such that any evaporating refrigerant will still cool the cabinet, so the cooling potential from the system start-up is not wasted.

Two questions should be answered to define the value of such a storage tube:

- How significant of a problem is liquid slugging in microgravity? If the problem turns out to be of minor importance, the efforts for a storage tube would be rendered disproportional.
- Are there suitable tube insertions that can store liquid refrigerant and ensure a slow release upon startup? If such materials cannot be found, the storage tube will not be effective.

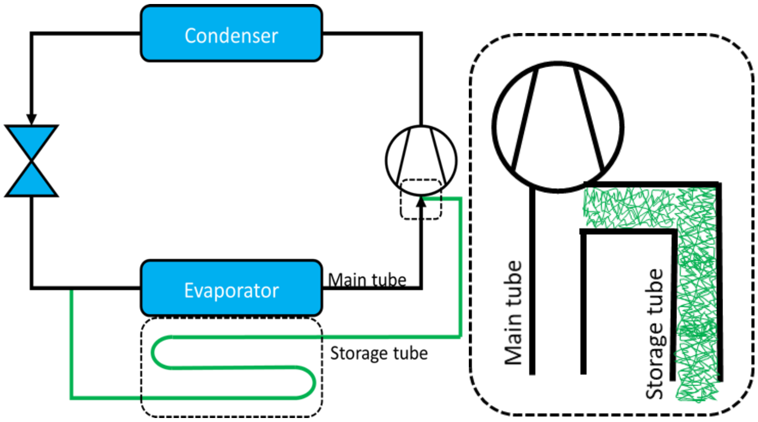

Figure 2: Concept of storage tube for transient passive compressor protection in microgravity

2.3 Tube Insertion Selection

Materials of interest for the insertion are porous materials with enough space to attract and hold the liquid refrigerant in microgravity, while obstructing flow enough to prevent the immediate movement of the liquid refrigerant to the compressor upon cycle start-up.

To ensure that capillary forces wick the liquid refrigerant into the storage tube, the selected insertion material should have a large surface area per unit volume. Porous materials of varying types were selected and tested for work described in this paper. The selection of insertion materials and sample lengths was mostly based on trial and error, to understand which general type of material accomplishes the goal of reducing liquid refrigerant flow the most effectively.

3. EXPERIMENTAL SETUP

3.1 Overview of Test Rig

The primary purpose of the test rig is to observe the transient behavior of two-phase refrigerant upon compressor start-up. Therefore, the test rig has a test section which is connected to a compressor. The test section can be charged from a tank of liquid refrigerant by opening a ball valve. The compressor discharges refrigerant directly into this tank to allow repeated execution of the experiment with a given amount of refrigerant. The test stand has two operating configurations: one to observe fluid behavior inside a single straight tube and the other to test for liquid flooding using a commercial evaporator. The assembled test stand is shown in Figure 3.

At the beginning of a test, a controlled quantity of liquid R-134a is charged into the test section. This quantity is controlled by observing the changes in a visual liquid level meter attached to the tank when opening the ball valve to the test section. Level indicators are marked at every centimeter along the sight glass and as such level measurements are precise to 0.25 cm (9 grams). After charging the test section the ball valve was completely closed.

A G5TWIN refrigerant recovery unit was used to simulate the compressor due to its robustness against liquid slugs. The pressure and temperature were measured at the end of the test section, which simulates the compressor suction port in all experiments. The start-time of operation of the recovery pump was logged automatically by a voltage signal. When the recovery pump was started, the operator visually inspected the outlet of the test section and pressed a push button for the time that liquid was visible. The data was then post-processed to find the time until the first liquid reached the test section and the duration of liquid being visible in the test section. Also, the time until the pressure dropped to 30 kPa was calculated in a post-processing procedure.

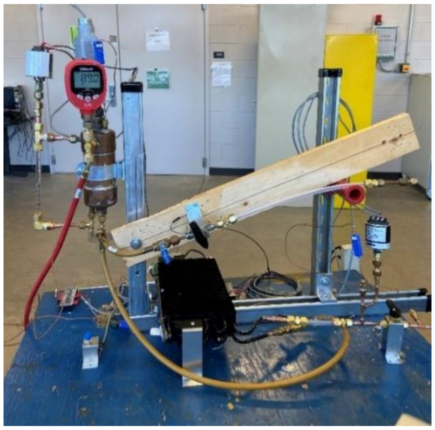

Figure 3: Picture of assembled experimental setup in evaporator configuration.

3.2 Straight Tube Configuration

The transparent tube test section consisted of three polycarbonate tubes separated by brass compression fittings. This enabled replacement of the middle section with test tubes having different insertions. The single tube configuration allows observation of the fluid-dynamics upon startup throughout the test section. The test section is mounted to an inclinable wooden board, shown on the schematic in Figure 4.

For the experiments, three different insertion materials were selected to test their ability to restrict the movement of liquid R-134a in transient cycle conditions. The selected materials are a stainless steel filtration disc, densely packed aluminum metal shavings, and filtration felt. An empty tube was used as a control sample. The lengths of the samples are shown in Table 1, and the insertion samples are shown in Figure 5. The length of the test section from the beginning of the clear tube to the pressure transducer and thermocouple measures 36 cm. The middle section for the insertions is 11.5 cm long. A series of tests with different charge levels were conducted to investigate the liquid flooding behavior as a function of the charge and the tube insertion.

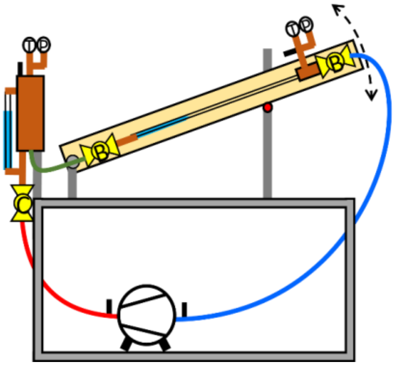

Figure 4: Schematic of single-tube testing rig.

Figure 5: Tube insertion specimens tested. From top to bottom:
No insertion, stainless steel disc, dense shavings, and felt.

Table 1: Insertion tube and sample lengths.

Insertion	None	Stainless Steel Disc	Dense Shavings	Felt
Length of Sample Tube (cm)	11.5	11.5	11.5	11.5
Length of Insertion (cm)	N/A	0.158	11.5	4.2

3.3 Evaporator Configuration

To better emulate the start-up in a real VCC, the clear tube was replaced with an evaporator for this configuration. A schematic of the evaporator setup can be seen in Figure 6. The evaporator has an inner volume of 195 cm^3 and can be oriented either horizontally or vertically. The evaporator is shown in the vertical orientation in Figure 7. Similar to the clear tube, the evaporator was tested with varying amounts of charge. The liquid flooding intensity was evaluated by measuring the time until the first liquid and the time of liquid flooding at the outlet of the evaporator. Both were determined by visual inspection of a transparent tube installed at the evaporator outlet. Tests were conducted in both orientations to examine the effect on the observed compressor flooding. The compressor was turned off when the pressure in the test chamber reached 30 kPa, ensuring that all liquid refrigerant had boiled off and that most refrigerant vapor had been removed from the test section. After each test run, the evaporator was heated with a heat gun to reach repeatable starting conditions.

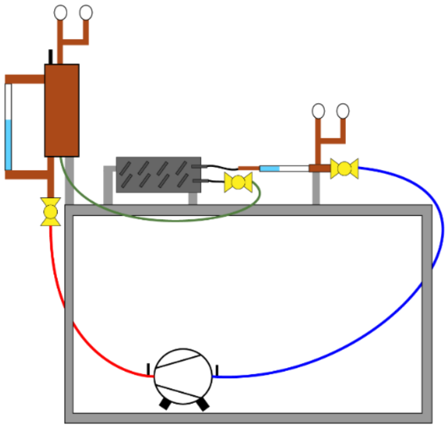

Figure 6: Schematic of evaporator testing rig in horizontal configuration.

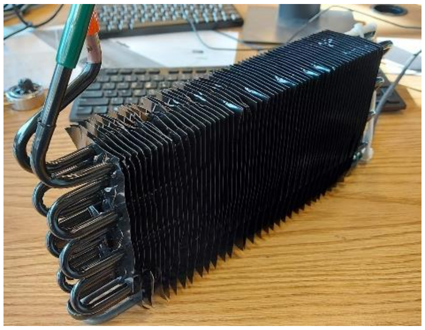

Figure 7: Evaporator model used in two-phase refrigerant experiments.

3.4 Data Processing and Fluid Imaging

The pressure and temperature in the test section and in the refrigerant tank were measured continuously. Additionally, two Boolean states named “OnOff” and “LiquidYesNo” were recorded. The OnOff signal is connected to the power supply of the recovery pump and allowed identification of when an experiment was started. The LiquidYesNo signal is connected to a manual push button pressed by the operator when liquid refrigerant is observed to pass through the viewing chamber into the compressor inlet. The combination of these two signals is used in the calculation of the elapsed time in which liquid flooding occurred and when liquid flooding occurred relative to the start of the recovery pump. The sight glass was calibrated manually using water to determine the change in inner volume between each indicator. A change in 36 g of refrigerant for every 1 cm indicator was calculated based on the calibration data. This data is saved in an Excel file and merged with the continuously recorded data after testing.

Multiple adjustments were made to the testing rig to allow for higher quality fluid observation and imaging. A photography technique known as backlighting was used, wherein a diffused light illuminated the testing area from behind. This helped to create a distinct outline of the refrigerant in the polycarbonate tubing while reducing glare. A Samsung A71 smartphone was used to record and photograph the fluid behavior.

3.5 Uncertainty analysis

The experiment requires reading charge levels from a sight glass and hitting a push button at the occurrence of liquid at a certain location in a test section. Both measurements are very susceptible to human error. The authors estimate the uncertainty for the charge level to be +/- 2g for the straight tube testing and +/- 4g for the evaporator testing. A conservative estimate for the accuracy of the push button signal is +/- 1 second. Error bars were not included in the plots for better readability but can be easily estimated since the uncertainty is absolute and therefore independent of the absolute value on the x and y-axes.

3.6 Data Acquisition Hardware

This project also serves as a demonstration for a low-cost data acquisition system. Analog, digital and thermocouple data is collected using an Arduino which runs a C++ script. The data is sent to a computer using a serial connection to allow operation independently of internet or network availability. The computer runs a python script to save and display the data in real time. The DAQ was found reliable and useful despite the inexpensive hardware totaling less than $50. The associated source code is openly available (Ore, 2021).

4. RESULTS AND DISCUSSION

4.1 Qualitative Flow Behavior

The test section was inclined to accumulate the entire liquid phase at the closed end. Upon cycle startup a frequent observation was the quick movement of liquid towards the compressor inlet. The liquid appeared to be propelled by vapor bubbles forming inside the liquid phase, pushing the liquid towards the compressor as they grew with the decreasing pressure. The bubbles eventually dispersed the liquid refrigerant resulting in a “spray-like” behavior. A picture of this situation is shown in Figure 8 (left). Shortly thereafter, the liquid accumulated at the bottom of the tube and started to recede backwards. The faster traveling vapor caused waves on the liquid surface and eventually pushed the liquid phase forward again. This behavior is termed “wave-like” here and shown in Figure 8 (right). When liquid slugging occurred, it was usually observed as intermittent pulses but rarely a continuous stream of liquid.

The presence of compression fittings within the observation section are a potential source of error for false observations due to the reduced inner diameter as compared to the polycarbonate tubing. The behavior before and after the fittings was similar. However, likely due to the obstruction caused by the compression fitting, there was a delay between the behavior of the fluid before and after the fittings. While one side would be experiencing spray-like flow, the other would be shown receding and displaying wave-like behavior.

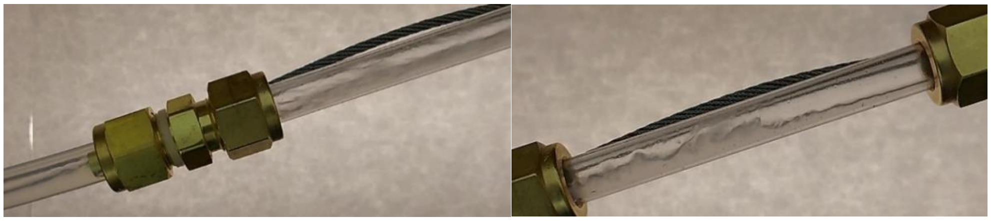

Figure 8: (left) Refrigerant behavior immediately upon compressor startup (right) Observed “wave-like” behavior moments after initial startup.

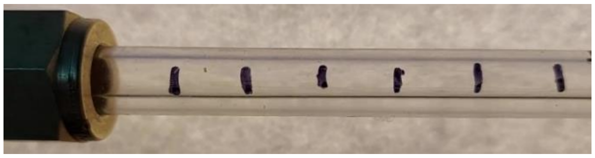

Figure 9: "Sewer situation" refrigerant flow, where liquid refrigerant seems to stand at the bottom of the tube without moving during the transient period.

A different behavior was observed when the tube was horizontal and the charge filled approximately one third of the height of the tube. Upon cycle start-up, the liquid refrigerant was stationary and calm at the bottom of the tube instead of displaying spray- or wave-type behavior. This behavior is pictured in Figure 9, which was taken as the recovery pump was on. The refrigerant evaporated in place such that there was no liquid slugging. This is in contrast to experiments with inclined test sections, where a smaller inclination angle increased the likelihood of liquid slugging. The hypothesis is that the large surface area of the refrigerant allowed sufficient evaporation to prevent flashing. As a result, only vapor reached the compressor suction port.

4.2 Quantitative comparison of tube insertions

Different storage tube insertions were tested to understand their effectiveness for preventing liquid slugging. Each insertion was tested with different charge levels. For each test run, the outlet of the test section was inspected for liquid flooding. Hence, the result of each test run was binary (liquid slugging occurred or it did not). For each insertion, it was observed that low charge levels did not cause liquid flooding while high charge levels caused liquid flooding. In between there was a transition range of charge levels which led to different outcomes upon repeating the experiment. Results of the insertion testing can be seen in Figure 10, with points representing individual tests and solid bars representing the transition range for each insertion. The transition ranges are defined to reach from the lowest charge level that caused liquid flooding to the highest charge level that did not cause liquid flooding.

The felt insertion was found most effective at restricting liquid refrigerant flow. The stainless steel disc insertion had the highest but also the widest transition ranges out of all samples. The dense shavings insertion shows only a very small resistance to liquid flow as its transition range is similar to the transition range of the dense shavings.

During testing, the dense shavings insertion was observed to more evenly disperse the liquid refrigerant among the vapor refrigerant, as it allowed most of the liquid to flow through with a spray-like behavior. Conversely, during the felt and stainless steel disc insertion testing, liquid refrigerant appeared to build up behind the felt and disc insertions. This backup of liquid refrigerant led to flashing in place of the liquid that was unable to pass through.

4.3 Evaporator Testing

The amount of liquid entering the compressor cannot be measured with the current test setup. Instead, the measured times until and the duration of liquid slugging are used to characterize the liquid flooding behavior of the evaporator.

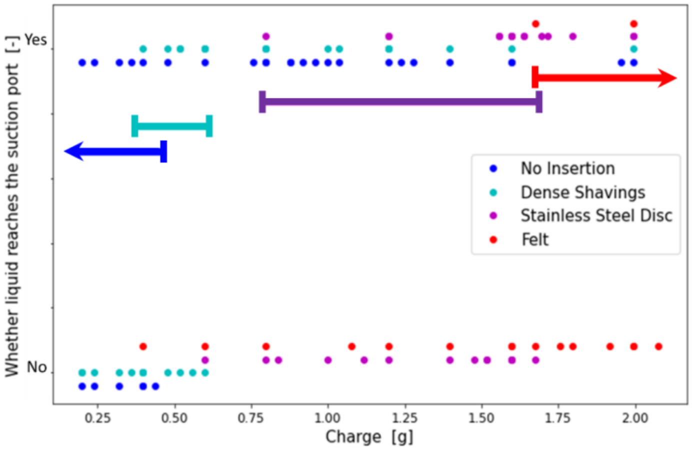

Figure 10: Compressor flooding test results at a height difference of 2 cm as a function of liquid refrigerant charge for tube insertions.

The time elapsed before the first liquid reached the compressor inlet displayed the same general trend for both evaporator orientations. As the liquid charge increased within the evaporator, the time until the first slug reached the compressor inlet decreased as shown in Figure 11 (left). A small effect of the orientation could be seen in the elapsed time during liquid flooding. This is shown in Figure 11 (right) where the red points for the vertical orientation show generally longer elapsed times than the points for the horizontal orientation. No liquid flooding was detected for any charge levels below 55g.

The liquid flooding is initially clearly visible but fades out with time. The end of liquid flooding is therefore not as clearly defined as the beginning, leading to a greater uncertainty in the elapsed time of liquid flooding.

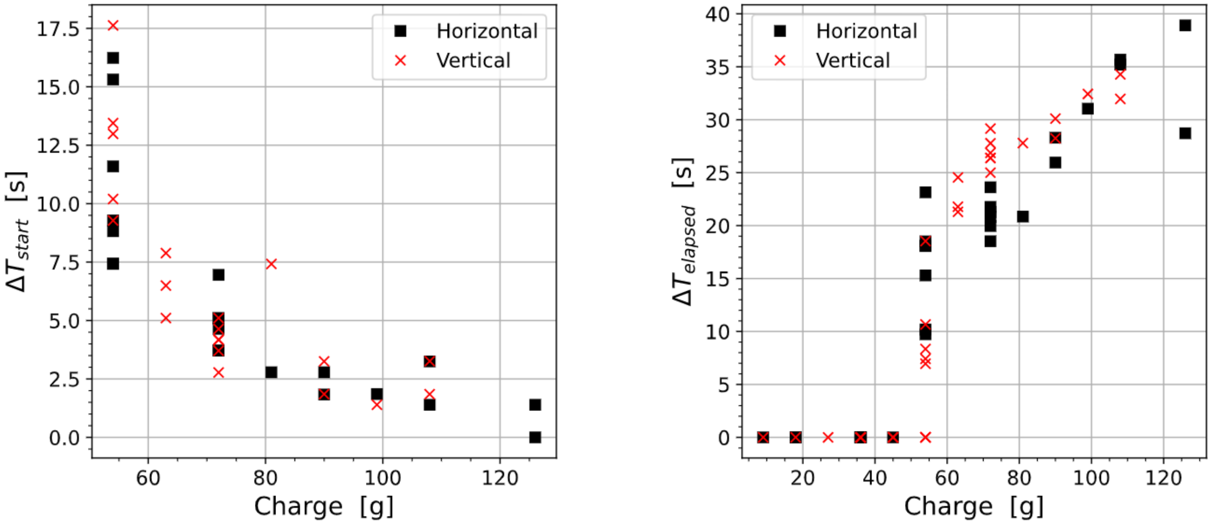

Figure 11: Time elapsed until start of liquid slugging as a function of charge mass (left), duration of liquid slugging as a function of charge mass (right) for evaporator in vertical and horizontal positions.

Pressure drop data collected during the evaporator testing shows that the elapsed time for the cycle pressure to drop to 30 kPa correlates to the amount of liquid refrigerant charged into the system. Higher refrigerant charges yielded longer elapsed times for the refrigerant to empty the evaporator. The elapsed times were generally higher in the vertical position than in the horizontal position, as shown in Figure 12 (left). An example of pressure drop curves for the same charge (72 grams) at different orientations can be seen in Figure 12 (right). The curves have an offset due to different initial pressures but follow a linear trend for about 40 seconds. Afterwards, the pressure from horizontal test runs decreases slightly faster and reaches the 30 kPa threshold earlier than when the evaporator is oriented vertical.

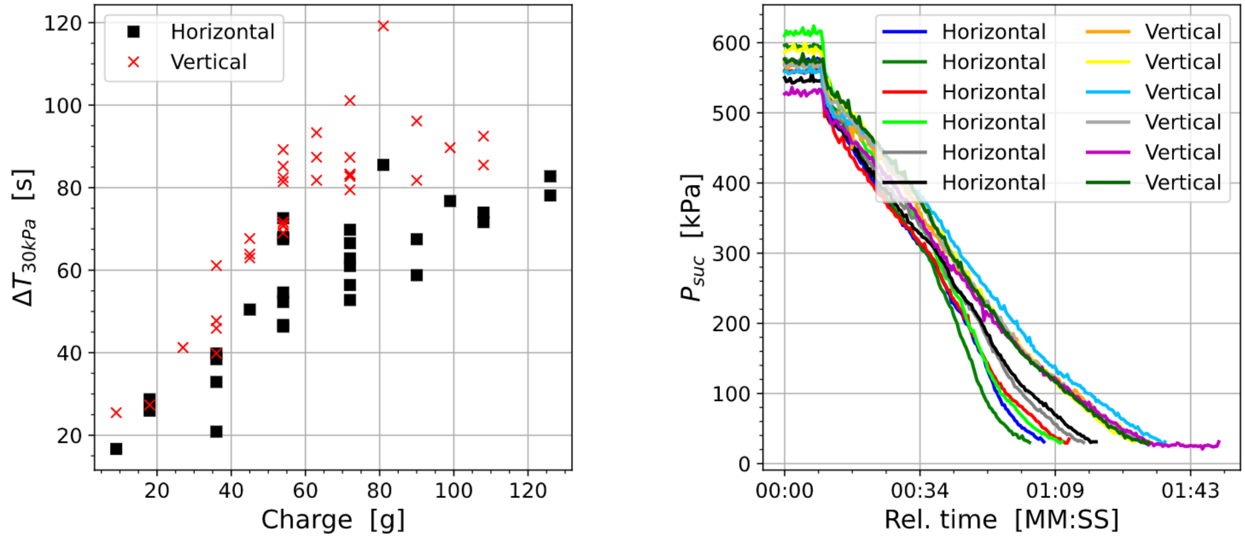

Figure 12: Elapsed time for pressure drop to occur as a function of mass charge (left), Example pressure drop curve for vertical and horizontal charges of 72 g (right).

5. IMPROVEMENTS AND FUTURE TESTING

Plans for future test stand improvements include creating an index refraction box around the polycarbonate tubing to further reduce glare and increase the quality of fluid imaging. Attempts will be made to use binary processing to model the mass flow rate of the liquid slugging. To determine the charge more accurately, a liquid level sensor will be installed on the system to allow for more precise charge measurements.

The time until flooding and the elapsed time during flooding in the evaporator testing was similar for the horizontal and vertical orientation which suggest orientation independence. Zero gravity testing could show whether the liquid slugging phenomena are also *gravity independent*, which is often confused with but not the same as terrestrial *orientation independence*. The time until the first flooding is generally below 15 seconds and therefore a particularly suitable parameter for parabolic flight testing, where zero gravity periods range from 15 to 20 seconds. The other parameters (time elapsed during flooding and time until 30 kPa) are usually longer than 20 seconds and cannot be completely captured within one zero-gravity parabola.

6. CONCLUSIONS

Vapor compression cycles are an energy-efficient option for spacecraft application but the potential of compressor flooding in microgravity poses a serious risk. Due to a lack of prior literature on two-phase flow in microgravity it is unknown if or when the liquid refrigerant will reach the compressor inlet upon cycle start-up. While a concept of microgravity-compliant passive compressor protection has been developed, more information is needed on the behavior of two-phase refrigerant in microgravity to determine if it is viable and even necessary. This study investigated the dependence of two-phase transient refrigerant flow on gravity for both a single tube and an evaporator in preparation for parabolic flight testing. Key conclusions from the experiment are as follows.

[1] Transient liquid refrigerant in an inclined tube displayed “wave-like” and “spray-like” behavior as it moved towards the compressor inlet upon start-up, rather than a steady flow.
[2] Conversely, liquid refrigerant appeared to sit still when the tube was completely level with the compressor inlet and evaporated in place with no indication of pulse or wave behavior.
[3] Useful flow visualization methods such as backlighting were achieved using simple technology suitable for parabolic flights.
[4] The felt tube insertion was found to be the most effective of the insertion samples tested at restricting liquid refrigerant flow into the compressor inlet.

[5] The total elapsed time in which compressor flooding occurred displayed a dependence on the evaporator orientation. Flooding occurred for a slightly longer time in the vertical position.
[6] Test cycles in the horizontal orientation of the evaporator were observed to experience a more rapid pressure drop than the vertical configuration.

The test stand will continue to be improved upon and additional experiments run to prepare for parabolic flight testing. Parabolic flight test results will be compared to the results found in this paper to identify significant differences in terrestrial and microgravity behavior.

NOMENCLATURE

T	time	(seconds)
P	Pressure	(kilopascals)
V	Volume	(meters cubed)
α	Crank Angle	(degrees)

Subscript

30kPa	to reach 30 kilopascals
suc	suction
(ini)	initial

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