NON-CONDENSABLE GASES AND OSCILLATING HEAT PIPE OPERATION

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ABSTRACT

The Oscillating Heat Pipe (OHP) is a novel, wickless heat pipe that relies on the phase change induced motion of a contained working fluid to transport heat between the evaporator and condenser. This paper investigates the effects of non-condensable gas (NCG) on OHP operation. A brief synopsis of the existing literature is presented before discussing the experimental setup, method, results, and conclusion. This paper clearly shows that: 1) NCG injection into an OHP produces an overall rise in the steady-state operating temperature, pressure, and thermal resistance; 2) Like LHPs OHPs are more tolerant of NCG than conventional heat pipes.

Keywords: OHP, Pulsating Heat Pipe, PHP, NCG, Reliability.

1. INTRODUCTION

With the technological advances in semiconductor devices and the ever-increasing power levels and power densities associated with modern satellites, moving and rejecting waste heat in order to control component temperatures has become a progressively challenging problem. Future satellite missions are expected to need heat-rejection capability measured in the 100’s of W/cm², consistent with the general electronics trends of miniaturization and increasing power densities. Passive thermal control solutions are generally preferable for transporting waste heat since they are more reliable than active alternatives and do not lead to additional parasitic heat loads. Current passive technologies cannot deal with these extreme heat levels and heat fluxes; however, there are several novel passive technologies that have the potential to meet these future thermal management needs.

Oscillating or Pulsating Heat Pipes (PHPs) are one of the emerging passive technologies that may be capable of meeting these extreme heat rejection needs. The OHP was developed in 1990 by Hisaeru Akachi; however, the OHP received very little attention until the turn of the century. During the last ten years, a great deal of experimental and numerical work has been carried out in order to advance our understanding of the unique fluid flow and heat transfer characteristics of OHPs.

There are many variants on the basic OHP, shown in Fig. 1, but in every case the fluid flow and heat transfer are governed by the same fundamental physics. An OHP is a simply formed, wickless heat pipe that relies on the phase change induced motion of a contained working fluid to transport heat between the evaporator and condenser. The primary OHP driving force is the result of the difference in working fluid saturation pressure that exists in the evaporator and in the condenser. So long as the evaporator is kept sufficiently hot and the condenser sufficiently cold, the oscillatory motion is self-sustaining.

OHPs are different from traditional heat pipes in that they do not require a wick structure to move the condensed working fluid back to the evaporator. Unlike thermosyphons, however, OHPs are gravity-independent above a critical heat flux (Taft et al., 2013).

In addition to being simple and gravity-independent, OHPs have the potential for better heat transfer capability than standard heat pipes because the majority of the heat transfer associated with OHPs is due to forced convection and the transfer of sensible heat, whereas the heat transfer in a standard heat pipe is dominated by latent heat transfer (Shafii et al., 2001). In an OHP, the effect of latent heat is primarily to drive the oscillatory motions. The simplicity of OHPs may result in a considerable cost and weight savings. The improved heat transfer capability and reduced mass of OHPs have led many to realize that they are ideal for some spacecraft thermal control applications (Shafii et al., 2001; Gu et al., 2004; Gu et al., 2005; Zhang and Faghri, 2003; Taft et al., 2013).

Researchers around the globe are working to transition OHPs to spacecraft thermal control systems. As additional researchers independently verify OHP operation in microgravity, research must turn to answering the reliability and repeatability concerns of space systems engineers. Some of the potential OHP reliability concerns include start-up, non-condensable gas (NCG) effects, freeze-tolerance, material

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compatibility, and hermeticity. Material compatibility and hermeticity are problems faced with traditional heat pipes, and are relatively well understood for common heat pipe working fluids and envelope materials. Start-up, non-condensible gas effects, and freeze-tolerance, however, have some subtleties, potentially both pro and con, in the OHP as a result of the lack of a wick. JAXA has, at least partially, addressed the start-up issue by using a condenser mounted heater to ensure that fluid can be driven to the evaporator prior to start-up if needed (Maeda et al., 2011). This paper investigates the effects of NCG on OHP operation.

The paper starts by presenting a brief synopsis of the existing literature, before discussing the experimental setup, method, results, and conclusion. This paper clearly shows that NCG does not prevent OHP operation; however, it does cause some performance degradation.

2. BACKGROUND

2.1 NCG Formation

According to Nikitkin et al. the three most important factors in determining heat pipe reliability are micrometeoroid protection, NCG formation, and leakage of the working fluid to space (1998). Singh et al. note that NCG is “one of the most common causes for the heat pipe failure which can occur during the fabrication as well during the operational lifespan of the device” (2010).

There are several causes of NCG formation, but the most prevalent is chemical compatibility issues between the working fluid and the heat pipe envelope and/or wick. Improperly chosen working fluid, wick, and envelope combinations can lead to chemical reaction and the formation of NCG, typically hydrogen in the case of ammonia as a working fluid. Fortunately, chemical compatibility issues have mostly been solved for the common working fluid, wick, and envelope combinations. The major heat pipe manufacturers have documented lifetime compatibility of common heat pipe and Loop Heat Pipe (LHP) working fluids, wick and envelope combinations for more than 4 decades.

Unfortunately, minor changes in manufacturing and cleaning processes can lead to unforeseen chemical reactions resulting in the formation of NCG. Additionally, while OHPs typically implement familiar envelope materials (e.g. copper, aluminum, stainless steel), they are introducing new working fluids, whose chemical compatibility is not as well understood.

Although it is rare, and often ignored by domestic spacecraft manufacturers, Nikitkin et al. also cite ionizing radiation as a potential gas generation mechanism (1998). They state that within the former Soviet Union, the breakdown of the heat pipe’s working fluid due to ionizing radiation is considered to be significant. Singh et al. add that although very rare, working fluid breakdown can also occur as a result of the dissimilar electrolytic potentials of the container and wick material (2010).

In addition to NCG formation, NCG can be inadvertently introduced to the system during charging. An improperly degassed working fluid is likely to have NCGs in solution.

2.2 NCG in Heat Pipes and Loop Heat Pipes (LHPs)

The sensitivity and effect of NCG on two-phase thermal control systems varies widely as a result of the system design. Heat pipes and Loop Heat Pipes (LHPs) are of particular interest for spacecraft thermal control, and will be briefly discussed here as a comparison to the OHP. The sensitivity of traditional heat pipes to NCG, which can cause performance degradation and complete failure, is well known. On the other hand, there is relatively little literature documenting the effect of NCG on LHPs.

Bienert et al. and Nikitkin et al. showed that an aluminum-ammonia LHP is insensitive to the presence of NCG at up to six times the projected end-of-life NCG inventory (1997; 1998). However, at 10 times the projected end-of-life NCG inventory, the NCG was shown to increase startup time and operating temperature in LHPs. For this case, the evaporator temperature was ~20 °C above tests in which there was no NCG.

Singh et al. investigated the effect of NCG on a miniature copper-water LHP (2010). Singh et al.’s findings are generally in agreement with Bienert et al. and Nikitkin et al. Singh et al. found that “the overall effect of the NCG is to elevate the steady-state temperature of the loop and increase the start-up time required by the evaporator to achieve stable conditions for a given heat load” (2010). With an estimated 0.0436 μg of NCG, start-up time increased by 1 min 10 sec and the steady-state evaporator temperature increased by ~10 °C.

2.3 NCG in OHPs

Saturation pressure plays an important role in virtually all OHP models as the primary driving force. However, there appears to be very little research in which OHP pressure measurements were collected, and even less attention has been paid to NCG effects.

Miyazaki and Akachi, and separately Kim et al., varied the heat flux and charging ratio to study the pressure oscillation characteristics of OHPs; however, the base OHP pressure was not altered (1996; 2003). In his paper “Characteristics of an Open Loop Pulsating Heat Pipe,” Riehl points out that plug/slug flow dynamics are directly dependent on the amount of non-condensable gas in the system (2004). He discusses the vacuum level, outgassing process, and final working fluid purity of his experimental setup. Taft et al. build on Riehl’s comments, noting that few researchers document the extent to which they pull a vacuum on their OHP before filling, and even fewer go through a rigorous degassing of the working fluid before fill (2012). It was hypothesized, that inconsistency in the way in which researchers fill their OHP experiment setups may account for some of the variability in predicting startup temperatures and heat fluxes, as it is likely that many, if not most, researchers are inadvertently introducing NCG to their test setups.

O’Conner et al. showed that the effect of adding air to a system is to increase the degree of subcooling of the working fluid (1996). It was shown that the total system pressure can be found using Eq. (1):

\[ P_{total} = P_{partial \, vapor} + P_{partial \, gas} \]  

(1)

where

\[ P_{partial \, vapor} = P_{sat} [T_{bulk \, liquid}] \]  

(2)

and \( P_{sat} \) is the saturation pressure taken at the bulk liquid temperature. \( P_{partial \, gas} \) is the partial pressure of any NCG in the system. The effective saturation temperature, \( T_{sat \, eff} \) of the system can then be found using Eq. (3):

\[ T_{sat \, eff} = T_{sat} [P_{total}] \]  

(3)

Finally, the degree of subcooling is

\[ \Delta T_{sub\text{-}cooling} = T_{sat \, eff} - T_{bulk \, liquid} \]  

(4)

3. EXPERIMENTAL APPARATUS

A Flat Plate OHP (FP-OHP) design, as shown in Fig. 2, 3, and 4, was constructed as an embedded OHP in an aluminum structural panel. The OHP has a total of 20 turns and covers a footprint of ~25x25cm2. The entire FP-OHP structural panel is 30x30x0.6cm3. Traditionally, an OHP may be manufactured in two separate pieces, later brazed together. However, ultrasonic consolidation (UC) was used to manufacture the OHP. The OHP core, seen in Fig. 3, was machined from Al-6061; the ~1.3mm facesheet was added, sealing the OHP to the bottom surface, and consists of Al-1100 and Al-3003. UC is an additive/subtractive manufacturing technique that is ideally suited for the production of structurally integrated OHPs. UC allows for the creation of high
strength materials with internal features that significantly exceed the strength to weight ratio of many current aerospace materials.

The OHP performance was measured using the experimental setup shown in Fig. 5. The system consisted of two power supplies (one powering the data acquisition system and a second powering a heater), an ice bath, heater, aluminum water block, and data acquisition system (DAQ). Water was circulated from the ice bath through the aluminum water block at 1.0 GPM using a submersible pump. Heating and cooling were conducted on an area of 7.6x30.5 cm² and 12.7x30.5 cm², respectively, as shown in Fig. 6. Thermal paste (Artic Silver 5) was used as the thermal interface material between all contact surfaces. Four C-clamps were used with insulating pads to apply clamping pressure between the OHP and both the water block and heater.

In order to read pressure measurements inside the OHP, Swagelok® VCR fittings and Omega® pressure transducers were integrated into the panel in both the condenser (0-206 kPa ± 0.689 kPa) and evaporator section (0-3.45 MPa ± 0.002 MPa). After using a helium leak detector to ensure a leak rate of <1E-7 atm·cc/sec, vacuum (3E-3 Torr) was pulled on the sealed OHP and acetone (high performance liquid chromatography grade) was added with a 0.8 ±0.01 fill ratio, by mass.

The square channel (1.3x1.3 mm²) adheres to the maximum allowable diameter, $D_{max}$, for liquid to form vapor bubbles in a capillary tube when using acetone as a working fluid in a standard gravitational environment:

$$D_{max} = 1.84 \frac{\sigma}{g(\rho_l-\rho_v)}$$  \hspace{1cm} (5)

where $\sigma$ is the working fluid surface tension, $\rho_l$ is the working fluid liquid density, $\rho_v$ is the working fluid vapor density, and $g$ is gravity.

The averages consisted of the 3 RTD’s most closely located to the heater and chilled water block, respectively. The overall calculated conductance uncertainty is less than ±0.24 W/K, or approximately ±2.2%. Likewise, the total thermal resistance uncertainty is less than ±2.2%.
4. METHOD

This FP-OHP was originally built for microgravity performance testing. Between two parabolic aircraft flights, the system was put through an extensive ground test campaign. Between July 2nd, 2012 and July 11th, 2012 the OHP was tested at multiple orientations and power input levels. However, since this OHP was previously shown to be gravity independent above ~300W, this paper focuses on test results from the horizontal orientation (Taft et al., 2013). Heat input ranged from 100W to a maximum power input of 500W. Testing was conducted both low-power to high-power and high-power to low-power, but in either case the power input was adjusted in 50W increments. Each power level was held until a steady state condition was achieved and was then recorded for approximately five minutes. This procedure was performed three separate times to effectively produce a range of thermal resistances at each power level and orientation.

After the flight campaign, the OHP and test fixture were left to sit in an ambient environment for ~10 months. The clamping pressure between the OHP and both the water-block and heater was not adjusted, and the high temperature polyethylene foam insulation surrounding the OHP, water block, and heater was left in place. Between April 3rd, 2013 and April 10th, 2013 the OHP was again tested. The only difference between the tests was the OHP non-operating, ambient-temperature pressure, which had risen from 49.6 kPa to 77.2 kPa.

It’s worth noting that even at 49.6 kPa the OHP pressure is higher than would be predicted for a pure working fluid. At room temperature, or 24 °C, the saturation pressure of acetone is 29.6 kPa, indicating that even during the first test series NCG was accounting for 20.0 kPa of the measured pressure. This initial NCG loading is likely the result of an incomplete degassing process. Due to the operational constraints of microgravity performance testing the OHP was charged on the tarmac, and the working fluid was not fully degassed prior to fill. It has been noted that acetone can hold a significant volume of air in solution, according to Kretschmer et al. as much as 20% at 25 °C (1946).

Using the ideal gas equation, Eq. (7), the mass, m, of NCG can be estimated.

\[
m = \frac{P V}{R T}
\]  

where V is volume and R is the gas constant of air. Using the measured pressure and temperature, and assuming that the working fluid is incompressible (i.e. the volume available to the NCG is the loop volume not occupied by liquid), it was estimated that ~2.71 mg of NCG was in the system during the initial test series. It is worth noting that this is significantly more NCG than would be expected at the end-of-life in a commercially manufactured aerospace-grade heat pipe or LHP. As OHPs continue to gain popularity, commercial manufacturing processes must be transferred and validated for OHP manufacture. It is not unreasonable to expect aerospace-grade OHPs to be manufactured to the same stringent tolerances currently being used for heat pipes and LHPs.

As the OHP sat idle for ~10 months additional NCG bled into the system. As opposed to brazing off the OHP fill ports, Swagelok® valves were used to temporarily seal the OHP while Swagelok® VCR plugs were used to plug the OHP. This sealing method provided more flexibility in filling/re-filling the OHP for various tests; however, it did not provide the long-term hermeticity that a crimped and brazed connection would provide. It is believed that the additional pressure rise can be attributed to leakage of some of the air contained between the valves and VCR plugs around the valve stems into the OHP. During the second test series, NCG accounted for 47.6 kPa of the measured pressure at room temperature. Again using Eq. (7), it was estimated that ~4.23 mg of NCG was trapped in the system during the second test series.

5. EXPERIMENTAL RESULTS AND DISCUSSION

It has previously been reported that variation in OHP performance between tests is larger than typical experimental errors (Taft et al., 2013). It is hypothesized that this variation in performance could be the result of an OHPs chaotic operating nature, which has been well documented in the literature (Qu et al., 2009; Maezawa et al., 1996; Maezawa et al., 2000). In this test sequence, it is also possible that some variation is the result of slight differences in the ice-bath temperature. In either case, it was observed that performance variation at ~6% exceeded the measurement uncertainty during this test sequence. As such, error bars have been omitted from the charts as the measurement uncertainty is small compared to the natural performance variation. Instead, the average values for each of three separate tests in the two test series were plotted.

Figure 7 shows the OHP thermal resistance as a function of power input and OHP non-operating, ambient-temperature pressure. As the OHP internal pressure is increased, the OHP performance decreases. On average, this performance degradation is 0.03 K/W or 16.5%. It’s worth noting that at 100 W power input, the OHP is not oscillating, and the measured resistance is almost entirely the result of conduction through the panel and working fluid. The absence of oscillations results in there being little difference in the measured resistance, regardless of the increased system pressure. The empty panel resistance is 0.44 K/W.

Figure 8 shows the OHP evaporator pressure as a function of power input and OHP non-operating, ambient-temperature pressure. As the OHP evaporator pressure rises with increased ambient-temperature pressure. On average, the pressure rises 33.4 kPa or 27%. The average pressure difference is slightly more than the NCG attributed 27.6 kPa difference at non-operating, ambient-temperature conditions. The additional 5.8 kPa difference is likely the result of the system’s increased operating temperature.

Figure 9 shows the OHP evaporator temperature as a function of power input and non-operating, ambient-temperature pressure. Above 100 W power input, the OHP evaporator temperature rises with increased ambient-temperature pressure. On average the temperature rises 7.3 °C or 11%. This temperature increase is on-par or better than the LHP performance demonstrated by Singh et al., Bienert et al, and Nikitkin et al.

Using Eq. (3) and Eq. (4), the effective saturation temperature and subcooling are calculated for the two different NCG pressure states. Figure 10 shows the effect that NCG has on the saturation temperature.
Fig. 8 OHP evaporator pressure as a function of power input and OHP non-operating ambient-temperature pressure.

Fig. 9 OHP evaporator temperature as a function of power input and OHP non-operating, ambient-temperature pressure.

The degradation of OHP performance as the base system pressure is increased is not surprising, as the addition of NCG to the system serves to subcool the system.

Fig. 10 OHP subcooling resulting from NCG.

6. CONCLUSIONS

The results of this investigation clearly show that the addition of NCG to an OHP will not prevent operation. In fact, since there is so little documentation and almost no direct pressure measurement, it seems likely that many of the OHPs discussed in the literature contain some level of NCG. Although it does not prevent operation, NCG, and the corresponding increase in system base pressure, do degrade performance.

As cleaning/charging processes are further developed and validated for commercial manufacturing of aerospace-grade OHPs, and chemical compatibility of typical OHP working fluids is better understood, the quantity of NCG injected into and or formed in a typical OHP will be vastly reduced. This improvement should provide increased consistency in the thermal performance results of the many OHP studies being conducted worldwide.

Regardless, the ability of an OHP to continue operation, even with the formation of non-condensable gases, provides for a resilient thermal control system. Resiliency may be another perk in using the OHP for spacecraft thermal control; however, NCG formation is only one piece of the OHP reliability puzzle. Future work must address the other factors affecting reliability.

In summary, it was shown that:

1. NCG injection into an OHP produces an overall rise in the steady-state operating temperature, pressure, and thermal resistance, but does not prevent operation.

2. Like LHPs, OHPs are more tolerant of NCG than conventional heat pipes.

NOMENCLATURE

\[ D \] \quad \text{Diameter (m)}
\[ g \] \quad \text{Gravity (m/s}^2\text{)}
\[ P \] \quad \text{Pressure (Pa)}
\[ Q \] \quad \text{Heat Input (W)}
\[ R \] \quad \text{Gas Constant of Air (kPa-m}^3\text{/kg-K)}
\[ T \] \quad \text{Temperature (K)}
\[ UA \] \quad \text{Conductance (W/K)}
\[ V \] \quad \text{Volume (m}^3\text{)}

\text{Greek Symbols}

\[ \rho \] \quad \text{Density (kg/m}^3\text{)}
\[ \sigma \] \quad \text{Surface Tension (N/m)}

Subscripts

\text{cond} \quad \text{Condenser}
\text{evap} \quad \text{Evaporator}
\text{max} \quad \text{Maximum}
\text{i} \quad \text{Liquid}
\text{sat} \quad \text{Saturation}
\text{sat eff} \quad \text{Effective Saturation}
\text{v} \quad \text{Vapor}

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