Topical: Thermal Fluids Research and Development Relevant to Oscillating Heat Pipes

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Abstract:

Oscillating Heat Pipes (OHP) or Pulsating Heat Pipes (PHP) are an emerging two-phase thermal control technology that could enable new NASA mission concepts and operations. These passive devices have shown unmatched capability to accommodate high heat fluxes and significant heat loads with minimal mass and volume usage. However, the high performance of OHPs relies on complex coupled physical phenomena including thin liquid film evaporation, condensation, boiling, and convection super-imposed with high-speed oscillatory fluid flow in micro channels. We identify significant research topics to develop a comprehensive understanding of OHP operation and infuse this game-changing technology into NASA Missions

Background

Future NASA missions will require high performance thermal control systems to enable operation. Human and unmanned robotic space exploration depend upon the reliable operation of mission-critical electronics, batteries, high-capability sensors, Radioisotope Thermoelectric Generators, and crucial infrastructure elements such as space stations or Lunar human bases. These systems require reliable and effective thermal control and heat rejection. Heat rejection is crucial for harsh Lunar thermal environments where surface temperature changes from 120°C during the day and -180°C during the night. Human and robotic presence increases power consumption and heat rejection requirements. Furthermore, operation of the base during the cold lunar night environment requires the ability to conserve stored energy by switching off, or at least reducing, the thermal path to the sink.

The trend toward miniaturization has highlighted the importance for effective thermal control solutions accommodating the attendant higher heat fluxes. For example, the increasing use of wide bandgap power devices such as those found on GaN and SiC substrates will significantly improve specific power metrics up to two orders of magnitude from 0.25kW/kg (current) to 25kW/kg (future metric), for all power processing needs. Successful implementation of these technologies requires new power electronic cooling topologies to reliably maintain electronics temperatures that generate higher heat fluxes and heat generation rates within the architectural limitations of smaller packages. Oscillating Heat Pipes have the potential to meet such needs.

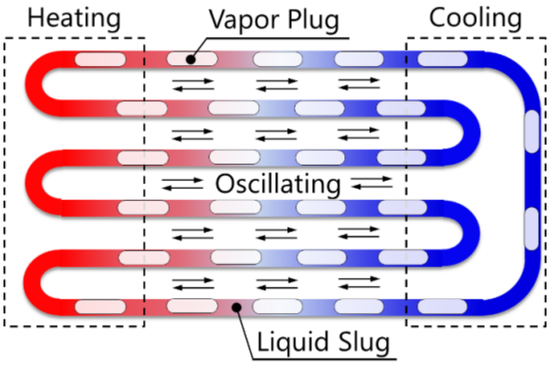

Fig. 1 Schematic of an Oscillating Heat Pipe

Oscillating Heat Pipes (OHPs), also known as pulsating heat pipes (PHP), are among the few two-phase thermal management technologies which have demonstrated the required heat acquisition demands and integrated characteristics. The OHP transports heat by phase change of liquid films created by oscillation of liquid slugs driven by a pressure wave augmented by single phase heat transfer from the liquid slugs. Oscillating heat pipes consist of a single meandering capillary channel or tube that wraps between hot and cold zones; these zones typically form distinct evaporator and condenser sections with a nominally adiabatic heat transport zone separating them (Fig. 1). The channel volume is evacuated and then partially filled with a working fluid. Due to the capillary dimension of the tubing, the fluid forms distinct liquid plugs and vapor plugs within the channel. As heat is applied to the evaporator, a temperature change occurs in the vapor plugs which creates a pressure difference driving the liquid slug motion which, in turn, generates pressure changes in neighboring vapor plugs by compressing or expanding the vapor plug volume. The pressure wave propagates along the fluid in the channel. The liquid slug motion creates a thin liquid film layer (10s of µm thick) between the channel wall and the vapor plugs. Heat conduction through the thin film results in a very high heat transfer coefficient between the vapor saturation temperature and the channel wall temperature. This heat transfer at the evaporator occurs as latent heat transfer, with evaporation from the surface resulting in a thinner liquid film. Movements of the liquid slugs creates a new liquid film in the evaporator. The balance between this liquid film dry-out and its replenishment from the next liquid slug sets one of the performance limits of OHPs. Sensible heat transfer directly to the liquid slugs is also an important heat transfer path in OHPs. Establishing the magnitude of the latent to sensible heat transfer fraction as a function of OHP design and working fluid remains an important unresolved question. Finally, the heat stored in the vapor plug is dissipated through the film in the condenser and by sensible heat transfer from the liquid slug.

OHPs are an enabling thermal management technology: (1) the enhanced conductance of OHPs due the two-phase heat transfer, (2) the ability to fabricate OHPs from relevant substrates (e.g., Si, SiC, used for advanced power electronics or wide band gap electronic devices, 3D structures such as electronics chassis, card carriers and thermal straps, or refractory alloys for high temperature operation), (3) OHP working fluids enable operation from the cryogenic range (helium) to high temperatures (liquid metals).

Space Based Oscillating Heat Pipe Research

Oscillating heat pipes are elegantly simple yet remarkably efficient two - phase heat transfer heat transfer devices. OHP heat acquisition and transport phenomena consists of complex coupled physical processes including thin liquid film evaporation, condensation, boiling, and rapid oscillatory fluid flow. Thus, the OHP operation generates a unique set of co-dependent thermal phenomena that demands better characterization of the interactions among these processes. Furthermore, oscillating heat pipes tend to operate in regimes far from thermodynamic equilibrium. We identify the follow research areas to advance these technical goals:

1) **Thin liquid film formation physics in micro/mini channels in OHPs.**
As liquid slugs pass through the evaporator section of OHPs they deposit a liquid film that subsequently evaporates. This liquid film is believed to be critical in the operation of OHPs. Liquid film formation can be affected by different gravitational environments such as zero or partial gravity on the Lunar surface. In-Situ measurement of liquid film thickness while OHPs are operating in the space environment is required to understand the effect of different gravitational environments. Measurement of the fraction of heat input that is transported latent heat transfer as compared to that carried by sensible heat transfer in the liquid slugs is also required. Since OHPs have an envelope that contains micro/mini channels within them, unique measurement techniques such as the one utilizing ultrasonic reflection or electrical resistance may be required.

2) **Gravity effects on an OHP's thermal conductance and operational limits.**
While OHPs are not as susceptible to the effects of gravity as traditional heat pipes, their operation has been experimentally shown to have a dependence on gravity. In particular, OHPs show better thermal performance in the orientation where gravity assists liquids to flow into the evaporator (evaporator bottom and condenser top). In the partial gravitational environment such as Lunar and Mars, OHPs are expected to be utilized in the orientation where gravity assists but may also be used in orientations that require lift against gravity. In the adverse gravity orientation (evaporator top and condenser bottom), performance degradation is expected to be less compared to that in the Earth's 1-G environment. Different gravity environments affect not only the thermal conductance while the OHP is operating but also the operational limits such as maximum heat input before the OHP's evaporator dries out and the minimum heat input required to initiate good heat transfer in the OHP, i.e. start-up. Any equipment deployed on the Moon or Mars or in a zero-g application will first need to be tested in the lab both at the OHP-level and the subsystem/system level. Therefore, thermal performance measurements in different gravity environments is required to understand gravity effects on an OHP's thermal conductance and operational limits and to allow meaningful ground test of this equipment prior to launch.

3) Nucleation Physics in Isochoric micro-channel system driven by saturation pressure.
It is known that frequency and bubble size of nucleation and flow boiling are affected by zero gravity condition due to lack of buoyancy. Since nucleation of bubbles plays an important role in the pressure propagation within the liquids and liquid film formation inside OHPs, the effect of gravity on nucleation physics in isochoric micro-channels needs to be evaluated. Evaluation of thermal performance changes due to different nucleation physics in zero/partial gravity is also required. For nucleation frequency measurement, unique in-situ techniques such as utilizing vibration detection on the OHP envelope by strain gauges is required.

4) **Operation limits of OHPs.**
Understanding the operational limits of OHPs is critical for their successful design and implementation. This is exemplified by the well-known operating limits of traditional heat pipes such as the capillary-viscous limit and boiling limits. However, due to the unique physics of OHPs, different physical mechanisms are known to limit their operational behavior. The inherent complexity of OHP operation makes understanding these limits challenging.

5) **Performance models of OHPs.** The ability to predict how a specific OHP design will perform is crucial for their integration into critical systems. The physical complexity of their operation alone makes this a significant challenge. Additional complexities such as heat load distribution, channel layout, orientation, etc. make this an even more challenging topic. Models and modelling techniques must be established at all levels of fidelity from first order analytic models to high fidelity numerical models and CFD. While significant work has been done in this domain, there has yet to be a consensus on the appropriate approaches at the different levels of fidelity.

Summary:

This document outlines a series of OHP experimental research efforts consisting of in-situ measurements of temperature, liquid film thickness, and nucleation boiling frequency in different gravitational environments to provide fundamental data required to develop improved OHP operational models. This comprehensive initiative will provide NASA the required engineering tools to expand OHP's heat acquisition, transport and rejection in space environments. Improved modelling techniques of OHP operation and their limits of operation, validated and supported by the above experiments, are critical to transition of OHP technology into *critical flight and lander/base systems.*

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