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An investigation of a multi-layered oscillating heat pipe additively manufactured from Ti-6Al-4V powder

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ABSTRACT

A laser powder bed fusion (L-PBF) additive manufacturing (AM) method was employed for fabricating a multi-layered, Ti-6Al-4V oscillating heat pipe (ML-OHP). The $50.8 \times 38.1 \times 15.75\ mm^3$ ML-OHP consisted of four inter-connected layers of circular mini-channels, as well an integrated, hermetic-grade fill port. A series of experiments were conducted to characterize the ML-OHP thermal performance by varying power input (up to 50 W), working fluid (water, acetone, Novec™ 7200, and n-pentane), and operating orientation (vertical bottom-heating, horizontal, and vertical top-heating). The ML-OHP was found to operate effectively for all working fluids and orientations investigated, demonstrating that the OHP can function in a multi-layered form, and further indicating that one can 'stack' multiple, interconnected OHPs within flat media for increased thermal management. The ML-OHP evaporator size was found to depend on the layer-wise heat penetration which subsequently depends on power input and the ML-OHP design and material selection. Using neutron radiography, electron scanning microscopy and surface metrology, the ML-OHP channel structure was characterized and found to possess sintered Ti-6Al-4V powder along its periphery. The sintered channel surface, although a byproduct of the L-PBF manufacturing process, was found to behave as a secondary wicking structure for enhanced capillary pumping and wall/fluid heat transfer within the OHP. With the newfound capabilities of AM, many high heat flux thermal management devices, specifically those that employ mini- or micro-channels, can be 're-invented' to possess embedded channels with atypical geometries, arrangements and surface conditions.

1. Introduction

The miniaturization and enhancement of electronics packaging schemes continue to challenge the design and engineering of compact heat dissipation systems for thermal management [1]. With heat fluxes nearing $1\ kW/cm^2$ being realized and conventional, single-phase thermal management techniques are no longer viable. This has resulted in disruptive technology innovations such as near-junction/intra-cooling [2,3] and two-phase, (far-junction) surface-mounted heat spreaders/sinks [4,5]. With regard to 'far-junction' thermal management, methods are continually sought for effectively spreading thermal energy over relatively thin media to achieve their near-isothermal surface opposite to the adjoined heat source. One such device for high heat flux thermal spreading is the thermal ground plane (TGP). The TGP is a surface-mounted, two-phase heat spreader that operates passively [3,6,7]; relying on capillary structures such as porous/sintered media and mini/micro-channels for cyclic fluid pumping. Some examples of TGPs include flat heat pipes, vapor chambers, oscillating (or pulsating) heat pipes (OHPs) and other hybrid two-phase cooling technologies [5,8–12]. The mounting of a TGP typically requires that minimal stress occurs at the source-contacting interface to ensure minimal damage to heat-dissipating electronics. To this end, the heat source and TGP coefficient of thermal expansion (CTE) are often sought to be 'matched' for reducing interfacial stresses.

The OHP, as shown schematically in Fig. 1, is a partially-filled capillary structure that meanders, in a serpentine-fashion, through a heat source (i.e. evaporator) and sink (i.e. condenser) [13,14]. It can take the form of media-embedded, mini/micro-scale channels

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Nomenclature

Bo	Bond number
c_p	isobaric specific heat capacity, kJ/kg K
g	acceleration due to gravity, m/s^2
h_{lv}	enthalpy of vaporization, kJ/kg
j	thermocouple location
k	thermal conductivity, W/m K
P	power input, W
r	radius, m
T	time-averaged, steady-state temperature, °C
Greek symbols	
μ	dynamic viscosity, µPa s
ρ	density, kg/m^3
ψ	thermal resistance, °C/W
σ	surface tension, N/m
Subscripts	
avg	average
c	critical
eff	effective
H	hydraulic
l	liquid
v	vapor

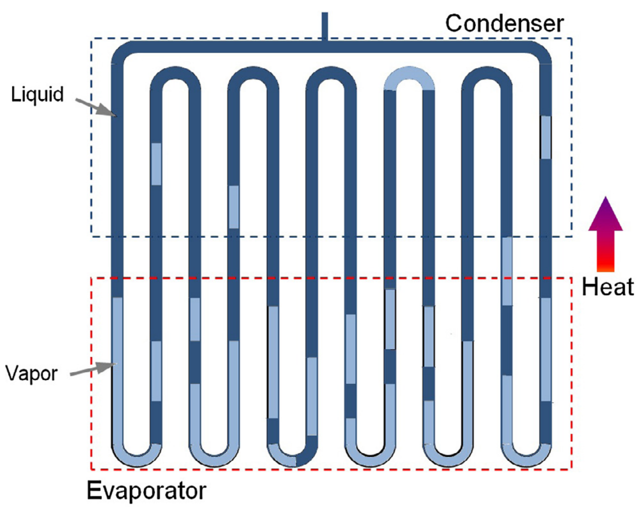

Fig. 1. Schematic of typical liquid/vapor distribution within an oscillating heat pipe (OHP) consisting of uniformly-sized evaporator and condenser.

(i.e. a flat plate OHP a.k.a. FP-OHP) or capillary tubing (i.e. a tubular OHP); each requiring a hermetic seal for optimal operation. Upon introduction of a sufficient temperature difference, or heat flux, the fluid inside the OHP vaporizes and expands unevenly along various sections of its evaporator resulting in its 'start-up'. Vapor pressure builds due to sensible heating and results in a non-uniform, oscillatory pressure field forming against liquid volumes. The oscillatory fluid motion, combined with phase-change heat transfer, allows for cyclic, fluid-driven heat transport from the OHP evaporator to the condenser. This cyclic phase change is typically evidenced by an OHP surface temperature field that oscillates with respect to time [15,16]. The type and amount of working fluid, channel/tube dimensions, number of channel/tube turns (a.k.a. 'U-turns', bends), operating orientation with respect to gravity, and heating/cooling areas are some of the many design/operating parameters affecting OHP thermal performance [17,18].

The working fluid selected for the OHP must demonstrate wicking behavior as governed by the channel/tube hydraulic radius, r_H, and operating environment (e.g. gravity). Conditions for capillarity, and thus effective OHP operation, can be estimated via the Bond number, *Bo*, i.e.:

$$\mathrm{Bo} = \frac{r_H^2 \Delta\rho_{lv} g}{\sigma} \lesssim \mathrm{Bo}_c \tag{1}$$

where σ is the liquid-to-vapor surface tension, $\Delta\rho_{lv}$ is the difference in density between the liquid and vapor phases, and Bo_c is the critical Bond number for capillarity and can range between 0.8 and 1.0 [14,19].

The thermophysical and rheological properties of the utilized working fluid dictate OHP thermal performance. A fluid's surface tension strongly influences evaporation heat transfer [20], as well as the pressure gradient along the OHP flow path [18]. Fluids with a lower latent heat of vaporization and dynamic viscosity tend to provide for slower flow speeds, moderate heat transfer and lower OHP start-up powers [18,21,22]. A fluid's specific heat capacity influences its single-phase heat transfer during oscillatory, forced convection within an operating OHP. Since the majority of OHP heat transfer is typically sensible [23], the specific heat capacity and thermal conductivity are important thermal properties of the working fluid. A fluid with a vapor pressure highly sensitive to temperature is desirable for increasing an OHP's pumping capability – which is needed for assisting its start-up and consistent operation [18]. Taft et al. [24] demonstrated that the latent heat of vaporization, surface tension, and density of working fluids play an important role in OHP start-up and that viscous fluids provide more dampened temperature oscillations during OHP operation. Both the surface tension and density of a working fluid can affect OHP channel sizing for various micro-to-macro gravity environments (i.e. the Bo is gravity dependent) [19,25]. In general, fluids with low dynamic viscosity and latent heat of vaporization reduce the heat rate required for OHP start-up by minimizing channel pressure drop [18,24]. Fluids with a smaller latent heat of vaporization can improve OHP performance by providing higher oscillating velocities (caused via higher vapor pressures).

Since OHP operation depends on the dominance of surface tension forces for ensuring capillary flow, the magnitude and direction of gravity will, in general, affect OHP thermal performance [13,17,25–30]. For terrestrial gravity environments (i.e. 1*g*), this dependence is often demonstrated experimentally by altering the OHP's operating orientation and relative positioning of its evaporator and condenser. An OHP in the vertical bottom-heating orientation (or 'mode') is descriptive of it being collinear with the gravity vector and its condenser above its evaporator; while an OHP in the horizontal orientation indicates that the OHP is perpendicular to the gravity vector. Riehl demonstrated that, for a constant fill ratio of 50%, the sensitivity of an OHP's thermal performance to working fluid is exaggerated when the OHP is operating in the horizontal orientation [31]. This was demonstrated for a variety of working fluids, including: water, methanol, acetone, isopropyl alcohol, and ethanol. The OHP's effective thermal conductivity was found to vary by ±19% when changing working fluids in the bottom-heating mode, while the variation was ±53% in the horizontal orientation.