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Thermal performance against gravity of an AlSi10 AM heat pipe with a diamond lattice structure

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Abstract. Metal Additive Manufacturing has gained momentum as a viable production technique for specialized heat transfer devices, in particular for industrial sectors characterized by small production numbers associated with high-performance requirements. Within the space industry, ESA is leading and funding several applied research programs to explore the possibility to employ AM for building electronic boxes with embedded heat pipes, in order to reduce manufacturing post-processing steps and contact thermal resistances. In the context of tender 1-10238, the project "Heat Pipe Solutions for High Power Systems" (HPS^2) has developed and tested lattice-based heat pipes, that are intended to be integrated in electronic modules. In this paper, the heat transfer performances as function of input power and tilt angle against gravity of a 150 mm long heat pipe with a 20 mm evaporator section and a 40 mm condenser section are presented and compared with the results of the models of performance limits, based on the measured properties of the lattice.

1 Introduction

The strive towards both increased performance and miniaturization of electronic components is no news in 2024, but challenges linked to efficient heat dissipation strategies in electronic boxes can be faced in innovative ways as new materials or technological processes reach a sufficient maturity. In particular, the space sector is investigating the limits of metal additive manufacturing (AM) techniques, as they allow to produce complex designs with minimum pre- or post- processing machining and, due to general small production volumes, is not affected by productivity issues. Regarding the electronic boxes, AM allows to build electronic modules with integrated heat pipes (HP). To this end, several works have already been carried out both focusing on building and testing both the wick and the entire HP, as done by Ameli [1], [2], and Wu [3]. Others, as Jafari [4], focused only on the porous structure which can be used as wick. The ThermALab and Metamat groups at Politecnico di Milano have carried out research to find suitable porous structures to be used as wick in AM-based AlSi10Mg HP [5]. While a sinter-like structure results in a low pore size, its permeability, as also shown by Gotoh et al. [6] is a severely limiting factor in the operation against gravity. Therefore, a more open diamond lattice structure has been developed and tested. This work shows the thermal performances of an AM AlSi10Mg HP filled with acetone, with three wicks based on a diamond lattice structure with different pore radius.

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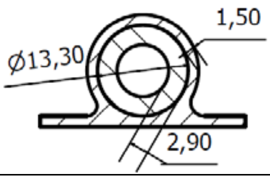
2 Materials and methods

2.1 Heat pipe geometry

The heat pipe consists of a 150-mm long straight tube, plus 10 mm for filleting, with one flat surface to ease the heaters' placement, while its section dimensions are resumed in Table 1. The HP has been closed initially with Fitok ball valves, as shown in Figure 1, however an upgrade to more robust needle valves by Fitok has been done to collect the results reported in this paper.

Table 1. HP section

Wick cross-section [mm^2]	94.70
Vapor-space cross-section [mm^2]	44.16
Total internal cross-section [mm^2]	138.86
Section drawing	

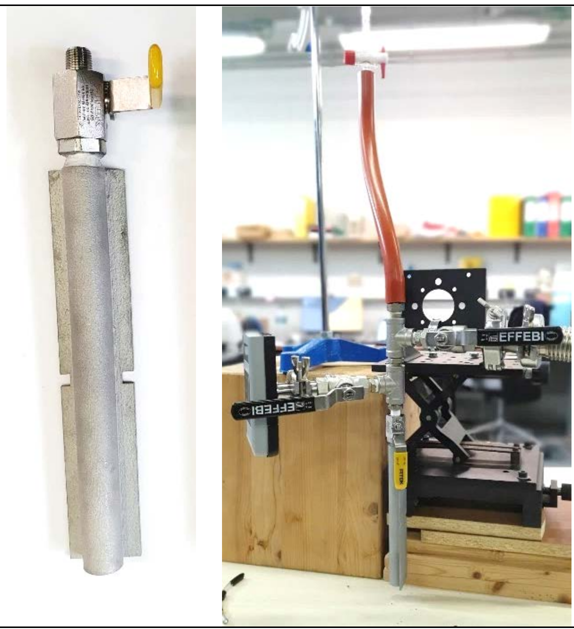


Figure 1. HP equipped with ball valve (left) and filling rig with attached HP (right).

2.2 Filling

While the intended working fluid at the end of the project is ammonia, in the first stage of trials, acetone has been used, since it allows quicker operations with less safety concerns both regarding accidental leaks in the filling and trial phase, which in the case of ammonia should be carried out under a laminar hood, and to operate at lower pressures, minimizing the risk of burst before the HPs are fully characterized in that regard. A simple rig to fill the HPs under vacuum has been built and it is shown in Figure 1 (right). The filling and trial set-up procedure is carried out as follows:

1. Acetone volume estimation (wick saturation + 10% + volume of valve + losses in the filling rig);
2. HP weighing before filling;
3. The HP is attached to the filling rig; vacuum is applied for 30 min while heating the HP with a heat gun. The rig pressure reaches 2.2e-2 mbar;
4. Weighing the HP after filling on precision balance to control the amount of charge;
5. Appling thermocouples and heater on the HP, heating the HP up to 65-70 °C (acetone saturation pressure > ambient pressure) and burping to remove NCG.

The procedure has been also tested introducing other steps, as HP washing in acetone in an ultrasonic bath and acetone degassing before filling, without noticeable variation on performances. The filled HP showed no variation in performance for inclinations along gravity for their whole length for up to a week, which is considered a satisfactory proof of partial vacuum holding in this first research phase.

To speed up the test procedure for research purposes, a simpler filling procedure, consisting of filling the instrumented HP under atmospheric pressure of a charge of acetone, closing the valve, heating it to at least 70 °C (minimum temperature) and burping the air and other NCGs has been tested and employed. This procedure is repeated, first with the HP working along gravity, then with the HP in quasi-horizontal direction. The procedure is considered over when the maximum temperature difference between the thermocouples stops diminishing.

2.3 Trial set-up

After the HP is filled, thermocouples are applied along its main axis. The configuration used to report the results adopts five evenly-spaced thermocouples applied both on the bottom (flat) surface and on the top surface. When the test results report only one value of temperature difference ΔT, that value refers to the difference between the temperatures measured by the thermocouples placed on the opposite side with respect to the heater, placed at sections corresponding to the middle of the evaporator and of the condenser. On the bottom surface a heater is applied, with a contact surface of 0.8 cm x 1.6 cm (total heated area of 1.28 cm^2), while on the other end a finned heat sink, or, for high power tests, a copper heat pipe, are applied. The total evaporator length is 1.6 cm, while the condenser length is 4 cm. The effective length of the heat pipe is 13 cm.

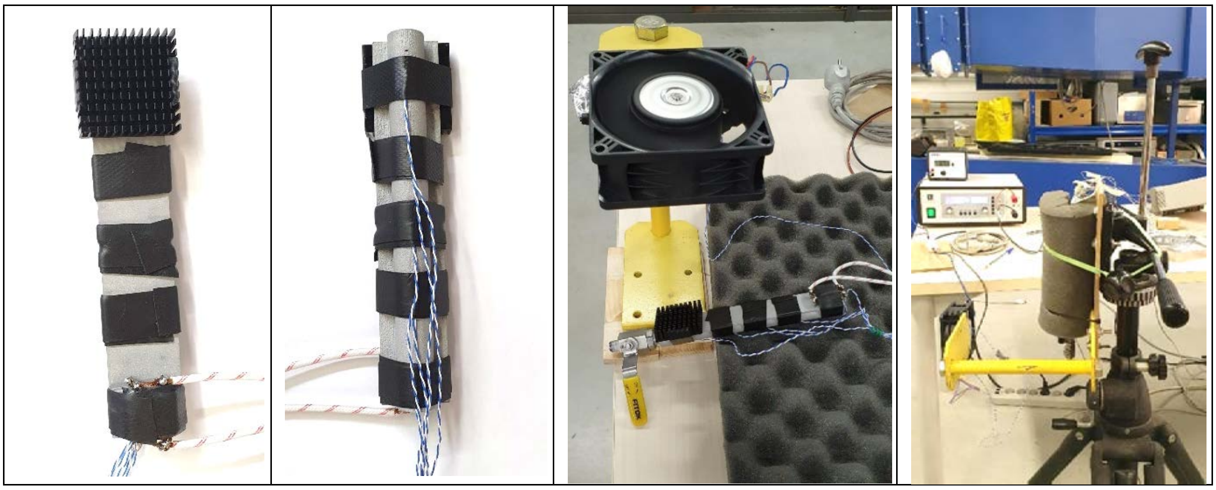


Figure 2. HP equipped with thermocouples, heater and heat sink (left), before and after installation on the test rig (right).

The HP is then placed on a rig that allows its rotation from directions along and against gravity, i.e. with the evaporator below and above the condenser, respectively, wrapped in foam to minimize heat dispersions in regions other than the condenser. A 24 V fan is mounted on the rig and allows the uniformity of convective boundary conditions at the condenser for all the orientations. The average temperature of the HP at different input power is regulated by adjusting the fan rotational speed. This set-up is shown in Figure 2.

As a general note, in order to verify the HP's performance in space, zero-gravity, conditions, tests at 0° inclination are always carried out at "0- °" orientation, which means with a little inclination against gravity, circa -1°.

3 Lattice design and properties

The lattice structures were selected according to the following criteria. First the lattice topology is fixed, the "diamond shape" in Figure 3. Three different values of unit cell length (C) and strut diameter (Φ) are selected considering the pore size, the lattice density and the technological limitations, and are reported in Table 2. They are named L1, L2 and L3 from the one with the smallest to the one with the largest unit cell, respectively. The main properties of the lattice, i.e. porosity ε, equivalent pore radius r_p and permeability K have been measured on dedicated samples and are reported in Table 2.

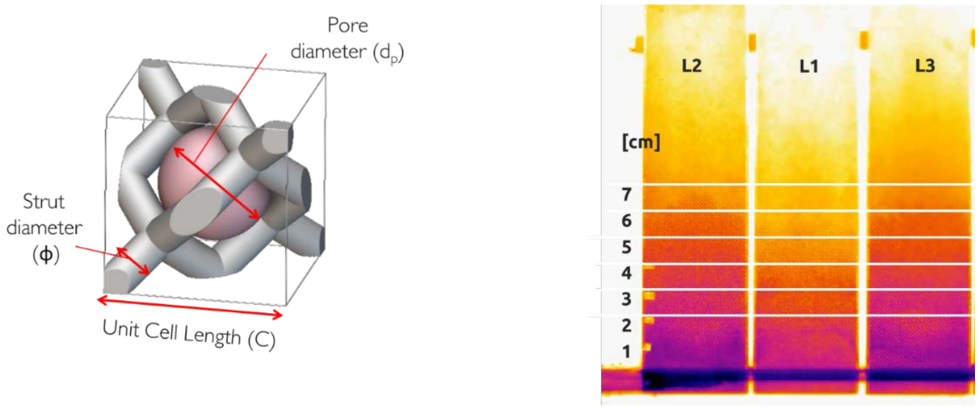


Figure 3. Diamond lattice unit cell (left), capillary rise test (right).

Table 2. Properties of the printed lattice porous structures. Values with asterisk (*) are measured.

	Unit Cell Length C [mm]	Strut Diameter Φ [µm]	Lattice density ρ_l [%]	Largest inscribed sphere diameter d_p [µm]	Porosity* ε [-]	Equivalent pore radius* r_p [µm]	Permeability* K [µm^2]
Lattice 1 (L1)	1.30	660	65	400	0.24	98.3	18
Lattice 2 (L2)	1.38	600	55	530	0.38	86.8	238
Lattice 3 (L3)	1.50	600	50	620	0.46	86.8	260

4 Results

4.1 Lattice 1

The HP equipped with lattice L1 does not operate against gravity, i.e. the HP is fully functioning for all positive angles, but behaves just slightly better than the pure conductor for all negative angles, as shown in Figure 4. This behaviour can be expected by looking at the low permeability of such lattice.

4.2 Lattice 2

The HP with L2 behaves as illustrated in Figure 5. In particular, at 20 W a drastic decrease in performance can be observed for Δz = -4.5 cm, or φ = -20 °. However, a slight dryout at the evaporator, which gives a 2.5 °C increment of temperature difference, can be observed from φ = -10 °. This behaviour is less evident for trials at 8 W, which shows a smoother transition between regions.

The influence of input power has been scrutinized more deeply for the HP in quasi-horizontal direction (φ = 0- °) and with a slight negative inclination (φ = -10 °), as shown in Figure 6. The HP in quasi-horizontal direction can withstand up to 25 W without significant changes in its temperature difference, while at φ = -10 ° the slight dryout at the evaporator causes the appearance of a small conductive region, which explains the linear temperature difference trend.

4.3 Lattice 3

The HP with lattice L3 was expected to show similar, if not better performance compared to D1L2, since while having similar capillary rise, the lattice is characterized by an increased porosity. However, the heat pipe tests showed a peculiar unstable behaviour illustrated in Figure 7. The causes of this behaviour should be more thoroughly investigated. A tentative explanation is that the liquid holds difficultly to the structure due to the larger mesh size of lattice L3 and periodically falls down before reaching the evaporator.

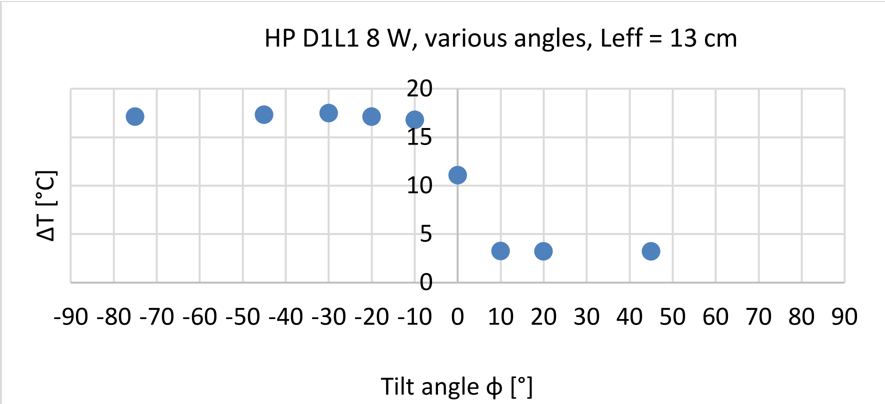


Figure 4. Temperature differences for various tilt angles, HP D1L1.

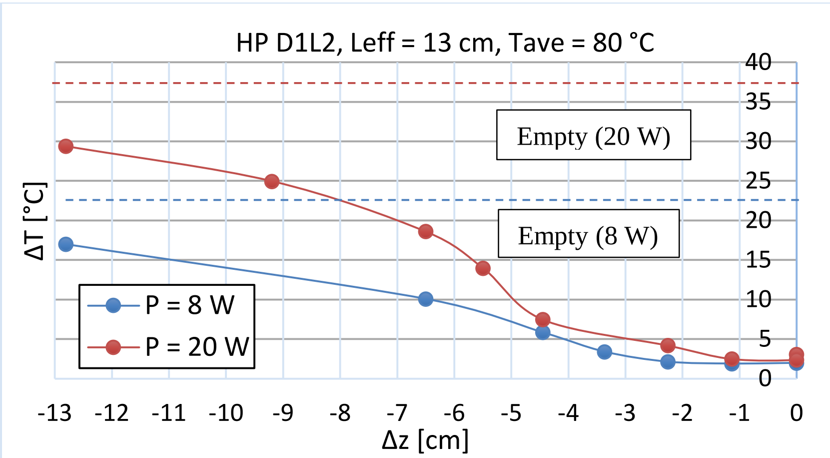


Figure 5. Temperature difference for HP D1L2 for various heights against gravity, for 8 W and 20 W of input power.

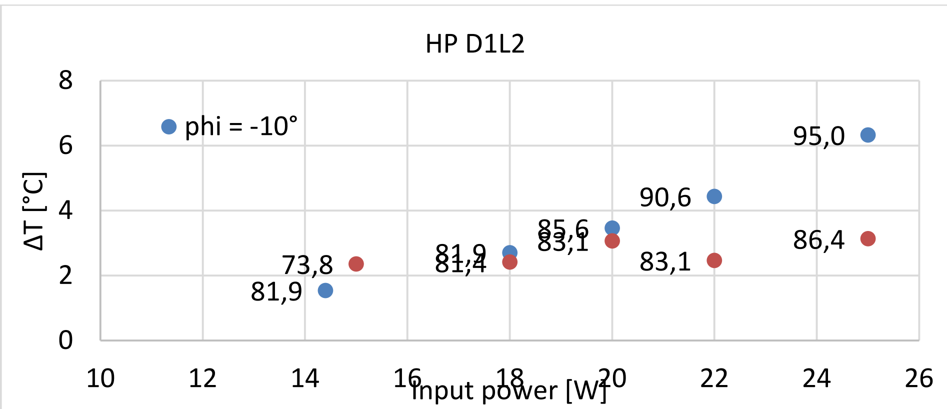


Figure 6. Temperature difference for HP D1L2 at various powers, for quasi-horizontal orientation, φ = 0- ° and φ = -10 ° (Δz = 2.26 cm). Numbers near the points are the average temperature of the HP during the trial.

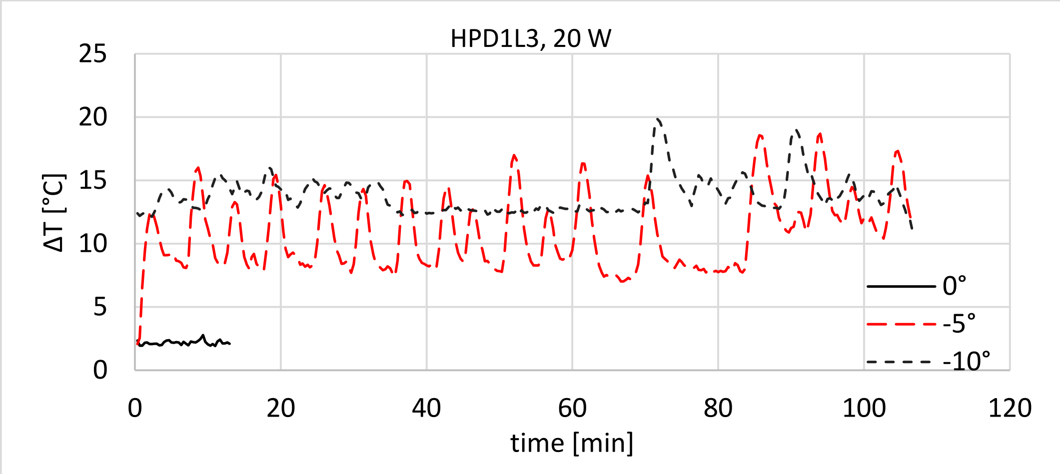


Figure 7. Temperature differential trend for HP D1L3 as function of time for various inclinations against gravity, for 20 W of input power.

5 Conclusions

Test heat pipes have been produced with three lattice structures, made by printing solid struts in a determined geometry. Two of the lattices have shown a good permeability, associated with a capillary rise of 6 cm with acetone, while the denser lattice, L1, shows both low permeability and low capillary rise.

Concerning the HP tests, one lattice structure, L2, has shown to carry a significant amount of power, up to 25 W, both at 0-° and at slight negative orientation. At -25°, or Δz = 5.49 cm, the temperature difference is below 15 °C. At the same time, lattice L3 which has similar properties to L2, shows instabilities in its behaviour against gravity. Therefore, in this context lattice L2 is preferable to L1 and L3.

Further work should be aimed at decreasing the pore size without compromising the permeability, by reducing the strut size.

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