Applied Thermal Engineering 111 (2017) 407–419

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

# Optimizing the design of a two-phase cooling system loop heat pipe: Wick manufacturing with the 3D selective laser melting printing technique and prototype testing

J. Esarte [a], J.M. Blanco [b,*], A. Bernardini [a], J.T. San-José [c]

[a] CEMITEC Aditech, Tajonar 20, 31006 Pamplona, Spain
[b] Dept. Ing. Nuclear y Mecánica de fluidos, Escuela Técnica Superior de Ingeniería de Bilbao, Universidad del País Vasco/E.H.U., Alameda de Urquijo s/n, 48013 Bilbao, Spain
[c] Dept. Ing. Minero metalúrgica y de materiales, Escuela Técnica Superior de Ingeniería de Bilbao, Universidad del País Vasco/E.H.U., Alameda de Urquijo s/n, 48013 Bilbao, Spain

## HIGHLIGHTS

- The optimization of a new LHP prototype for cooling an 80 W power LED was performed.
- Selective Laser Melting technique was used for the fabrication of the primary wick.
- A fully monitored test rig, designed here for this purpose characterized the wick.
- After a fully comparative test, methanol was selected against acetone and water.
- Effects of variations on both fluid charge and ambient temperature were addressed.

## ARTICLE INFO

*Article history:*
Received 10 June 2016
Revised 25 August 2016
Accepted 20 September 2016
Available online 21 September 2016

*Keywords:*
Ambient temperature
Experimental testing
Fluid charge
LED cooling
Loop heat pipe
Manufacturing
Wick optimization

## ABSTRACT

A key aspect for achieving the optimum performance of loop heat pipe devices is to ensure that the wick structure and its appropriate assemblage perform within their original thermal-physical design specifications. When manufacturing primary wicks, powder sintering is the most commonly used technique, due mainly to the economic costs associated with such processes. However it presents a drawback associated with the randomness of the internal wick structure that can result in an irregular liquid-vapor interface, penalizing its permeability and causing unsteady fluid-thermal behavior in the whole device. This work, implements the 3D printing technology known as “Selective Laser Melting” for the fabrication of the primary wick. Its advantage is that it controls the geometric size of the internal wick passages, aiming to achieve an optimal design according to the specified requirements. The key roles played by both fluid charge and ambient temperature are carefully addressed, so while lower mass charge is preferable for small loads, at the same power, the operating temperature is nevertheless higher for lower ambient temperatures. Finally, a case study is conducted with a loop-heat pipe for cooling an 80 W LED street lamp equipped with the wick that is characterized in this study. The case study addresses an exhaustive analysis of the improvements, in terms of selected working fluid and the way of fabrication of the wick through the use of a novel technique, where a restrictive condition in the maximum temperature of the fluid was imposed in comparison with other loop heat pipes of similar characteristics, equipped with non-optimized commercial wicks. It highlights the relevance of this optimization procedure in the performance from the start-up behavior under different working conditions: input power, ambient temperature and mass charge.

## 1. Introduction

Loop heat pipes (LHP) are passive thermal superconductors that deliver heat from the source to the drain in a very efficient way. They are self-activated and differ from conventional heat pipes (HP) in so far as gravitational forces have a much weaker influence on them [1]. The devices have two key parts for proper operation: the “primary wick” with the function of generating the necessary pressure imbalance to drive the fluid circulating through the LHP while generating vapor, and the “secondary wick” aiming to supply liquid from the compensation chamber to the evaporator. This

---

* Corresponding author.
*E-mail address:* jesusmaria.blanco@ehu.es (J.M. Blanco).

http://dx.doi.org/10.1016/j.applthermaleng.2016.09.123
1359-4311/

**Nomenclature**

| | |
|---|---|
| *CAD* | Computer Assisted Design |
| $D$ | tube diameter |
| *DLP* | Digital Light Processing |
| *FFF* | Fused Filament Fabrication |
| $H$ | maximum height of capillary (m) |
| $h$ | film coefficient (kJ/kg K) |
| *HP* | heat pipe |
| $h_{cc}$ | compensation chamber convection coefficient (kJ/kg K) |
| $h_{fv}$ | vaporization latent heat (kJ/kg) |
| $k$ | thermal conductivity (W/m K) |
| $K$ | porous media permeability ($m^2$) |
| $L$ | length (m) |
| *LED* | Light Emitting Diode |
| *LHP* | loop heat pipe |
| $\dot{m}$ | mass flow rate (kg/s) |
| $\overline{M}$ | molecular weight (g) |
| $P$ | pressure (Pa) |
| $\dot{Q}$ | heat load (W) |
| $r$ | pore radius (m) |
| $R$ | tube radius (m) |
| $R$ | thermal resistance (°C/W) |
| $\overline{R}$ | constant for the ideal gases (J/mol K) |
| $S$ | wick cross sectional area ($m^2$) |
| *SL* | stereolithography |
| *SLM* | Selective Laser Melting |
| $T$ | temperature (°C) |
| *TC* | transport capacity (W m) |
| $V$ | speed rate of the liquid front (m/s) |
| $v$ | average velocity (m/s) |
| $z$ | main direction of the fluid flow |

*Greek symbols*

| | |
|---|---|
| $\Delta$ | incremental |
| $\alpha$ | average convection heat transfer coefficient ($W/m^2$ K) |
| $\theta$ | angle of contact solid-liquid (wettability) |
| $\varepsilon$ | wick porosity (0/1) |
| $\lambda$ | thermal conductivity coefficient (W/m K) |
| $\rho$ | density ($kg/m^3$) |
| $\mu$ | dynamic viscosity ($kg\ s/m^2$) |
| $\upsilon$ | kinematic viscosity ($m^2/s$) |
| $\sigma$ | surface tension coefficient (N/m) |
| $\hat{\sigma}$ | accommodation factor |

*Subscripts*

| | |
|---|---|
| *a* | related to air |
| *amb* | related to ambient |
| *C* | related to capillary |
| *c* | related to condenser |
| *cc* | related to compensation chamber |
| *ccsat* | related to compensation chamber saturation |
| *e* | related to evaporator |
| *eff* | related to effective |
| *eq* | related to equilibrium |
| *f* | related to fluid |
| *l* | related to liquid |
| *L* | related to wick thickness |
| *max* | related to maximum |
| *S* | related to surface |
| *sat* | related to saturation |
| *sub* | related to sub-cooled |
| *v* | related to vapor |
| *vap* | related to vaporization |
| *w* | related to wick |
| *wa* | related to water |

secondary process is just in case the returned liquid is insufficient as a result of a change in the operating conditions, such as the start-up, sudden change in the thermal load to be dissipated, variations in the condensation conditions, etc [2].

Both the volume and the refrigerant charge must be such that there is always liquid in the compensation chamber to guarantee its self-fattened feature, even if the other compartments are also full. The development of numerical models for such devices can guarantee a correct design and full prediction of their behavior when working in the steady state [3]. These models implement standard values for the characteristic parameters of the wick (permeability, thermal conductivity, interface heat transfer, capillary pressure, etc.) [4] which are determined by the internal structure, due to its own manufacturing process, and the properties of the material itself [5,6].

The most widespread technology for the manufacturing of these wicks is the “sintered powder” technique; however, it presents the drawback of generating a random internal structure which promotes heterogeneity in the fluid-thermal behavior of the wick [7]. The use of a 3D laser print SLM (Selective Laser Melting) can solve this problem, because it allows full control over the internal structure of the wick. Nevertheless, it presents the disadvantages of higher cost, pore size limitations and suitable materials, although for the latter there are other 3D printing techniques, such as: “Stereolithography”, “Digital Light Processing” and “Fused Filament Fabrication”. Still widely applied in many types of rapid prototyping techniques, stereolithography (SL) was the first and the most accurate 3D process, as it can offer the finest surface finishes. The process involves turning a three-dimensional Computer Assisted Design (CAD) drawing into a solid object through the rapid and repeated solidification of liquid resin. Digital Light Processing (DLP) is used in additive manufacturing as a power source in some printers to cure resins into solid 3D objects. The exposed liquid polymer hardens and the build plate moves down so the liquid polymer is once again exposed to the light. The process is repeated until the 3D model is complete and the vat is fully drained, revealing the solidified model. Finally, the Fused Filament Fabrication (FFF) technique is an additive manufacturing technology. A specific tool deposits a filament of a material (such as plastic, wax or metal) on top or alongside the same material, sealing a joint (by heat or adhesion). The key advantages of the SLM technique are that the developer enjoys an immense degree of geometrical freedom, without the limitations and constraints of other manufacturing methods. It is also possible to individualize the products and to enlarge the number of variations in arbitrary ways [8]. The SLM process is a competitive alternative today, especially in areas where small batches of tiny components are required. These reasons led to the choice of the SLM technique for the design of the primary wick, as will be explained in depth later on.

## 2. Aims and methodology

The aim of this research is to build an LHP for cooling an 80 W LED street lamp and to optimize its functionality through the analysis of its thermal behavior. First of all, the wick design was manufactured by means of an innovative SLM technology. Then, a full