Applied Thermal Engineering 144 (2018) 495–503

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental studies on a miniature loop heat pipe with flat evaporator with various working fluids

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HIGHLIGHTS

- This paper presents experimental results on a mini-LHP with various working fluids.
- N-pentane has the lowest temperatures; methanol has the highest heat transport range.
- It is found that operating temperature follows a vapour figure of merit.
- Visualization reveals that there is no bubble formation prior to deprime.
- Deprime is accompanied with intense nucleation inside the CC.

ARTICLE INFO

Keywords:
Loop heat pipe
Flat evaporator
Visualization
Deprime
Nucleation
Heat leak

ABSTRACT

The goal of this paper is to experimentally study the thermal behavior of a miniature loop heat pipe (LHP) with flat evaporator and correlate the findings with visualization studies of the working fluid within the compensation chamber (CC). A miniature LHP with flat evaporator was fabricated and tested with four working fluids – acetone, methanol, n-pentane and ethanol for various heat inputs till deprime at two different sink temperatures. The CC of the LHP is provided with a glass view port for visualization of the working fluid using a high speed camera. The results show that among the fluids tested, n-pentane has the lowest operating temperature, whereas methanol has the broadest heat load range. Visualization studies with all the four fluids at both sink temperatures reveal that there is no bubble generation in the CC for any heat input level prior to deprime. It was also observed that during deprime, there is explosive nucleation in the CC due to intense heat leak into it, accompanied by a rapid rise in the operating temperature due to cessation of fluid flow in the loop.

1. Introduction

Loop heat pipes (LHPs) are two-phase heat transport devices that utilize evaporation and condensation of a working fluid, wherein the fluid circulation is maintained by capillary action developed in the wick structure. The working principle of an LHP is similar to that of a heat pipe; however, LHPs offer certain additional advantages [1]. As the wick structure in an LHP is restricted within its evaporator, a wick with very fine pores can be used in the evaporator, resulting in high capillary pressure. As the liquid and vapour lines use smooth walled tubes, the pressure drop is lower than in conventional heat pipes having a distributed wick structure. Hence, LHPs can transport larger heat loads and are less sensitive to orientation during their operation on ground. The major features that distinguish miniature LHPs from conventional LHPs are the heat transport level (up to 240 W) and the evaporator length/diameter (up to 80 mm/ϕ50 mm) [2–12].

Though the evaporator of an LHP may be cylindrical or flat (*i.e.* disc, square or rectangular shape), an LHP with flat evaporator is easier to mount on the surface of a hot source without a saddle. Thus, flat LHPs are often preferred for thermal management of electronic packages for space as well as ground applications [2–15]. Though working fluids such as ethanol, acetone, methanol, water and ammonia are commonly used in LHPs [8,16–19], water is not preferred in spacecraft as the non-operating temperature of spacecraft electronics can go down to −40 °C. High pressure fluids such as ammonia require thick-walled container to withstand the high operating pressure and are more hazardous to humans in human space programs. For thermal management of small electronics with heat dissipation up to ~100 W, there is scope for alternate working fluids (such as acetone, methanol, n-pentane and ethanol) that are less hazardous. Thus, issues related to design,

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https://doi.org/10.1016/j.applthermaleng.2018.08.092
Received 22 May 2018; Received in revised form 23 August 2018; Accepted 24 August 2018
Available online 25 August 2018

miniaturization of the heat transport devices and use of working fluids that are less hazardous are still open for research. Furthermore, studies in open literature that focus on visualization in a closed system of LHP or an open system of capillary structure for better understanding of the phenomenon occurring inside the LHP or the capillary structure are also very limited. "Open system" refers to an evaporator wherein fluid is *not* condensed and returned to the evaporator. "Closed system" refers to a full LHP containing evaporator, transport lines and a condenser. Visualization studies in open system of capillary structure reveal that bubbles form within the capillary structure at low heat loads; a two-phase zone appears at moderate heat loads and a stable vapour film occurs at higher heat loads [20–22]. A few visualization studies in LHP systems show that in addition to bubble formation within the capillary structure, the bubble cycle (*i.e.* bubble formation on the top of wick – bubble departure – bubble condensation in the CC) also occurs in the CC at both low and high heat loads [23–25].

The present paper focuses on experimental investigation of an LHP with flat evaporator using various working fluids – acetone, methanol, n-pentane and ethanol for heat inputs starting from 25 W till deprime (*i.e.* capillary limit in an LHP [26]). These fluids have different LHP figures of merit, which are considered to be a measure of performance of a fluid in an LHP [28,29]. Visualization studies in the LHP are aimed at understanding the phenomena occurring inside the CC for various heat inputs till deprime. The organization of the paper is as follows: Section 2 presents the description of the miniature LHP test rig used for the present study, instrumentation scheme, visualization arrangement and the details of the experiments. Section 3 presents the experimental results and discussion, followed by conclusions in Section 4.

2. Experimental studies

This section presents the details on the miniature LHP, instrumentation scheme, visualization arrangement and various test cases.

2.1. Description of the miniature LHP test rig

A three-dimensional view of the miniature LHP is shown in Fig. 1. The exploded view of the evaporator-CC assembly of the miniature LHP is shown in Fig. 2. The CC is made of stainless steel (SS316) and has a volume of 25 cm^3. The evaporator plate is made of aluminium alloy (Al-6061T6) with grooves (size: 0.4 mm × 0.9 mm, depth: 4.1 mm) for vapour removal. The average dimensions of a tooth are 0.85 mm (length), 0.91 mm (width), 4.1 mm (depth), and the gap between adjacent teeth is 0.41 mm. The LHP evaporator consists of a porous nickel wick of 45 mm diameter and 6 mm thickness. The porosity of the wick is 61.6 ± 1.2%, the permeability is $7.12 \times 10^{-13} \pm 0.18 \times 10^{-13}\,m^2$ and the maximum pore size is 5.03 ± 0.24 μm [29]. The area of contact of the grooved plate is 46.6% of the cross sectional area of the nickel porous wick. The top of the CC has a view port made of

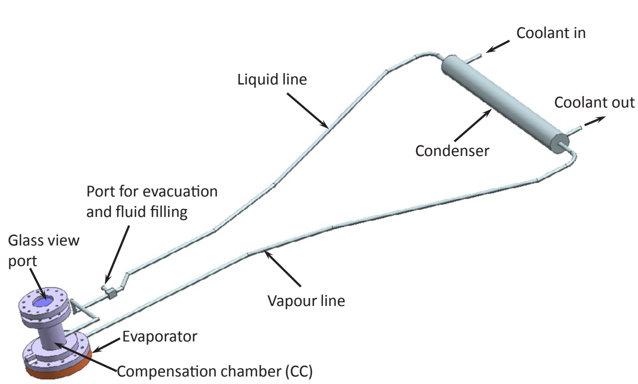

Fig. 1. Three-dimensional view of the miniature LHP assembly.

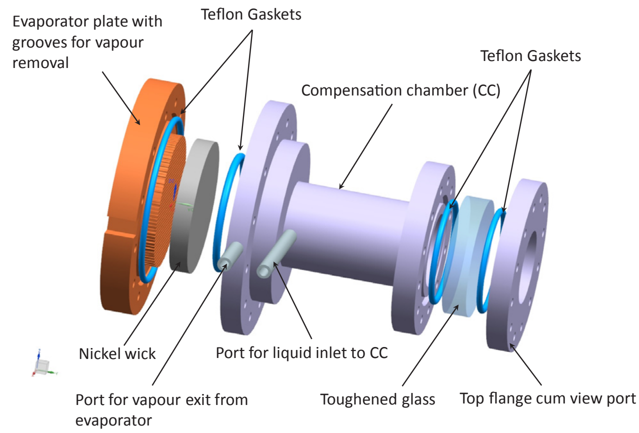

Fig. 2. Exploded view of the evaporator-CC assembly.

toughened glass to facilitate visualization inside the CC. The top surface of the glass is coated with an anti-reflective coating (Al_2O_3) to minimize the reflection of light rays from the illumination source during imaging. The liquid line, condenser and the vapour line are made of stainless steel SS316 tubes (*Swagelok*) and are of size (outer diameter × inner diameter × length): ϕ4.76 mm × ϕ2.98 mm × 695 mm, ϕ4.76 mm × ϕ2.98 mm × 260 mm and ϕ4.76 mm × ϕ2.98 mm × 260 mm, respectively. The condenser is connected to a *tube-in-shell* heat exchanger made of SS-316 tube and is of size – ϕ25 mm × ϕ21 mm × 260 mm.

2.2. Instrumentation scheme

A photograph of the LHP assembly is shown in Fig. 3. The fluid pressure inside the CC of the LHP is measured using an absolute pressure transducer (APT) with a measurement range of 0–5 bar (*GE-PMP 4070*). A constant input voltage of 20 V is supplied to the APT through a power supply (*Lambda ZUP60-7*). The output from the APT is a voltage that is proportional to the pressure. The saturation temperature corresponding to the absolute pressure measured by the APT is defined as the operating temperature of the LHP. The saturation temperature corresponding to the pressure can be calculated using the Antoine equation which is the state equation derived from the Clausius-Clapeyron relation [30].

The evaporator of the LHP is attached to a heater block made of Oxygen Free High Conductivity (OFHC) copper [Fig. 4,(a)] with six cartridge heaters (*Heater House, Bangalore*) connected in parallel with a total resistance of 26 Ω. The size of each heater is ϕ8 mm × 50 mm (diameter × length) and its nominal resistance is 147 Ω. Contact resistance between the surface of the heaters and the surface of holes inside the copper block is reduced with the help of a thin layer of thermally conductive silicone grease (*Stycast TC-8M*). The heater block is bolted to the evaporator of the LHP with a sheet of graphite foil of 0.2 mm thickness (*Sigraflex*) as the thermal interface material to minimize the contact resistance between the LHP evaporator plate and the heater block. A close-up view of the arrangement of the heater block with the LHP evaporator is shown in Fig. 4(b). The heater leads are connected to a power supply (*Lambda ZUP60-14*) *via* a digital multimeter (*Fluke 189*) for measuring the current.

T-Type thermocouples of 26 AWG (*TC Limited, UK*) are used for monitoring temperatures at various locations (CC, liquid line, condenser, vapour line, coolant line and CC insulation). Screening of all the thermocouples was done to ensure that the temperature readings are within ± 0.1 °C scatter at three temperatures, namely, −20 °C (in a bath of methanol in a cold fluid circulator [*Huber UC007*]), 0 °C (ice – water mixture) and 97 °C (boiling point of water at Bangalore which is at an altitude of around 0.9 km from the mean sea level). Although several thermocouples are used for temperature measurement, the test results in this paper are presented with reference to the temperature