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Miniature ammonia loop heat pipe for terrestrial applications: Experiments and modeling

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ABSTRACT

Thermal management is always an exigent topic in various applications like electronic equipment cooling, aerospace, and avionics, defence electronics, etc. Loop Heat Pipes (LHPs) are highly efficient, robust, two-phase, passive heat-transfer devices, increasingly becoming popular for thermal management of terrestrial and avionics applications. Miniaturization of the device and its ability to perform well in different orientations with respect to the gravitational vector are essential for its employment in terrestrial applications. In the present study, complete thermal characterization of the developed ammonia miniature loop heat pipe (mLHP) in different orientations, keeping into view possible terrestrial applications, has been carried out utilizing infrared thermography coupled with conventional thermometry. The maximum capacity obtained is about 225 W (for maximum evaporator temperature of 70 °C) and the thermal resistance was better than 0.5 K/W in all experimental trials irrespective of the orientations. The effect of orientation on the operation of mLHP is insignificant because of its small dimensions and the device can be safely considered to be orientation-free. From the results of the study, mLHP can regard as a quite promising thermal management technology for terrestrial applications. A mathematical model is developed to predict the steady-state evaporator temperature of the mLHP for a given heat load, sink temperature and surrounding temperature. The model has been validated with the experimental results and a good match is obtained.

1. Introduction

Thermal management of electronic components is one of the key problems that several industries demand to be resolved effectively and reliably. Two-phase heat transfer devices have the capacity to deal with this problem. Among them, Loop Heat Pipe (LHP), which was invented in the early 1980s in Russia is a promising solution for contemporary and future thermal management problems. LHP is a passive, flexible two-phase heat transfer device, which can transfer heat to large distances, with a minimal temperature difference [1,2]. It utilizes the latent heat of evaporation and condensation to transfer heat and the capillary force generated in the porous structure to circulate the working fluid. The device consists of an evaporator, a vapor line, condenser, liquid line and compensation chamber, as shown in Fig. 1. The evaporator contains a porous cartridge structure and the compensation chamber (CC) accommodates the extra working fluid during the operation.

Most of the research available in the literature is focussed to understand the behaviour and operation of LHPs in anti-gravity and acceleration fields in spacecrafts and aircrafts, via experimental and modeling approaches [1]. Usually, these devices have a cylindrical evaporator of 12 mm–28 mm in diameter. The length of the vapor and the liquid lines can reach 10 m or more, and their diameter is in the range of 3 mm–8 mm. The absence of a wick in these fluid transport lines makes them flexible, giving them any required shape [2].

In order to expand the field of LHP's application under terrestrial conditions, for instance, cooling of electronics and personal computers, it is necessary to miniaturize these devices. Hence, researchers have explored the use of 'miniature' loop heat pipe (mLHP) for the terrestrial applications. Several researchers have considered an LHP as an mLHP (miniature LHP) when the diameter of the evaporator cartridge is less than 6 mm and transport line diameter is 1–2 mm [1–6]. Maydanik and his team suggest that an LHP can be considered as 'miniature' if the diameter of the evaporator does not exceed ~8 mm and diameter of the transport lines are below about 3 mm [7]. Some researchers also tested mLHP having evaporator diameter up to 12 mm and diameter of liquid

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Nomenclature

A	area of cross-section (m^2)
c_p	specific heat at constant pressure (J/kgK)
C_f	Fanning friction factor (−)
d	diameter (m)
f	Darcy friction factor (−)
g	acceleration due to gravity (m/s^2)
Gr	Grashof number (−)
h	heat transfer coefficient (W/m^2K)
H	specific enthalpy of fluid (J/kg)
h_{lv}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/mK)
K	permeability (m^2)
l	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number ()
P	perimeter (m)
Pr	Prandtl number ()
$\dot{Q}$	heat energy (W)
r	radius (m)
R	thermal resistance (K/W)
Ra	Rayleigh number (−)
Re	Reynolds number (−)
t	thickness (m)
T	temperature (K/°C)
v	velocity (m/s)
x	vapor quality (−)

Subscripts

1ϕ	single-phase
2ϕ	two-phase
a	ambient
air	atmospheric air
ap	applied
avg	average
cb	copper block
cc	compensation chamber
cl	condenser line
cp	condenser plate
cw	sink coolant water
e	evaporator
eff	effective
h	hydraulic
i	inner
in	inlet
l	liquid
ll	liquid line
o	outer
out	outlet
s	sink
sat	saturation state
sc	sub-cooling
t	total
v	vapor
vg	vapor groove
vl	vapor line
w	wick
wf	working fluid

Special characters

β	coefficient of thermal expansion (1/K)
ε	surface roughness (m)
θ	angle of inclination (°)
μ	viscosity (Pa-s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

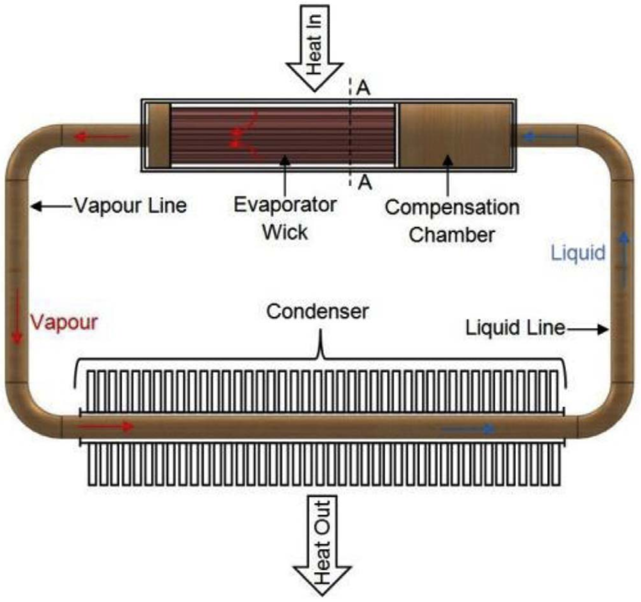

Fig. 1. Schematic of miniature loop heat pipe.

and vapor line up to 3.5 mm [8–11]. There is also literature available which suggests that an LHP can be considered as 'mLHP' if the evaporator diameter is up to 12 mm and diameter of vapor and liquid lines are less than ~3.5 mm.[1]

Chen et al. [4] tested the steady-state and transient performance of mLHP with the cylindrical evaporator of 5 mm diameter at different orientations and sink temperatures. Heat load reached up to 70 W with the minimum thermal resistance of 0.2 K/W. Local temperature oscillations were observed, especially for moderate heat loads ranging from 30 W to 70 W, at different locations on the mLHP, for different operating orientations ('horizontal', 'evaporator above condenser', and 'CC above evaporator'). It was found that with an increase in heat load, the amplitude of these temperature oscillations decreased, however, with an increase in its oscillating frequency. The lower heat load range at which commencement of oscillations occurred (typically between 30 W and 40 W, depending on the orientation), the amplitude of temperature oscillation could go up to 10 K in liquid line and up to 1 K in the evaporator. The oscillations decreased or stopped with an increase in the sink temperature.

Doctarau et al. [5] used an evaporator with inverted meniscus as well as the non-inverted meniscus in mLHP. For these evaporators, nonconducting and conducting porous structures were used, respectively. Results showed that mLHP with non-inverted meniscus provided better thermal performance.

Maydanik et al. [6] tested a series of ammonia LHP with cylindrical evaporators of 5 mm and 6 mm diameters, respectively. Successive efforts were made to increase the mLHP efficiency; the heat transfer

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[1] In present study, the LHP which is developed and performance tested has a cylindrical evaporator with an outside diameter of 8.0 mm while the fluid transport line is having an outside diameter of 2.0 mm. Hence, we categorize the LHP as a miniature device, mLHP.