International Journal of Heat and Mass Transfer 92 (2016) 929–939

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Performance of annular flow path heat pipe with a polymer insert controlling compactness for energy applications

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A R T I C L E I N F O

Article history:
Received 19 July 2015
Received in revised form 13 September 2015
Accepted 15 September 2015
Available online 6 October 2015

Keywords:
Heat pipe
Capillary limit
Annular vapor space
Compactness

A B S T R A C T

This study experimentally investigates the effect of the cross-sectional area of vapor path on the heat transfer performance of a water-filled heat pipe with a polymer insert for optimizing its design. The thermal resistance and the heat transfer coefficient of the heat pipe with a screen mesh wick were measured at a saturation pressure ranging from 6.0 kPa to 12.5 kPa. It is observed that the changes of the capillary limit and the overall heat transfer coefficient come from the reduction of the vapor space. When the cross-sectional area of the vapor path is reduced to 48.3%, the capillary limit of the heat pipe is decreased by 22.9%. But the overall heat transfer coefficient of the heat pipe is slightly decreased by 3–7%. When the cross-sectional area of the vapor path is reduced to 76.8%, the capillary limit and the heat transfer coefficient of the heat pipe are decreased by 40.7% and 21.0%, respectively. Therefore, the reduction of the overall heat transfer coefficient of the heat pipe has no great effects according to the cross-sectional area of the vapor path. The experimental results suggest the direction of the optimization of the heat pipe in terms of space management for compact devices. Or, if there is enough margin in capillary limit, the optimized compact vapor path without losing heat transfer performance too much can be acquired or excess space can be used for special applications such as neutron absorber in nuclear control rods and structural supports in the electronic cooling for compactness.

1. Introduction

After the invention of the heat pipe by Grover et al. [1] 50 years ago, much study has been done and many applications have been created in various fields including electric cooling devices, decay heat removal systems for nuclear power plants [2–4], and energy conversion systems. A central processing unit (CPU) has a high heat flux of 67 kW/m^2 [5]. It is difficult to use a heat sink that is attached to the CPU surface. A heat pipe can be used to transfer the energy away from the CPU surface to a heat sink, and it is possible to supply efficient cooling. Increases in heat flux and the power of electronic devices in a recent trend require highly integrated cooling device. To improve the capability for fully cooling the system heat, research on conventional heat pipes is focusing on advancing the working fluids, wick structure, and geometry of the heat pipes.

Because of increasing demand for better cooling performance, the need for more effective cooling systems has led to various studies of heat pipes using nanoparticles and with modifications in the wick structures. Recent studies of heat pipes showed that the theoretical and experimental heat transport capacity of a concentric heat pipe and its capillary limits are strongly related to the properties and geometries of the wick structures and on the surface coating phenomenon of the evaporator wick. Kole and Dey [6] studied the synthesis, thermal conductivity, and thermal performance of screen-mesh-wick heat pipes using water-based copper nanofluids which was wick coating phenomenon using nanoparticle. It was found that the thermal performance of the nanofluid-based heat pipe was predominately affected by a layer of Cu nanoparticles at the evaporator section. Schampheleire et al. [7] investigated the gravity-assisted-orientation heat pipe using three different wicks: a screen-mesh wick, a sintered-powder wick, and outperforms the fiber wick. The metal-fiber wick showed the greatest potential as a wick material for high-performance heat pipes. Table 1 summarizes some experimental investigations of heat pipes of various geometries.

A heat pipe is a high-heat-capacity, fully passive heat-transfer device that uses the evaporation, condensation, capillary wick structure, and working fluid in the pipe. In general, the vapor flow from the evaporation section to the condensation section is caused by a difference in vapor pressure. At the same time, the liquid flow from the condensation section to the evaporation section is produced by net forces such as capillary force and gravitational force.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.09.037
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Nomenclature

A	area [m^2]
g	acceleration of gravity [m/s^2]
h	heat transfer coefficient [W/m^2 K]
l	length [m]
L	latent heat [J/kg]
$\dot{m}$	mass flow rate [kg/s]
ΔP	pressure difference [Pa]
Q	heat input, power [W]
$\dot{Q}$	heat flow rate [J/s]
q''	heat flux [kW/m^2]
r	radius [m]
R	thermal resistance [°C/W]
T	temperature [°C]
$\bar{T}$	average temperature [°C]
ρ	density [kg/m^3]
ε	fractional void of the wick [–]
μ	dynamic viscosity [Pa·s]

Subscripts

a	adiabatic
c	condenser
c, max	maximum capillary
e	evaporator
eff	effective
g	gravity
l	liquid
o	overall
$pore$	effective pore
v	vapor
v, e	vapor of evaporator
v, a	vapor of adiabatic section
v, c	vapor of condenser
w	wick

Working fluids and wick structure modification are favorite topics for enhancing the capabilities of heat pipes, but the vapor path in concentric heat pipes is not considered owing to their low contribution. For these reasons, research on the effects of the cross-sectional area of the vapor path of heat pipe is neglected.

Current researches for annular heat pipes are focused on the enhancement of the heat transfer coefficient using the additional heat transfer surface inside of heat pipe. The annular heat pipe is manufactured using two pipes having different diameters, which can be possible to heating and cooling on the inner surface. It is one of the special methods for enhancing the heat transfer. Faghri and Thomas [8] described the concentric annular heat pipe's design, testing, and theoretical prediction of the capillary limit. The main objective was to compare the performance of the concentric annular heat pipe with that of a conventional heat pipe. The difference between the annular vapor space as well as the heat transfer area resulting from the additional surface area is seen in the two designs. The capillary limit of the annular heat pipe dramatically increased, resulting in a performance advantage. Faghri [9] indicated that the results are due to the difference in the cross-sectional shapes, with one circular and the other annular. Annular heat pipes exhibit a decreasing heat-transfer performance because of the vapor path. Kim et al. [10] used the annular heat pipe having cylindrical roll wire mesh wick for fixed wick structure at the inside surface. The thermal resistance of annular heat pipe has lower than copper black conduction. Boo and Park [11] suggested similar geometry and experimental investigation of the annular heat pipe with various fill charge ratios was conducted. Optimized designs of annular heat pipes were suggested according to the change of the fill charge ratios. During the star-up transient, fast response was observed between heat source and annular heat pipes comparison with a copper black cooling device. For that reason, the applications for fast response heating devices were suggested.

A concentric heat pipe having a medium-scale diameter (D = 10–20 mm) has a generally large vapor space compared with its wick space, so the vapor flow of the working fluid has a large enough cross-sectional area to satisfy the limits of the heat pipe. Reay and Kew [16] define the capillary limit by using the pressure difference in the heat pipe. When incompressible flow and homogeneous wicks can be assumed in a concentric heat pipe, the vapor pressure is neglected.

Recent applications of the heat pipe have focused on electrical devices because heat pipes exhibit excellent performance in cooling a device per unit volume. Concentric heat pipes have excess vapor space; therefore, it is possible to decrease the volume of the heat pipe without causing degradation. The researches did not consider the vapor flow path effect because of great margin until the flow degradation [12–15]. Recent enhancement studies for conventional heat pipe are focused on the wick structures

Table 1
Review of some heat pipe experimental studies.

Researchers	Working fluids	Temperature range (°C)	Wick	Geometry	Types
Faghri [8]	Water	−100	Copper groove wick	300:473:200 Diameter: 30 (mm)	Annular heat pipe
Kim et al. [10]	Water	40–160	Mesh wick (80)	60:80:60 Diameter: 25.4 (mm)	Annular heat pipe
Boo et al. [11]	Water	40–180	Mesh wick (80)	N/A Diameter: 25.4 (mm)	Annular heat pipe
Hung and Q'bert Seng [12]	Water	20–100	Groove wick	127:246:127 Diameter: N/A	Conventional heat pipe
Asirvatham et al. [13]	Silver nanoparticles dispersed in DI water	25–160	Copper mesh wick (100)	50:50:80 Diameter: 10 (mm)	Conventional heat pipe
Yang et al. [14]	Water	–	Groove wick	N/A	Conventional heat pipe
Zhang et al. [15]	δ-Al_2O_3-R141b nanofluids	24–40	Groove wick	140:60:140 (array) 30 * 2 (mm)	Flat heat pipe