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Investigating the effect of double-layer wick thickness ratio on heat transfer performance of loop heat pipe

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ABSTRACT

This study investigated the effect of double-layer wick thickness ratio on the heat transfer performance of loop heat pipe (LHP). With the outer layer of the wick being biporous to allow vapor to travel and the inner layer being monoporous to provide capillary force, the wick used in this study eliminated the problems with wick's structural strength and difficulty in vapor release encountered when using a monoporous wick. By changing the double-layer wick thickness ratio, the LHP heat transfer performance was enhanced.

Under a fixed total wick thickness, the double-layer wick thickness ratio was varied by adjusting the biporous and monoporous layers' thicknesses; higher thickness ratio corresponds to the wick having more biporous wick characteristics, and lower thickness ratio corresponds to the wick being more like a monoporous wick. In this study, the ratios investigated were 0.28, 0.42, 0.57, 0.71, 0.86, and 1. Results showed that at 0.57, the highest heat load under 85 °C was 1060 W, the total thermal resistance was 0.065 °C/W, the heat flux was 50 W/cm^2, the heat transfer coefficient was 188 kW/m^2 °C, and the porosity was 82%. Compared with the double-layer wick performance reported thus far, performance was increased by about 50%, and compared with that of the monoporous wick, the performance increase was about 200%. The best thickness ratio was successfully determined, and the critical heat load reached, for the first time, the order of kW. A trend line and empirical equation for LHP performance results for monoporous (thickness ratio 0) [1], double-layer (thickness ratio 0.28 ~ 0.86), and biporous (thickness ratio 1) wicks were fitted and established, providing a reference for future designs.

1. Introduction

LHP was invented by Maydanik et al. [2] and patented in the United States. As shown in Fig. 1, the LHP consists of an evaporator, a condenser, a compensation chamber, and liquid and vapor lines. When heat flux is added into the evaporator, the heat travels into the wick, and the vaporized working fluid travels through the channels formed by grooves on the wick's surface. The pressure provided by the vapor and the capillary structure together pump the working fluid to allow the whole LHP system to operate. The condenser then condenses the vapor into liquid form, and the working fluid travels to the compensation chamber, completing a cycle. Only the evaporator contains a wick; smooth pipes form the rest of the parts. According to current LHP studies, the evaporator's wick has been found to be the most critical factor in LHP's heat transfer performance. From thermal resistance analysis [3], the wick's design significantly impacts the LHP performance.

Traditional LHPs use monoporous wicks. In 1999, Liao and Zhao [4], through LHP flow visualization, observed that during the evaporation process in a monoporous wick, at low heat flux, vaporization occurs within the wick; with increasing heat flux, vapors pile up in the wick until boiling occurs eventually, inducing the formation of a vapor blanket that causes the thermal resistance to increase and dryout to occur. In order to eliminate this problem, vapor must easily escape from the wick, and biporous wick is one of the ways to solve this problem. North and Maydanik [5] first suggested the application of biporous wick to LHP. Chen et al. [6] found that biporous wick enhanced the heat transfer performance of heat pipes; they also suggested a pore size for the large pores. Since biporous wick has structural strength problems at high heat load, yet several reports have indicated that biporous wick has better performance than monoporous wick, Wu [7] suggested using double-layer wick in LHP to solve this problem.

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Nomenclature

A	heating area (mm^2)
h_e	evaporator heat transfer coefficient ($W/m^2\ ^\circ C$)
Q	heat load (W)
R_{LHP}	LHP total thermal resistance (°C/W)
T_b	temperature (°C)
T_v	vapor temperature (°C)
$T_{c,in}$	condenser inlet temperature (°C)
T_e	evaporator wall temperature (°C)
D_m	monoporous layer thickness (mm)
D_r	double-layer wick thickness ratio
D_t	total wick thickness (mm)
W_t	mass of wick saturated with working fluid (g)
W_W	mass of dry wick (g)
ε	wick porosity (%)

In the past, many studies concerning wick manufacturing have proposed many design ideas, including wicks with a primary wick and secondary wick [8,9]. However, detailed internal pore parameters and designs were not provided. Recently, more studies have been done on wick manufacturing and design; some tried ceramic materials [9] or other nonmetals as wick materials [10,11], some experimented with wicks with different pore sizes [11,12], some focused on enhancing anti-gravity properties of the wicks [13,14], and some tried multi-layer wicks [15]. In all, we found that both monoporous and biporous wick designs have already been proposed, but all of these reports lack key detailed internal design parameters necessary for successful manufacturing; especially concerning multi-layer wick designs, all reports indicate that they are currently still in the design processes only, and detailed design information have yet to be provided.

Wu combined monoporous and biporous capillary structures into a double layer wick design [7]. The outer layer would be biporous to allow vapor to escape easily, and the inner layer would be monoporous to provide structural strength and capillary force. Wu also pointed out that this type of wick surpasses the performance of biporous wick and that adjusting the inner-outer layer thickness ratio has high potential for further enhancement of LHP performance.

Therefore, in this study, at fixed total wick thickness, wicks of different thickness ratios (0.28, 0.42, 0.57, 0.71, 0.86, 1) were manufactured and tested in the LHP system for performance results. The results were then combined with results of monoporous wick LHP (thickness ratio 0) [1] for a total comparison.

1.1. Double-layer wick design

As shown in Fig. 2, in order to investigate the variations in thickness ratio (D_r), in this study we fixed the total thickness (D_t) and controlled the biporous layer thickness (D_b). Using Eq. (1), the inner monoporous layer thickness could be calculated, and the wick was then placed into the LHP for performance testing:

$$D_r = D_b/D_t,\ \ D_t = D_b + D_m \tag{1}$$

where D_r is the total wick thickness ratio, D_m is the monoporous layer thickness, D_b is the biporous layer thickness, and D_t is the total thickness of the wick.

D_t was fixed at 3.5 mm, and the baseline D_b was 1 mm ($D_r = 0.28$). At $D_b = 0.5$ mm ($D_r = 0.14$), the wick didn't have enough structural strength to form, thus $D_r = 0.28$ was used as starting point, followed by 0.42, 0.57, 0.71, 0.86, and 1. As D_r approached 1, the wick became more like a biporous wick; the results from LHP performance testing using these 6 different wicks, plus the results from using a monoporous wick [1] ($D_r = 0$), was then discussed together.

1.2. Double-layer wick manufacturing process

This study followed the method used in Wu [7] and used PMMA particles for mixing to form large pores. After mixing the polymer particles with nickel powder, the mixture was sintered to form the capillary structure. Following Tracey [16], the nickel powder manufactured by Inco was used, with type-255 as the main component; the diameter was around 3 μm, and the shape was spherical. The polymer used was PMMA, with density of 1.19 g/cm^3 and melting point of 140 °C; once the sintering temperature reached above PMMA's melting point, the particles began to decompose and evaporate, leaving behind large pores in the wick.

To manufacture a double-layer wick, two sintering processes were needed. The outer layer was made first, then the inner monoporous layer; the manufacturing parameters for the outer layer followed the process suggested in literature [17], using PMMA particles ranging from 250 ~ 297 μm in size and 35 vol% in content. The inner layer consisted of only nickel powder.

The outer layer manufacturing process is shown in Fig. 3; after mixing size 3 μm nickel powder with size 250–297 μm PMMA powder at 35 vol% and choosing to have 12 grooves [18] on the surface, the mixture was poured into a stainless steel mold with 12 grooves. After sealing the mold, it was placed into the sintering oven, setting the sinter parameters to rising temperature rate of 10 °C/min until constant temperature at 700 °C and adding hydrogen gas as the sintering atmospheric gas [19]; after cooling naturally, the wick and the mold were taken out of the oven, completing the manufacturing of the outer layer. Since PMMA vapor is slightly toxic, a cooling trap was placed in the oven to cool the PMMA vapor, preventing remains of PMMA vapor from escaping into the atmosphere.

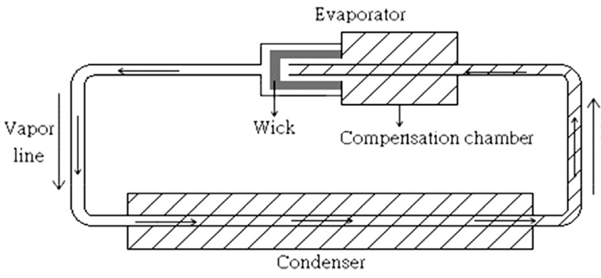

Fig. 1. Schematic of LHP.

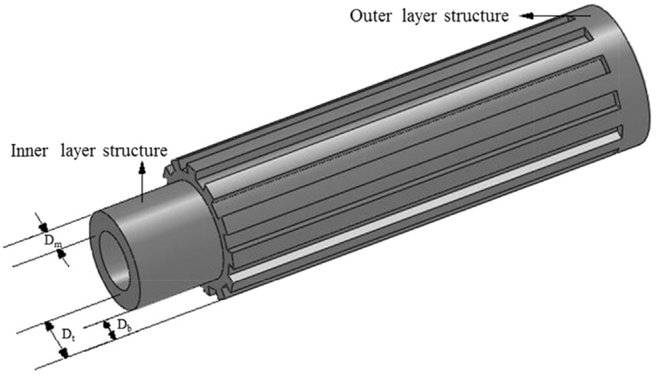

Fig. 2. Schematic of double-layer wick.