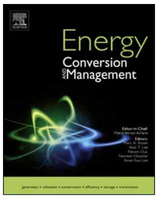
Energy Conversion and Management 156 (2018) 358–364

Contents lists available at ScienceDirect

Energy Conversion and Management

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



Fabrication and experimental evaluation of a polymer-based flexible pulsating heat pipe

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ARTICLE INFO

Keywords:
Pulsating heat pipe
Polymer
Flexible heat spreader
Long-term reliability

ABSTRACT

A polymer-based flexible pulsating heat pipe (FPHP) as a flexible heat spreader was developed, and a series of experiments were conducted to evaluate the thermal performance and the long-term reliability of the FPHP. The FPHP consisted of a multilayer laminated film and a low-density polyethylene (LDPE) sheet. HFE-7000 was used as the working fluid, and the width, length, and thickness of the FPHP were 53.4 mm, 85.5 mm, and 1 mm, respectively. To minimize the permeation of non-condensable gases (NCGs) in a lateral direction, the heat-sealed flanges were covered with the indium coating. Owing to the indium-coated flanges, the long-term reliability of the FPHP drastically increased. The lifetime of the FPHP was defined to evaluate the long-term reliability. The FPHP had a lifetime of 18.2 days in the acceleration test environment, which was equivalent to 306 days in a standard atmosphere and 17 times longer than the previous polymer-based PHP. The FPHP had the thermal resistance of 2.41 K/W, which is 37% lower than that of the copper reference sample in a vertical orientation. Under bending conditions as well as in a horizontal orientation, the FPHP still operated well as a PHP, but the thermal resistance increased slightly. The fabrication method of the FPHP is effective in minimizing the permeation of NCGs in a lateral direction and can pave the way for fabricating a thin flexible heat spreader that has high flexibility, high thermal performance, and long-term reliability.

1. Introduction

With the development of technology, electronics are going through drastic changes in their shape and performance. Recently, there has been a growing demand for flexible electronics, such as flexible display panels and wearable devices. The improved performance of flexible electronics involving these trends causes a local heating problem, which is the main reason for malfunctions and safety concerns [1]. Therefore, an advanced heat spreader, which is flexible and thin with high thermal performance is greatly needed. A pulsating heat pipe (PHP), which is comprised of a smooth meandering tube, is noted for a promising solution due to its simple and wickless design [2]. During the last three decades, various studies have been conducted to understand the operational characteristics of PHPs. In most of these studies, PHPs were fabricated using rigid materials such as copper, aluminum, glass and silicon [3–8]. These rigid materials have high gas barrier properties. However, as a heat spreader for flexible devices, rigid materials are not suitable due to their remarkably low flexibility.

Polymer is an appropriate material for a flexible PHP due to its high flexibility. Some researchers have previously developed polymer-based PHPs. Lin et al. [9] fabricated the first polymer-based PHP, which had 6 channels with width, length, and diameter of 50 mm, 56 mm, and 2 mm, respectively. They use polydimethylsiloxane (PDMS) as a base material and two kinds of working fluids: methanol and ethanol. Ji et al. [10] also made a similar sized PDMS-based PHP and investigated the effect of nanofluid on the thermal performance under an electric field. Recently, Qu et al. [11] developed a tubular type flexible PHP using fluororubber tubes. The length, outer diameter and inner diameter of the PHP were 1.07 m, 6 mm, and 4 mm, respectively. However, these previous studies used metal tubes or plates at the evaporator and condenser sections. Such a combination of polymer and rigid section at the evaporator and condenser part was used to reduce the wall thermal resistance. The polymer wall should be thick enough for structural stability, but the wall has a high thermal resistance [12,13] due to the low thermal conductivity of polymers. These combination types have inherent limitations regarding flexibility. In addition to the flexibility limitation, the long-term reliability is another issue to overcome for fabricating polymer-based PHPs. Polymer-based PHPs have a serious drawback in maintaining their thermal performance due to the high gas permeability of the base material. Ogata et al. [14,15] fabricated a PHP using UV-curable polymer resin and polyethylene terephthalate (PET) film and investigated the change in the thermal performance over time.

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https://doi.org/10.1016/j.enconman.2017.11.022
Received 28 August 2017; Received in revised form 20 October 2017; Accepted 8 November 2017

Nomenclature

A	area [m^2]
C_0	molar volume [m^3/mol]
D	diameter [m]
K	gas permeability [m^2/s·Pa]
P	pressure [N/m^2]
Q_{in}	input power [W]
R	gas constant [J/mol·K]
R_{th}	thermal resistance [K/W]
t	time [s]
T	temperature [K]
V	volume [m^3]

Greek symbols

δ	permeation length [m]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

acc	acceleration test environment
atm	standard atmosphere
con	condenser
eva	evaporator
i	gas species
l	liquid phase
v	vapor phase

Even though PET has quite low gas permeability among polymer [16], the thermal performance of their PHP decreased very rapidly in a day due to the permeation of NCGs [17–20] and the leakage of the working fluid [21]. To reduce permeation and leakage, they improved their design by gluing a gas barrier film onto the top and bottom of the PHP. With this modification, the PHP was able to maintain its thermal performance for 18 days. However, the long-term reliability is still a major stumbling block for polymer-based PHPs.

This study proposes a fabrication method for a new type of polymer-based flexible PHP (FPHP) to overcome the difficulty associated with the long-term reliability. A series of experiments were performed to investigate the thermal performance and the long-term reliability of the FPHP. The thermal performance of the FPHP was investigated for four cases (i.e., vertical orientation, horizontal orientation, vertical evaporator and horizontal condenser position (VE-HC), and vertical condenser and horizontal evaporator position (VC-HE)). An accelerated life test was also conducted to verify the long-term reliability of the FPHP. The long-term reliability of the FPHP was evaluated to compare the lifetime, which was defined as exposure time the thermal performance decreases more than 10% of its initial value. Based on the experimental result, the effect of the indium-coated flanges on the long-term reliability was evaluated.

2. Experiments

2.1. Fabrication of the FPHP

PHPs are two-phase systems that transfer heat from the evaporator to the condenser by the pulsating or oscillating motion of the working fluid in the form of slug-train units. The diameter of a channel (D) is restricted to a specific range for slug-train units to be formed, and the criterion governed by the Bond number is presented as follows [22]:

$$D \leqslant 1.84\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}} \tag{1}$$

Table 1
Thermophysical properties of HFE-7000 at 23 °C.

Properties (unit)	
Liquid density (kg/m^3)	1400
Kinematic viscosity (cSt)	0.32
Surface tension (dynes/cm)	12.4
Latent heat of vaporization (kJ/kg)	142
Boiling point @ 1 atm (°C)	34
Specific heat (J/kg·K)	1300

where σ, g, ρ_l, and ρ_v are the surface tension, gravity acceleration, liquid density and vapor density, respectively.

In this study, the low-density polyethylene (LDPE) base, which has very low Young's modulus, and a wrapping film form the meandering square channel with a height of 0.81 mm. The base has width of 53.4 mm and length of 85.5 mm, and the number of turns of the FPHP is 12 with a dual diameter channel of 1.4–0.7 mm to maximize the thermal performance [23]. HFE-7000 (3M®) is used as the working fluid, and the thermophysical properties of the working fluid is summarized in Table 1. The multilayer laminated film has 5 layers shown in Fig. 1, and each layer has a specific purpose. A linear low-density polyethylene (LLDPE) is the innermost layer, which is widely used as a sealant polymer and the same kind of polymer as the base material. In the middle of the layer, Al-foil with a thickness of approximately 7 µm forms a gas barrier. The outermost layer is polyethylene terephthalate (PET), which has good chemical and mechanical resistance for protecting the whole film structure. We used a commercial film known as the vacuum envelope. The thickness of each layer could be changed, but the thickness of the Al-layer should be thicker than approximately 10 µm to effectively block gas permeation [24].

The fabrication method is as follows; the LDPE base was cut into a closed-loop PHP shape by a femtosecond laser (L2K Plus, Inc) shown in Fig. 2. On the femtosecond time scale, the thermal damage to the surface can be minimized because the time scale, during which the electrons are excited is shorter than the electron-phonon scattering time [25]. The surface of the base was washed with an ethanol and distilled water to remove any dust and impurities. After that, a multilayer laminated film was attached to the base with suitable heat and pressure, and the four sides of the base were sealed with a width of 6 mm. The total thickness of the FPHP fabricated in this study is 1 mm. However,

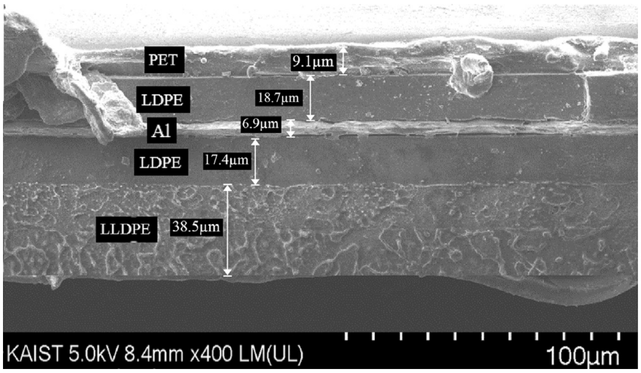

Fig. 1. SEM image of the multilayer laminated film.