Renewable and Sustainable Energy Reviews 91 (2018) 630–638

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

How to improve the thermal performance of pulsating heat pipes: A review on working fluid

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ARTICLE INFO

Key words:
Pulsating heat pipe
Working fluid
Nano-fluid
Dry-out
Start-up

ABSTRACT

Pulsating Heat Pipes (PHPs) are cooling devices that are compact in size and have an ability to transfer heat in low temperature differences. Working fluids strongly affect the thermal performance of PHPs. In this paper, effects of some thermophysical parameters relating to working fluids, such as boiling point, latent heat of vaporization, surface tension, thermal conductivity and dynamic viscosity, are presented based on experimental and numerical studies done in recent years. Addition of nanoparticles to fluids, or making nanofuild, is a new method of improving thermophysical properties of fluids. Recently, many studies are carried out on thermophysical properties of nano-fuild. Results indicate that using nanofuild could improve thermal performance of heat pips. Finally, in this review, flow regimes of some working fluids are represented under different conditions to obtain a better insight into the effect of input heat on working fluid flow pattern. It is concluded that lower dynamic viscosity and surface tension and higher thermal conductivity improve thermal performance of PHP. For lower heat inputs, lower boiling point of working fluid is more favorable due to faster start-up onset; however, at higher heat loads it causes some problems, such as dry-out.

1. Introduction

Heat pipes are two-phase heat transfer devices [1] which have much higher effective thermal conductivity compared with solid materials such as metals [2]. There are different types of heat pipes including gravitational, wick, and rotating heat pipes with various applications like heat recovery, building heating, applications in heat exchangers, automotives, and etc. [3–9]. In addition, heat pipes are widely used in energy systems for various purposes such as cooling fuel cell, desalination systems, solar collector and water heater [10–17]. Moreover, heat pipes are used for improving energy efficiency through heat recovery or extracting more energy in renewable energy systems in shorter time [18–21]. For instance, in recent years, heat pipes are used in heat storage systems [22] to accelerate discharge process due to their high capacity in heat transfer.

One type of heat pipes is pulsating heat pipe [23] which was invented by Akachi et al. [24]. A PHP consists of small pipe [24] with some turns and generally has three main parts [25,26]: evaporator section where receives heat, condenser section where dissipates heat and adiabatic section which is optional and used when there is a gap between evaporator and condenser. PHPs are filled with working fluid after evacuation. Fluid motion plays the most important roles in heat transfer in a PHP. The working fluid evaporates in evaporator by receiving heat and condenses in condenser by heat dissipation [27,28]. Fluid motion in PHP are due to pressure instabilities in different turns of PHP caused by temperature differences. There are two types of PHPs. closed loop and open loop PHPs. In closed loop PHPs, ends of the PHP are connected to each other and in open loop PHPs, tubes' ends are not connected.

Pulsating heat pipes (PHP) are widely used for cooling tools which have compact sizes such electronic devices. Due to decreasing size of electronic devices which leads to higher heat generation rate, many studies have been carried out to improve thermal performance of PHPs. Although the PHPs were initially used just for cooling electronic devices, more applications have been found for them in recent years [29]. For instance, by applying some types of working fluids, it is possible to utilize them under unusual conditions such as cryogenic condition. In addition, due to their high capacity in heat transfer, utilizing PHPs in renewable energy especially solar energy is developing significantly to achieve systems with higher efficiencies by improving their thermal

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https://doi.org/10.1016/j.rser.2018.04.042
Received 21 March 2017; Received in revised form 20 November 2017; Accepted 14 April 2018
1364-0321/

Nomenclature

D	inner diameter of PHP (m)
μ	dynamic viscosity (N s/m^2)
g	gravitational constant (m/s^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)
LHV	Latent Heat of Vaporization (kJ/kg)
SRWF	Self Re-Wetting Fluid

performance. Now a days, different structures of pulsating heat pipe, such as flat plate PHPs, make them appropriate for more applications.

Many parameters affect thermal performance of PHPs such as geometry [30,31], inclination angle, filling ratio, working fluid, flow regime [32] and cooling condition [33,34].

Some studies focused on PHP geometry to achieve better thermal performance [35,36]. Ebrahimi et al. [37] investigated the effect of interconnecting channels of a flat plate PHP to improve PHP performance. Other methods, such as inserting fin in a PHP, can improve its heat transfer performance [38]. Wang et al. [39] achieved better start-up performance of a PHP by using corrugated configuration in the evaporator section. Moreover, PHP material [40,41] and design play important role in thermal performance of PHPs, especially inner surface of PHPs influence the heat transfer capability [42]. It was observed that PHP with sintered surface had better start-up performance which was attributed to secondary capillary force in the PHP.

Another important parameter is inclination angle [43], PHPs usually work better in vertical mode (evaporator at the bottom and condenser at the top of PHP) due to gravity force; however, under certain conditions it is possible to work in horizontal modes; for instance, Kwon et al. [44] investigated a dual diameter tube and concluded that PHP has the ability to work stably in horizontal mode.

Filling ratio, which is defined as the ratio of working fluid in the tube to the total inside volume of tube, affects thermal performance of PHPs and influences the thermal performance in different ways. It is an important parameter for start-up occurrence in PHPs [45]. Moreover, high filling ratios prevent fluid motion in PHP and low filling ratios increase the possibility of dry-out (when there is not enough liquid in the evaporator section to evaporate and transfer heat); Therefore, there is an optimal filling ratio for PHPs which depends on some factors such as working fluids, heat input and tube diameter. Some scientific studies have been conducted to obtain the optimal filling ratio [46,47].

Working fluid is probably the most important factor which affecting thermal performance of PHPs. During recent years, many scientists have focused on working fluids and their properties on the thermal performance of PHPs. Some correlations are proposed for PHPs heat transfer based on thermophysical properties of working fluids [48]. Qu et al. [49] studied some PHPs with different inner diameters which were filled with water and ethanol as working fluids and proposed correlation to predict their heat transfer characteristics. Their results indicated that the best working fluids may differ for different tube diameters [49], since thermophysical properties of working fluids affects the critical diameter and thermal performance of PHP. Using nano-fluid is a method to improve heat transfer [50–52] which is applied in pulsating heat pipes.

Flow regime in PHPs is another parameter which affecting the thermal behavior of PHPs. Some models are proposed to predict flow regimes in PHPs [53]. Flow patterns can be influenced by some elements such as working fluids and heat inputs [54]; generally, higher heat inputs lead to higher fraction of vapor. Hence, introducing an appropriate working fluid for a PHP depends on some factors such as tube inner diameter, heat input, inclination angle and working temperature.

Studies show that even though the thermal performance of heat pipe have been a source of interest for many researchers, papers on the effects of thermophysical properties of working fluid has been more regarded. Various factors to improve thermophysical properties of working fluid in PHPs have been investigated experimentally and theoretically. In this study, influences of several thermophyscial properties of working fluid which affect heat transfer performance of PHPs are represented in order to provide adequate information for selection of working fluid based on application of PHP and working condition. In addition, valuable researches on the improvement of working fluids used in PHPs are reviewed to obtain a better insight in readers for selecting the most appropriate working fluid from the point of view of the latent heat of vaporization and boiling point, surface tension, thermal conductivity and dynamic viscosity. Moreover, it is tried to collect various studies have focused on application of nano-fluid in PHPs due to their potential for improvement of thermal performance. A comprehensive literature review is conducted on the applied nano-fluids in PHPs. Results of applied nano-fluids are summarized in a Table 1 which it can provide for researchers an appropriate reference for selecting the best type and concentration of nano-fluid based on required application. In addition to thermophysical properties of working fluid, flow regime inside PHPs, which plays an important role in thermal performance of PHPs, under various working condition are reviewed in this paper.

2. Effect of working fluids' properties on thermal performance of PHPs

Working fluid thermophysical properties influence thermal performance of PHPs significantly. PHPs with different working fluids have been studied to achieve better thermal performance. On the other hand, existence of some elements such as non-condensable gases (NCGs) in working fluids leads to the deterioration of thermal performance of PHPs due to weaker motion of fluid and prevent flow oscillation in PHPs [55]. In this paper, different properties affecting the thermal performance are represented.

2.1. Effect of boiling point and latent heat of vaporization

In the most of researches, different working fluids such as water [56], methanol, 2-propanol [57], acetone, ethanol and R123 were tested as working fluids in PHPs with inner diameter less than 2 mm and different filling ratio from 20% to 90%. Based on obtained results at high heat inputs, fluids with higher latent heat of vaporization (LHV) showed better heat transfer ability in the PHP. Average temperature of the evaporator section of PHPs with higher LHV fluid is lower than other fluids [57]. In addition, PHP charged with low LHV such as acetone showed more forceful pulsation in both vertical and horizontal modes at lower heat inputs which can be attributed to its lower boiling point. In addition, fluids with lower LHV and boiling point have more potential for dry-out. Moreover, it was resulted that at higher heat inputs, before dry-out onset, by increasing heat inputs the thermal resistances of PHPs indicated a decreasing trend [56]. The experimental results showed that in the start-up phase optimal filling ratios for fluids with lower LHV were higher than the others. Small specific heat, small dynamic viscosity and high pressure gradient versus temperature, which was the most important parameters for low LHV fluids, led to better start-up performance of the PHP. Liu et al. [33] showed that methanol had the shortest time and lowest temperature for start-up which was attributed to its lower specific heat and saturation temperature in comparison with water and ethanol [58]. Moreover, another research by Cui et al. [59] was done to understand the effect of working fluid on the thermal performance of a closed-loop PHP with inner diameter of 2 mm. This study showed that at a certain cooling condition, before dry-out onset, there was a limit for heat transfer. At lower heat inputs, fluids with lower LHV such as acetone had better thermal performance which can be attributed to its lower boiling point.