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A review on pulsating heat pipes: From solar to cryogenic applications

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HIGHLIGHTS

- Pulsating heat pipes (PHPs) are compact cooling equipment used for various applications.
- PHP can be used in renewable energy systems, cooling electronic devices, heat recovery systems.
- Various applications of PHPs are reviewed and analyzed.
- PHPs are efficient and reliable devices for utilization in various energy systems.

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ABSTRACT

Pulsating heat pipes (PHPs) are compact cooling equipment used for various applications. This type of heat pipes can be used in renewable energy systems, cooling electronic devices, heat recovery systems and many other applications. Since PHPs have superior thermal performance, by applying them in energy systems enhance their efficiency. In addition, PHPs are a reliable medium for cooling various devices which have high heat flux. In this study, various works conducted on the applications of PHPs are reviewed and analyzed. It is concluded that PHPs are efficient and reliable devices for utilization in various energy systems. Moreover, at very low temperatures, such as cryogenic applications, they can transfer heat efficiently. For instance, by applying cryogenic PHP it is possible to achieve up to 12,000 W/m K which is much higher than metal thermal conductivity at those temperatures.

1. Introduction

Heat pipes are efficient cooling apparatuses which are widely developed in recent years for various purposes and applications such as cooling blades of turbines [1,2], water heating systems [3] and solar stills [4]. There are several types of heat pipes including rotating heat pipes [5], wick heat pipes [6,7], thermosiphons [8] and pulsating heat pipes [9,10]. Heat pipes are generally categorized based on the mechanism of fluid motion inside them. The working principle of heat pipes is based on fluid vaporization at the heat source and condensation of the generated vapor at the heat sink [11,12]. The main sections of heat pipes are thus the evaporator and the condenser which are in the vicinity of the heat source and heat sink, respectively. In addition, an adiabatic section can be added in the cases that there is a large distance between the evaporator and condenser [13]. Due to their efficient heat transfer performance, heat pipes are utilized extensively in various applications, especially in renewable energy systems [14–18].

Standard or conventional heat pipes utilize the capillary force for liquid return [6,19]. The capillary force can be provided by a wick or grooves inside the tube [7,20–22]. Rotating heat pipes utilize the centrifugal force in order to return the condensed fluid from condenser to the evaporator [23]. Generally, in these types of heat pipes a higher centrifugal force lead to better thermal performance [24,25]. The main reason for liquid motion in the thermosiphons is gravity force [26,27]; as a consequence, thermosiphons are more sensitive to the orientation compared with other types of heat pipes [28]. Pulsating heat pipes

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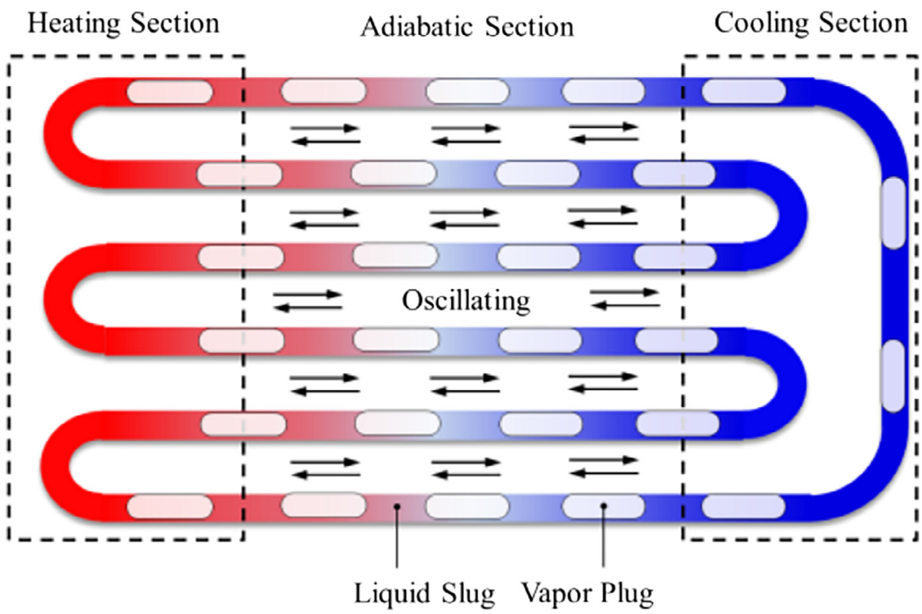

Fig. 1. Schematic of a PHP (reprinted from Daimaru et al. [31], with permission from Elsevier).

consist of a small diameter tube (capillary tube) with several bends as shown in Fig. 1 [29,30]. The heat received in the evaporator section leads to vapor generation, growth in the size of bubbles and increase in vapor pressure, which causes the motion of the fluid toward the condenser [20]. By heat dissipation in the condenser section, the pressure of bubbles decreases and condensation occurs. Growth and collapse of the bubbles inside the tube leads to a pulsating motion of the fluid inside the PHPs [20].

In addition to the more compact size compared with other types of heat pipes, PHPs have a simpler structure compared to standard heat pipes, since they do not require a wick structure [32]. They also have a more compact size compared to thermosiphons. Therefore, PHPs can be used in several applications which have small size.

Several studies have been carried out in recent years which show the enhanced thermal performance of PHPs [33]. Some of them are focused on the structure of the PHPs to improve fluid circulation in order to obtain better thermal behavior [34-36]. For instance by interconnecting the channels of the PHP the fluid circulation in the tube can be facilitated [34] or using non-uniform channels leads to a more stable pulsation of the fluid in horizontal mode compared with the PHP which has uniform channels [37]. Some other studies have concentrated on the working fluid of the PHPs [9,38–42]. The most practical approach for the enhancement of the thermal performance of PHPs is by using surfactants or nanofluids [42–46]. Improvement in thermal performance of PHPs by using nanofluids is attributed to higher thermal conductivity of the nanofluids compared with the pure fluids and the increase in nucleation sites due to existence of nano particles.

Further to the structure and working fluids, other parameters such as filling ratio, orientation and the material of tube are investigated in various studies in order to find the most influential parameters and achieve enhancement of the heat transfer [47–51]. High filling ratio prevent fluid motion in the tube and the low volume fraction of fluid increase the possibility of dry-out onset [52,53]; therefore, there is an optimal filling ration for the PHPs [54,55]. The PHPs usually work better in vertical or near vertical orientation [56] which can be attributed to the gravity assistance of the fluid return from the condenser to the evaporator. Tubes with high thermal conductivity are more favorable to be used in PHPs because they have lower radial thermal resistance.

In addition to the studies conducted for the investigation of effective factors on the thermal performance of PHPs, there are several works which are focused on the application of PHPs. In this study, various studies performed on the application of PHPs are reviewed and analyzed in order to get a better insight into the potential of PHPs and the possible applications which may emerge in the future. Initially, the applications of PHPs in solar energy are represented. Based on the reviewed studies, PHPs can be used in various fields of solar energy such as PV modules, heating, desalination systems, solar thermal application. Subsequently, the applications of PHPs in other energy systems such as fuel cells is represented. Finally, the studies related to use of PHPs in heat exchangers and cooling devices are presented. In addition to high temperature applications, PHPs can be utilized in systems with very low operating temperature which are known as cryogenic pulsating heat pipes.

2. Applications of PHPs

The main applications of pulsating heat pipes are shown in Fig. 2. These are presented in this section.

2.1. Phps in solar energy systems

Due to the environmental problems related to the fossil fuels consumption and the finite quantities of the sources of these fuels, renewable energy systems have been developed significantly recently [57–59]. Solar energy can be applied for different purposes such as for power generation, heating, desalination and many others [60–65]. Electricity generation with solar energy can be done by using PV modules (direct method) or using solar energy equipment to produce thermal energy and converting the absorbed heat to electricity in conventional power plants [66–69]. PHPs are applicable in solar energy systems in order to improve their efficiency or for heat transfer purposes.

The working temperature of PV modules affects their efficiency [70,71]. A lower temperature of PV cells leads to higher efficiency and electrical output. Alizadeh et al. [72] proposed a method for cooling PV modules by using a PHP. In this approach, a single turn PHP was used for PV cooling and the temperature was obtained by numerical simulation. The considered configuration is shown in Fig. 3. In order to simulate the heat transfer of PHP, the effective thermal conductivity of the PHP was considered as a function of temperature difference between the evaporator and condenser sections. The temperature of a PV