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Enhancing thermal performance of a two-phase closed thermosyphon with an internal surface roughness

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ABSTRACT

Enhancement of energy conversion devices has become an important task to reduce size and cost, and design efficient systems. In this work, enhancement of heat transfer performance of a two-phase closed thermosyphon has been investigated by making an internal surface roughness. Thus, a new advanced machining technique (Electrical Discharge Machining) is employed to modify the surface characteristics of a TPCT. The experimental work has been carried out at two initial sub-atmospheric pressures (3 and 30 kPa), heat input range of (90–160 W) and a fill ratio of 50% using water as a working fluid. The results of the new thermosyphon have been compared with a plain copper TPCT to consider the enhancement in thermal performance resulting from resurfacing of the thermosyphon wall. The results revealed that using internal wall roughness in TPCT can enhance its thermal performance by reducing the evaporator temperature, thereby the total thermal resistance decreasing by about 42% and 13% at initial pressures of 3 kPa and 30 kPa, respectively. On the other hand, the evaporator thermal resistance decreases and the evaporator heat transfer coefficient increases by about 115% and 68% at initial pressures of 3 kPa and 30 kPa, respectively. However, the condenser thermal performance decreases using the resurfaced TPCT compared with plain thermosyphon.

1. Introduction

Energy demand has increased rapidly worldwide due to inefficient use and conversion of energy in different applications. Therefore, reduction of losses and enhancing heat transfer processes in energy systems have become an essential area of research in recent years (Jouhara et al., 2017). Heat pipe offer an effective way to transfer thermal energy by utilising the latent heat of the working fluid by means of evaporation and condensation passively in a closed container. Due to their relatively low thermal resistance, compact and employing a small quantity of the working fluid, they have widely used in different applications such as solar thermal systems, heat exchangers and electronics cooling. Heat pipes consist of two main sections: the evaporator where the heat is absorbed by the working fluid; and the condenser in which heat is rejected. After the heat is added to the evaporator section, the liquid reaches its saturation temperature and evaporates generating vapour. Due to the difference in the vapour pressure between the evaporator and the condenser, it rises to the condenser (with the assistance of the bouncy forces) where it condenses delivering its latent heat to the coolant at the condenser. At that time, the vapour condenses due to a lower temperature in the condenser and returns to the evaporator by gravity, if the heat pipe is wickless (thermosiphon), or by capillary force, if a wick heat pipe is used. A special attention has been paid to a two-phase closed thermosyphon (TPCT) due to its simplicity and cost-effectiveness (Alammar et al., 2017).

Electrical Discharge Machining (EDM) is an advanced fully controlled technique that uses the electric spark to remove small pieces from a metal workpiece forming different shapes or surface roughness. This performs by applying a high-frequency electrical current through an electrode which producing a very high-temperature resulting in erosion of a tiny piece of the metal. The electrode is controlled to erode a specified thickness of metal from the sample. Both the workpiece and electrode are submerged in a dielectric fluid for cooling purposes and removing the resulting eroded material (Johnson Waukesha).

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Nomenclature

D	Diameter of thermosyphon, m
h	Heat transfer coefficient, W/m^2 °C
I	Current, Am
K	Thermal conductivity, W/m °C
Q	heat input, W
R	Thermal resistance, °C/W
T	Temperature, °C
V	Voltage, v

Subscripts

av	Average
c	Condenser
e	Evaporator
i	Inside
o	Outside
t	total

Several research works have been carried out to investigate enhancing the thermal performance of heat pipes using two different techniques. The first technique employs addition of nanoparticles to the working fluid to increase its thermal conductivity and enhance heat pipe performance. Different studies have investigated the effect of using various nanoparticles with water such as CuO nanoparticles (Yang et al., 2008; Liu et al., 2010; Manimaran et al., 2012; Cheedarala et al., 2016), Al2O3 nanoparticles (Noie et al., 2009; Aly et al., 2017), silver nanoparticles (Paramatthanuwat et al., 2010; Ghanbarpour et al., 2015), iron oxide nanoparticles (Huminic et al., 2011; Huminic and Huminic, 2013), graphene nanoparticles (Sadeghinezhad et al., 2016) and multiwalled carbon nanotubes functionalized with ethylenediamine EDA-MWCNT nanoparticles (Shanbedi et al., 2012a). It was found that the best nanoparticles concentration which provided the highest thermal performance was 1.0 wt% (Yang et al., 2008; Shanbedi et al., 2012b), 0.1 wt% (Sadeghinezhad et al., 2016), 0.06 wt% (Cheedarala et al., 2016) and 3 wt% (Aly et al., 2017). Different studies showed that using nanofluid increased the heat transfer coefficient by 46% (Yang et al., 2008) and 30.4% (Aly et al., 2017), increased CHF by 30% (Yang et al., 2008) and 79% (Cheedarala et al., 2016), increased thermal performance (Liu et al., 2010), by 14.7% (Noie et al., 2009), 70% (Paramatthanuwat et al., 2010), 93% (Shanbedi et al., 2012b), 37.2% (Sadeghinezhad et al., 2016) and reduced the thermal resistance (Sureshkumar et al., 2013) by 62% (Manimaran et al., 2012), 48% (Sadeghinezhad et al., 2016) and 18.2% (Aly et al., 2017). Also, it was concluded that some nanoparticles may deposit on the heat pipe wall making a coating resulting in an increase of the surface wettability (Sadeghinezhad et al., 2016; Cheedarala et al., 2016).

On the other hand, some researchers have implemented different surface characteristics to enhance the thermal performance of heat pipes (Han and Cho, 2002). investigated the performance of a micro-grooved thermosyphon heat pipe for different working fluids, number of grooves and operating temperatures. They found that the number of 60 grooves correspond to the highest condensation heat transfer performance which was 2.5 times higher than that of a plain thermosyphon. Also, the condensation heat transfer coefficients of grooved thermosyphons filled with methanol and ethanol were 1.5–2 and 1.3–1.5 times higher compared to the plain one, respectively, and water provides the highest heat transfer rate. The thermal characteristics of two thermosyphon heat pipes with straight and helical grooves filled with water have been investigated by (Han and Cho, 2005) for different inclinations, fill ratios and operating temperatures. It is concluded that the fill ratio of 30% exhibits the highest heat flux. In addition, angles of 25–30° and 40° provide the best thermal performance for helical and straight grooves, respectively (Jiao et al., 2005). studied theoretically and experimentally the effect of thin-film evaporation in a groove heat pipe. They reported that the performance of the grooved heat pipe is highly affected by the thin film evaporation where the reduction in evaporator temperature is considerably larger than in condenser temperature. Also, the thin film region is enlarged by the decrease in the contact angle which increases the heat transfer performance. A similar mathematical study to (Jiao et al., 2005) has been carried out by (Jiao et al., 2007), but the thin fill region inside the groove was divided into three different regions instead of one region. A numerical thermal model has been developed to predict the thermal performance of a micro-grooved flat plate heat pipe and validated with an experimental study (Lefèvre et al., 2008). They found that the optimum dimensions of the rectangular groove are 0.36, 0.7 and 0.1 mm corresponding to groove width, height and fin width, respectively. These dimensions provide a maximum heat flux and lowest thermal resistance (Yong et al., 2010). investigated the performance of a heat pipe with micro-grooves manufactured by Extrusion–ploughing process. The study reported that the heat transfer limit for the grooved heat pipe fabricated by the new technique is larger than that for the normal grooved heat pipe, thus the low heat transfer limit for axially micro-grooved heat pipe can be resolved (Wong and Lin, 2011). investigated the impact of surface wettability on the performance of evaporator in a mesh wicked flat plate heat pipe with water, methanol and acetone as working fluids. They concluded that the heat transfer limit decreases as the contact angle of the copper surface with water increases, while it is unaffected by methanol and acetone (Solomon et al., 2012). studied the effect of nanoparticles coating on the thermal performance of screen wicked heat pipe. Results revealed that the heat transfer coefficient and thermal resistance of the evaporator increases and reduces by 40%, respectively, while the thermal performance in the condenser section decreases compared with an uncoated heat pipe. It is also reported that reduction of 19%, 15%, and 14% is achieved at heat loads of 100, 150 and 200 W respectively. Thermal characteristics of a horizontal grooved heat pipe with different surface wettability for the three sections, evaporator, adiabatic and condenser has been investigated by (Hu et al., 2013). The study revealed that significant decrease is achieved in the total thermal resistance due to the change to the surface characteristics to hydrophilic, gradient wettability and normal surface for evaporator, adiabatic and condenser sections, respectively. Also, more than 42% increase in the dry out limit of the grooved heat pipe is obtained.

(Rahimi et al., 2010) changed the surface characteristics of the evaporator and condenser to investigate their influence on the thermal performance of a two-phase closed thermosyphon using water as a working fluid. The study showed that the thermosyphon efficiency can be increased by 15.27%, whereas a decrease of 2.35 times in the thermal resistance is obtained compared with the plain TPCT. Another surface modification study has been carried out by (Solomon et al., 2013) to test the heat transfer performance of an anodized Aluminium thermosyphon charged with acetone. It is found that a maximum reduction in thermal resistance and increase in heat transfer coefficient of the TPCT evaporator is 15% compared with non-anodized thermosyphon. In addition, a negligible effect of anodized TPCT is observed on the condenser thermal performance (Hsu et al., 2014). employed different surface characteristics in terms of contact angle in the evaporator and condenser sections to investigate the thermal performance of a TPCT. Experimental results showed that when evaporator and