Energy 61 (2013) 139–147

Contents lists available at SciVerse ScienceDirect

Energy

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

Experimental investigation of an inclined-condenser wickless heat pipe charged with water and an ethanol–water azeotropic mixture

Hussam Jouhara*, Zaki Ajji, Yahia Koudsi, Hatem Ezzuddin, Nisreen Mousa

Atomic Energy Commission, P.O. Box 6091, Damascus, Syria

ARTICLE INFO

Article history:
Received 26 July 2012
Received in revised form
11 September 2012
Accepted 13 September 2012
Available online 17 October 2012

Keywords:
Two phase closed thermosyphon (TPCT)
Heat exchanger
Thermal resistance
Azeotrope
Inclined condenser

ABSTRACT

This paper examines the advantages of using the ethanol–water azeotrope as a wickless heat pipe working fluid and the suitability of an inclined condenser structure for a horizontal evaporator operation. Water has, also, been tested as a working fluid for the heat pipe for comparison with the azeotrope results. The tested wickless heat pipe, or as sometimes is referred to as two-phase closed thermosyphon (TPCT), is made from copper with a condenser section that is 12° inclined from the evaporator section. Ethanol–water azeotrope is chosen as a TPCT working fluid as of the expected benefits and thermal characteristics enhancements of this azeotropic mixture is thought to bring. A variable output electrical heater was used to heat the evaporator section. The condenser section was cooled using an enhanced heat exchanger equipped with a twisted 304 stainless steel tape to cause the cooling water to spiral around the condenser section wall. The effect of the evaporator inclination angle, working fluid and power throughputs on the temperature distribution along the heat pipe and the TPCT overall thermal resistance have been investigated. The TPCT was found to function normally under all the considered evaporator inclination angles (including the horizontal position). In addition, many advantages for the use of the ethanol–water azeotrope have been discovered and reported.

1. Introduction

Wickless heat pipes, which are also known as two phase closed thermosyphons (TPCT), are hermetically sealed tubes containing a working fluid in both the liquid and vapour phases. They utilise the highly efficient thermal transport process of evaporation and condensation to maximize the thermal conductance between a heat source and a heat sink. They are often referred to as thermal superconductors as they transfer large amounts of heat energy across a small temperature gradient. TPCTs offer the favourable features of high effective thermal conductance, passive and reliable operation, effective thermal coupling between a heat source and a heat sink, temperature homogenisation and modest cost. Unlike conventional heat exchangers they do not require external pumping [1,2].

TPCT technology has now a proven track record in many industries such as low noise and efficient electronics cooling systems [3–5], electronics thermal management systems with dielectric fluids charged heat pipes [6], the cooling of high-performance electronics components that operate at high working temperatures and thermal heat sinks with near isothermal surface conditions [7–9]. The application of the heat pipe technology has also matured in water heating systems [10–14], ground source heat pumps [15,16] and space applications [17,18]. Its potential in nuclear sea water desalination is also covered so that traditional heat exchangers can be replaced with heat pipe based systems in order to reduce tritium contamination in the product water [19,20]. Its application in solar heat energy systems has been reported by many researchers, Refs. [21–24] to name a few.

The TPCT transfers heat energy from a heat source to a heat sink by utilising a complex phase change process in the evaporator and condenser regions. El-Genk and Saber [25], reported correlations to predict the boiling heat transfer coefficient in the evaporator section of a TPCT that take into account the separate effects of pool boiling in the lower region as well as laminar convection and/or boiling within the continuous liquid film. Liquid pool boiling correlations, such as those of Rohsenow [26], Kutateladze [27] and Shiraishi et al. [28], among many others, have also been used with varying degrees of success.

Nusselt's theory for filmwise condensation is generally used to predict the heat transfer coefficient in the condenser region of the TPCT provided the film Reynolds number is sufficiently low [28–30]. In situations with higher Reynolds numbers, waviness and turbulence may enhance the heat transfer and correlations exist to

* Corresponding author. Tel.: +963 11 2132580; fax: +963 11 6112289.
E-mail addresses: pscientific4@aec.org.sy, pscientific@aec.org.sy (H. Jouhara).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2012.09.033

predict these [30]. Hashimoto and Kaminaga [31] proved that liquid entrainment could deteriorate the condensation heat transfer for low Reynolds numbers.

Many publications exist concerning experimental work on the performance of TPCTs with different working fluids. The most common TPCT working fluids is water due to its high figure of merit, availability, cost, non-toxic and environmentally neutral properties [1,32]. Other working fluids, for low to intermediate operating temperatures, including, but not limited to, R-11, R-12, R-22, R113 have been tested in heat pipes made from various shell materials [28,33–38].

Due to environmental concerns and the high global warming potential (GWP) of earlier refrigerants, R134a has been tested as a TPCT working fluid by many researchers [39–42]. Ethanol [28,33] as well as 3M Fluorinert™ heat transfer liquids [6,43] have been proven to be suitable working fluids for TPCTs that function under certain conditions. Binary mixtures have also been utilised as TPCTs working fluids. Kiatsiriroat et al. [44] have reported thermal performance enhancement of TPCTs using non-azotropic ethanol–water and TEG–water binary mixtures. In their study, Rohsenow pool boiling correlation have been utilised to predict the boiling heat transfer in the evaporator region while using Nusselt filmwise condensation correlation to predict the condensation heat transfer coefficient. The authors have reported an improved performance for the TPCT that uses ethanol–water binary mixture. This was not found to be the case when triethylene glycol (TEG) water was used as the working fluid.

The effect of the TPCT inclination angle has been studied by some researchers. Negishi and Sawada [45] have shown that the working fluid filling ratio and changing the inclination angle between 10° and 90° had no effect on the performance of the TPCT while drastic deterioration in performance was observed at inclination angle of less than 5° from horizontal axis. This is to be expected as the TPCT relies on gravity to return the condensate back to the evaporator section. Similar findings were reported by Payakaruk et al. [46] where the filling ratio of the working fluid in the TPCT did not affect its thermal performance while the working fluid with the lower latent heat of vaporisation caused degradation in the TPCT performance at inclination range from 20° to 70°.

In some engineering applications, horizontal evaporator positioning is desirable (electronics cooling, concentrated solar collectors…etc). This has been possible so far by utilising loop or wicked heat pipes. Taking into account the relatively high space requirements for loop heat pipes [39] and the cost of wicked heat pipes [1,47], TPCTs are more desirable due to their lower cost and space requirements. However, for TPCTs to function with horizontal evaporator orientation, the return of the working fluid condensate back to the evaporator section has to be secured so that the TPCT fully functions.

In this paper, the thermal performance of copper TPCT charged with water as well as an azeotropic mixture of ethanol–water is reported. The physical size of the investigated TPCT is typical for use in heat exchanger devices such as the receivers of networked concentrated solar collectors (parallel and/or serial networks), the thermal management of industrial electrical and electronic systems, commercial heat exchangers and other heat transfer systems.

The azeotropic mixture of ethanol–water was chosen for testing since it allows sub-zero operation of the TPCT and is compatible with copper as the shell material. Unlike non-azeotropic mixtures, this fluid is azeotropic, hence liquid and vapour compositions (during the boiling and condensation cycle) are identical, hence the fluid behaves like a pure substance. In addition, the utilisation of this fluid is believed to enhance the performance of the TPCT at the various tested power throughputs and inclination angle ranges. For performance comparison, water, as a working fluid, was also tested. Correlations for predicting the heat transfer in the evaporator and condenser sections have been used and their output has been compared with the experimental measurements and the thermal performance characteristics of both the working fluids.

The tested TPCT has the condenser section at an angle, ψ, of 12° from the evaporator axis. Therefore, when the evaporator angle, θ, is at 0° (horizontal positioning), the condenser will be at 12°, which is large enough to secure the return of the condensate working fluid back to the evaporator, hence full operation capability of the TPCT.

The new findings are believed to enrich the literature with new information regarding TPCTs that are capable of horizontal evaporator operation and the benefits of utilising azeotropic mixture of ethanol–water as working fluids.

2. The experimental apparatus

Fig. 1 shows a schematic diagram of the experimental apparatus used in this investigation. The apparatus consists of the TPCT, framework, cooling water flow circuit and instrumentations.

2.1. The TPCT

As is shown in Fig. 2, the TPCT was manufactured from a 22 mm outer diameter, 1.5 m long smooth copper tube with a tube wall thickness of 0.9 mm. It consists of an evaporator, adiabatic and condenser sections.

2.1.1. Structure

The evaporator section of the TPCT is 1 m in length and is heated by a resistance wire heater with a maximum power output of 0.8 kW. The heater was evenly wrapped around the evaporator section to ensure it was equally spaced and not directly above a thermocouple which would be measuring the surface temperature of the evaporator. The use of the electric heater provides a simple and accurate method of measuring the variable rate (using a variac) at which heat is added.

The evaporator section and its heater were wrapped in a layer of fire-proof insulation layer before wrapping them with two thick layers of high and medium temperature thermal insulation layers to minimise any heat losses from the evaporator to the ambient.

The condenser section of the TPCT is 400 mm in length and is at 12° inclination angle from the evaporator section (Fig. 2). The condenser section was cooled using an enhanced heat exchanger that has a twisted 304 stainless steel tape to cause the cooling water to spiral around the condenser section wall. The condenser heat exchanger is detailed in Fig. 3.

The heat exchanger and the exposed wall between the evaporator and the condenser section (the adiabatic section) were well insulated to ensure no heat energy interactions are taking place with the ambient. This has allowed the use of its wall temperature as an indicator of the TPCT working temperature (T_v).

2.1.2. Working fluids

The adopted working fluid filling ratio has ensured half of the evaporator is filled while the TPCT undergoes steady state operation at $Q = 800$ W with horizontal evaporator. The reason behind this ratio is to ensure the bottom half of the evaporator section is full of working fluid while the evaporator is at 0°. The TPCT was charged with the specified amount of working fluid and was sealed off when non-condensable gases (NCGs) were totally removed.

Two working fluids were tested distilled water and azeotropic ethanol–water mixture.