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Experimental analysis of a heat pipe operated solar collector using water–ethanol solution as the working fluid

A. Jahanbakhsh, H.R. Haghgou, S. Alizadeh *

Materials & Energy Research Centre (MERC), P.O. Box 31787/316, Karaj, Iran

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Abstract

In this paper heat pipes have been constructed and tested using solutions of ethanol and water as the working fluid at different tilt angles and concentrations. Tests were carried out to investigate the effects of ethanol concentration as well as the pipe evacuation and the use of a wick inside the pipe to ensure a continuous performance of the system. The tests indicate that ethanol in the solution enhances the heat pipe performance at low heat flux, and that concentrations of 50% and 75% show the best performance characteristics in transferring the heat. An efficiency of about 52% was obtained for the heat pipe operated solar collector in this case. It was concluded that the evacuation of a heat pipe or using a wick do not add much effect to the enhancement of a heat pipe performance, and that the collector had its highest heat transfer coefficient at a tilt angle of 35°.

Using the results from testing the heat pipes, a thermo-syphon type solar water heater was developed, using the high efficiency heat pipe with evacuated glass cover tubes. The results of these experiments revealed that the collector water flow rate and evacuation of the glass cover tubes had little effect on the enhancement of the solar collector thermal performance.

Keywords: Heat pipe; Solar energy; Water heater; Heat transfer

1. Introduction

Heat pipes are considered as the most efficient device to transfer heat which compared with a solid metal bar with the same dimensions and material can transfer hundreds of times more energy from one location to the other. This process is carried out using a working fluid such as water which is evaporated in the hot region of the pipe and subsequently releases the latent heat by condensation in the cold region. A heat pipe is simply a tube blocked at one end into which the working fluid, which is approximately 5–30% of the volume of the pipe, is injected (Faghri, 1995). As a consequence there exists a two phase flow of gas and liquid inside a heat pipe. In the case that the pressure in the evaporator increases due to excessive evaporation the temperature of the rest of the pipe is subsequently increased. The heat is, therefore, transferred to the condenser following the condensation of the vapor. Conversely, if the heat is ejected in one part of the pipe the pressure is adjusted in that part by condensation and the equilibrium is, consequently, restored inside the pipe.

In a heat pipe in order for the heat to be transferred, liquid should always be present in the evaporator section of the pipe. For this reason a wick is often used, which is located along the pipe interior wall and for most of the pipe length. This will cause the liquid to be returned to the

* Corresponding author at: Mechanical Engineering Dept., Islamic Azad University.

E-mail address: shahab_alizadeh@hotmail.com (S. Alizadeh).

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Nomenclature

R_h thermal resistances on the outer surface of the evaporator (m^{2}°K/w)
R_c thermal resistances on the outer surface of the condenser (m^{2}°K/w)
h_h heat transfer coefficient on the outer surface of the evaporator (w/m^{2}°K)
h_c heat transfer coefficient on the outer surface of the condenser (w/m^{2}°K)
$R_{f.h}$ resistance due to the residuals on the outer surfaces of the evaporator (m^{2}°K/w)
$R_{f.c}$ resistance due to the residuals on the outer surfaces of the condenser (m^{2}°K/w)
$R'_{f.h}$ and $R'_{f.c}$ residual factors (°K/w)
$R_{wi.h}$ and $R_{wi.c}$ resistances in the wick by the saturated liquid inside the wick (m^{2}°K/w)
$R_{i.e}$ and $R_{i.c}$ resistances contributed by the phase change inside the heat pipe (m^{2}°K/w)
$h_{i.e}$ and $h_{i.c}$ convection heat transfer coefficients related to the liquid–vapor interface in the evaporator and condenser; respectively (w/m^{2}°K)
$R_{w.h}$ and $R_{w.c}$ wall resistance in the evaporator and condenser (m^{2}°K/w)
S_h and S_c outer surface of evaporator and condenser wall (m^{2})
R_o and R_i outer radius and Inner radius (m)
R_δ vapor passage radius (m)
k_w wall conductivity (w/m°K)
k_{eff} effective conductivity of wick and saturated liquid (w/m°K)
K_l and k_g liquid and vapor conductivity (w/m°K)
L_e and L_c evaporator and condenser length (m)
$\bar{h}$ mean heat transfer coefficient (w/m^{2}°K)
ρ_l and ρ_v liquid and vapor density (kg/m^{3})
g gravity = 9.81 (kg m/s^{2})
h_{fg} latent heat of vaporization (w/m^{2}°K)
h'_{fg} $h'_{fg} = h_{fg} + 0/375 C_{p.l}(T_g - T_w)$ (kj/kg)
μ_l and μ_v liquid and vapor viscosity (kg/m s)
T_g saturated temperature (°K)
T_w wall temperature (°K)
C_{pl} specific heat of liquid (kj/kg°K)
q_e heat flow (kj)
P_{sat} and P_a saturated and atmospheric pressure (kpa)
t_{wick} wick thickness (m)

evaporator from the condenser by the capillary action provided by using the wick inside the heat pipe.

Heat pipes have the capability of simultaneous operation at low temperature drops while in high temperature ranges (2–4000 K). As a consequence they are suitable devices for use in flat plate solar energy collectors. The working fluid in a heat pipe has a direct effect on the efficiency and the overall heat transfer coefficient as well as the operating temperature range of the heat pipe. Water, ethanol and methanol and even a mixture of these substances are commonly used as the working fluid within the temperature range of solar energy collectors. Chun et al. (1998) experimentally studied the operation of a heat pipe using acetone, methanol, ethanol, water and a solution of water and alcohol as the working fluid (Chun et al., 1998). They observed that a working fluid could highly affect the operation of a heat pipe. Kang et al. (2003) did similar experimental work using water, ethanol and a their solutions as working fluid in a closed loop heat pipe and determined their influence on the heat pipe operating temperatures (Kang et al., 2003). Savino et al. (2007) in a separate experimental work investigated that ethanol solution as a working fluid shows better performance in a heat pipe compared with pure water. Guo et al. (2010) experimentally found that compared with pure water ethanol solution, as working fluid, could provide better results when used in low diameter and low capacity heat pipe.

In evacuated pipe solar energy collectors, the conservation of evacuation in the pipes and the leakage prevention are the key points in preserving a high performance for the heat pipe. There has been substantial research work in this area by different investigators. Zambolin and Col (2010) conducted experimental research on evacuated tube solar energy collectors as well as simple flat plate solar collectors. They found that unlike the simple flat plate collector the performance of the evacuated tube collector showed little dependency on the time of the day. Moreover the evacuated tube collector had almost a constant efficiency during the day with a higher collector outlet temperature compared with the simple flat plate collector (Zambolin and Col, 2010). Ayompe et al. (1999) conducted the daily, monthly and annual performance comparison of an evacuated tube flat plate solar collector and a simple flat plate collector using the TRNSYS simulation software. They found that the energy collected by the evacuated tube collector was substantially higher than the simple flat plate collector (Ayompe et al., 1999).

In the literature survey carried out in this study, little work has been conducted on water–ethanol solution as the working fluid. The only two cases identified were the work conducted by Guo et al. (2010) and Savino et al. (2007). Guo investigated that for his heat pipe experimental work the 40% ethanol solution had the best performance at a heat fluxes below 30 W. At a heat fluxes above 30 W, however, the water acts better. Also Savino in his research