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Effects of different working fluid use on the energy and exergy performance for evacuated tube solar collector with thermosyphon heat pipe

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ABSTRACT

In this study, the effects of six different working fluids, hexane, petroleum ether, chloroform, acetone, methanol and ethanol on the energy and exergy performance are investigated in evacuated tube solar collectors with thermosyphon heat pipe under three different air velocities as 2, 3 and 4 ms^{-1}. The six evacuated tube solar collectors with thermosyphon heat pipe with the same dimensions and properties are designated for the air heating and tested under the outdoor climatic conditions of Uşak, Turkey. The lowest energy and exergy efficiencies occur in the THPETC-Hexane under 2, 3 and 4 ms^{-1}, the highest energy efficiency occurs in the THPETC-Acetone for air velocity of 2 and 3 ms^{-1} and in the THPETC-Chloroform for air velocity of 4 ms^{-1}. The highest exergy efficiency occurs in the THPETC-Acetone for air velocity of 2 ms^{-1} and in the THPETC-Chloroform for air velocity of 3 and 4 ms^{-1}.

1. Introduction

Thermosyphon Heat Pipe (THP), which is fundamentally a gravity-assisted wickless heat pipe, uses the evaporation and condensation of the working fluid inside to transfer heat. In opposition to the conventional heat pipe using capillary force to return the liquid to evaporator, a THP utilizes gravitation to go back the condensate [1].

THP has a lot of supremacy including simpler structure, smaller thermal resistance, higher efficiency and lower production cost. Also, it contains no mechanical moving parts and typically requires no maintenance. All these advantages enable the THP to be widely used in a number of fields, including industrial heat recovery, electronic component and turbine blade cooling, solar energy systems, climatization processes, preservation of permafrost, deicing of roadways, and so on [1].

THPs can be easily integrated into most types of solar collector, too. The application of heat pipes to solar collectors has several advantages. Besides the heat pipe's having high heat transfer ability, it removes drawbacks such as freezing and overheating encountered in many applications of solar collectors [2,3].

THPs have been used widely in evacuated tube solar collectors. A thermosyphon heat pipe evacuated tube collector (THPETC) consists of a thermosyphon heat pipe inside a vacuum-sealed tube. The vacuum envelope minimizes heat losses which occur with convection and conduction, so the collectors can operate at higher temperatures than flat plate collectors (FPCs). Also, they have higher efficiency at low incidence angles giving them an advantage over FPC in day-long performance [2].

The main difference in thermal performance between a heat pipe solar collector (HPSC) and conventional one lies in the heat transfer processes from the absorber tube wall to the energy transporting fluid. In the HPSC, the processes involved are evaporation, condensation and convection, whereas for conventional solar collectors, heat transfer occurs only in the absorber plate. Solar collectors with heat pipe have lower thermal masses, resulting in a faster response times [3].

Despite those advantages mentioned above, heat pipe solar collectors only account for a minor market share [4]. State of the art heat pipe collector show handicaps which currently lower their efficiency and durability and confine their application. One major drawback has been seen in the high thermal resistance of the heat pipe connection to the absorber or to the manifold of state of the art collectors, which results in a reduced efficiency. Also, the European

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Nomenclature

A	area (m^2)
C_p	specific heat (kJ kg^{-1} K^{-1})
$\dot{Ex}$	exergy rate (W)
F_R	solar collector heat removal factor
h	enthalpy (kJ kg^{-1})
I	solar radiation (W m^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
$\dot{Q}$	heat transfer rate (W)
R	ideal gas constant (kJ kg^{-1} K^{-1})
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
THP	thermosyphon heat pipe
$THPETC$	thermosyphon heat pipe evacuated tube collector
U_L	heat transfer loss coefficient (W m^{-2} K^{-1})
η	efficiency
ρ	density (kg m^{-3})
Ø	diameter (mm)
Ψ	flow exergy (availability) (W)
$(\tau\alpha)$	transmittance-absorptance product

Subscripts

a	ambient
atm	atmosphere
c	cross sectional
$cond$	condenser
$dest$	destroyed
f	fluid (air)
in	inlet
L	loss
m	mean
o	restricted dead state
out	outlet
sol	solar
u	useful
I	first law (energy)
II	second law (exergy)

research project [4], Quality Assurance in Solar heating and cooling Technology (QAiST), has revealed a relatively low long term stability of heat pipe collectors. Furthermore, noncondensible gases are introduced into the heat pipes by improper filling procedures or by chemical reactions between the working fluid and the container material, resulting in deviating power outputs. In addition, current heat pipe design restricts collectors to inclined or only quasi horizontal (>0°) orientation, lowering the degree of design flexibility [4].

The thermal performance of a THPETC is significantly affected by structure and geometry, manifold chamber, concentration of solar radiations, inclination angle, filling ratio and thermo physical properties of working fluid. Among those, working fluid is one of the most important factors, which can directly determine whether the THPETC is effective in the operation.

There are many studies on performance analyses of the HPETCs and comparisons with other solar collector such as flat plate solar collector, evacuated tube solar collector in the literature. In order to improve the performance of HPETCs, investigators have focused on concentrator (internal or external) at the HPETCs, working fluids, filling ratio and heat pipe's back surface emissivity. Some of these studies can be summed up as follow.

Redpath et al. presented experimental data from a heat-pipe evacuated tube solar water heater (ETSWH) subjected to the Northern Maritime Climate. They showed two laboratory models of the manifold chamber of a thermosyphon heat-pipe ETSWH constructed to the same dimensions to exhibit comparable behavior when exposed to the same similar rates of heat input as heat-pipe ETSWH. They presented and discussed information on internal heat transfer relationships and flow distributions [5]. Ayompe et al. presented the energy performance results of two solar water heaters with 4 m^2 flat plate collector (FPC) and 3 m^2 heat pipe evacuated tube collectors (ETCs) operating under the same weather conditions in Dublin, Ireland on daily, monthly and yearly basis. The annual average collector efficiencies are found to be 46.1% and 60.7% while the system efficiencies are obtained as 37.9% and 50.3% for the FPC and ETC respectively. Also, they found that both SWH systems are not economic [6]. Ayompe et al. developed a TRNSYS simulation model for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors. They compared model with experiment results for collector outlet fluid temperature and validation of the model was proved [7]. Hayek et al. investigated experimentally the overall performance of two solar collectors as the water-in-glass and heat pipe designs under local Mediterranean weather conditions. The results are in good agreement with similar results published by manufacturers and independent testing authorities. The heat-pipe-based collectors are better than the water-in-glass designs and their efficiency is almost 15–20% higher. Their payback periods are, however, much higher owing to their larger initial cost in the local market [8]. Nkwetta et al. compared the performance of an evacuated tube heat pipe solar collector with concentrated evacuated tube single-sided coated heat pipe absorber. They tested then at five different transverse angles (0–40°) with a collector title angle of 60° to the horizontal. They calculated the energy collection rates, efficiency and the heat loss coefficients of each solar collector and compared them with each other [9]. Nkwetta et al. conducted an optical evaluation and analysis of an internal low-concentrating evacuated tube heat pipe solar collector designed to enhance the collection of solar radiation. At different transverse angles, they used ray trace techniques which determine optical efficiencies, related optical losses and flux distribution on the absorber of the internal low-concentrating evacuated tube heat pipe solar collector [10]. Nkwetta and Smyth analyzed and compared two profiles of concentrated evacuated tube heat pipe solar collectors made of single-sided and double-sided absorber. They tested these innovative concentrated evacuated tube heat pipe solar collectors at a tilt angle of 60° to the horizontal and compared collection efficiency, heat loss coefficients and energy collection rates at five different transverse angles (0–40°) under in-door conditions [11]. Redpath evaluated the performance of two proprietary thermosyphon heat-pipe evacuated tube solar water heaters exposed to a northern maritime climate for one year and produced a correlation allowing the annual performance of these systems [12]. Du et al. designed and built an experimental platform for testing solar collectors at Southeast University, China. They investigated experimentally the performance of an evacuated heat pipe solar collector, in which a heat-pipe is used to transfer the heat from the collector to the water, by using the developed platform. They focused at the investigation on the instantaneous efficiency and its correlations