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Energy-exergy analysis of a multipurpose evacuated tube heat pipe solar water heating-drying system

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ABSTRACT

The current study was aimed to design, manufacture and examine a solar heating-drying system experimentally. The heat pipe evacuated tube collector in this system, in addition to supplying the required energy for water heating, supplied the energy needed for a dryer. Moreover, a water heat recovery system was considered for the dryer to enhance the overall efficiency of the system and to make maximum use of solar energy intake. Also, a mathematical model was developed for the energy and exergy analysis of the collector as well as validation with experimental results. In order to simulate the hot water consumption, the consumption pattern of a students' dormitory hall was used for the case study. The given system was tested under the weather conditions of Sanandaj city and the obtained results indicated the effectiveness of the heat recovery system. The findings showed the optimal number of collector pipes to be 15. Fluctuations of fluid temperature during hot water discharge and replacement with cold water caused fluctuations in collector outlet fluid temperature. Also, a direct association was observed between hot water consumption pattern and system performance. The changing trend of exergetic efficiency was ascending over time. At the end of the day, this efficiency reached its maximum level, about 10.6%. The performance of exchanger was highly dependent upon the ambient temperature and in the volumetric flow rate of 0.0328 m^3/s, the maximum outlet air temperature of dryer was about 45.5 °C. Also, maximum use of the auxiliary system was reported in the early morning (1.5 h), which was reduced over time. After 14:00 pm, the solar system was able to supply the required energy for the system individually. Finally, the findings of regression analysis showed the most accurate equation for expressing the effectiveness of the dryer as a function of environmental and functional parameter of x (which is equal to $(T_{w,i} - T_{amb})/G$) expressed as $\varepsilon = 112.21x^3 - 47.095x^2 + 5.8257x + 0.1139$.

1. Introduction

Heat pipes are double-phase instruments, with very high thermal conductivity, that are used for heat transfer. Heat pipes have lower thermal resistance than other metals, and many limitations of conventional collectors are removed by making use of a compact heat pipe system. High thermal conductivity, acting as a heat flow transmitter and isothermal level are the very significant characteristics of heat pipes for solar applications [1].

In recent years, several studies have been conducted to examine the use of heat pipes in solar water heating systems. Radhwan et al. experimentally evaluated solar water heaters by two methods, natural and forced water circulation. In the designed system, R-11 working fluid was used in the heat pipes. The findings showed that the slope of the condenser connected to the collector frame significantly affected the performance of natural water cycle system. However, this effect was trivial in the case of forced water cycle system [2]. A theoretical and experimental comparison of heat pipe solar collectors with conventional solar collectors was carried out by Ismail and Abogderah. They utilized methanol as working fluid in heat pipes. Moreover, for better condensation, the collector slope was considered to be 15° more than the normal state. The obtained results showed that heat pipe solar collector had a better efficiency than conventional solar collector [3].

Further, Hussein performed a theoretical and experimental analysis of heat pipe solar collectors without capillary structures. A cross flow heat exchanger was used as a condenser and distilled water was utilized as working fluid. The findings revealed that the performance of heat pipes without capillary structures was dependent on the inlet cooling water temperature, absorber plate materials and length and thickness of condenser. Also, the mass flow rate of the cooling water, which provided the optimal use of the system, was determined [4,5]. Jun-feng et al. made a comparison

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Nomenclature

A	area (m^2)
a	air
C_p	specific heat capacity (J/kg K)
c	collector
D	diameter (m)
d	diameter (m)
$\dot{E}x$	exergy rate (kW)
F	view factor
G	Solar radiation (W/m^2)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)/specific enthalpy (kJ/kg)
h_{fg}	latent heat (J/kg)
I	insolation (W/m^2)
k	thermal conductivity (W/m K)
L	length (m)
m	mass flow rate (kg/s)
N	number
$\dot{q}$	heat transfer rate (W)
$\dot{Q}$	heat transfer rate (W)
R	thermal resistance (K/W)
s	specific entropy (kJ/kg K)
T	temperature (K)/total
t	thickness (m)
U	heat transfer rate coefficient (W/m^2 K)
u	useful

Greek letters

α	absorptivity
ε	emissivity/effectiveness
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
σ	Stefan Boltzmann constant (W/m^2 K^4)
τ	transmittance
η	efficiency (%)

Indices

ab	absorber
amb	ambient
c	coating material on absorber/collector
e	evaporator
dest	destroyed
g	glazing cover
he	heat exchanger
hp	heat pipe
i	inner/inlet
k	location
l	liquid
o	outer/outlet
p	pipe
t	tank
v	vapor
Sc	solar collector
Sr	solar radiation
w	wick
u	useful
0	dead state

of solar water heaters with all glass vacuum tube collectors and heat pipe solar water heaters. A forced water convection system was designed and implemented. To analyze the performance of the system, instantaneous efficiency was determined. The findings showed that the heat pipe solar water system had less heat loss and better performance [6].

In addition, Ayompe and Dumpy analyzed the thermal performance of an evacuated tube heat pipe solar water heater collector. The field data were obtained by installment and operation of this experimental system in Dublin, Ireland over a year. An automatic subsystem was also used to control outlet hot water and submerged electric heater. The maximum output of collector and system efficacy levels were reported to be 63.2% and 52%, respectively. At last, it was found out that using a better strategy to control the pump in very cloudy days could improve the performance of the system [7]. Brahim et al. studied the addition of fin arrays to the condenser area of heat pipe solar collectors. A transient theoretical model was developed for the analysis of the performance of the solar heating system and the results of modelling were compared with experimental results in different periods of the year. Two types of working fluid (water and methanol) were used in the heat pipes and the results showed the performance of water system was slightly better than methanol system. Further, adding fin to the condensers of heat pipes increased the efficiency of the system. The trend of changes for system efficiency was ascending as the number of fins was increased. At last, the maximum density of the network was found to be 100 double-layer networks per inch [8]. A solar water heater installed on the wall of a balcony to be used in high-rise buildings was designed and made by Li et al. The collector was placed vertically on the walls of the balcony. The outlet hot water of collector was transmitted to the storage tank by a convertor and was then sent to the location where it was used. Four residential apartments with definite water consumption patterns were selected and the system performance in supplying their required hot water was evaluated. Meanwhile, theoretical analysis was carried out by TRNSYS software. According to experimental results, the average daily output of solar collector was reported to be about 40% [9].

Drying agricultural products is essential for maintaining them. This is done either by using fossil fuels through an artificial mechanical drying process or by placing the crops under solar radiation using an evacuated-tube air collector. The first method is very costly and has negative effects on environment and the latter is completely dependent upon weather conditions. In contrast, using solar dryers is comparatively easier and more efficient [10].

In a study, different drying systems were evaluated by Mustayen et al. Also, the environmental effects of solar energy, which play a vital role in solar dryers, was mentioned. Finally, the technologies that could improve the solar dryers were presented and discussed [11]. A review study was conducted by Chauhan et al. about the application of computational software in simulation of the performance of dryer system. These software are used to design and predict the performance of different kinds of solar dryers and to calculate such parameters as humidity rate, drying rate, etc. and are of great importance. Moreover, the developments and capabilities of various software in simulation of solar dryers were analyzed in this review study [12].

Predicting the performance of solar thermal dryers needs the convective heat transfer coefficient (absorber to the air flow) to be determined. In order to determine that, three types of solar dryers, direct (cabinet), indirect and mixed, was constructed by Singh and Kumar. The experiments were performed under steady-state air flow and no-load condition. Then for each dryer, free and forced heat transfer coefficients were presented in terms of dimensionless