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Numerical investigation on effect of riser diameter and inclination on system parameters in a two-phase closed loop thermosyphon solar water heater

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ABSTRACT

In this work, the effect of riser diameter and its inclination angle on system parameters in a two-phase closed loop thermosyphon solar water heater has been numerically investigated. Here, receivable heat flux by the collector, circulating mass flow rate, driving pressure, total pressure drop, heat transfer coefficient in risers and collector efficiency are defined as system parameters. For this aim, a model of two-phase thermosyphon solar water heater that is acceptable for various inclinations is presented and variations of riser diameter and inclination are considered. The riser tube size is varied from 1.25 cm to 2.5 cm with inclination range 2–75°. The system absolute pressure is set as 3567 Pa and water is chosen as working fluid. The results show that higher inclination angle is required for higher latitude location to obtain maximum solar heat flux. At local solar noon of 21.996 north latitude, the optimum inclination angle increases in the range of 24–44° with increasing of riser diameter giving maximum circulating mass flow rate from 0.02288 kg/s to 0.03876 kg/s. The longer two-phase heat transfer characteristics can be obtained at smaller inclination angles and mass flow rate for all riser tube sizes. Therefore, it is observed that the optimum inclination angles and diameters for solar heat flux, circulating mass flow rate and heat transfer coefficient in two-phase thermosyphon systemdo not coincide. From this work, better understanding and useful information are provided for constructing two-phase thermosyphon solar heaters.

1. Introduction

Solar energy is one of the renewable energy resources that hold a great potential for developed and developing countries in the future. Nowadays, it is being widely used for both heating and electricity generation. For heating applications, thermosyphon solar water heating systems are the most economic devices since no pumping power is required to operate the system. There are two basic types of thermosyphon solar water heaters according to the phase of working fluid used in the system. These are single-phase and two-phase solar water heaters. Components and working principle of each type are schematically described in Fig. 1a and b.

Generally, both types of loops mainly consist of solar collector (evaporator), upriser, condenser, storage tank and return pipe. In single-phase type, the whole system is filled with fluid and the flow is created by buoyancy and gravity forces that develop from density gradient induced by temperature difference in the system. The collector receives the solar heat flux and heats the fluid. Thus, the fluid in the collector gets hot and obtains lower density compared to the fluid in return pipe. Because of density difference on both sides, fluid from collector side goes up and the heavier liquid from return line takes place in the collector. Then, the hot fluid releases heat in the storage tank via condenser and returns to the collector to form circulation. In two-phase system, the system is partially filled with working fluid. Then, the fluid attains boiling and phase change process (from liquid to vapor) that is not occurred in the former type.

Single-phase solar water heaters are more economical and they have very simple structure. However, the market of single-phase solar heaters has been limited to warm climate since they have some drawbacks such as freezing and low system performance in extremely cold climate [1]. Thus, the use of two-phase solar water heating systems is becoming popular in both domestic and industrial applications. Since it has boiling and condensing process, heat transfer coefficient is far higher than for single phase convective heat transfer. Moreover, overall performance is higher than that in conventional single-phase systems [2–4]. The performance of two-phase solar thermosyphon systems depends on several system parameters such as solar heat flux that received by collector, circulating mass flow rate, driving pressure, pressure drop and heat

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Nomenclature

Symbols

A	cross-sectional area of pipe, surface area (m^2)
Co	convective number
c_p	specific heat constant (J/kg K)
Bo	bio number
d, D	diameter (cm, m)
F_{fl}	fluid-surface parameter
F_{rL}	Froude number
f	fanning friction factor, function of
e	surface roughness of pipe (m)
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^{-2})
H	hydro static head (m)
h	convective heat transfer coefficient (W/m^2 K)
I_0	solar constant (W/m^2)
i	enthalpy (J/kg K)
K	resistance coefficient
k	thermal conductivity of fluid (W/m K)
L	length (m)
m°	mass flow rate (kg/s)
N_d	number of days
N_u	Nulset number
P	pressure (Pa)
Pe_D	Pedal number
q''	solar heat flux (W/m^2)
Re	Reynolds' number
T	temperature (K)
V	velocity (m/s)
x	vapor quality
Z	axial distance (cm, m)

Greek symbols

α	collector inclination angle (°)
δ	solar declination angle (°)
ε	transmittance
μ	viscosity of fluid (N-s/m^2)
ϕ	solar hour angle (°)
ρ	density of fluid (kg/m^3)
θ	latitude of location (°)
σ	surface tension (N/m)
τ	atmospheric transmittance

Subscript

avg	average
CBD	convective boiling dominant
c	collector
cond	condenser
fitting	fittings
in	inlet
L	liquid
Lv	liquid vapor
m	mixture of liquid and vapor, mean
NBD	nucleate boiling dominant
ONB	onset nucleate boiling
r	riser
ret	return line
Sat	saturation
TP	two-phase
up	upriser
v	vapor

transfer characteristics in the system. To get stable operation and best performance, previously mentioned parameters must be balanced in the system. In turn, these parameters also depend on physical structural of the systems and they have interrelation to each other. Therefore, it makes the system requires optimum physical structure.

Since it is a necessarily important research area, a number of studies have been done on both single-phase and two-phase thermosyphon systems. Yilmaz [5] conducted numerical modeling for two-phase solar water heating system. In the modeling, non-homogenous two-phase flow, heat transfer in the collector and condenser were considered, and variation of the properties of the working fluids with temperature was taken into account. He presented that an optimum collector pipe diameter existed, and the homogeneous flow model was not sufficient to describe the two phase flow in the collector. Joudi and Al-tabbakh [6] carried out computer simulation on performance of a two-phase thermosyphon solar water heater by using R-11 as working fluid. Finally, he drew a conclusion that performance of two-phase system was higher than that of single-phase system. Belessiotis and Mathioulakis [7] has proposed a methodology that can be used for both designing the solar heating system and analyzing test results to improve the system. It was tested by validating with experimental data collected from a single phase solar thermosyphon solar water heater. Islam et al. [4] tested the performance of a two-phase solar collector in a water heating system by using acetone, methanol and water as working fluids. He performed experimental measurements by changing working fluid and evaluated instantaneous efficiency of the collector. He observed that working with methanol could give the best efficiency than water and acetone. Thus, his information was based only on working fluids and local solar hour. Samanci and Berber [2] experimentally investigated the performance of single-phase (water) and two-phase (R-134a) closed thermosyphon water heating systems that had the same specifications. He found that two-phase system was 42.8% more efficient than single-phase type. The other information provided is collector outlet temperature and storage tank temperature with variation of local solar time. Milanez and Mantelli [8] presented theoretical and experimental studies on the heat transfer limit due to pressure drop in a two-phase thermosyphon loop. He found that his numerical prediction data had a good agreement with experimental data. He explained that the larger the heat transfer rate through the loop thermosyphon, the larger the working fluid velocity and the larger the pressure drop. However, information related to collector inclination was not found in this work. Esen and Esen [9] has performed experimental study on efficiency of two-phase solar water heater by using various refrigerants. The results showed that the refrigerant R410A gives the highest thermal efficiency and he recommended that further studies are needed to optimize the collector parameters. In experimental observations done by Ordaz-Flores et al. [10], using acetone as working fluids in phase change system (two-phase thermosyphon) could give higher thermal efficiency compared to methanol. He also observed that creating partial vacuum could enhance the performance of the system. Hussein [11] reported comparison of experimentally measured and simulated results of temperature distribution in a constructed two-phase closed thermosyphon solar water heater. His investigations were emphasized on transient thermal performance of the system. The same author [12] has done optimization of two-phase thermosyphon solar water heater focusing on ratio of storage tank