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Theoretical and experimental study for temperature distribution and flow profile in all water evacuated tube solar collector considering solar radiation boundary condition

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ABSTRACT

This study investigated a three-dimensional transient numerical simulation of water flow inside evacuated tube solar collector connected to a storage tank. It validates the distribution of the temperature inside the evacuated tube with experimental data from other studies. Variation of the solar radiation intensity and angle of incidence were discussed. The Effect of radiation variation on temperature contours and flow circulation inside the tube was discussed as well. The simulation results showed an agreement with the experimental data by an average relative error ranging from 4.2 to 7.8% at the validated points of temperature measurements. The structure of the flow inside the tube is affected by the variation of solar radiation in intensity and incidence angle. This variation causes the streamlines inside the tube to form two different shapes. The first shape is linear profile beside the top surface of the tube upwards and inclined with the tube. The second shape is a helical one inside the tube declared at the end of the simulation time and was confirmed by a vision experiment. The helical shape is formed due to the synchronous motion of the sun rays on the outer surface of the tube and the motion of the flow upwards. This is clear when the buoyancy velocity increases around the solar noon time.

1. Introduction

Evacuated Tube Solar Collector ETSC is a promising type of the solar collectors that minimizes the heat losses. This is due to vacuum region between the coated absorber and the surface with direct contact with ambient air. This in turn reduces convection and conduction losses. Beside the existence of the vacuum, the absorber tube is coated by a material that has high radiation absorptivity and low radiation reflectivity for the solar irradiance. Due to these enhancements, the temperature can be higher in the ETSC than the flat plate collector.

There are many configurations for use of ETSC. It can be utilised with all water (also called passive) system which depends on the flow circulation by free buoyancy between the tube and the connected storage tank. The construction of all water ETSC with storage tank is illustrated in Fig. 1. Many research works were investigated in all water ETSC. Budihardjo and Morrison (2009) presented an experimental and simulation performance evaluation for thermosyphon circulation in single-ended ETSC and compared its performance to the flat plat collectors. Bracamonte et al. (2015) studied the effect of tilt angle on the thermal conversion efficiency and tank thermal stratification effect using experimental setups and numerical simulation. ETSC can be used with heat pipe thermosyphon connected with manifold systems in which many research works were presented such as Ersöz (2016), Daghigh and Shafieian (2016) and Javier et al. (2014). A third configuration uses ETSC with concentrators to be used in medium temperature applications. This topic was investigated by some studies such as Rabie et al. (1982), and Olczak and Olek (2016). Ma et al. (2010) and Tong et al. (2015) investigated the use of ETSC with U-tube forced circulation systems. On the other hand, Liu et al. (2014) investigated its use with concentric tubes forced circulation systems. Other configuration and systems can be found at Sabiha et al. (2015).

Budihardjo et al. (2007) studied the natural convection circulation in these experimentally and numerically under a fixed circumferential heat flux distribution. They considered evacuated tubes mounted over a diffuse reflector. They deduced a correlation of the flow rate inside the tube which is due to free convection. Huo et al. (1991) presented a visualized experiment using a translucent electric heating film on the outer surface of a glass tube to simulate the solar gain. They showed the transmission of the

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Nomenclature

α	solar elevation angle
Ψ	solar azimuth angle
$\Psi 1$	tube azimuth angle
β	tube inclination angle on the horizontal
X	south direction
Y	east direction
Z	vertical direction
X1	tube axis direction
Y1	horizontal axis of the tube Cross section
Z1	vertical axis of the Tube Cross section
$\theta_{Y1\text{-sun}}$	angle between the sun rays and Y1 axis
$\theta_{x1\text{-sun}}$	angle between the sun rays and X1 axis
θ	angle between the projection line of sun ray on the tube cross section and the horizontal axis Y1 of the tube cross section
$\vec{u}_{Y1}$	unit vector in the direction Y1
$\vec{u}_{Sun}$	units vector in sun ray directed from the earth to sun
$\vec{u}_{X1}$	unit vector in the direction X1
HA	hour angle
δ	declination angle
φ	local latitude
d	number of day in the year from 1 to 365

cold water from the tank inside the tube and its limitations. Morrison et al. (2004) investigated numerically the thermal performance of single ended all water ETSC. They mentioned the existence of inactive region near the end of the tube that might influence the performance of the collector. They stated that the flow profile inside the tube forms longitudinal closed circuits over the length of the tube. Morrison et al. (2005) studied numerically the thermal performance of Evacuated tube for predicting flow rate inside the ETSC with a fixed Circumferential heat distribution on an evacuated tube mounted over a varying diffuse reflector shapes. Shah et al. (2007) investigated numerically as well the thermo fluid performance of evacuated tubes oriented horizontally and connected with vertical manifold.

Due to the high cost spent in the experimental research work, many researches were conducted to develop numerical models. This minimizes the dependency on the experimental work and helps conduct the performance analysis with lower costs. Many experimental and numerical researches were presented for studying the thermal and flow characteristics inside the single-ended ETSCs.

Motivated by the aforementioned studies and the need for enhancing the design of ETSC, the work presented in this study introduces an investigation using computational fluid dynamics for the thermal performance of the single ended all water ETSC of one tube. This study is a three dimensional, transient simulation which considers the time variation of solar radiation intensity and incidence angle as a boundary condition. The simulation results were compared to experimental measures for the temperature distribution inside the evacuated tube to judge the simulation accuracy.

2. Numerical modelling

In the numerical study, the ETSC with tank was modelled for investigating its thermal performance. Therefore A 3D model for both the evacuated tube with double glassing and the tank was constructed using a structured grid. The solar irradiance was applied as boundary condition of direct and diffuse parts that vary with time. The change of solar radiation direction was also considered according to the longitude, latitude of the place and the orientation of the collector. The thermal and optical properties of the coating material for the inner tube and transparency of the outer one were considered. The Discrete Ordinates (DO) model was used for solar radiation modelling in the transparent domains of glass and vacuum. The gravitational acceleration was also considered to validate the buoyant flow resulting from tube inclination by 46°. The flow in the tube is considered to be laminar, transient. Flow and energy equations were solved for a period of 6 h transient simulation. SIMPLE scheme was used for velocity/pressure coupling. The CFD software used in this study is Ansys Fluent 14.5.

2.1. Geometry and mesh

The geometry consists of two concentric glass tubes with the outer one transparent having transmittance of 0.91.while the inner one is coated with a material of high absorption coefficient of 0.907. The tube is single ended whereas the open end is connected to the storage tank. The geometry is shown at Fig. 2.

The mesh is divided into three regions which are glass of thickness 2 mm for the inner and outer tubes, vacuum between the two glass tubes, and water in the tank and inside the inner tube. For keeping low aspect ratio between the adjacent cells of water and glass (two cells thick with 1 mm each), cells with very small thickness were constructed in the water region of the tube. This thickness increases gradually in the tube centre direction to decrease the number of cells as possible. The mesh used was structured with 299,800 hexahedral elements created by ANSYS-ICEM. The model boundaries are illustrated in Fig. 2. One cross-section of the mesh is illustrated in Fig. 3.

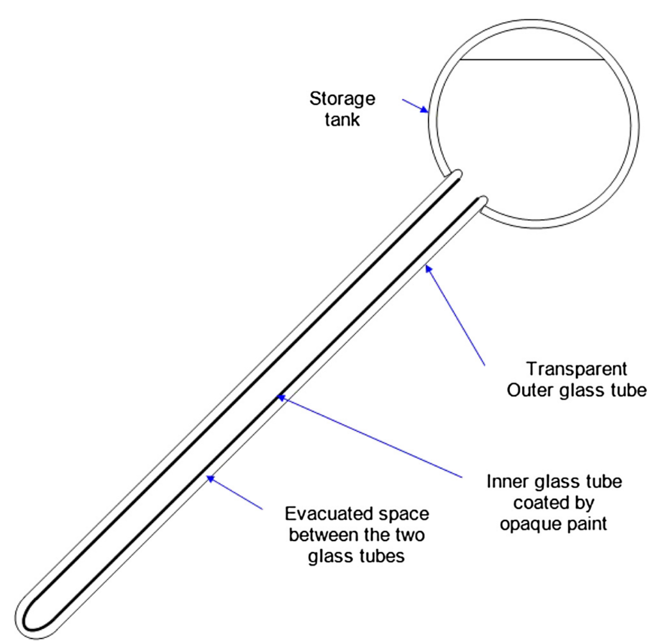

Fig. 1. All water Evacuated tube solar collector configuration.