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Modified mathematical model for evaluating the performance of water-in-glass evacuated tube solar collector considering tube shading effect

A.E. Kabeel*, A. Khalil, S.S. Elsayed, A.M. Alatyar

Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

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ABSTRACT

The aim of this paper is to introduce a procedure for simulating the absorbed solar radiation and heat transfer process in water-in-glass evacuated tube solar collectors. The procedure is developed to calculate the daily utilized solar energy and outlet collector temperature for different tilt angles, collector azimuth angles and geometric parameters without requirement for any experimental factor determination. Total absorbed solar radiation is evaluated by integrating the flat-plate solar collector performance equations over the tube circumference taking into account the shading of the adjacent tubes and variance of transmissivity–absorptivity product with the incidence angle of radiation. The heat transfer into the collector fluid is evaluated by subtracting the heat loss from the total absorbed solar radiation. Comparison between calculated and measured tank temperature shows a good agreement between them under different heating loads. Performance of solar collector at different tilt angles, collector Azimuth angles, tubes spacing and collector mass flow rate is investigated theoretically.

In Egypt (30° Latitude angle), the results show that 10°, 30° and 45° are the optimum solar collector tilt angles during the summer, vernal and autumnal equinox and winter operation respectively. Also, the utilized solar energy increases about 2.8% when the mass flow rate increases 100%, and the solar collector with south-facing has the best performance except for vertical tube solar collector. The simulation results also show that solar collector with wide tube spacing reduce the shading effect and hence increase the absorbed radiation. The final tank temperature as a function of collector's mass flow rate for three different days; 21 March, 21 June and 21 December is also investigated. The total incidence radiation, absorbed solar radiation and utilized heat per tube are presented for the three optimum tilt angles 10°, 30° and 45°. Efficiency curve of water-in-glass evacuated tube collector is also set into comparison with flat plate solar collector and salt gradient solar pond.

1. Introduction

The use of renewable energy finds a lot of interest nowadays due to the need of reducing the adverse environmental effects produced by the conventional energy sources, reducing the global energy demand from fossil fuel energy sources and preserving the provided reserves of oil and gas for the next decades.

Solar energy is the most reliable alternative energy source due to its abundance than other types of renewable energy.

Solar energy can be used for several applications such as water heating system, solar heating and cooling in air conditioning system, drying of agricultural products, distillation of sea water and electrical power generation by Photovoltaic cells. Solar collectors are the major devices used to deliver energy at moderate to high temperature for water heating, air conditioning and industrial process heating applications.

In solar collector, the incoming solar radiation is absorbed and converted into heat and then this heat transferred to the fluid flowing through the collector, there are basically two types of solar collectors: flat plate and evacuated tubes solar collector.

Evacuated tubes solar collectors can operate at higher temperatures than flat plate solar collectors due to the reduced convection loss obtained by vacuum envelope between tubes, they have

* Corresponding author.
E-mail addresses: kabeel6@f-eng-tanta.edu.eg, Kabeel6@hotmail.com (A.E. Kabeel).

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Nomenclature

A	area, m^2
c	tube spacing, m
c_p	specific heat at constant pressure, kJ/kgK
d	diameter, m
ETC	evacuated tube collector
$F_{C\text{-}S}$	view factor between collector and sky
$F_{C\text{-}ref}$	view factor between collector and ground
FPC	flat plate collector
G	total absorbed radiation, W/m^2
Gr	Grashoff number
H	utilized solar energy, kW h per tube per day
h	heat transfer coefficient, W/m^2K
I	total incidence radiation, W/m^2
k	thermal conductivity, W/mK
l	tube length, m
L	latitude angle
M	mass of water volume inside collector tank, kg
M	mass circulation rate, kg/s
N	number of tubes
Nu	Nusselt number
Pr	Prandtl number
Q_U	heat utilized, W
Q_L	Heat loss, W
q	heat flux, W/m^2
Re	Reynolds number
r	radius, m
t	time, s
T	temperature, °C
U	overall heat transfer coefficient, W/m^2K

Greek letters

μ	dynamic viscosity, pa·s
β_{ex}	expansion coefficient
β_o	tilt angle of collector
γ_c	azimuth angle of collector plane
δ	declination angle
η	efficiency
θ	incidence angle
ν	kinematic viscosity, m^2/s
ρ	reflectivity
σ	Stefan–Boltzmann constant
$\tau\alpha$	transmissivity-absorptivity product
ω	hour angle
ϵ	emissivity

Subscripts

a	ambient air
abs	absorber coating
ap	aperture
b	beam radiation
c	collector
d	diffuse radiation
g	glass
H	horizontal surface
i	inner
in	inlet
k	conduction
l	loss
n	normal
o	outer
out	outlet
r	radiation
ref	reflected
t	tube
u	utilized
v	convection
w	mean/bulk water

another priority as they collect both direct and diffuse radiation, evacuated tubes solar collectors become favorable during cold, cloudy and windy days than flat plate solar collectors.

Various studies have been carried out to evaluate the thermal performance of evacuated tubes solar collector.

Barrett [1] developed evacuated tubes solar collector model using the incidence angle modifier which can be approximated by the product of two separate incidence angle modifiers: transverse and longitudinal incidence angle modifiers for evacuated tubes solar collector. This technique has widely been used, among others, by Budihardjo and Morrison [2], Qin and Furbo [3]and Chow [4].

Heat transfer and flow pattern inside solar tubes for different operating conditions were also investigated. Wang and LiTing [5,6] studied the flow patterns inside horizontal tube with constant heat flux through fluid flow visualization experiments. Ren and Zhang [7] studied the natural convection in three-dimensional semi-closed cavity through numerical simulation and experiment, gave the empirical formula of convective heat transfer.

Beekley and Mather [8] first developed a mathematical procedure to estimate collectible radiation on a single tube of evacuated solar tube collectors. After then, Shah and Furbo [9] developed theoretical model to predict the optical and thermal performance of vertical evacuated tubes solar collectors without need of transverse incidence angle modifier by integrating the flat-plate collector's performance equations over the whole absorber circumference, also the model determines the shading from adjacent tubes as a function of the solar azimuth angle, but the model wasn't able to calculate for tilted pipes.

Tang, Gao [10] developed a detailed mathematical procedure to estimate daily collectible radiation on single tube of all-glass evacuated tube solar collectors based on solar geometry, results showed that the yearly optimal tilt-angle of solar tube collectors should be lower than the site latitude for maximizing the annual energy collection. This model developed a detailed procedure to calculate the total incidence radiation but doesn't account the absorbed radiation.

In the present work, total absorbed solar radiation by water-in-glass evacuated tube solar collector with tilted pipes is evaluated by integrating the flat-plate solar collector performance equations over the tube circumference taking into account the shading of the adjacent tubes and variance of transmissivity–absorptivity product with the incidence angle of beam radiation. The heat transfer into the collector fluid is evaluated by subtracting the heat loss from the total absorbed solar radiation.

2. Evacuated tube modeling

Water-in-glass solar water heater consists of an evacuated tubes and a storage tank mounted above the collector. The tube consists of three parts: two concentric glass tubes closed at one end while the other end is opened to the tank and the annular space between