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Effect of the collector tilt angle on thermal efficiency and stratification of passive water in glass evacuated tube solar water heater

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HIGHLIGHTS

- Experimental setup was used to validate a simplified 3D CFD transient simulation.
- Tilt angle has significant effect on energy gain, flow patterns and stratification.
- Low tilt angles lead to low velocities and marked thermal stratification.
- High tilt angles lead to full thermal mixing and lower temperatures.
- Stratification index exponentially dependent on the tilt angle is proposed.

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ABSTRACT

Passive solar water heaters are extensively studied and used around the world. Nevertheless, little is known about thermal stratification in their storage tank as most research on these devices reports averaged temperatures and energy conversion efficiency. Here we address the issue by analyzing the impact of the slope on thermal behavior of the device at low tilt angles, of particular interest for sub-tropical regions. In the present work the effect of the tilt angle on flow patterns, energy conversion efficiency and the stratification effect was studied with experimental setups and tridimensional numerical simulations as well. The study was performed using a commercial "water in glass evacuated tube solar water heater" (WGET-SWH) with nominal capacity of 40 L and 8 evacuated tubes. Experiments were carried during four weeks varying the tilt angle of the collector. The data gathered during the clearest days were used to validate the tridimensional Computational Fluid Dynamics (CFD) model. The numerical model was used to study the effect of several tilt angles (10°, 27° and 45°) with the same energy input. It was found that the tilt angle has significant effect on daily solar energy gain, flow patterns inside the storage tank and stratification. Nevertheless, it was found little impact on the thermal efficiency due to the low magnitude of heat losses though the vacuum tubes. Also, 10° tilt angle allowed to achieve significant higher temperatures and thermal stratification, along with a thermal inactive area at the bottom of the tank. Conversely, the content of the storage tank for the 45° tilt angle is fully mixed at the end of the heating process. This occurred mainly due to the relative position of the tubes' opening inside the tank and the mixing effect of the convective water flow. A non dimensional number to quantify the stratification effect is proposed and it was found an exponential dependence on the tilt angle. Some considerations regarding the use of WGET-SWHs on subtropical regions are made. No charge or discharge processes were considered in this work.

1. Introduction

Water heating represents a significant amount of energy consumption around the world. For residential accommodations it can be about 10 to 30% of the energy demand and up to 60% for health care facilities [1]. The growing concern about the environmental effects and the escalate on oil prices in last two decades along with the continuously increasing energy demand had lead to higher attention on solar technologies [2–6]. Solar water heating has been extensively studied and it has been reported that it can supply about 70% of sanitary water heating demand on residential and commercial facilities [7]. The most common models for low to

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Nomenclature

A_c	solar collection area (m^2)
c_v	isochoric specific heat ($J\,kg^{-1}\,K^{-1}$)
D	inner diameter of the storage tank (m)
E	total internal energy (J)
EN	non dimensional energy input number
e	specific internal energy ($J\,kg^{-1}$)
Fo	fourier number (non dimensional time lapse)
H	daily irradiation ($J\,m^{-2}$)
h	specific enthalpy (J/kg)
h_{tot}	specific total enthalpy (J/kg)
I	irradiance ($W\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
KE	total kinetic energy (J)
m	mass (kg)
$\hat{\mathbf{n}}$	surface normal vector
p	pressure (Pa)
ST_{Wu}	Wu and Bannerot's stratification coefficient (K^2)
ST	stratification index
SHW	solar water heater
T	absolute temperature (K)
T^*	non dimensional temperature $T^* = T/T_o$
T'	buoyancy temperature reference (K)
T_o	ambient temperature (K)
t	time (s)
t^*	non dimensional time $t^* = t/t_{total}$
t_{total}	total simulation time (s)
U	global heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\mathbf{u}$	velocity ($m\,s^{-1}$)
V	volume (m^3)
V_{nom}	nominal volume of the storage tank (m^3)
WGET-SWH	water in glass evacuated tube solar water heater
x_i, x_j	coordinates vector (m)
z	height measured from the bottom of the tank (m)
z_e	relative height of the tube opening from the bottom of the tank (m)
z^*	non dimensional height measured from the bottom of the tank $z^* = z/D$
z_e^*	non dimensional relative height of the tube opening measured from the bottom of the tank $z^* = z/D$
α	global absorptivity of the selective coating of the inner tube
β	tilt angle of the solar collector (degree)
β_V	coefficient of volume thermal expansion (K^{-1})
ρ	density ($kg\,m^{-3}$)
ρ'	buoyancy density reference ($kg\,m^{-3}$)
ε	global emissivity of the selective coating of the inner tube
τ	global transmissivity of the outer tube
$(\overline{\tau\alpha})$	effective transmissivity-absorptivity product
μ	viscosity (Pa s)
η	thermal efficiency

medium temperature applications are the single glazed flat plate solar collector and the water in glass evacuated tube solar water heater (WGET-SWH) due to their simplicity, high efficiency and low cost of maintenance and operation [1,8].

A WGET-SWH typically consists in a set of absorber tubes in direct connection with the storage tank. Each absorber tube consists in two concentric glass tubes sealed at one end leaving an evacuated annular space, while the inner tube is covered with radiation selective coatings [9]. The inner tube is flooded and the water is heated as most of the solar radiation is transmitted through the outer tube and absorbed by the inner tube, heat losses are minimal and mostly owing to longwave radiation. Hot water rises to the storage tank as a consequence of buoyancy forces and its replaced by cold water from the tank, establishing a water circulation driven by natural convection as long as the energy input persist [10]. The operation of these WGET-SWH is highly dependent on the tilt angle of the tube respect to the ground as it will affect the total irradiance on the absorber and the natural convection heat transfer [11].

China is one of the biggest manufacturers and consumers of WGET-SWH. On 2012 a solar collector area of about 250,000,000 m^2 for residential water heating was installed in this country, 90% of which was WGET-SWH [8]. This country has also set a mid-term goal of a solar collector area of 300,000,000 m^2 by 2020 [12]. This would mean a continuous growth of SWH manufacturing not only for the chinese market but also for its commercialization overseas.

Commercial WGET-SWH usually includes a support structure with a fixed tilt angle, in most cases of 45°. Tang et al. in 2011 [11] studied the effect of the tilt angle on a commercial model with nominal capacity of 130 L and a set of 18 evacuated tubes of 1.8 m long, by comparing the thermal performance of WGET-SWH with tilt angles of 22° and 46°. They found little effect of the tilt angle on the energy conversion efficiency although it had a great influence on the maximum temperatures achieved and the energy collection. They also found that the commercial tilt angle is not adequate for the southern regions of China as it collected less energy than the lower angle (22°).

Since most works dealing with passive integrated solar water heaters report average temperatures of the storage tank [13–16] little is known about thermal stratification in such devices. This work aims to quantify thermal stratification on WGET-SWHs and the effect of the tilt angle on these phenomena, in particular for angles below 22° usually not taken into account [10,11] despite their importance for sub-tropical regions.

Thermal stratification is usually a desirable effect in hot water storage tanks, as it could lead to higher operating temperatures [17,18], lower auxiliary energy consumption [19,20] and higher exergy outputs [21] than fully mixed storage, that is, energy storage at homogeneous temperature. It has been proved that the mass velocity of the input/output flows has a negative effect on stratification due to the mixing effect of the flow kinetic energy [22–24]. As consequence, low flow active water heating systems have proven to offer higher solar fractions than fully mixed tank systems [19]. Several stratification promoters had also been studied such as perforated plates, tubes, porous medias and fabrics [25,26]. Several definitions of indexes, efficiencies and performance numbers have been created for the quantitative evaluation of the stratification process [27,28]. Nevertheless, most of them are only applicable to forced convection systems, such as the MIX number [25]. To our knowledge, no studies dealing with stratification in collector-storage integrated passive systems as the WGET-SWH have been published until now.

Since high initial costs still are the main disadvantage of SWHs, these technologies had been widely applied only in countries with special energy policies that stimulate and subsidize renewable energy investments [1]. Hence, a proper installation, operation and maintenance are critical for the viability of these technologies.

In the present work the effect of the tilt angle on flow patterns, energy conversion efficiency and the stratification effect was