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Design and thermal performance optimization of a forced collective solar hot water production system in Morocco for energy saving in residential buildings

Saïf ed-Dîn Fertahi[a,b,*], T. Bouhal[a,b], F. Gargab[a,b], A. Jamil[a], T. Kousksou[b], A. Benbassou[a]

[a] Université Sidi Mohamed Ben Abdellah (USMBA), École Supérieure de Technologie de Fés, Route d'Imouzzer BP 2427, Morocco

[b] Université de Pau et des Pays de l'Adour (UPPA) – IFR, Laboratoire des Sciences pour l'Ingénieur Appliquées á la Mécanique et au Génie Electrique (SIAME), Av. Jules Ferry, 64000 Pau, France

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ABSTRACT

This paper presents a comprehensive study that aims to assess the energetic performances of a solar hot water collective system under a realistic load consumption profile in Morocco. The case study which has been considered in this work is a residential building located in Fez city. Several parameters are involved into the performance assessment of the collective system. Hence, it was essential to identify the parameters on which we will act in order to carry out the parametric study. In fact, the technology of evacuated tube collectors (ETC) with heat pipes were selected as a fixed study parameter, while a set of other indicators were investigated contributing to the collective hot water system design and optimization, such as the solar collector panel total area, the connecting methods between the collector's field which could be serial, parallel or mixed connection, the collective hot water storing volume configurations in addition to the intrinsic optical efficiencies of the world's manufacturers solar collectors. In order to achieve the assessment of the energetic performances of the collective system, four parametric studies were described and carried out to ensure its design and optimization during the dynamic mode operation.

The most relevant findings from this research paper are presented as follows. Incrementing the collector's field area to 120 m^2 optimizes the thermal efficiency of the collective system, and the hydraulic booster consumption is reduced. Besides, it would be advantageous to use a total area of 80 m^2 to satisfy the hot water need demand over the four seasons, since the overall collective system thermal efficiency remain above 60%. Moreover, is was possible to ensure a seasonal solar fraction which is greater than 50% by connecting a collective storage tank with a volume of 1500 l and a solar collector panel with an area of 100 m^2. Last but not least, the effect of the row's number as well as the number of collectors connected per row on the overall collective system's solar fraction was also investigated through this study.

1. Introduction

At the present usage level, it is accepted worldwide that the non-renewable energy resources will be available only for a limited period. Accordingly, the need for renewable energy resources has emerged and become very urgent. As an absolutely clean energy, solar energy is one of the most important energy source that has been highlighted so far (Koroneos and Tsarouhis, 2012). Solar water heaters technologies represent a solar thermal application, since they are now well developed and could be easily implemented at a low cost (Ascione et al., 2015).

A number of strategic studies on solar water heaters are available in the literature to investigate various aspects such as their national or international integration in the market, the price of their maintainability, marketing (Kalogirou, 2009). Recently, in North Africa's and Middle East countries (MENA) (Kousksou et al., 2015) several strategic studies on solar water heaters were conducted. For instance, in Algeria, the market potential and the development prospects of the solar water heater field were presented in the work of Sellami et al. (2016). Moreover, Al-Soud and Hrayshat (2009) studied the integrating possibility of a 50 MW concentrating solar power plant for Jordan country. In Lebanon, Ruble and Khoury (2013) investigated the barriers and the different achievements of domestic solar water heaters. Furthermore, a review on the renewable energy implementation progress in the Gulf Cooperation Council countries was released by Bhutto et al. (2014). For

* Corresponding author at: Université Sidi Mohamed Ben Abdellah (USMBA), École Supérieure de Technologie de Fés, Route d'Imouzzer BP 2427, Morocco.
E-mail address: fertahi.sayfdin@gmail.com (S.e.-D. Fertahi).

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Nomenclature

η	efficiency [–]
Q_u	useful energy [W/m^2]
A_c	collector area [m^2]
I_t	the total horizontal radiation [W/m^2]
$\dot{m}$	flow rate [kg/s]
C_p	specific heat at constant pressure [J/K kg]
T_{out}	outlet temperature [K]
T_{in}	inlet temperature [K]
η_0	zero loss efficiency [–]
a_1	first order heat loss coefficient [W/K m^2]
a_2	first order heat loss coefficient [W/K^2 m^2]
T_m	mean temperature [K]
T_a,T_{amb}	ambient temperature [K]
$\dot{m}_L$	fluid mass flow rate to the load and/or of the makeup fluid [kg/s]
T_L	temperature of the fluid replacing that extracted to supply the load [K]
U_i	loss coefficient between the tank and its environment (per unit area) [W/K m^2]
A_i	surface area of the ith tank segment [m^2]
C_{pf}	specific heat of the tank fluid [J/K kg]
T_i	temperature of the ith tank segment [K]
γ_f	a control function that defines if the auxiliary heater is off or on. 1 is off, 0 is on
$\dot{Q}_i$	rate of energy input by the heating element to the ith segment
ΔE	internal energy change of the tank
V_t	tank volume
ρ_f	fluid density
N	number of fully mixed (uniform temperature) tank segments (N < 15)
T_h	temperature of the fluid entering the storage tank from the heat source
f	solar fraction [–]
Q_{load}	Energy to load [W]
$Q_{Auxiliary}$	auxiliary energy of the booster system [W]
γ_i	a control function defined by $\gamma_i = \dot{m}_h \sum_{j=1}^{i-1} \alpha_j - \dot{m}_L \sum_{j=i+1}^{N} \beta_j$
α_I	a control function defined by $\alpha_i = 1$ if $i = S_h$; 0 otherwise
β_i	a control function defined by $\beta_i = 1$ if $i = S_L$; 0 otherwise
$\dot{Q}_s$	rate at which sensible energy is removed from the tank to supply the load
T_{env}	temperature of the environment surrounding the tank [K]

Abbreviations

ETC	Evacuated Tube Collector
MENA	Middle East and North Africa
SWH	Solar Water Heaters
DHW	Domestic Hot Water

residential and hotels applications, Delgado and Campbell (2014) worked on the adaptation and sizing of Solar Water Heaters in Desert Areas. Also, a systematic literature review released by Qazi et al. (2015) is addressing the importance of the artificial neural network in the prediction and design of solar radiation solar systems.

In South Africa, Ferrer (2017) carried out an average economic performance of solar water heaters for low density dwellings across. The potential and reality of the solar water heater program were studied in Tshwane townships (Curry et al., 2017), which is a South African City. South Africa was also considered as a studied case in Aigbavboa (2015), to highlight the low-income housing Residents' challenges with their Government after the integration of Solar Water Heaters (SWH) in buildings.

In Mexico, the Yucatan Peninsula, Quej et al. (2017) estimated the daily global solar radiation by day of the year in six different located cities. In addition to this, more precisely in urban and rural households also located in Mexico, Rosas-Flores et al. (2016) were interested in the potential energy saving by using solar water heaters. Their study was based on geographical information system.

In China, high priority in the promotion of buildings that are integrating solar water heaters in urbanized areas was presented in He et al. (2015) through an overview on the potential, recommendations, and experience of this solar technology. Moreover, Urban et al. (2016) proved that solar PV and more precisely solar water heaters are two different energy pathways to decrease the carbon emission in China. An overview about the development of solar water heater industry in China was also presented (Runqing et al., 2012), and an integrated approach to assess the performance of solar water heater in the urban environment was developed by Li and Liao (2014).

Solar water heaters are considered as a potential application in Turkey (Benli, 2016). In Australia, Rezvani et al. (2017) assessed the reliability of solar water heaters through Monte Carlo analysis. Their techno-economic integration possibility into the market was also considered in their study. In Taiwan, Chang et al. (2008) presented an outlook for solar water heaters. Also, Lin et al. (2015) estimated their payback period for residential buildings.

Actually, energy efficiency has become a priority in buildings (Bouhal et al., 2017b,c). Thus, Saini et al. (2017) carried out an economic analysis of various photovoltaic technologies' types which are integrated with greenhouse solar drying system. Moreover, Energy consumption and water rationalization in shower systems used in dwelling houses for single families was debated by Kordana's study (Kordana et al., 2014). The energy efficiency design for sustainable housing development was introduced through the studies of Roufechaei et al. (2014). As for another study, Chao et al. (2015) focused on the sustainable residential development that are using rainwater-sourced hot water supply through the establishment of water consumption characteristics. Besides, Baljit et al. (2016) conducted a review on two major solar integrated applications in building's sector, namely photovoltaic and solar thermal systems such as individual solar water heaters, and Jaisankar et al. (2011) released a comprehensive review on solar water heaters. Furthermore, residential and hotel buildings were considered as a case study by Zambrana-Vasquez et al. (2015) to assess the environmental impact of domestic solar hot water systems.

The life cycle environmental impact of a solar water heater was assessed (Koroneos and Nanaki, 2012). In fact, Arnaoutakis et al. (2017) realized comparative experimental Life Cycle Assessment of two commercial solar thermal devices for domestic applications. Besides, an ontology-based decision was presented in Kontopoulos et al. (2016) as a supporting tool to optimize the selection of domestic solar hot water system.

Interesting released scientific studies are currently investigating the key parameters in the operating conditions of solar hot water systems. In fact, Bouhal et al. (2017a) studied the impact of load profile and collector technology on the annual solar fraction savings of solar domestic water heaters under various Moroccan climatic conditions. In addition to this, Taheri et al. (2013) assessed the efficiency of a compact solar water heater. Besides, TRNSYS simulation tool is currently widely used to model the dynamic operation of solar water heaters (Shrivastava et al., 2017). In Quebec, Moreau and Laurencelle (2012) elaborated a field study of Solar Domestic Water Heaters. They also conducted a set of simulation to enhance the performance of an integrated collector in a storage solar water heater. In India, most of its industries that were taken as a case study are currently using solar

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