Renewable and Sustainable Energy Reviews 30 (2014) 526–537

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Dynamic thermal models and CFD analysis for flat-plate thermal solar collectors – A review

Luca A. Tagliafico, Federico Scarpa*, Mattia De Rosa

University of Genoa, DIME/TEC, Division of Thermal Energy and Environmental Conditioning, Via All'Opera Pia 15A, 16145 Genoa, Italy

A R T I C L E I N F O

Article history:
Received 31 May 2013
Received in revised form
3 October 2013
Accepted 19 October 2013

Keywords:
Solar collector
Dynamic models
Domestic water heating

A B S T R A C T

The detailed analysis of a solar collector is a complex task, due to the high number of parameters affecting its performance. In the last 40 years, several dynamic procedures have been developed and tested using numerical approaches, to obtain the behavior of the thermal solar collector without performing the set of complicated and expensive experimental tests usually adopted in steady-state approaches. Moreover, thanks to the improvement of the computing performance, these numerical models provide useful tools in reproducing for complex system behavior. In fact, when multiple energy sources are coupled together to build integrated systems (i.e., Solar-Assisted Heat Pumps, Ground-Source Solar-Assisted Heat Pump, etc.) the dynamics of each equipment has an noticeable influence on the behavior of the whole system. Therefore, these tools can be also profitably used to develop and optimize dynamic control criteria for these systems. In this context, a great effort has been made in the last years to improve the predictive potential of the dynamic models for solar collectors. Finally, thanks to the increase of the computational performance in the last years, Computational Fluid-Dynamics (CFD) approach has become a powerful tool to investigate the heat transfer phenomena. A lot of works have been made using both commercial and in-house developed codes, investigating several aspects concerning the heat transfer mechanism in a solar collector.

In the present work, an updated review of models for flat-plate thermal solar collectors is presented, including a proper classification and a description of their main characteristics and performance. A short description of the main works involving CFD analysis on thermal solar collectors is reported too.

Contents

* Corresponding author. Tel.: +39 010 353 2312; fax: +39 010 311 870.
E-mail address: fscarpa@ditec.unige.it (F. Scarpa).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.10.023

Nomenclature

A	area (m^2)
c_f	water specific heat ($J\ kg^{-1}\ K^{-1}$)
C_b	thermal conductance between plate and tubes ($W\ K^{-1}$)
D	tube diameter (m)
F_γ	thermal heat removing factor (–)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
$I_{p,n}$	global solar radiation normal to the panel surface ($W\ m^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{Q}$	heat transfer rate (W)
R	thermal resistance ($K\ W^{-1}$)
T	temperature (°C)
U	transmittance, global heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)

Greek symbols

α	absorbance coefficient (–)
β	surface tilt angle (rad)
β_{PV}	cell efficiency temperature coefficient (K^{-1})
δ	thickness (m)
ε	emissivity (–)
η	efficiency (–)
η_0	electrical efficiency at standard conditions (–)
σ	Stefan Boltzmann's constant ($W\ m^{-2}\ K^{-4}$)
τ	time (s)
τ_g	solar transmission coefficient for glass windows (–)

Subscripts

e	external
f	fluid
g	glass
i	internal
p	plate
w	water

1. Introduction

Nowadays, solar thermal systems have reached a large diffusion as domestic and commercial appliances. A standard thermal solar collector can be used both for domestic hot water (DHW) production and for heating purpose. Several system configurations have been developed in the last years to reduce the energy consumption of heating systems and their operating costs. The coupling of different energy sources (i.e., solar, geothermal, electrical energy, etc.) enables the realization of integrated systems with a high thermal performance optimization which, despite the higher initial system cost, can lead to remarkable energy savings, if compared with standard heating systems [1]. A first example can be found in the photovoltaic hybrid solar panel (PV–T), which permits the production of both electrical and thermal energies by coupling a photovoltaic solar panel with a set of tubes with cooling purpose (a detailed review of these systems can be found in [2,3]). Two different goals are achieved: (i) thermal energy can be produced and used for heating purposes and (ii) a lower working temperature of the solar cells is obtained and, consequently, the electrical conversion efficiency is increased. In the last years, new techniques have been investigated in order to increase the performance of the PV panels. As an example, it is possible to keep low the cell temperature by using phase change materials which can absorbe (or discharge) a large amount of energy during phase changes [4,5]. Moreover, the use of nanoparticles within the working fluids (nanofluids) permits to enhance the heat transfer, therefore increasing the thermal performance of the collector [6]. A further technique can be found by coupling the PV-panel to the evaporator of a heat pump, thus realizing a photovoltaic solar-assisted heat pump [7]. In this way it is possible to keep low the panel temperature and, in the same time, to provide the user with high temperature thermal energy.

Generally, several high performance system configurations have been developed: Solar-Assisted Heat Pumps (SAHP), Ground-Source Solar-Assisted Heat Pump (GS-SAHP) and Photovoltaic Solar-assisted Heat Pump (PV-SAHP). Ozgener and Hepbasli [8] and Ji et al. [9] described various plant arrangements in which solar collectors (both photovoltaic and thermal) can be coupled with heat pumps and geothermal storage. In all these configurations, the dynamic characteristics of each component have a strong influence on the short term thermal performance of the whole system. A careful design must involve a control strategy analysis to optimize energy savings during operation. In particular, the behavior of the solar collector, which is heavily influenced by the very quick variation of the external conditions during daytime (mainly due to solar irradiation), affects the working conditions and thus the performance of the system. Therefore, the understanding and the ability in predicting the dynamic behavior of solar collectors can give a strong incentive to develop suitable and optimized regulation strategies, especially when the collectors are directly coupled with other devices.

Moreover, a numerical model able to reproduce collector dynamic behavior represents a useful tool in order to perform more reliable external tests then those required by the usual standards [9–11], thus resulting in reduced execution time and costs.

To this end, several numerical models have been developed in the last years to describe the dynamic thermal behavior of flat-plate thermal solar collectors. Stepping from the early work by Smith [12], the main procedures adopted to model flat-plate thermal solar collectors are reported and analyzed in this paper. A list of the main works on this topic is reported in Table 1.

Since most of these models have been developed to obtain better external test procedure, a list of the main references about these testing procedures is given too. Finally, since during the last ten years, several computational fluid-dynamic analyses (CFD) of the thermal solar panel have been performed, a short description of these works is reported too, to complete and update the early review by Schnieders [13].

2. Steady state approach

The governing equations describing the phenomenon, based on the conservation of physical quantities (mass, momentum and