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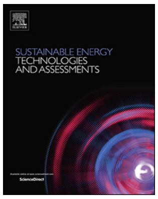

Original article

Development of an analytical model for the daily performance of solar thermal systems with experimental validation

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ABSTRACT

Flat plate collectors are the most widespread solar thermal collectors for low-temperature level applications as domestic hot water production and space heating. The objective of this study is to present a simple and analytical model for the prediction of the daily performance of an integrated system with flat plate collector. The developed model is tested with experimental results from a laboratory integrated system. This experimental set-up is investigated with details in order to determine its thermal performance and its dynamic response. After the validation of the developed model, the model is extended to realistic weather data for the climate conditions of Athens (Greece). The integrated system is evaluated energetically and financially by examining twelve typical days, one for every month. It is found that the investigated system can produce 2171 kW h thermal energy during the year with a mean thermal efficiency equal to 54.24%. The payback period is calculated at 5.03 years, an acceptable value which indicates sustainability. The present analysis clearly indicates that the developed model can be used for quick and accurate calculations on solar thermal systems in order to evaluate and optimize them on a daily basis.

Introduction

Solar energy utilization is one of the most promising renewable energy sources for achieving the sustainability [1,2]. Solar thermal collectors are widely used in a great variety of applications for thermal heat production in households up to electricity production in CSP plants [3,4]. Among the solar collectors, flat plate technologies are the most usual systems for low-temperature level applications (for instance domestic hot water production) and they are mature and reliable technologies [5,6].

Flat plate collector is a collector kind which operates in low-temperature levels up to 90 °C with an adequate thermal efficiency up to 70% [7]. The specific cost of this technology (without storage system cost) is low and it is generally ranged from 100 €/m^2 to 200 €/m^2. Thus, flat plate collectors are used in numerous applications worldwide as domestic hot water (DHW) production, space heating, space cooling with sorption machines and electricity production [8]. Among the previous applications, space heating and DHW production are the most ideal applications because they demand heat production at low-temperature levels (45–50 °C) where the FPC present high thermal performance [9,10].

In the literature, there is a plenty of studies associated with the flat plate collectors. The first thermal models have been developed by Hottel and Woertz at 1942 [11]. Later, numerous improved and more detailed models have been developed as from Klein [12], Close [13], Wijeysundera [14] and Taherian [15]. Moreover, numerous CFD studies have been performed in order to optimize and to improve the FPCs. Fan et al. [16] developed a CFD model in Fluent and compared it with respective experimental results. This model had good agreement with the experimental results, especially in high flow rates. Selmi et al. [17] performed a CFD analysis with the software CFD-ACE + and the developed model was close to the experimental results. Other CFD studies can be found in the literature in Refs. [18–21].

The dynamic simulation of the solar thermal system is usually performed using software tools. TRNSYS is the most widespread simulation tool with numerous developed studies on solar thermal systems [22–25]. Moreover, there are other tools as COLTEST which had been used in the study of Hossain et al. [26]. Another way to estimate the daily performance of solar thermal systems is by using the Input/Output method of ISO 9459-2 for small or great solar fields. This method predicts the system performance using three coefficients. The determination of these is usually performed experimentally. However, Belessotis et al. [27] calculated these coefficients and they explained their physical meaning. Moreover, they have validated their results with respective experimental studies [28] for great solar fields. The studies [27,28] have used theoretical models for estimating the daily

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Nomenclature

A_c	collecting area, m^2
c_p	specific heat capacity, J/kg K
E	energy, J
F_{ex}	exchanger efficiency parameter, –
F_R	heat removal factor of the collector, –
F'	efficiency factor of the collector, –
G_T	incident solar irradiation, W/m^2
$G_{T,max}$	maximum solar incident irradiation during the day, W/m^2
H_T	daily solar irradiation, kW h/m^2
k_1	first parameter of Eq. (15), –
k_2	second parameter of Eq. (15), –
m	mass flow rate, kg/s
m_1	first term parameter of Eq. (26), –
m_2	second term parameter of Eq. (26), –
m_3	third term parameter of Eq. (26), –
m_4	fourth term parameter of Eq. (26), –
N	day duration, s
T	temperature, °C
t	time, s
U_L	thermal loss coefficient of the collector, W/m^2 K
$(UA)_{ex}$	total heat exchanger coefficient, W/K
$(UA)_T$	total tank thermal loss coefficient, W/K
V	storage tank volume, m^3

Greek symbols

Δt	time period, s
η	efficiency, –
ρ	density, kg/m^3
$(\tau\alpha)$	transmittance absorbance product, –

Subscripts and superscripts

am	ambient
end	end of the operation
fm	fluid mean
in	fluid inlet
loss	thermal losses
m	mean
s	storage tank
sol	solar
st	stored
start	start of the operation
out	fluid outlet
u	useful

Abbreviations

CFD	computational fluid dynamics
CSP	concentrating solar power
DHW	domestic hot water
FPC	flat plate collector
IRR	internal rate of return
NPV	net present value
PP	payback period
SPP	simple payback period

performance of solar thermal systems, something that is not usual in the dynamic analysis of them.

In this study, an analytical method is developed in order to test the daily performance of an integrated solar thermal system. This analysis aims to give a quick and accurate way for estimating the dynamic performance of solar systems, as well as their daily and yearly useful energy yield. The solar collector is a laboratory flat plate collector of 2.14 m^2 coupled to a storage tank of 0.15 m^3. This system is investigated for all the year period for the climate conditions of Athens, Greece. The results show the yearly and the monthly energy performance, as well as a brief financial evaluation, are performed. The developed model is tested with experimental results. Emphasis is given in the presentation of the experimental procedure in order to prove the accuracy of the obtained values. This model can be used for the quick and accurate evaluation of solar thermal systems. The innovation of this work is based on the simplicity of this presented model. Moreover, the analytical equations are solved for a reasonable solar irradiation profile, the fact that makes the presented model be important. The results of this work can be used for the thermal and financial evaluation of integrated solar thermal systems with flat plate collectors and for the system optimization.

Materials and methods

Experimental set-up and experimental investigation

The experimental set-up is given in Fig. 1. This configuration is developed in the Thermal Department of School of Mechanical Engineering in National Technical University of Athens (Greece). This system is a laboratory integrated solar flat plate collectors with lamps. This system has been installed for experimental purposes in the laboratory. This system operates under steady-state conditions with incident solar irradiation equal to 500 W/m^2 and flow rate 1.85 L/min. It is important to state that during the experiments, the flow rate was kept

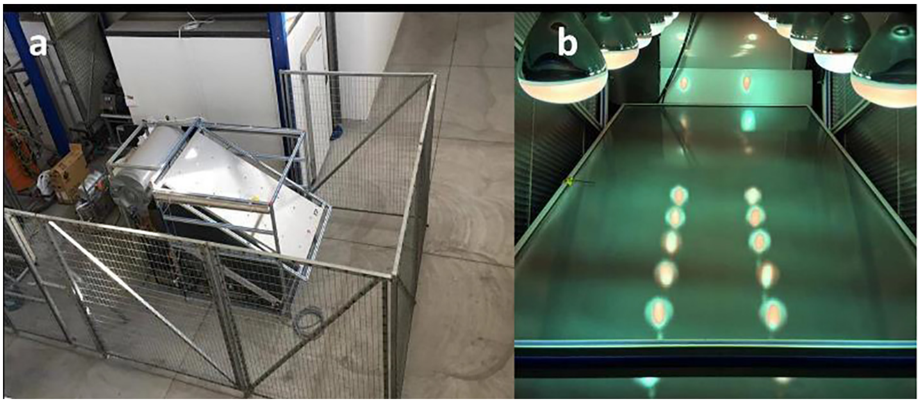

Fig. 1. The examined FPC collector a) The total experimental setup b) View of the lamps.