MODELING OF A SOLAR WATER COLLECTOR OF A MULTIFUNCTIONAL HELIOTECHNICAL SYSTEM

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https://doi.org/10.5281/zenodo.18383727

ARTICLE INFO

Received: 24th January 2026
Accepted: 25th January 2026
Online: 26th January 2026

KEYWORDS

Flat-plate solar collector; Energy balance model; Transient heat transfer; Implicit finite difference method; Solar water heating; Thermal performance simulation.

ABSTRACT

A mathematical model based on energy balance equations is developed to describe the transient thermal behavior of a flat-plate solar water collector. The proposed model enables the determination of the time-dependent temperature variations of the transparent cover, air gap, absorber plate, insulation layer, and working fluid (water). The collector is divided into several control volumes perpendicular to the fluid flow direction, and distributed-parameter energy balance equations are formulated for each component. The resulting system of coupled differential equations is solved numerically using the implicit finite difference method. Thermophysical properties of the working fluid, absorber, and air layer are evaluated as temperature-dependent parameters, while heat transfer coefficients are determined dynamically in real time. The model is applied to simulate the performance of the collector under actual operating conditions. Theoretical results indicate that the average outlet water temperatures on May 17 and May 18, 2025, reach 54.4 °C and 60.7 °C, respectively. The developed approach provides an effective tool for predicting the thermal performance of flat-plate solar collectors and can be used for their design optimization and operational analysis.

Introduction

In the study by Mateus and Oliveira, the potential application of solar energy in air-conditioning systems was investigated [1]. To reduce the consumption of conventional fossil fuels, solar-based cooling and heating systems were integrated. The baseline evaluation was performed using a simulation model implemented in the TRNSYS software environment for different types of buildings, including hotels, residential dwellings, and office buildings. Three locations characterized by distinct climatic conditions were selected for analysis: Rome, Lisbon, and Berlin. The results indicated that the solar energy contribution ranged from 20% to 60%. The highest economic efficiency from solar energy integration was achieved in singlefamily residential buildings and hotels. Furthermore, it was reported that the integration of solar energy reduced operational costs by approximately 35% to 45%.

Physical model and assumptions

Ekramian et al. [2] conducted a numerical investigation to examine the influence of various parameters on the thermal performance of a flat-plate solar collector (FPSC). Different geometrical configurations and operating conditions were considered to assess the effects of the collector tilt angle, tube cross-sectional geometry, mass flow rate, absorber thickness, absorber material, absorber absorptivity, and the transmittance of the transparent cover on the thermal efficiency of the FPSC. The geometry of the tube cross-section was found to have a significant impact on performance. Specifically, the efficiency of an FPSC equipped with circular tubes was 4.8% higher than that of a collector with triangular cross-section tubes. Moreover, the thermal efficiency of the FPSC increased with increasing fluid velocity, absorber absorptivity, absorber thickness, and transparent cover transmittance.

Based on the aforementioned studies, energy balance equations describing the heat transfer processes between the individual components of the FPSC are formulated. In the proposed approach, the collector is divided into five regions perpendicular to the flow direction (transparent cover, air gap, absorber plate, working fluid, and insulation), and an energy balance equation is established for each region. The resulting system of differential equations is solved using the implicit finite difference method [3,4]. The application of this numerical scheme enables the elimination of the limitations associated with previously reported solution techniques. The thermophysical properties of the working fluid, absorber plate, and air gap are evaluated in real time, while the spatial and temporal distributions of the heat transfer coefficients are determined dynamically. The control volume of the FPSC illustrated in Figure 1 is subsequently analyzed.

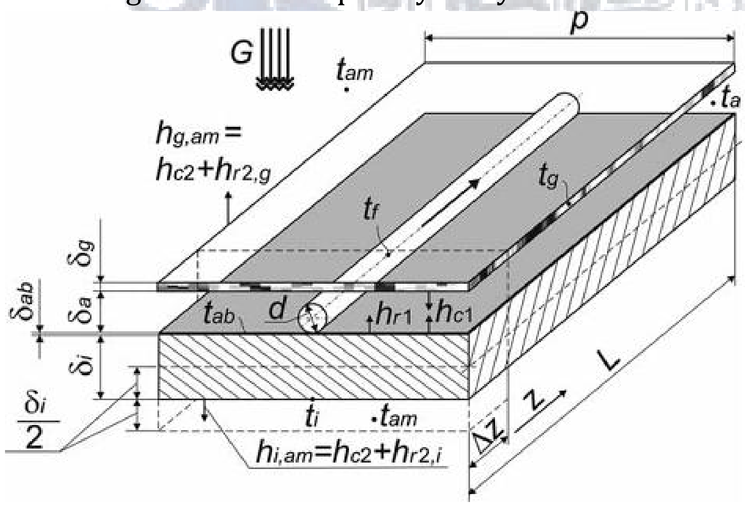

Figure 1. Control volume of the analyzed flat-plate solar collector (FPSC) with a single-layer transparent cover.

Results and discussion

In this approach, the exact spacing of the tubes is taken into account. In the proposed distributed-parameter model, calculations are performed along a single tube in the direction of the working fluid flow. The tube dimensions are assumed to be identical to those of the tubes installed in the existing flat-plate solar collector (FPSC). The mass flow rate of the fluid is also calculated with respect to a single tube. The proposed method is based on the assumption that the working fluid flows uniformly through all tubes of the FPSC under a parallel-channel flow configuration.

The proposed one-dimensional model is intended to simulate the operation of the FPSC while accounting for time-dependent boundary conditions:

(a) all elements within the analyzed control volume correspond exactly to the elements of the actual FPSC;

(b) the mass flow rate of the working fluid is determined as follows [5]:

$$m_{i.j} = m_u/n \tag{1}$$

(v) all thermophysical properties of the working fluid, absorber plate, transparent cover, and the air gap between the transparent cover and the absorber are evaluated in real time as temperature-dependent properties (the properties of the transparent cover and the insulation are assumed constant) [6];

(g) all heat transfer coefficients are determined in real time.

Based on the above assumptions, the energy balance equations are formulated for each component of the flat-plate solar collector (FPSC), as follows:

for the single-layer transparent cover:

$$c_{sh}\rho_{sh}V_{sh}\frac{dt_{sh}}{d\tau} = \alpha G A_{sh} + h_{r,a-sh}(t_a - t_{sh})A_a + $$
$$+ h_{k,sh-t.m}(t_{t.m} - t_{sh})A_{sh} + h_{k,sh-h}(t_h - t_{sh})A_{sh} \tag{2}$$

- for the air gap between the transparent cover and the absorber plate:

$$c_h\rho_h V_h\frac{dt_h}{d\tau} = h_{k,sh-h}(t_{sh} - t_h)A_{sh} + h_{k,a-h}(t_a - t_h)A_a \tag{3}$$

- for the absorber plate:

$$c_a\rho_a V_a\frac{dt_a}{d\tau} = \alpha\tau G A_a + h_{r,a-sh}(t_a - t_{sh})A_a + h_{k,a-h}(t_a - t_h)A_a +$$
$$+\frac{k_i}{\delta_i}(t_i - t_a)A_a + \pi d_{ich}\Delta z h_s(t_s - t_a) \tag{4}$$

- for the working fluid (water):

$$c_s\rho_s V_s\frac{dt_s}{d\tau} = m_s i_s|_z - m_s i_s|_{z+\Delta z} + \pi d_{ich}\Delta z h_s(t_s - t_a) \tag{5}$$

- for the insulation material:

$$c_i\rho_i V_s\frac{dt_i}{d\tau} = \frac{k_i}{\delta_i}(t_a - t_i)A_a + h_{k,i-t.m}(t_{t.m} - t_i)A_i \tag{6}$$

Conclusion:

A mathematical model based on energy balance equations was developed to determine the temporal variations of the temperatures of the transparent cover, air layer, absorber plate, insulation, and water in the solar water collector of a heliotechnical system.

The developed model of the flat-plate solar collector (FPSC) was solved using the implicit finite difference method. According to the theoretical results, the average outlet temperatures of the water flowing through the FPSC tubes on May 17 and May 18, 2025, were found to be 54.4 °C and 60.7 °C, respectively.

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