4Evolution

SimTerm2022 PROCEEDINGS

20th International Conference on Thermal Science and Engineering of Serbia

Niš, Serbia, October 18-21

ENERGY EFFICIENCY ECONOMY ECOLOGY

SimTerm2022

PROCEEDINGS

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Numerical investigation of the insulation use possibility in the glass tube solar collector with a flat absorber plate

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Abstract: This paper presents a numerical investigation of the new solar collector (SC) type – the glass tube SC with a fixed flat absorber plate and with insulation (FFAPI). The thermal performance of the FFAPI was analyzed using Ansys Fluent software. The reference sample (to justify the FFAPI application) was played by the (control) glass tube SC with a flat absorber plate and without insulation (FFAP). Both SCs are composed of the same glass and absorber dimensions. The ambient conditions of their work are also the same. Two variables are defined for an arbitrarily chosen summer day (26 July – weather file downloaded from the Ansys Fluent database). The first variable is the water inlet temperature (40°C, 45°C and 50°C). The second variable is solar radiation, which is a function of time (8:00 h, 10:00 h, 12:00 h, 14:00 h and 16:00 h). In the first case (water inlet temperature 40°C), the FFAPI heat power is 0.63-12.83% higher than the FFAP. With increasing temperature, these differences become even greater. In the second case (45°C) this difference is 5.02-21.12%. In the third (50°C) 10.95-33.31%. All in favor of the FFAPI.

Keywords: Fixed flat absorber plate, Glass tube, Insulation, Numerical simulation, Solar collector, Thermal analysis.

1. Introduction

By reducing heat losses, the thermal performance (operating temperature, heat power, thermal efficiency) of the SCs can be significantly improved. This is achieved by using quality materials (anti-reflective glass, selective absorbers, insulating materials, vacuum technologies, working fluids, etc.), which depend on the design solution itself.

The evacuated tube solar collectors (ETSCs) group was not an exception (spared) in this regard. This is evidenced by a large number of researches, including numerical ones, available in the literature.

ETSC with U pipe (simplified) numerical investigation is shown in [1]. Numerical results showed agreement with experimental results (maximum experimental error was between 6.9-12.7%). On the other side (example [2]), the use of various nanofluids and selective coatings (Al_2O_3 and CuO) can also improve ETSC performance, but such research is mostly experimental (the same applies to flat plate solar collectors, ie. FPSCs). Although compound parabolic concentrators (CPCs) are a special category of solar collectors (example [3]), there are examples when the aforementioned reflectors are combined with ETSC. ETSC numerical research (with and without fixed parabolic reflector) and inserted nano-PCM fin (in space between the heat pipe and voice tube) are shown in [4]. The results showed that the smaller thickness of the fins has a positive effect on heat transfer. The same effect is achieved using a parabolic reflector (unlike ETSC without its use). One more important conclusion is reached in [4]: working fluid outlet temperature from heat pipe can be increased by 2°C by adding only 1% copper to the PCM. In a review paper [5], which is based on numerical optimization studies, studies of both nanofluids and reflectors' influence on ETSCs' thermal performance are presented. Fixed, flat, single-sided reflector under horizontally packed ETSC was mathematically investigated in [6]. A similar investigation (experimental and theoretical) is given in [7]. Parabolic selective coating effect (with different dimensions) on the inside of the external glass tube ETSC was analyzed in [8]. The thermal efficiency of this SC type can be 65-72%, when solar radiation is about 950 W/m2, the water inlet temperature is between 45-70°C and ambient temperature is about 31.2°C. In global terms, the thermal efficiency of this specific ETSC construction is about 10% better than the classic ETSC construction. ETSC combination with an external (fixed) CPC can also be considered a good solution because in this way theoretical thermal efficiency is reached at about 68.9% [9]. Three methods (Solidworks software package, analytical method and experimental measurement) to investigate 4 commercial ETSC types with U pipe and external mini-CPC in [10] were used. Simulation and analysis results differ from the experimental by 3.7% and 9.3%, respectively.

In this paper, the new SC construction is numerically (with Ansys Fluent software) presented, which combines glass tubes (characteristic for ETSC), fixed flat absorber plate (characteristic for FPSC) and insulation (also used in FPSC). It is the glass tube SC with a fixed flat absorber plate and insulation (FFAPI), i.e. the fixed SC construction with great potential for future application.

2. Research subject

2.1 CATIA design

The subjects of research are (Fig. 1): the glass tube SC with a fixed flat absorber plate and with insulation (FFAPI, Fig. 1a) and the glass tube SC with a fixed flat absorber plate and without insulation (FFAP, Fig. 1b).

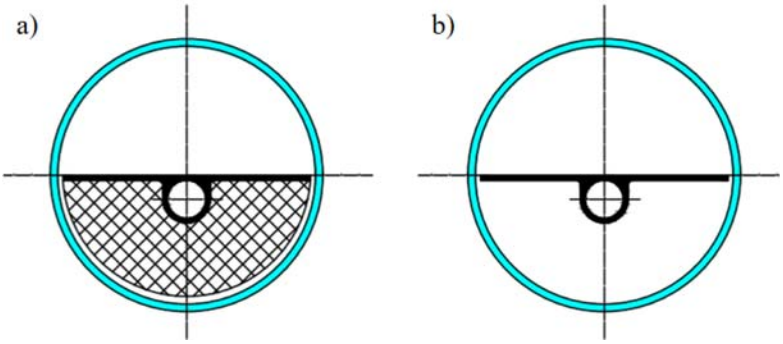

Fig. 3. Cross-section view of the glass tube SC with a fixed flat absorber plate. a) With insulation (FFAPI), b) without insulation (FFAP).

From Fig. 1. (Fig. 1a and Fig. 1b) it can be seen that the fixed flat absorber plate (dimensions 800x100 mm and thickness 2 mm) has a circular cross-section flow channel (inner diameter Ø15 mm) on the bottom side. The insulating layer (Fig. 1b) is located inside the glass tube (outer diameter Ø110 mm, thickness 3 mm and length 800 mm), under the absorber plate. The thermal characteristics of the materials used are given in Tab 1.

Tab. 1. The thermal characteristics of the materials used.

Layer	Material	ρ [kg m^{-3}]	c_p [J kg^{-1} K^{-1}]	λ [W m^{-1} K^{-1}]	μ [Pa s]	a [-]	τ [-]
Gas fluid	Air	1.225	1006.43	0.0242	0.0000179	-	0.9
Fixed flat absorber plate	Aluminum	2719	871	202.4	-	0.9	-
Insulation	Mineral wool	14	840	0.037	-	-	-
Working fluid	Water	998.2	4182	0.6	0.001003	-	-

2.2 ANSYS design

Thermal analysis was preceded by the formation and definition of the following domains (Fig. 2): two fluid domains and three solid domains (FFAPI, Fig. 2a) and two fluid domains and two solid domains (FFAP, Fig. 2b).

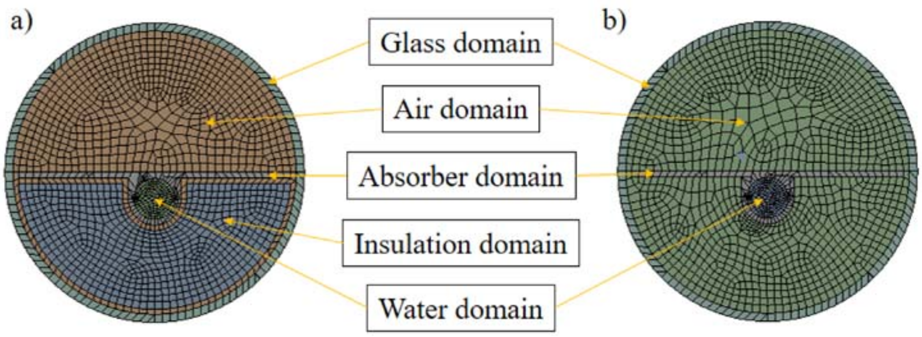

Fig. 2. Fluid and solid domains. a) FFAPI, b) FFAP.

Global network parameters (Automatic Method) were used to create a network of discretization elements, the so-called control volumes (Fig. 2a and Fig. 2b) with the following dimensions (Sizing tab): Relevance Center – Fine, Smoothing – High and Span Angle Center – Fine).

2.3 Thermal performances

In the mathematical sense, the heat transfer mechanisms (conduction, convection and radiation), for the case of turbulent flow regime (k-ε standard model) of water and air, must be in accordance with the Laws of Conservation, i.e. Principles of Conservatism.

The Conservation of Mass (the First Principle of Conservatism) can be described by Eq. (1) [11]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

The Second Principle of Conservatism, i.e. the Conservation of Momentum is defined by the Navier-Stokes equations, i.e. Eqs. (2)-(4) [11]:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+X \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+Y \tag{3}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial P}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+Z \tag{4}$$

And finally, the Third Principle of Conservatism refers to the Conservation of Energy Eq. (5) [11]:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

SCs thermal power can be determined analytically, by applying the First Law of Thermodynamics for open systems Eq. (6) [12]:

$$\dot{Q}_{SC}=\dot{m}_{SC}\cdot c_P\cdot\Delta T_{SC}=\dot{m}_{SC}\cdot c_P\cdot\left(T_{SC-out}-T_{SC-in}\right) \tag{6}$$

3. Discrete Transfer Radiation model

In this case, it is used Discrete Transfer Radiation (DTR) model. For this model, the radiation transfer equation is solved along straight rays Eq. (7) [13]:

$$\frac{dI}{ds}=-a\cdot I+\frac{a\cdot\sigma\cdot T^4}{\pi} \tag{6}$$

DTR is a simple model that is convenient for simulating the effects of shading [13].

4. Scenario simulations

The thermal characteristics of the mentioned SCs (Fig. 1) were tested by the software Ansys Fluent, with identical weather conditions (Tab. 2). In the same table, all boundary conditions (constant and variable) used in this study are shown.

The water speed was adopted according to the recommendations that the mass flow rate through the SC should be 0.0015 kg s^{-1} m^{-2} [14]. The adopted heat transfer coefficient from the outside of the SCs (from the glass tube to the surrounding air) corresponds to the air speed of 1 m s^{-1} [14].

For each time moment (Tab. 2), the Ansys Fluent software has data related to solar radiation (direct, diffuse and reflected) on a horizontal surface (Tab. 3).

Tab. 2. Boundary conditions.

Scenario	Variables		Constants		
	$T_{SC\text{-}in}$ [K]	Time [h]	$c_{SC\text{-}in}$ [m s^{-1}]	T_A [K]	h_A [W m^{-2} K^{-1}]
I	313	8:00; 10:00; 12:00; 14:00; 16:00	0.0068	303	5.8
II	318				
III	323				

Tab. 3. Solar radiation on a horizontal surface for 26 July.

Time [h]	I_{DIR} [W m^{-2}]	I_{DIFF} [W m^{-2}]	I_{RREFL} [W m^{-2}]
8:00	777.86	104.03	58.09
10:00	852.23	113.97	83.14
12:00	867.35	116	90.27
14:00	838.94	112.2	77.58
16:00	735.18	98.32	48.42

5. Results and discussion

The following figures show characteristic surface temperature fields for the FFAPI (Fig. 3) and the FFAP (Fig. 4), for different values of $T_{SC\text{-}in}$.

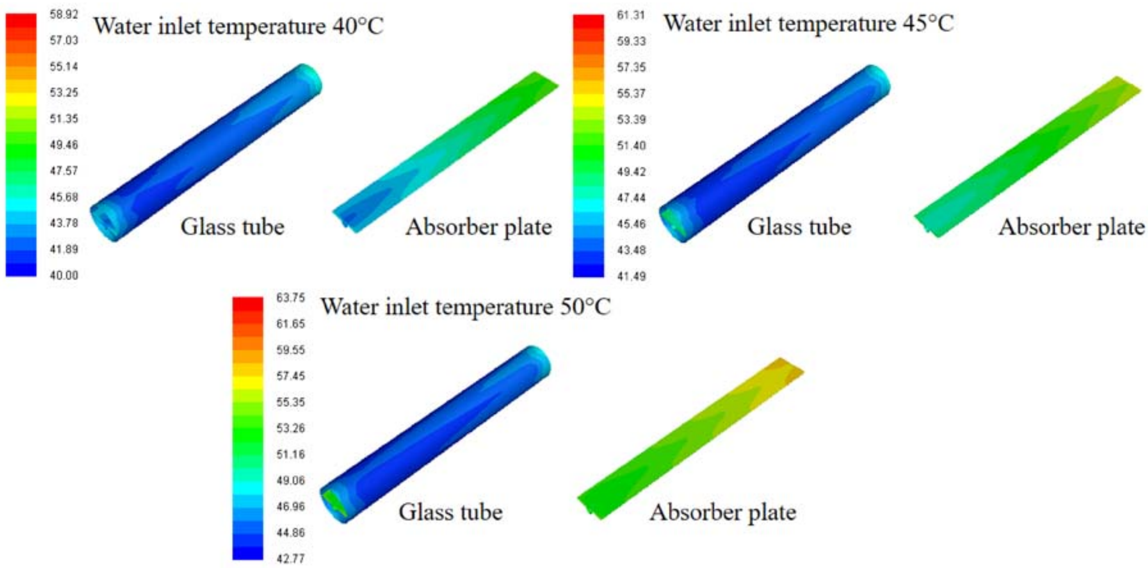

Fig. 3. Characteristic surface temperature field of the FFAPI (26 July, 10:00 h).

Viewed longitudinally, the temperature gradient of the fixed flat absorber plate surface increases with the increase of the water inlet temperature (Fig. 3 and Fig. 4). Therefore, the absorber plate average temperature for both SCs is the highest when the water inlet temperature is also the highest, i.e. 50°C (upper limit of numerical investigation). On the other hand, the outside glass tube surface temperature is fairly balanced, although it also increases with increasing $T_{SC\text{-}in}$.

The comparison of the SCs heat powers, during an arbitrarily chosen day (26 July), depending on the water inlet temperature, is shown in the following figures: for $T_{SC\text{-}in}$=313 K (Fig. 5), for $T_{SC\text{-}in}$=318 K (Fig. 6) and for $T_{SC\text{-}in}$=323 K (Fig. 7).

For $T_{SC\text{-}in}$=313 K (Fig. 5), the FFAPI heat power during the 26 July is: 36.01 W (8:00 h), 41.69 W (10:00 h), 39.93 W (12:00 h), 41.1 W (14:00 h) and 32.83 W (16:00 h). The FFAP heat power during the same day is: 33.07 W (8:00 h), 40.7 W (10:00 h), 39.68 W (12:00 h), 39.62 W (14:00 h) and 29.09 W (16:00 h). The smallest difference (in favor of the FFAPI) was achieved at 12:00 h (0.63%), while the largest was achieved at 16:00 h (12.83%). For $T_{SC\text{-}in}$=318 K (Fig. 6), the FFAPI and FFAP heat powers during the 26 July are, respectively: 8:00 h (33.23 W and 28.76 W), 10:00 h (38.89 W and 36.35 W), 12:00 h (37.13 W and 35.36 W), 14:00 h

(38.28 W and 35.3 W), 16:00 h (30.05 W and 24.81 W). On a daily basis, the FFAPI is 9.52% better than the FFAP.

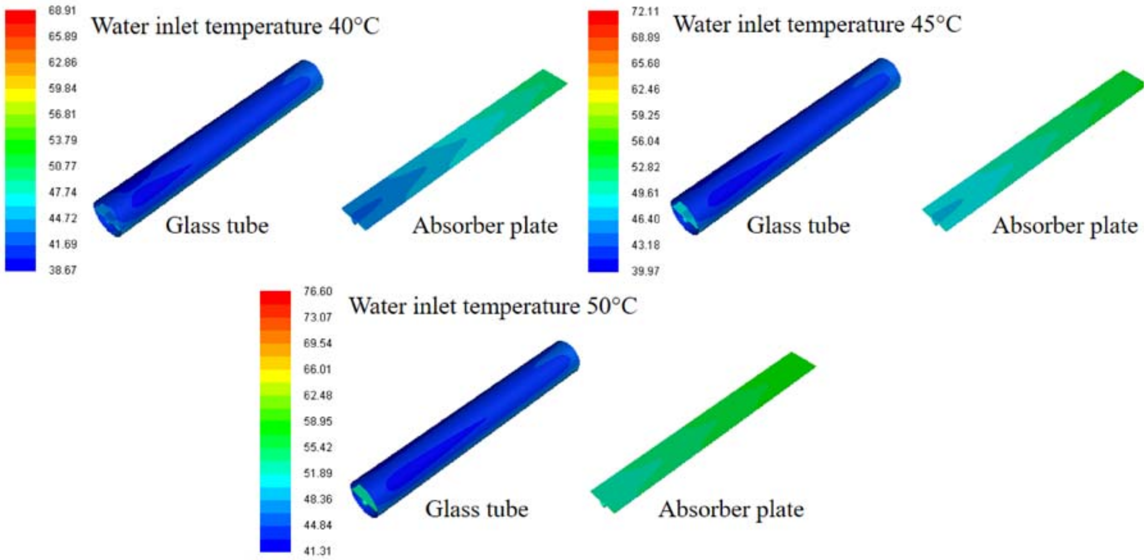

Fig. 4. Characteristic surface temperature field of the FFAP (26 July, 10:00 h).

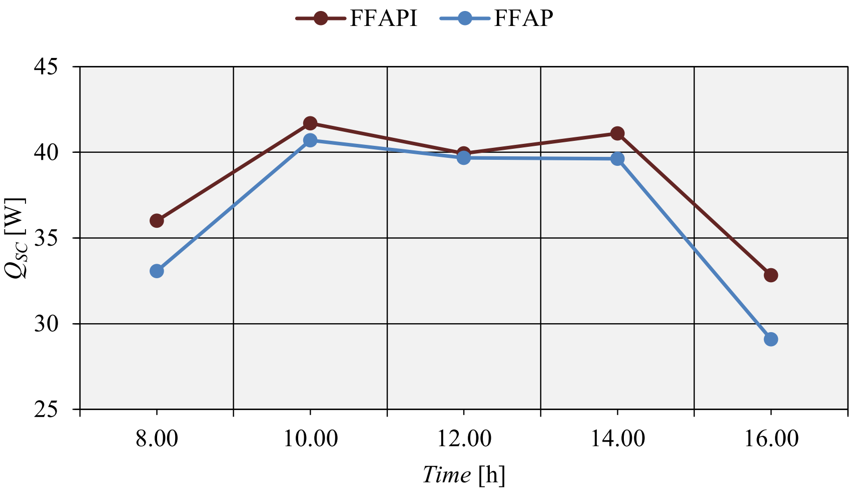

Fig. 5. Heat powers of the FFAPI and FFAP (26 July, $T_{SC\text{-}in}$=313 K).

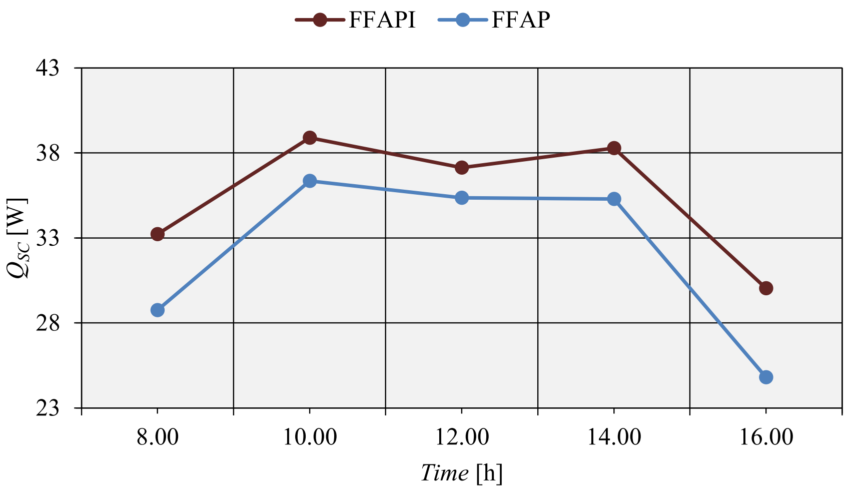

Fig. 6. Heat powers of the FFAPI and FFAP (26 July, $T_{SC\text{-}in}$=318 K).

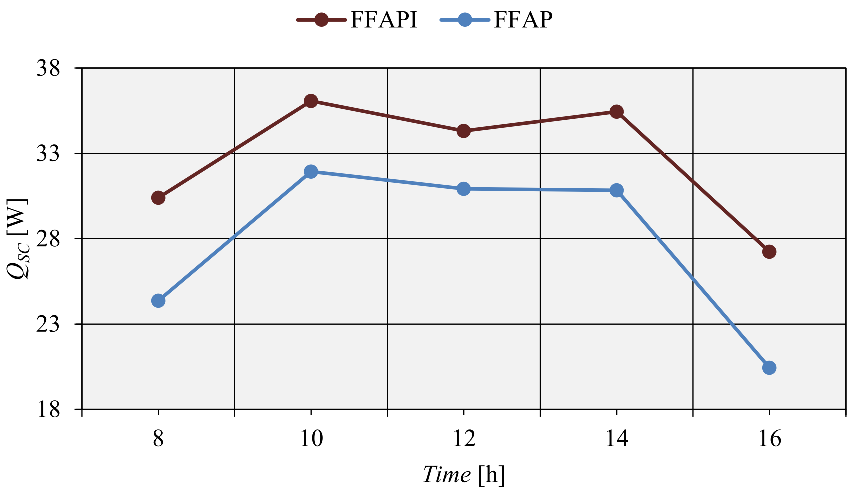

Fig. 7. Heat powers of the FFAPI and FFAP (26 July, $T_{SC\text{-}in}$=323 K).

The biggest differences, in favor of the FFAPI, were achieved when $T_{SC\text{-}in}$=323 K (Fig. 7). In percentage terms, they amounted to: 24.75% (8:00 h), 12.96% (10:00 h), 10.95% (12:00 h), 14.93% W (14:00 h) and 33.31% (16:00 h). The average daily thermal power of the FFAPI was 27.24 W, while for the FFAP this value was 23.08 W.

6. Conclusion

The paper presents a new SC construction – the glass tube SC with a fixed flat absorber plate and with insulation (FFAPI). The FFAPI thermal performance was investigated using the Ansys Fluent software package. The reference sample (to justify the FFAPI application) was played by the (control) glass tube SC with a flat absorber plate and without insulation (FFAP). Based on a certain number of simulations, the following was concluded:

- The SCs heat losses increase with an increase of the water inlet temperature.
- By using insulating materials in the construction of SCs, they can be reduced by over 30%, depending on the water inlet temperature and ambient conditions.
- The new SC concept, i.e. FFAPI contributes to the further development of solar technology.
- The FFAPI design may have greater commercial application in the future.

Nomenclature:

Latin symbols:

a	–	Absorption, in [-],
c	–	Speed, in [m s^{-1}],
c_P	–	Specific heat, in [J kg^{-1} K^{-1}],
h	–	Specific heat, in [W m^{-2} K^{-1}],
I	–	Solar radiation, in [W m^{-2}],
$\dot{m}$	–	Mass flow rate, in [kg s^{-1}],
$\dot{Q}$	–	Heat flux, in [W],
T	–	Absolute temperature, in [K].

Greek symbols:

Δ	–	Difference,
λ	–	Thermal conductivity, in [W m^{-1} K^{-1}],
μ	–	Dynamic viscosity, in [Pa s],
ρ	–	Density, in [kg m^{-3}],
σ	–	Stefan–Boltzmann constant, in [W m^{-2} K^{-4}],
τ	–	Transparency, in [-].

Subscripts:

A	–	Ambient,
DIFF	–	Diffuse,
DIR	–	Direct,
in	–	Inlet,
out	–	Outlet,
REFL	–	Reflected.

Abbreviations:

CPC – Compound parabolic concentrator,
ETSC – Evacuated tube SC,
FFAP – Glass tube SC with a fixed flat absorber plate and without insulation,
FFAPI – Glass tube SC with a fixed flat absorber plate and with insulation,
FPSC – Flat-plate SC,
SC – Solar collector.

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