Experimental and Numerical Study of Thermal Performance for Flat Plate Solar Water Heater in Najaf

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Abstract. This work presented the numerical and experimental study of the thermal performance of a flat plate collector (FPC). This study focuses on analyzing the performance of (FPC) in the climatic conditions of Najaf and calculating the thermal energy produced by the collector for domestic use, which reduces the electricity consumption that Iraq is witnessing a severe shortage in its supply. Also, various working fluids (water, oil engine, ethylene glycol-water mixture) were tested to determine the best working fluid that improves the collector's efficiency. The experiments were performed in Najaf, Iraq (32° 2' N / 44° 18' E) on January 9, 2019. The simulation study of the (FPC) is performed by COMSOL Multiphasic 5.3 software. The numerical results were validated with experimental results and there was good convergence between them. The results showed that the average daily efficiency of the solar collector (FPC) was 37.17%, and the highest outlet water temperature of the collector was 57.1°C. The collector achieved a useful cumulative useful heat during the day of about 3.3557 MW, this contributes to reducing the use of electricity and achieving the required economic feasibility of use (FPC). Finally, the engine oil gave better results in improving efficiency compared to other working fluids.

1. Introduction

A solar water heater is a device that uses the thermal energy generated from the sun's rays in heating water for homes and commercial purposes. Solar heaters produce hot water with temperatures ranging from (40-97) °C. And it has an advantage that they reduce dependence on electrical energy and reduce environmental pollution, as well as produce more energy than photovoltaic panels and achieved desired economic feasibility. The solar collector is designed to convert the solar radiation falling on the aperture area into heat in the absorber part and transfer heat from it by the working fluid [1,2]. The thermal solar system consists mainly of a collector, heat transfer system including (working fluid and circulation pump), and a storage tank.

There are several types of solar water heaters, but the most popular type is flat plate collector (FPC). Because it is cheap, can be manufactured locally, and is easy to install and maintain. It is used for both
domestic and industrial applications that require low and medium temperatures [3][4]. The solar collector is affected by collector design, type of working fluid, and weather conditions. Therefore, many efforts are currently focused on improving (FPC) performance through various technologies. These studies include increasing the absorber’s ability to capture solar radiation, reducing heat loss from the collector, enhancing the thermal properties of working fluids, and some studies focus on affecting the weather conditions in different locations on the collectors. Finally, many researchers studying the economic feasibility of using these collectors in the long term. In recent decades, There are several studies done on the thermal performance of (FPC), among them: Harrabi, et al. [5] studied numerical and experimental exergetic and energetic performances of (FPC) according to EN 12975 procedure. The suggested method allows measuring the effects of uncertainty in both thermophysical properties of the working fluid and operation conditions on estimating the performance of the (FPC). The analysis gave good agreement between the numerical and experimental results. The results indicated that the ambient temperature is the parameter most influencing the performance estimate and that a deviation of approximately ± 1°C may affect the energy efficiency of 13.7% and exergy efficiency of 3.9%. Rashid et al. [6] investigated numerically the effect of the use of rectangular channels and fins in (FPC). The study was conducted with flow rates ranging between (9-13) kg/s. the thermal performance analysis and flow characteristics show that a solar water heater with a fin was more efficient when it was without a fin. The results showed the heat transfer coefficient increases when the mass flow rate increase. It was proved that the performance of the collector improved with the increase in turbulence flow in the channel. And the use of the rectangular channel with the fins in the flow path of the collector improved the efficiency by 28% compared to without using the fins. Morrison and Braun [7] searched in a comparative study of the solar water heaters working by thermosyphon using two models of tank-type: vertical and horizontal. The numerical simulation was inconsistent with the results obtained from two different places. This study showed that the thermosiphon system works well when it can prepare sufficient hot water for daily use. It has been proven that the horizontal tank system gave better results than the vertical tank system when they are working under the same weather conditions. Chow et al. [8] investigated the daily production of the solar water heater (SWH) from domestic hot water (DHW) in a virtual building in Hong Kong, by fixing central (SWH) in the west and south vertical facades of the building. The economic feasibility study focused on technical and cost terms. The simulation results showed that the thermal efficiency of (SWH) was 38.4%, the average annual temperature of the hot water was 41.4°C, The annual thermal energy extracted is estimated at 904GJ, and the payback period was 9.2 years, The payback period could be shorter if taking into account the reduction of energy consumed in cooling as a result of the solar collector blocking the solar radiation on the facades of the buildings. Hobbi and Siddiqui [9] studied the performance of flat plate collectors working to provide domestic hot water to a single family home in Montreal, Canada. The study was conducted by simulation using the TRNSYS software tool to analyze all major design parameters of the collector to determine its optimum value. Considering the optimization parameter was the solar fraction. The numerical results showed that when increasing the circulation flow leads to a rapid increase in solar fraction and collector efficiency. The system can produce 30–62% in winter and 83–97% in summer from hot water needs. Finally, the locally coated non-selective collector can save 54% of the annual water heating needs. Serale et al. [10] studied improving the thermal performance of (FPC) produced limited temperature. The thermal improvement requires using latent heat stored from the slurry phase change material (PCS) Besides, heat, surfactants. The study suggested the integration of the solar thermal system with slurry
PCMs where the existing model system was introduced on n-eicosane PCS. The results showed the thermal and physical properties of the system increased compared to using a regular solar collector. Sami et al. [11] evaluated the economic and energetic possibility of the integration of the (FPC) with houses that have high energy performance. In this study, four houses are chosen in different locations that have different weather in Algeria. The investigation of this study depends on using the F-Chart method and meteorological data for specific rejoin. The study focused on minimizing the area for (FPC) to reduces the installation cost versus energetic and economic aspects. The results explained the solar water heater contributed to saving energy about 57% and 46% in southern and northern regions respectively. And the saving in the annual operating cost of (FPC) reached 69% southern and 51% in northern regions respectively. Yousefi et al. [12] studied improving the efficiency of (FPC) by using nanofluid (Al2O3-water) with working fluid. Nanofluid used in experiments has a mass concentration of 0.2% and 0.4 %. The nanoparticle has a diameter of 15 nm and the working fluid flow value is variable (1-3) L/min. Results explained the enhancement in the collector efficiency was 28.3% when using 0.2% wt Al2O3 nanofluid compared to if a water-based fluid was used, the maximum enhancement in efficiency with a surfactant was 15.63%. Catalin-George and Sebastian [13] studied numerically investigation efficiency of (FPC) in distinct weather in Romania. The effect of the slope angle on the efficiency of a collector in all locations is examined with flow rate (24, 36, 48) kg/h. The numerical results revealed that the better slope angle of (FPC) was 45° in different values of flow rate in all locations, and the difference between inlet and outlet water temperature of (FPC) ranged from 10 °C to 15 °C. Ranjith and Karim [14] investigated experimentally and numerically impact of testing propylene glycol–water mixture in (FPC) as working fluid in different volume concentrations (25, 50, 75, 100%) of propylene glycol (PG) with varied flow rates values (0.008, 0.0167, 0.024) kg/s. The results indicated the collector efficiency decrease when using propylene glycol–water in a mass flow rate of 0.0167 kg/s at 25% PG, and efficiency of collector increase when (PG) volume concentration was 25% to 50%. While at volume concentration from 50% to 100% at a mass flow rate of 0.024 kg/s, the efficiency increased by 5% and 14%, respectively. Saw and Owolabi [15] evaluated experimentally the efficiency enhancement of (FPC) by use phase change material PCM and nanoparticle. The collector was installed with a tilt angle of 10° and had a mass flow rate of 0.5 kg/min. The experimental result showed when using PCM and (Nano-PCM) the outlet water temperature of the collector was 40.2°C and 40.8°C respectively, and without the PCM state, the temperature of outlet water of the collector was 35.2°C. The enhancement in solar collector efficiency reached 6.9% and 8.4% when used PCM and nano-PCM respectively.

The purpose of the research is to study the experimental and numerical performance of (FPC) in Najaf city and calculate the efficiency and thermal energy produced. To reduce dependence on electrical energy, which is witnessing a severe shortage of supply in Iraq. Also, several types of working fluids have been tested to improve efficiency.

2. The experimental work:

2.1. Description of the system

The thermal performance of solar heaters is tested in several ways, depending on the purpose of using the hot water produced. The study will focus only on evaluating the thermal performance of the collector within the heating system. Figure (1) shows the solar heating system to heat the room. The system consists of several parts and the main part is the solar collector (FPC) and it has the
specifications shown in Table 1. (FPC) is installed above the college building in the south direction and a tilt angle of 30° as shown in Figure 2.

![Scheme of the experimental rig](image)

**Figure 1.** Scheme of the experimental rig

| Specification                                      | details                      |
|---------------------------------------------------|------------------------------|
| Dimension of collector                            | (2000x1000x80) mm            |
| The thickness of the glass cover                  | 3.2 mm                       |
| Glass transmittance                               | 95%                          |
| The thickness of the aluminum Absorber plate      | 0.4 mm                       |
| Absorber plate absorptivity                       | 95%                          |
| The emissivity of absorber                        | 5%                           |
| Copper header tube diameter                       | 22mm / 2 headers             |
| Copper riser tube diameter                        | 8mm / 7 risers               |
| Glass wool insulation thickness                   | 50 mm                        |
| The air gap between absorber and glass            | 25mm                         |
The indoor radiator is fixed on the wall inside the laboratory with dimensions (100x60) cm, as shown in Figure (3). The (FPC) is connected to the radiator by insulated tubes. A flowmeter is installed to measure the flow of working fluids entering the collector. The flow rate is controlled by a set of valves and the heating system operating by forced convection in a closed system.

A data logger has (7) thermocouples type (T) fixed in different places on the collector: two thermocouples fixed at inlet and outlet pipes of a collector, two thermocouples fixed on the back and edge of the (FPC), and three thermocouples fixed on different locations of the glass cover. The solar
Irradiance is measured by the solar radiation sensor and ambient temperature and wind speed measured from the Meteorological station in the laboratory, as shown in Figure (4).

![Solar irradiation sensor and data logger](image)

**Figure 4.** Showed the solar irradiance sensor and data logger

### 2.2. Test procedures

The solar system is investigated empirically at Engineering Technical college/ Al-Furat Al-Awsat University in Najaf, Iraq (32° 2' N / 44° 18' E). The solar collector (FPC) is tilted at an angle of 30° facing the south direction. Tests were conducted on January 9, 2019, for the period 9:00 AM to 5:00 PM. After sunrise, the (FPC) gradually heats the working fluid due to sunlight falling on it. Then the electric pump circulates the working fluid from the collector to the radiator inside the room, causing the radiator temperature to rise. Then heat transfer occurs between the radiator surface and the room air by free convection, this will warm the room gradually. Then the working fluid returns from the radiator to the solar collector to be heated again. The working fluid flows inside the system at a constant volume flow rate of 60 L/h.

### 3. System Modeling and Simulation:

Flat plate collector studied by 3-D numerical investigations conducted by (CFD) approach and governing equations were analyzed by COMSOL Multiphase 5.3 software tool. And the numerical analysis was done by the finite element method. The study took into account many processes: the model exposed to the solar irradiance causing heat generation in the absorber plate, convection heat transfer and radiation occur between side walls and glass cover with the surrounding, radiation heat transfer between the absorber plate and glass cover is considered, and convection heat transfer between an absorber plate and air gap. The solar energy absorbed was simulated by taking data of weather conditions for Najaf city on January 9, 2019, which was recorded by a weather station in the laboratory. Data recorded included, wind speed, solar irradiance, and ambient temperature. The mass
flow rate inside the system was 60L/hr. An inlet water temperature of collector data taken from experimental data.

3.1. The domain of the computational simulation

Transient conditions simulations are performed on a flat plate collector that has an area of a (2 m²). Due to the large difference in the dimensions of the pipe diameter (0.008 m) and the length of the absorber tube (1.85 m), an excellent mesh distribution is required in the tube cross-section. There are assumptions that must be taken into account for the simplified simulation model as follows:

- The heat loss by radiation in the margins of the collector is ignored.
- Neglecting heat loss at the bottom base of the collector.
- The working fluid flow remains constant in the collector and is divided equally in all riser tubes.
- The field of the flow is symmetric to the (y – z) plane, And a half-section of elements (tube, absorber plate, air gap, and glass cover) is considered for the numerical study. The domain of the computational simulation is shown in Figure (5).

![Figure 5. Showed a schematic of the CFD model](image)

One of the requirements for a numerical solution is to know the boundary conditions of the model, which are:

1- In the inlet tube:
   a) \[ \int \rho \cdot U_{in} \, dA \]  
   When \( m = (0.016667/7) \text{kg/s} \)  
   b) \( T_{in} = T_{in(t)} \) as shown in Fig (10)  

2- In the outlet tube:
   a) \( P_0 = 0 \) (gauge pressure)  

(1) \( \int \rho \cdot U_{in} \, dA \)  
(2) \( T_{in} = T_{in(t)} \) as shown in Fig (10)  
(3) \( P_0 = 0 \) (gauge pressure)
b) \( \frac{\partial T}{\partial x} = 0 \) \hfill (4)

3- At the wall, a non-slip condition was imposed on the walls \( U = 0 \)

4- The symmetry is taken on the plan in the middle of the tube.

\( u_n = 0 \), normal component of velocity equal zero \hfill (5)

5- Initial temperature \( T_i = T_{am} \) \hfill (9) at 9:00 am

6- Convective heat flux on outer glass cover

\[ Q_c = h_c \left( T_g - T_a(t) \right) \] \hfill (7)

\[ h_c = 5.7 + 3.8V_{out}(t) \] \hfill (8)

Where \( V_{out}(t) \) wind speed which is changing with time taking values from the weather station.

7- Heat absorber by glass

\[ Q_g = A_c. G(t). \alpha \] for glass \( \alpha = 0.05 \) \hfill (9)

\( A_c= Aperture \) collector area

8- Heat absorbed by the absorber plate

\[ Q_p = A_c. G(t). \alpha_p \] for plate \( \alpha_p = 0.95 \) \hfill (10)

9- Insulation wall \( Q_n=0 \) \hfill (11)

3.2. The Governing Differential Equations

Governing differential equations describe the thermo-physical behavior of many heat and mass transfer processes that occurs at (FPC). The equations of the fluid flow and heat transfer in the system are considered. The assumptions are taken into account: incompressible, laminar, steady flow, And three-dimensional, The physical properties will be considered constant, viscous Newtonian flow within the (FPC) are governed by the equations of continuity, momentum, and energy [16]. the continuity equation for flow inside the tube can be written as:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \] \hfill (12)

The momentum equations can be written in the x, y, and z directions as follows:

\[ \frac{\partial u}{\partial t} + \rho \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} = -\frac{\partial P}{\partial x} + \mu \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \] \hfill (13)

\[ \frac{\partial v}{\partial t} + \rho \frac{\partial v}{\partial x} + \rho u \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} = -\frac{\partial P}{\partial y} + \mu \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] \] \hfill (14)
\[
\frac{\partial w}{\partial t} + \frac{\rho u \partial w}{\partial x} + \frac{\rho v \partial w}{\partial y} + \frac{\rho w \partial w}{\partial z} = - \frac{\partial P}{\partial z} + \mu \left[ \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] - \rho gz
\] (15)

The energy equations for fluid and the structure of (FPC) are as following:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right]
\] (16)

The efficiency of the collector is the useful energy of (FPC) to the solar energy incident on the aperture area of a collector as follows.

\[
\eta = \frac{Q_u}{I_r A_c}
\] (17)

\[
Q_u = A_c F_R \left[ S - U_e (T_{pm} - T_a) \right]
\] A. Kalogirou [17] (18)

3.3. Meshing

The process of creating the mesh is critical in the numerical simulation. In this work, the grid was generated by using COMSOL Multiphysics 5.3 software. The type of the mesh works directly on the accuracy of the numerical result. The grid was made a successively finer type and another fine type at locations where it was needed, as shown in Figure (6).
To choose the appropriate mesh type in the solution of the model, eight numbers of grid points were selected to check the values change of the temperature differences between the outlet and the inlet. Figure (7) shows that the region of meshes starting from 150,000 to 450,000 has no significant effect on the temperature difference. Therefore grids generation with 150,245 was considered an acceptable computational field.

4. Validation Model:

Ekramian et al. [18] investigated a numerical study of the same solar collector model that Cruz-Peragon et al. [19] used in his experimental work for the same parameters and conditions. The study performed on the (FPC) contains 15 riser tubes. The thickness of the absorber plate and glass cover are
2 mm and 4 mm, respectively. The distance between one tube and another was 30 mm and the inner diameter of the tube was 10 mm, and the tube’s length of 450 mm. A flat plate collector examined under constant operation condition: Solar irradiance was 936.8 W/m², ambient temperature, Inlet water temperature, and water flow rate are, 23.2 °C31°C and 6.42 kg/h respectively. So a single riser was considered and the average temperature of the fluid in four sections was taken through the simulation. The numerical results of E. Ekramian explained that the average relative error between the experimental and numerical results is about 5.5%. While in our work, a simulation study was performed on (FPC) and under the same operating conditions in the work of Cruz-Peragon et al. The simulation results are highly accurate and close to the experimental results, and the mean relative error ratio of the experiment to the numerical results was about 0.062%.

![Figure 8](image)

**Figure 8.** showed the comparison between numerical and experimental temperature

5. The results and Discussions

5.1 The experimental Results:

The experimental work was conducted in period 9:00 AM to 5:00 PM on January 9, 2019, in Najaf, the weather was clear sky, relatively cold, and solar irradiance in intermediate limits. The ambient temperature ranged from 9.8°C in the morning to reach a maximum value 17°C at 4:00 pm. Solar radiation starts at low rates at sunrise and reaches the highest value at the noon period then returns to decrease in the afternoon as shown in Figure (9). The inlet water temperature of (FPC) was constantly changing due to the flow of water in a closed system as it increased by a certain amount in each cycle, The wind speed was high most of the time, ranging between (1.8 to 4) m/s, as shown in Figure (10).
Figure 9. showed hourly variation in ambient temperature and solar irradiance

Figure 10. showed the inlet fluid temperature and wind speed

The experiments were conducted at a flow rate of 60 L/hr. Figure(11) showed the change in the outlet water temperature ($T_{\text{out}}$) during the period 9:00 am to 5:00 pm. An analogy is observed between the change in ($T_{\text{out}}$) and the solar irradiance and noted ($T_{\text{out}}$) increases as the intensity of solar radiation increases. ($T_{\text{out}}$) starts with low values at the beginning of sunrise and then gradually increases to reach the highest value of 57.1 °C at 12:58 pm. In the afternoon the values of ($T_{\text{out}}$) begin to decrease, reaching the lowest value at sunset. Figure (12) showed the temperature difference between the outlet and inlet water of the collector ($\Delta T$). Temperature difference indicates the ability of the collector to heat water and allows comparison between other types of collectors under the same conditions and specifications. The collector efficiency increases as the temperature difference increases. It noted the change in ($\Delta T$) values is almost similar to the change in ($T_{\text{out}}$) and the maximum of ($\Delta T$) reached 12.5 °C.
Figure 11. showed the time variation for the outlet temperature of the collector ($T_{out}$)

Figure 12. showed the time variation for the difference between outlet and inlet temperature of the collector ($\Delta T$)

The heat obtained from (FPC) is called useful heat ($Q_u$) which is the heat that is extracted from the collector by passing the working fluid through the absorbent part. The useful heat values are low at the beginning of the sunrise and gradually increase to reach the peak value of 886W at midday then its values gradually decrease in the afternoon until reach the lowest value at sunset as shown in Figure (13). The results indicate that in the period from 10 am to 3 pm, the solar collector can cover all or a large part of the required heat while at other times the values are much lower than the required heat.
Figure 13. showed the time variation of the useful heat of the collector ($Q_u$).

5.1.1 The effect of testing different working fluids on collector efficiency:

The type of working fluid is one of the influencing factors to improve collector efficiency because they have different thermal properties. Experiments were carried out on the water on January 9, 2019, (ethylene glycol –water) mixture (50-50)% on January 10, 2019, and oil engine grade (10W-30) on January 12, 2019. The results showed that the engine oil gave better results in enhancement efficiency than other liquids as shown in Figure (14). The overall daily efficiency of water, (ethylene glycol-water) mixture, and oil engine were 42.73%, 48.31%, and 64% respectively. The working fluids tests showed variation in collector efficiency is due to the difference in physical properties (density, viscosity, thermal conductivity, and specific heat) and noted that the most important physical property affecting the increase in heat transfer is specific heat. As the engine oil, has the lowest specific heat of $1.99 \text{[kJ/kg.c]}$ while the specific heat of ethylene-glycol-water mixture and water were $3.686 \text{[kJ/kg.c]}$ and $4180 \text{[kJ/kg.c]}$ respectively. The heat transfer increases as the specific heat of the working fluid are low and vice versa, This gives preference to engine oil in increasing heat exchange and extracting the maximum amount of useful heat from the collector. Although the engine oil gave the highest efficiency of the collector, it has disadvantages represented by its high viscosity, which causes the pressure drop and needs more energy to pump it than other liquids.
Figure 14. showed the time variation of the collector efficiency for using different types of working fluid

5.3 Numerical Results:

The performance of a solar collector is investigated numerically and the analysis of the simulation model is presented. Figure(15) Shows the experimental and numerical outlet water temperatures of the collector \(T_{\text{out}}\). It was observed that the variation of the experimental and numerical values of \(T_{\text{out}}\) was similar during most of the test period, and the two curves were almost identical. and this indicates the high accuracy in solving the numerical study and the relative error of experimental to numerical temperatures was less than 0.42% as shown in Figure (16). The temperature contour of the section from a flat plate collector contains one riser tube shown in Figure (17).

Figure 15. hourly variation for numerical an experimental \(T_{\text{out}}\) of the collector
Figure 16. show relative error between numerical and experimental temperatures readings

Figure 17. Temperature contour

6. Conclusion:

A flat plate collector (FPC) is investigated numerically and experimentally in cold weather conditions of Najaf city, Iraq. The heat generated by (FPC) used to heat buildings. The results indicated a good convergence between the experimental and numerical results. And the maximum relative error ratio between numerical experimental results was 0.42%. The maximum (T_{oa}) of the collector was 57.1 °C, the maximum value for the instantaneous efficiency of the collector reached 50.44%, While the overall daily collector efficiency was 37.17%. It was concluded that a flat plate collector test achieved good
results in Najaf city, which has relatively high solar radiation rates and achieving a daily cumulative amount of useful heat of 3.3557MW. This energy contributes to reducing electricity consumption and reducing environmental pollution and working to provide hot water used in heating buildings and domestic use. Finally, the engine oil gave better results in improving efficiency compared to other working fluids.

**Keywords**: Experimental work, Flat plate collector, Numerical model, Working fluids.

**Nomenclature**

\( Q_u \)  
Useful work \( (W/m^2) \).

\( I_T \)  
Solar irradiation \( (W/m^2) \).

\( \eta \)  
Efficiency of the collector.

\( A_c \)  
Aperture area of the collector \( (m^2) \).

\( T_{in} \)  
Temperature of inlet water \( (^\circ C) \).

\( \rho \)  
Working fluid density \( (kg/m^3) \).

\( T_{out} \)  
Temperature of outlet water \( (^\circ C) \).

\( S \)  
Solar radiation absorbed by \( (FPC) \) \( (W/m^2) \).

\( U_L \)  
The overall coefficient of heat loss on the collector area \( (W/(m^2 K)) \).

\( U_{in} \)  
Inlet working fluid velocity \( (m/s) \)

\( Q_c \)  
Convection heat transfer \( (W) \)

\( T_{pm} \)  
Temperature of the plate \( (^\circ C) \).

\( I_T \)  
Solar irradiation \( (W/m^2) \).

\( T_a \)  
Ambient temperature \( (^\circ C) \).

\( T_g \)  
Glass cover temperature \( (^\circ C) \).

\( \alpha \)  
Absorption coefficient

\( h_c \)  
Convection heat transfer coefficient \( (W/m^2.\circ C) \)

\( V_{out} \)  
Wind speed \( (m/s) \)

\( F_R \)  
The ratio of the actual useful energy gain that would result if the collector-absorbing surface had been at the local fluid temperature

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