



Research Article

Study of Solar Collector Potential in Thailand Using Computational Fluid Dynamics Approach

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Abstract

Due to the proximity of Thailand being near the equator, there is a significant potential for harnessing an excess amount of solar energy using a solar collector. The solar collector harvests solar energy by acting as a passive heat exchanger, receiving solar energy, and transferring it to a fluid medium to be further utilized. This study presents the analysis of temperature outlet and pressure drop of a solar collector in Thailand, utilizing Earth's geological location, date, and time for solar energy calculations and employing computational fluid dynamics (CFD) to predict the collector's efficiency. The CFD approach offers a reduction in the cost of experiments and environmental impact by minimizing waste from constructing experimental prototype equipment. A closed loop solar collector for a water heater system with the width of 100 mm and the length of 1,000 mm made with copper is selected for this study. The boundary conditions of the model are collected from the experimental data to ensure high accuracy during the validation process. The grid independence is done to ensure high accuracy simulation with CFD. The study also compares the collector performance with another geological location and with different water mass flow rates in the range of 0.554 to 2.582 g s⁻¹. The results confirm the potential of solar collectors in Thailand by achieving efficiency an of 69.61% at 11 a.m. with 2.332 g s⁻¹ of mass flow rate.

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Introduction

Global CO₂ emissions have risen significantly, enhancing the natural greenhouse effect and accelerating global warming [1]. In response, there has been a desire to reduce CO₂ emissions from the fossil fuel in the energy sector [2], alternative sustainable and environmentally friendly energy sources are investigated to produce new method of providing an energy without sacrificing the world. Solar energy is one of the energy sources that are sustainable and environmentally friendly. However, harvesting this energy comes with some challenges. Solar collector is one of the equipment used for harvesting solar energy for usage. Solar collector is passive heat exchanger that capture heat from the sun and transfer the energy into its medium, usually water. Solar collectors are widely used around the world due to their simplicity to implement

and construct the equipment into preciously installed processes. Flat plate solar collector is one of the solar collectors that is mostly used in domestic sector [3], due to their simply design, easy installation, and construction process combine with it cost effectiveness [4].

Thailand's geographical location near the equator makes it highly suitable for solar energy applications, as this region receives abundant solar irradiation. The study by Janjai et al. [5] investigated the potential of solar energy for the generation of electricity in Thailand using satellite data revealed that northeast and central region of Thailand receive the highest solar irradiation in the range of 1350–1400 kWh m⁻² year⁻¹. However, optimizing solar collectors for Thailand's specific conditions remains underexplored.

Previous researchers have studied various aspects of solar collectors, including thermal performance, cost-effectiveness, and environmental impact. Kalogirou [6] presented thermal performance, economics and environmental protection from thermosyphon solar water heater and found positive along with economical availability with 2.7 years of payback period and life cycle savings of €2240 for system with electricity backup and by using the solar energy. It could save 70.3% in greenhouse gases compared to conventional sources of electricity. This study provided information to support that solar energy systems are efficient, cost effective and environmentally friendly. Other studies in computational fluid dynamics (CFD) show more insight on potential, and optimization of solar collectors by simulating the fluid behavior and heat transfer within the system. Alkhafaji et al. [7] studied the simulation of laminar flow in flat plate solar collector with computational fluid dynamics, and found that using latitude and time for the calculation of heat flux and simulating computational fluid dynamics in software Ansys Fluent could provide accurate results compared to experimental data in the same geographical location up to 8.36% error for operating fluid temperatures at the outlet. Farajzadeh et al. [8] studied open source computational fluid dynamics named OpenFoam for turbulent flow in flat plate solar collector and found that the maximum deviation for the outlet temperature at almost 11%. The study also investigated the volumetric flow rates with 1.5, 2.0, and 2.5 L min⁻¹ of 0.1 wt% of Al₂O₃ nanofluid in water and found that 2.0 L min⁻¹ of flow rate provided the maximum thermal efficiency, while 2.5 L min⁻¹ would provide a higher average thermal efficiency for continuous running in a day. This suggested that the flow rate of medium inside the solar collector could significantly affect efficiency. Razika et al. [9] investigated the effects of volumetric

flow rate between 2.2 – 9 L h⁻¹ and inclination angle between 0–60° for solar collector using high power lamp to simulate solar energy and found that higher mass flow rate leads to higher efficiency, while the inclination angle that facing the source of solar energy leads to maximum efficiency with 0° of inclination angle. This also suggests that inclination angle significantly affects the thermal performance of solar collectors.

Reviewing the literature highlights that the potential of solar collectors in Thailand has yet to be exploited in many operating conditions, especially its performance even though this location receive high solar irradiation. This study aims to assess the potential of flat plate solar collectors in Thailand utilizing computational fluid dynamics. This study investigates the impact of local conditions and varying operational parameters such as mass flow rate on thermal performance as a metric. This work seeks to provide accurate performance models tailored to Thailand's specific solar potential, offering a foundation for future solar energy implementations in the region.

Methodology

The geometry of solar collector is according to the study by Alkhafaji et al. [7]. The closed loop flat plate solar collector is constructed with copper absorber width of 100 mm and length of 1,000 mm. The pipe is made of copper with an inner diameter of 14.26 mm. The collector is covered with wood as insulation and glass on the top for the light to pass. Figure 1 illustrates the full system. The energy storage tank role is used to transfer the energy from the collector into it. This is done for further use of energy, for example a hot shower during the night which cannot simply do without energy storage. However, this study only simulates the solar collector part for the investigation.

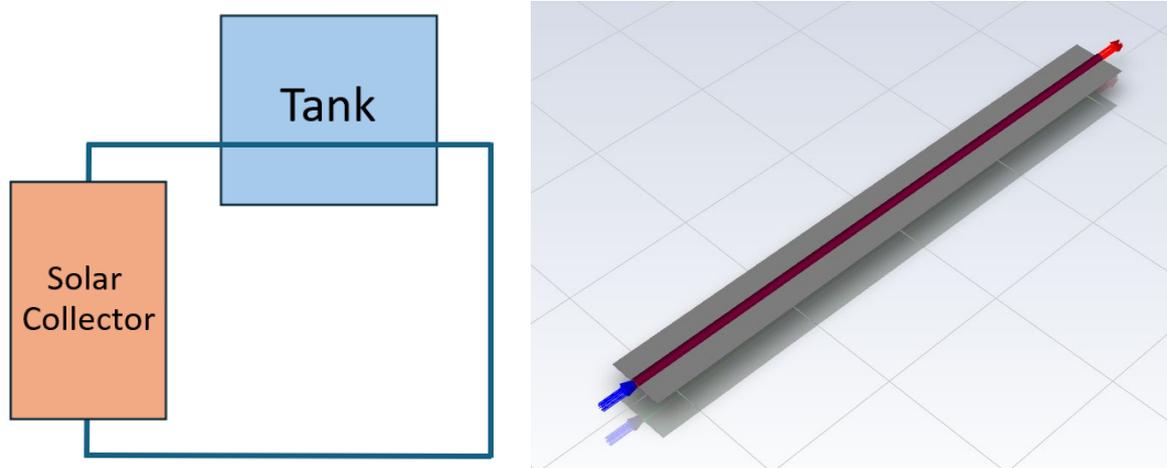


Figure 1 Solar collector system, (not true scale, left) and solar collector geometry in CFD (right).

The mesh is generated using Fluent Meshing solver with poly-hexcore. The grid independence is evaluated by running the system with solar loading and measuring the outlet temperature of the solar collector with water at 1.267 g s^{-1} mass flow rate. The grid independent test is run to ensure that the model provides accurate results without sacrificing too much computational cost by comparing it with another model with higher number of cells.

This study adopts the P1 model to predict the effects of radiation. This combined with solar ray tracing for loading the solar heat flux into the system will provide how the sun affects the collector accurately. The inputs for the solar loading include Global position (latitude, longitude, time zone), date and time, mesh orientation, solar irradiation method and sunshine factor. This solar loading model assumes uniformed heat flux and fair-weather conditions.

For the validation of solar collector model, input parameters will be adapted from the experimental data by Alkhafaji et al. [7], which was conducted on November 15th located in Baghdad, Iraq, between time of 8 a.m. to 3 p.m., with 33° of inclination angle. This data provides a foundation for model validation by offering experimental results that allow for comparison with simulated outcomes.

For the analysis of potential of solar collector in Thailand and adapt it in Thai context, some assumptions are made. Bangkok is selected to represent Thailand because Bangkok is a city in central region of Thailand, which receives intense solar energy [5]. The conditions will perform from 8 a.m. to 3 p.m. on April 13th which is in a month that provides the highest energy in Bangkok, Thailand [10]. Furthermore, Stanciu et al. [11] suggested the optimum inclination angle to achieve the highest energy of flat plate solar collector located in the area of equator-tropics should be 0° . Thus, the inclination angle of solar collector in Thailand is 0° for the simulation in Thailand to maximize the absorbed energy. Heat loss is tuned to match the simulation results with experimental data.

The governing equations used in this study consist of continuity equation (Eq. 1), momentum equation (Eq. 2), energy equation (Eq. 3), and radiation equation (Eq. 4). All of these are run on Ansys Fluent software.

$$\nabla \cdot (\rho v) = 0 \quad (\text{Eq. 1})$$

$$\nabla \cdot (\rho v v) = -\nabla P + \nabla \cdot (\mu \nabla v) \quad (\text{Eq. 2})$$

$$\nabla \cdot (\rho v C_p T) = \nabla \cdot (k \nabla T) + S \quad (\text{Eq. 3})$$

$$-\nabla \cdot q_r = aG - 4an^2\sigma T^4 \quad (\text{Eq. 4})$$

Where ρ is density, v is velocity, P is pressure, μ is viscosity, C_p is specific heat capacity, T is temperature, k is thermal conductivity, S is defined heat sources, q_r is radiation flux, a is absorption coefficient, G is incident radiation, n is refractive index, and σ as Stefan-Boltzmann constant.

The heat flux boundary conditions are according to the P1 model. The inlet mass flow rates and temperature will follow the real experimental data. The solver algorithm used in this study is SIMPLE. Due to the system operating in the laminar regime, the viscous equation is chosen to be laminar. After the process of validating and analyzing the potential of Thailand location. To investigate the effect of different mass flow rates, the amount of flow rate at different times in the base case scenario is multiplied by 1.5 and 2 as shown in Figure 2. In this investigation, the inlet temperature will be assumed to be the same as the base case, which could be developed by building a larger heat exchanger inside the tank.

There are limitations associated with the particular model employed in this research. First, the assumption of laminar flow limits the model's accuracy to only laminar flow regime. Additionally, the P1 radiation model assumes a uniform heat flux and fair-weather conditions, simplifying radiative effects. Making the model not fully captures the complexities of solar radiation, especially under variable atmospheric conditions. The model's use of a simple copper plate geometry does not account for complex structural designs or material variations found in commercial flat plate solar collectors. This study adapts parameters for Bangkok, Thailand. However, it does not investigate seasonal or specific local climate factors that could alter performance. These limitations highlight areas for future study to improve the model's applicability and accuracy in predicting solar collector performance under realistic conditions.

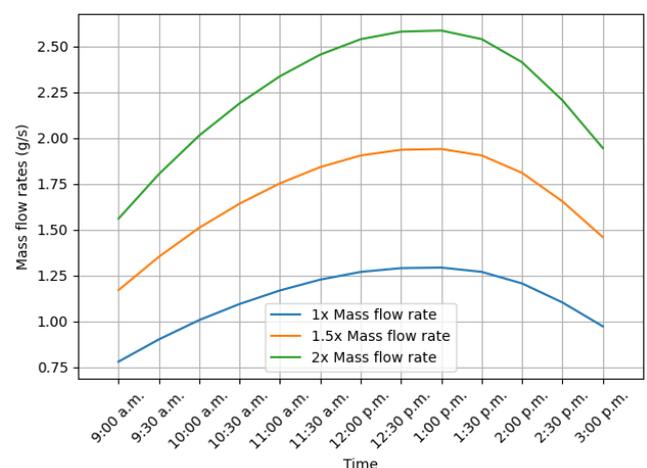


Figure 2 Mass flow rates over time.

Metrics for validation process are absolute error (Eq. 5) due to their simplicity and clarity. This equation is used to measure the deviation between simulation results and experimental data. Thermal efficiency (Eq. 6) is commonly used to determine the performance of flat plate solar collector [12]. Pressure drops and %difference in grid independent test is calculated as Eq. 7 and Eq. 8 respectively. %difference is used to measure the change of outlet temperature across the iteration, which shows how much the simulation results changed as the number of cells increased. This study aims for low %difference as it indicates that the solution is becoming grid independent. Thus, the model has acceptable discretization error [13].

$$\%error = \frac{|Experimental\ Data - Simulation\ results|}{Experimental\ Data} \times 100 \quad (Eq. 5)$$

$$\eta = \frac{\dot{m}C_p(T_o - T_i)}{A_c G} \times 100 \quad (Eq. 6)$$

$$\Delta P = (P_i - P_o) \quad (Eq. 7)$$

$$\%difference = \frac{|T_{o,previous\ step} - T_o|}{T_{o,previous\ step}} \times 100 \quad (Eq. 8)$$

Where η is thermal efficiency, \dot{m} is mass flow rate, subscript i mean at inlet and subscript o mean at outlet, A_c is collector area, and G solar irradiance. ΔP is the pressure drop, P or pressure has the same subscription meaning as temperature.

Results and discussion

The results from the CFD model with different number of cells are compared together for the grid independent test as shown in Table 1.

Table 1 Comparison for grid independent test

Number of cells (million)	Outlet temperature (K)	%difference
0.440	323.24	-
0.872	322.96	0.09
1.113	322.87	0.03

These results demonstrate that after 0.872 million cells, 1.113 million cells result in the difference between outlet temperature comparing to the previous step is 0.03% difference. Therefore, the solution grid independent test is acquired with 0.872 million cells as the chosen number of cells for further study.

The validation process of CFD model is performed by comparing its results with experimental data from Alkhafaji et al. [7]. The compared data shown in Figure 3 is the outlet temperature of flat plate solar collector

using water as a heat transfer medium. The experimental data is obtained from a setup in Baghdad, Iraq. While a sensitivity analysis could further highlight the impact of location-based differences, it was not conducted in this study due to the initial focus being on establishing fundamental validation before expanding into parameter variability. Future research could include sensitivity analysis to look at the influence of these assumptions in greater depth. Despite this, the model agrees well with experimental data, and the largest absolute error of the CFD model is 5.01% at 10 a.m. The reported maximum thermal efficiency is 59.87% at 1 p.m., while in this study at 1 p.m., achieved thermal efficiency of 56.31%. The maximum absolute error at this time is 5.83%, providing another satisfactory convergence between experiment and simulation. In this model, the maximum thermal efficiency is acquired at 12 p.m. with 58.70%. Moreover, the outlet temperature exhibits similar behaviour compared to other experiment [14–15]. Therefore, this flat plate solar collector using CFD approach is suitable for further study.

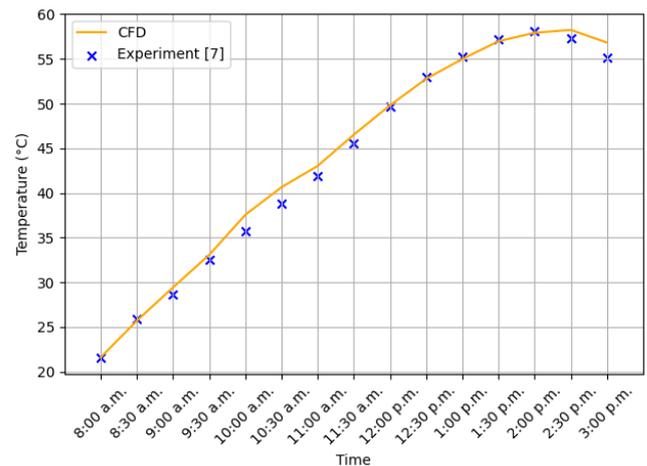


Figure 3 Outlet temperature of CFD model compared to experimental data.

Figure 4 shows the results of 2 locations with the same mass flow rate and inlet temperature, the solar heat flux of April 13th at Bangkok, Thailand could heat the outlet temperature of flat plate solar collector up to 58.34°C, similar to Baghdad, Iraq. The amount of pressure drops across the day is also similar compared to Baghdad, Iraq. Both outlet temperature and pressure drop are roughly the same. The maximum thermal efficiency of solar collector is 58.01% at 11:30 a.m. This will be considered as a base case scenario.

Both locations may produce similar thermal efficiency due to the reasons that both locations receive high solar irradiance throughout the day. Even if Baghdad is further away from the equator than Bangkok, both cities are close enough to the equator to benefit from

relatively high amounts of sunlight. Moreover, the inclination angle for Bangkok is modified to provide the highest energy. This may ensure that solar collectors in both locations could absorb high amounts of energy. Since both location's configurations are identical, this may lead to comparable pressure drops as pressure drop in laminar flow tends to be stable [16].

After varying the mass flow rate to 1.5 and 2 times of the original mass flow rate assuming the same inlet temperature. As shown in Figure 5, the higher the mass flow rate, the higher the outlet temperature. At the 1.5 times mass flow rate, maximum outlet temperature and thermal efficiency are 56.02°C and 64.53%, respectively. The maximum outlet temperature happens at 2:30 p.m., while maximum thermal efficiency happens at 11 a.m. For the 2 times mass flow rate, maximum outlet temperature and thermal efficiency achieve the highest with

54.75°C and 69.61% at 2:30 p.m., and 11 a.m., respectively. Comparing this to the base case, even if the outlet temperature decreases by 3.59°C by increasing the mass flow rate to 2 times compared to base case. This could increase its maximum efficiency by 11.6%. High flow rates lead to high convective heat transfer [17], while reducing contact time between fluid and solid. Reducing fluid temperature could cause a higher heat transfer rate between the solid and fluid because the temperature difference is higher [18]. This indicates a tradeoff, while higher flow rates improve efficiency due to enhanced heat transfer. The outlet temperature reduced as heat was removed faster. Higher mass flow rates also cause pressure drops to increase, which would require more pumping power [19] and may lead to structural stress on the system, presenting a balance between thermal gains and energy costs.

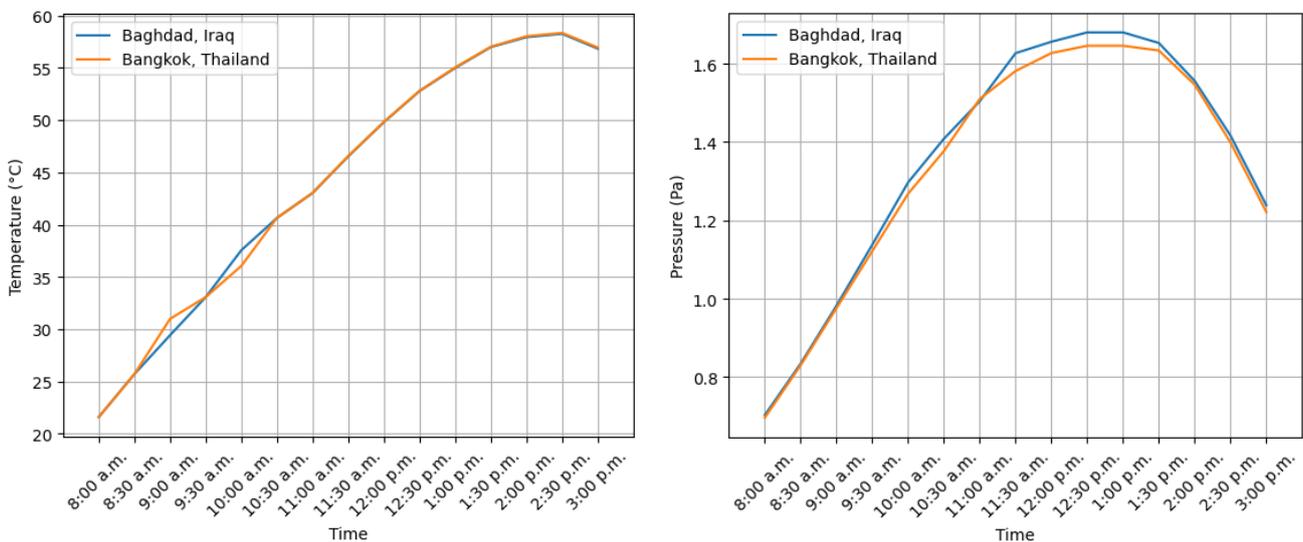


Figure 4 Outlet temperature (left) and pressure drop (right) of Baghdad, Iraq compared to Bangkok, Thailand.

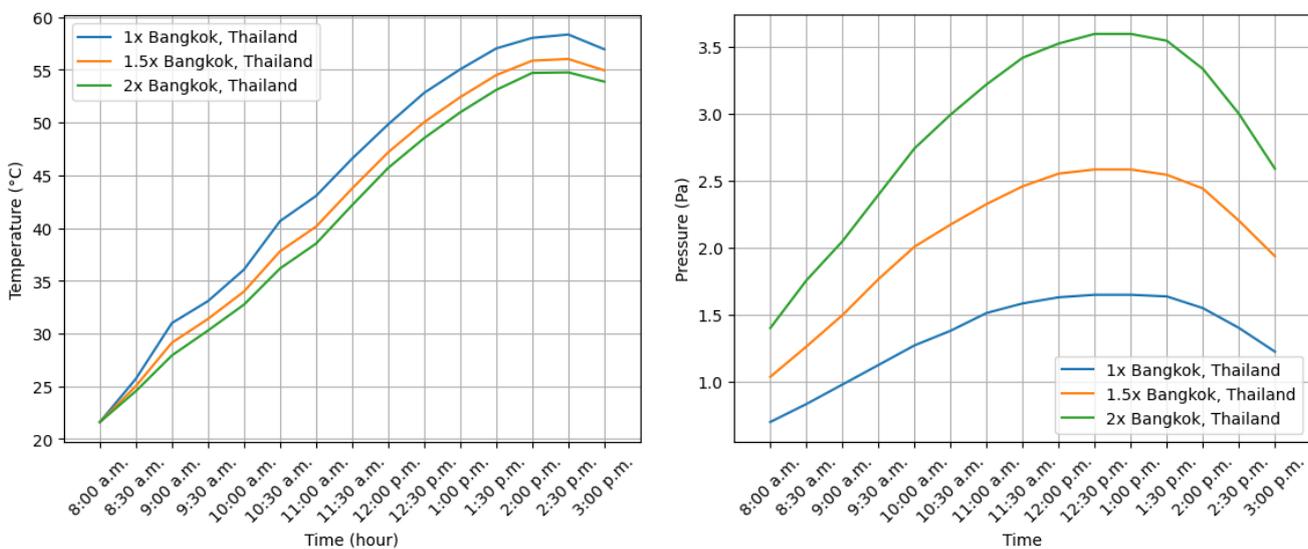


Figure 5 Outlet temperature (left) and pressure drop (right) of different mass flow rates in Bangkok, Thailand.

These results are similar to other studies. Yildizhan et al. [20] studied the closed loop flat plate solar collector and found that increasing mass flow rates of heat transfer oil lead to an increase in energy and exergy efficiency. Abo-Elfadl et al. [21] studied flat plate solar air heater and found that increasing mass flow rates could increase thermal efficiency from 46.3% to 71.1%. However, Wang et al. [22] numerically investigated the effects of mass flow rates and found that increasing mass flow rates could lead to approximately equivalent amounts of efficiency. This may be due to an increase in convective heat transfer as the mass flow rates increase and cause thermal resistance to decrease. However, higher mass flow rates may lead to a negligible reduction in thermal resistance. This study operated the flow in laminar regime, while Wang et al. [22] used the flow in turbulence regime. This may cause the efficiency in this study to not stagnate as the mass flow rates increased, which is one of the limitations of this study. Moreover, the simple copper plate geometry also limits these results, which may differ in real-world applications where factors like structural complexity and material fatigue play roles.

Investigation of cost and strength analysis of flat plate solar collector are necessary in further studies under varying mass flow to provide more commercial viability. Moreover, turbulence operating conditions should be done to compare the advantages and disadvantages of different operating conditions, providing a more comprehensive understanding for flat plate solar collectors.

Conclusion

Thailand is a country near the equator, providing significant potential for solar energy. Flat plate solar collectors could harness solar energy by using water as a heat transfer medium and transferring it into the energy storage tank. However, experimental prototypes could be expensive and provide environmental impact. This study uses computational fluid dynamics to numerically calculate the outlet temperature and pressure drop of the solar collector for further analysis like thermal efficiency. This computational fluid dynamics, or CFD could reduce the cost of experiment and explain phenomena inside the solar collector with an environmentally friendly approach. The study begins with creating a geometry replicate from experimental data. The grid independent test is done to ensure high accuracy without high computational cost usage. Then, the validation process is done using the outlet temperature of the model compared to the experiment. This provides a maximum absolute error of 5.01%. Subsequently, the numerical calculation is performed for the flat plate solar collector in Bangkok, Thailand on April 13th using

solar load model with location, date, and time as parameter inputs. This shows that Thailand provides similar outlet temperature and pressure drop compared to Baghdad, Iraq. Additionally, increasing mass flow rates could lead to higher thermal efficiency up to 69.61% at 11 a.m. with 2.332 g s⁻¹ of mass flow rate.

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