ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article *Araştırma Makalesi* DOI: 10.5281/zenodo.14670880

Effect of Rectangular Flow Elements and Different Fluids Used on Efficiency in High Emissivity Solar Collector

Yüksek Emisiviteli Güneş Kollektörlerinde Dikdörtgen Türbülatörlerin ve Kullanılan Farklı Akışkanların Verimliliğe Etkisi

Fırat TUNA[1]
Ahmet Numan ÖZAKIN[1]
Abdüssamed KABAKUŞ[2]
Gökhan ÖMEROĞLU[1]

[1]Atatürk University, Faculty of Engineering, Mechanical Engineering Erzurum, Türkiye .

[2]Artvin Çoruh University Artvin Vacational School
Artvin, Türkiye

ABSTRACT

This study investigates the effects of turbulators (1, 5 and 9 per tube in a spiral arrangement) and advanced matte black coatings that providing high emissivity (Black 2.0 and Black 3.0) on the thermal performance of flat plate solar water heater (FPSWH) systems. It also evaluates the effect of different heat transfer fluid (HTFs) (ethylene glycol, ammonia and water) at varying flow rates using ANSYS-Fluent software for simulation. An experimental design approach based on Response Surface Methodology (RSM) was used to optimize the system parameters for maximum efficiency. The findings highlight the importance of optimizing absorber plate designs, improving heat transfer mechanisms and integrating advanced materials to enhance FPSWH performance. The adoption of solar water heaters not only reduces dependence on fossil fuels but also aligns with global sustainability goals by reducing environmental impacts and addressing energy security concerns. As solar energy continues to dominate renewable energy applications, hybrid technologies and developments in FPSWH systems are critical to meet the growing global energy demand in a sustainable manner.

Keywords: Solar energy, Optimization, FPSWH, CFD Analysis

ÖZ

Bu çalışmada, türbülatörlerin (spiral şekildeki tüp başına 1, 5 ve 9) ve mat siyah kaplamanın (Black 2.0 ve Black 3.0) düz plakalı güneş enerjili su ısıtıcı sistemlerinin termal performansı üzerindeki etkileri araştırılmıştır. Ayrıca, simülasyon için ANSYS-Fluent yazılımı kullanılarak farklı akış hızlarında farklı ısı transfer sıvılarının (etilen glikol, amonyak ve su) etkisi değerlendirilmiştir. Maksimum verimlilik için sistem parametrelerini optimize etmek amacıyla Yüzey Yanıt Metodolojisi'ne (RSM) dayalı deneysel bir tasarım yaklaşımı kullanılmıştır. Bulgular, soğurucu plaka tasarımlarını optimize etmenin, ısı transfer mekanizmalarını iyileştirmenin ve FPSWH performansını artırmak için gelişmiş malzemeleri entegre etmenin önemini vurgulamaktadır. Güneş enerjili su ısıtıcılarının benimsenmesi yalnızca fosil yakıtlara olan bağımlılığı azaltmakla kalmaz, aynı zamanda çevresel etkileri azaltarak ve enerji güvenliği endişelerini ele alarak küresel sürdürülebilirlik hedefleriyle de uyumludur. Güneş enerjisi yenilenebilir enerji uygulamalarına hâkim olmaya devam ederken, hibrit teknolojiler ve FPSWH sistemlerindeki gelişmeler, büyüyen küresel enerji talebini sürdürülebilir bir şekilde karşılamak için kritik öneme sahiptir.

Anahtar Kelimeler*:* Güneş enerjisi, Optimizasyon, FPSWH, CFD Analizi

Received/Geliş Tarihi: 09.12.2024
Accepted/Kabul Tarihi: 06.01.2025
Publication Date/Yayın Tarihi: 17.01.2025

Corresponding Author/Sorumlu Yazar:
Ahmet Numan ÖZAKIN
E-mail: ahmet.ozakin@atauni.edu.tr

Cite this article: Tuna F., Özakın A.N., Kabakuş A., Ömeroğlu G., (2024), Effect of Rectangular Flow Elements and Different Fluids Used on Efficiency in High Emissivity Solar Collector *Journal of Energy Trends*, 1(2), 59-66

Introduction

A substantial amount of energy is consumed for water heating in hospitals, residential applications, and various industries. Conventional energy sources, such as coal, natural gas, and oil, are widely used around the world to meet energy demands. However, the usage of these energy sources for water heating is extensive, leading to greenhouse gas emissions that contribute to environmental pollution and climate change. Furthermore, the depletion of fossil fuels has become a growing concern. To reduce the consumption of fossil fuels, various renewable energy sources are considered viable alternatives (Jamar et al. 2016; Özakin & Kaya, 2020).

In developing countries, solar energy is a prominent alternative in numerous industrial and manufacturing sectors to reduce fossil fuel consumption and mitigate environmental impact. Solar water heating (SWH-Solar Water Heater) is an effective method of utilizing solar energy to produce hot water or steam for industrial heating and polygeneration. When selecting solar thermal collectors, factors such as energy requirements, required temperature range, and system economics are significant. Among various solar thermal collectors, flat plate solar water heaters (FPSWH) are widely utilized due to their simple construction, smooth operation, low maintenance needs, and cost-effectiveness (Vengadesan et al. 2020).

However, the thermal efficiency of the FPSWH (Flat Plate Solar Water Heater) system is a critical factor in designing an economically viable SWH system. The more cost-effective the system, the lower its efficiency tends to be, while higher efficiency may lead to a greater total annual cost (TAC). In renewable energy utilization, the energy payback period (EPBP), which measures the time required for a solar system to recover the energy invested in its construction, is an important factor. A thermoeconomic FPSWH system can achieve reduced TAC and improved collector efficiency.

As global energy demand continues to rise due to population growth, industrialization, and improved living standards, solar energy remains the most widely used renewable energy source, being environmentally friendly, economically advantageous, clean, and carbon-free (Bazri et al. 2019). Solar thermal applications are especially common for domestic and industrial water heating purposes due to their simplicity and effectiveness (Li et al. 2017; Abuska, 2018; Bazri et al. 2019).

Solar water heaters (SWH) are commonly employed in both industrial and residential sectors to reduce the consumption of conventional fuels by preheating water. Two popular types of solar water heaters are the Flat Plate Solar Water Heater (FPSWH) and the Evacuated Tube Collector (ETC) solar water heater. The ETC utilizes double glass pipes with an inner heat pipe to absorb solar radiation, and its heat loss is minimized by evacuating the space within the tube (Li et al., 2020). FPSWH is a widely used collector, designed to provide temperatures between 50–100 °C. The thermosiphon FPSWH operates on natural water circulation due to the thermosiphon effect, while the forced circulation FPSWH uses a pump in a closed-loop system. According to Diego-Ayala and Carrillo (2016), the forced circulation system generally performs better in terms of daily energy efficiency due to forced convection.

Various methods have been explored to improve FPSWH efficiency. Enhancements include optimizing the optical properties of absorber materials, adding more glass covers to reduce heat loss, and using polymer absorbers or nanofluids as heat transfer fluids (HTFs). Additionally, new absorber plate designs, mini and micro channels for fluid flow, and energy storage integration have been shown to improve performance (Pandey & Chaurasiya, 2017).

FPSWH systems traditionally suffer from low thermal efficiency due to poor heat transfer between the absorber and HTF. To address this, both active and passive methods are employed. Passive methods focus on enhancing heat transfer in absorber tubes, using devices such as twisted tape (Sandhu et al., 2014), wire coil inserts (García et al. 2013), vortex generators (Silva et al. 2019; Wang et al. 2019), and other flow inserts to create turbulence and improve fluid mixing. Additionally, different nanofluids (e.g., aluminium oxide/water, CuO/water, and SiO_2/water) have been studied to enhance heat transfer and increase the efficiency of water heaters (Boyaghchi & Montazerinejad, 2016; Said et al. 2016; Shojaeizadeh & Veysi, 2016).

Integrating Thermal Energy Storage (TES) with FPSWH allows solar energy to be stored for use during evening hours, significantly boosting overall efficiency (Bazri et al. 2019). The thermal performance of solar water heaters thus involves optimizing absorber designs, heat transfer fluids, thermal energy storage, and improving heat transfer mechanisms.

Another research area is hybrid solar energy systems that combine solar thermal and photovoltaic (PV) technologies. While solar thermal and PV technologies are well-commercialized, the hybrid solar thermal-PV system, which simultaneously provides hot water and electricity, is still under extensive research and development. Although only a few studies have been published on this hybrid system, many researchers are working toward its commercialization (Michael & Iniyan, 2017).

Due to the depletion of conventional energy sources and their adverse environmental impacts, the adoption of renewable energy for water heating has become increasingly critical. Solar energy emerges as a prominent alternative, particularly in developing countries, where it is widely applied in industrial and residential sectors. Flat plate solar water heaters (FPSWH) are commonly utilized due to their simplicity, cost-effectiveness, and low maintenance requirements. However, improving the efficiency of these systems has driven innovations such as advanced heat transfer fluids (e.g., nanofluids), optimized absorber plate designs, and the integration of thermal energy storage. Furthermore, hybrid technologies that combine solar thermal and photovoltaic systems are gaining attention for their ability to simultaneously produce hot water and electricity. These advancements aim to enhance energy efficiency and reduce reliance on fossil fuels, contributing to sustainable energy solutions.

In this study, the effects of adding different numbers (1-5-9 for a single pipe of the spiral) of elements that create local turbulence in the flow (turbulators) and the matte black coatings Black 2.0 and Black 3.0 on the flat plate solar collector on the system performance has investigated. Additionally, in this research, the effects of different fluids (Ethylene glycol, Ammonia and Water) and their flow rates on system performance were evaluated using ANSYS-Fluent software. In this article, variable parameters were also optimized by making an experimental plan with the Response Surface (RSM) experimental optimization method.

Material and Methods

In this study, which was conducted to heat the domestic water more effectively by using solar energy, simulations were performed with three different numbers of rectangular turbulators, three different absorbency coatings, three different heat transfer fluids and three different flow rates. The geometries in which the analyses were made are shown in Figure 1.

In the experiments designed with the Response Surface experiment optimization method, solutions were made by creating mesh elements for the geometries given in Figure 1. In this step, the analyses were first made by starting with a mesh element number of around 250,000 and were progressed in iterations, resulting in the fluid outlet temperature converging to a certain value. As a result, analyses were made by obtaining approximately 555,000 mesh elements and 0.945 "Orthogonal Quality" before starting the analyses. The mesh network structure used in the relevant analyses is shown in Figure 2.

In the model where the mesh structure is seen in Figure 2, the aluminum pipe is fixed to the copper plate. It is noticeable that the mesh structure on the plate is denser in the parts where the rectangular fins placed in the aluminum pipe to increase the turbulence of the flow and increase heat transfer. Analyses were performed with pressure based, k-epsilon turbulence model and under steady state conditions.

(a)

(b)

(c)

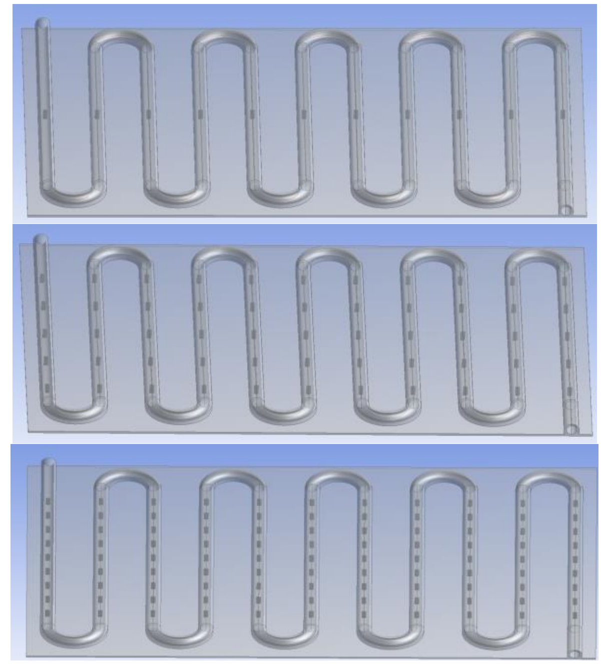

Figure 1.
Cases with 1, 5 and 9 rectangular turbulators on the pipe. a: 1 turbulator, b: 5 turbulators, c: 9 turbulators.

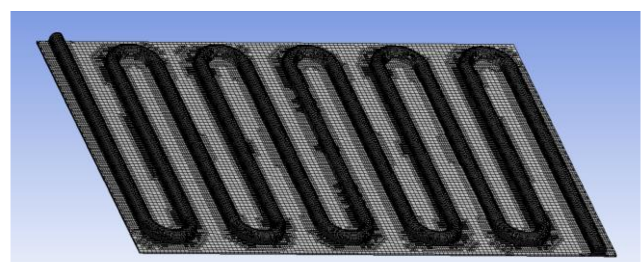

Figure 2.
Cell structure of mesh elements used in the analysis.

The Response Surface Method was used to determine the experimental design and optimum parameter values. This method is a common method used to determine the variable parameters and parameter values affecting the result variable. In the Response Surface Method, after the problem is first determined, the variable parameters and the result variable are determined. After the parameter levels are determined, the appropriate experimental design is selected. After the experiments are carried out according to the experimental design, the accuracy of the design is tested with variance analysis. Finally, the optimum parameters and their values are determined (Öztürk et al. 2023). The selected experimental parameters and values are shown in Table 1.

Table 1.
Design parameters and levels.

Parameters	Levels Low	Middle	High
Number of Turbulators	1	5	9
Flow rate (kgh^{-1})	50	100	150
Fluid	Water	Ammonia	Ethylene glycol
Collector type	Standard	Black 2.0	Black 3.0

Results And Discussion

In the numerical study, the optimum parameters affecting the thermal efficiency of the flat plate solar collector were determined. In the analysis, the fluid type, collector type, fluid flow rate and turbulator number were determined as variable parameters. The experimental design and analysis were carried out using the Minitab 18 program. The experimental design was determined with the "Central composite" approach using the response surface method. The experimental design and heat values created for the heat energy obtained from the solar collector are given in Table 2.

As a result of the variance analysis performed for the heat energy obtained from the collector. the R2 value was determined as 99.99% and R2adj as 99.97%. R2 expresses the accuracy of the experimental design and the R2adj value is the corrected squares value obtained by removing the insignificant values. The fact that the R2 and R2adj values are close to each other and to 100% indicates that the experimental design and results are significant (Öztürk et al. 2023). When the R2 values obtained as a result of the analysis are examined. it is seen that the design used is significant. The effect rates of the variable parameters on the amount of heat obtained from the collector are given in Table 3.

When the variance analysis table is examined. it is seen that the parameters with a P-value less than 0.005 are the main effects of flow rate. number of turbulators and fluid. This shows that the parameters in question have a significant effect on the result variable. It is seen that the parameter that affects the result variable the most is the fluid fluid type with 56.48%. The result variable is affected by the collector type with 1.20%.

Figure 3 shows the Pareto chart showing the parameters affecting the heat energy obtained from the collector (the result variable) in the form of a column chart. In the Pareto chart. the columns passing the reference line (2.12 in this study) are effective on the result variable. When the Pareto chart is examined. it can be said that in addition to the main effects of fluid type and collector type. the square effect of the fluid type and the combined effect of fluid type and collector type are the parameters affecting the result variable.

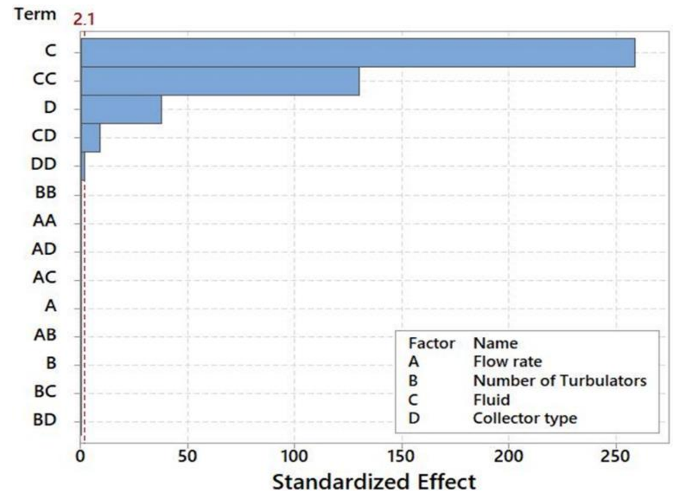

Figure 3.
Pareto chart for heat energy obtained from the collector.

Figure 4 shows the contour graph of the number of turbulators and flow rate for the Black 3.0 collector and Ammonia. It is seen that the maximum amount of heat obtained from the solar collector for the Black 3.0 collector and Ammonia is at a collector with 1-9 turbulators and a flow rate of 100 kgh^{-1}.

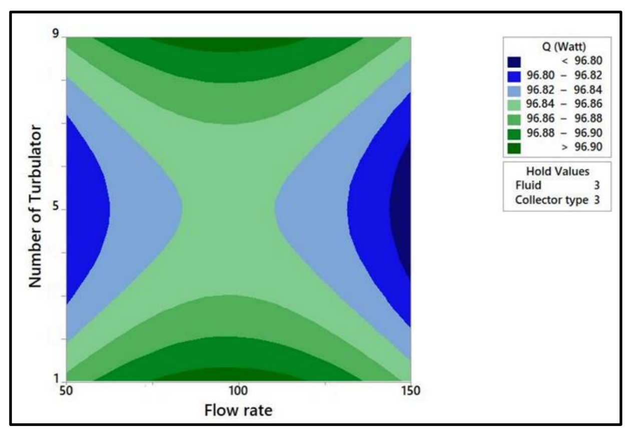

Figure 4.
Number of turbulators vs flow rate graph for Black 3.0 collector and ammonia.

Figure 5 shows the flow-fluid contour graph for the Black 3.0 collector and the 9-turbulator collector. When the graph is examined. it is seen that the highest heat energy is in Ammonia. Also. the amount of heat obtained with the change in flow rate has not changed.

Figure 6 shows the flow-collector type contour graph for Ammonia and 9 turbulators. When the graph is examined, it is seen that the amount of heat obtained from the collector increases as the flow rate increases. It is seen that the maximum amount of heat obtained from the solar collector for the 9 turbulator collector and Ammonia is Black 3.0 collector type and 150 kg/h flow rate.

Table 2.
Experimental plan and Q values.

Flow rate ((l.h^{-1})	Number of Turbulators	Fluid	Collector Type	Q(watt)
50	1	Water	Black 3.0	59.31
50	9	Liquid ammonia	Black 3.0	97.01
100	5	Ethylene glycol	Black 2.0	51.05
50	9	Liquid ammonia	Standard	90.14
150	1	Liquid ammonia	Black 3.0	96.94
100	5	Ethylene glycol	Black 2.0	51.05
50	5	Ethylene glycol	Black 2.0	50.85
100	5	Ethylene glycol	Black 2.0	51.05
50	1	Liquid ammonia	Black 3.0	97.01
150	1	Water	Standard	55.08
100	1	Ethylene glycol	Black 2.0	51.05
50	9	Water	Black 3.0	59.32
100	5	Ethylene glycol	Black 2.0	51.05
150	9	Liquid ammonia	Standard	90.20
50	1	Liquid ammonia	Standard	90.14
100	5	Ethylene glycol	Black 3.0	53.19
150	9	Water	Black 3.0	59.26
150	5	Ethylene glycol	Black 2.0	51.02
100	5	Ethylene glycol	Standard	49.44
100	5	Ethylene glycol	Black 2.0	51.05
50	9	Water	Standard	55.13
100	5	Liquid ammonia	Black 2.0	93.04
150	9	Water	Standard	55.08
150	1	Liquid ammonia	Standard	90.20
50	1	Water	Standard	55.13
100	5	Ethylene glycol	Black 2.0	51.05
100	5	Water	Black 2.0	56.94
100	9	Ethylene glycol	Black 2.0	51.05
150	1	Water	Black 3.0	59.26
100	5	Ethylene glycol	Black 2.0	51.05
150	9	Liquid ammonia	Black 3.0	96.94

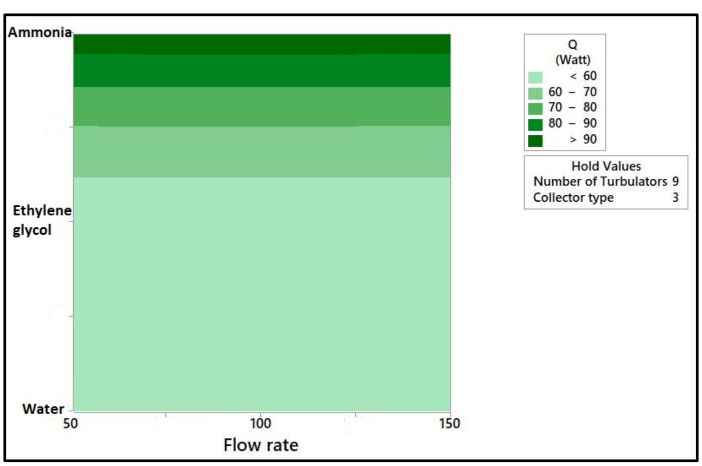

Figure 5.
Flow rate-fluid graph for standard collector and 9 turbulators.

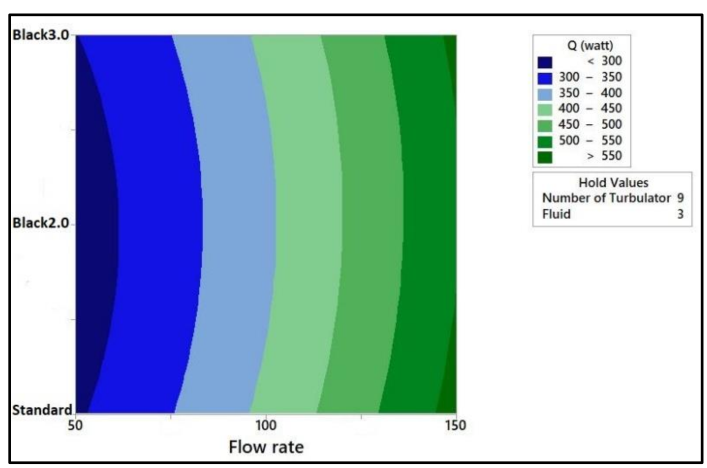

Figure 6.
Flow rate - collector type chart for ammonia and 9 turbulators.

Table 3.

Variance analysis for heat energy obtained from the collector.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	10524.4	99.99%	10524.4	751.74	8507.43	0.000
Linear	4	6071.6	57.68%	6071.6	1517.91	17178.10	0.000
Flow rate	1	0.0	0.00%	0.0	0.00	0.00	0.960
Number of Turbulators	1	0.0	0.00%	0.0	0.00	0.00	1.000
Fluid	1	5945.2	56.48%	5945.2	5945.16	67281.00	0.000
Collector Type	1	126.5	1.20%	126.5	126.48	1431.42	0.000
Square	4	4445.9	42.24%	4445.9	1111.47	12578.42	0.000
Flow rate*Flow rate	1	2416.9	22.96%	0.0	0.01	0.07	0.791
Number of Turbulators*Number of Turbulators	1	373.9	3.55%	0.0	0.01	0.13	0.719
Fluid*Fluid	1	1654.8	15.72%	1495.8	1495.76	16927.36	0.000
Collector Type*Collector Type	1	0.3	0.00%	0.3	0.29	3.32	0.087
2-Way Interaction	6	6.9	0.07%	6.9	1.15	13.00	0.000
Flow rate*Number of Turbulators	1	0.0	0.00%	0.0	0.00	0.00	1.000
Flow rate*Fluid	1	0.0	0.00%	0.0	0.00	0.04	0.848
Flow rate*Collector Type	1	0.0	0.00%	0.0	0.00	0.05	0.827
Number of Turbulators*Fluid	1	0.0	0.00%	0.0	0.00	0.00	1.000
Number of Turbulators*Collector Type	1	0.0	0.00%	0.0	0.00	0.00	1.000
Fluid*Collector Type	1	6.9	0.07%	6.9	6.88	77.90	0.000
Error	16	1.4	0.01%	1.4	0.09		
Lack-of-Fit	10	1.4	0.01%	1.4	0.14		
Pure Error	6	0.0	0.00%	0.0	0.00		
Total	30	10525.8	100.00%				

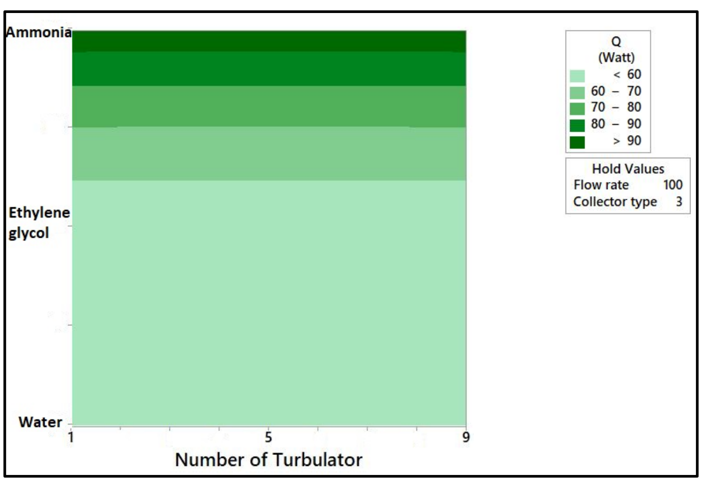

Figure 7.

Fluid type-turbulator number graph for 100 kg/h flow rate and Black 3.0 collector.

Figure 7 shows the contour graph of the number of fluid-turbulators for a flow rate of 100 kg/h and Black 3.0 collector. Changing the number of turbulators did not change the amount of heat obtained from the collector. It is seen that the maximum amount of heat obtained from the solar collector for a flow rate of 100 kg/h and Black 3.0 collector is in the collector with ammonia.

Figure 8 shows the collector type-turbulator contour graph for 100 kg/h flow rate and ammonia. It is seen that the maximum amount of heat obtained from the solar collector for 100 kg/h flow rate and ammonia is with the Black3.0 collector.

Figure 9 shows the collector type-fluid contour graph for 100 kg/h flow rate and 9 turbulators. It is seen that the maximum heat amount obtained from the solar collector for 150 kg/h flow rate and ammonia is with Ammonia and Black3.0-Standard collector.

Figure 10 shows the optimum parameter values. The sharper the curves change in this graph. the more effective it is on the result variable. When the graph is examined, it is seen that the parameters that affect the result variable the most are the fluid type and the collector type. Flow rate and Number of turbulators did not make a big difference on the amount of heat obtained from the collector. y (96.9112) represents the maximum heat energy obtained from the collector. Red lines show the optimum parameter values. As a result. the optimum parameter values for maximum collector efficiency were determined as 100 kg/h flow rate. 9 turbulator numbers. ammonia fluid type and Black 3.0.

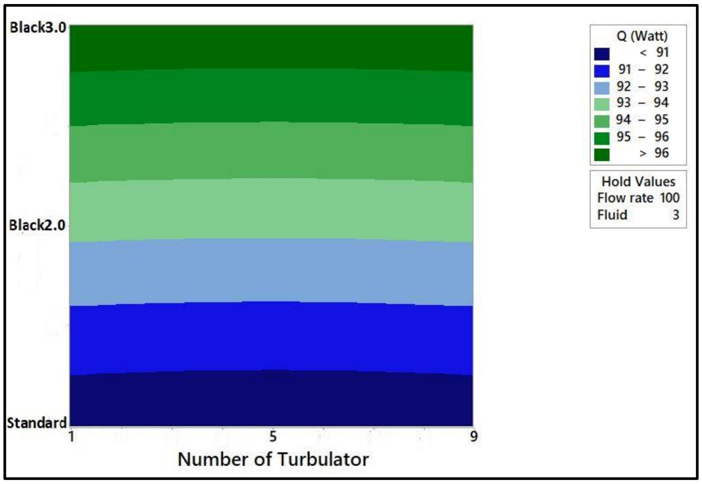

Figure 8.
Collector type-turbulator number graph for 100 kg/h flow rate and ammonia.

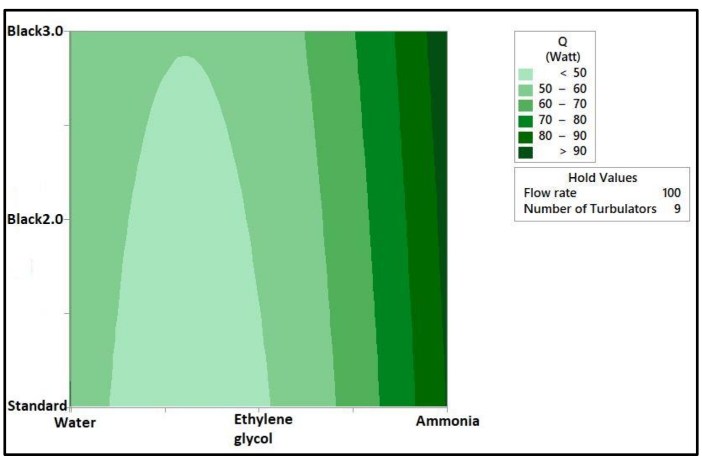

Figure 9.
Collector type-fluid chart for 100 kg/h flow rate and 9 turbulators.

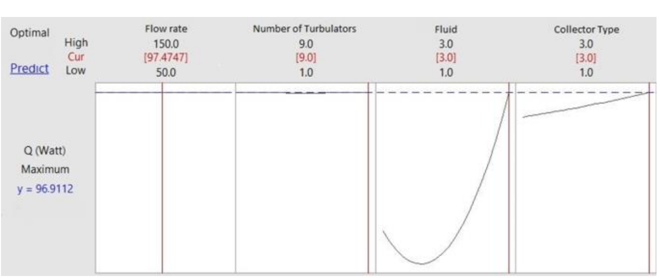

Figure 10.
Optimum parameter values for maximum heat energy obtained from the collector.

Peer-review: *Externally peer-reviewed*
Author contributions:
F. Tuna: Writing, Literature search, analysis
A. N. Özakın: Supervision, literature search, writing manuscript, methodology
A. Kabakuş: Supervision, conceptualization
G. Ömeroğlu: Investigation, analysis
Financial disclosure: *This study was funded by Atatürk University Coordination Unit of Scientific Research Projects, under Grant No. of FYL-2024-14223.*
Conflict of Interest: *The author has no conflicts of interest to declare.*

References

Abuşka, M. (2018). Energy and exergy analysis of solar air heater having new design absorber plate with conical surface. *Applied Thermal Engineering, 131, 115-124.*

Bazri, S., Badruddin, I. A., Naghavi, M. S., Seng, O. K., & Wongwises, S. (2019). An analytical and comparative study of the charging and discharging processes in a latent heat thermal storage tank for solar water heater system. *Solar Energy, 185, 424-438.*

Boyaghchi, F. A., & Montazerinejad, H. (2016). Multi-objective optimisation of a novel combined cooling, heating and power system integrated with flat plate solar collectors using water/CuO nanofluid. *International Journal of Exergy, 21(2), 202-238.*

Da Silva, F. A., Dezan, D. J., Pantaleao, A. V., & Salviano, L. O. (2019). Longitudinal vortex generator applied to heat transfer enhancement of a flat plate solar water heater. *Applied Thermal Engineering, 158, 113790.*

Diego-Ayala, U., & Carrillo, J. G. (2016). Evaluation of temperature and efficiency in relation to mass flow on a solar flat plate collector in Mexico. *Renewable Energy, 96, 756-764.*

García, A., Martin, R. H., & Pérez-García, J. (2013). Experimental study of heat transfer enhancement in a flat-plate solar water collector with wire-coil inserts. *Applied Thermal Engineering, 61(2), 461-468.*

Jamar, A. M. Z. A. A., Majid, Z. A. A., Azmi, W. H., Norhafana, M., & Razak, A. A. (2016). A review of water heating system for solar energy applications. *International Communications in Heat and Mass Transfer, 76, 178-187.*

Li, Q., Moya, W., Esfahani, I. J., Rashidi, J., & Yoo, C. (2017). Integration of reverse osmosis desalination with hybrid renewable energy sources and battery storage using electricity supply and demand-driven power pinch analysis. *Process Safety and Environmental Protection, 111, 795-809.*

Michael, J. J., & Selvarasan, I. (2017). Economic analysis and environmental impact of flat plate roof mounted solar energy systems. *Solar energy, 142, 159-170.*

Özakın, A. N., & Kaya, F. (2020). Experimental thermodynamic analysis of air-based PVT system using fins in different materials: Optimization of control parameters by Taguchi method and ANOVA. *Solar Energy, 197, 199-211.*

Öztürk, A., Sönmez, F., & Kabakuş, A. (2024). Determination of optimum parameters using different nano fluids in heat pipe heat exchangers with response surface method. *Chemical Engineering Communications*, 211(5), 725-735.

Pandey, K. M., & Chaurasiya, R. (2017). A review on analysis and development of solar flat plate collector. *Renewable and Sustainable Energy Reviews*, 67, 641-650.

Said, Z., Saidur, R., & Rahim, N. A. (2016). Energy and exergy analysis of a flat plate solar collector using different sizes of aluminium oxide based nanofluid. *Journal of cleaner production, 133, 518-530.*

Sandhu, G., Siddiqui, K., & Garcia, A. (2014). Experimental study on the combined effects of inclination angle and insert devices on the performance of a flat-plate solar collector. *International Journal of Heat and Mass Transfer*, 71, 251-263.

Shojaeizadeh, E., & Veysi, F. (2016). Development of a correlation for parameter controlling using exergy efficiency optimization of an Al2O3/water nanofluid based flat-plate solar collector. *Applied Thermal Engineering, 98, 1116-1129.*

Vengadesan, E., & Senthil, R. (2020). A review on recent development of thermal performance enhancement methods of flat plate solar water heater. *Solar Energy, 206, 935-961.*

Wang, Y., Liu, P., Shan, F., Liu, Z., & Liu, W. (2019). Effect of longitudinal vortex generator on the heat transfer enhancement of a circular tube. *Applied Thermal Engineering, 148, 1018-1028.*