Chapter 5

Simulation-Based Investigation of Heat Collection in Various Absorber Plate Materials for Solar Water Heating Systems

Mara Niebling[1]

Coskun Firat[2]

Altin Maraj[3]

A. Talat Inan[4]

Abstract

The main component of a solar water heating system is the collector. The absorber plate is another crucial component of the collector. For a more effective system, the absorber layer should, to the greatest extent possible, be made of materials with good thermal properties. In this study, in addition to copper and aluminum, new materials such as pyrolytic graphite and glass for the absorber plates of solar water heaters are presented. Along with a performance comparison analysis of the collector utilizing various materials, the costs of each material are also reported. It was concluded that pyrolytic graphite provided the best heat transfer. There is different type of pyrolytic graphite with different thermal conductivity. Calculations, however, show that even the PG with the highest thermal conductivity (1800/15 W/mK in plane and in z-direction, respectively) only slightly increases the temperature of the usable energy. In other words, increasing the thermal conductivity above a certain level does not improve the performance of the solar panel. Glass is another material which offers a better performance while maintaining very low thermal conductivity. Despite having different heat transfer mechanisms when used as absorbers, pyrolytic graphite and glass can be offered as a new material for absorber plates because they outperform conventional materials like copper. In comparison to copper, the efficiency of the collector with the pyrolytic graphite absorber was found to be 2% higher.

1 Ms., Johannes Gutenberg University, Mainz, Germany

2 Assoc. Prof. Dr., Istanbul Technical University, Energy Institute, Istanbul, Türkiye, coskun.firat@itu.edu.tr, Orcıd: 0000-0002-2853-8940, (corresponding)

3 Assoc. Prof. Dr., Polytechnic University of Tirana, Faculty of Mechanical Engineering, Tirana, Albania, amaraj@fim.edu.al, Orcıd: 0000-0003-3976-9303

4 Assoc. Prof. Dr., Marmara University, Faculty of Technology, Istanbul, Türkiye, ainan@marmara.edu.tr, Orcıd: 0000-0003-2720-5711

https://doi.org/10.58830/ozgur.pub130.c534

1. Introduction

Sunlight is an almost infinite resource on our planet [1]. Solar water heater (SWH) systems harness the sunlight with a solar thermal collector and convert it into heat. Thus, SWHs are environmentally friendly heat exchangers and run without to minimal operation and maintenance costs. The first solar water heater was patented in 1891 by Kemp and thereafter, the development and improvement of SWHs started [2]. Nowadays, solar water heating is one of the cheapest and resource-efficient applications which supplies domestic hot water [3]. According to Ekramian et al. [4], solar energy is one of the best alternatives to fossil energy sources. Especially, in developing countries, often located in sunny regions, solar energy offers great opportunity. Accordingly, SWHs are gaining increasing importance as a sustainable alternative to conventional energy sources. One of the main components of SWHs is the absorber plate, and its selection plays a significant role in the overall efficiency of the system. This study aims to investigate the performance of different absorber plate materials and to provide insights into the design of more effective solar water heating systems.

Flat-plate thermal collectors (FPTCs) are the most studied and used technology among different SWH systems, because of the simplicity and the working temperature range suitable for domestic solar water heating as well as space heating applications. A common size is 1m×2m×0.15m [5]. They are made with a strong frame, an often-glazed glass front, a solid back and insulation on the sides and the back. The absorber plate is mostly under the glass cover since glass transmits more than 90% of the incident short-wave solar radiation and emits only part of the long-wave radiation emitted by the absorber plate [6]. Traditionally, flat plate collectors have two bigger water tubes, called manifolds, at the top and the bottom as well as several thinner riser tubes that run perpendicular [5]. The tubing allows a heat transfer fluid (HTF), often water, to run through the collector.

The absorption and transmission properties of an absorber plate depend on the material as well as the coating of the plate [6]. Ideally, an absorber should absorb all incoming radiation and emit no heat back to the atmosphere. So, the optical, chemical and structural properties of absorber plates and coatings have been changed to improve the absorption (in the solar spectrum or short-wave) to emission (long-wave) ratio [7]. Most absorber plates are made out of metals like copper, aluminum and steel with relatively high thermal conductivities of about 50 to 400 W/mK showed an increase in absorber efficiency with absorber conductivity [4]. However, this dependence is not linear. Even though the thermal conductivity of copper is almost twice that of aluminum, the efficiency of the SWH is just slightly better. The use of corrugated absorber plates that both increase the absorber surface area and friction are beneficial for efficiency [8]. Lu et al. improved the absorber plate with a Copper Oxide nano-structure selective coating [8, 9]. Non-metallic materials like engineering [10] and commodity [11] polymers also can be used as solar absorber plates, especially for un-glazed SWHs. It has been shown that the absorption and emission coefficients of a polyethene absorber are about 0.85 and 0.1, respectively, which is quite comparable with selectively coated solar absorbers with absorption and emission coefficients of about 0.95 and 0.05 [12].

Efficiency for solar air heaters is found for adding porous material on top of the absorber plate to create a swirling airflow and avoid thermal boundary layers [16-18]. Likewise, inserting wire coil into the tubes of a water heating collector can lead to an efficiency increase of up to 4.5% since it changes the flow characteristics of the HTF [19]. The effective surface area of a collector highly influences the collector's performance. To increase the surface area, he investigated semi-spherical absorber plates [20]. On top of that, he focused on collecting not only direct, but also diffuse and reflected radiation to maximize collector efficiency [21].

In this study, various materials such as copper, aluminum, pyrolytic graphite, and glass were tested for their efficiency in absorbing and transferring heat. The study found that pyrolytic graphite and glass are new materials that outperform conventional materials such as copper in terms of heat transfer efficiency.

Additionally, the study also reports on the cost-effectiveness of each material, which is a crucial factor for practical implementation. The results showed that pyrolytic graphite is more expensive than copper, while glass is relatively cheaper. However, both materials offer better performance while maintaining low thermal conductivity. This information can help manufacturers and designers to select the most appropriate absorber plate material for their solar water heating systems.

The significance of this study lies in the fact that it provides a better understanding of the performance of different absorber plate materials, which can lead to the development of more efficient and cost-effective solar water heating systems. The use of pyrolytic graphite and glass as absorber plate materials can lead to significant improvements in the overall efficiency of solar water heating systems. The findings of this study can also help policymakers in promoting the use of renewable energy sources by making solar water heating systems more attractive and cost-effective. In conclusion, this study can contribute significantly to the development and advancement of sustainable energy solutions.

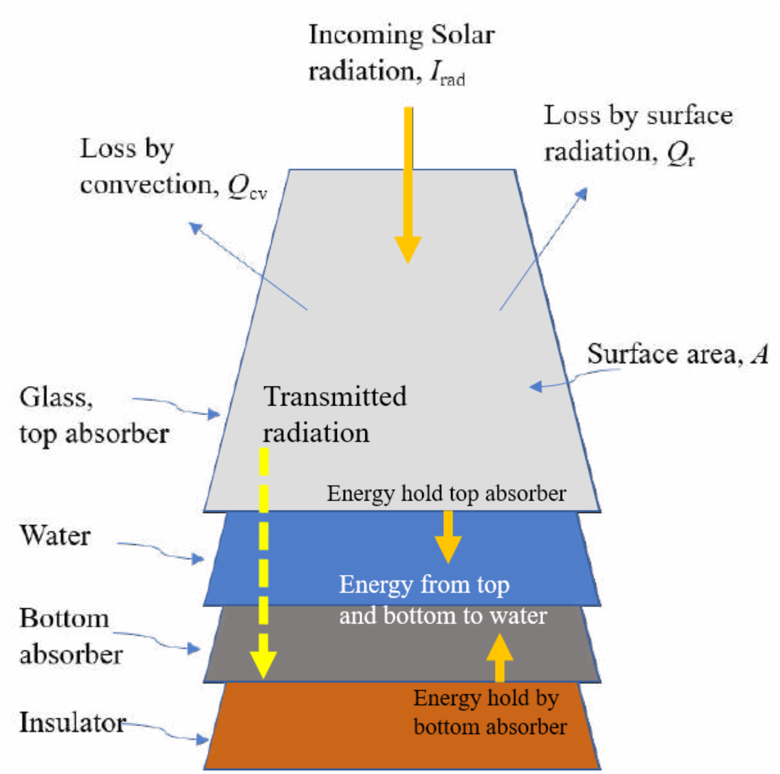
2. Thermal performance principles of SWH

When an increase in heat difference between the inlet and outlet fluid temperature of a solar collector, the system efficiency is increasing. This is reflected in the efficiency (η) as follows:

$$\eta = \frac{Q_u}{G}. \tag{1}$$

The useable energy Q_u that heats the fluid inside the collector is included in the efficiency equation together with the incoming solar radiation I_{rad}, which is connected to the energy arriving ($G=A.\ I_{rad}$) onto the collecting area (A). The discrepancy between G and Q_u results from losses to the environment, such as radiation and convection, or from heating all collector materials. The mechanism for this heat transfer in the collector is shown in Fig. 1.

Figure 1. Heat transfer mechanism in the collector



Water is used as an HTF. Thus, the usable heat Q_u is dependent on the specific heat of water c_w and its mass flow rate $\dot{m}_w \dot{m}_w$ as it is shown in Eq.(2) as [24]:

$$Q_u = \dot{m}_w c_w (T_o - T_i). \tag{2}$$

It was assumed that the bottom and sides of the collector had perfect thermal insulation in order to make the analytical calculations easier, namely $\vec{n}.\vec{q} = 0$ with the surface normal $\vec{n}$ and the heat flow $\vec{q}$. It was also assumed that the radiation arriving at the surface strikes perpendicularly. In that case, the full incoming radiation hits the top surface of the flat-plate collector. Given that glass has an emissivity of 0.94, where 1 indicates perfect transmission of incoming radiation, the reflection losses are minimal and can be disregarded.

When the collector surface is hotter than the ambient temperature, energy will be lost through radiation Q_r and convection Q_{cv} if there is an airflow as well. Furthermore, when heat is conducted through different media, additional heat losses occur. They can be imagined as heat resistances R of the materials and their boundary layers. The thermal resistance of a solid (Eq.3) depends on the thermal conductivity k, the thickness l and the surface area A, of the materials [26]:

$$R = \frac{l}{kA}. \tag{3}$$

The higher the thermal resistance of a material, the better its insulating properties. The sum of all thermal resistances, including conductive, convective, and radiative losses, yields the total system energy loss, Q_L (Eq.4). Due to energy conservation, these losses are exactly the difference between the incoming energy and the useful energy in a perfectly insulated collector:

$$Q_L = Q_r + Q_{cv} + Q_c = G - Q_u. \tag{4}$$

Since we assumed perfect insulation of the collector, the useful energy Q_u can be calculated by subtracting the losses from the incoming solar radiation energy.

The mathematical model of the thermal heat transfer mechanism must be recorded in order to determine the water output temperature. The incoming solar energy is split into losses to the environment due to convection (Q_{cv}) and surface radiation (Q_r), and some of the remaining energy (Q_g) is stored by conduction in glass (Q_{cg}), and also transmitted to the bottom side of the glass (Q_{gt}) [24]:

$$G = Q_r + Q_{cv} + Q_g. \tag{5}$$

$$Q_r = \sigma\varepsilon_g A\left(T_g^4 - T_a^4\right). \quad (6)$$

$$Q_{cv} = h_v A\left(T_g - T_a\right). \quad (7)$$

$$Q_g = Q_{cg} + Q_{gt} = \frac{k_g A}{l_g}\left(T_g - T_a\right) + \tau_g Q_g, \quad (8)$$

where AA is the surface area, $\sigma\sigma$ is the Stefan-Boltzmann constant, T_a is the ambient temperature, ε_g is the surface emissivity, T_g is the temperature, k_g is the thermal conductivity coefficient, l_g is the thickness and τ_g is the transmittance of glass. The surface convection heat transfer coefficient h_v depends on the wind speed vv as [27]:

$$h_v = 11.4 + 5.7v. \quad (9)$$

Thus, the energy on the glass is rewritten as;

$$Q_g = \frac{k_g A}{l_g(1-\tau_g)}\left(T_g - T_a\right), \quad (10)$$

by considering Eqns. (5–10), the glass temperature (T_g) can be determined from the energy balance.

$$G = \frac{k_g A}{l_g(1-\tau_g)}\left(T_g - T_a\right) + \sigma\varepsilon_g A\left(T_g^4 - T_a^4\right) + h_v A\left(T_g - T_a\right). \quad (11)$$

A portion ($\tau_g \tau_w Q_g$) of the remaining energy ($\tau_g Q_g$)is subsequently transmitted onto the absorber layer while the other portion of it (Q_w) is transferred to water. Writing the energy balance will yield the mean water temperature (T_{mw}).

$$\tau_g Q_g = Q_w + \tau_g \tau_w Q_g. \quad (12)$$

$$\tau_g \frac{k_g A}{l_g(1-\tau_g)}\left(T_g - T_a\right) = h_w A\left(T_{mw} - T_g\right)$$

$$+ \tau_g \tau_w \frac{k_g A}{l_g(1-\tau_g)}\left(T_g - T_a\right) \quad (13)$$

where h_w is the convection heat transfer coefficient and τ_w is the transmittance of water. The energy transmitted onto the absorber layer will be stored there by conduction heat transfer. The absorber temperature (T_m) can be obtained by using this energy balance;

$$\tau_g \tau_w \frac{k_g A}{l_g(1-\tau_g)}\left(T_g - T_a\right) = \frac{k_m A}{l_m}\left(T_m - T_{mw}\right) \quad (14)$$

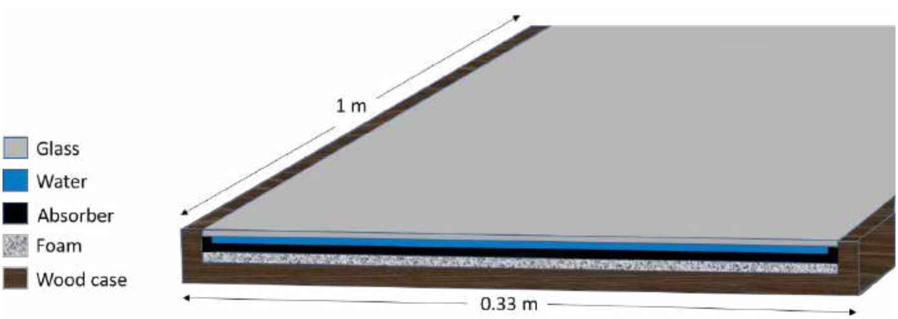
The output water temperature (T_{out}) can then be determined by considering the energy balance between usable energy and the energy transferred to the water from the top and bottom layers as well as by convection;

$$\frac{k_m A}{l_m}(T_m - T_{mw}) + \frac{k_g A}{l_g}(T_g - T_a) = \dot{m}_w c_w (T_o - T_i)$$
$$+ h_w A(T_{mw} - T_g). \tag{15}$$

3. Material selection and simulation design

Similar values and assumptions as in the analytical study (Sect-2) were used in the simulation. It is based on the finite element method (FEM) which divides the collector model into multiple small grid elements to solve separately. The collector model (Fig. 2) is scaled to 0.33 m × 1.00 m to prevent using more computing power than necessary.

Figure 2. Sketch of the model flat-plate collector



If the absorber plate is allowed to be placed loosely inside the collector, it can change in size as a function of temperature without restrictions or increased pressure [7]. The current study differs from that since it was determined that water flows through an envelope-like channel between the glass and the absorber.

The insulation layer of solar water heaters is often made of insulating wool or foam [13]. In the present study, polyurethane foam is selected as insulator that is suited to insulate the collector from +130 °C to -40 °C [28]. The top layer of the model collector is made of glass, which is widely used for solar collectors due to its favorable transmission to emission ratio [8]. The simulations assume that the solar radiation impinges normal to the surface with an irradiance of I_{rad} = 1000 W/m^2, as in the ASTM standard [29].

In a study, Shariah et al. found that the thermal conductivity and characteristic factor of a collector from a negatively curved hyperbole that is asymptotic to 1. Thus, increasing the thermal conductivity up to 100 W/mK improves the collector's performance significantly. Whereas, for higher conductivities the asymptotic behavior of the function dominates and higher thermal conductivity only raises the efficiency slightly [30]. Still, we introduce annealed pyrolytic graphite [31] as an absorber material as it could still increase the efficiency slightly. Additionally, glass was tested as an absorber plate material even though its thermal conductivity is low. Currently, the most popular materials for the absorber plate of solar water heaters are made of copper and aluminum [4].

Pyrolytic graphite (PG) sheets (also commonly referred to as thermal interface graphite pads or graphite film) is created from a high temperature sintering process, heating a polymer film to its decomposition temperature in a vacuum and allowing it to carbonize then graphitize until ultimately left with a highly oriented graphite material. Graphite's sheet-like crystals known as graphene are stacked on top of each other, allowing for extremely high in-plane thermal conductivity (x-y direction/a-b plane) compared to its through-plane thermal conductivity (z direction/c plane) [32]. A summary on comparing the absorber materials used in previous studies in the literature on solar water heating systems is given in Table 1.

Table 1. Used materials and their properties at 21 °C [8, 23, 33-36].

Material	Thermal conductivity [W/(mK)]	Density [kg/m^3]	Cost [\$/kg]
Pyrolytic graphite (PG)	1050 (in plane x-y) 20 (in z-direction)	1500	3.68
Pyrolytic graphite (PG)	1800 (in plane x-y) 15 (in z-direction)	2170	3.68
Copper sheet (Cu)	386	8930	7.35
Aluminum sheet (Al)	238	2700	2.45
Silica glass	1.38	2203	6.12 \$/m^2
Polyurethane foam	0.03	30-80	3.68
Water (HTF)	0.58	1000	0.80 \$/m^3

The PG sheets offer up to five times the thermal conductivity of copper, at only a fraction of the weight. There are numerous advantages of PG sheets, especially when compared to their metallic counterparts [32]:

- High in-plane thermal conductivity up to 1950 W/mK.

- Lightweight when compared to its metallic counterparts such as aluminum or copper.
- Highly anisotropic structure allows for high thermal conductivity only in the x-y plane.
- Can be die-cut into customizable shapes.
- Offered with adhesives for fast installation (peel-and-stick attachment).
- Can be laminated with plastics, metals, or foam to improve performance.

There are many applications of PG in thermal management as heat sinks, as thermal interface material and as thermal energy storage material due to its high thermal stability. PG has been used as a heat sink material due to its high thermal conductivity. In a study by Wen et al. (37), PGs was used for the thermal management of a fuel cell system. They found that PGS reduces the maximum cell temperature and improves cell performance at high cathode flow rates. The temperature distribution is also more uniform in the cell with PGS than in the one without PGS.

4. Results

In this study, in the analytical and the numerical calculations, copper, aluminum, glass, and aPG sheet are taken into consideration as the absorber materials to perform the collector with various absorbers. The Table 2 lists the materials' thermal characteristics as well as the weather conditions for the calculations.

Table 2. The weather conditions and the thermal properties of the materials used in the collector.

Solar radiation	1000 W/m^2
Aperture area of the collector	0.33 m^2 (1 x 0.33)
Emissivity of glass	0.94
Stefan-Boltzmann constant	5.67 x 10^{-8} W/m^2K^4
Ambient temperature	20 °C
Transmittance of the glass	0.97

Transmittance of water	0.83
Thickness of glass	0.003 m
Wind speed	2 m/s
Heat transfer coefficient of water	3000 W/m^2K
Water inlet temperature	15 ^oC
Mass flow of water	0.002 kg/s
Specific heat capacity of water	4186 J/kgK
Thickness of absorber	0.005 m

As an example, Figure 3 shows the temperature distribution inside the panel using a PG (1050/20) absorber.

Figure 3. Temperature distribution in the panel with an absorber made of PG.

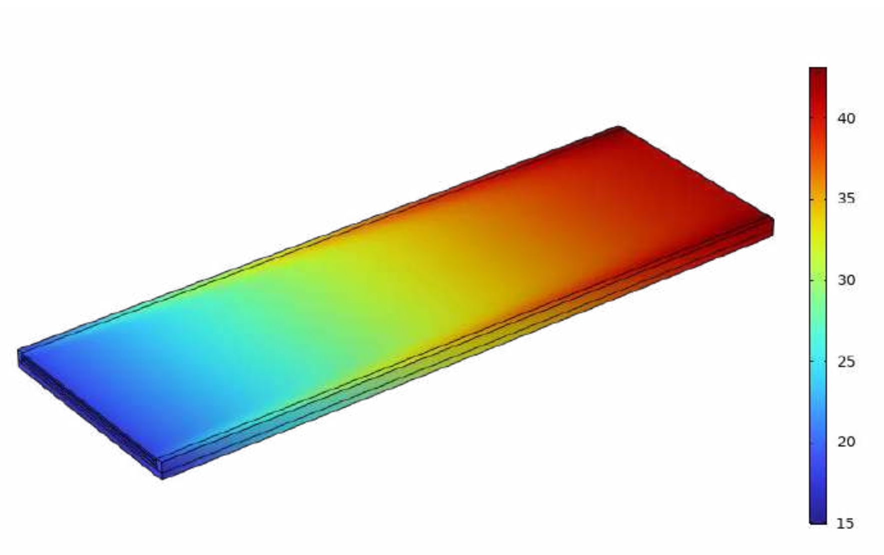


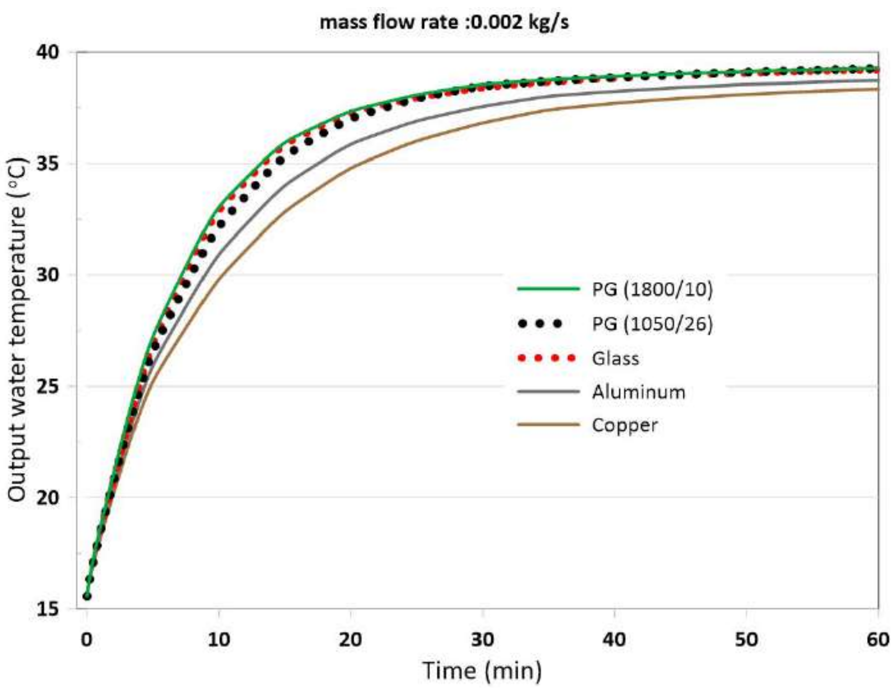
Table 3 shows the outcomes of stationary analytical and numerical calculations. Analytical calculations are performed assuming perfect isolation, but no assumption was made in the numerical calculations. In other words, one can see the heat transfer in numerical calculations for the collector's case and insulator layer (foam) as well.

Table 3. Stationary analytical and numerical results for the output water.

Absorber material	Analytical result, T_o (°C)	Numerical result, T_o (°C)
Copper	38.54	38.73
Aluminum	38.87	39.04
Glass	39.40	39.50
PG (1050/20)	39.44	39,51
PG (1800/15)	39,46	39,53

Pyrolytic graphite provides the best heat transfer according to time-dependent numerical simulations shown in Figure 4. Moreover, PG (1800/15) gives slightly higher results to those expected for highly conductive materials in [30]. In other words, increasing the thermal conductivity beyond a certain level will not improve the performance of the solar panel dramatically.

Figure 4. Material performance comparison. The legend shows used absorbers.



According to the stationary heat transfer calculations, the collector efficiency related to absorber material is given in the Table 4.

Table 4. **The stationary collector efficiency related to absorber material.**

Absorber material	Inlet water temperature (°C)	Outlet water temperature (°C)	Collector efficiency (%)
Copper	15	38.73	64.09
Aluminum	15	39.04	64.92
Glass	15	39.50	66.17
PG 1050/20	15	39.51	66.19
PG 1800/10	15	39.53	66.25

*Efficiency is based on the specific study and may vary depending on the design and operating conditions of the solar water heating system.

5. Conclusion

In this study, new materials such as pyrolytic graphite, glass for absorber plate of a solar water heater were introduced. A comparative performance analyze of the collector is done with different materials as well as the costs of each material is also presented.

The results make the model presented in this study remarkable with respect to absorber plates currently made of copper. Absorber plate made of pyrolytic graphite rise the water temperature faster and make the collector efficiency better than conventional materials such as copper and aluminum. Glass also offers better performance while maintaining a very low thermal conductivity. This is because longer wavelengths are produced when photons pass through glass and/or water and lose energy. As a result, long wavelength photons are trapped between the layers and their energy is transferred to the water. It is observed that the system's efficiency is 66% and the water temperature rises more quickly when both glass and pyrolytic graphite are used as absorbers.

Another reason that the model may give different results than expected may be due to the more complex computation of the flow properties and the unusually shaped channels that vary spatially.

It was seen that there is a potential in improving the efficiency of solar water heaters by further material studies. To verify the results from the analytical calculations and the numerical simulations, a collector prototype should be built and tested.

References

[1] C´edric Philibert. "The present and future use of solar thermal energy as a primary source of energy", *International Energy Agency,* Paris, 2005.

[2] R. Shukla, K. Sumathy, P. Erickson, and J. Gong, "Recent advances in the solar water heating systems: A review", *Renewable and Sustainable Energy Reviews*, 19:173–190, 2013.

[3] I. Sarbu and C. Sebarchievici, "Chapter 5 - solar water and space-heating systems", Eds. I. Sarbu and C. Sebarchievici, *Solar Heating and Cooling Systems*, pages 139–206. Academic Press, 2017.

[4] E. Ekramian, S. G. Etemad, and M. Haghshenasfard, "Numerical analysis of heat transfer performance of flat plate solar collectors", *Journal of Fluid Flow, Heat and Mass Transfer*, 1, 2014.

[5] B. Ramlow and B. Nusz, Solar *Water Heating*. 2nd edition, New Society Publishers, 2006.

[6] I. Sarbu and C. Sebarchievici, "Chapter 3 - solar collectors", Ed.s: I. Sarbu and C. Sebarchievici, *Solar Heating and Cooling Systems*, Academic Press, London, 2017.

[7] A. Amri, Z. T. Jiang, T. Pryor, C. Y. Yin, and S. Djordjevic, "Developments in the synthesis of flat plate solar selective absorber materials via sol-gel methods: A review", *Renewable and Sustainable Energy Reviews*, 36, 316–328, 2014.

[8] E. Vengadesan and R. Senthil, "A review on recent development of thermal performance enhancement methods of flat plate solar water heater", *Solar Energy*, 206: 8, 935–961, 2020.

[9] Y. Lu and Z. Chen, "Experimental study on thermal performance of solar absorber with CuO nano structure selective coating", *Energy Procedia*, 158, 1303–1310, 2019.

[10] S. Kahlen, G. M. Wallner, and R. W. Lang, "Aging behavior of polymeric solar absorber materials–Part 1: Engineering plastics", *Solar Energy* 84:9, 1567-1576, 2010.

[11] S. Kahlen, G. M. Wallner, and R. W. Lang, "Aging behavior of polymeric solar absorber materials–Part 2: Commodity plastics", Solar Energy 84:9, 1577-1586, 2010.

[12] Y. Selikhov, J.J. Klemeš, P. Kapustenko, O. Arsenyeva, "The study of flat plate solar collector with absorbing elements from a polymer material", Energy 256, 124677, 2022.

[13] S. A. Sakhaei and M. S. Valipour, "Performance enhancement analysis of the flat plate collectors: A comprehensive review", *Renewable and Sustainable Energy Reviews*, 102:3, 186–204, 2019.

[14] H. Pandya and A. K. Behura, “Experimental study of v-through solar water heater for tilt angle and glass transmissivity”, *Energy Procedia*, 109, 377 – 384, 2017.

[15] R. P. Garcia, S. del Rio Oliveira, and V. L. Scalon, “Thermal efficiency experimental evaluation of solar flat plate collectors when introducing convective barriers”, Solar *Energy*, 182, 278–285, 2019.

[16] Z. F. Huang, A. Nakayama, K. Yang, C. Yang, and W. Liu, “Enhancing heat transfer in the core flow by using porous medium insert in a tube”, *International Journal of Heat and Mass Transfer*, 53:2, 1164–1174, 2010.

[17] P. Waramit, P. Chanmak, R. Peamsuwan, and B. Krittacom, “Forced convection enhancement of air flowing inside circular pipe with varying the pitch (p) of wire-mesh porous media”, *Energy Reports*, 7:11, 70–82, 2021.

[18] B. Krittacom, S. Bunchan, and R. Luampon, “Heat transfer enhancement of solar collector by placing wire mesh stainless porous material on the solar absorber plate of indirect forced convection solar dryer”, *Thermal Science and Engineering Progress*, 32:7, 2022.

[19] R. H. Martin, J. Perez-Garcia, A. Garcia, F. J. Garcia-Soto, and E. Lopez-Galiana, “Simulation of an enhanced flat plate solar liquid collector with wire-coil insert devices”, *Solar Energy*, 85:3, 455–469, 2011.

[20] C. Armenta-Deu, “Performance test in semispherical solar collectors with discontinuous absorber”, *Renewable Energy*, 143, 950–957, 2019.

[21] C. Armenta-D´eu. “Effective Absorber Area in Semispherical Solar Collectors with Spiral Cylindrical Absorber”, *Journal of Solar Energy Engineering*, 141:6, 2019.

[22] W. M.K. Van Niekerk and T. B. Scheffler, “Measured performance of a solar water heater with a parallel tube polymer absorber”, *Solar Energy*, 51: 1, 339–347, 1993.

[23] S. Gupta, S. Rajale, F. Raval, M. Sojitra, A. Kumar Tiwari, A. Joshi, and R. Singh, “Comparative performance analysis of flat plate solar collectors with and without aluminum oxide-based nano-fluid”, *Materials Today: Proceedings*, 46, 5378–5383, 2020.

[24] A.A.M. Sayigh, Solar Energy Engineering, Academic Press Inc., London, 1997.

[25] J. Carvill, *Mechanical Engineer’s Data Handbook*, Butterworth - Heinemann, oxford, UK, 2009.

[26] F. P. Incropera, D. P. Dewitt, T. L. Bergman, A. S. Lavine, Fundamentals of Heat and Mass Transfer: With Introduction to Mass and Heat Transfer, 6.th Ed., John Wiley & Sons Incorporated, MA, USA, 2007.

[27] R. J. Cole, N. S. Sturrock, “The convective heat exchange at the external surface of buildings”. Building and Environment, 12:4, 207–214, 1977.

[28] A. Demharter, “Polyurethane rigid foam, a proven thermal insulating material”, *Cryogenics*, 38, 113–117, 1998.

[29] Standard tables for reference solar spectral irradiance at air mass 1.5: Direct normal and hemispherical for a 37-degree tilted surface, https://www.astm.org/g0173-03r20.html, accessed 10.01.2023.

[30] A. M. Shariah, A. Rousan, Kh. K. Rousan, and A. A. Ahmad, Effect of thermal conductivity of absorber plate on the performance of a solar water heater”, *Applied Thermal Engineering*, 19:7, 1999.

[31] <URL> https://www.schukat.com/, accessed on 27/01/2023

[32] <URL> https://hpmsgraphite.com/pyrolyticgraphitesheet, accessed on 27/01/2023.

[33] <URL> https://www.indiamart.com/, accessed on 27/01/2023.

[34] <URL> Panasonic Industry,” pgs” graphite sheet, https://www.digikey.com/en/product-highlight/p/panasonic/ pyrolytic-graphite-sheets, accessed on 27/01/2023.

[35] <URL> Su Birim Fiyatları, https://www.iski.gov.tr/web/tr-TR/musteri-hizmetleri/su-birim-fiyatlari1, accessed on 27/01/2023.

[36] <URL> Cam fiyatları - 1 m2 cam ne kadar? https://birimfiyatim.com / cam-fiyatlari-1-metrekare-cam-ne-kadar/, accessed on 27/01/2023.

[37] Chih-Yung Wen, Guo-Wei Huang, Application of a thermally conductive pyrolytic graphite sheet to thermal management of a PEM fuel cell, Journal of Power Sources, 178:1, 2008, 132-140.