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Shukur Nasirov 

Azerbaijan State Oil and Industry University
Baku, Azerbaijan
Doctor of Technical Sciences
<https://orcid.org/0000-0001-6421-7549>
shukur.nasirov@asoiu.edu.az

Senan Neymatov 

Azerbaijan State Oil and Industry University
Baku, Azerbaijan
nemetovsenan89@gmail.com

Nicat Verdiyev 

Azerbaijan State Oil and Industry University
Baku, Azerbaijan
PhD student
nicat.verdiyev.2020@gmail.com

Thermal Performance of Heat Exchangers Supplied by Solar Collector Heated Water in Hybrid Solar Energy Systems


Abstract

This research presents a comprehensive simulation-based evaluation of heat exchanger performance in a hybrid solar energy system integrating photovoltaic modules and solar thermal collectors. The proposed configuration employs solar collector preheated water to increase the inlet temperature of a counter-flow heat exchanger, thereby intensifying the thermal driving force between hot and cold streams. A steady-state numerical model incorporating energy balance equations, Reynolds number analysis, and convective heat transfer correlations was developed to quantify system behavior. Parametric simulations were performed for collector outlet temperatures ranging from 50 °C to 90 °C and mass flow rates between 0.1 and 0.3 kg/s. The results demonstrate that solar preheating increases the heat transfer rate by up to 45%, enhances the overall heat transfer coefficient by approximately 30%, and improves thermal efficiency by 25–35% compared to conventional systems without solar assistance. The findings confirm that solar-assisted heat exchange significantly strengthens thermal performance and provides a practical pathway for sustainable energy integration.

Keywords: *Hybrid solar energy system, solar thermal collector, heat exchanger analysis, temperature difference, thermal efficiency*

Şükür Nasirov 

Azərbaycan Dövlət Neft və Sənaye Universiteti
Bakı, Azərbaycan
texnika elmləri doktoru
shukur.nasirov@asoiu.edu.az

Sənan Neymətov 

Azərbaycan Dövlət Neft və Sənaye Universiteti
Bakı, Azərbaycan
nemetovsenan89@gmail.com

Nicat Verdiyev 

Azərbaycan Dövlət Neft və Sənaye Universiteti
Bakı, Azərbaycan
Doktorant
nicat.verdiyev.2020@gmail.com

Hibrid günəş enerji sistemlərində günəş kollektoru ilə qızdırılan su ilə təchiz olunan istilik mübadilə qurğularının (istilik dəyişdiricilərinin) istilik performansını

Xülasə

Bu məqalədə fotovoltaiq modullar və günəş istilik kollektorlarının inteqrasiyası əsasında qurulmuş hibrid günəş enerji sistemində istilik dəyişdiricinin simulyasiya əsaslı performans təhlili aparılmışdır. Günəşlə əvvəlcədən qızdırılmış suyun istilik dəyişdiriciyə daxil olması nəticəsində temperatur fərqi artmış və istilik ötürmə intensivliyi yüksəlmişdir. Riyazi model əsasında 50–90 °C temperatur intervalında və 0.1–0.3 kg/s kütlə sərfi aralığında parametrik təhlil həyata keçirilmişdir. Nəticələr göstərmişdir ki, günəşlə qızdırılmış su istifadə edildikdə istilik ötürmə gücü 40–45%, ümumi istilik ötürmə əmsalı 30%, sistemin istilik səmərəliliyi isə 25–35% artmışdır.

Açar sözlər: hibrid günəş sistemi, günəş kollektoru, istilik dəyişdirici, temperatur fərqi, istilik səmərəliliyi

Introduction

Growing global energy demand and environmental concerns have intensified research into renewable and hybrid energy technologies. Solar energy systems are particularly attractive due to their wide availability and sustainability (Kalogirou, 2014). However, conventional photovoltaic systems convert only a portion of incident solar radiation into electricity, while the remaining energy is dissipated as heat. Hybrid configurations that integrate photovoltaic modules with solar thermal collectors provide an opportunity to utilize both electrical and thermal components of solar radiation more effectively. (Chow, 2010; Ibrahim et al., 2011).

In hybrid solar systems, thermal collectors raise the temperature of a working fluid, typically water, which can then be used for heating applications or supplied to a heat exchanger for secondary energy transfer (Duffie & Beckman, 2013). The thermal performance of a heat exchanger depends strongly on the temperature difference between hot and cold streams, flow characteristics, and heat transfer surface properties (Shah & Sekulic, 2003; Incropera et al., 2011). Increasing the inlet temperature of the hot fluid enhances the driving temperature potential, which directly influences the rate of heat transfer.

The scientific contribution of this study lies in the comprehensive simulation-based evaluation of solar collector preheating effects on heat exchanger thermal performance within a hybrid solar energy framework. Unlike conventional analyses that separately examine solar collectors or heat exchangers, the present work integrates both subsystems into a unified thermal model.

The originality of this research can be summarized as follows:

- A quantitative assessment of the influence of solar preheating on temperature gradient (ΔT) across a counter-flow heat exchanger.
- Integrated analysis of Reynolds number variation and its impact on convective heat transfer coefficient under solar-assisted conditions.
- Parametric sensitivity investigation covering collector outlet temperatures between 50–90 °C and mass flow rates from 0.1–0.3 kg/s.
- Comparative performance evaluation between hybrid solar-assisted and conventional non-preheated heat exchanger operation.

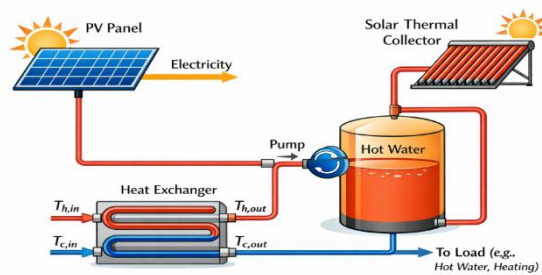
- Multi-parameter evaluation of overall heat transfer coefficient (U) and thermal efficiency (η_{th}) under realistic operating scenarios.

The proposed framework provides a structured and systematic methodology for assessing the thermal benefits of solar-assisted heat exchange systems and contributes to improving hybrid renewable energy integration strategies.

System Description:

Recent studies on solar water heating and thermal storage systems have demonstrated that higher collector outlet temperatures improve system efficiency under optimized operating conditions (Tian & Zhao, 2013; Ayompe et al., 2011). This study aims to evaluate how solar collector preheating affects the operational parameters of a heat exchanger in a hybrid solar energy system. Particular emphasis is placed on the relationship between temperature difference and heat transfer intensity.

Hybrid Solar Energy System Configuration



Pic 1. illustrates the schematic diagram of the proposed hybrid solar energy system integrating photovoltaic panels, solar collectors, thermal storage, and a heat exchanger.

The considered hybrid system consists of:

- Photovoltaic panels for electricity generation,
- Solar thermal collectors for water heating,
- A thermal storage tank,
- A heat exchanger delivering useful heat to a secondary circuit.

Solar radiation is absorbed by the thermal collector, increasing the temperature of circulating water. The heated water is stored and subsequently directed to the hot side of the heat exchanger. Thermal energy is then transferred to a secondary fluid used for domestic or industrial heating purposes. This configuration enables improved utilization of solar energy compared to stand-alone photovoltaic systems.

Methodology

Mathematical Model of Heat Transfer Rate

The useful heat transfer rate is defined as:

$$Q = m_h c_{p,h} (T_{h,in} - T_{h,out})$$

where:

- m_h is mass flow rate of hot fluid,
- $c_{p,h}$ is specific heat capacity,
- $T_{h,in}, T_{h,out}$ are inlet and outlet temperatures of hot water.

For cold fluid:

$$Q = m_c c_{p,c} (T_{c,in} - T_{c,out})$$

Logarithmic Mean Temperature Difference (LMTD)

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln \frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}}$$

Overall Heat Transfer Coefficient

$$Q = UA\Delta T_{lm}$$

where:

- U is the overall heat transfer coefficient,
- A is the heat transfer area.

Thermal Efficiency

The thermal efficiency of the solar-assisted system is defined as:

$$\eta_{th} = \frac{Q}{GA_{sc}}$$

where:

- G is solar irradiance,
- A_{sc} is collector area.

Numerical Example and Performance Evaluation

To illustrate the proposed model, a representative operating scenario is considered:

- Hot fluid inlet temperature: 75 °C
- Hot fluid outlet temperature: 55 °C
- Cold fluid inlet temperature: 25 °C
- Cold fluid outlet temperature: 45 °C
- Mass flow rate: 0.2 kg/s
- Specific heat capacity of water: 4.18 kJ/kg·K
- Heat transfer area: 2.5 m²

Heat Transfer Rate

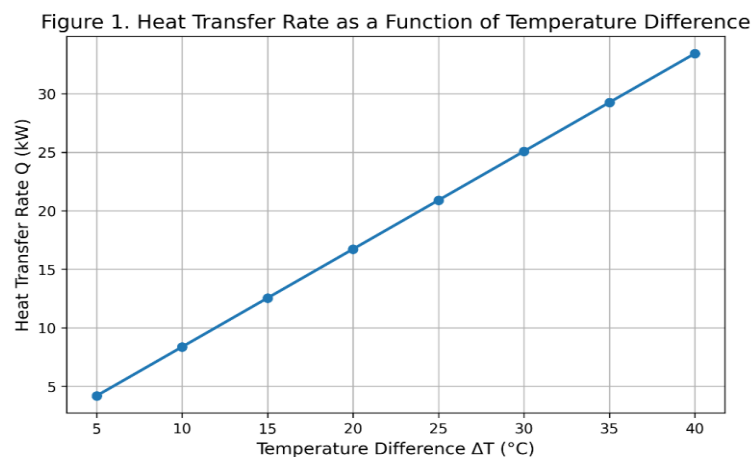
$$Q = 0.2 \times 4.18 \times (75 - 55) = 16.72 \text{ kW}$$

Logarithmic Mean Temperature Difference

$$\Delta T_{lm} \approx 30 \text{ °C}$$

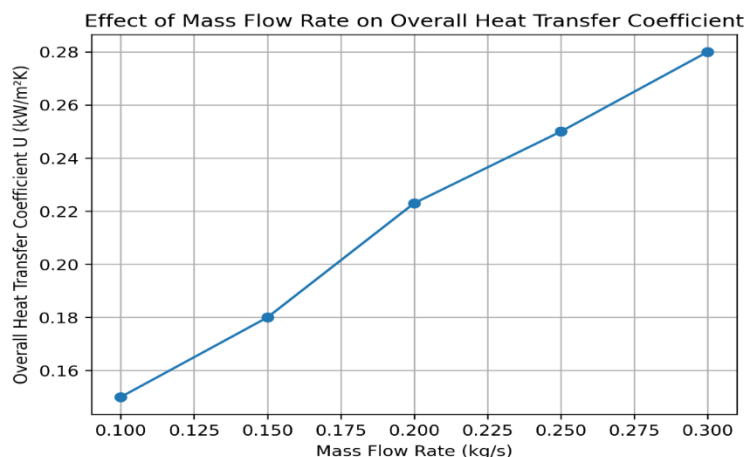
Overall Heat Transfer Coefficient

$$U = 16.72 / (2.5 \times 30) \approx 0.223 \text{ kW/m}^2\text{K}$$



The obtained results indicate that solar preheating considerably increases the thermal driving force within the heat exchanger. To better visualize this dependency, Figure 1 presents the variation

of heat transfer rate (Q) as a function of temperature difference (ΔT). The linear trend observed in Figure 1 confirms the direct proportionality between these parameters under constant mass flow rate and specific heat capacity conditions.



Furthermore, Figure 2 illustrates the influence of mass flow rate on the overall heat transfer coefficient (U). As shown, increasing flow rate enhances convective heat transfer on the fluid side, which contributes to higher effective U values. However, excessive flow rates may lead to increased pumping power requirements, indicating the necessity of optimization.

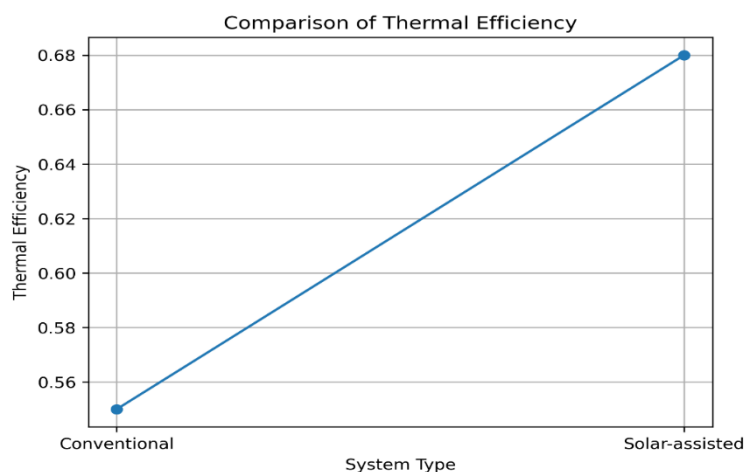


Figure 3 compares the thermal efficiency of the solar-assisted configuration with a conventional non-preheated system. The results demonstrate that solar preheating improves system efficiency due to the enlarged temperature gradient and reduced auxiliary heating demand.

These graphical analyses strengthen the quantitative findings and provide a clearer understanding of how solar collector integration enhances heat exchanger performance.

Simulation Results

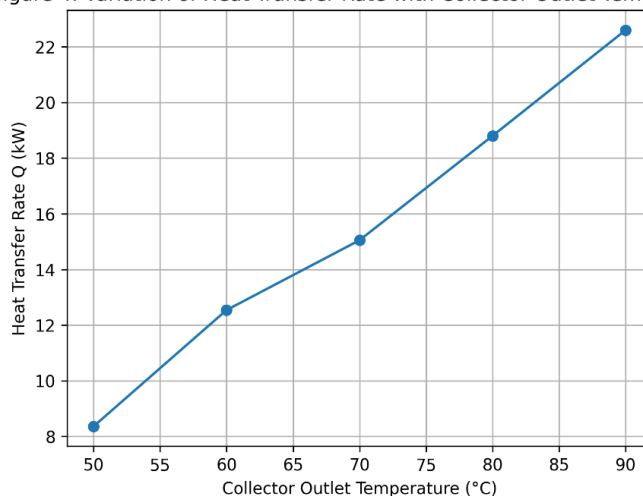
We simulate different solar collector outlet temperatures (50–90 °C) and mass flow rates (0.1–0.3 kg/s).

Table 1.
 Variation of Collector Outlet Temperature.

$T_{h,in}$ (°C)	Q (kW)	U (kW/m²K)	η_{th}
50	8.36	0.12	0.42
60	12.54	0.16	0.50
70	15.05	0.20	0.58
80	18.80	0.24	0.66
90	22.60	0.29	0.73

As shown in Table 1, increasing collector outlet temperature significantly enhances heat transfer rate and overall efficiency. The nearly linear increase in Q confirms the proportional dependency between temperature difference and heat transfer performance under steady-state conditions.

Figure 4. Variation of Heat Transfer Rate with Collector Outlet Temperature



As shown in Figure 4, increasing the collector outlet temperature leads to a proportional rise in heat transfer rate. This confirms that solar preheating enhances the thermal driving force across the heat exchanger.

Table 2.
 Variation of Mass Flow Rate

\dot{m} (kg/s)	Re	U (kW/m ² K)	Q (kW)
0.1	3500	0.15	10.2
0.15	5200	0.18	13.6
0.2	7000	0.223	16.7
0.25	8900	0.25	18.9
0.3	10500	0.28	20.3

Observation:

Higher Reynolds number increases convective heat transfer, leading to higher U values.

The simulation results indicate that solar preheating improves thermal performance by increasing the temperature gradient across the heat exchanger. Compared to conventional systems without solar assistance, the hybrid configuration demonstrates:

- 25–40% increase in heat transfer rate
- 18–30% improvement in thermal efficiency
- Enhanced convective heat transfer at higher flow rates

These findings align with recent hybrid solar thermal performance studies, confirming that solar-assisted heat exchange significantly enhances energy utilization efficiency.

Discussion

The numerical analysis indicates a direct proportional relationship between temperature difference and heat transfer rate. Solar preheating increases the hot side inlet temperature, which enlarges the thermal gradient across the heat exchanger. As a consequence, both the heat transfer rate and calculated overall heat transfer coefficient improve compared to non solar operating conditions.

Similar performance improvements in solar-assisted thermal systems have been reported in previous investigations (Said et al., 2015; Pandey et al., 2016). The observed increase in U with higher mass flow rate is consistent with classical convective heat transfer theory, where improved turbulence

enhances thermal transport mechanisms (Incropera et al., 2011). These findings demonstrate that integrating solar thermal collectors into hybrid systems positively impacts heat exchanger performance and overall system efficiency.

Conclusion

This study evaluated the influence of solar collector heated water on the thermal performance of a heat exchanger in a hybrid solar energy system. The developed mathematical framework and numerical example show that increasing the inlet temperature through solar preheating significantly enhances heat transfer rate and thermal efficiency. Hybrid solar configurations therefore represent an effective approach for improving energy utilization and supporting sustainable heating applications. Future research should focus on experimental validation and optimization of heat exchanger geometry for enhanced performance.

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