



REVIEW ARTICLE

THERMAL ANALYSIS OF A HYBRID SOLAR THERMAL-COLLECTOR: EXERGY ANALYSIS

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ARTICLE DETAILS

ABSTRACT

Article History:

Received 19 March 2025
Revised 22 April 2025
Accepted 26 April 2025
Available online 11 May 2025

In this research a prototype flat-plate solar-thermal collector that uses wickless-heat-pipes and parallel coolers is developed and evaluated. The study conducted indoor-experiments using a solar simulator to assess collector's thermal performance. Design details and an exergy analysis of the collector are provided. The investigation aimed to improve the efficiency of flat-plate solar collectors for low-temperature applications by integrating heat-pipe technology. The study examined various experimental-parameters, including collector's tilt-angles (5,10,20,30,40°), solar irradiance levels (475,625,850,1050 W/m²), water flow-rates (0.0235-0.0387 kg/s), and inlet temperatures (30,35,40,45 °C). The results showed that inlet, outlet, and gained exergy values are increased positively with higher water flow rates and inlet temperatures. Higher inlet temperatures, in particular, led to significant increases in exergy gains, inlet fluid exergy, and outflow exergy. The higher exergy losses are due to the temperature difference between the absorber-plate of the solar-collector and the Sun's surface. The uncertainty of the solar-experiments is found =7.299%.

KEYWORDS

Solar-thermal collector; Heat-pipes; Indoor solar-experiments; Exergy analysis.

1. INTRODUCTION

The sharp rise in global energy demand is due to the intense economic activities in developing countries (Fabian et al., 2024). In addition, to the exponential growth in the world's population, which is projected to reach 10 billion by 2050 (UN, 2019), and 10.3 billion by the 2080s (UN, 2024). For more than a century, industries and society have relied predominantly on fossil-fuels as their main-energy source (Hassan et al., 2023; Saeed and Abidin, 2024a). This reliance exacerbates climate change, environmental pollution and greenhouse gas emissions (Eze et al., 2022; Foley et al., 2017; Giovanni et al., 2024; Kılıç, 2022). Rapid modernization and increased energy demand have accelerated global warming, highlighting the need for renewable energy sources to address environmental challenges (Anil et al., 2024; Holechek et al., 2022). Moreover, the rapid depletion of fossil fuel reserves has become a significant concern, driving the shift towards alternative, eco-friendly energy sources (Carfora et al., 2019; Fabian et al., 2024).

The global demand for innovative renewable energy technologies is rising, as evidenced by the significant increase in world energy consumption (IEA, 2023). The environmental degradation caused by the unrestricted use of fossil fuels has led to a greater emphasis on renewable energy as an alternative. Renewable energy sources, such as solar energy, are advantageous due to their environmental friendliness and limitless supply (Ahmed et al., 2024; Hanif et al., 2022; Eghosa and Sufianu, 2021). Researchers and scientists advocate for energy sustainable transitions, stressing the importance of prioritizing energy-efficient solutions, and adopting, strategically, energy renewable-sources (Ekim et al., 2023; Giovanni et al., 2024; Buonomano et al., 2024; Vardopoulos et al., 2023). Providing reliable energy that meets the needs of the population is not only beneficial for society but also essential for the economic growth of any country (Suriyan et al., 2023). Consequently, various alternative energy sources, especially renewable ones, have been investigated and

considered for implementation as practical solutions (Asif et al., 2023; Sudarsan et al., 2023). This investigation of alternative energy sources is become a global-trend (Kachare and Shinde, 2019; Saeed and Abidin, 2024). Renewable energy is the energy obtained from continuous and natural-energy-flows in the immediate-environment (Fabian et al., 2024; Kerr and Kerr, 2019).

Solar thermal collectors (STCs) are used to transform solar radiation into heat (Saeed and Abidin, 2024b). This heat is then used to provide hot-air, hot-water, or directly supply heat to a fluid, such as in direct solar-assisted heat pumps (Vengadesan and Senthil, 2020; Hossain et al., 2011; Yu et al., 2023). Furthermore, they can be used independently or integrated into the building structure (Ioannidis et al., 2017; Barone et al., 2023). Specifically, non-concentrating collectors can be further broken down into flat plate solar collectors (FPSC) and evacuated tube collectors (ETC). FPSC collectors are often chosen due to their cost-effectiveness and straightforward installation process (Said, 2015). In addition, FPSCs have the advantage of low maintenance, needing little cleaning, and no sunlight tracking system.

In flat plate solar collectors, heat is directly transferred from sunlight to the working fluid, typically water. Due to these benefits, FPSCs are commonly used in household water heating systems. However, radiation and convection lead to heat losses, which decrease the thermal efficiency of FPSCs. Consequently, numerous studies have been conducted to enhance their thermal performance (Duffie et al., 2020; Hussein et al., 2024). They are extensively used in both domestic and industries, as they represent the most straightforward model in solar thermal systems. Efficiency and cost are critical factors in optimizing FPSCs. Additionally, efficiency tends to decline sharply at higher temperatures, and significantly, limiting their application (Zhenga et al., 2024).

When solar energy is utilized for heating purposes such as air conditioning or domestic hot water production, evacuated tube collectors are among

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10.26480/amm.02.2025.60.69

the most commonly used types, representing approximately 70% of globally installed solar systems (Raisul et al., 2013). This widespread use is due to their high thermal efficiency and minimal space requirements (Nájera-Trejo et al., 2016). On the other hand, flat-plate solar thermal collectors offer a simpler design and easier installation and maintenance compared to evacuated tube collectors. These systems are not only highly adaptable but also efficient, providing benefits that include seamless integration into various applications and the straightforward nature of their design (Kalogirou, 2009). Essentially, flat-plate solar thermal collectors consist of an absorbent surface designed to capture solar radiation. Once the solar energy is absorbed, it is converted into heat, which is then efficiently transferred to a heat transfer fluid that circulates outside the absorbent surface (Giovanni et al., 2024; Omeiza et al., 2024). Flat Plate Solar Collectors are the pioneering systems in this field and are widely applicable. However, they experience significant heat loss, which reduces their thermal efficiency. Currently, the efficiency of these solar systems can be enhanced through optimization techniques and the use of advanced technologies and materials (Ahmed et al., 2024).

Exergy is considered as a measure of the quality or usefulness of energy. It is the maximum work amount that can be achieved from a stream of energy or matter, or from a system, as it reaches equilibrium with a reference-environment. In contrast to energy, exergy is used up in real processes because of the irreversibilities, but in ideal processes it is conserved (Rezac and Metghalchi, 2004; Rosen, 2007). Exergy, is the achievable work, measures useful energy and can be consumed/depleted (Delly et al., 2006; Rosen, 2007; Rosen, 2007). The application of exergy analysis has gradually progressed, with some researchers and engineers currently employing it, albeit often limited to the first law of thermodynamics (Cornelissen, 1997). Thermodynamic probability and exergy are expressed in entropy and energy units, respectively. Accordingly, in comparison to the respective energy values the exergy data are more realistic and useful. Therefore, exergy analysis offers a more accurate perspective of a process, often differing significantly from standard energy analyses (Ryszard, 2010). There are two approaches to second-law analysis: the exergy model and the entropy generation from irreversibility, both yielding similar results (Chamoli, 2013).

Maximizing exergy efficiency in thermodynamic processes reduces exergy destruction. Solar radiation is a crucial exergy source. Direct radiation, when fully concentrated, has over 90% exergy, while diffuse radiation has 72.6% and 9.6% exergy for single and scattering, respectively (Petela, 2003; Badescu, 2004; Viorel, 2007; Viorel, 2007; Badescu, 1991). Consequently, solar collectors are frequently utilized in power generation systems. However, due to various irreversible processes, some exergy flux is inevitably lost within solar system components (Viorel, 2007; Izquierdo et al., 2002). Minimizing these irreversibilities is essential to maximize exergy gain. Thermal energy storage tanks, in particular, are associated with exergy consumption and loss (Viorel, 2007; Badescu, 2002a; Gunnewiek et al., 1993). Regarding the optimal functional region, which involves measuring inefficiencies, their comparative amounts, and positions, exergy or second-law analysis is the most informative and useful method (Farahat et al., 2009; Luminosu and Fara, 2005). Thermal performance modelling is crucial in the exergy analysis of solar collectors (Hossein et al., 2005).

To assist designers in achieving optimal solar collector designs and reducing exergy losses, exergy analysis is conducted (Rosen, 2007; Chamoli, 2013; Zhong et al., 2014). This analysis is applied in the design of flat-plate solar collectors, as well as in the simulation and evaluation of energy systems (Hepbasli, 2008; Soteris, 2012). Calculating solar radiation exergy is essential when using exergy analysis techniques to evaluate the performance of solar energy systems (Hepbasli, 2008; Bejan, 1988). The objectives of this study are to present the design-concept-details of a prototype flat-plate wickless-heat-pipes solar-collector with parallel condensers-coolers, in addition to the thermal analysis in the form of exergy analysis.

2. MATERIALS AND METHODS

A prototype flat-plate wickless-heat-pipes solar-collector with parallel condensers-coolers is developed and tested. Detailed drawings of the collector are provided in Figure A1 (Appendix), with dimensions and specifications listed in the Table A1 (Appendix). In this collector, each heat-pipe's condenser-cooler features an inlet for cooling water and an outlet for hot-water. All inlets are connected to a single manifold, and all outlets are connected to another manifold, as illustrated in Figure A1. A photo of the made collector is shown in Figure 1.

Indoor solar experiments are conducted, using a Laboratory Solar Simulator, to evaluate the thermal performance of the developed solar collector. This simulator is located at the Centre for Integrated-Design for

Advanced-Mechanical-Systems, Faculty of Eng. & Built Environ., Malaysia National University; Bangi, Malaysia). The simulators play important roles in conducting solar-energy research (Codd et al., 2010). They are typically, simulate the Sun-light, with approximately, similar spectrum and intensity (EMSS, 2024).

Various experimental factors are tested, including, solar irradiance levels (475, 625, 850, 1050 W/m²), inlet temperatures (30, 35, 40, 45°C), water flow-rates (0.0235, 0.0387 kg/s), and collectors tilt angles (5, 10, 20, 30, 40°). The heat pipes specification and dimension are given in Table A1 (Appendix). The diagram of the data collecting system is shown in Figure A2 (Appendix). According to the first law of thermodynamics, energy can be changed from one form to another, but it cannot be created or destroyed (Balmer, 2011; Çengel et al., 2019). Therefore, for any energy conversion process: input energy is equals to the useful energy plus the losses. The energetic efficiency of a process, based on the first law of thermodynamics, is the ratio of useful energy to input energy.

As in the second law of thermodynamics, the quality of energy conversion can be assessed using exergetic analysis. This principle states that heat cannot be entirely converted into work without other effects (Delly et al., 2006). Consequently, low-temperature waste heat is unavoidable in heat engine operations (Balmer, 2011; Krenz, 1980). This principle implies that during any energy transformation, the quality of energy, as measured by its ability to perform work (exergy), either degrades or remains unchanged (Delly et al., 2006). The exergy efficiency of a process, based on the second law, is the ratio of useful exergy to input exergy. This inequality highlights that, unlike energy, exergy is not conserved during processes. The definitions and the formulae of the exergy terms, that can be used in the exergy-analysis are given by Eq. (1) through (12).

Total exergy balance (Imad, 2022; Piyush et al., 2022):

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_d \quad (1)$$

Ex_{in} , is the exergy in (W), Ex_{out} , exergy out (W), Ex_d , Ex_d , destroyed exergy (W).

Solar-radiation exergy rate from the Sun on the collector surface (exergy inflow of solar-energy on surface) (Ex_{i-s}) (Imad, 2022; Zhai et al., 2013):

$$Ex_{i-s} = I_T A_c \left(1 - \frac{T_a}{T_s}\right) \quad (2)$$

Ex_{i-s} , is the solar radiation exergy (W), I_T , incident solar radiation (W/m²), A_c , collector area (m²), T_a , ambient temperature (°C), T_s , apparent solar (sky) temperature (K).

Absorbed solar-radiation exergy by the collector's plate (Ex_{abs}) (Zhenga et al., 2024, Imad, 2022):

$$Ex_{abs} = Q_s \left(1 - \frac{T_a}{T_s}\right) = I_T (\tau\alpha) A_c \left(1 - \frac{T_a}{T_s}\right) \quad (3)$$

Ex_{abs} , is the absorbed exergy (W), Q_s , energy absorbed by absorber plate (W), $(\tau\alpha)$, absorptance-transmittance product (absorber plate-glass cover) (-).

The rate of the inlet-exergy carried by the fluid-flow (Ex_{i-f}) (Farahat et al., 2009; Zhong et al., 2014):

$$Ex_{i-f} = \dot{m} C_p \left((T_i - T_a) - T_a \ln \left(\frac{T_i}{T_a} \right) \right) \quad (4)$$

Ex_{i-f} , is the inlet fluid exergy (W), \dot{m} , mass flow rate (kg/s), C_p , the specific heat (J/kg °C), T_i , fluid inlet temperature (°C),

The rate of outlet-exergy carried by fluid-flow (Ex_{o}) (Zhenga et al., 2024; Imad, 2022):

$$Ex_{o} = \dot{m} C_p \left((T_o - T_a) - T_a \ln \left(\frac{T_o}{T_a} \right) \right) \quad (5)$$

T_o , fluid outlet temperature (°C),

Useful-exergy rate (Ex_g) (Chamoli, 2013; Kotas, 2012):

$$Ex_g = Ex_o - Ex_{i-f} \quad (6)$$

Ex_g , is the gained exergy (W).

Ex_g expressed by (Zhenga et al., 2024; Imad, 2022) as:

$$Ex_g = \dot{m} C_p \left[(T_o - T_i) - T_a \left(\ln \frac{T_o}{T_i} \right) \right] \quad (7)$$

Leakage-exergy ($Ex_{loss,L}$), is caused by heat-leakage from absorber-plate

to the environment (Farahat et al., 2009; Imad, 2022):

$$Ex_{loss,L} = U_L A_c (\bar{T}_p - T_a) \left(1 - \frac{T_a}{T_p}\right) \quad (8)$$

$Ex_{loss,L}$, exergy leakage (W), U_L , heat loss coefficient (W/m² °C), T_p , mean temperature absorber plate (°C),

Solar-radiation losses from the collector surface to the absorber-plate (Ex_{s-p}) (Zhong et al. 2014; Imad 2022):

$$Ex_{loss,s-p} = I_T [A_c - (\tau\alpha)_e A_c] \left(1 - \frac{T_a}{T_s}\right) \quad (9)$$

$Ex_{loss,s-p}$, exergy loss collector's surface-absorber plate (W).

Exergy-losses due to the temperature-difference between the surface of absorber-plate and the Sun (Ex_{p-s}) (Imad, 2022; Zhai et al., 2013):

$$Ex_{loss,p-s} = (\tau\alpha)_e I_T A_c T_a \left(\frac{1}{T_p} - \frac{1}{T_s}\right) \quad (10)$$

$Ex_{loss,p-s}$, exergy loss collector's plate-sun (W).

Exergy-loss rate due to temperature-difference between the absorber-

plate and the fluid ($Ex_{loss,\Delta T}$) (Zhong et al., 2014; Imad, 2022):

$$Ex_{loss,\Delta T} = \dot{m} C_p T_a \left[\ln\left(\frac{T_o}{T_i}\right) - \frac{(T_o - T_i)}{T_p} \right] \quad (11)$$

$Ex_{loss,\Delta T}$, exergy-loss absorber plate-fluid (W).

Exergy efficiency: is the ratio of useful-exergy (Ex_{g}) to solar radiation exergy ($Ex_{in,s}$), (Zhenga et al., 2024; Piyush et al., 2022):

$$\eta_x = \frac{\dot{m} C_p [(T_o - T_i) - T_a] \left(\ln\left(\frac{T_o}{T_i}\right)\right)}{I_T A_c \left(1 - \frac{T_a}{T_s}\right)} \quad (12)$$

η_x , solar collector exergy efficiency (-).

The uncertainty in the solar tests (Bayrak et al., 2013; Kumaran et al., 2013):

$$W_t (\%) = [(x_1)^2 + (x_2)^2 + \dots + (x_n)^2]^{0.5} \quad (13)$$

W_t , uncertainty in the measurement, x_n , individual factors (uncertainty (-)).

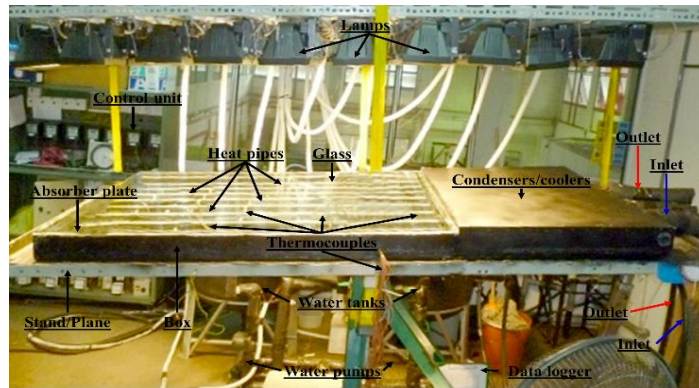


Figure 1: Flat-plate wickless-heat-pipes solar collector

3. RESULTS AND DISCUSSIONS

3.1 Exergy Analysis

Exergy analysis is a technique used for assessing systems and processes and is based on the second law of thermodynamics (Rosen, 2007). The irreversibility of heat transfer (which occurs within the solar collector, between the solar collector and the Sun, and between the solar collector and the surrounding air), affects the amount of energy exergy obtained by solar thermal collectors (Chamoli, 2013).

3.1.1 Effects of Water Flow-rates on the Exergies

Figure 2, illustrates the absorbed exergy (Ex_{abs}), inlet-fluid exergy ($Ex_{i,f}$),

outflow exergy (Ex_{o}), and gained exergy (Ex_g). The values for $Ex_{i,f}$, Ex_{o} , and Ex_g increase as the water flow rate rises from m_1 (=0.0235kg/s) to m_2 (=0.0387kg/s). These exergy values also rise with the increase in inlet temperature while maintaining a constant water flow rate. The increment in the exergy is a function of used fluids in the collectors (Hanif et al., 2022; Soteris et al., 2016). An increase in fluid mass flow rates within a solar energy collector enhances the rates of exergy collection (Chamoli, 2013). According to Zhong et al., at inlet temperatures lower than the optimal level, increasing the fluid mass flow rate leads to a decrease in the useful exergy rate. Conversely, when the solar collector operates at fluid inlet temperatures higher than the optimal level, increasing the mass flow rate of the fluid results in an increase in the rate of exergy gain.

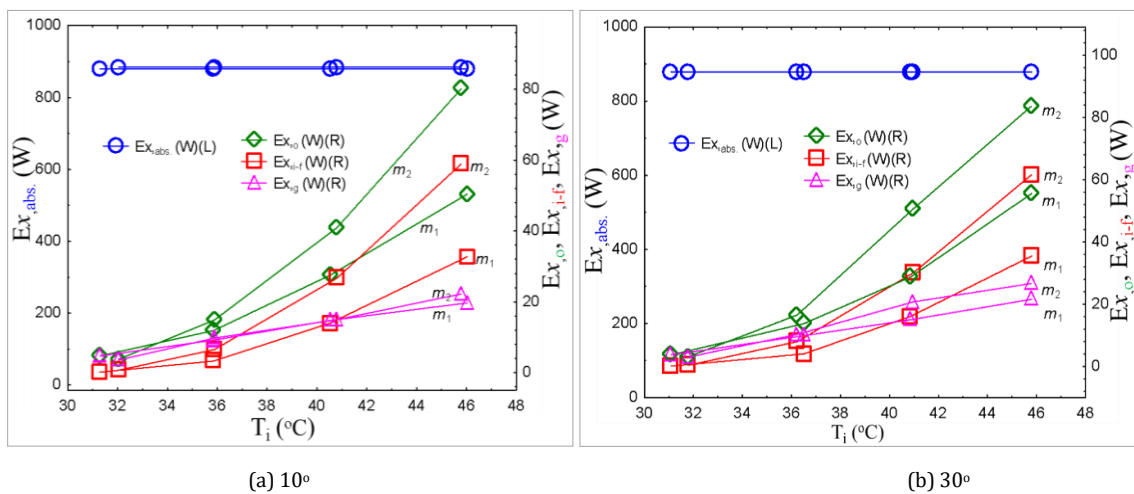


Figure 2: Ex_{abs} , $Ex_{i,f}$, Ex_{o} , Ex_g : 1050W/m²

3.1.2 Effects of Collector Tilt Angles on the Exergies

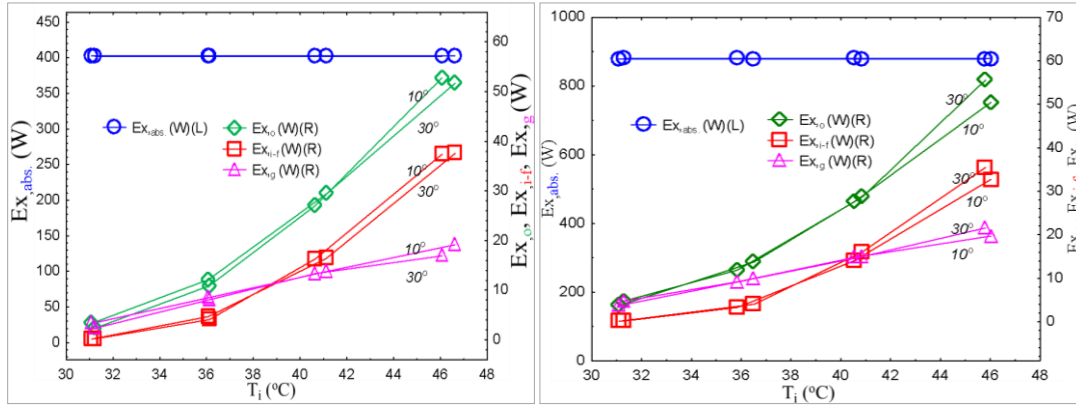
Figure 3 illustrates how the tilt angles of the collector influence absorbed exergy, outflow exergy, and gained exergy. The analysis focuses on tilt angles of 10° and 30°, with solar irradiance levels of 475 and 1050 W/m².

At inlet temperatures ranging from 30°C to 40°C, the values of $Ex_{i,f}$, Ex_{o} , and Ex_g are similar; however, at an inlet temperature of 45°C, slight variations are noted. Generally, the $Ex_{i,f}$, Ex_{o} , and Ex_g values tend to increase with both tilt angles and inlet temperatures.

A group researcher observed that heat transfer rate rises with tilt angles from 20° to 31.5°, but increasing the tilt angle beyond this range adversely affects the heat transfer rate (Nishandar et al., 2015). A study analyzed the impact of various tilt angles (30°, 45°, 60°, and 75°) on temperature distribution through the collector, finding the highest air temperatures at an inclination angle of 30° (Neema and Mustafa, 2020). A group researchers evaluated the thermal performance of solar water heaters with solar collector tilt angles of 22° and 46°, concluding there is no significant variation in daily thermal efficiency between these angles (Tang et al., 2011). Some researcher found that water-ethanol collectors perform better than those using water as the working fluid, with maximum efficiency at a tilt angle of 31.5° (Harde et al., 2014).

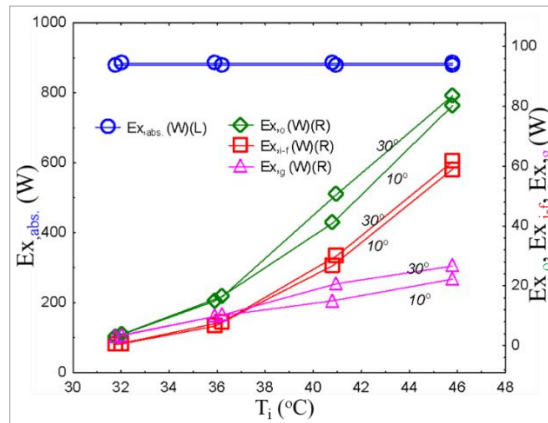
A study demonstrated that the solar collector with a 30° tilt angle and

reflector outperformed a 45° tilt angle (Vishal et al., 2013). This result suggested that increasing the tilt angle did not positively influence the thermosiphon effect inside the evacuated tubes. In a study stated that for stationary non-tracking solar collectors, the optimal tilt angle is the latitude of the location minus the solar declination angle (Duffie and Beckman, 2013). Some researchers suggested that the optimal angle is the latitude of the location ±10°-15°, depending on the application and season (Kalogirou, 2003). A group researcher recommended a tilt angle of latitude -15° in summer and latitude +15° in winter (Gunerhan and Arif, 2007). Some researchers highlighted that the collector's inclination should be based on the location's latitude for optimal performance (Ahmadreza et al., 2014).



(a) 0.0235kg/s, 475W/m²

(b) 0.0235kg/s, 1050W/m²



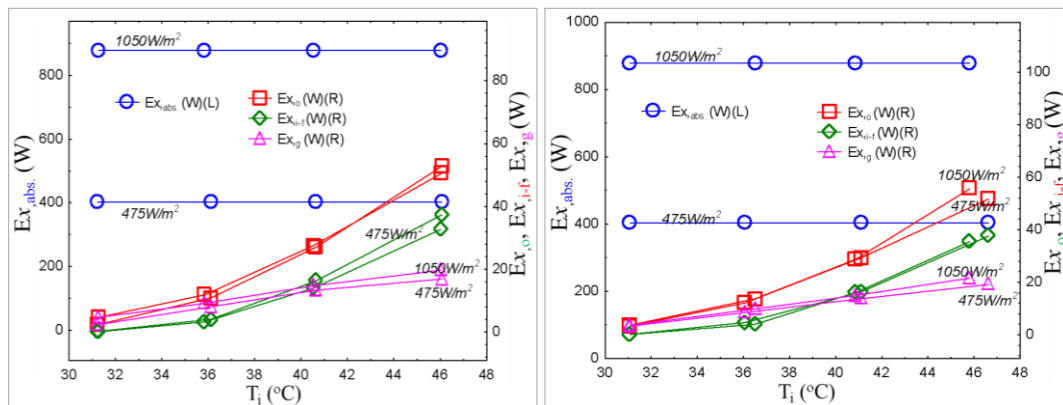
(c) 0.0387kg/s; 1050W/m²

Figure 3: Ex_{abs} , Ex_{i-f} , Ex_o , Ex_u : 10° - 30°

3.1.3 Effects of Irradiance Levels on the Exergies

The impact of solar irradiance on absorbed exergy (Ex_{abs}), outflow exergy (Ex_o), and gained exergy (Ex_g) is illustrated in Figure 4. As shown, the values of Ex_{abs} , Ex_o , and Ex_g increase with higher solar radiation. This

trend is also noted by (Zhong et al., 2014). For instance, Ex_{abs} rises from ≈400 to 900 as solar irradiance increases from 475 to 1050 W/m². However, Ex_o and Ex_g show only slight increases with higher solar irradiance. Moreover, as the inlet temperature rises, Ex_{i-f} , Ex_o , and Ex_g also increase.



(a) 10°, 0.0235kg/s

(b) 30°, 0.0235kg/s

Figure 4: Ex_{abs} , Ex_{i-f} , Ex_o , Ex_g : 475 - 1050W/m²

A series of experiments are conducted with fixed inlet temperature (T_i), which is maintained at the value of the ambient temperature (T_a) (i.e., $T_i \approx T_a \approx 30.5^\circ\text{C}; \pm 1.0^\circ\text{C}$). The absorbed exergy (Ex_{abs}), inlet-fluid exergy (Ex_{i-f}), outflow exergy (Ex_o), and gained exergy (Ex_g) are then plotted against the tilt angles (Figure 5). As it depicted in Figure 5, the absorbed exergy (Ex_{abs}) significantly increases with higher solar irradiance levels, rising from approximately 520 (at 625 W/m^2) to around 880 (at 1050 W/m^2). The

values of Ex_{i-f} remain consistent due to the constant inlet temperature. Both the outflow exergy (Ex_o) and gained exergy (Ex_g), generally increase with higher solar irradiance, with optimal values observed at 850 W/m^2 . Additionally, as the tilt angle increases, the outflow exergy (Ex_o) and gained exergy (Ex_g) show varying trends depending on the water flow rates of 0.0235 kg/s and 0.0387 kg/s , respectively.

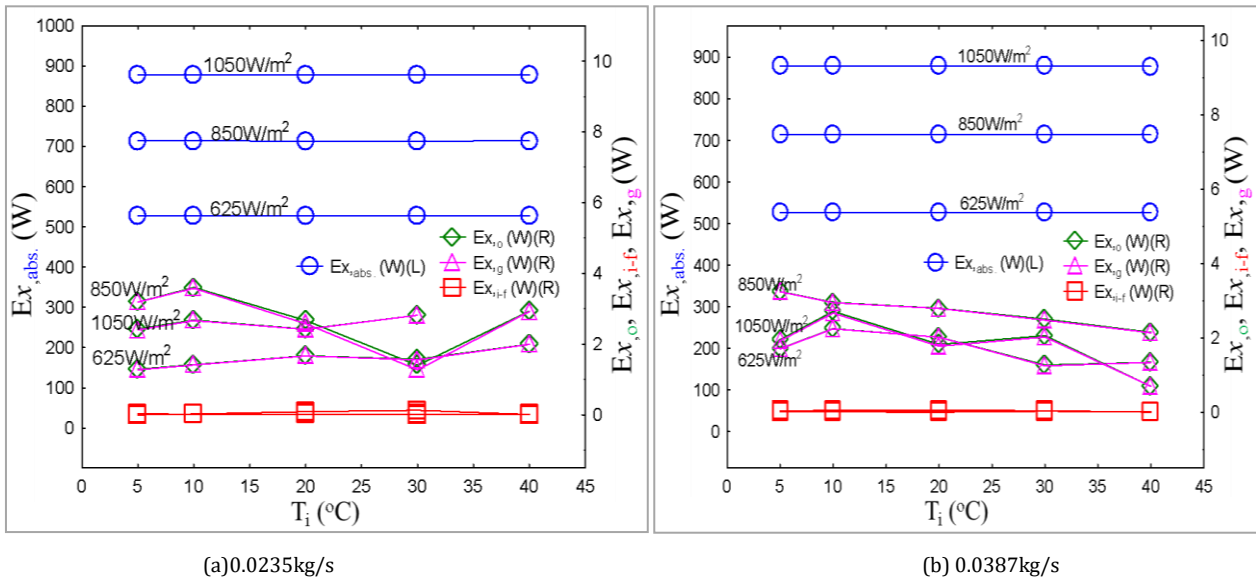


Figure 5: Exergy (Ex_{abs} , Ex_{i-f} , Ex_o , Ex_g): 625, 850, 1050w/m²

3.1.4 Exergy Losses

A group researcher found that, the flat plate collectors experience about 73% exergy destruction (Zhong et al., 2014). A group researcher determined exergy losses of 97.81% in the solar collector and 41.76% in the overall system (Wael et al., 2018). In a study showed that about 75% of exergy destruction results from the temperature differential between the sun and the absorber plate, which can be mitigated by raising the absorber plate temperature (Shigeru et al., 2018).

3.1.5 Effects of Water Flow-rates on the Exergy Losses

Figure 6 illustrates the exergy losses between the collector’s plate and the

Sun ($Ex_{loss,p-s}$), collector’s surface and plate ($Ex_{loss,cs-p}$), collector’s plate and fluid ($Ex_{loss,p-f}$), and exergy leakage ($Ex_{loss,L}$). The most significant exergy losses arise from the temperature difference between the Sun’s surface and the solar collector’s absorber plate (Zhong et al., 2014). At a collector tilt angle of 10° (1050 W/m^2), increasing the water flow rate from m_1 (0.0235 kg/s) to m_2 (0.0387 kg/s), results in minor variations in $Ex_{loss,p-s}$, $Ex_{loss,p-f}$ and $Ex_{loss,L}$. However, these variations become more pronounced at a tilt angle of 30° , where $Ex_{loss,p-s}$ increases with the water flow rate, while $Ex_{loss,p-f}$ and $Ex_{loss,L}$ decrease. Additionally, $Ex_{loss,L}$ increases with the fluid inlet temperature, whereas, $Ex_{loss,p-s}$ and $Ex_{loss,p-f}$ decrease as the inlet temperature rises, aligning with the findings of (Zhong et al., 2014).

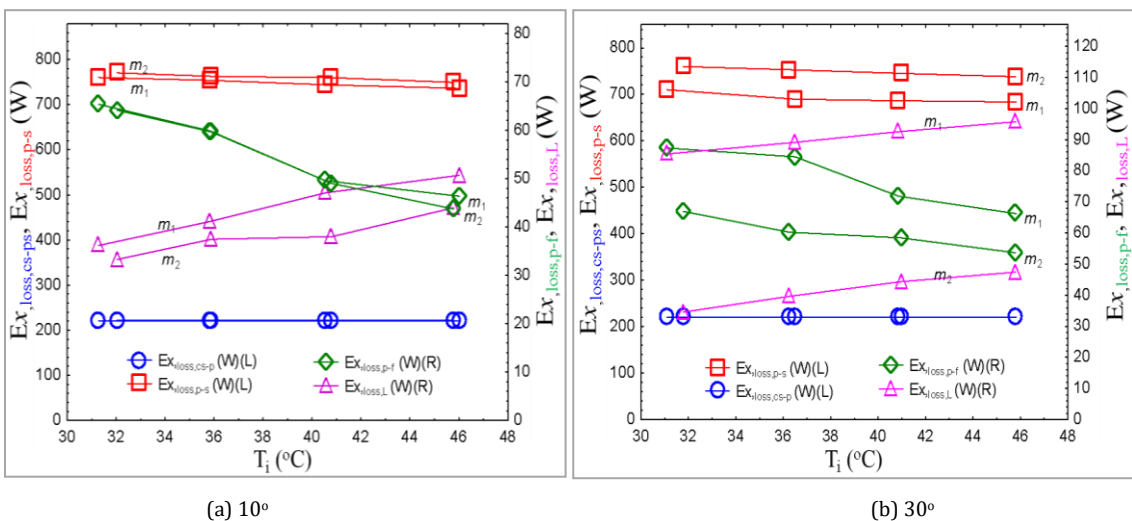
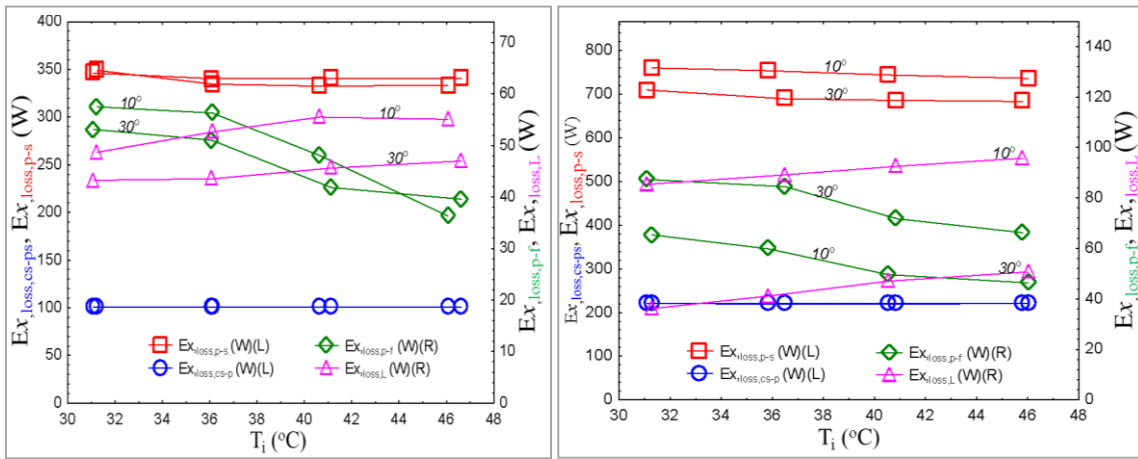


Figure 6: Exergy losses: 1050W/m²

3.1.6 Effects of Tilt Angles on the Exergy Losses

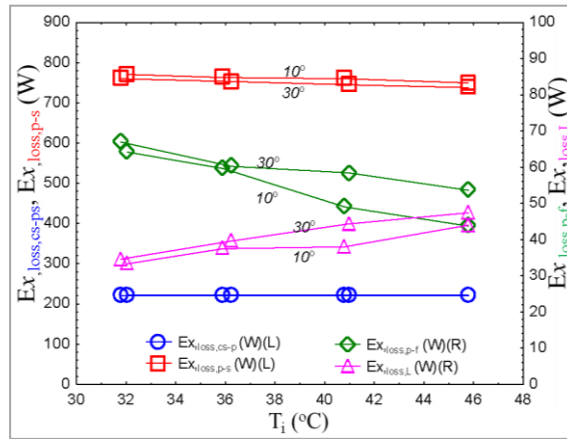
Figure 7 illustrates the impact of the collector’s tilt angle on exergy losses. The primary exergy loss (approximately 72%) is attributed to the temperature difference between the Sun’s surface and the solar collector’s absorber plate, which agreed with (Zhong et al., 2014). At low solar irradiance (475 W/m^2), increasing the tilt angle from 10° to 30° results in an increase in $Ex_{loss,p-s}$, while $Ex_{loss,p-f}$, and $Ex_{loss,L}$ decrease with the tilt

angle. Additionally, $Ex_{loss,L}$ increases with the inlet fluid temperature, whereas $Ex_{loss,p-f}$ and $Ex_{loss,p-s}$ decrease, as similar findings are reported by (Imad, 2022). Furthermore, the exergy-loss between collector’s surface and the plate ($Ex_{loss,cs-p}$), remains consistent. At solar irradiance of 1050 W/m^2 and water flow rate of 0.0235 kg/s ; the effect of tilt angles becomes noticeable. However, increasing the flow-rate at this solar irradiance level, makes the values comparable Figure 7c.



(a) 475W/m², 0.0235kg/s

(b) 1050W/m², 0.0235kg/s



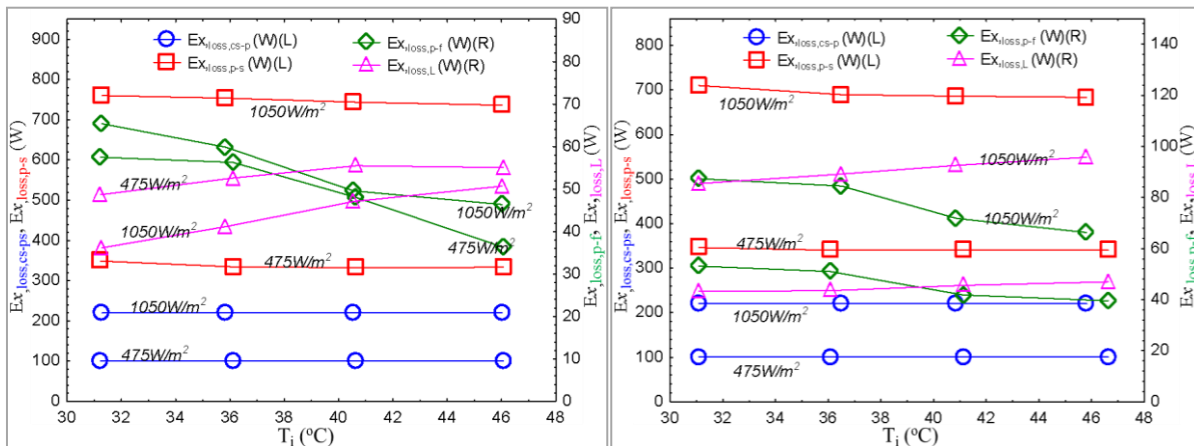
(c) 1050W/m², 0.0387kg/s

Figure 7: Exergy losses: 10° - 30°

3.1.7 Effects of Solar Irradiance on the Exergy Losses

Figures 8a and 8b demonstrate the impact of solar irradiance on the exergy losses of the solar collector at tilt angles of 10° and 30°, respectively. As shown, increasing solar irradiance from 475 to 1050 W/m² leads to greater exergy losses, including those between the

collector's plate and the Sun ($Ex_{loss,p-s}$), the collector's surface and plate ($Ex_{loss,cs-p}$), and exergy leakage ($Ex_{loss,L}$). This trend is also observed by (Imad, 2022). Moreover, $Ex_{loss,p-f}$ and $Ex_{loss,p-s}$ decrease with higher inlet fluid temperatures, while $Ex_{loss,L}$ increases with rising temperatures, as it aligned with the findings (Zhong et al., 2014; Imad, 2022).



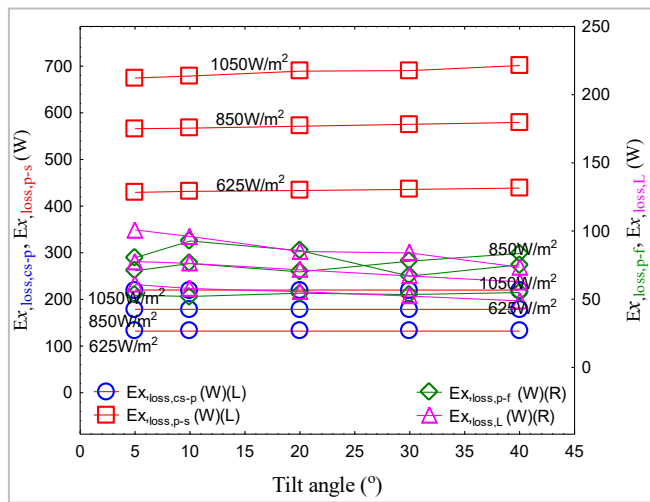
(a) 10°

(b) 30°

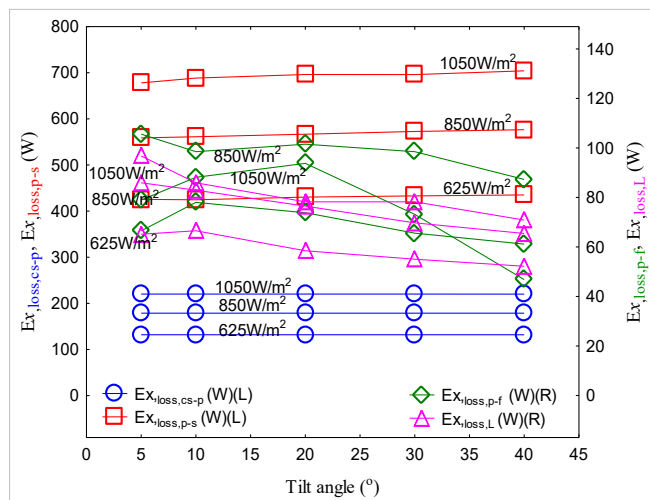
Figure 8: Exergy losses: 475 - 1050W/m²

Figures 9a - 9b illustrate the influence of experimental parameters on the collector's exergy losses at a fixed inlet temperature (T_i), which is set close to the ambient temperature (T_a) ($\approx 30.5^\circ\text{C}$). These figures plot the exergy loss between the collector's plate and the Sun ($Ex_{loss,p-s}$), exergy loss between the collector's surface and plate ($Ex_{loss,cs-p}$), exergy loss between the collector's plate and the fluid ($Ex_{loss,p-f}$), and exergy leakage ($Ex_{loss,L}$),

against various tilt angles. As shown, $Ex_{loss,p-f}$ and $Ex_{loss,L}$ decrease with an increase in the collector's tilt angle, while $Ex_{loss,p-s}$ slightly increases with the tilt angle. Generally, at $T_i \approx T_a$, tilt angles have a minimal effect on the collector's exergy losses, though, exergy losses increase with higher levels of solar irradiance (Imad, 2022).



(a) 0.0235kg/s



(b) 0.0387kg/s

Figure 9: Exergy losses (5° - 40°): 625,850,1050w/m²

3.2 Exergy Efficiency

The instantaneous exergy efficiency of a solar collector is defined as the ratio of the increase in water exergy to the exergy of the solar radiation (Chamoli, 2013; Viorel, 2007; Zhong et al., 2014; Farzad and Emad, 2013). In simpler terms, it represents the proportion of useful exergy provided to the exergy absorbed by the solar collector (Hepbasli, 2008; Singh et al., 2000). Table 1 shows the exergy efficiency of the solar collector under various experimental conditions. According to the table, exergy efficiency tends to increase with higher inlet temperatures, as it also reported in a study, although it shows an inverse correlation with solar irradiance (Shigeru et al., 2018). Furthermore, exergy efficiency experiences a slight decline as water flow rate increases, as it also reported by (Imad, 2022).

The results indicate that the exergy efficiency values are comparable with similar studies. For examples, Kalogirou, (2009) reported 0.0596 exergy efficiency, Imad, (2022) observed 0.085, while both Farzad and Emad, (2013) and Jafarkazemi and Ahmadifard, (2013), reported a value of 0.08. In other study, they found exergy efficiencies of 0.036 for simulations and 0.019 for experimental work (Luminosu and Fara, 2005). In some researchers showed an average exergy efficiency of 0.0863 using pulsating heat pipe solar collectors (Kargarsharifabad et al., 2014). A group researcher achieved exergetic efficiencies of 0.3909, 0.3901, and 0.3863 with a collector area of 8.365 m² and thermal storage of 5.52 m³, at collector tilts of 35°, 40°, and 30°, respectively (Hanif et al., 2022).

Some researchers reported that the exergy efficiency of a solar collector ranges from 0.0202 to 0.0337 (Gunerhau and Hepbasli, 2007). A group researcher found an exergy efficiency of 0.048 at a solar irradiation of 916 W/m² and an air temperature of 15.4°C, with a maximum efficiency of 0.045 at 1000 W/m² (Gheorghian et al., 2020). An researcher observed that the maximum exergy efficiency with and without a porous media solar air-heater was 0.0342 and 0.0516, respectively (Afaq, 2019). In other study, researcher found an exergy efficiency of 0.0372 (Shigeru et al., 2018). Allouhi and Amine conducted a comprehensive analysis of flat plate

collector and heat pipes and found an exergy efficiency of 0.067 (Allouhi and Amine, 2019).

A group researcher experimentally determined that the maximum exergetic efficiencies of a flat plate collector are 0.113 for the rod, 0.109 for the tube, and 0.083 for the rising tube without a heat transfer enhancer (Balaji et al., 2018). A study reported maximum exergy efficiencies ranging from 0.052 to 0.082 for mass flow rates between 0.0019 and 0.0022 kg/s (Subhra, 2016). A group researcher tested solar collectors with copper and aluminium absorber plates, found average exergy efficiencies of 3.91% for collector with copper and 3.2% for one with aluminium plate (Piyush et al., 2022). The inlet temperature has two effects on exergy efficiency: first, as it increases, the difference between the sun and the absorber is reduced, resulting in lower exergy destruction. Secondly, higher inlet temperatures lead to increased heat losses, resulting in greater exergy losses. Combining these two factors, a gradual change in exergy efficiency is observed, reaching a maximum value at a certain-point (Shigeru et al., 2018).

Table 1: Exergy efficiency of the solar collector							
Angle (°)	Flow-rate (kg.s ⁻¹)	Solar Irrad. (W.m ⁻²)	Exergy efficiency (-)				Aver.
			T _i (°C)				
			30	35	40	45	
10	0.0235	475	<0.01	0.02	0.05	0.10	0.05
		1050	<0.01	0.01	0.03	0.05	0.02
30	0.0235	475	<0.01	0.02	0.06	0.10	0.05
		1050	<0.01	0.02	0.05	0.08	0.03
	0.0387	1050	<0.01	0.01	0.04	0.07	0.03

Many methods are available in the literature to perform the uncertainty analysis (Holman, 2012). The uncertainty in these solar tests, can be calculated using Eq. (12). The uncertainty analysis is desired to prove or validate the accuracy of the experimental results (Imad, 2022; Holman, 2012). The main Sources of uncertainties or the errors in the measurements, are shows in Table 2. The calculated uncertainty value is 7.2986%; which is falls within the acceptable range for such experiments. For instance, in some study, reported an uncertainty value of 10% (Nishandar et al., 2015; Hussam and Hasnain, 2012).

Table 2: Sources of uncertainties	
Sources	Errors (%)
Data logger	±0.10
Digital balance	±0.10g
Digital temp. controller	±0.5
Water flow meter	±5.0
Voltage regulator	±5.0
User clarifications	±1.0
Pyranometer	<1.0 (1750 Wm ⁻²)
Thermocouples	± 0.75% or 1.0°C

4. CONCLUSIONS

A prototype of a flat-plate wickless heat-pipe solar collector with parallel condenser-coolers was made and evaluated, focusing on its thermal behaviour in the form of exergy analyses. The study presented the effects of various experimental factors on different exergies (outflow, gained, losses, leakage, and efficiency). The uncertainty in the experiments is found as 7.3%. The results showed a maximum exergy efficiency of 10% and an average efficiency of 3.5%. For future improvements, it is recommended to:

- Use thinner thermal glass cover (4mm windows glass was used in this study) to increase transmissivity and energy absorption by the absorber plate and heat pipes.
- Increase the number of heat pipes (e.g., 15 instead of the 8 used in this study) to extract more energy.
- Use small Fresnel lenses in the evaporator section to concentrate more heat to the heat pipes.
- Try different liquids like acetone (which has a lower boiling point than water).
- Use heat pipes with varying dimensions and filling ratios.

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