HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

Efficiency improvement of the hybrid solar collector systems

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PhD Thesis

by

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CONTENTS

1. INTRODUCTION, OBJECTIVES

Solar energy has two essential systems for utilisation: the first is the thermal collector, which produces thermal energy, and the second is the PV module, which makes electrical energy. The combination of these two systems is the photovoltaic/thermal module (PV/T). In combination with reducing costs and decreasing the area needed for installation, the hybrid PV/T module simultaneously delivers heat and electric power to the load. This system incorporates an absorber plate with a PV module to further reduce the heat generated behind the PV module, which circulates a cooling fluid to capture surplus heat generated by the module. Various applications can utilise this fluid, including space heating, hot water supply, and industrial preheating.

Subsequent research over the past few decades has focused on optimising PV/T systems, including configuration modifications, flow patterns, and energy generation characteristics. However, several gaps persist regarding construction modifications, particularly concerning configurations employing air and water as coolants. Moreover, the potential contribution of such systems towards sustainability remains largely unexplored. Consequently, the research has undergone several modifications aimed at enhancing performance. Accordingly, the main objectives of the present work are to investigate the following:

- To build and validate a new multi-controller platform of PV/T units within the common functional tools in the simulation of the solar system TRNSYS tool environments to be a base-tool for further performance enhancement.
- Develop a new configuration of copper fins, louvered fins and examine their effects on the PV/T module performances.
- Develop a new design of bi-fluid PV/T utilising the design of louvered fins and serpentine tube.
- To study the effect of the solar cell temperature and how it decreased using a developed PV/T module via a new correlation.
- To assess the sustainability contribution by calculating the wasted heat removed by solar cells compared to the developed PV/T module.
- To study the potentiality of ternary MWCNTs-MgO-BN nanofluid as a high thermal conductivity fluid to improve PV/T performance.
- To experimentally develop a new correlation of thermal conductivity of the chosen nanofluid as a base equation for further investigations.

2. MATERIALS AND METHODS

This chapter provides a comprehensive overview of the materials, techniques, and equipment utilised in the experimental measurements and the scientific approaches implemented to achieve the research objectives.

2.1. TRNSYS dynamic model

The first assessments were conducted in this research on a conventional PV/T module installed at a Solar Lab of the MATE university by developing a dynamic and mathematical model within the TRNSYS tool, which enables comprehensive simulations to evaluate system behaviour across diverse conditions. This model was developed using the Fortran programming language to build a multifunctional approach dynamic model in the TRNSYS environment. The model comprises interconnected components represented by unique icons, facilitating parameter exchange. Fig. 1 shows the linked components and particular types used to build the hybrid system parts.

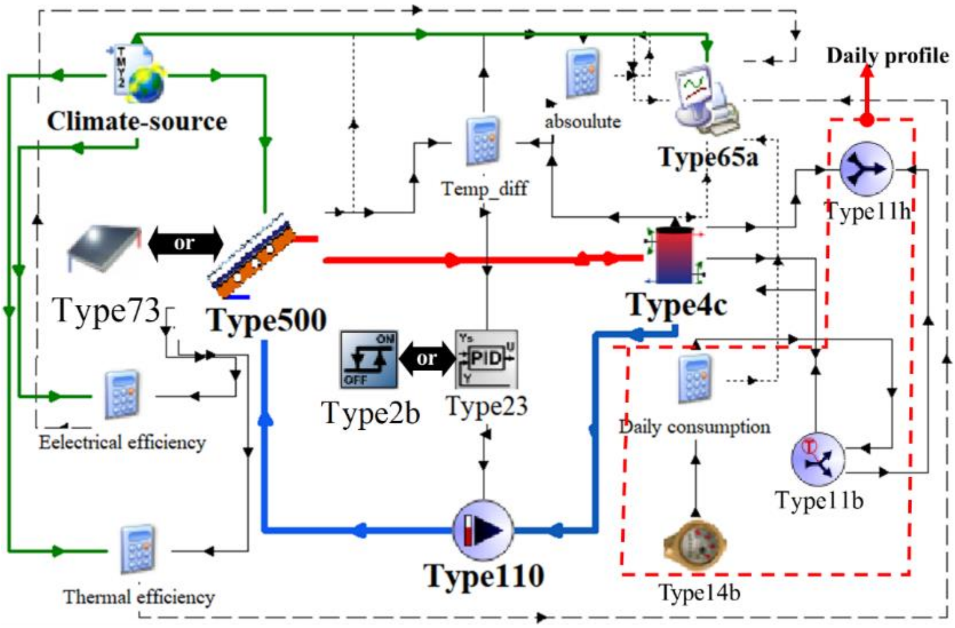


Fig. 1. Model demonstration

As depicted in Fig. 1, the model outlines the main flow: the PV/T module (Type500) generates electrical energy and hot water. The electrical energy is directed to the result monitoring processor (Type65a), while the hot water is stored in the tank (Type4c) and utilised according to the daily profile components. Subsequently, the water returns to the PV/T module via the pump (Type110) for recirculation.

2.2. Creating of the bi-fluid PV/T module

A modulated PV/T air-water module was constructed, fabricated, and verified for efficiency improvements of the hybrid solar collectors by enhancing the heat removal from the solar cells of the PV module to the circulated coolants.

The major configuration investigated in this experimental research was a hybrid solar collector using two methods for heat extraction: water and air heat exchangers, using a copper absorber with louvered fins (LF) and a serpentine tube (see Fig. 2). The name is PV/T, with louvered fins and a serpentine tube (LFS-PV/T).

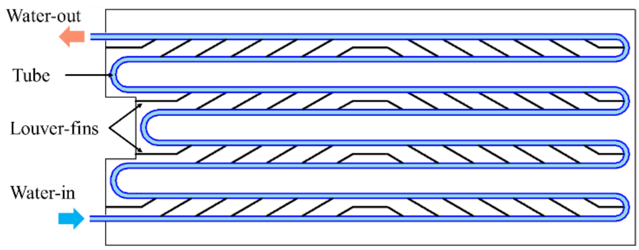


Fig. 2. Final sketch of the new absorber

A polycrystalline PV module was used to construct a new PV/T module. A copper plate was cut based on the area of the solar cells to configure the new absorber. Louvered fins were soldered to the copper absorber and fixed in the direction of the airflow. A serpentine tube was soldered to the absorber plate among the louvered fins. The new absorber adhered behind the PV module using a high thermal resistor. Fig. 3 illustrates the final configuration of the new LFS-PV/T module. Fig. 4 shows the actual image of the complete system used in this study.

Fig. 3. Factual pictures of the LFS-PV/T module creation process

The new module was compared with air-cooled and water-cooled PV/T modules. Modules equipped with louvered fins were compared to those supplied with vertical fins.

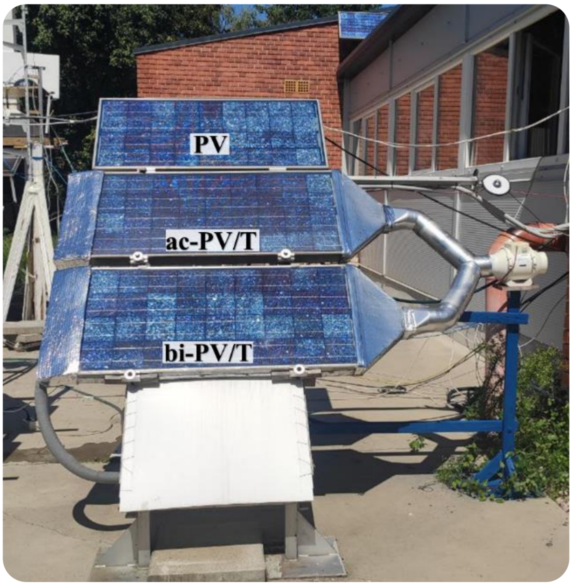


Fig. 4. Actual image of an experimentation systems

2.3. Preparing nanofluids

This research uses multi-walled carbon nanotubes (MWCNTs), magnesium oxide (MgO), and boron nitride (BN) nanoparticles to create four ternary and binary nanoparticles based on different weight ratios. Nanofluids were prepared for each nanoparticle through six volume concentrations: 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5%. Nanofluids have been prepared as follows: ternary hybrid nanofluids, MWCNTs–MgO–BN, binary hybrid nanofluids, MWCNTs–MgO, binary hybrid nanofluids, MWCNTs–BN and binary hybrid nanofluids, MgO–BN. Fig. 5 describes the detailed steps for preparing hybrid ternary and binary nanofluids.

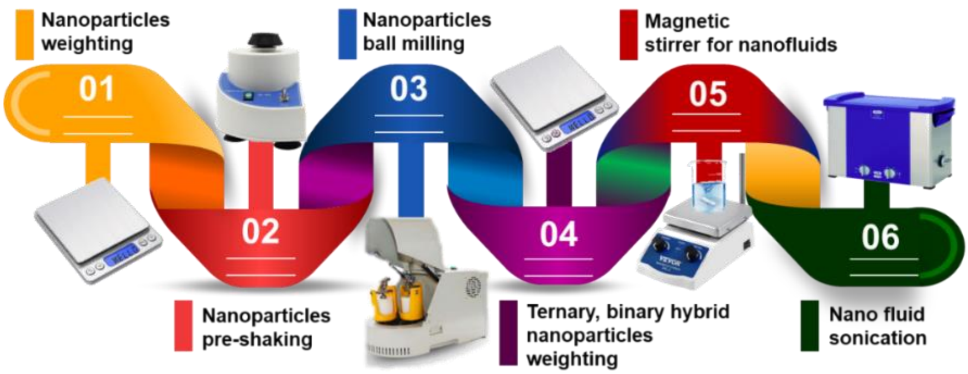


Fig. 5. Experimental steps of nanofluid preparation

2.4. Evaluation of nanofluids

Based on the previous section, 24 nanofluid samples were prepared. The task at hand is to select effective nanofluids. Due to the high cost and limited availability of testing equipment, this research introduces a new instrument for nanofluid evaluation. As illustrated in Fig. 6, the instrument comprises three cylindrical cans: A is steel, while B and C are plastic. The space between B and C is filled with compressed sawdust for insulation, with cylinders A and B left empty.

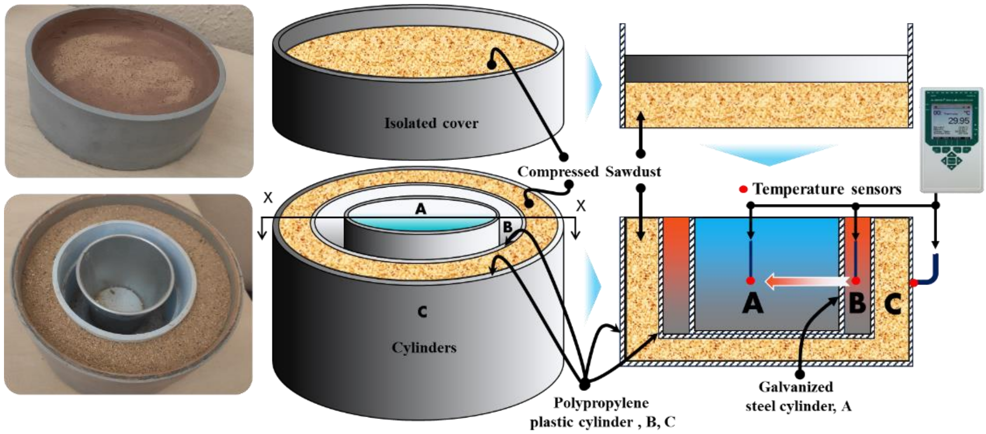


Fig. 6. Configuration of the evaluation instrument

Temperature sensors were fitted and linked to the data logger. Subsequently, the procedure entails filling cylinder B with boiling water and cylinder A with nanofluid. Since T_B is higher than T_A, heat will transfer thermodynamically from cylinder B to cylinder A until equilibrium is achieved, with $T_A = T_B$. At this stage, the time until the equilibrium state will be calculated. This metric, termed thermal equilibrium time, is a novel characteristic introduced by this research.

Consequently, the nanofluid with a shorter time will be deemed the most efficient. This instrument possesses a unique feature for nanofluid evaluation, distinguishing it from other instruments worldwide. A particularly compelling aspect of this instrument is its cost-effective manufacturing.

2.5. Performance assessment of bi-fluid PV/T

The electrical productivity of the presented PV/T modules was evaluated against that achieved by the reference PV module. The following standard formula identifies the electrical power (P_{el}) productivity:

$$P_{el} = I\,V,$$

where *I* and *V* are the current and the voltage of the PV/T module. The following equation defines the ratio of the output power as electrical power to the input power as solar radiation received by the solar cell area as the momentary electrical production efficiency (η_{el}):

$$\eta_{el} = \frac{P_{el}}{S\,A},$$

where *S* and *A* are the solar radiation and the area of the module.

The utilised thermal achievement of the bi-PV/T modules is categorised into two heat gains, water and air, according to the type of hybrid collector. The following verified the air heat-gain equation:

$$Q_{u,a} = \dot{m}_a cp_a (T_{a-out} - T_{a-in}),$$

where $\dot{m}_a$ and cp_a are the air mass flow rate and the specific heat. The water heat-gain equation is:

$$Q_{u,w} = \dot{m}_w cp_w (T_{w-out} - T_{w-in}),$$

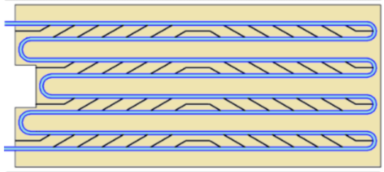
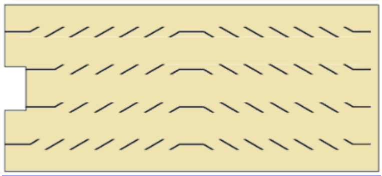
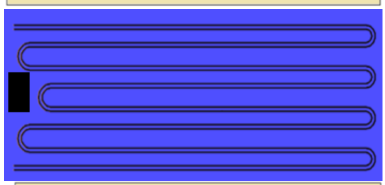
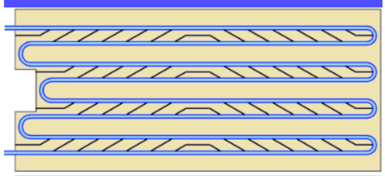
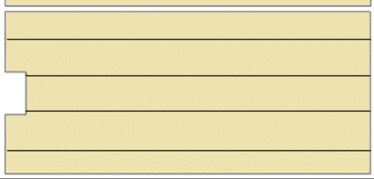
where $\dot{m}_w$ and cp_w are the water mass flow rate and the specific heat. The heat-gain efficiency of the bi-PV/T modules is specified as a ratio of output energy as a heat-gain to the output energy as incident solar radiation formulated in the following equations:

$$\eta_{th.bi-PV/T} = \frac{Q_{u,a} + Q_{u,w}}{S\,A}.$$

2.6. Experiments summary

Based on the previous subsections of the creation processes made in this research, three PV/T modules were created to achieve and fulfil the research objectives. First, the novel construction with louvered fins and serpentine tube that utilise water and air cooling at the same time; second was the classical air-cooled module without fins; the third was the water-cooled module via utilising serpentine tube connected directly to the backside of the PV module. Among these three modules, Table 1 lists all modification cases conducted on these modules in this research.

Table 1. The presented research solar modules

Case	Absorber	Fins	Tube / fluid	Sketch of absorber
0	None	None	None/none	
1	Copper	None	None/air	
2	Copper	Louvered	Serpentine/ water	
3	Copper	Louvered	None/air	
4	None	None	Serpentine/ water	
5	Copper	Louvered	Serpentine/ Nanofluids	
6	Copper	Vertical	None/air	

3. RESULTS

This chapter presents the most important results obtained from the experimentation and their discussions.

3.1. Multi-functional platform of the PV/T module

Based on the achievements caught based on the TRNSYS models developed in this research of the proposed PV/T system through multiple aspects and modifications, Figs. 7 and 8 show the results of each approach used for evaluation. As clearly shown in the figures above, the basic system of this research, PID-controlled PV/T (PV/T-ID), was the most efficient system among the other two PV/T systems in terms of electrical performance, while the FPC was the most efficient in terms of thermal performance.

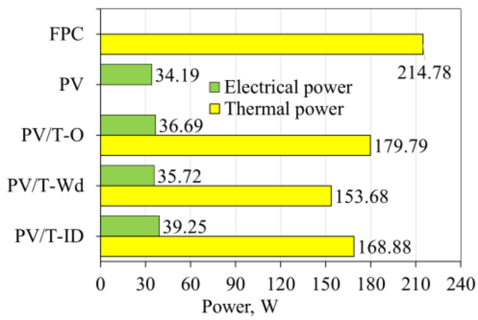


Fig. 7. Power comparison for study systems

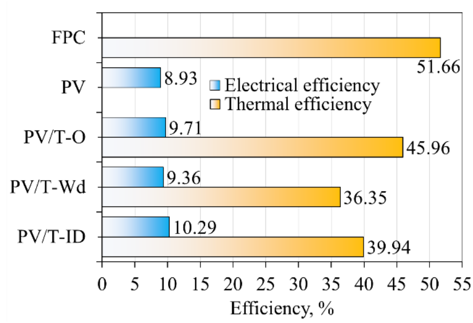


Fig. 8. Efficiency comparison for study systems

Based on the literature utilising the PID controllers through the solar system and the studies that used it within their TRNSYS dynamic model, the PID controller depends on the temperature difference between stored water and the outlet temperature of the collector. And this assumption was a usual option. This research used a new consideration: changing the temperature difference used by a PID controller in a PV/T-ID system to a difference between the cell temperature and stored water with the new symbol as a PV/T-ID2 system. Fig. 9 shows the performance difference between these two cases.

The results clarified in Fig. 9 indicate that the PV/T-ID2 thermal and electrical performance was more efficient than the PV/T-ID. Thus, the proper temperature difference in the PID controller is between the stored water and the PV cell temperatures. Thermal power was enhanced by 6.5%, and the electrical power was improved by 7.1% compared to the standard PID-controlled system.

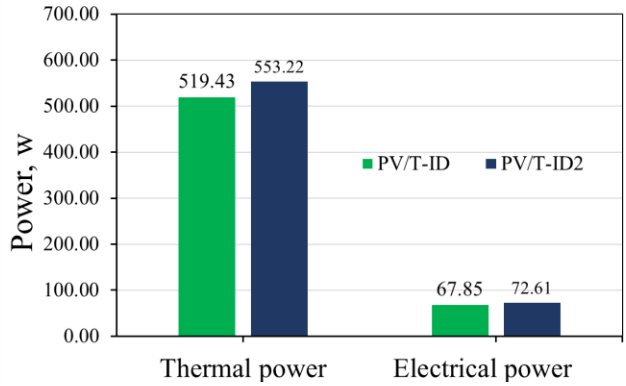


Fig. 9. Performance difference between PV/T-ID and PV/T-ID2

3.2. Effect of the louvered fins

This assessment compares the performance of three absorber configurations equipped with louvered fins, vertical fins, and no fins attached to an air-cooled photovoltaic/thermal module under steady-state conditions. Fig. 10 depicts these absorber sketches.

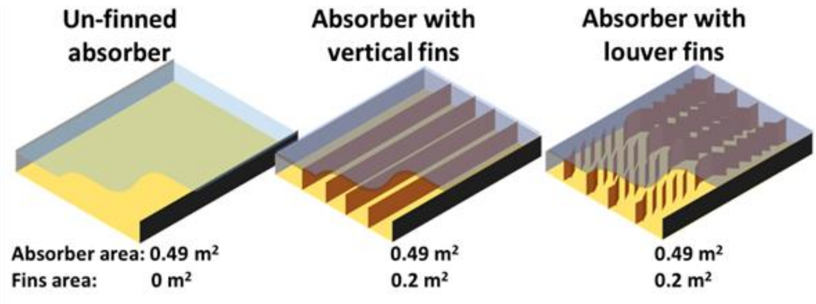


Fig. 10. Sketches of the three absorbers

Fig. 11 illustrates the thermal power of the three modules. The enhancement of the thermal behaviour of the PV/T module that employed the louvered fins compared to the other modules is clearly noted. The average daily value of the thermal power of the three modules is 139, 166, and 320 W for the first, second, and third modules, respectively.

The performance of the three systems used in this research is clarified by the electrical and thermal efficiencies, as illustrated in Fig. 12; the PV/T module that employs the louvered fins has the highest performance compared to the other investigated PV/T modules. The average electrical and thermal efficiencies for the modules with louvered fins, vertical fins, and un-finned are 7.34%, 69%; 6.98%, 36.6%, and 6.53%, 33.8%, respectively.

As a result of the heat extraction, the electrical power generation increases accordingly, with the PV temperature decreasing. Fig. 13 illustrates the imaging of the productivity behaviour among the studied modules. The average electrical power and PV temperature values for the modules with louvered fins, vertical fins, and un-finned are 36.4 W, 40.6 °C; 34 W, 45 °C and 31 W, 47 °C respectively.

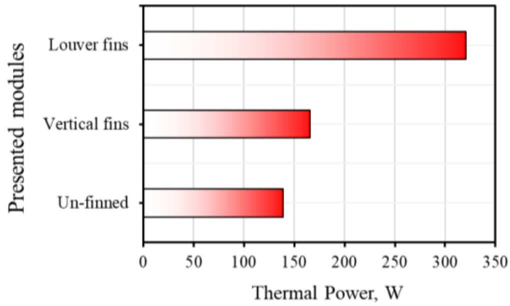


Fig. 11. Thermal power of the presented modules

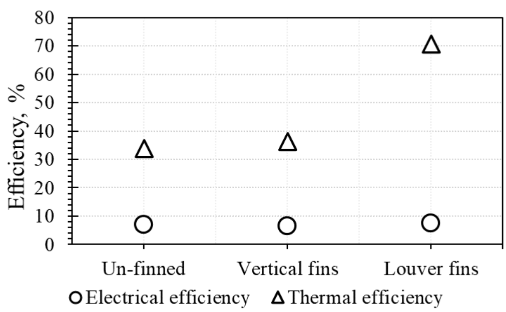


Fig. 12. Electrical and thermal efficiencies

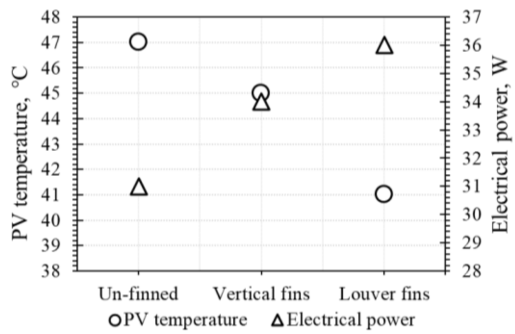


Fig. 13. Electrical generation versus the PV temperature of modules

3.3. Design of the louvered fins and serpentine tube

This assessment presents the comparative results pertaining to the novel design of a bi-fluid PV/T module, integrating louvered fins and serpentine tubes, juxtaposed with modules featuring solely louver fins or devoid of fins altogether. The experiments were conducted to obtain the results from the following three cases:

1) The classical unit of the hybrid solar collector uses air as the coolant (AC-PV/T),
2) A new module with louvered air fins and a serpentine water tube (LFS-PV/T),
3) Same case 2, but without water circulation in the serpentine tube (ALF-PV/T).

In Fig. 14, notable temperature variations among the three cases are evident. The second case (LFS-PV/T) exhibited the lowest surface temperature, followed by the third (ALF-PV/T) and the first (AC-PV/T). Temperature differences were significant when solar radiation exceeded 1000 W/m². On average, temperatures were 57.1 °C, 45.73 °C, and 38.9 °C for AC-PV/T, ALF-PV/T, and LFS-PV/T modules, respectively.

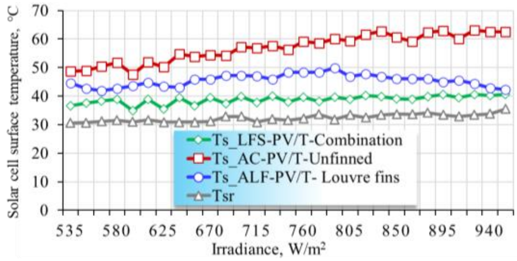


Fig. 14. Surface temperatures of the solar cells

Based on the result obtained in these investigations, Fig. 15 shows an overall thermal and electrical view of the modifications for the three cases.

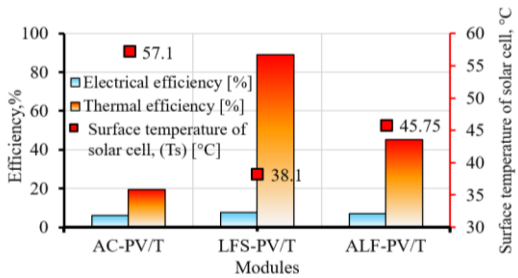


Fig. 15. Thermal and electrical view of the modules

A TH9260-thermal camera took three thermal images for all three cases during the recording period on June 20. The first image was a static situation when the systems were not working (see Fig. 16), the second was when the systems worked without water circulation (see Fig. 17), and the last was with water circulation (see Fig. 18).

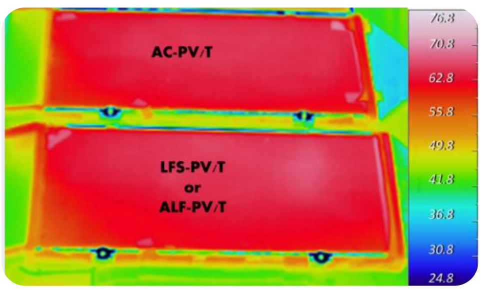


Fig. 16. The image of the thermal camera when the systems were not working

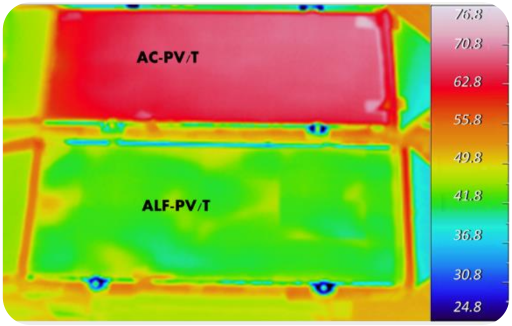


Fig. 17. The image of the thermal camera when the water was not circulated

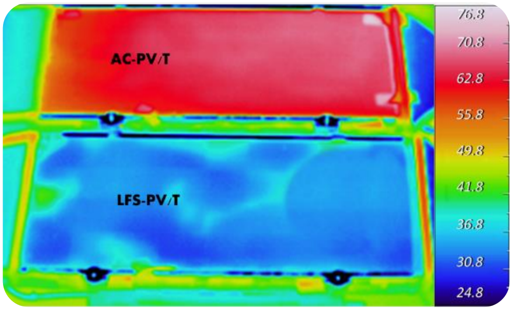


Fig. 18. The image of the thermal camera when the water was circulated

As shown in the three thermal images (Figs. 16-18), which provide thermodynamic viewpoints of the three cases in this research and verify thermal matching with the experimental results of the new configuration that used louvered-fins and serpentine tubes, the LFS-PV/T module is the best in terms of thermal behaviour.

3.4. Correlation between solar cell temperature and solar intensity of the new PV/T

The solar cell temperature is the main effective factor in the solar energy systems performances and to make correlations to address how cell temperature is decreased as a result of the new PV/T design of this research.

So, this assessment compared an experimental performance comparison to the new PV/T (that utilised louvered fins and serpentine tube) with a classical air-cooled PV/T and the standalone PV module and the water tank was in a static state. Fig. 19 represents the cross-section layout (side view-inlet and outlet view) of these three modules.

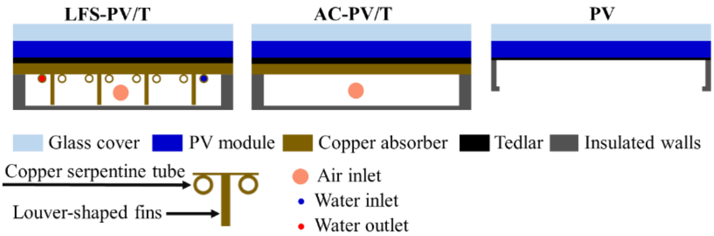


Fig. 19. The cross-section layout of the solar modules

The full-period PV cell temperatures for the three modules used in this research are shown in Fig. 20: the new hybrid LFS-PV/T system, the conventional AC-PV/T system, and the PV reference module. It is straightforward to notice that the cell temperature of the PV module (standard case) is greater than the temperature of the cells in both the LFS-PV/T and the AC-PV/T. Consequently, the idea behind the new module (LFS-PV/T) indicates that the average cell temperature dropped by 19.2 °C compared to the standard PV unit.

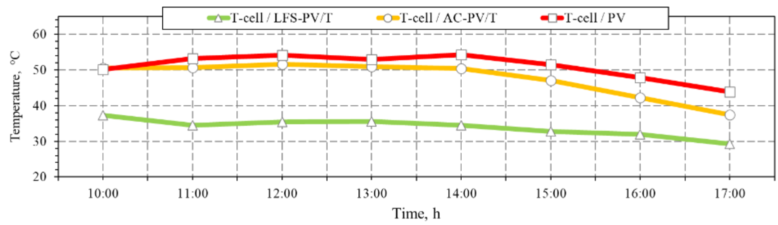


Fig. 20. Cell temperatures of the LFS-PV/T, AC-PV/T, and PV modules

It is clear from looking at Fig. 20 that the temperature of the PV cell increases gradually with the amount of direct solar energy received per unit area. This research presented a polynomial function of the temperature concerning the radiation for each of the three proposed systems. As clarified in Fig. 21, Table 2 represents the correlation formulas for each configuration used in this assessment.

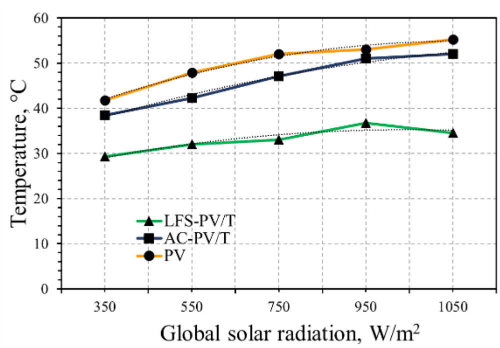


Fig. 21. The temperature of the modules as a function of radiation

Table 2. Correlations formulas of the research configuration

Module	Correlations formulas
LFS-PV/T	$T_{cell} = 22.96 + 0.022\,S - 9.4 \times 10^{-6} S^{\,2}$
AC-PV/T	$T_{cell} = 29.91 + 0.027\,S - 4.8 \times 10^{-6} S^{\,2}$
PV	$T_{cell} = 28.89 + 0.046\,S - 2.014 \times 10^{-5} S^{\,2}$

3.5. Quantifying the wasted heat toward sustainability contributions

This section highlights the scientific contribution of the newly developed LFS-PV/T module towards achieving sustainability goals compared to the standalone PV module. Fig. 22 depicts heat dissipation from PV and LFS-PV/T module surfaces via convection and radiation. "Wasted heat" refers to heat lost to the surroundings; when minimised, it becomes useful through a PV/T module. Temperature differentials caused notable variations, with max wasted heat at 213 W (PV) and 47 W (LFS-PV/T).

The sustainability index (SI), calculated based on the exergetic efficiencies of the systems, has recently been focused on evaluating the sustainability contribution of renewable energy systems. Fig. 23 shows the behaviour of the sustainability indices of the PV and LFS-PV/T modules. The SI values ranged from 1.15 and 1.6 for LFS-PV/T and between 1.03 and 1.06 for the PV module.

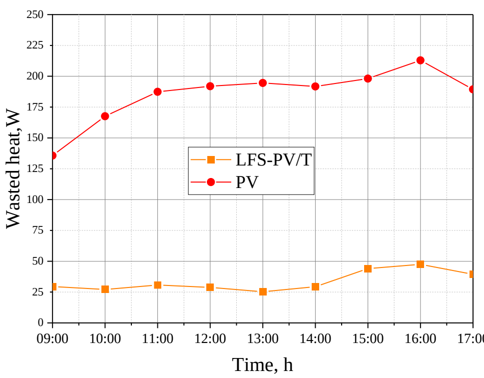


Fig. 22. Wasted heat generated from the PV and LFS-PV/T modules

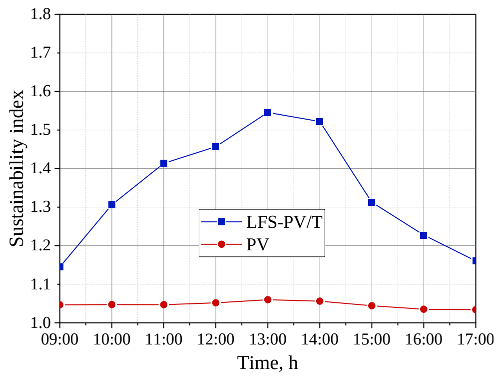


Fig. 23. Sustainability index of the LFS-PV/T and PV modules

3.6. Effect of ternary nanofluid as a heat transfer fluid

The hybrid ternary nanofluid composed of MWCNTs, MgO, and BN at a 0.5% volume concentration exhibits the shortest thermal equilibrium time and stands out as the most efficient nanofluid, as determined by the assessment instrument employed in this research. This nanofluid was selected to enhance the new PV/T module performance and compared with water-based units and a standalone PV unit as a reference module. The most significant parameter to measure and evaluate is the cell temperature of the PV modules; accordingly, Fig. 24 displays the variation of these temperature profiles for water-cooled (LFS-PV/T) and nanofluid-cooled (LFS-PV/T-NF) modules examined in this research over test time compared to the PV module. Radiation has a dramatic effect on the surfaces of solar cells. These surfaces rise in temperature due to the radiation and their ability to transfer heat from them to their surroundings or the parts attached to them.

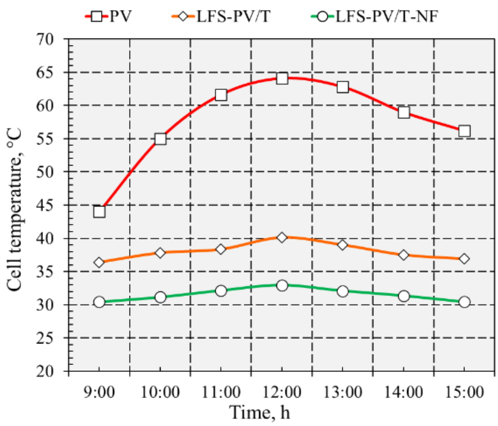


Fig. 24. The electrical power of the studied modules

Fig. 25 depicts the variations in thermal and electrical powers throughout the daily experiment (from 9:00 to 15:00) for various scenarios, including LFS-PV/T-NF, LFS-PV/T, and PV modules. The figure demonstrates that the utilisation of nanofluids in the LFS-PV/T-NF module results in a 37.65% increase in thermal power compared to the LFS-PV/T module. It can be seen in Fig. 25 that the LFS-PV/T and LFS-PV/T-NF modules produce more electricity than the PV module by 32.37 and 55.75%, respectively.

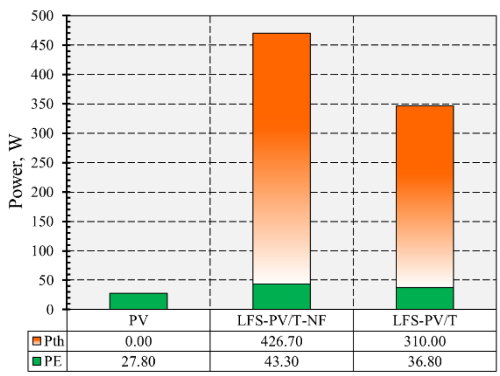


Fig. 25. Average electrical and thermal power values of studied modules

4. NEW SCIENTIFIC RESULTS

This section presents the new scientific findings from the research work as follows:

1. Multi-functional platform of the PV/T module

Based on the new functional TRNSYS model, in order to evaluate the performance and behaviour of the PV/T module, I have developed multi-aspect approaches and several controllers. I proved that the PID controller has an effective electrical performance, and the ON-OFF controller has an effective thermal performance. Accordingly, I enhanced the electrical efficiency of PV/T that PID controlled by 6.5% compared to the ON-OFF controlled system. The maximum electrical productivity also reached 48.5 W for the PID-controlled system and 45 W for the ON-OFF-controlled system.

Additionally, based on the modifications I made to the programming code of the PID controller within the TRNSYS environment, I improved the thermal and electrical productivity of the PV/T module by 6.5% and 7.1%, respectively, compared to the standard TRNSYS PID-controlled PV/T. Accordingly, the developed model can be used to comprehensively evaluate the performance of PV/T systems in multiple circumstances. Furthermore, the findings align closely with the existing literature on measurements within the same field.

2. Effect of the louvered fins

I have developed and evaluated a novel fin configuration, a louvered fin, which proved its thermal effectiveness in the air heat exchanger. It is mounted to the copper absorber to configure air-cooled-based PV/T and compared with vertical-fins-based PV/T and no-fins PV/T modules. Furthermore, these louvered fins are first used in configuring PV/T modules.

Based on the experimental results, I have proved that the essence behind the idea of using louvered fins is to improve the thermal behaviour of the temperature distribution of the PV/T module through the path changing of an airflow caused by the louvered fin shape makes sufficient time for convective heat transfer from the fin's surfaces to the airflow. This process created a more significant difference in temperature between the inlet and the outlet, thus enhancing the thermal performance. Examining the two fin configurations in this study, I found that the module's thermal efficiency increased by 48% and 54% when equipped with louvered fins, as compared to vertical fins and unfinned modules. The Reynolds number, recorded at 6312 throughout the experiment, signifies the onset of turbulent flow within the system's configuration. This turbulent airflow manifests intricate dynamics, fostering heightened convective heat and energy transfer mechanisms across the system.

3. Design of the louvered fins and serpentine tube

I have developed and evaluated a novel configuration of a bilateral-based (LFS-PV/T) module with a unique design of a flat-plate absorber fitted with louvered fins and a serpentine-shaped tube using water and air as coolants simultaneously. The copper alloy was utilised to create the absorber, fins, and tube.

Based on the experimental findings, I evidenced that the novel design developed uniform cooling of the PV/T module compared to the classical air-cooled PV/T module. A dramatic decrease in the surface temperature of the solar cell was achieved; the created bi-fluid PV/T module decreased the surface temperature by 31.7% compared to the air-cooled module. Accordingly, I have enhanced the thermal and electrical performances of the created module compared to the classical air-cooled module. The thermal and electrical efficiency of the two examined modules were 19.4 and 6.1% for the air-cooled module and 89.1 and 7.7% for the bilateral-based PV/T module, respectively.

PV/T systems typically entail a higher initial investment compared to individual PV modules or flat plate collectors. However, their dual functionality makes them a cost-effective investment. With reduced installation costs and space optimisation, PV/T systems offer attractive returns by simultaneously generating electricity and thermal energy, making them a prudent investment choice.

4. Correlation between solar cell temperature and solar intensity of the new PV/T

Based on comparing assessments of the experimental results among the bi-fluid PV/T, air-cooled PV/T, and PV module, I have identified new proposed correlations to estimate the relation between the solar cell temperatures (T_{cell}) and the amount of solar radiation (S) received by solar modules, thus, evaluating how solar cells temperature increases with solar radiation. The solar radiation range utilised in these correlations is arranged between 350 and 1050 W/m^2:

For the bi-fluid LFS-PV/T:

$$T_{cell} = 22.96 + 0.022\,S - 9.4 \times 10^{-6} S^{2}$$

For the air-cooled AC-PV/T:

$$T_{cell} = 29.91 + 0.027\,S - 4.8 \times 10^{-6} S^{2}$$

For the PV:

$$T_{cell} = 28.89 + 0.046\,S - 2.014 \times 10^{-5} S^{2}$$

I found that the increase in cell temperature with solar radiation is the lowest for the new bi-fluid PV/T module created in this research. Accordingly, the new configuration of the PV/T module is well addressed in terms of how the new methodology utilised has a positive potential to decrease the cell temperature based on the correlation between the solar cell temperature and the solar intensity. Accordingly, the cell temperature decreased by 19.2 °C compared to the standard PV module.

5. *Quantifying the wasted heat towards the enhancement of sustainability contributions*

I have introduced a new thermodynamic mathematical model to calculate the wasted heat to the surroundings by the PV module to assess the contribution of the created bi-fluid PV/T toward sustainability through exergy analysis and sustainability index.

Based on the experimental results coupled with the thermodynamic model, I enhanced the sustainability contribution of the new PV/T. The amount of wasted heat released by the new bi-fluid PV/T module was lower by approximately 77.6% compared to the amount of wasted heat released by the PV module used as a reference. The sustainability index is the most crucial evaluation parameter focused on by scientific research to evaluate energy systems, as it is directly proportional to the conversion efficiency of the system. The sustainability index has been improved using PV/T modification, achieving 1.15–1.6 and 1.03–1.06 for the bi-fluid PV/T and the PV module, respectively. Thus, the examined design of hybrid solar collector systems has an efficient sustainability contribution and has the potential to support sustainable buildings towards net-zero energy buildings.

6. *Effect of ternary nanofluid as a heat transfer fluid*

I have developed a novel instrument that provides a new fluid characteristic by measuring the time required to reach a thermal equilibrium state to select the efficient fluid, where the lowest time means the highest thermal conductivity. I have examined and justified using ternary and nanofluids containing MWCNTs, MgO, and BN as heat transfer fluid.

Based on the experimental results of the proposed technique, a fluid that reaches thermal equilibrium quickly absorbs heat faster, indicating higher thermal conductivity. Accordingly, the appropriate nanofluid was ternary nanofluid MWCNTs-MgO-BN with a volume concentration of 0.5%, utilised in the bi-fluid PV/T model.

I improved the performance of the PV/T module. The nano-based PV/T module exhibits a 30.8% thermal efficiency higher than the water-based PV/T module. The average daily electrical efficiencies for the two modules experienced a rise of 41.7% and 20.2%, respectively, compared to the PV module. Employing a nanofluid leads to a more significant reduction in the surface temperature of the modules. Thus, the use of nanofluid results in superior electrical efficiency. The tested nanofluid can, therefore, be effectively used in thermal solar energy systems, including solar collectors and PV/T modules.

7. Effect of the reflective surface on the PTSC performance

Based on experimental results, I have identified a new proposed correlation for MWCNTs–MgO–BN ternary nanofluids (with 0.25% GA surfactant) thermal conductivity enhancement ratios. This correlation is valid for volume concentrations ranging from 0.05% to 0.5% and temperatures ranging from 25 °C to 55 °C.

$$kR = \frac{k_{tn}}{k_{bf}} = 0.9159 + 0.95 \times \left[\frac{(\phi)^{0.332}}{(T)^{0.297}}\right].$$

According to experimental results, I have found that the thermal conductivity of 0.5% MWCNTs–MgO–BN was evaluated at 25 °C and was 20.8% higher than the thermal conductivity of the base fluid.

5. CONCLUSION AND SUGGESTIONS

An experimental analysis was conducted to evaluate the performance of photovoltaic thermal modules (PV/T) through dynamic modelling, novel creation, a combination of the two heat transfer fluids (water and air), the effect of the solar cells' temperature, sustainability contribution and the effect of the nanofluid as high thermal conductivity heat transfer fluid under climate conditions of Gödöllő city.

Firstly, a new element for a PV/T module was built, evaluated, and simulated in TRNSYS tool to predicted performance. The main conclusion behind the points above is that the most efficient PV/T system in electrical conversion was the PV/T system with a PID controller. A novel configuration of fins was employed within the copper absorber to assess the air-cooled PV/T module performance of so-called louvered fins. The new fins were evaluated by comparison with the vertical fin absorber and unfinned absorber. The enhancement result showed that the thermal efficiency of the louvered fin unit increased by 48% and 54% compared to the vertical fin and unfinned units, respectively.

Besides, a novel design of the louvered fins and the serpentine tube was mounted directly to the copper absorber to configure a bi-fluid photovoltaic thermal module (LFS-PV/T) to enhance the performance. The thermal and electrical efficiency of the three examined systems were 19.4 and 6.1% for the AC-PV/T system, 89.1 and 7.7% for the LFS-PV/T system, and 45.1 and 6.9% for the ALF-PV/T system, respectively. Based on the thermodynamic model conducted in this research, the created LFS-PV/T module makes an efficient contribution to sustainability and has the potential to support sustainable buildings towards NZEBs.

Based on the results achieved by the new fluid thermal equilibrium time instrument, it was proven that the ternary MWCNTs-MgO-BN nanofluid was efficient. Utilising this nanofluid in the LFS-PV/T presents a dramatic performance improvement. The PV/T module exhibits a 30.8% higher thermal efficiency than the LFS-PV/T module that uses water. The average daily electrical efficiency experienced a rise of 20.2% compared to the water-based module. Employing a nanofluid leads to a more significant reduction in the surface temperature of the modules. Thus, the use of nanofluid results in superior electrical efficiency.

However, the work is still open to enhance the efficiency of the PV/T system. In addition to the simulation improvements, the work still has the potential for many studies that could consider the flow rate control related to the temperature of the solar cell based on the demand for what power is needed from the PV/T module; it requires a complicated mechatronics control system.

6. SUMMARY

EFFICIENCY IMPROVEMENT OF THE HYBRID SOLAR COLLECTOR SYSTEMS

Comprehensive and detailed experimentation was conducted to analyse the thermal and electrical performance improvements of photovoltaic thermal modules. The first assessments were conducted on a conventional PV/T module installed at a solar lab of the MATE university through the TRNSYS tool, and the second experiments were conducted on a novel created PV/T module by utilising a conventional PV module available in the Solar Lab of MATE University. The creation assessments experimentally verified and evaluated a novel design of the bilateral module of a PV/T module that utilises water and air as coolants. The novel bi-fluid photovoltaic thermal module LFS-PV/T utilises copper louvered fins and serpentine tubes soldered to the copper absorber within the LFS-PV/T module. Several configurations were created to be compared with the new module to evaluate the performance improvements accordingly. A thermodynamic model was developed to assess the sustainability contribution of the new module.

Apart from the reconfiguration, another performance enhancement factor in the field of solar systems is the heat transfer fluid, and the most common and recently used in solar systems are nanofluids., which are used as heat transfer fluid. This research investigated the potentiality of the ternary nanofluids containing MWCNTs-MgO- BN to improve the efficiency of the created PV/T module. The selection and evaluation of the nanofluids were obtained based on the new FTET instrument created in this research.

Based on the experimentation findings, the louvered fins confirmed the effectiveness of the essence behind their shape. The thermal efficiency of the unit with louvered fins was enhanced by 48% and 54% compared to the vertical fins and unfinned units.

The path changing of an airflow caused by the louvered fin shape makes sufficient time for convection heat transfer from the fin's surfaces to the airflow. This process created a more significant difference in temperature between the inlet and the outlet, thus enhancing the thermal performance. The electrical efficiency of the examined LFS-PV/T module was improved by 27.6% compared to the PV module, and the thermal efficiency was improved by 94% compared to the classical air-cooled PV/T.

Investigating ternary MWCNTs-MgO-BN nanofluid enhances the thermal and electrical performances of the LFS-PV/T module. The nano-based modules produce more electricity than the water-based LFS-PV/T module by 23%. These findings indicate that the nano-based module, which shows the highest thermal power enhancement, also exhibits the highest electrical power enhancement.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Alshibil A.M.A.,** Víg P., Farkas I. (2021): Performance evaluation of a hybrid solar collector in two different climates, European Journal of Energy Research, 1(2), pp. 17-20. https://doi:10.24018/ejenergy.2021.1.2.11
2. **Alshibil A.M.A.,** Víg P., Farkas I. (2022): Multi-aspect approach of electrical and thermal performance evaluation for hybrid photovoltaic/thermal solar collector using TRNSYS tool, International Journal of Thermofluids, 16, pp. 100222. https://doi.org/10.1016/j.ijft.2022.100222 (Scopus: D1)
3. **Alshibil A.M.A.,** Víg P., Farkas I. (2023): Thermodynamical analysis and evaluation of louver-fins based hybrid bi-fluid photovoltaic/thermal collector systems, Renewable Energy, 206 (April 2023), pp. 1120-1131. https://doi.org/10.1016/j.renene.2023.02.105 (Scopus: D1, IF = 8.7)
4. **Alshibil A.M.A.,** Víg P., Farkas I. (2023): Sustainability contributions of hybrid solar collector toward net-zero energy buildings concerning solar cells wasted heat, Energy for Sustainable Development, 74 (June 2023), pp. 185-195. https://doi.org/10.1016/j.esd.2023.04.001 (Scopus: D1, IF: =5.5)
5. **Alshibil A.M.A.,** Víg P., Farkas I. (2023): Experimental performance comparison of a novel design of bi-fluid photovoltaic-thermal module using louver fins, Energy Reports, 9 (December 2023), pp. 4518-4531. https://doi.org/10.1016/j.egyr.2023.03.110 (Scopus: Q1, IF = 5.2)
6. **Alshibil A.M.A.,** Víg P., Farkas I. (2023): Evaluation of fin configurations for an air-cooled hybrid photovoltaic-thermal solar collector, Thermal Science journal, online first (00), pp. 84. https://doi.org/10.2298/TSCI230116084A (IF = 1.7)
7. **Alshibil A.M.A.,** Víg P., Farkas I. (2024): Thermal equilibrium time as a novel characteristic of nanofluids evaluation: an experimental investigation of a MWCNTs+MgO+BN/distilled-water ternary nanofluid, Journal of Molecular Liquids, x(x), pp. x-x. https://doi.org/xxxxxx (Scopus: D1, IF = 6) (under review)
8. **Alshibil A.M.A.,** Víg P., Farkas I. (2024): Performance enhancement attempts on the photovoltaic/thermal module and the sustainability achievements: a review, Energy, x(x), pp. x-x. https://doi.org/xxxxxxxxxxxx (Scopus: D1, IF = 9) (under review)

International conference proceedings:

9. **Alshibil A.M.A.,** Víg P., Farkas I. (2021): Heat transfer behaviour of hybrid solar collector module for liquid-based type, Proceedings of I4SDG Workshop 2021, in Mechanisms and Machine Science, Springer, pp. 20-29. https://doi.org/10.1007/978-3-030-87383-7_3.
10. **Alshibil A.M.A.,** Víg P., Farkas I. (2021): Seasonal performance evaluation of hybrid solar collectors in a hot climate area, Proceedings of the 3rd Faculty of Industrial Technology International Congress, Bandung, Indonesia, pp. 136-140. ISSN: 2962 – 1798.