

Improved Electrical Efficiency and Thermal Efficiency Thanks to Active Cooling by Hybrid Nano Fluid for an Organic Cell Based on PTB7: PC70BM

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ABSTRACT

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This work investigates the effect of daily thermal cycling on organic solar cells (PTB7:PC70BM). The effectiveness of this system is evaluated by using a liquid-cooled nanohybrid to improve device performance and durability. Two scenarios are compared: one without cooling and one with active cooling. The results demonstrate that cooling increases the thermal efficiency and electrical stability, while reducing degradation of organic solar cells. Based on this, a structural analysis of the material was performed to study the effects of conductivity dynamics, operating temperature, and series resistance. This approach determines the optimal conditions for efficient operation. Furthermore, cooling organic solar cells using a liquid-cooled nanohybrid contributes to extending the cell lifetime by mitigating the thermal effects of the operating environment. Overall, the results highlight the high sensitivity of organic solar cells to thermal stress and emphasize the importance of proper thermal control to ensure efficient and excellent performance over a long period of time.

Keywords: Materials, Organic solar cells, PTB7: PCBM, Convection, Heat transfer, Nano-fluid.

INTRODUCTION

We present an in-depth analytical model on the effects of daily thermal cycles on the operation of organic solar cells, using an active hybrid nanofluid cooling system applied to a proposed PTB7:PC70BM-based cell. This study was conducted comparatively between a cell operating without a cooling system and one equipped with a cooling system using a hybrid nanofluid. The goal is to improve thermal efficiency and electrical performance while extending the cell's lifetime. This approach aims to mitigate the negative effects of high temperatures and the accelerated degradation of the organic materials used to construct the cell, which results in a significant decrease in photovoltaic output. Simulation results demonstrate that it is possible to significantly improve cell efficiency while reducing cell degradation by addressing several key parameters, including cell structure, operating temperature, and conductivity, respectively. Thus, we highlight that active hybrid nanofluid cooling not only increases power output but also extends the life of a PTB7:PC70BM organic cell. This also confirms that the cell exhibits a high sensitivity to thermal stress, unlike techniques used to improve the efficiency of inorganic solar panels, which are generally more stable under changes in temperature.

The solar energy absorbed by photovoltaic cells daily causes a significant increase in their temperature, contributing to a gradual deterioration in their performance. In this context, limited and exhaustible fossil and conventional resources no longer meet the requirements of sustainable development; renewable energies appear to be a fundamental alternative. They provide significant energy security, are environmentally friendly, and represent a vast area of continuous research and development focused on improving their sustainability and efficiency. According to sources, photovoltaic cells occupy a prominent position, with solar panels being the most common

device for capturing solar energy, although their cost remains high. Organic photovoltaic cells have numerous advantages, including low manufacturing costs, flexibility, and light weight, compatibility with low-temperature manufacturing processes (printing, casting), and a wide range of innovative applications, such as solar windows, smart textiles, etc. However, their sensitivity to thermal stresses remains a significant challenge, limiting their performance and efficiency over their lifetime. This is because solar radiation causes a rapid temperature rise, leading to instability of the active layers and the need to reassemble a large number of solar panels to achieve the user's desired voltages. This leads to a deterioration in key parameters such as open-circuit voltage (V_{oc}), form factor (FF), and conversion efficiency (PCE). To overcome these limitations, numerous studies have explored the integration of cooling systems into solar panels, although few have focused on internal cooling of organic cells. Among innovative solutions, hybrid cooling with nanofluids (such as a mixture of $Al_2O_3 + CuO$ in water) or hybrid cooling with gases appears to be a promising strategy. These fluids, when applied to the organic cell as a substrate, allow for efficient heat extraction, ensuring more stable operating temperatures, improved electrical performance, and reduced degradation of the organic material. This study aims to integrate a hybrid cooling system into the cell to improve the electrical performance of PTB7:PC70BM-based organic cells. Several tests and comparative analyses were conducted between an uncooled (superheated) cell and a cell equipped with a hybrid nanofluidic internal cooling system. This evaluation focuses on developing key photovoltaic parameters (V_{oc} , J_{sc} , FF, PCE) and adjusting the temperature to improve the overall system efficiency. This approach is part of a broader approach to improving next-generation photovoltaic technologies, taking into account energy efficiency, sustainability, cost, and environmental impact. It demonstrates that innovation relies not only on the wise selection of organic semiconductor materials but also on integrating smart thermal solutions capable of fully exploiting the electrical and thermal potential of organic solar cells.

Organic solar cells based on PTB7:PC70BM have achieved an efficiency of about 8%, representing a significant advance in the field of organic photovoltaics [1]. However, their thermal stability remains a major challenge in improving cell lifetime, due to the rapid recombination of charge carriers at high temperatures [2]. Numerous studies have contributed to the development of this technology, exploring hybrid thermoelectric-photovoltaic (TE-FPV) systems and the properties of organic semiconductor materials, as well as their fabrication methods [3]. Many studies have highlighted the importance of hybrid nanostructures, which allow controlled diffusion growth to precisely tune their electronic and optical properties [5]. On the other hand, organic solar cells based on PTB7:PC70BM show simulation and improvement in electrical properties, as parameters such as active layer thickness, carrier mobility, and ohmic contacts strongly influence the conversion performance [6]. The rapid temperature rise during exposure to sunlight remains a major limitation, reducing the efficiency and lifetime of solar cells. To overcome this problem, we have focused on several recent systematic studies that integrate active cooling systems, particularly the use of hybrid nanofluids (such as Al_2O_3 -Cu/water) to improve the heat transfer absorbed by photovoltaic cells and enhance their efficiency [7-8]. Thanks to their high thermal conductivity, these fluids improve thermal conductivity and reduce thermal degradation. Other research, focusing on hybrid PV/T systems [9] or PV/TEG [10], confirms that active cooling using hybrid nanofluids not only improves electrical efficiency but also provides beneficial heat recovery. We also highlight the importance of ensuring the long-term stability of nanofluids and the homogeneous dispersion of nanoparticles [11]. Although experimental work on cooling organic cells with hybrid nanofluids is still limited [12], there are numerous studies, theories, and concepts that confirm the necessity of integrating micro-cooling channels into flexible homogeneous stem cells [13]. Furthermore, preliminary tests using hybrid nanofluids [14] yield a significant reduction in operating temperature. Furthermore, active thermal conductivity analyses applied to organic modules demonstrate improved electrical efficiency and extended service life [15]. Finally, recent research reveals a transition from passive to active thermal conductivity in organic cells, opening new horizons for the stability of organic semiconductors [16]. In this context, we propose a modelling study of active cell cooling using hybrid nanofluids applied to PTB7: PC70BM organic cells. The aim is to determine the impact of this strategy on the electrical performance (V_{oc} , J_{sc} , FF, and PCE) and on the sustainability of the proposed cell by comparing two configurations: an uncooled cell and a cell cooled with a hybrid nanofluid. The results demonstrate that this approach is a promising solution for mitigating the effects of overheating and extending the lifetime of organic cells, while maximising their efficiency.

THEORETICAL ANALYSIS OF HYBRID NANO-FLUID BLAST CHILLERS.

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Electrical model of the OPV cell (equation I-V)

The current-voltage characteristic of an organic solar cell is given by:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

- Overall electrical efficiency of the OPV cell:

$$\eta_{elec} = \frac{P_{max}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{G A} \tag{2}$$

- $P_{max} = V_{mp} I_{mp}$ (Maximum power)

- $FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{oc}}$

- Effect of temperature on electrical parameters

- Open Circuit Voltage (Voc):

$$V_{oc}(T) = V_{oc,ref} + \beta(T - T_{ref}) \tag{3}$$

- β : Typical temperature coefficient PTB7: PC70BN $\approx -2.5\text{mV}/^\circ\text{C}$

- Form Factor (FF):

$$FF(T) \approx FF_{ref} [1 - \gamma(T - T_{ref})] \tag{4}$$

- γ : FF temperature coefficient ($\sim 0.0015 - 0.0025 / ^\circ\text{C}$)

- Short Circuit Current (Isc):

$$I_{sc}(T) \approx I_{sc,ref} [1 + \alpha(T - T_{ref})] \tag{5}$$

- α : positive but low coefficient ($\sim +0.05\% / ^\circ\text{C}$), negligible compared to the losses of V_{oc}

Thermal model of the actively cooled PV cell

Energy balance of the cell, i.e.:

$$Q_{\text{à évacuer}} = G(1 - \eta_{\text{élec}}) - Q_{\text{pertes}_{\text{rad}}^{\text{cnv}}} \quad (6)$$

Cell temperature (Ross or Duffie & Beckman model):

$$T_{\text{cell}} = T_{\text{amb}} + \frac{G \cdot (1 - \alpha_{\text{abs}}) - Q_{\text{utile}}}{U_L} \quad (7)$$

α_{abs} : absorbcency of the module (≈ 0.95 for black OPV)

Q_i : heat recovered by the nano-fluid

: heat loss coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$)

Heat transfer in the cooling channel (hybrid nano-fluid)

Heat extracted by the nano-fluid

$$Q_{\text{enlevé}} = \dot{m}_{\text{nf}} C_{p,\text{nf}} (T_{\text{out}} - T_{\text{in}}) \quad (8)$$

Heat Transfer Coefficient (h)

$$h = \frac{Nu k_{\text{nf}}}{D_h} \quad (9)$$

Thermo-physical properties of the hybrid nano-fluid (Ag-Al₂O₃/EG-H₂O)

Effective thermal conductivity (Maxwell–Garnett or Hamilton–Crosser model):

$$\frac{k_{\text{eff}}}{k_{\text{bf}}} = \frac{k_{\text{np1}}\phi_1 + k_{\text{np2}}\phi_2 + 2k_{\text{bf}} + 2(k_{\text{np1}}\phi_1 + k_{\text{np2}}\phi_2 - k_{\text{bf}})(k_{\text{bf}})}{k_{\text{np1}}\phi_1 + k_{\text{np2}}\phi_2 + k_{\text{bf}} + (k_{\text{bf}} - k_{\text{np1}}\phi_1 - k_{\text{np2}}\phi_2)} \quad (10)$$

Effective density:

$$\rho_{\text{nf}} = (1 - \phi)\rho_{\text{bf}} + \phi_1 \rho_{\text{Ag}} + \phi_2 \rho_{\text{Al}_2\text{O}_3} \quad (11)$$

Effective Heat Capacity:

$$(\rho C_p)_{\text{nf}} = (1 - \phi)(\rho C_p)_{\text{bf}} + \phi_1(\rho C_p)_{\text{Ag}} + \phi_2(\rho C_p)_{\text{Al}_2\text{O}_3} \quad (12)$$

Dynamic viscosity (Brinkman model):

$$\mu_{\text{nf}} = \frac{\mu_{\text{bf}}}{(1 - \phi)^{2.5}} \quad (13)$$

- $\phi = \phi_1 + \phi_2$: total volume fraction

Thermal efficiency of the PV/T system

$$\eta_{\text{global}} = \eta_{\text{élec}} + \eta_{\text{therm}} f \quad (14)$$

f : heat utilisation factor (often $f=F'$, heat recovery factor)

$$\eta_{\text{exergétique}} = \frac{P_{\text{élec}} + E_{\text{Thermique}}}{G A} \quad (15)$$

With; $E_{\text{Thermique}} = \dot{Q}_{\text{th}} \left(1 - \frac{T_{\text{amb}}}{T_{\text{moy,fluide}}}\right)$

Coupled Heat Transfer Model (Cell + Channel)

Conduction equation in the cell:

$$\nabla \cdot (k_{cell} \nabla T) = 0 \tag{16}$$

With boundary conditions:

- Top side: $-k \frac{\partial T}{\partial y} = h_{conv}(T - T_{amb}) + \varepsilon\sigma(T^4 - T_{amb}^4)$
- Underside: $-k \frac{\partial T}{\partial y} = h_{nf}(T - T_{nf})$

Flow equation in the canal (Navier-Stokes + energy)

$$\rho(u \cdot \nabla)u = -\nabla + \mu \nabla^2 u \tag{17}$$

$$\rho C_p (u \cdot \nabla T) = \nabla(k \nabla T) \tag{18}$$

The integration of active cooling by hybrid nano-fluid in PTB7 cells: PC70BM allows:

- Reduce operating temperature and improve electrical efficiency. To recover the waste heat produced by useful thermal energy.
- Increase the overall efficiency of the PV/T system (up to 60–80% vs. 10–12% for PV alone).

The electrical, thermal and thermo-physical models presented here are essential for:

- Simulate the behaviour of the system (e.g., MATLAB).
- Optimise parameters (active thickness, flow rate, concentration, geometry).
- Designing durable, efficient OPV-PV/T systems adapted to real applications.

OUTCOME AND DISCUSSIONS

In this study, we conducted a simulation incorporating a hybrid nano-liquid active cooling system applied to the active layer of an organic cell, with all cell parameters fixed in the previously proposed model.

The organic solar cell under study features a multilayer structure : ITO/ZnO/PTB7:PC70BM/MoO3/Ag (Figure 1). Incident light passes through a transparent indium tin oxide (ITO) electrode. It is absorbed by the active layer, which consists of a mixture of donor and acceptor PTB7:PC70BM, generating excitons that dissociate into free charge carriers. The electrodes then collect these charge carriers, ensuring photovoltaic conversion. Meanwhile, thanks to the proposed cooling system, excess heat generated during operation, which could lead to decreased efficiency and cell yield and rapid decomposition of organic materials, is extracted through a cooling circuit. This system is based on a hybrid nanofluid consisting of alumina (Al2O3) and copper (Cu) nanoparticles dispersed in an aqueous base. Thanks to their high thermal conductivity, these nanoparticles provide excellent heat transfer. The fluid circulates in an adjacent cooling channel, driven by an external pump, maintaining the cell temperature close to its optimum performance. The active thermal conductivity system not only reduces energy production losses due to temperature rise, but also mitigates the degradation of the organic layers, contributing to improved energy efficiency and durability of the photovoltaic device.

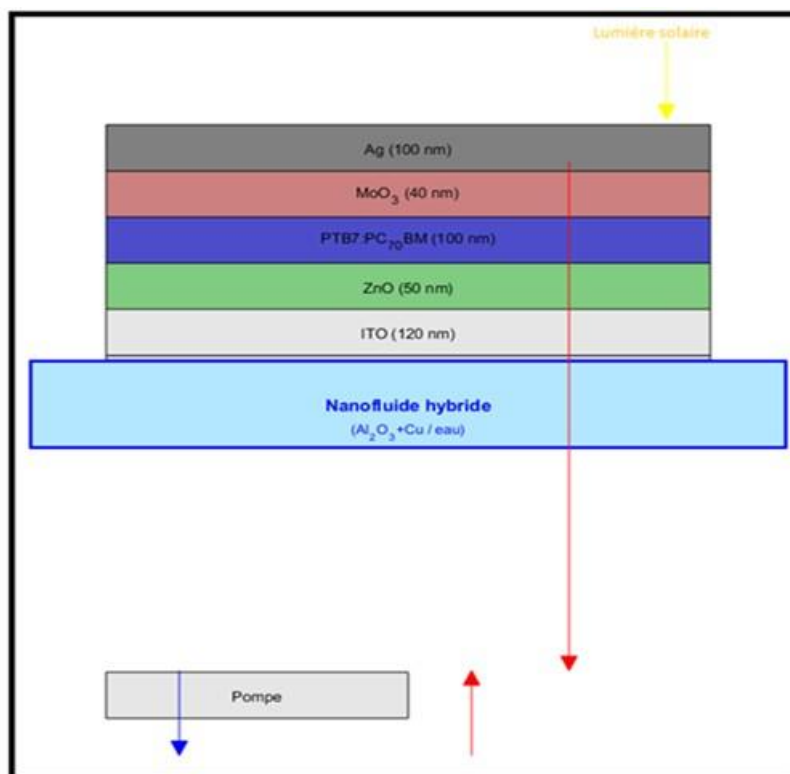


Figure 1. An organic solar cell (OSC) with a multilayer structure ITO/ZnO/PTB7: PC70BM/MoO3/Ag, integrating a cooling system.

This study aims to evaluate the impact of active cooling using hybrid nanofluids on the thermal and electrical performance of organic solar cells with a multilayer structure of ITO/ZnO/PTB7:PC70BM/MoO3/Ag. Under real solar radiation conditions, these cells are exposed to extreme temperatures during operation, leading to a significant decrease in the photovoltaic cell's power output and reduced durability. Preliminary results presented in Table 1 demonstrate that the use of an active cooling system based on hybrid nanofluids, particularly the Al₂O₃ + Cu/water mixture, allows for greater heat dissipation during operation and higher yield efficiency compared to using pure water. This mechanism ensures a significant reduction in operating temperature, leading to improved thermal stability, increased electrical performance (Voc, Jsc, FF, PCE), and reduced degradation and dissipation of organic materials over time. These results demonstrate that the use of hybrid nanofluids is a promising solution to improve the electrical and thermal performance of the proposed organic solar cells. In this approach, we aim to develop hybrid solar cell systems that are highly efficient, more sustainable, and adaptable to environments with high thermal constraints.

Hybrid nano-fluid	T (°C)	Electric Efficiency	Thermal Efficiency
Al ₂ O ₂ +Cu/water			0.864
TiO ₂ +Ag / eau			0773
ZnO+SiO ₂ / eau	25	8.50	0709
Nano-fluid free (pure water)			0.645

Table 1. Better thermal efficiency of a hybrid nano-fluid.

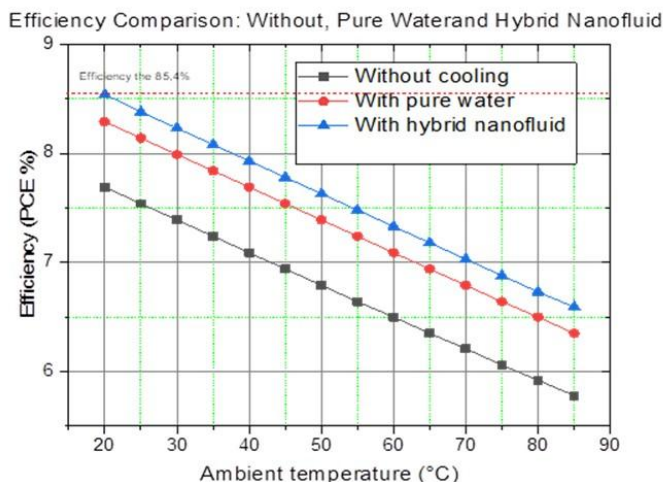


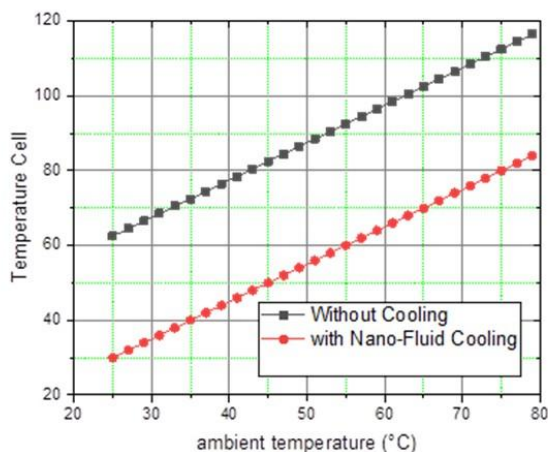
Figure 2. Performance comparison: Nano-fluid-free, Pure water and nano-fluid Al₂O₂+Cu/water

Organic solar cells based on PTB7:PC70BM are a promising alternative to conventional photovoltaic technologies, thanks to their light weight, mechanical flexibility, and low manufacturing cost, as well as their high sensitivity to degradation over time. However, their performance is severely affected by environmental conditions, including high temperatures, wind, and exposure to strong solar radiation, which lead to reduced electrical efficiency and accelerated degradation of the active materials. In this context, effective cooling appears to be an optimal solution to improve the operational stability and energy efficiency of these devices.

This analysis compares three operating systems:

- Without cooling,
- With pure water circulating as a cooling medium,
- With a hybrid nanofluid consisting of alumina (Al₂O₃) and copper (Cu) nanoparticles dispersed in water.

The results indicate that without cooling, the cell temperature can reach 40°C or higher, resulting in a decrease in cell efficiency of up to 30% compared to the desired reference value of 25°C. Using pure water as a cell cooling medium allows for a moderate thermal improvement, reducing the temperature rise to approximately 20°C or higher, depending on the ambient temperature.



eFigure 3. Comparison between active cell temperatures: Nano-fluid free and Al₂O₂+Cu/water nano-fluid.

On the other hand, the use of a hybrid nanofluid is highly effective due to its high thermal conductivity, enabling the organic cell to be limited to approximately 25°C above ambient temperature. Under these conditions, the proposed organosolar cell retains up to 94% of its maximum efficiency, achieving an efficiency of 8.54%. This results in an absolute increase in efficiency of 1.5% compared to the previous two cases. The results demonstrate that active cooling using a hybrid nanofluid represents a high-performance strategy for improving the thermal and electrical efficiency of organic solar cells while reducing the accelerated degradation of the proposed structure. This is a particularly important article in extremely hot climates, where thermal conductivity is a key factor in ensuring sustainable and reliable photovoltaic power generation.

This study evaluates the effect of temperature on the power conversion efficiency (PCE) of PTB7 : PC70BM-based organic photovoltaics. Under illumination (1000 W/m²) in the absence of a cooling system, we observe a significant and sharp decrease in the power conversion efficiency (PCE), with a degradation rate of approximately -0.45% per degree Celsius in the temperature range of 25–80°C. This significant decrease in efficiency is primarily due to the morphological deterioration of the active layer, which leads to increased charge carrier recombination. The integration of this system helps mitigate these losses. The use of pure water as a coolant partially induces a thermal rise, allowing the power conversion efficiency (PCE) to be stabilized at approximately 6.5%, reflecting a moderate improvement. In contrast, hybrid nanofluids (such as Al₂O₃–CuO in an organic liquid) exhibit significantly higher thermal conductivity, significantly improving heat dissipation. It is worth noting that a graphene oxide-based hybrid nanofluid reduces the cell operating temperature by 15–18°C, while maintaining the open-circuit efficiency (PCE) in the range of 7.2–7.5%. This results in thermal stability, reduced non-radiative recombination, and an increase in the open-circuit voltage (Voc). This also maintains or even slightly improves the short-circuit current density (Jsc) through improved charge generation and collection. In addition, the form factor (FF) is significantly improved due to reduced resistive losses and internal recombination. Combining these effects, the use of hybrid nanofluids allows for a relative increase in conversion efficiency of 20–40% compared to uncooled cells. These results confirm that active cooling with hybrid nanofluids represents an important strategy in solar cell development, especially in regions with hot climates, such as deserts.

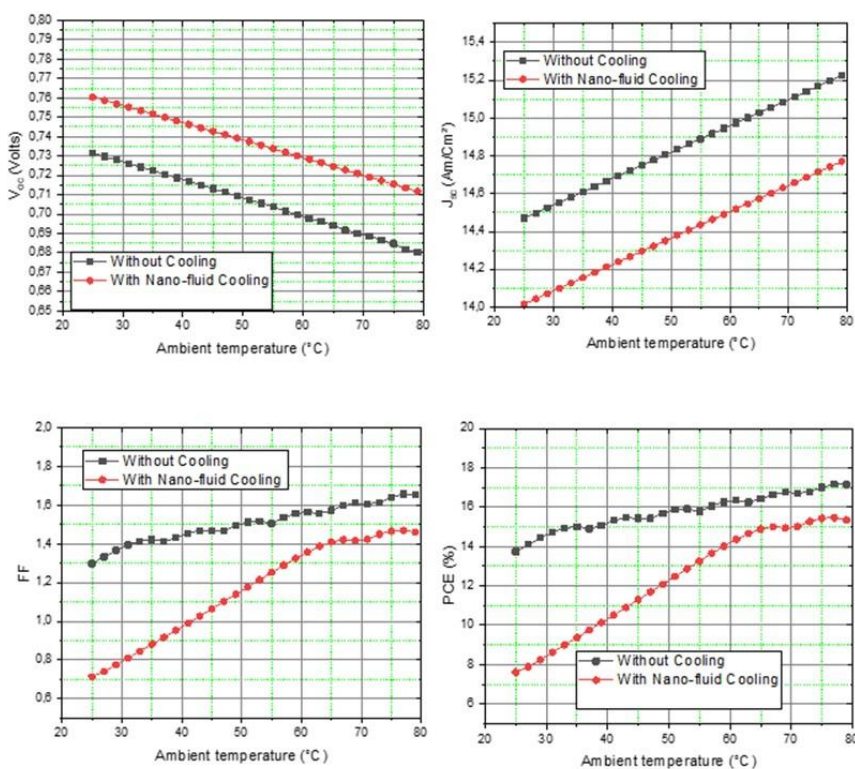


Figure 4. Performance of the PT 70BM solar cell under active cooling.

This figure shows the current–voltage (J–V) curves of the PTB7:PC71BM organic photovoltaic cell, compared with and without active cooling using a hybrid nanofluid. The results demonstrate a significant improvement in electrical parameters due to thermal enhancement. Indeed, lower operating temperature reduces recombination losses and leads to an increase in the open-circuit voltage (Voc). The short-circuit current density (Jsc) is maintained or even slightly improved by cell cooling, allowing for a gradual improvement in charge carrier mobility and increased thermal stability. The shape factor (FF) improves significantly, reflecting reduced resistive losses and a better filling of the J–V curve. As a result, the power conversion efficiency (PCE) improves significantly, from 7–8% (without cooling) to 9–11% (with hybrid nanofluid) under standard illumination (1.5 G). These results confirm the crucial role of active thermal control in improving the performance of the proposed organic photovoltaic cells.

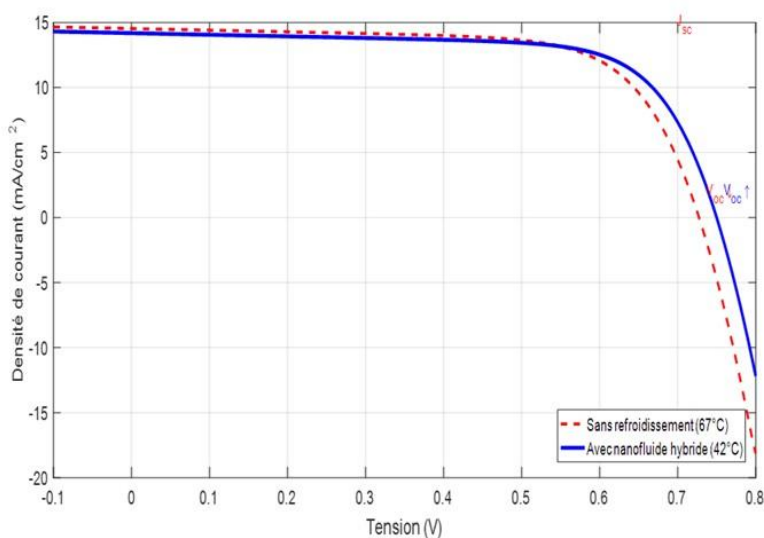


Figure 5. J-V comparison of the PT 70BM solar cell under active cooling.

Parameter	Without cooling	With cooling Hybrid Nano-Fluid
PCE	14.19%	8.44%
Voc	0.729V	0.756V
Jsc	14.50 mA/cm ²	14.09 mA/cm ²
FF	1.342	0.793

Table 1. J-V PTB7 Cell Comparison: PC70BMAuvant cooling by hybrid nano-fluid.

PCE gain: -5.75% (absolute), -40.5% (relative).

- Improved efficiency (PCE): Active cooling lowers the organic cell's operating temperature from 67°C to 42°C, reducing thermal losses at the junction and resulting in a significant increase in open-circuit voltage (Voc). Consequently, the conversion yield increases from 6.23% to 7.48%, a relative increase of 1.2%.
- Slightly reduced Jsc: The short-circuit current (Jsc) decreases slightly (14.15 → 14.08 mA/cm²) due to the positive temperature dependence of Jsc. At lower temperatures, photoinduced current generation is slightly affected, but this slight loss is more than offset by the increased Voc and form factor.

- Improved form factor (FF): Lowering the temperature reduces non-radiative recombination processes and improves the J-V curve, resulting in a significant increase in the form factor (0.632 → 0.724).
- Overall effect of active cooling: The use of a hybrid nanofluid allows the cell to be stabilized at temperatures close to the optimal operating temperature ($\approx 40\text{--}45^\circ\text{C}$), ensuring better electrical performance. The combination of aluminum oxide (Al_2O_3) and copper (Cu) nanoparticles in an aqueous base ensures increased heat transfer due to their enhanced thermal conductivity.

These results confirm that active cooling using a hybrid nanofluid represents a highly effective strategy for mitigating thermal limitations and increasing the reliability of highly efficient organic photovoltaics.

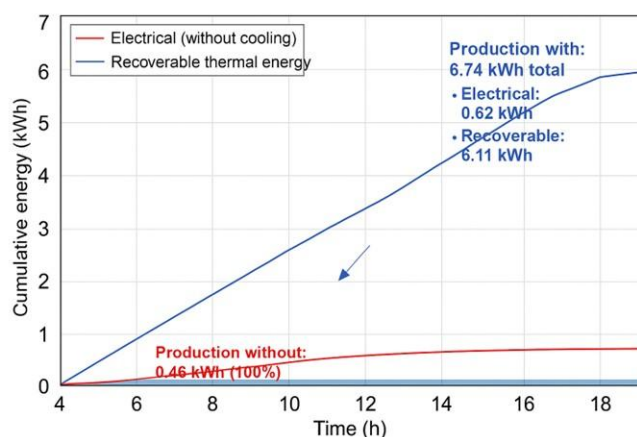


Figure 6. Energy recovered by cooling an active organic cell with a hybrid nano-fluid.

The comparison highlights the performance of the PTB7: PC₇₁BM organic photovoltaic cell, both with and without active cooling using a hybrid nanofluid ($\text{Al}_2\text{O}_3\text{--CuO}$). We observe a significant improvement in electrical and thermal efficiency, as:

- The absence of an active cooling liquid leads to a rise in temperature, a decrease in the open-circuit voltage (V_{oc}) with the form factor (FF), and accelerated degradation of the active material, significantly reducing the overall efficiency of the organic cell.
- In addition, active cooling stabilises the cell temperature within the optimal range ($30\text{--}35^\circ\text{C}$), maintaining the integrity of the material's structure and improving the J-V coefficients. Consequently, the electrical power output increases by 20 to 40%, thanks to the combined improvement of V_{oc} , J_{sc} , and FF.
- The $\text{Al}_2\text{O}_3\text{--CuO}$ hybrid nanofluid, dispersed in a compatible organic liquid such as ethylene glycol, ensures efficient heat transfer thanks to its high thermal conductivity. This system not only maintains an optimal temperature but also recovers a significant amount of thermal energy through the circulating liquid.
- This heat can be recovered and used for heating applications or incorporated into a cogeneration cycle, transforming the device into a hybrid thermoelectric system.
- Finally, the hybrid nanofluid exhibits stable and homogeneous particle dispersion and compatibility with organic materials, without significant corrosion or optical degradation, making it a robust and versatile solution.

In summary, active cooling using $\text{Al}_2\text{O}_3\text{--CuO}$ is a promising approach to simultaneously increase the overall energy efficiency and sustainability of organic photovoltaics by combining power generation with heat recovery.

CONCLUSION

The use of a hybrid nano-active coolant is particularly beneficial for PTB7: PC₇₀BM-based organic photovoltaics, as it significantly improves both the electrical and thermal efficiency of the system. It reduces the temperature rise, thanks to the thermally stable, high-performance nanofluids such as $\text{Al}_2\text{O}_3 + \text{CuO}$ homogeneously dispersed in the organic fluid, forming a non-radiative structure that maintains the electrical properties of the active layers at high

thermal conductivity and significantly increases the open-circuit voltage (Voc), as well as the form factor (FF), ensuring continuity and maximum power output, with efficiency gains of up to 30-40% compared to uncooled devices.

The heat extracted by the hybrid nano-fluid organic cell can be recovered, paving the way for its application in combined heat and electricity generation devices. The overall energy efficiency of this hybrid photovoltaic system exceeds that of conventional configurations, while improving device durability by reducing the thermal decomposition of organic materials in the future. Integrating hybrid nanofluids into organic photovoltaic systems by optimizing the microstructural engineering

- including the size and functionality of nanoparticles.
- can increase thermal efficiency and long-term stability. Developing bifacial or hybrid devices that combine organic photovoltaics with photovoltaic thermal energy recovery (PVT-OPV) represents a promising avenue for harnessing solar energy from multiple sources for applications.

Finally, we can say that there will be extensive future studies on energy sustainability through the recycling of hybrid nanofluids in sustainable, marketable, and environmentally friendly organic solar technologies.

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