# 3D numerical study of a PVT system with hBN/Water nanofluid: influence of mass flow rate on electrical and thermal performance

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**Abstract.** Heat accumulation in photovoltaic-thermal systems (PVT-Ss) cells typically limits their performance by reducing their electrical and thermal efficiency. In response to this issue, this three-dimensional numerical study was conducted using COMSOL software to analyze the performance of a PVT-S using hBN/water nanofluid as a heat transfer fluid. The main objective was to assess the effect of fluid mass flow rate on cell temperature, fluid outlet temperature, and electrical and thermal efficiency. The study was conducted for mass flow rates of 15, 45, 95, 145, and 195 L/h, with an inlet temperature of 26°C and solar irradiance of 1100 W/m². The results show that increasing the flow rate leads to a significant decrease in cell and outlet fluid temperatures, from 58.049°C to 35.939°C and from 55.477°C to 31.164°C, respectively. Due to this thermal improvement, the electrical and thermal efficiency increased by 10.462% and 56.091%, respectively.

## 1 Introduction

The energy development of nations consequently depends on renewable sources more and more, and solar energy plays an essential role in this transition [1]. The rapid growth of PV technology allows for the use of it in urban constructions and isolated installations in the rural areas enabling the generation of clean electrical energy and contributing also to the fight against the greenhouse effect [2]. The PV cells are not indifferent to the temperature [3]. in fact, starting from a temperature lower than 25 °C the electrical efficiency (EE) goes from 0.4 to 0.65% per degree Celsius [4], therefore reducing the total efficiency of the module. The silicon cells convert only 20% of the solar energy into electricity, losing the remainder as heat. The accretion of heat promotes the increase of the entropy of the module, which can lead to anterior aging or even to reduce its life. To overcome this issue, PVT-Ss have been developed [5]. These devices use a cooling mechanism that reduces the temperature of the modules, recovering at the same time the surplus heat for thermal applications, such as heating water or buildings. Therefore, the PVT-S optimizes electricity production while recovering thermal energy, offering an energetic transition of a suitable and efficient solution to exploit solar potential fully.

A series of methods of cooling have been analyzed, among which the means of cooling by water, air, phase change materials (PC), and nanofluids have been mentioned; among

these, the nanofluids are more effective in reducing the temperature of the module and improving its electric and thermal performance. Different types of nanofluids have been studied in the literature; for example, Ali et al. [6] made analyses to determine the performance obtained by a PVT-S working with single and double coil absorbers using $Al_2O_3$–Cu/water nanofluids. The double coil and the particle volume fraction increase improve thermal and electric equipment, giving an overall maximum efficiency of 90.47% and a PEC factor of 1.23. Alqatamin et Su [7] studied an optimized PVT-S combining a perforated V-shaped heat sink and high-conductivity nanofluids (CNT/water and $Al_2O_3$/water). They showed that CNT/water nanofluid significantly improves electrical and thermal efficiencies, reduces PV cell temperatures, and increases the concentration of nanoparticles, further enhancing thermal performance. Satpute et al. [8] studied a PVT-S with spiral flow absorber using water and CuO-water nanofluid. The nanofluid reduced the temperature of the modules, increased its efficiency electrically (9.05%) and thermally (67.40%) and increase EE (overall energy efficiency) (31.22%). Almetwally et al. [9] studied a hybrid PVT-S in which a ZnO-water nanofluid is used as a coolant in conjunction with natural convection. The increase in concentration of the nanoparticles assessed did improve the efficiency electrically (15.56%) and thermally (75.60%) over water cooling, addressing at the same time, adequate stability of the coolant and heat recovery at an optimum level. Radhi et al. [10] studied an inventive PVT-S which contained $Al_2O_3$ nanofluid and a phase change material, attaining an EE of 13.17% and thermal efficiency (TE) of 86.5%, through a marked reduction in the cell temperature, and improved result of 39.24% over the cell performance of other conventional PV means. Almeshaal and Altohamy [11] determined experimentally a PVT/PCM system, employing water, in simultaneous conjunction with a CuO based nanofluid. Its determination was to economically produce satisfactory thermal storage possibilities and satisfactory overall energy efficiency of the device. Increase of the nanofluid contribution produced satisfactory heat transfer means, which resulted in a marked reduction of temperature in the cell and a conspicuous improvement in its overall results. Maximum energy efficiency was reached at 82.1% and an average reduction of the temperature in the cell produced was 8.7%. Also, an increase in energy efficiency of 37.7% was achieved over the uncooled PV methods. Best results were gained with a CuO value of 0.3% and flow-rate (FR) of 1.5 litres/min.

In this work, we present a three-dimensional numerical study for the evaluation of the electrical and thermal performance of a new PVT-S. The three-dimensional model was constructed in the software COMSOL Multiphysics, allowing to solve the equations of conservation of energy, mass, and momentum simultaneously. The system studied uses a water-based nanofluid as heat-transfer fluid, where hexagonal boron nitride (HBN) has been selected due to its excellent thermal properties. This study is mainly aimed at evaluating the effect of this nanofluid for the cooling of PV cells, obtaining more stability in their operating temperature and increasing thermal energy recovery, thereby achieving a better overall energy efficiency of the PVT-S.

## 2 Structure and materials of the PVT system

To satisfy the need for both heat recovery and a better energy efficiency, the PVT-S system is produced by combining the classic components of a standard PV module (see Fig. 1), with an optimized heat exchanger. It consists of solar cells, a glass cover, EVA encapsulation and a Tedlar backsheet, whereas the heat exchanger will ensure heat transfer is efficiently carried out between the heating transfer fluid and the panel surface. This heat exchanger consists of a plate with 62 channels arranged in parallel, ensuring uniform circulation of the hBN/water nanofluid. On either side of the plate are two manifolds, one at the inlet and the other at the outlet of the heat exchanger. The water exits the inlet manifold, is distributed through the

openings of each of the 62 channels, passes through the plate, and reaches the outlet manifold on the opposite side. This configuration ensures uniform distribution of the incoming fluid, ensuring intense heat exchange across the entire active surface of the panel. The geometric dimensions of the system and the parameters used in the numerical model are shown in detail in Tables 1 and 2.

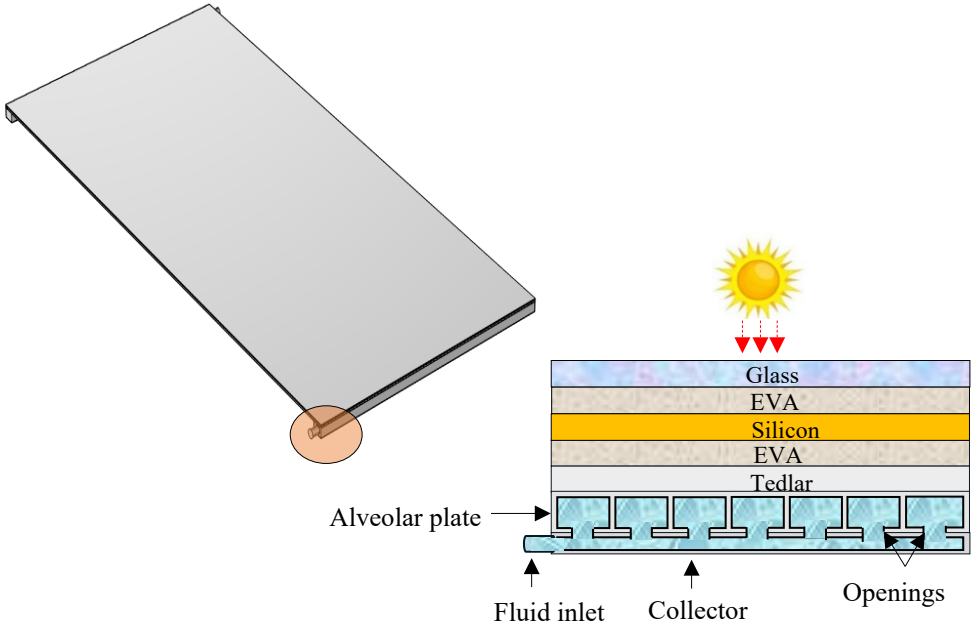


**Fig. 1**. Three-dimensional view of the PVT-S under study.

**Table 1**. Description of materials and their thermal properties [12,13].

| Materials | EVA | Silicon | Glass | Tedlar | Aluminum |
|---|---|---|---|---|---|
| Thickness (mm) | 0.5 | 0.192 | 3 | 0.3 | 0.4 |
| k [W/m.K] | 0.311 | 148 | 1.8 | 0.15 | 237 |
| $C_p$ [J/kg.K] | 2090 | 700 | 500 | 1250 | 900 |
| ρ [Kg/m$^3$] | 950 | 2329 | 2500 | 1200 | 2700 |

**Table 2**. Optical and thermal characteristics considered for modeling [12].

| Description | Value |
|---|---|
| Glass cover emissivity $\varepsilon_g$ | 0.04 |
| Overall heat loss coefficient from PVT surface (Ut) | 150 W/m²·K |
| Temperature coefficient of EE ($\mu_c$) | −0.0045 /°C |
| Cell packing factor ($P_c$) | 0.95 |
| Collector dimensions (L × W) | 1.960 m × 0.960 m |
| Glass cover transmissivity $\tau_g$ | 0.96 |
| Standard ambient/reference temperature $T_r$ (°C) | 25 °C |
| PV module reference efficiency $\eta_c$ (%) | 15 % |
| Heat transfer coefficient from glass to ambient ($U_{ga}$) | 13.96 W/m²·K |
| Solar cell absorptivity $\alpha_c$ | 0.90 |

## 3 Numerical Simulation Methodology

### 3.1 Characteristics of the Working Fluid

In this research, the heat transfer fluid chosen is a hBN/water nanofluid at a concentration of 2%. Thermophysical properties of hBN nanoparticles and water are summarized in Table 3. These data serve as a basis for calculating the effective properties of the nanofluid using equations (1) to (4), which allow its heat capacity, thermal conductivity, density, and viscosity to be estimated [14].

**Table 3**. Thermophysical properties of hBN nanoparticles and water [15,16].

| Materials | Conductivity (W/(m.k)) | Density (kg/m$^3$) | Viscosity (Pa·s) | Specific heat capacity (J/(kg.k) |
|---|---|---|---|---|
| hBN | 400 | 2290 | - | 740 |
| Water | 0.6 | 998,2 | 0.001003 | 4181,8 |

$$C_{Pnf} = \frac{(1-\varphi)\cdot(\rho c_p)_w + \varphi\cdot(\rho c_p)_p}{(1-\varphi)\cdot\rho_w + \varphi\cdot\rho_p} \quad (1)$$

$$\rho_{nf} = (1-\varphi)\cdot\rho_w + \varphi\cdot\rho_p \quad (2)$$

$$\mu_{nf} = \frac{\mu_w}{(1-\varphi)^{2.5}} \quad (3)$$

$$k_{nf} = \left( \frac{k_p - (m-1)\cdot\varphi\cdot(k_w - k_p) + (m-1)\cdot k_w}{k_p + (k_w - k_p)\cdot\varphi + (m-1)\cdot k_w} \right) k_w \quad (4)$$

### 3.2 Governing equations

Heat dissipation in the PVT-S is affected by conduction in the solid parts, as described by equation (5), and by convection-conduction in the flow channels. The fluid, supposed to be incompressible and in laminar flow, is governed by the equations of continuity, energy, and momentum denoted respectively by (6), (7), and (8) [17].

$$\nabla^2 T = 0 \quad (5)$$

$$\nabla . u = 0 \quad (6)$$

$$\rho(u.\nabla)u = -\nabla P + \mu\nabla^2 u \quad (7)$$

$$\rho C_p u.\nabla T = \nabla.(k\nabla T) \quad (8)$$

### 3.3 Boundary conditions

- Received Incoming heat flux: $-k_g \frac{\partial T_g}{\partial z} = G$

- Energy extracted from the system via convection: $-n \cdot q = h_{g-amb}(T_{amb} - T_g)$
- Non-slip condition: $w = 0, u = 0, v = 0$
- Diffuse surface: $-n \cdot q = \varepsilon_g \sigma({T_{amb}}^4 - {T_g}^4)$, where $\sigma$ $\left(= 5,670367 \times 10^{-8}\ \mathrm{Wm^{-2}\ K^{-4}}\right)$ is the Stefan-Boltzmann constant.
- At the solid-fluid interface: $\left(\frac{\partial T_s}{\partial n}\right)_{fluid} = \frac{k_{solid}}{k_{fluid}}\left(\frac{\partial T_s}{\partial n}\right)_{solid}$

✓ Heat exchanger inlet and outlet conditions:

- At the system inlet: $u = U_{in}, v = w = 0, T = T_{in}$
- At the system outlet: $P = 0$

✓ Thermal insulation applied to all other PVT-S surfaces: $\frac{\partial T_s}{\partial n} = 0$

### 3.4 Mathematical formulations

The main equations used to calculate the electrical and thermal performance of the PVT-S system are summarized in Table 4 [12,17,18].

**Table 4.** Mathematical equations used to calculate the performance of the PVT-S.

| Equation | Description |
|---|---|
| $E_{in} = \tau_g \alpha_c p_c G A$ | Energy absorbed by PVT-S |
| $T_c = \frac{P_c.G\left(\tau_g.\alpha_c - \eta_c\right) + \left(U_{ga} T_{amb} + U_t T_{ted}\right)}{\left(U_{ga} + U_t\right)}$ | Solar cell temperature |
| $E_{th} = \dot{m}\, C_f (T_{out} - T_{in})$ | Thermal energy removed by water |
| $\eta_{el} = \eta_c(1 - \mu_c(T_c - T_r))$ | Electrical efficiency |
| $\eta_{th} = \frac{E_{th}}{E_{in}}$ | Thermal efficiency |

### 3.5 Mesh independence study

The complexity of the geometry under study meant that an unstructured mesh was adopted and generated using the physics-controlled meshing sequence. As shown in Fig. 2, the PVT-S's mesh structure combines free tetrahedral elements for the volume and triangular surface elements. Following the mesh independence test, the fine mesh, consisting of 6,982,728 elements, was selected as the most appropriate, ensuring both good accuracy of results and reasonable computation time.

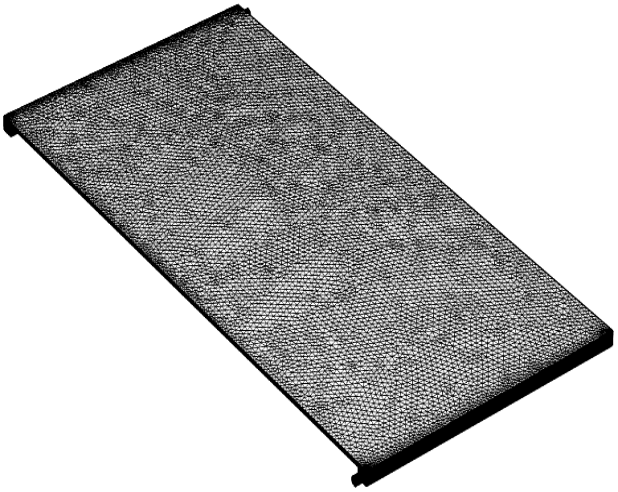

**Fig. 2**. PVT-S mesh illustrating the combination of tetrahedral and triangular elements.

## 4 Results and discussion

This study aims to evaluate the thermal and electrical performance of the PVT-S when cooled by an hBN/water nanofluid. The analysis examined the effect of different mass FRs (15, 45, 95, 145, and 195 L/h) on the system's behavior, considering a fixed inlet temperature of 26°C and solar irradiance of 1100 W/m².

The influence of increasing the mass FR on cell temperature is shown in Fig. 3. Notably, the temperature decreases as the mass FR increases, equating to a 22.11 °C reduction when the FR increases from 15 to 195 L/h. This decrease is due to improved heat transfer as a result of circulating hBN/water nanofluid, which is able to absorb and remove heat more effectively than previously, again contributing to better cooling of the cells. This condition tends to also produce an increase in the system's efficiency.

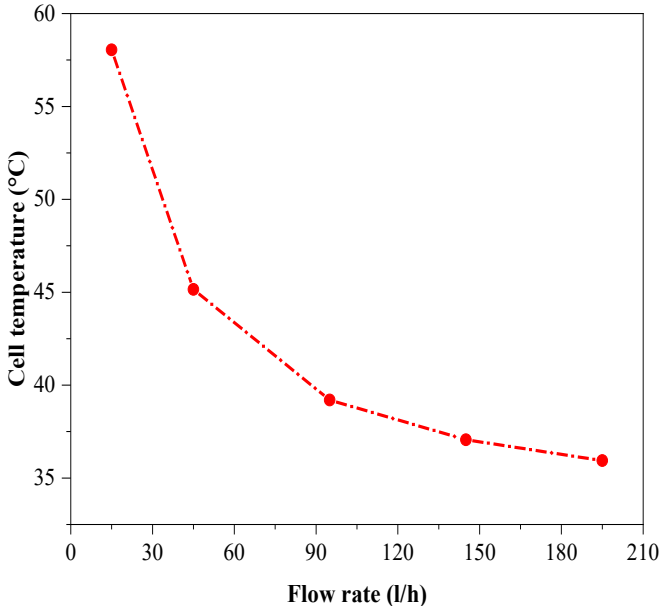

**Fig. 3.** Effect of the mass FR of the hBN/water nanofluid on the temperature of the PVT-S cells.

The reduction of temperature of the PV cells has a key importance in improving the energy efficiency of the system, it can be seen in Figure 4. As the mass FR of the heat transfer fluid increases from 15 to 195 L/h, the energy efficiency of the PVT-S goes up from 12.769% to 14.261%. This progression ensues from the inverse relationship that exists between the temperature of the cell and the output voltage, lower temperatures impart a greater voltage to the cells, which produces a more efficient conversion of solar energy into electrical energy by them. Again, the higher mass FR imparted to the heat transfer fluid produces a better cooling of the cells, which leads to an improved removal of accumulated heat and less thermal losses. This helps to stabilize the temperature of the modules, and to limit the evil prejudices of overheating, leading to a better and more efficient working of the PVT-S system, and resulting in a general increase of the energy efficiency.

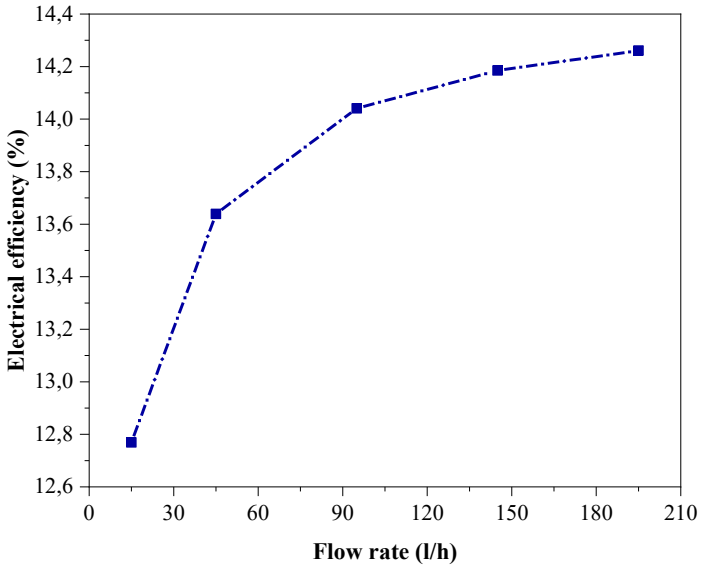


**Fig. 4**. Effect of the mass FR of hBN/water nanofluid on the EE of the PVT-S.

Fig. 5 illustrates the effect of rising mass flow rate (FR) on the fluid temperature at the outlet of the model PVT-S. There is a considerable reduction in temperature (24·31°C) when the FR is raised from 15 to 195 L/h. This decrease in temperature is the result of the fluid's increased ability to absorb and conduct away the heat supplied by the PV cells since an increased mass FR increases the efficiency of the heat exchange process between the cells and nanofluid and prevents excessive heat build-up in the module. Therefore, the system benefits from better thermal stability throughout and this can help contribute towards improved energy performance and life of components in the system.

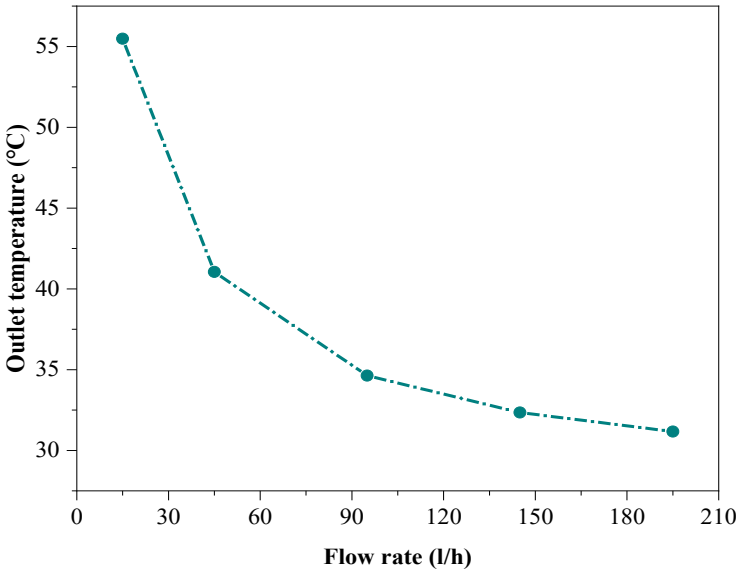


**Fig. 5.** Effect of the mass FR of hBN/water nanofluid on the outlet temperature of the fluid in the PVT-S.

The increase in the mass FR produces a great effect on the systems TE, as can be seen in the figure 6, altering it from 31.918 % to 72.692 % when varying the FR from 15 to 195 L/h. This improvement is due principally to the increase in the capacity of the nanofluid hBN /water to extract the heat of the PV cells and to dissipate it in an efficient way. As the FR increases, this fluid tends to pass through the circuit before, therefore the convection is more effective preventing the accumulation of the heat in the interior of the panel. This behaviour will transform in a reduction of the thermal gradients and in a more homogeneous temperature and smaller cell. With this is obtained that for greater quantity of solar energy it is transformed in useful thermal energy, improving the performance of the PVT-S.

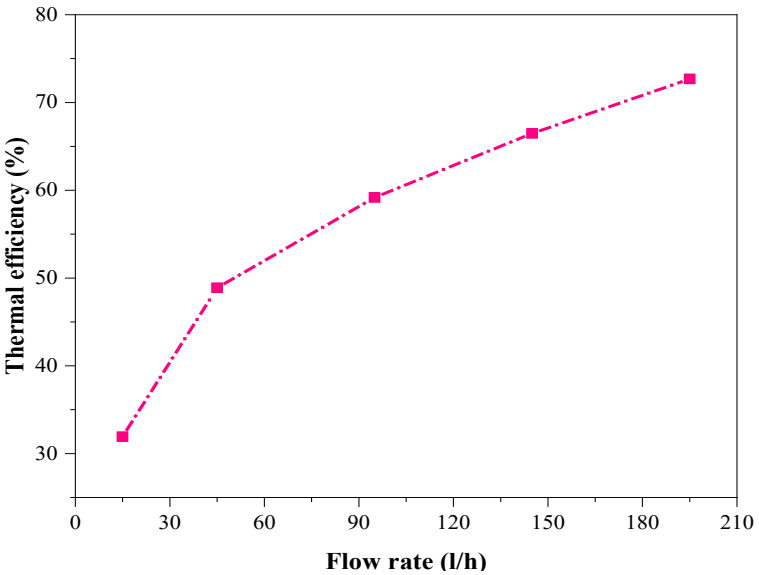


**Fig. 6**. Effect of the mass FR of hBN/water nanofluid on the TE of the PVT-S.

## 5 Conclusion

In this 3D numerical study, carried out using COMSOL software, the performance of a PVT-S using hBN/water nanofluid as a heat transfer fluid was analyzed. The results showed that with increasing FR of the nanofluid, the temperature of the output fluid and that of the PV cells was reduced greatly leading to thermal and electrical efficiency of the system. When for example, the FR was increased from 15 to 195L/h, the PV cell temperature was reduced by 22.11ºC and that of the output fluid was reduced by 24.31ºC, leading to an increase in the EE of the system from 12.769% to 14.261% and TE of the system from 31.918% to 72.692%. These results show that it is very important to increase the FR of the nanofluid as this is a very important variable to enhance the performance of PVT-S and also that the use of hBN/water nanofluids is beneficial to enhance the energy and TE of PVT-S.

Future work is required to improve and further investigate the current system using nanofluids, in various ways. For example, it would be beneficial to characterise and confirm the thermal and electrical behaviour of the PVT-S under realistic conditions, in order to verify the models and computational results produced experimentally. Calculations of the effects of the different kinds of nanofluids, their concentrations and thermophysical properties, on the heat transfer and hence overall performance of the system would be useful.

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