A Hybrid Nanofluid of Alumina and Tungsten Oxide for Performance Enhancement of a Parabolic Trough Collector under the Weather Conditions of Budapest

Otabeh Al-Oran* and Ferenc Lezsovits

Department of Energy Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Muegyetem rkp. 3., 1111 Budapest, Hungary; lezsovits@energia.bme.hu

* Correspondence: aloran@energia.bme.hu

Abstract: Recently, there has been significant interest in the thermal performance of parabolic trough collectors. They are capable of operating and generating highly variable temperature ranges, which can be used in various applications. This paper, therefore, addressed the thermal performance model of using a parabolic trough collector under the radiation intensity level found in Budapest city, as well as the effect of inserting a hybrid nanofluid as the thermal fluid. First, a new modified hybrid nanofluid of alumina and tungsten oxide-based Therminol VP1 is used to enhance the thermal properties of the thermal fluid to be more efficient to use. This enhancement is performed under various volume concentrations and has a volume fraction of 50:50. Second, in order to demonstrate the effectiveness of the thermal element, mathematical energy balance equations were solved and simulated using MATLAB Symbolic Tools. The simulation is presented for two cases: one under a constant radiation intensity and the other under the radiation intensity level of Budapest. For both cases, the results of the dimensionless Nusselt number, heat transfer coefficient, pressure drop, exergy efficiency, and energy efficiency are described. The major findings show that a volume concentration of 4% (Al$_2$O$_3$ and WO$_3$) based Therminol VP1 was the most efficient volume concentrations in both cases. For the first case, the maximum enhancement of the Nusselt number and the heat transfer coefficient are 138% and 169%, respectively. These results enhanced the thermal and exergy efficiencies by 0.39% and 0.385% at a temperature 600 K, flow rate of 150 L/min, and radiation intensity of 1000 W/m$^2$. For the second case, the maximum exergy and energy values are recorded at midday under Budapest’s summer climatic conditions and reach 32.728% and 71.255%, respectively, under the optimum temperature of 500 K and flow rate of 150 L/min. Accordingly, the mean improvement in thermal and exergy efficiencies approximately equal to 0.25% at a high concentration, regardless of the season (summer or winter).

Keywords: solar energy; parabolic trough collector; thermal performance enhancement; radiation intensity; hybrid nanofluid; thermal efficiency; Budapest

1. Introduction

The accelerated increase in the cost of electricity is associated with a deterioration in the level of fossil fuels, which coincides with a rise in demand, in addition to the various environmental problems. These problems represent the primary motive to the search for clean and sustainable energy sources to replace fossil fuels [1]. Different alternative energy sources have been used in recent years (e.g., solar, wind, geothermal, and biomass energies) have had remarkable effects on minimizing pollution and in achieving sustainable development [2]. Many reasons support the use of solar energy as a source of energy more than other renewable sources because of its availability, ease of transportation for energy production, and its ability to be integrated with other applications [3]. Therefore, several kinds of research have been carried out on solar energy aiming to investigate its ability to produce adequate energy from the solar radiation intensity as well as its economic...
effects. In addition, researchers have investigated the effects of solar energy resulting from association with other applications, such as heating [4], cooling and air conditioning [5], and industrial processes [6].

Concentrated solar power (CSP) improves the utilization of solar energy and reaches a high energy output. Such applications include linear Fresnel lenses [7], parabolic trough collectors (PTCs) [8], and solar towers [9]. However, PTCs offer the ability to produce temperatures that have a superior efficiency as well as a limited cost when compared with other CSP applications. On this basis, several studies related to PTCs have aimed to investigate the geometry of the designs, optical efficiency, and methods to improve heat transfer. These studies have been summarized in several review papers [10,11]. In their prestigious reviews, Abed and Afgan [12,13] summarized several techniques that have been utilized in the literature to improve the thermal efficiency of PTCs that, in turn, increase energy productivity at an acceptable cost. Olia et al. [14] presented comprehensive details, on the present situation of using nanofluids in low- to medium-temperature PTC applications. Different methods (passive and active) were investigated experimentally and numerically for the improvement of thermal transfer in the PTC recipient section and their effect under the various conditions have been expounded in various studies [15,16]. Kumar and Reddy [17] numerically demonstrated how to test the improvements in thermal efficiency by using porous disks in PTC tubes using computational fluid dynamics (CFD). Jamal-Abad [18] experimentally tested the use of copper metal foam on the thermal efficiency of the recipient tube of a manufactured PTC.

Recently, enhancements in PTCs have been reached using new modified thermal fluids called nanofluids. Those nanofluids have been obtained by adding nanoparticles, which have small diameters (10 nm–100 nm) to base fluids types to enhance their thermal properties. In fact, this is done to improve the PTC’s thermal efficiency [19]. Interest in using nanofluids as an enhancement category has been indicated by the gradual increase of their use through in researches (either experimentally or numerically) [20]. Thermal enhancement using alternative fluids aims to raise the rate of fluid mixing or heat removal on the absorber tube’s inner surface. Based on this, various evacuated or unevacuated tubes with different shapes have been examined under the impact of utilizing various types of nanofluid. Sarafraz et al. [21] evaluated the performance of an evacuated tube solar collector, using a carbon acetone nanofluid in the heat pipe. The results demonstrated that a thermal efficiency of 91% was achieved, above that of the average thermal efficiency (72.6%) when using acetone alone. Peng et al. [22] numerically compared the thermal performance of a U-shaped evacuated tube resulting from the adding several nanoparticle oxides (CuO, Al₂O₃, and TiO₂) to water. Their results were conducted under volume concentrations of up to 4%, with a constant flow rate of 0.005 kg/s, and a constant temperature equal to 303 K. The results showed an increase in the thermal performance and efficiency of the evacuated tube in the simulations, particularly when using CuO/water nanofluid at a high concentration. Sarafraz and Safaei [23] experimentally assessed the effect of graphene nanoplatelet-based methanol in evacuated tube collectors under various conditions. Their results showed that using 0.1% wt of graphene–methanol nanofluid leads to an improvement in the thermal efficiency of the ETSC system of 95%. Abed et al. [24] numerically compared the performance enhancements of PTC receiver tubes, which was achieved by adding various nanoparticles (TiO₂, Al₂O₃, CuO and Cu) to water under a uniform heat flux boundary. The key result showed that the maximum enhancement reached 21.5% using a TiO₂/water nanofluid at a 6% volume concentration and a Reynold number equal to 70,000. In other research, Abed et al. [25] numerically investigated the impact of realistic heat flux boundary conditions on the PTC receiver tube. In detail, the thermal performance of the PTC for six metallic oxides dispersed in three base fluids as mononanofluids were compared under a wide range of conditions. Regardless of the choice of the base fluid, silicon dioxide is the most efficient nanoparticle tested and the most efficient concentrations. Recently, Abed et al. [26] numerically investigated the effect of utilizing swirl inserts, with and without SiO₂/Therminol VP-1 nanofluid, on the thermal–
hydraulic performance of PTCs. Their results showed that the large swirl inserts with a 6% nanofluid concentration were considered to be the optimal configuration; this can be attributed to the high improvements achieved in terms of the exergy and energy efficiencies of the PTC, which reached 14.47%, and 14.62%, respectively. Applying a nanofluid or base fluid, on the theoretical side, remained to be understood, which was accomplished by analyzing the thermal energy balance equation and heat transfer methods, which have been explained in detail by several researchers (i.e., Duffie and Beckman in their book [27], and Forristall in his research [28]). Forristall solved the energy balance equations for the receiver part of the LS2 model using Engineering Equation Solver (EES) software. In conclusion, the obtained results were compared with the experimental ones of the PTC-type LS2 in various cases [28].

Different kinds of metallic and nonmetallic nanoparticles have been used to improve the thermal properties of different types of base fluids, such as water, ethylene glycol (EG), and oil. Moreover, these nanoparticles and their improvement effects have been examined in various studies, and were conducted experimentally or theoretically. From the theoretical side, enhancement results of using nanofluids in PTC applications were based on solving the energy balance equation of the heating collecting element (HCE) using various software programs [29,30]. Table 1 presents and summarizes the specifications and the results of several theoretical studies that used oil as a base fluid.

| Author Ref. | PTC Model | L,W/m | d_o,d_i | Nanofluids | Max, Increase% |
|-------------|-----------|-------|---------|------------|----------------|
| Allouhi et al. [31] | LS3 PTC | Therminol Vp-1 | TiO_2, CuO, Al_2O_3 | 5% v | -0% | 9% | 83% CuO |
| Khular et al. [32] | (7.84,5) (70,66) | Therminol Vp-1 | Al_2O_3 | 0.05% | -10% | - | - |
| Mwesigye et al. [33] | (5.9) (80,76) | Therminol Vp-1 | SWCNT | 2.5% v | 4.4% | - | 234% |
| Benabderrahmane et al. [34] | (2,-) (32,35) | Therminol Vp-1 | CNT | 1% v | - | - | - |
| Mwesigye et al. [35] | (5.9) (80,76) | Therminol Vp-1 | Cu | 0-6% v | 12.5% | - | 32% |
| Okonkwo et al. [36] | LS2 | Therminol Vp-1 | Fe_2O_3, CuO, Al_2O_3 | 3% v | 0.22% Al_2O_3 | - | - |
| Mwesigye et al. [37] | (5.7-9) (80,76) | Therminol Vp-1 | Ag, Cu, Al_2O_3 | 0-6% v | 13.9% | - | 7.9% |
| Kasaiean et al. [38] | (2,0.7) (28,26) | Thermal-oil | MWCNT | 6% v | 0.5% | - | 15% |
| Bellos and Tzivanidis [39] | LS2 PTC | Syltherm-800 | CuO, Cu, Fe_2O_3, TiO_2, Al_2O_3, SiO_2 | 6% v | 2.2% Cu | - | -24% Cu |
| Basbous et al. [40] | LS2 PTC | Syltherm-800 | CuO, Cu, Ag, Al_2O_3 | 5% v | - | - | 36% Ag |
| Bellos and Tzivanidis [41] | Euro trough ET-150 | Syltherm-800 | CuO, Al_2O_3 | 4% v | 1.26% CuO | - | 40.9% |
| Al-Oran et al. [42] | LS2 PTC | Syltherm-800 | CeO_2, Al_2O_3, CuO, CeO_2 + Al_2O_3, CuO + Al_2O_3 | 4% v | 1.09% CeO_2 + Al_2O_3 | 1.03% CeO_2 + Al_2O_3 | 200.7% CeO_2 + Al_2O_3 |
| Bellos and Tzivanidis [43] | LS2 PTC | Syltherm-800 | TiO_2, Al_2O_3/Hybrid | 3% v | Mono 0.7% Hb 1.8% | - | Mono 56% Hb 204% |
According to Table 1, various nanoparticles were examined using different oil types and showed varying enhancement results. Most of the previous studies used LS2 PTC as a study model due to its relevant experimental results [44]. Using nanofluid as an enhancement method has received great interest in recent years, especially those that use nanoparticle samples from Al2O3 and CuO, despite the effects of metallic nanoparticles and other nanoparticles. Results showed minor thermal efficiency enhancements compared with the convection heat transfer coefficient. A few studies presented the effects of using nanofluids on exergy efficiency [31,42]. The vast majority of studies took radiation intensity as a constant value, while only one study took this value by varying the daytime hours according to the weather conditions of the Moroccan city, Ouarzazate [31]. A modified nanofluid, a “hybrid nanofluid” (HNF), which consists of two or more nanoparticles dispersed in a base fluid, was used in only two studies and showed attractive results compared with mono nanofluids [42,43].

As seen in the previous section, there is limited research concerning the application of hybrid nanofluids on PTC performance in the literature, despite its positive aspects, and the ability of which can be summarized as producing better thermal performances than mononanofluids and achieving reasonable costs by mixing expensive nanomaterials with cheap ones under optimum mixing ratios [42,45]. In addition, there are no works available that focus on using hybrid nanofluids and analyzing the energetic and exergatic changes in a PTC under the climatic conditions of Budapest as a case study. Thus, in this study, the thermal performance of the PTC LS2 model was investigated under two cases; the first one, by applying a constant radiation intensity, and in the second one, under the dynamic radiation intensity of typical sunny and winter days in Budapest. The radiation intensity data of this location were obtained using the Hottel model. The ambient temperatures were obtained from the weather station located on the roof of the Energy Department of Budapest University. In addition, the major effects of inserting HNFs of untested nanoparticles that consist of tungsten and alumina oxide-based Therminol VP1 were obtained under various concentration volumes (0–4%) for a volume fraction equal to 50:50. The improvement effect of tungsten oxide nanoparticles is only mentioned as a mononanofluid for two solar application types; the evacuated tube [46] and the PTC [47].

2. Model Specifications

Parabolic Trough Collector

The PTC comprises mirrors formed in the shape of a parabola, which are useful for transforming and concentrating radiation onto the heat collecting element (HCE), where thermal fluid (TF) flow occurs, as shown in Figure 1. Nowadays, an HCE is designed to be more efficient using different methods, as such it is covered with a glass envelope, coated with a highly absorptive material, and evacuated. All of these methods aim to reduce the heat losses and to enhance heat transfer to the thermal fluid, of which the turning of affects the thermal efficiency of the PTC.

The present study investigated the effects of utilizing a new HNF as the thermal fluid in the receiver part of a type LS2 PTC to enhance its thermal performance. Furthermore, the receiver tube of this model is affected by constant and variable radiation intensity on typical sunny and winter days in Budapest as a case study. Hybrid nanofluids of WO3 and Al2O3-based Therminol VP1 is used under a volume fraction of 50:50 for different concentrations. The main dimensions of the examined LS2 model, from the literature, are presented, as shown in Table 2 [42].

In conclusion, the thermal performance results of the base fluids were compared with the experimental data sheet tests that were used by Dudley to validate the results [44]. At the same time, the operating conditions used throughout this research are summarized in Table 3.
3. Mathematical Model Description

The mathematical model of the energy balance equation was analytically solved using MATLAB symbolic code. Building a steady-state heat energy balance equation described the heat transfer mode for the heating of the thermal fluid, the absorber, and the glass cover up to the surrounding area. The thermal performance of using a PTC was tested for Budapest weather conditions as a case study, where the solar radiation is time-dependent and uniformly distributed around the receiver part. Moreover, the effect of using a modified hybrid nanofluid, which consisted of Al₂O₃ and WO₃ with Therminol VP1, was investigated. As such, the thermal properties of the base fluid varied with the inlet temperature while the thermal properties of the nanoparticles were constant, as presented in the following sections.

Table 2. LS2 parabolic trough dimensions.

| LS2 Parameter [Symbols] | Specifications | Parameter [Symbols] | Specifications |
|-------------------------|----------------|---------------------|----------------|
| Length of the PTC [L]   | 7.8 m          | Emittance of glass cover [ε] | 0.9           |
| Aperture width of the PTC [W_a] | 5 m        | Max optical efficiency [\eta_{opt}] | 74.5%         |
| Aperture area [A_a]     | 39 m²          | Glass cover absorbance [α_c]  | 0.02          |
| Absorber inner diameter [d_a] | 0.066 m      | Glass cover transmittance [τ_c] | 0.95          |
| Absorber outer diameter [d_{ao}] | 0.07 m   | Absorber absorbance [α_s] | 0.96          |
| Glass inner diameter [d_{ci}] | 0.115 m      | Concentrator reflectance [ρ_c] | 0.94          |
| Glass outer diameter [d_{co}] | 0.121 m      | Intercept factor [γ] | 0.93          |
| Emittance of the absorber [ε_c] | 0.2          | Concentration ratio [C] | 22.74         |

Table 3. Constant and variable operating conditions.

| Parameter                | Symbols | Case (1) | Case (2) |
|--------------------------|---------|----------|----------|
| Radiation intensity      | G_b     | 1000 W/m² | Summer 880 | Winter 260 |
| Surrounding convection   | h_{out} | 10 W/m²·K | 10 W/m²·K |
| Ambient temperature      | T_{amb} | 300 K    | Variable with time |
| Inlet temperature        | T_{in}  | 300 K–600 K | 500 K |
| Volume flow rate         | V_{flow} | 150 L/min | 150 L/min |
| Nanoparticle volume fractions | ϕ     | 0–4%     | 0–4%     |
3.1. Radiation Model

In this work, the instantaneous efficiency was examined for a type LS2 PTC under the conditions of typical sunny and winter days in Budapest. First, the geographical location (47°48′ N/19°03′ E) was used to estimate the main angle that defined the radiation intensity. In this study, transmitted beam radiation was obtained using the Hottel model under an altitude of 0.1 km for various types of weather conditions for this location, as expressed in Equation (1). Next, the beam radiation was defined, as expressed in Equation (2) [27]; the ambient temperatures were obtained from the weather station of the Budapest University of Technology and Economics.

\[
\tau_b = a_0 + a_1 \exp \left( \frac{-k}{\cos \theta_z} \right) \tag{1}
\]

\[
G_b = G_{on} \cdot \tau_b \tag{2}
\]

Thus, factors \(a_0, a_1\), and \(k\) were calculated and implemented in MATLAB code depending on the altitude of the location. The corresponding values for these factors are 0.133, 0.763, and 0.125, 0.748, and 0.386, for winter and summer seasons, respectively. \(G_b\) is the beam radiation and \(G_{on}\) is the extraterrestrial radiation (W/m²). In this research, the PTC was assumed to be continuously tracked along the E–W direction. The incident angle specified for this system was based on declination angle \(\delta\) and hour angle \(\omega\) for typical sunny and winter days, as in Equation (3) [48].

\[
\cos(\theta) = \left( 1 - \cos^2 \delta \sin^2 \omega \right)^{1/2} \tag{3}
\]

The incident angle modifier of the LS2 model PTC that was used to describe the radiation intensity effect on the glass cover and absorber was defined as a fourth-order polynomial and is represented by Equation (4) [49].

\[
k_\theta = \cos(\theta) + 0.000884 \theta - 0.00005369 \theta^2 \tag{4}
\]

Accordingly, the optical efficiency can be calculated for each angle by multiplying the incident angle modifier \(k_\theta\) in the maximum optical efficiency \(\eta_{opt,max}\), which is acquired for a zero-incident angle, as shown in Equation (5).

\[
\eta_{opt} = k_\theta \cdot \eta_{opt,max} \tag{5}
\]

3.2. Thermal Model

This section aims to solve the energy balance equation, employing the analytical expression used in literature, by describing the thermal model inside the receiver tube of the PTC at different nodes [42,50]. In this section, heat gain, heat losses, and temperatures are presented to obtain the thermal efficiency enhancements under the radiation intensity conditions of Budapest and the effect of using hybrid nanofluids at various concentrations. The solution was plotted and expressed using MATLAB symbolic code for a dynamic radiation intensity and different concentrations to cover a broad range of conditions.

The assumption of this solution is based on simplifying the heat losses (convection and radiation) from the outlet diameter of the glasses cover in Equation (6) to be as in Equation (7); this is achieved by assuming the cover temperature to be close to ambient temperature, which leads to writing the fourth-order temperature using the Taylor series, as in Equation (8). This assumption has proved to have accurate results, as published in different studies in the literature [42,50]. Moreover, comparing the thermal efficiency and temperature results of the model with the available experimental results showed a minor variation, which supports the use of this assumption in this type of research.

\[
Q_{loss} = A_{co} \cdot \varepsilon_c \cdot \sigma \cdot \left( T_{co}^4 - T_{am}^4 \right) + A_{co} \cdot h_{out} \cdot (T_{co} - T_{am}) \tag{6}
\]
\[ Q_{loss} = \left\{ A_{co} \cdot \varepsilon_c \cdot \sigma \cdot 4 \cdot T_{am}^3 + A_{co} \cdot h_{out} \right\} \cdot (T_{co} - T_{am}) \]  
(7)

\[ T_{co}^4 - T_{am}^4 \simeq 4 \cdot T_{am}^3 \cdot (T_{co} - T_{am}) \]  
(8)

To simplify the definitions of the output results in Equations (9)–(14), various symbols, called \( K \), with values from 1 to 5, are used. Those symbols are based on collecting the known parameters between brackets, as shown in Equation (7) and summarized in Table 4 [42].

| Symbols | Definition |
|---------|------------|
| \( K_1 \) | \( A_{co} \cdot \varepsilon_c \cdot \sigma \cdot 4 \cdot T_{am} + A_{co} \cdot h_{out} \) |
| \( K_2 \) | \( A_{ri} \cdot \varepsilon_r \cdot \sigma \cdot 4 \cdot T_{am} + A_{ri} \cdot h_{out} \) |
| \( K_3 \) | \( \left\{ 1 + \frac{4 \cdot T_{in}^2}{K_1} \right\}^{-1} \) |
| \( K_4 \) | \( \eta_{opt} \cdot \left\{ 1 + \frac{4 \cdot T_{in}^2}{K_3} \right\}^{-1} \) |
| \( K_5 \) | \( K_2 \cdot \left\{ 1 + \frac{4 \cdot T_{in}^2}{K_3} \right\}^{-1} \) |
| \( \varepsilon_r^* \) | \( \left\{ \frac{1}{\varepsilon} + \frac{1 - \varepsilon_c}{\varepsilon_c} \cdot A_{ro} \cdot \varepsilon_r \right\}^{-1} \) |

Thermal efficiency for the PTC can be determined as:

\[ \eta_{th} = K_4 - K_5 \cdot \frac{T_{in}^4 - T_{am}^4}{A_{a} \cdot G_b} \]  
(9)

Thermal losses \( (Q_{loss}) \) are expressed as:

\[ Q_{loss} = (\eta_{opt} - K_4) \cdot Q_s + K_5 \cdot (T_{in}^4 - T_{am}^4) \]  
(10)

Moreover, the equations below express the temperatures of the fluid (outlet and mean), the receiver, and the cover glass.

\[ T_{out} = T_{in} + \frac{K_4}{m \cdot C_p} \cdot Q_s - \frac{K_5}{m \cdot C_p} \cdot (T_{in}^4 - T_{am}^4) \]  
(11)

\[ T_{fm} = T_{in} + \frac{K_4}{2 \cdot m \cdot C_p} \cdot Q_s - \frac{K_5}{2 \cdot m \cdot C_p} \cdot (T_{in}^4 - T_{am}^4) \]  
(12)

\[ T_r = T_{in} + \frac{K_4}{K_3} \cdot Q_s - \frac{K_5}{K_3} \cdot (T_{in}^4 - T_{am}^4) \]  
(13)

\[ T_c = T_{am} + \frac{\eta_{opt} - K_4}{K_1} \cdot Q_s + \frac{K_5}{K_1} \cdot (T_{in}^4 - T_{am}^4) \]  
(14)

Some parameters should be known to determine the thermal behavior of the PTC. The parameters that are expressed in Equations (15)–(18) are the heat transfer coefficient \( (h) \) and various dimensionless numbers, such as Prandtl \( (Pr) \), Reynolds \( (Re) \), and Nusselt \( (Nu) \) [50].

\[ h = \frac{Nu \cdot k}{d_{rl}} \]  
(15)

\[ Pr = \frac{\mu \cdot C_p}{k} \]  
(16)

\[ Re = \frac{4 \cdot m}{\pi \cdot d_{rl} \cdot \mu} \]  
(17)

\[ Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \]  
(18)
The dimensionless Nusselt number of the base fluid was obtained using the Dittus-Boelter in Equation (18) to cover the turbulent regime flow, while Minea’s equation (Equation (19)) was used for the Nusselt number for the HNF [51]. The usage of Equation (19) is based on its ability to evaluate the Nusselt number a variety of aluminum-oxide-containing hybrid nanofluids in a mixture under a turbulent flow regime under a total volume fraction of up to 4%.

\[ Nu = 0.0074 \cdot Re^{0.9} \cdot Pr^{0.67} \cdot \phi^{0.063} \]  

(19)

As seen in the literature, many researchers based their approaches on evaluating the Nussult number of hybrid nanofluids using the experimental model proposed by Minea in Equation (19), as was done by Al-Oran et al. [42], Bellos et al. [43], and Khan et al. [52]. Moreover, in this research, the exergy efficiencies of hybrid and base fluids and their changes were defined based on the following equations. Equation (20) was used to demonstrate the output exergy [53] and Equation (21) represents the Petela formula that was used to measure the obtainable solar exergy [54]. These equations are used to define exergetic efficiency, as shown in Equation (22), where this parameter is intended to determine the ability of the PTC to generate electricity [53].

\[ E_u = Qu - \dot{m} \cdot C_p \cdot T_{am} \cdot \ln \left( \frac{T_{out}}{T_{in}} \right) \]  

(20)

\[ E_s = A_a \cdot C_h \times \left[ 1 - \frac{4}{3} \left( \frac{T_{am}}{T_{sun}} \right) + \frac{1}{3} \left( \frac{T_{am}}{T_{sun}} \right)^4 \right] \]  

(21)

\[ \eta_{ex} = \frac{E_u}{E_s} \]  

(22)

Finally, a pressure drop assessment was also presented to compare the effect of using different hybrid nanofluid concentrations versus the base fluid. Accordingly, the Darcy friction factor obtained using the Blasius equation, and was used to evaluate the pressure drop values with temperatures for all thermal fluids, as explained using Equations (23) and (24), which cover the turbulent flow regimes [55].

\[ f_{r, the} = 0.079 / (Re)^{0.25} \]  

(23)

\[ \Delta P_{the} = f_{r, the} \cdot \frac{L}{d_i} \left( \frac{1}{2} \rho \cdot u^2 \right) \]  

(24)

3.3. Thermal Fluid Specifications

This section is concerned with the equations and the main correlations that are found in the literature to describe the thermal properties of obtained hybrid nanofluids. In detail, the classical models in the following equations were used to describe the thermal properties of hybrid nanofluid flow inside of an absorber tube; this model is based on assuming that the suspension of nanoparticles and fluid can be described as effective material properties [56]. In addition, to simplify all the equations and correlations, different symbols were used to describe the obtained thermal properties. In this research, hybrid nanoparticles of alumina and tungsten oxide, which are described by \( \eta_{p1} \) and \( \eta_{p2} \), were added to Therminol VP1 as a base fluid, described by \( b_f \) to define a modified hybrid nanofluid that is described by \( h_{nf} \). The thermal efficiency was examined under the conditions of the dynamic radiation intensity in Budapest, and the effect of using hybrid nanofluids for different total volume fractions (\( \phi_{tot} \)) varied from 0 to 4%.

The total volume fraction combination obtained by inserting tungsten oxide and alumina oxide is defined by Equation (25) [57].

\[ \phi_{tot} = \phi_{np1} + \phi_{np2} \]  

(25)
Equation (26) expresses the hybrid nanofluid density (kg/m$^3$) [58].

$$\rho_{hnf} = \varphi_{np1} \rho_{np1} + \varphi_{np2} \rho_{np2} + (1 - \varphi_{tot}) \rho_{bf}$$ (26)

A large part of the literature used the specific heat capacity (J/kg·K) formula represented in Equation (27); this is because of its precision for a wide range of volume concentrations [58].

$$C_{p,hnf} = \frac{\varphi_{np1} C_{p, np1} + \varphi_{np2} C_{p, np2} + (1 - \varphi_{tot}) \rho_{bf} C_{p, bf}}{\rho_{hnf}}$$ (27)

The thermal conductivity of the hybrid nanofluid (W/m·K) was obtained using the Bruggeman correlation, as shown in Equation (28); this is because it is valid over an extensive range of volume fractions and temperatures for nanofluids obtained by mixing nanoparticles with oil, as in References [37,59,60].

$$k_{hnf} = 0.25\left[(3\varphi_{tot} - 1)k_p + (2 - 3\varphi_{tot})k_{bf}\right] + \Delta^2$$ (28)

where

$$k_p = \left(\frac{k_{np1} \varphi_{np1} + k_{np2} \varphi_{np2}}{\varphi_{tot}}\right)$$ (29)

$$\Delta = \left[(3\varphi_{tot} - 1)k_p + (2 - 3\varphi_{tot})k_{bf}\right]^2 + 8k_{bf}k_p$$ (30)

Finally, the Brinkman model correlation was used to obtain the nanofluid’s dynamic viscosity, as represented by Equation (31) [61].

$$\mu_{nf} = \mu_{bf} \frac{1}{(1 - \varphi)^{2.5}}$$ (31)

In this study, Therminol VP1 was used as the base fluid due to its ability to work safely at high temperatures without any change in phase; regression analysis of the datasheet for different thermal properties was obtained as polynomial functions with temperatures, as represented by the following equations (Equations (32)–(36)) [62].

$$C_{p, bf} = 4.394 \times 10^{-8} T^4 - 7.7663 \times 10^{-7} T^3 + 0.049862 T^2 - 11.017 T + 2125$$ (32)

$$\rho_{bf} = -2.379 \times 10^{-6} T^3 + 0.002737 T^2 - 1.871 T + 1439$$ (33)

$$k_{bf} = 1.062 \times 10^{-11} T^3 - 1.9367 \times 10^{-7} T^2 + 2.035 \times 10^{-5} T + 0.1464$$ (34)

$$\mu_{bf} = -7.723 \times 10^{-6} T^3 + 8.3409 \times 10^{-3} T^2 - 3.0154 T + 3.661 \times 10^2$$ (35)

For 285.15 K $\leq$ T $\leq$ 373.15 K.

$$\mu_{bf} = 1.6543 \times 10^{-10} T^4 - 3.9844 \times 10^{-7} T^3 + 2.017 \times 10^{-4} T^2 - 0.1476 T + 23.165$$ (36)

For 373.15 K $\leq$ T $\leq$ 698.15 K.

In this research, the examined nanoparticles’ thermal properties were obtained from the literature, as shown in Table 5 [42,46]. Both proposed nanoparticle types in our model had a high purity and a spherical shape with diameter sizes equal to 90 nm and 20 nm for WO$_3$ and Al$_2$O$_3$, respectively. At the same time, the spherical shape supported the usage of the Bruggeman model (Equation (28)) in our approach since it depends on a spherical solid–fluid mixture [26].
### Table 5. Nanoparticle thermal properties [42,46].

| Property/Nanoparticles          | Aluminum Oxide Nanoparticle Al₂O₃ | Tungsten Oxide Nanoparticle WO₃ |
|---------------------------------|-----------------------------------|--------------------------------|
| Specific heat Cp,np/J·kg⁻¹·K⁻¹  | 765                               | 315.4                          |
| Density ρ,np/kg·m⁻³             | 3970                              | 7160                           |
| Thermal conductivity k,np/W·m⁻¹·K⁻¹ | 40                                | 16                             |

### 4. Results and Discussions

#### 4.1. Thermal Model Validation

Validation of the thermal model was performed using Syltherm 800 as a base fluid. The obtained results showed high accuracy compared to the Sandia National Laboratory (SNL) results for the LS2 PTC model, which were determined by Dudley [44]. Different cases under different operating conditions have been selected to validate the deviations in the efficiency and outlet temperature for the base fluid, Syltherm 800. As presented in the following table, the results showed a high accuracy with a maximum deviation of 1.5% and 3.8% for the efficiency and outlet temperature, respectively Table 6.

#### Table 6. Validation model with SNL outlet temperature and efficiency results [44].

| Cases | G_b (W/m²) | T_amb (°C) | T_in (°C) | V_f (L/min) | T_out (°C) | η_eff (%) |
|-------|-------------|------------|-----------|-------------|------------|-----------|
|       | Dudley [21] | Model      | Deviation | Dudley [21] | Model      | Deviation |
| 1     | 933.7       | 124        | 0.29      | 72.51       | 0.29       | 1.51      |
| 2     | 968.2       | 147        | 0.06      | 72.1        | 0.06       | 1.13      |
| 3     | 962.3       | 147        | 0.13      | 71.6        | 0.13       | 0.65      |
| 4     | 909.5       | 147        | 0.38      | 70.4        | 0.38       | 0.48      |
| 5     | 937.9       | 147        | 0.16      | 69.1        | 0.16       | 0.29      |
| 6     | 880.6       | 147        | 0.08      | 68.7        | 0.08       | 0.42      |
| 7     | 920.9       | 147        | 0.11      | 64.8        | 0.11       | 0.42      |
| 8     | 903.2       | 147        | 0.02      | 66.1        | 0.02       | 0.8       |
| Mean  |             | 0.64       |           | 0.78        |            |           |

In addition, the current model was validated by comparing the outlet temperature results of the use of alumina oxide/water nanofluid under a 1% volume concentration with the experimental results determined by Tagle et al. in their study [63]. Figure 2 presents the validation of the present model outlet temperatures with the experimental results; all the results showed high accuracy, with a maximum deviation of less than 0.47% for the outlet temperature.

#### 4.2. Thermal Performance Results and Discussions

Through this research, an appropriate flow rate was determined for several cases, based on the relationship of efficiency versus different flow rates for different inlet temperatures. When the beam radiation intensity was taken to be 1000 W/m², and the ambient temperature was 300 K (as described in Figure 3), the results showed a decrease in the thermal efficiency with the inlet temperature increase. The flow rate after 150 L/min did not deliver a significant change in efficiency, as such there was no need to further increase the flow rate because as it required more input pumping power. Therefore, in this study, the thermal performance of the PTC was simulated under a constant flow rate equal to 150 L/min.
4. Results and Discussions

4.1. Thermal Model Validation

The present model was validated against the experimental results reported by Tagle et al. [63], as shown in Figure 2. The validation model with SNL outlet temperature and efficiency results [44] were used to compare the present model against the experimental results. The ambient temperatures were obtained from the weather station of Budapest University of Technology and Economics for typical sunny and winter days. These conditions were utilized to examine the thermal performance of the PTC under those weather conditions using different HNF concentrations. The evaluated results showed a slight deviation of less than 0.47% for the thermal efficiency versus different flow rates for different inlet temperatures. The results indicate that the hybrid nanofluid in the PTC and the sensitivity of our model compared to previous work, Figure 4 depicts the thermal efficiency in order to explain the advantage of using the hybrid nanofluid in the PTC and the sensitivity of our model compared to previous work, Figure 4 depicts the thermal efficiency with the inlet temperature increase.

4.2. Thermal Performance Results and Discussions

Through this study, the solar radiation intensity that was used in this study was obtained using the Hottel model. The ambient temperatures were obtained from the weather station of the Budapest University of Technology and Economics for typical sunny and winter days. These conditions were utilized to examine the thermal performance of the PTC under those weather conditions using different HNF concentrations. The preprocessing of the cosine of incident angle considering the sun-tracking approach, which was continuously tracked along the E–W direction was used, as shown in Equation (3). Thus, Figure 5 shows the variance between the radiation affecting the PTC on those days. Figure 5a presents a typical sunny day when the maximum radiation intensity was obtained at midday and was recorded at 880 W/m². Moreover, the maximum ambient temperature for the same day was recorded at 30.8 °C. Figure 5b presents the radiation intensity and

![Figure 2](image2.png)

**Figure 2.** Validation of the present model against the experimental results reported by Tagle et al. [63].

![Figure 3](image3.png)

**Figure 3.** Effect of change in flow rate and inlet temperature on thermal efficiency.

In order to explain the advantage of using the hybrid nanofluid in the PTC and the sensitivity of our model compared to previous work, Figure 4 depicts the thermal efficiency with the inlet temperature increase.

| Temperature (K) | Thermal Efficiency (%) |
|-----------------|------------------------|
| 350             | 66.64                  |
| 400             | 65.64                  |
| 450             | 69.3                   |
| 500             | 70.74                  |
| 550             | 70.74                  |
| 600             | 73.6                   |

| Flow Rate (L/min) | Thermal Efficiency (%) |
|-------------------|------------------------|
| 30                | 62.0                   |
| 60                | 64.2                   |
| 90                | 64.6                   |
| 120               | 65.2                   |
| 150               | 65.8                   |
| 180               | 66.4                   |
| 210               | 66.8                   |
| 240               | 67.2                   |
| 270               | 67.6                   |
| 300               | 68.0                   |

The variance between the radiation affecting the PTC on those days. Figure 5a presents a typical sunny day when the maximum radiation intensity was obtained at midday and was recorded at 880 W/m². Moreover, the maximum ambient temperature for the same day was recorded at 30.8 °C. Figure 5b presents the radiation intensity and
ambient temperature distributions for a typical winter day when the maximum recorded values equaled 260 W/m² and 5.5 °C, respectively.

Figure 4. Thermal efficiency with various inlet temperatures for different mono and hybrid nanofluids.

Figure 5 shows the thermal properties of the base fluid and the HNFs versus temperatures at different concentrations. According to Figure 6, the thermal properties of the examined HNFs followed the trend of Therminol VP1. In detail, the thermal conductivity, viscosity, and density decreased as the inlet temperatures increased while the specific heat capacity increased linearly with the increase in inlet temperature. Moreover, the thermal conductivity, viscosity, and density were increased as concentration increased while the specific heat capacity decreased as concentration increased.
Based on evaluation of the thermal properties of the base fluid and HNFs under various input temperatures, their effects on the heat transfer coefficient results and the dimensionless Nusselt number, obtained using Equations (15), (18) and (19), are presented in Figure 7A,B. Figure 7A,B shows a 3D representation of the results, which reflect a similar trend for the heat transfer coefficient and dimensionless Nusselt number with an increase in inlet temperatures and concentrations. The highest heat transfer coefficient and dimensionless Nusselt number occurred at the high temperature and at high HNF concentrations, and those values were equal to 2236 W/m²-K and 1427. For the sake of comparison, Figure 8 presents the enhancements that were evaluated for the heat transfer coefficient and Nusselt number. This study’s maximum enhancement value was reached using a high concentration HNF volume equal to 169% for the heat transfer coefficient, and reached 138% for the Nusselt number. It is important to note that the main reason for the enhancement difference between the Nusselt number and the heat transfer coefficient is due to the definition of evaluating the heat transfer coefficient using Equation (15). Figure 9 shows the pressure drop trends of various TFs. The significant and variable effects of the different hybrid nanofluid concentrations versus the base fluid itself are clear and are basically linked to the change in density of the various concentrations. As shown in Figure 6A, the hybrid nanofluid concentration of 4% had a high density, thus it had a significant increase in the pressure drop compared with the base fluid and other concentrations. In addition, the pressure drop decreased with increasing temperatures, which was clearly visible and was linked to the dynamic viscosity decrease due to a high inlet temperature.

Figure 6. Thermal properties versus temperatures for base fluid and HNFs. (A) Density and dynamic viscosity; (B) thermal conductivity and specific heat capacity.

Figure 7. The 3D representation for the (A) heat transfer coefficient and (B) Nusselt number versus concentrations and temperatures.
Figure 7. The 3D representation for the (A) heat transfer coefficient and (B) dimensionless Nusselt number versus inlet temperatures.

Figure 8. Enhancement (A) heat transfer coefficient and (B) dimensionless Nusselt number versus inlet temperatures.

Figure 9. Pressure drop for the base fluid and hybrid nanofluids at different temperatures and concentrations.

The obtained thermal and exergy efficiencies versus the variable inlet temperatures and concentration volumes of the HNF are presented under a constant volume flow rate equal to 150 L/min in Figure 10 and , respectively. Figure 10 shows the main result, that the highest thermal efficiency (74.273%) was obtained at a high concentration of HNFs and at a low temperature. This result can be attributed to the low heat losses at low temperatures. On the other hand, the maximum calculated enhancement result, which reached 0.39%, was obtained at a high temperature and a high concentration. This can be due to the increase in the heat transfer coefficient, as shown in Figure 7A, and the increase in the heat losses. Therefore, the values of the Nusselt number augmentations and the heat transfer coefficient enhancements are higher than the thermal efficiency enhancements, as shown in Figure 8, which means that using nanofluids results in better heat transfer conditions between the tube and the VP1 thermal oil. However, the thermal losses, especially at low temperatures, are extremely low. Thus, the thermal efficiency enhancement margin is restricted [43]. Figure 11 presents the exergy efficiency for different temperatures and concentrations, where the results of the base fluid can be justified as in [53]. According to the obtained results, the highest value is observed at high concentrations and temperatures, and reached 37.828%; this is due to the fact that the amount of heat for useful exergy grows.
obtained results, the highest value is observed at high concentrations and temperatures, and reached 37.828%; this is due to the fact that the amount of heat for useful exergy grows.

Figure 10. Thermal efficiency for base fluid and hybrid nanofluid under different temperatures and concentrations.

Figure 11. Exergy efficiency for base fluid and hybrid nanofluid under different temperatures and concentrations.

4.3. Thermal and Exergy Efficiencies Assessment under the Weather Conditions of Budapest

In this section, the assessment of the energy and exergy efficiencies of the PTC model showed the effect of inserting HNFs at various volumes, side by side, with the radiation intensity in Budapest was used as a case study. Figure 12 expresses the optical efficiency and the incident angle modifier for the different angles used in this assessment because of its importance in expressing a daily simulation of this collector. The results show an inverse relationship between the optical efficiency values and the increase in values of angles where the maximum optical efficiency is achieved at angle 0° and equals 74.5%. The assessment of the thermal and exergy efficiencies for the chosen days (21 June and 21 September) over time are presented in Figure 13 and Figure 14, respectively. The volume flow rate and the inlet temperature were constant and equal to 150 L/min and 500 K. In contrast, the ambient temperature and radiation intensity changed over time for the volume concentrations of 0, 2% and 4%. Figure 13 presents the thermal efficiency obtained over time for typical winter and summer days. It was found that the maximum thermal efficiency was observed at
midday for both typical days, and the maximum value reached in the summer equaled 71.255%, with an enhancement equal to 0.26% at a concentration 4% compared with the base fluid. Figure 14 demonstrates the exergy efficiency for the same days and times. It was found that the maximum exergy efficiency was observed at midday for both typical days, and the maximum value reached in summer equaled 32.728%, while it reached 30.732% in winter with an average enhancement equal to 0.25% at a concentration 4% compared with the base fluid. These results can be justified as shown in Figure 10 and , as well as in previous research [53]. For more details, Table 7 shows the obtained results for the useful heat, loss heat, exergy, and energy efficiencies at midday of the chosen days (21 June and 21 September), and all concentrations of the proposed hybrid nanofluid. The table shows an increase in heat gain using nanofluids, but there is no great variance between the concentrations; the maximum heat gain was observed at a volume concentration of 4% and equaled 25,371 W compared with the base fluid that reached 25,300 W.

![Figure 12](image1.png)

Figure 12. Incident angle modifier and optical efficiency for the different angular values.

![Figure 13](image2.png)

Figure 13. Thermal efficiency of the base fluid and HNFs for sunny and winter days in Budapest.
Figure 13. Thermal efficiency of the base fluid and HNFs for sunny and winter days in Budapest.

Figure 14. Exergy efficiency of the base fluid and HNFs for sunny and winter days in Budapest.

Table 7. Major found results.

|                | Therminol VP1 | 1%   | 2%   | 3%   | 4%   |
|----------------|---------------|------|------|------|------|
| \( \eta_{\text{eff,summer}} \) | 71.065        | 71.224 | 71.238 | 71.246 | 71.255 |
| \( \eta_{\text{eff,winter}} \)  | 63.528        | 63.66 | 63.672 | 63.682 | 63.688 |
| \( \eta_{\text{ex,summer}} \)  | 32.64         | 32.712 | 32.718 | 32.72 | 32.728 |
| \( \eta_{\text{ex,winter}} \)   | 30.65         | 30.718 | 30.724 | 30.728 | 30.732 |
| Heat loss (W)  | 1306          | 1249  | 1245  | 1241  | 1239  |
| Heat gain (W)  | 25,300        | 25,357 | 25,360 | 25,365 | 25,371 |

On the other hand, the heat losses for the nanofluid concentrations compared with Therminol VP1 showed decreases, with heat losses that reached 1239 W at high concentrations. The major results showed a maximum enhancement equal to 0.25% for both efficiencies at the highest concentration and at midday.

5. Conclusions

In this paper, the radiation intensity in Budapest was used and simulated using the Hottel model, while ambient temperatures were obtained from a weather station at the energy laboratory. The simulations of the thermal performance were based on solving the analytical expression using MATLAB symbolic tools. Moreover, the results were validated with experimental results from the literature [44,63]. Finally, the thermal model performance of the LS-2 PTC was used to display the effects of using HNFs of Al\(_2\)O\(_3\)-WO\(_3\)/based Therminol VP1 under different concentrations and weather conditions. The key findings obtained in this study are summarized as follows:

- Utilizing concentrated solar applications (PTC) under Budapest’s weather conditions showed their ability to produce energy, especially in summer. The maximum intensity of the beam radiation reaching the parabolic reflectors approached 880 W/m\(^2\) on typical sunny days, and it reaches 260 W/m\(^2\) on typical winter days.
- In order to explain the effect of the dimensionless Nusselt number and heat transfer coefficient in increasing exergy and energy efficiencies, experiments were performed for HNFs under different concentrations (0–4%) and temperatures (300–600 K) at a constant volume flow rate of 150 L/min. Using a 2% volume concentration yielded
1402 W/m²·K for the Nusselt number and 2060 W/m²·K for the heat transfer coefficient. In comparison, a maximum Nusselt number of 1427 W/m²·K and a heat transfer coefficient of 2236 W/m²·K were obtained using a 4% volume concentration with a maximum temperature of 600 K.

- Thermal and exergy efficiencies achieved the highest improvement using high concentrations and high temperatures, reaching 68.384% and 37.828%, respectively; this means that the enhancement ratio equaled 0.39% for the thermal efficiency and 0.38% for the exergy efficiency.
- For HNFs, the maximum exergy and energy values were recorded at midday under Budapest’s summer climatic conditions, and reach 32.728% and 71.255%, respectively, under the optimum temperature of 500 K and flow rate 150 L/min. These results and the low impact of increasing the concentrations, in this case, can be attributed to simulating the effects under high volume flow rates and using a highly efficient commercial PTC (which has an evacuated tube). Despite the low enhancement results (0.25%), which were attributed to the reasons mentioned above, it was acceptable and justified [31]. On the other hand, there were promising findings on the financial feasibility in the literature for the effects of nanofluid prices. For example, Ehyaei et al. [64] found that nanofluid use did not contribute to a major increase in the overall cost of PTCs. In addition, Kasaiean et al. [38] found in their research that the payback period of nanofluid-based PTC usage is lower than the payback period of nanofluid-free PTCs.

6. Limitations and Recommendations

The thermal efficiency and exergy efficiency results are satisfactory due to the slight increase obtained, which can be justified based on the limited heat losses resulting from the use of high-performance commercial PTCs. The system reliability also clarifies the improved efficiency at higher inlet temperatures obtained because of the increased heat losses and the great increase in convective heat transfer. Thus, this research offers a reliable indication of the enhancement effect of using a new modified hybrid nanofluid under various intensities of radiation (constant and dynamic). However, more intensive research is still required, especially on the experimental assessment of the thermal properties of HNP in oil. In addition, work is needed on the monetary viability of PTCs based on nanofluids to determine whether the additional expense of nanofluid usage can be balanced with increased performance.

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