

Performance Improvement of Parabolic Trough Collector With Thermal Oil-Based Metal-Oxide Nanofluids

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Abstract. In this study, the effects of using thermal oil-based nanofluids on the parabolic trough collector (PTC) thermal performance are examined. A methodology is developed to predict the thermophysical properties of several combinations of thermal oils and nanoparticles. Specifically, Syltherm 800 and Therminol VP-1 are selected as they are common heat transfer fluids (HTF) to be combined with Al_2O_3 and CuO nanoparticles. The nanoparticle dispersion volume fractions (ϕ) are varied from 0.0% to 3.0% with increments of 0.25%. Additionally, it has been performed a parametric case study for a PTC plant, located in Rome to further emphasize the potential effects of using nanofluids in bulk-scale CST systems. The addition of nanoparticles to thermal oils used as HTFs in PTC systems results in a non-linear increase in both dynamic viscosity and thermal conductivity, leading to increased pumping power requirements and a moderate increase in thermal performance. The capacity factor and annual thermal energy are improved within the margins of 1.5% and 4%, respectively; however, these gains were offset by a significant rise in electricity consumption, especially for Therminol VP-1 based nanofluids due to plateau in thermal conductivity and nonlinear rise in dynamic viscosity against increasing volume fraction of nanoparticles. Unlike Therminol VP-1, the addition of nanoparticles has led to enhance the thermophysical properties of Syltherm 800 in the operational temperature range which led to an increase the annual thermal energy and capacity factor experiencing nonlinear increases in both thermal conductivity and dynamic viscosity.

Keywords: PTC, Nanofluid, Performance

1. Introduction

Nanofluids have gained attention due to their strong potential to enhance the thermal properties of heat transfer fluids (HTF) used in concentrated solar thermal (CST) systems [1]. Nanofluids, which are base fluids infused with nanoparticles, exhibit enhanced thermal properties such as higher thermal conductivity and improved heat transfer compared to conventional fluids. These enhancements make nanofluids particularly effective as HTFs in concentrated solar power thermal (CST) systems, where they could help improve energy efficiency and solar energy conversion rates due to enhanced and homogenized heat transfer

[2]. In this study, it has aimed to examine the potential benefits and drawbacks of using metal-oxide nanoparticle-impregnated thermal oils in PTC systems. The first section of this work covers the determination and prediction of the thermophysical properties of thermal oil-based nanofluids obtained by dispersion of selected metal-oxide nanoparticles, which are Al_2O_3 and CuO to be combined with two commonly used HTFs in PTC systems, which are Syltherm 800 and Therminol VP-1. These properties are predicted as functions of volume fraction, ranging from 0.0% to 3.0% with increments of 0.25% and temperature ranging from 10°C to 400° in accordance with well-established correlations in the literature. Having the thermophysical properties are determined, in the second section of this work, it has been performed a parametric case study on the integration of thermal-oil-based metal oxide nanofluids in a 10 MW_t PTC system to be installed in Rome ($41.89^\circ\text{N}, 12.46^\circ\text{E}$). The performance metrics such as annual thermal energy and capacity factor are presented as functions of thermal oil and metal-oxide nanoparticle combination. Furthermore, a thermal energy storage unit is added to the case study of the PTC system performance simulation, considering a storage duration of 8 hours. The parametric PTC performance simulations have been conducted using PySAM, a Python package to make calls to the software SAM (System Advisor Model) developed by NREL [3-4].

2. Methodology

2.1 Determination of Thermophysical Properties of Nanofluids

This section describes the methodology for assessing the thermophysical properties of nanofluids suitable for CST systems and their potential contribution to the thermal performance of the PTC system. To use in the correlation for thermophysical properties of nanofluids, the thermophysical properties of base materials are first collected. Since the metal-oxide nanoparticles show less significant change in thermophysical properties against change in temperature, the properties of these particles are averaged over temperature [5]. The thermophysical properties of Syltherm 800 and Therminol VP-1 are supplied by the manufacturers and provided in Section 3.1 in comparison with altered thermophysical properties of nanofluids [6-7].

Table 1. Thermodynamic Properties of Base Fluids and Metal-oxide Nanoparticles [5-7] All temperatures are in $^\circ\text{C}$.

Property	Al_2O_3	CuO	Therminol VP-1	Syltherm 800
Molecular Weight (g/mol)	101.96	79.55	166	317
Density (kg/m^3)	3970	6500	$963.4 - 1.0161 T$	$1.118 T + 1098.1$
Specific Heat ($\text{J/kg}\cdot\text{K}$)	765	540	$1.7076 T + 1574.4$	$2.6919 T + 1513.5$
Thermal Conductivity ($\text{W/m}\cdot\text{K}$)	36	20	$0.1387 - 0.002 T$	$1.428 - 0.0002 T$
Dynamic Viscosity (Pa·s)	-	-	$0.01e^{0.011T}$	$0.0052 - 9 \times 10^{-4} \ln(T)$

The density of the nanofluid is calculated by taking the volume fraction into consideration as [8],

$$\rho_{nf} = \rho_{np}\phi + \rho_{bf}(1 - \phi) \quad (1)$$

where the subscripts nf , np and bf are for nanofluid, nanoparticle and base fluid, respectively. The specific heat is then predicted by proportionally distributing the heat gain or loss based on

the thermal capacitances of both the base fluid and the nanoparticle, considering their volumetric fractions as [9],

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_{np} \quad (2)$$

The dynamic viscosity is then determined using Corcione's non-dimensional correlation, which requires the equivalent diameter of a base fluid molecule to scale and normalize the nanoparticle diameters [10]. This approach considers only characteristic diameters and volumetric fractions to predict the effective dynamic viscosity of the nanofluid as,

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1 - 34.87 \left(\frac{d_p}{d_f} \right)^{-0.3} \phi^{1.03}} \quad (3)$$

where d_f is the equivalent diameter of a base fluid molecule, determined by,

$$d_f = 0.1 \left(\frac{6M}{N\pi\rho_{f0}} \right)^{\frac{1}{3}} \quad (4)$$

where M is the base fluid's molecular weight, N is the Avogadro number, and ρ_{f0} is the base fluid's mass density determined at the temperature $T_0 = 293K$.

Determination of the thermal conductivity of nanofluid is rather complicated and has always been a major concern since it has been found that there are several factors affecting this property [11]. According to Hassani et al., the thermal conductivity of a nanofluid is determined by several parameters related to either the medium (base fluid), such as temperature, thermal conductivity, or the physical properties of nanoparticles, such as Brownian velocity and size of nanoparticles. The Brownian velocity is caused by the Brownian motion of nanoparticles inside the base fluid. Therefore, the relation between thermal conductivity and the chosen variables is expressed in a functional form given in Eq.5.

$$k_{nf} = f(\phi, k_f, k_p, v_{Br}, C_p, d_{ref}, d_p, T, v_f, T_b) \quad (5)$$

Thermal conductivity is then assessed using the correlation of Hassani et al., which utilizes the Buckingham Π -Theorem to factor in variables including the Brownian velocity and nanoparticle diameter. The Brownian velocity of the nanoparticles is calculated according to Eq. 6.

$$v_{Br} = \sqrt{\frac{18k_B T}{\pi \rho_p d_p^3}} \quad (6)$$

where k_B is the Boltzmann constant (1.3807×10^{-23} J/K). The non-dimensional correlation selected for this work, which has been originated by Hassani et al., is provided in Equation 7 given below. According to Equation 7, the thermal conductivity of nanofluids strongly affected by the Brownian velocity of the nanoparticles, the volume fraction of the nanoparticles and Prandtl number of the base fluid alongside with the thermal conductivities of the nanoparticle and base fluid.

$$\frac{k_{nf}}{k_f} = 1.04 + \phi^{1.11} \left(\frac{k_p}{k_{bf}} \right)^{0.33} Pr^{-1.7} \left[\frac{1}{Pr^{-1.7}} - \frac{262}{\left(\frac{k_p}{k_{bf}} \right)^{0.33}} + \left(135 \left(\frac{d_{ref}}{d_p} \right)^{0.23} \left(\frac{v_f}{d_p v_{Br}} \right)^{0.86} \left(\frac{C_p}{T^{-1} v_{Br}^2} \right)^{-0.1} \left(\frac{T_b}{T} \right)^{-7} \right) \right] \quad (7)$$

2.2 PTC Annual Performance Case Study

Having the nanoparticle-added fluid properties determined, a parametric case study is conducted for a PTC system to be installed in Rome, Italy with a heat sink thermal power of 10 MWt. The parametric annual performance calculations have been done using PySAM, a Python package to make calls to the software SAM (System Advisor Model), a public-usage software developed by National Renewable Energy Laboratory (NREL). To be better compatible with the software, the authors have used NREL's open-access meteorological database, NSRDB, for typical meteorological year (TMY) data to be employed in the annual system performance simulation [12]. The annual performance simulation parameters for PTC system case that had been kept constant throughout this work is provided in Table 2 given below. The rest of the input parameters are assumed as the default settings of the Industrial Process of Module for PTC of SAM.

Table 2. PTC Performance Simulation Parameters

Parameter	Value/Name
Design Point DNI	950 W/m ²
Loop Inlet/Outlet HTF Temperatures	300°C / 385°C
Parabolic Trough Collector	SkyFuel - Skytrough
PTC Receiver	Schott PTR80
Field Aperture Area / Solar Multiple	39360 m ² / 2.5
Installation Location Latitude/Longitude	41.89/12.46
Freeze Protection Temperature for field HTF	50 °C
Storage HTF Fluid / Storage Duration	Pressurized Water / 8h

The data for irradiation, dry bulb temperature and wind speed -in monthly averaged form- taken from TMY data for installation location provided by NSRDB are given in Figure 1. Monthly averaged irradiation data, given in Figure 1, show that Daily Total Direct Normal Irradiation, DNI, approaches to 8 kWh/m²/day in months of summer, underlying the significant potential of concentrated solar thermal/power systems in the area. In Figure 1, it has been shown that the monthly averaged wind speed is somehow stable around the value of 2.3 m/s, and the monthly averaged dry bulb temperature is about 10 °C in winter, exceeds 20°C in June and approaches to 30 °C in July and August.

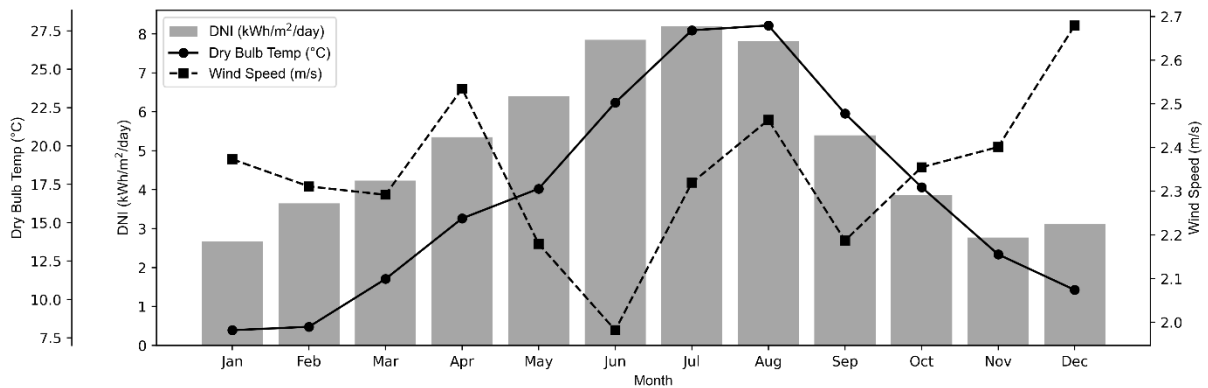


Figure 1. Monthly Averaged Daily Total Direct Normal Irradiation (DNI), Dry Bulb Temperature and Wind Speed Data taken from TMY Data for Installation Location, Rome, Italy [13]

3. Results and Discussion

3.1 Effect of Metal Oxide Nanoparticles on Thermophysical Properties of Selected Thermal Oil

This section discusses the improvements to the thermophysical characteristics of Syltherm 800 and Therminol VP-1. The variations in the thermophysical properties compared to the base fluid are demonstrated at various temperatures. To demonstrate the effects, the combinations of CuO and Al₂O₃ nanoparticles with Syltherm 800 and Therminol VP-1 are given in Figures 2-5, respectively. Figures 2-5 show that for each nanoparticle, as the volume fraction increases, the density also increases, and the specific heat decreases linearly by definition. Figures 2-5 demonstrate that the dispersion of nanoparticles in the thermal oils reverses the decreasing trend for thermal conductivity against increasing temperature. The results demonstrated in Figures 2 and 4 for an operating temperature of 350°C show that the thermal conductivity can increase by a factor of 1.98, 4.17 and 5.96 for CuO-based nanofluid and 2.25, 3.17 and 5.25 for Al₂O₃ for Syltherm 800 based fluid. In addition, Figures 3 and 5 show that the thermal conductivity can increase by a factor of 1.09, 1.46 and 1.88 for CuO-based nanofluid and 1.16, 1.33 and 1.68 for Al₂O₃ for Therminol VP-1 volume fractions (ϕ) of 1.0%, 2.0% and 3.0%, respectively. This increase could be attributed to the metallic bonds introduced by the nanoparticles inside the fluid matrix. These promising results emphasize that even for the small volume fractions, the impregnation of nanoparticles in thermal oils could enhance the thermal performance of base fluids significantly.

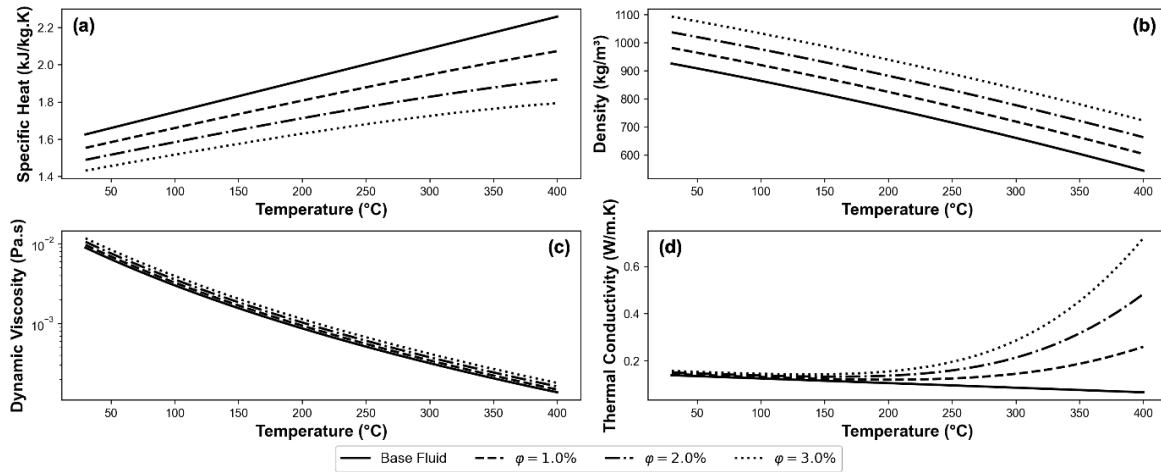


Figure 2. Thermophysical Properties of Syltherm 800 + CuO Nanofluid as functions of Temperature (a) Specific Heat ($\text{kJ/kg}\cdot\text{K}$), (b) Density (kg/m^3), (c) Dynamic Viscosity ($\text{Pa}\cdot\text{s}$), (d) Thermal Conductivity ($\text{W/m}\cdot\text{K}$)

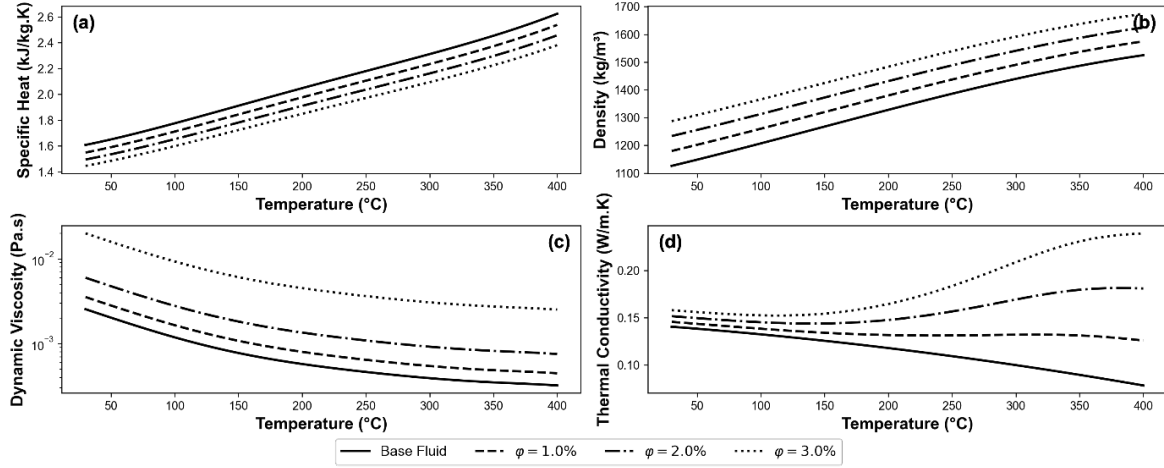


Figure 3. Thermophysical Properties of Therminol VP-1 + CuO Nanofluid as functions of Temperature (a) Specific Heat ($\text{kJ/kg}\cdot\text{K}$), (b) Density (kg/m^3), (c) Dynamic Viscosity ($\text{Pa}\cdot\text{s}$), (d) Thermal Conductivity ($\text{W/m}\cdot\text{K}$)

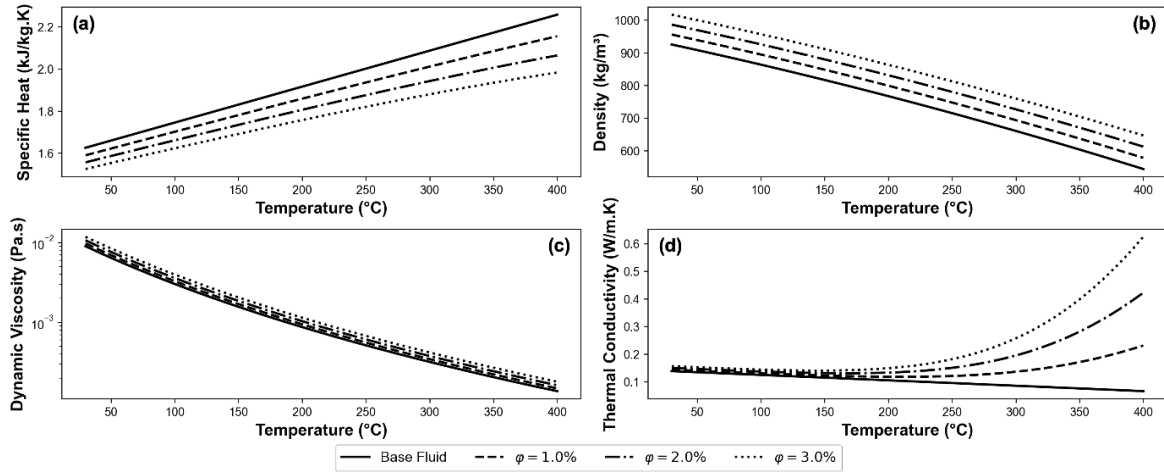


Figure 4. Thermophysical Properties of Syltherm 800 + Al_2O_3 Nanofluid as functions of Temperature (a) Specific Heat ($\text{kJ/kg}\cdot\text{K}$), (b) Density (kg/m^3), (c) Dynamic Viscosity ($\text{Pa}\cdot\text{s}$), (d) Thermal Conductivity ($\text{W/m}\cdot\text{K}$)

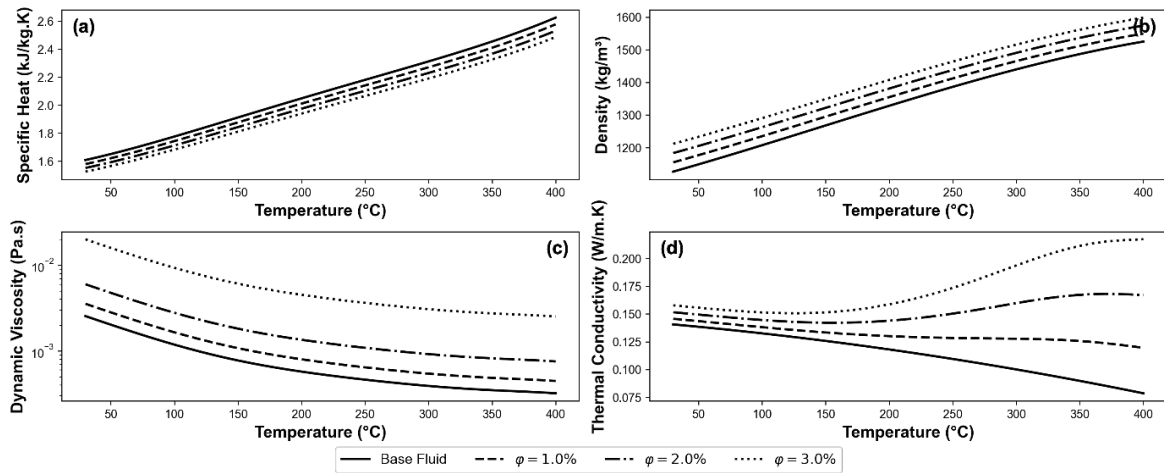


Figure 5. Thermophysical Properties of Therminol VP-1 + Al_2O_3 Nanofluid as functions of Temperature (a) Specific Heat ($\text{kJ/kg}\cdot\text{K}$), (b) Density (kg/m^3), (c) Dynamic Viscosity ($\text{Pa}\cdot\text{s}$), (d) Thermal Conductivity ($\text{W/m}\cdot\text{K}$)

On the other hand, the dispersion of nanoparticles in the selected thermal oils has been predicted to increase the viscosity of the base fluid, as shown in Figures 2-5. For operating temperature of 350°C, the dispersion of metal-oxide nanoparticles has led to increasing the dynamic viscosity by a factor of 1.08, 1.18 and 1.31 for Syltherm 800 based nanofluids and 1.25, 1.69 and 5.65 for Therminol VP-1 based nanofluids -since dynamic viscosity correlation does not take the nanoparticle material itself- for both CuO and Al₂O₃ volume fractions (ϕ) of 1.0%, 2.0% and 3.0%, respectively. This could be attributed to the stagnation of the flow near the nanoparticles, effectively making it harder for the flow to push itself.

3.2 Integration of Thermal Oil-Based Metal Oxide Nanofluids in Parabolic Trough Collector Systems as Heat Transfer Fluids

In this section, the potential advantages and drawbacks of employing thermal-oil-based metal-oxide nanofluid in PTC systems are discussed for moderate/high-temperature process heat applications in terms of selected performance metrics, which are Annual Thermal Energy in GWh-t, Capacity Factor, and Annual Electricity Consumption in MWh-e.

According to Table 3, for a 10MW-t PTC system with 8 hours of storage to be installed in Rome, Italy, the dispersion of Al₂O₃ and CuO nanoparticles in Syltherm 800 could result in capacity factors and annual thermal energy production with insignificant differences due to diminishing effects of the exponential increase in the thermal conductivity and linear decrease in the specific heat in the operational temperature range and, as opposed to, exponential increase in dynamic viscosity and linear increase in density as the volume fraction increases. Hence, the output results are averaged over nanoparticle volume fraction alongside the operational temperature range. Table 3 compares the performance of two heat transfer fluids, Syltherm 800 and Therminol VP-1, as well as nanofluid versions impregnated with Al₂O₃ and CuO nanoparticles using the system simulation software, SAM by NREL. The capacity factor is quite consistent across all fluids, with deviations within 1.5%. The inclusion of nanoparticles increases electricity consumption, especially with CuO, resulting in the maximum consumption in Syltherm 800/CuO (971.1 MWh-e). Therminol VP-1 has the largest thermal energy production, at 28.89 GWh-t, albeit its nanofluid versions marginally lower this statistic. On the other hand, when nanoparticles are added to Syltherm 800, thermal energy production increases somewhat, with Syltherm 800/CuO reaching 28.13 GWh-t. Overall, the usage of nanoparticles increases power consumption due to an exponential increase in dynamic viscosity while producing outcomes in thermal energy output within the margin of 1%.

Table 3. The effects of thermal oil-based nanofluids on selected performance parameters, averaged over the operational temperature range and the studied volume fraction range

Heat Transfer Fluid	Capacity Factor (%)	Annual Electricity Consumption (MWh-e)	Annual Thermal Energy (GWh-t)
Syltherm 800	31.65	869.2	27.70
Syltherm 800 / Al ₂ O ₃	32.08	918.3	28.10
Syltherm 800 / CuO	32.13	971.1	28.13
Therminol VP-1	31.82	323.2	28.89
Therminol VP-1 / Al ₂ O ₃	31.81	342.7	27.82
Therminol VP-1 / CuO	31.67	357.1	27.76

4. Conclusions

To conclude, in this study, first, a methodology for the prediction of thermophysical properties of thermal oil base metal-oxide nanofluids. This methodology is adapted from well-established literature to the selected thermal oils, Syltherm 800 and Therminol VP-1. Then a parametric case is performed for a 10 MW-t PTC system to be installed in Rome, Italy. The results show

an increasing shift in density and a decreasing shift in specific heat for each combination of nanoparticle and thermal oil as the volume fraction of nanoparticles increased. However, the nanofluids, in terms of thermophysical properties, are predicted to show a non-linear increase in both dynamic viscosity and thermal conductivity, which brings the optimization problem of using these fluids. The nonlinear increase in thermal conductivity with temperature is expected, as the prediction model is influenced by temperature and Brownian velocity, which depends on the square root of the fluid's temperature. This is clear in Syltherm 800-based nanofluids. In contrast, Therminol VP-1-based nanofluids show a plateau in thermal conductivity due to a decline in the base fluid's conductivity. On the other hand, the dynamic viscosity of both Therminol VP-1 based nanofluids and Syltherm 800 based nanofluids are strongly correlated by negative of the inverse of the volume fraction of the nanoparticle. The addition of nanoparticles to the selected thermal oils in PTC systems yields mixed results. Syltherm 800/ Al_2O_3 improves capacity factor by 1.36% and thermal energy by 1.44%, but the annual electricity consumption rises by 5.65%. Syltherm 800/ CuO shows similar trends, with a 1.52% increase in capacity factor, 1.55% rise in thermal energy, and an 11.72% increase in electricity use. For Therminol VP-1, adding Al_2O_3 keeps capacity factor stable but reduces thermal energy by 3.71% and increases electricity consumption by 6.03%. Therminol VP-1/ CuO leads to a 0.47% drop in capacity factor, a 3.91% reduction in thermal energy, and a 10.50% increase in annual electricity consumption. While nanoparticle-infused oils improve capacity factor and thermal energy slightly, the gains are offset by significantly higher electricity consumption, especially due to increased viscosity and pumping power demands. In conclusion, the annual performance simulation results show an exponential increase in electrical energy consumption due to more pumping power required caused by a substantial increase in dynamic viscosity. However, increases in both capacity factor and annual thermal energy are obtained within the margin of 1.5% and 4%, respectively.

As a promising area for future research, it is suggested to explore adaptive operational strategies for nanofluid-based PTC systems. These strategies involve optimizing with respect to fluctuating solar conditions, specific nanoparticle concentrations, combinations of base fluids, and various operating conditions, all aimed at maximizing thermal efficiency while minimizing hydraulic penalties associated with increased effective dynamic viscosity. While the viscosity gain works to our benefit here, the energy gains will be limited if it is enhanced above a certain threshold. Therefore, the effect of the nanoparticle addition on viscosity should also be studied and validated experimentally to determine the limits. Additionally, the use of nanofluids in CST technologies would benefit from research focused on their long-term stability, maintenance attributes, and economic impact.

Data availability statement

The simulation data are based on publicly available resources from NREL's SAM and NSRDB. Custom code and processed data can be shared by the corresponding author upon reasonable request.

Underlying and related material

No additional materials are deposited for this contribution.

Author contributions

Levent Güner: Conceptualization, Data Curation, Methodology, Software, Visualization, Writing-original draft. **Onur Taylan** and **A. Alperen Günay:** Conceptualization, Methodology, Project Administration, Supervision, Writing-review&editing.

Competing interests

The authors declare that they have no competing interests.

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