Energy Proceedings
Vol 55, 2025
ISSN 2004-2965

Performance of Solar Flat Plate Collectors with s-CO2 as Heat Transfer Fluid[#]

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ABSTRACT

In the present work, a simple numerical model is developed to estimate the performance of a solar flat plate collector (FPC) with water and CO_2 as heat transfer fluids. An experimental test rig validates the model with water as heat transfer fluid (HTF). Though water is an excellent working fluid, it cannot be used in places where the ambient temperature falls below 0°C. Though antifreeze solutions can be added to water, this decreases the overall efficiency of the collector. In this context, using supercritical CO_2 (s-CO_2) in place of water can offer enhanced performance in addition to an extended operating temperature range. Hence in this study, the analysis is done with s-CO_2 and water by considering four different cases under different operating conditions. The performance of both the HTFs is compared by using dimensionless quantities such as Reynolds number, Nusselt number, and Prandtl number. It has been observed that the outlet temperature and thermal efficiency of solar water heating system (SWHS) achieved are superior when the rate of mass flow is decreased, and the diameter of the riser tubes is made smaller. It has also been observed that substituting s-CO_2 with water as the HTF in a solar FPC improves the overall performance. The solar collectors containing s-CO_2 have high operating pressures, phase-changing potential with the change of ambient temperature, and considerable property variations around the critical point of the fluid, which are the major challenges for designing this type of SWHS. Thus, these subjects demand an extensive investigation.

Keywords: Flat Plate Collector, Solar Water Heating System, Thermal efficiency, Supercritical-CO_2

NONMENCLATURE

Abbreviation		
HTF	Heat Transfer Fluid	
FPC	Flat Plate Collector	
SWHS	Solar Water Heating System	
s-CO_2	Supercritical Carbon dioxide	
Symbols		
A_p	absorber plate surface area,	[m^2]
C_p	specific heat	[J/kgK]
d	tube diameter	[mm]
F_r	heat removal factor	---
I_T	solar irradiance	[W/ m^2]
$\dot{m}$	mass flow rate	[kg/s]
$\dot{Q}u$	useful heat gain	[W]
U_L	net heat loss coefficient	[W/m^2K]
η	thermal efficiency	

1. INTRODUCTION

Over the past few decades, there has been a substantial development in the usage of solar energy as a response to the decreasing availability of fossil fuel resources, as well as due to concerns over air pollution and global warming brought on by the widespread consumption of non-renewable fossil fuels. Solar energy is most secure since it is plentiful as well [1]. A small percentage of the available incidence of solar energy has the potential to meet the energy requirements of a whole country if it is gathered effectively. In many parts of India, the average yearly solar irradiation ranges from 4 to 7 kWh/m^2/day, and there are around 250-300 sunny days throughout the course of the year. This indicates that the nation receives more than 5000 trillion kilowatt hours of solar energy per year [2].

Solar energy has become very popular as a means of producing both electricity and hot water over the last couple of decades. A solar water heating system (SWHS) is a very effective and simple method of using solar energy to provide hot water or heat a building. When used to generate hot water, solar water heating systems are eco-friendly, long-lasting, and highly efficient. [3]

The direct solar water heating system (SWHS) has a solar collector as its primary component, which harnesses solar energy and converts it into heat. This

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This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

heat is then transferred to a fluid, often water or air, which then accumulates in a reservoir. A pump is used to circulate the HTF in the riser tubes. Figure 1 represents a simplified diagram of a direct SWHS.

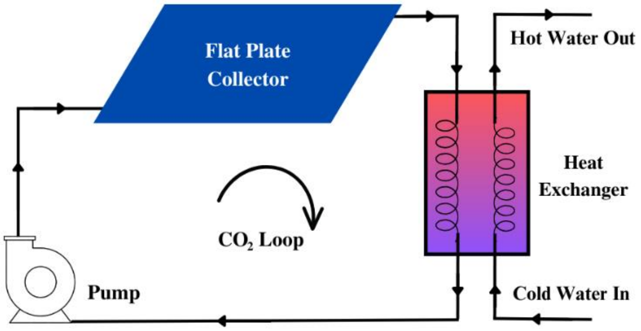

Figure 1: Direct solar water heating system

The SWHS that uses an FPC is the cheapest, easiest, and least difficult to manufacture, operate and maintain. In contrast to collectors of the concentrating kind, which can only gather direct solar energy, this type of collector can utilize both scattered and direct solar irradiation. FPCs have become quite common in houses, apartments, institutional buildings, healthcare centers, educational institutions and industrial areas, etc. An FPC consists of an absorber plate, riser tubes, glazing, thermal insulation, and casing as primary components. Figure 2 illustrates a cross-sectional view of an FPC.

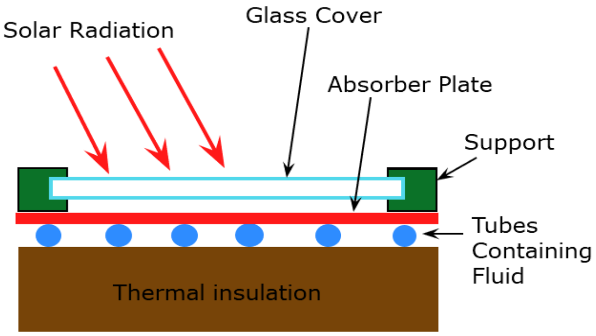

Figure 2: A cross-section of a flat plate collector

2. LITERATURE REVIEW AND OBJECTIVE

Many scholars [3-10] have made significant contributions to the field of water heating systems by employing solar energy and have worked with a wide variety of geometries, working fluids, absorber plates, and insulation materials. Koca et al. [4] performed some experiments to find how a phase-changing material (PCM) affects the energetic and exergetic performance of a flat plate collector. The optimal working fluid was determined to be Mobiltherm-605. The calculated exergy efficiency was 2.2%, and energy efficiency was 45.2%.

The improvements to the optical clarity of the absorption materials increase the amount of solar energy that was received. Adding more glass covers reduce the amount of heat that is lost. The overall performance and efficiency of these collectors may be greatly improved by choosing the right heat transfer fluid. Different heat transfer fluids possess unique thermal properties that directly impact energy absorption, heat transfer, and overall system effectiveness. Numerous research studies have focused on water-based systems and have demonstrated their thermal efficiency and effective heat transfer characteristics [5]. However, the freezing point of water limits its application in cold climate conditions.

The use of carbon dioxide (CO_2) as an effective fluid for transferring heat in solar flat plate collectors has gathered a significant amount of interest due to its unique properties and environmental advantages. CO_2 possesses several properties that make it an attractive heat transfer fluid. It has a high heat capacity, enabling efficient heat absorption and transfer within the collector. CO_2 also exhibits a relatively low boiling point (-78.5 °C) at atmospheric pressure, allowing it to operate effectively under varying temperature conditions. Additionally, CO_2 is non-flammable, non-toxic, and readily available, making it a safer and environmentally friendly choice [6-8].

A nano-fluid is a fluid in which particles are typically between 1 and 100 nanometres in size. Nanofluids have been utilized to enhance the thermal properties of the HTF, including its conductivity, specific heat capacity, diffusivity, and convective heat transfer ability. The flat plate SWHS has been the subject of a transient numerical analysis by Genc et al. [6] using a nanofluid composed of alumina and water, with the circulation of working fluid at 0.004 and 0.06 kg/s. It was noted that the highest thermal efficiency was obtained at a greater mass flow rate of 0.06 kg/s, which was around 83%.

To determine how a modification to the shape of absorber tube might affect the performance of an FPC, Yamaguchi et.al. [7] conducted an in-depth study. As a part of their investigation, the researchers investigated how the performance of the FPC was impacted by the rate of mass transfer as well as the materials of the absorber plate and the tubes. After comparing semi-circular and standard circular collectors, it was found that the semi-circular collector had a higher output temperature because it has a larger absorbing area. Although a large amount of experimental work on solar energy-based FPC has been published [7-10], limited research utilizing a numerical approach has been published. In order to advance the research, the simulation-based study of solar FPC became increasingly important. Nevertheless, the implementation of s-CO_2 as the heat transfer fluid could make the functionality of these systems even better at what they do.

It is believed that s-CO_2 may give improved performance, however a survey of the literature [3-5] reveals that both the practical as well theoretical research efforts on s-CO_2 based solar water heaters are very few. Therefore, this study aims to develop a mathematical model for analyzing the effectiveness of a solar FPC by taking s-CO_2 as primary working fluid in a closed cycle of indirect solar water heating system. This model will be applied to the weather and climate conditions of India.

3. METHODOLOGY OF THE STUDY

A flat plate collector is employed as the source for heat acquisition in the experimental test rig for a solar water heating system. Additional components of the rig consist of an artificial solar flux generator in the arrangement of halogen lights, a hot water storage tank, flow control valves, and a data acquisition system. Table 1 provides the technical specifications of the solar flat plate collector.

Table 1: Technical details of the solar collector

S.N.	Variables	Value
1.	Absorber plate area	1.7 m^2
2.	Angle of tilt for FPC	37°
3.	Riser tubes inner diameter	8 mm
4.	Riser tubes outer diameter	9 mm
5.	Thermal conductivity (absorber plate)	240 W/mK
6.	Thermal conductivity (back insulation)	0.04W/mK
7.	Bottom-side insulation thickness	0.05 m
8.	Top-side insulation thickness	0.5mm
9.	Heat transfer fluid	s-CO_2

For mathematical modelling, the specifications of various components of the FPC e.g., glazing, absorber plate, riser tube spacing, rise tube inner diameter, and the riser tube thickness considered match with that of the testing apparatus. A small number of preliminary experiments provided the basic information for the modelling, including the ambient temperature, inlet water temperature, insolation at the FPC top surface, and wind speed. Considering the energy, momentum and continuity equations, we can determine the absorber plate temperature, as well as the outlet temperature of the fluid flow in the riser tube. The absorber plate and heat transfer fluid temperature are dependent on the average fluid flow rate in the riser tubes. It is observed that the flow with a low Reynolds number produces a homogeneous temperature distribution in riser tubes [11].

In this study, a mathematical model is developed to analyze the fluid flow behavior, the amount of useful heat gained per collector tube that are connected in parallel, and the outlet temperature. s-CO_2 is considered for usage as a fluid for transferring heat in solar collectors for indirect solar water heating systems so that it is possible to gain the advantages of the enhanced heat transmission capabilities of CO_2 at or near its critical temperature. There is a noticeable variation in the properties of s-CO_2 as compared to the water. So, in the case of s-CO_2, it is very essential to capture the property variations and hence a discretization technique is applied here. The specific heat variations with operating pressure in riser tubes is shown in Figure 3.

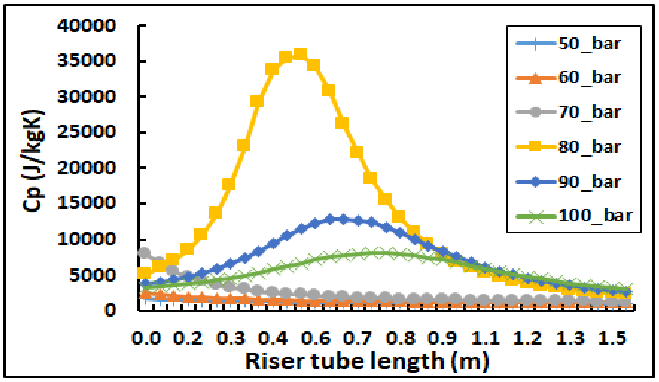

Figure 3: Variation of specific heat along the length of the riser tube at different operating pressures

3.1 Governing Equations:

To facilitate the analysis, it is presumed that the flow of the fluid and the transfer of heat are in a steady state, the solar flux is consistent over the upper surface area of the FPC, and the loss of the heat via both the top and the bottom ends is to the same environment conditions.

The gain of useful heat is calculated by:

$$Q_u = \dot{m}C_p(T_{f,out} - T_{f,in}) \quad (1)$$

Where, C_p, $\dot{m}$, $T_{f,out}$, and $T_{f,in}$ are the heat capacity, the rate of mass flow, outlet temperature and inlet temperature of the heat transfer fluid, respectively. The equation (1) represents the net increment of usable heat that an operating fluid is able to absorb from the collector absorption plate. However, this estimate does not take into consideration the effects that the heat loss coefficient as well as the collector optical efficiency have on the thermal efficiency. In order to account for both heat and optical loss, the following equations are used.

$$Q_u = F_r A_p\{S - U_l(T_{f,in} - T_a)\} \quad (2)$$

$$S = \eta_o I_t \quad (3)$$

Where S is the amount of solar energy per surface area that is absorbed by the collector, η_o is the collector's optical effectiveness, and I_t is the amount of solar irradiation that falls on the upper surface of the collector. To get the heat removal factor, we use the formula: [11]

$$F_r = \frac{\dot{m}}{A_p U_l}\left[1 - \exp\left(-\frac{F' U_l A_p}{\dot{m} C_p}\right)\right] \tag{4}$$

$$F' = \frac{1/U_l}{W/[\pi d \alpha_f] + W/[(d+(W-d)F)U_l]} \tag{5}$$

Here, the efficiency factor can be calculated as,

$$F = \frac{tanh[\frac{m(W-d)}{2}]}{[\frac{m(W-d)}{2}]} \tag{6}$$

Where, m is a design factor and can be obtained as,

$$m = \sqrt{U_l / K_p \delta_p} \tag{7}$$

The convection heat losses are through the top surface of the collector only. It is assumed that losses though sides of the collector are negligible. The heat losses are calculated as: [12]

$$U_l = U_t + U_b \tag{8}$$

$$U_t = \left[\frac{1}{\frac{C}{T_p}\left[\frac{T_p - T_a}{1+f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\frac{1}{\varepsilon_p + 0.00591 h_w} + \frac{1 + f + 0.133\varepsilon_p}{\varepsilon_g} - 1}\right] \tag{9}$$

$$U_b = \frac{k_i}{\delta_b} \tag{10}$$

where, U_t , U_b are the convective heat loss coefficient for top and bottom surfaces while U_l is the net convective heat loss coefficient. δ_b is the thickness of the insulation provided at the bottom and k_i is the conductivity of the same. The rate at which heat dissipation take place from the upper surface of the collector is given by: [12]

$$\dot{Q}_{t,l} = h_w(T_c - T_a) + \sigma\varepsilon_g(T_c^4 - T_{sky}^4) \tag{11}$$

Here, the temperatures of the surrounding air, the collecting surface, the absorber plate, and the sky are denoted by T_a, T_c, T_p, and T_{sky}, respectively. The following equation may be derived by taking into account how the temperature is distributed throughout the collector: [21]

$$(T_{f,out} - T_a - \frac{S}{U_l})/(T_{f,in} - T_a - \frac{S}{U_l}) = (\exp\left(-\frac{F' U_l A_p}{\dot{m} C_p}\right) \tag{12}$$

The thermal efficiency of the flat plate collector is obtained by: [18, 21]

$$\eta_{th} = \frac{\dot{m} C_p[(T_{f,in} - T_a - \frac{S}{U_l})(\exp\left(-\frac{F' U_l A_p}{\dot{m} C_p}\right) - 1]}{A_p I_T} \tag{13}$$

The Reynolds number is obtained by: [8]

$$R_e = \frac{\rho V_{avg} D_i}{\mu} \tag{14}$$

The Nusselt number for CO_2 as HTF is evaluated by Pitla et al. [11],

$$Nu = Nu_b \left(\frac{\mu_b}{\mu_w}\right)^{0.11} \left(\frac{k_w}{k_b}\right)^{0.33} \left(\frac{h_w - h_b}{C_{pb}(T_w - T_b)}\right)^{0.35} = \frac{\alpha_t d}{k_b} \tag{15}$$

Where, Nu_b is the Nusselt number obtained at bulk temperature

$$Nu_b = \frac{(f/8) Re Pr}{12.7\sqrt{f/8}\,(Pr^{2/3} - 1) + 1.07} \tag{16}$$

The convective heat transfer coefficient for water is obtained by using the Dittus–Bolter correlation as given: [10]

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \tag{17}$$

When both frictional and momentum effects are taken into account, pressure decreases. The pressure drop in the riser tube and its variation along the length of the riser tube was observed and it can be calculated by: [11]

$$p_f^i - p_f^{i+1} = \frac{G_f^2}{2\rho_f}[f\frac{\Delta L}{d} + \left(\frac{\rho_f^i}{\rho_f^{i+1}} - \frac{\rho_f^{i+1}}{\rho_f^i}\right)] \tag{18}$$

Where, the friction factor (f) is obtained by: [9]

$$f = [0.79 ln(Re) - 1.64]^{-2} \text{ (for turbulent flow)} \tag{19}$$

$$f = 64/Re \text{ (for laminar flow)} \tag{20}$$

3.2 Grid independence analysis

In this study, to capture the property variation of s-CO_2, the grid independence analysis is done by considering different number of segments (n) of the riser tube, e.g., n = 10, 20, 30, 35 & 50. It was observed that after 35 segments of the riser tube, there is negligible variation in the results found from the analysis. The obtained thermal efficiency at 35 segments was 85.94% that with 50 segments was 85.95% and hence n = 35 segments was selected for further analysis of the system [13].

4. RESULTS AND DISCUSSION

The analysis is done by considering four different cases with different operating conditions and fluids. These are shown in table 2. The length of tube (L_t) for all the cases is 1.5 m. The operating pressure for the s-CO_2 was 90 bar while it is 1 bar for water. It was observed from figure-3, that near the critical point, s-CO_2 has large property variation with operating temperature which varies along the length of the tube. This needs to be accounted for in the analysis to arrive at accurate results.

Table 2: The 4 different cases considered

Case	HTF	Property	m_f (kg/s)	d_i (mm)	d_o (mm)
Case 1	s-CO_2	Constant	0.01	8	9.52

Case 2	s-CO_2	Variable	0.001	8	9.52
Case 3	s-CO_2	Variable	0.001	5	6.52
Case 4	water	Constant	0.01	8	9

The fluid flow and heat transfer depend on the dimensionless parameters, namely Reynolds number and Prandtl number. The observed variation of Prandtl number along the length of the riser tube for all operating cases is shown in figure 4. Unlike the Reynolds number, the Prandtl number, is only affected by the fluid properties only. Prandtl number does not depend upon the geometrical parameters of the collector, and hence when the tube diameter is varied, negligible variation in the Prandtl number is observed.

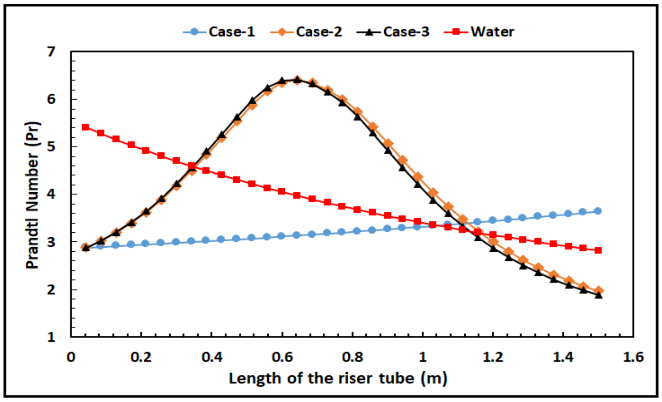

Figure 4: Variation of Prandtl number

Figure 5 represents the variation of Nusselt number. It can be seen that Nusselt number variation for water is negligible, while it is significant and much higher for s-CO_2, indicating excellent heat transfer properties of s-CO_2.

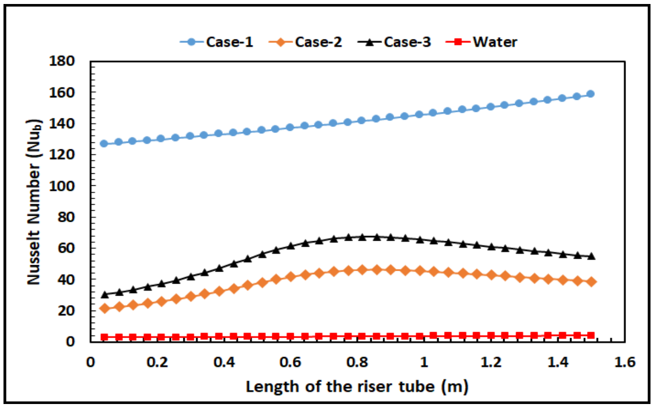

Figure 5: Variation of Nusselt number

Figure 6 shows a comparison between pressure drop for different cases. It is seen that for same mass flow rate and tube inner diameter, the pressure drop is smaller for water due to its lower Reynolds number. As expected, for s-CO_2, the tube diameter affects the pressure drop significantly. Considering both pressure drop and heat transfer, a flow rate of 0.001 kg/s per tube of 8 mm inner diameter gives better performance compared to the other cases.

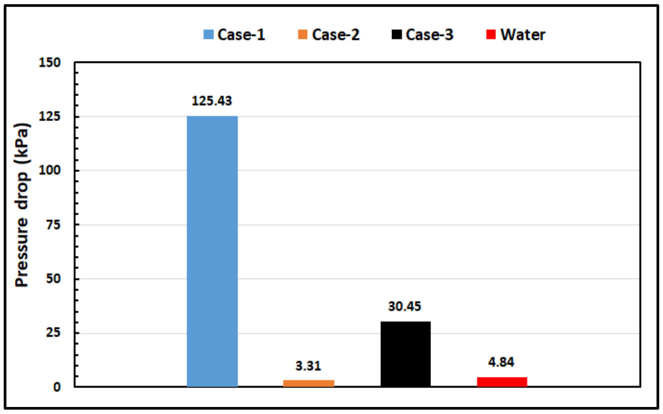

Figure 6: Total Pressure drop in the riser tubes

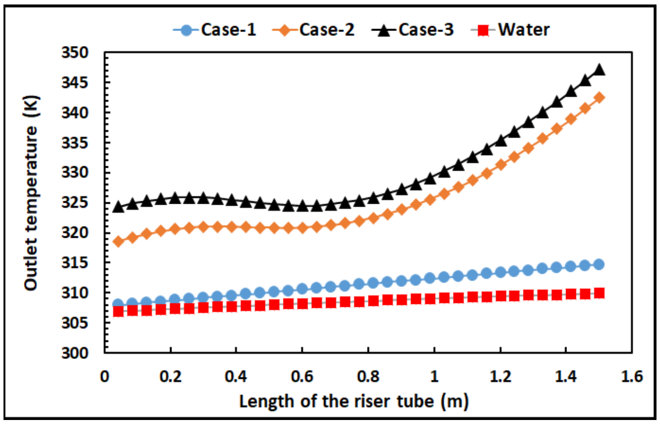

Figure 7: Outlet temperature from the FPC

The fluid temperature variation along the tube length is shown in figure 7. The figure indicates that for the same mass flow rate and tube diameter, the outlet temperature with s-CO_2 is high as compared to water, indicating good thermal performance of s-CO_2.

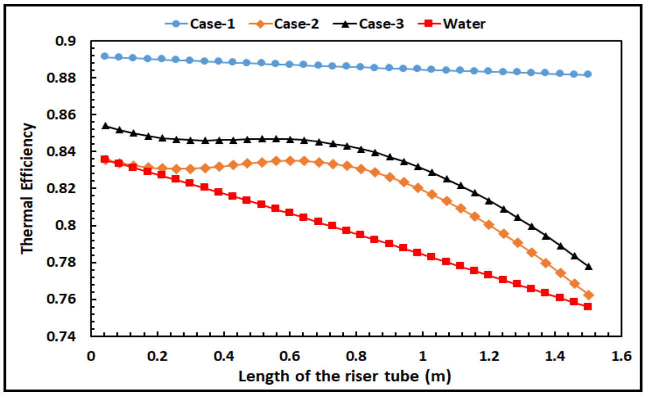

Figure 8: Thermal efficiency of the collector

The observed variation of thermal efficiency of the FPC along the riser tube length was observed with all three cases for s-CO_2 and water as HTF and it is shown in figure 8. It shows that the flat plate solar collector efficiency can be higher when s-CO_2 is used as the HTF instead of water. This is because s-CO_2 has more favorable thermophysical and transport properties than water. Consequently, s-CO_2 might be a promising HTF in solar collectors, provided its high working pressures are taken into account.

5. CONCLUSIONS

A simple analytical model is established to understand the design and operating conditions and predicted the functionality of a solar flat plate collector with s-CO_2 as a potential working fluid. Experimental findings using water as the heat transfer fluid verify the model [13]. The theoretical and experimental findings show a high degree of quantitative and qualitative consistency. The effectiveness of both fluids under a variety of different operational situations is evaluated and compared. According to the theoretical findings, case-3 with s-CO_2 delivers better thermal performance than cases-1 and 2, as well as water, under all conditions. Under case-3 outlet fluid temperature is about 11.2% higher than case-1. Hence, case-3 is suggested here for optimum working conditions as it provides the desired outlet temperature of the fluid with slightly lower thermal efficiency.

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