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Segmental application of two heat absorption intensification methods in parabolic trough collector solar loop

Bartosz Stanek[a], Daniel Węcel[b], Łukasz Bartela[c]

[a] Silesian University of Technology, Gliwice, Poland, bartosz.stanek@polsl.pl, CA
[b] Silesian University of Technology, Gliwice, Poland, daniel.wecel@polsl.pl,
[c] Silesian University of Technology, Gliwice, Poland, lukasz.bartela@polsl.pl

Abstract:

Due to climate change and worldwide policies, the importance of renewable energy sources is increasing significantly. Increasing its share of total energy consumption is essential to reduce CO_2 emissions and achieve energy independence. A commonly available source of heat is solar energy, which can be efficiently used and converted using a specific technology. For the generation of medium and high-temperature heat, CSP technologies are used, with parabolic trough collectors (PTC) being the most mature. In heat industrial power, this technology is used on a reduced scale, with a smaller aperture. The scale-down of the geometry and the lower temperature stage compared to traditional high aperture PTCs provides opportunities for optimisation and the use of alternative materials. As the temperature and heat flow parameters change in different sections of the absorber, it is optimal to introduce different methods in different areas of the solar loop. This article presents the optimization results of the use of non-selective but highly absorptive and cost-effective solar coating and twisted tape inserts in solar loop sections. The research was conducted for a case study which was a medium-sized industrial facility with a heat demand of a maximum of 250 °C. A numerical model was used for this study, validated by a previously performed experiment using a solar simulator. The results showed that both methods lead to an intensification of heat absorption, almost 45% of the absorbers can have a low-cost non-selective coating and twisted tapes with a twisted ratio of 1 and 2 can be applied inside the absorber pipes. The maximum efficiency gain was 1.3%.

Keywords:

solar energy; parabolic trough collectors; renewable energy; heat absorption; concentrated solar power.

1. Introduction

The development of renewable energy sources in parallel with energy storage is necessary to increase energy independence from fossil fuels, the availability and price of which have been strongly influenced by international policy in recent years [1,2].Due to rising raw material prices, the profitability of most technologies previously not considered due to their relatively high cost and the long payback period is increasing [3]. Another but extremely important aspect in favour of increasing the share of low- and zero-carbon sources is the positive impact on the environment [4]. Energy requirements can be roughly divided into two, in the form of electricity and heat [5]. Considering only solar energy as a clean energy source, for electricity generation the most common sources are photovoltaic panels. Heat can be generated using PV panels and heat pumps, but this solution is mainly considered for small domestic installations [6].

The greatest need for heat is in industry, which uses it in various processes. Depending on the characteristics of the company, heat can be used for manufacture of food and dairy products [7,8], drying and sterilization [9], steam production [10]. Heat, in the temperature range up to about 300 °C, can be efficiently generated by parabolic trough collectors with a low concentration ratio. It is a mature technology that has recently been scaled down and adapted to produce heat at lower temperature levels [11,12].

Reducing the temperature level opens up opportunities to increase the efficiency of these installations and reduce their manufacturing cost. It is therefore necessary to look for solutions that can be easily applied to this scaled-down version of a mature technology. These treatments are intended to increase the popularity of solar technologies mainly in the industry sector.

The methods proposed in this article for intensifying heat absorption can be divided according to their location of application: outside and inside the absorber. The first is the use of the no-selective and cost-effective coating in the individual preliminary sections of the absorber, in such a way as to increase efficiency and reduce the investment cost of the installation. The proposed coating differs from the regularly used one

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in that it is not selective, so radiation losses are high but are compensated by the extremely high absorptivity of this coating. The methodology associated with such a coating application has been presented in previous work [13]. A second method of heat intensification is the use of twisted tape inserts, which is a fairly popular and mature research topic [14–16]. Twisted tapes have been tested experimentally and numerically for a wide range of parameters [17,18]. Solutions that modify traditional twisted tapes, such as the application of perforation [18] or peripherally cut [19] as well as double application [20], are also analysed. However, the literature provides no sufficient data on the application of twisted tapes for low-concentrated parabolic trough collectors, which are characterised by different boundary conditions, such as radiation distribution, temperature range or mass flow.

In this analysis, a numerical study supported by experimental results has been carried out, where we propose to use the two previously described methods sequentially in an absorber loop. The research questions that this article answers are as follows.

- Does the application of the two proposed methods increase the efficiency of the installation?
- How can both methods of heat intensification be used optimally?

2. Methods

An analysis of the combination of the two heat intensification methods developed was carried out using a mathematical model and the results of numerical tests and experimental study. Figure 1 shows the assumptions accompanying the analysis. Three absorber configurations were tested in the absorber loop. The case 1, also called the reference case, was the use of tubular absorbers with a selective coating throughout the whole absorber loop. Case 2, involved included partial application of non-selective, but cost-effective coatings in part of the absorbers in such a way that the efficiency of the installation did not decrease. Case 3 shows the addition of twisted tapes inserts to the previous (from case 2) results. In summary, the analysis first aimed to determine the number of absorbers that could be covered with a no-selective coating and then to add an additional method of intensifying heat collection through twisted tapes applied inside the absorber.

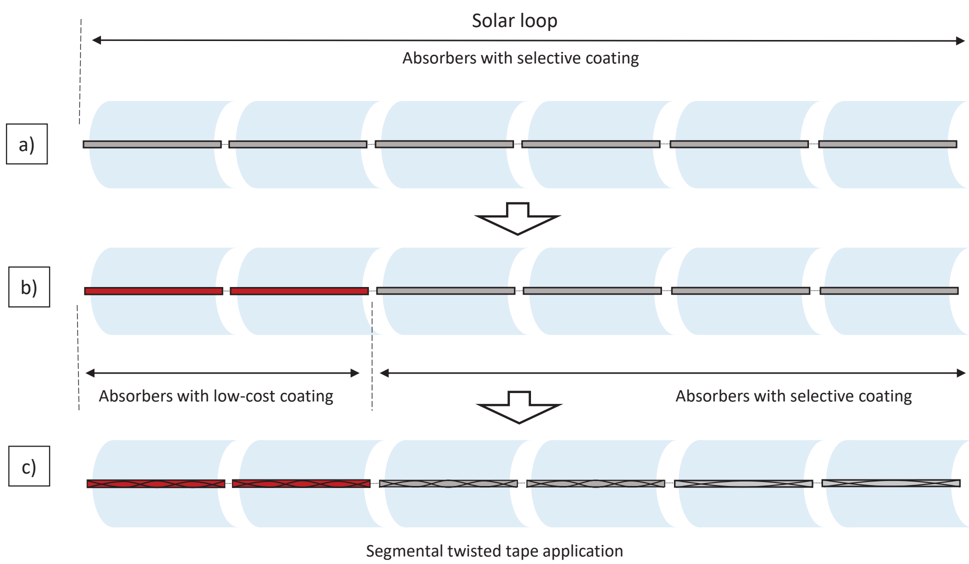

Figure. 1. Coating and twisted tapes application strategy: a) refence CASE 1 (all absorbers covered by selective coatings), b) CASE 2 with no-selective and selective coatings, c) CASE 3: combination of coatings applications and segmental twisted tapes coatings (in configuration as case 2).

2.1. Analysis assumptions

The following section outlines the assumptions that were used in the model.

2.1.1. Parabolic trough collector – geometry and operation parameters

The analysis considers a low-concentration parabolic trough collector that can produce heat for industrial applications. The geometric and optical parameters are shown in Table 1, and the most important ones which are particularly important are: aperture width 1800 mm, absorber length 1000 mm, absorber external diameter 33.7 mm. The assumed parameters are based on parabolic trough collectors manufactured serially [21].

Table 1. Geometrical and optical parameters of analysed parabolic trough collector.

Parameter	Symbol	Value	Unit
Focal length	f	0.647	m
Aperture width	W_{ap}	1.8	m
Absorber length	L_{abs}	1	m
Absorber external diameter	$d_{abs,e}$	33.7	mm
Absorber internal diameter	$d_{abs,i}$	30.7	mm
Absorber wall thickness	th_{abs}	1.5	mm
Glass env. external diameter	$d_{c,e}$	56	mm
Glass env. internal diameter	$d_{c,i}$	51	mm
Glass env. wall thickness	th_c	2.5	mm
Transmittance of glass envelope	τ_c	0.93	-
Clean mirror reflectance	η_{ref}	0.9	-
Dirt factor	η_{dirt}	0.96	-

The installation was assumed to consist of 90 absorbers connected in series, with an inlet temperature of 60 °C and a maximum outlet temperature depending on weather conditions but not exceeding 250 °C. For the analyses, the mass flow was assumed to be constant at 0.3 kg/s.

2.1.2. Heat transfer fluid

The heat transfer fluid used in the analysis was Therminol VP-1, an Eastman product widely used in solar installations and successfully used in our previous publications [22]. The operating temperature of this fluid is 12 – 400 °C. In the analysis, the data of this fluid as a function of temperature was used, based on the manufacturer's data [23]. Table 2 presents, as an example, the fluid parameters for extreme temperatures occurring in the system, i.e. 60 °C and 250 °C.

Table 2. Example Therminol VP-1 parameters [23].

Temperature, °C	Density, kg/m^3	Heat capacity, kJ/kg	Thermal conductivity, W/(m·K)	Viscosity, mPa·s
60	1032	1.662	0.1323	1.76
250	867	2.181	0.1055	0.288

2.1.3. Coatings assumptions

The analysis examined the effect of two coatings on the absorber surface. The first one was selective coating reported by Lu et al. [24] as suitable for SHIP installations. It has high absorptivity and low emissivity which reduces radiation losses. The alternative coating analysed is Pyromark 2500, which is a non-selective coating but with extremely high absorption [25]. Due to its lack of selectivity, the emissivity of the Pyromark is also high, but it is characterised by low cost and very simple application. The parameters of both these coatings are shown in Table 3.

Table 3. Coatings parameters.

Coating type	Coating name	Absorptivity	Emissivity
Selective	Mo/Al_2O_3	0.9	0.08
No-selective	Pyromark	0.965	~0.8

2.1.4. Twisted tapes

Two geometries of twisted tapes were analysed in this work, first one with twisted ratio (Tr) 1 and the second one with 2, the width of each twisted ratio was assumed equal to 28 mm and thickness 1 mm. The material used is steel. The insert is assumed to be centred on the axis of the absorber, which in reality can be realised by a specially shaped handle that centres the twisted insert. The study analysed inserts with a low twisted ratio to find the limit for which there is a benefit to its use. The twisted ratio was defines as Eq. (1):

$$Tr = H/d_{abs,i} \tag{1}$$

where, H is 180° turn length and $d_{abs,i}$ is internal diameter of absorber.

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2.2. CFD model

Numerical calculations were performed in ANSYS Fluent using a discretised 3D domain. The analysis was performed for the steady state. CFD tests were performed in the heat transfer fluid region, where constant mass flow and inlet temperature were assumed. It was assumed that twisted tape is used as a swirl flow forming element and is not involved in heat transfer. In the analysis, the k-ω SST turbulence model listed in the literature as the most optimal for this type of analysis was used [26]. To determine the influence of the numerical grid on the results, a grid independence test was performed, analysing five grids with the parameters shown in Table 4.

Table 4. Analysed numerical meshes.

Grid no.	Number of elements	Average Nusselt number
1	244 283	273.6
2	1 320 067	286.6
3	1 933 627	290.0
4	2 337 226	290.4
5	3 076 697	290.6

The results showed that the difference between grids 3 - 5 is about 0.2%, so it was decided to choose grid number 4, which is shown in Figure 2.

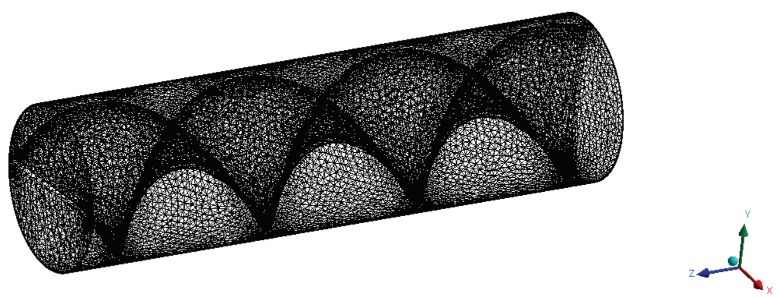

Figure. 2. Mesh used in CFD for absorber and twisted tape.

The parabolic trough collector is an installation based on a tracking system which makes it possible to utilise direct solar radiation during operation. Thus, the concentrated radiation reaching the surface of the absorber is not uniform. In CFD studies, this factor should be considered and a polynomial described distribution of radiation should be introduced by using a defined function. To obtain this distribution, optical studies were performed using the Monte Carlo Ray Tracing Method in APEX software, which has been successfully used in our previous studies [27]. An absorber with applied radiation distribution is shown in Figure 3.

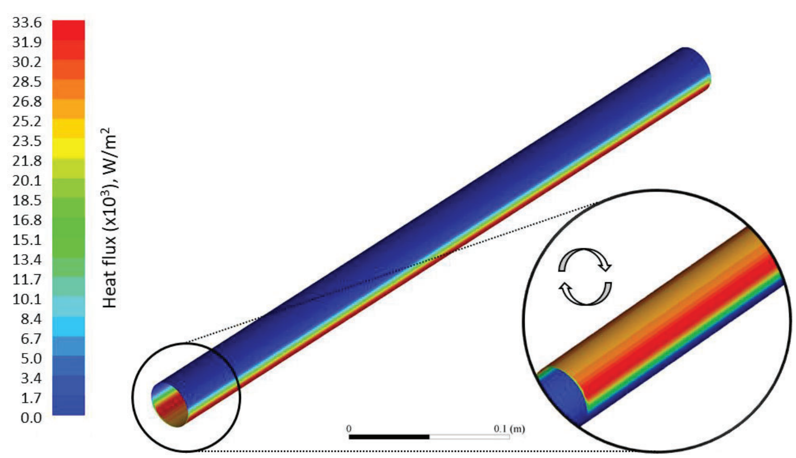

Figure. 3. Heat flux distribution on external absorber surface.

2.3. Mathematical model

In this study, a previously developed mathematical model of a parabolic solar concentrator was used, which is described in detail and validated in publication [13]. The distinguishing feature of this model from others available in the literature of the subject is the separation of heat absorbed by concentrated radiation and direct radiation (which was not reflected from the parabolic mirror). This radiation passes through a different pathway, therefore the efficiency must be calculated separately. For the high aperture PTC analysis, the influence of this factor is small, but for the low concentrated PTC, the contribution of direct radiation is more significant. The heat absorbed by the absorber is defined as Eq. (2) – (4):

$$Q_u = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}), \tag{2}$$

$$Q_u = (Q_{u,CSP} + Q_{u,SP}) - Q_{loss}, \tag{3}$$

$$Q_u = ((A_{ap} - d_{abs,e} \cdot L) \cdot G_B \cdot \eta_{opt,CSP} \cdot cos\,\theta \cdot IAM + (d_{abs,e} \cdot L) \cdot G_B \cdot \eta_{opt,SP}) - Q_{loss} \tag{4}$$

where, $\dot{m}$ is mass flow rate, c_p is specific heat, T_{in} and T_{out} are inlet and outlet temperatures, $Q_{u,CSP}$ is the concentrated solar energy, $Q_{u,SP}$ is the non-concentrated solar energy, Q_{loss}- energy losses, A_{ap} is the aperture surface area, $d_{abs,e}$ is the absorber external diameter, G_B is the direct solar irradiance, $\eta_{opt,CSP}$ is the optical efficiency for CSP, θ is the incident angle, IAM is the incidence angle modifier, L is absorber length, $\eta_{opt,SP}$ is the optical efficiency for solar power. The individual efficiencies for concentrated irradiance and non concentrated irradiance, their components and how they are calculated are presented in a previous paper [13].

Furthermore, when twisted tapes are used, it is necessary to consider the effect of the pressure drop on the requirements of the circulating pump. For this purpose, efficiency of PTC is defined as Eq. (5):

$$\eta_{PTC} = \frac{Q_u - \frac{W_p}{\eta_{el}}}{Q_s} \tag{5}$$

where, W_p is required pump power, Q_s is heat from sun and η_{el} is average reference electricity production efficiency. For purposes of this analysis, the value 32.7% is selected [28].

A pumping work demand for the fluid movement is calculated as Eq. (6):

$$W_p = \frac{\dot{m} \cdot \Delta P}{\rho} \tag{6}$$

where, ΔP is pressure drop, ρ is fluid density. The pressure drop was determined using the Darcy-Weisbach equation.

2.4. Models validation

Validation of the numerical model presented in section 2.3 was performed using the solar radiation simulator test rig and parabolic trough collectors presented in previous publications [29] and conference presentations [30]. The test stand is shown in Figure 4.

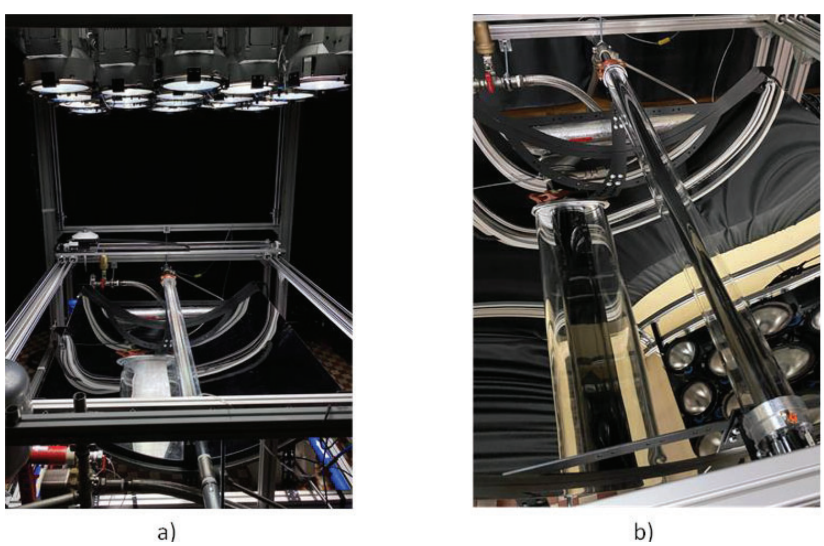

Figure. 4. Experimental test stand: a) solar simulator and parabolic trough collector under experimental campaign, b) linear absorber covered by Pyromark coating in collector focal length.

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The test rig consists of 18 metal halide lamps, each with a nominal power of 575 W, and a parabolic solar concentrator with aperture and length of 1000 mm, and absorber with diameter of 33.7 mm covered by Pyromark coating with glass envelope and vacuum in between. For temperature incensement for plane absorber the RMSD was 1.02, for absorber with twisted tape with twisted ratio 3.8 RMSD was 1.43. For pressure drop measurement RMSD was as follows: plane absorber RMSD = 5.8, absorber with insert Tr = 3.8 RMSD = 7.5.

Validation of the mathematical model presented in section 2.4 was performed using experimental data provided by the National Renewable Energy Laboratory (NREL) [31] and indicated an RMSD of 2.54 for absorber temperature and 3.52 for heat loss, which confirms its agreement with reality.

3. Results and discussion

The first part of the analysis was to determine the maximum number of absorbers in preliminary sections of the solar loop that would not result in a reduction in efficiency compared to the reference value (all absorbers covered with selective coating CASE 1). Tests were carried out for various values of direct radiation and the results are shown in Figure 5. For $G_B \geq 300$ W/m^2, the potential for partial replacement of absorbers with low-cost coatings is clearly visible. For $G_B = 300$ W/m^2, the maximum number of absorbers with Pyromark coating that can be used is 40. For higher radiation values, the possible number of absorbers increases, but assuming a worst-case scenario, a value of 40 was chosen for further consideration.

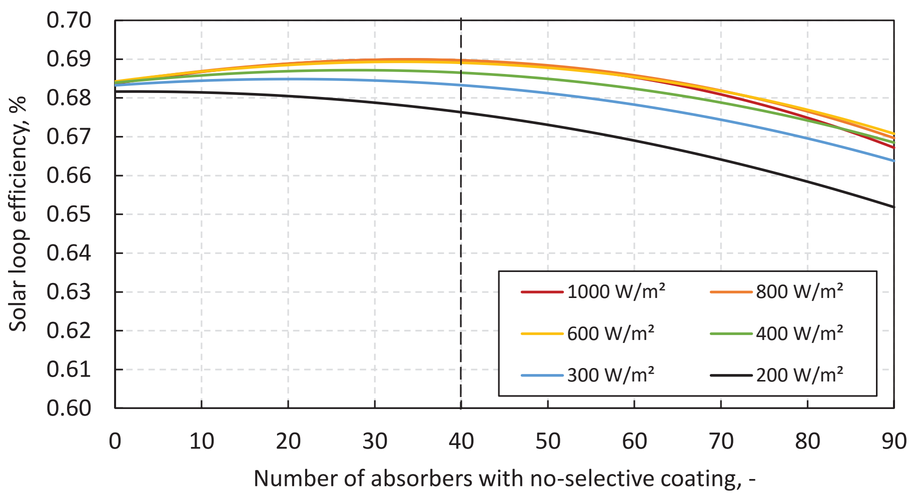

Figure. 5. Absorber loop efficiency as a function of absorber numbers with no-selective coating.

The next stage of the analysis was to test the effect of twisted tapes on increasing the intensity of heat absorption by the fluid. Twisted tapes cause swirl flow, which intensively mixes the fluid inside, resulting in an increase in velocity and thus in the number of Reynolds and an intensification of heat absorption. What is more, this flow character results in a reduction in the temperature difference at the absorber surface, which reduces material stress and increases the life span of the installation. However, the placement of any element inside the tubular absorber results in increased pressure losses which force higher own energy needs to drive the circulation pump.

Considering the pumping demand (Eq. (6)) in the efficiency of the PTC loop (Eq. (5)), it is possible to determine the efficiency increment resulting from the use of an insert with a specific twisted ratio. Fig. 6 shows the increase in efficiency ratio relative to the reference case for a specific thermal fluid temperature. The graph highlights two data series, for twisted ratio 1 and 2. It can be seen that the use of both these inserts results in an efficiency gain relative to the reference case. However, it was observed that for fluid temperatures above 200 °C the efficiency of PTC with twisted ratio 1 decreases significantly. This is due to the high velocity and relatively high-pressure drop relative to the increased intensification of heat absorption and the increased power requirement of the pump. It was therefore decided that for temperatures up to 200 °C it was appropriate to use tape with ratio 1, and above this temperature tape with ratio 2.

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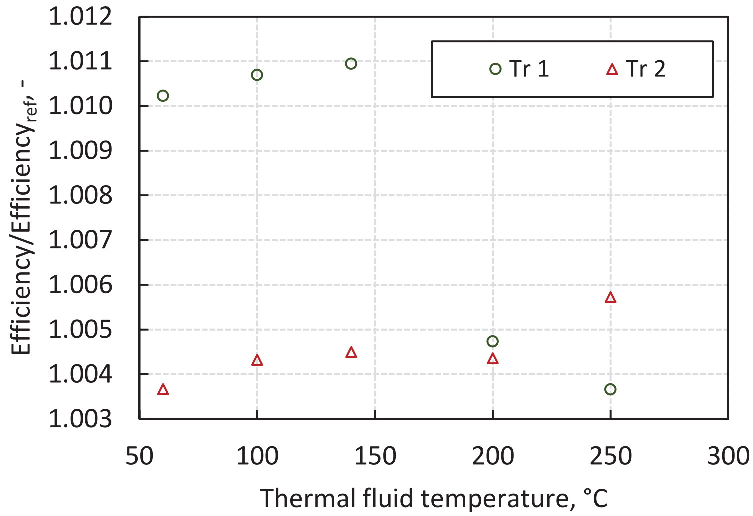

Figure. 6. Efficiency with twisted tapes to reference efficiency ratio as a function of heat transfer fluid temperature for different twisted ratio inserts.

As the application of twisted tapes has to be done for specific sections of the PTC, the next part of the analysis was, for a predefined sequence of specific absorber types, to determine where to apply which type of twisted tape. For this purpose, it was determined that a temperature above 200 °C of fluid would occur in the furthest sections of the absorbers for the case of the highest radiation value. The efficiency of absorber loop and thermal oil temperature along loop length were therefore determined and presented in Fig. 7. Based on the results, it was determined that defined temperature in the absorber loop, consisting of 90 absorbers, could occur after the 60 absorbers, so it was decided to use inserts with twisted ratio 1 in preliminary 60 metres. After the 60th absorber, twisted tape with Tr = 2 was used.

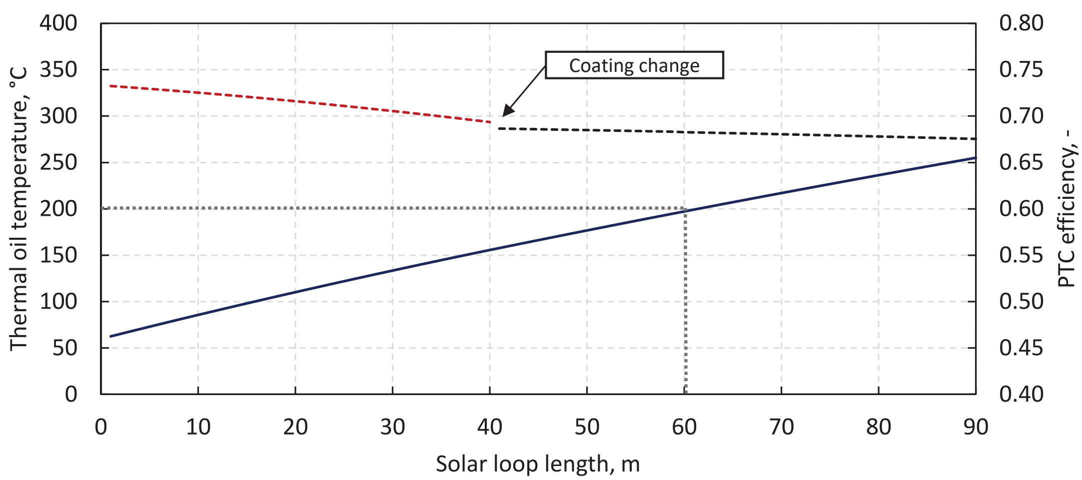

Figure. 7. Thermal oil temperature and efficiency along solar loop for G_B = 1000 W/m^2 and T_{amb} = 23°C.

To directly compare the results, a wide-parameter analysis was performed for G_B ranging from 300 to 1000 W/m^2, T_{amb} from 2 to 35 °C and wind speed of 0.1 - 5 m/s while maintaining a constant mass flow of 0.3 kg/s and T_{in} 60 °C. Case 1 has the lowest efficiency, but the most constant curve. As the parameter represented on the x axis increases, the efficiency slightly decreases. Each of the methods analysed intensifies heat absorption and increases the overall efficiency of the installation. By using absorbers with a high absorptivity value, the highest efficiency gains when the installation is operating in high solar radiation is visible. The increased absorptivity along the length of the installation largely contributes to increased heat collection and efficiency. Emission losses are largely compensated by the high absorptivity. For periods with low insolation and temperature, there is no increased heat absorption and losses to the environment are high, but no greater than the reference case. The use of twisted tapes has the effect of intensifying heat absorption throughout the whole analysed range. In periods of high solar radiation, swirl flow reduces the

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temperature of the absorber wall and intensively mixes the heat transfer fluid. During periods of low insolation, twisted tape has the effect of increasing the velocity and the Reynolds number and increases heat extraction. Using only the method related to the coatings, the maximum efficiency gain will be around 0.7%, for using both methods in the configuration presented, the efficiency gain is between 0.3% and 1.3%.

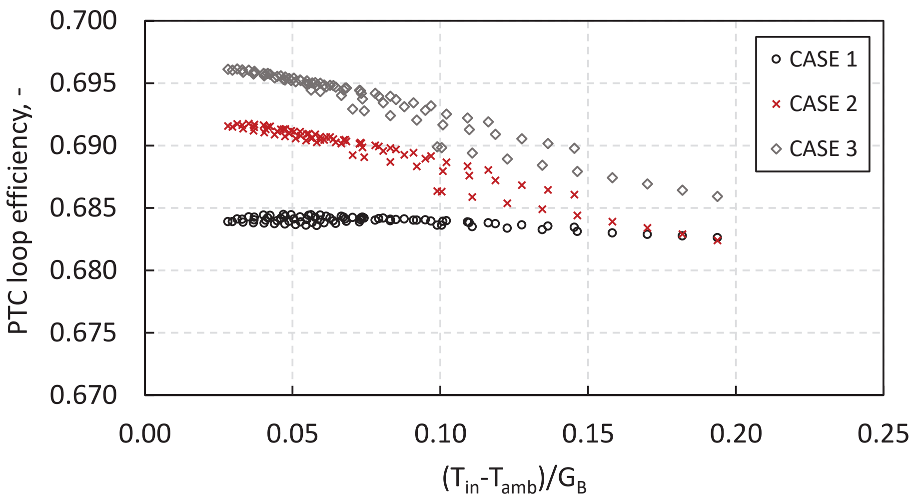

Figure. 8. PTC loop efficiency curves for 3 analysed cases.

4. Conclusions

This paper presents two methods to intensify heat absorption: externally by using a highly absorptive coating, and internally by using twisted tapes to increase flow turbulence. The following conclusions can be drawn.

- Both of the proposed methods intensify the heat collection in the absorber.
- It has been shown that it is optimal to cover 40 of the 90 absorbers with a no-selective coating.
- Besides the increased heat uptake of the absorber in this configuration, it is possible to reduce investment costs due to the low price and simplicity of the Pyromark coating application.
- Numerical tests have shown that both inserts analysed increase the heat absorption efficiency and that up to a temperature of heat transfer of 200 °C it is optimal to use an insert with twisted ratio 1, above this temperature with twisted ratio 2.
- Analysing the entire solar loop consisting of 90 absorbers, the following parameter combinations were determined: non-selective coating up to 40 absorbers, from 41 absorbers selective coating, insert with twisted ratio 1 up to 60 absorbers, from 61 absorbers twisted ratio 2.
- Efficiency increment after proposing Pyromark coatings increased from 0% to 0.7% with both methods, from 0.3% to 1.3%.

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Nomenclature

A	area, m²
c_p	specific heat, J/(kgK)
CSP	concentrated solar power
d	diameter, m
f	focal length, mm or m
G	direct normal irradiance, W/m²
H	180° turn length
IAM	incidence angle modifier
L	length, m
$\dot{m}$	mass flow
PTC	parabolic trough collector
Q	heat
RMSD	Root mean square deviation
T	temperature, °C
th	thickness, mm
Tr	twisted ratio
W	width, mm or m; or power, W
ΔP	pressure drop, Pa

Greek symbols

η	efficiency
ρ	density, kg/m3
τ	transmittance

Subscripts and superscripts

abs	absorber
amb	ambient
ap	aperture
B	beam
c	envelope
CSP	concentrated solar power
dirt	dirt factor
e	external
el	electrical
i	internal
in	inlet
loss	loss
opt	optical
out	outlet
p	pumping
ref	reflectance
s	solar
SP	solar power
u	useful

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