DOCTORAL THESIS IN ENVIRONMENTAL ENGINEERING, MINING AND ENERGY
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Multi-variant experimental and numerical analysis of selected design and energetic aspects of parabolic trough collectors

Wielowariantowa analiza eksperymentalno-obliczeniowa wybranych zagadnień konstrukcyjnych i energetycznych dla technologii parabolicznych koncentratorów promieniowania słonecznego

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DOCTORAL THESIS EXTENDED SUMMARY

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Title: Multi-variant experimental and numerical analysis of selected design and energetic aspects of parabolic trough collectors

The following description sums up the essential parts of the scientific dissertation written as the article guide book (based on 4 selected papers), submitted to discipline of Environmental Engineering, Mining and Energy. For the full description book, please see the doctoral thesis, where full description and 4 papers are included.

1. Motivation and objectives

Low-concentration parabolic trough collectors are highly versatile systems that, when properly designed and parameterised to suit the characteristics of a particular industry sector, can cover a significant proportion of the heat demand at different desired temperature levels. Despite the maturity of the concentration technology and the many studies related to full-scale PTC, the different, reduced geometry and thermodynamic parameters offer the potential for the application of new solutions and materials that will both increase the efficiency of the technology and reduce the price of the selected components, which may influence the spread of this type of solar installation even in areas with lower average annual insolation. This could lead to an increasing share of renewables in the total energy mix, resulting in lower emissions and higher independence from fossil fuels. The materials used in the concentrators are simple to manufacture and later recycle, so this type of device has an additional positive impact on the environment relative to other solar energy technologies. It is essential, to search for areas and solutions that can intensify the heat absorption of parabolic trough collectors and enable comparative studies of these devices under stable and repeatable solar conditions. Therefore, this thesis aims to investigate different types of heat intensification on the inner and outer sides of absorbers in parabolic trough collectors and to examine their impact on entire solar loop installations.

The scientific problems discussed in this thesis are related to three selected elements of parabolic trough collectors, however, with comprehensive consideration of the entire technology: heat extraction enhancement inside the absorber through the use of inserts in a suitable arrangement, heat absorption intensification through using highly absorptive non-selective coating, and analysis of the influence of the crucial element in PTC such as the active solar tracker on the efficiency of the heat concentration and absorption process.

The following research activities were formulated to reach the objectives of this thesis.

- Comprehensive design and construction of a solar radiation simulator test stand, enabling tests to be carried out on different types of absorbers, under stable and repeatable conditions.
- Identification of processes and development of a mathematical model for heat transfer in a parabolic trough collector.
- Conducting a series of experimental analyses to validate the developed models.

- Investigating the impact of twisted tapes located inside a linear absorber and their arrangement in a solar loop to maximise the efficiency of a parabolic trough collector.
- Investigating the effect of different types of highly absorbing coatings on the outer surface of the absorber and their segmental application along the length of the solar loop.
- Development of a numerical optical parabolic concentrator model and performance of a series of analyses to identify the impact of tracking error on PTC efficiency.

2. Scope of the thesis

The doctoral thesis consists of 6 chapters.

Chapter 1 is Introduction chapter.

Chapter 2 is devoted to a description of the test bench modelling required for experimental research on parabolic trough collectors and the process of heat absorption by heat transfer fluid in tubular absorbers. Due to the varying natural atmospheric conditions over time, to investigate linear absorbers under constant and repeatable conditions, the author of this thesis designed and then comprehensively constructed a stand based on a solar radiation simulator enabling the simulation of near-natural radiation not dependent on the time of year or day. For this purpose, a series of numerical analyses were carried out using the Monte Carlo Ray Tracing Method to determine the most suitable type of light source, the optimum geometry of the parabolic cross-section reflectors and their arrangement against the parabolic trough collector. The study considered the desired spectrum of the simulated radiation analysis, its scattering and non-uniformity and how these factors affect the radiation concentration process. This part of the thesis also identifies the estimated cost of the radiation simulator, detailing specific components, which was missing in the literature on the subject. The results of performed analyses were crucial in further work, which was a comprehensive construction of the test stand by the author of this thesis.

Chapter 3 presents the results of an analysis aimed at intensifying heat extraction inside the linear absorber using twisted tape inserts, segmentally positioned in different sections of the solar loop. A low-concentrated ratio installation was considered, which could be used as an additional heat source for industrial applications. The study was conducted using a CFD model and a two-dimensional mathematical heat transfer model. The mathematical model of heat transfer is described in detail in the next chapter. The calculations were validated with experimental results, carried out on a developed laboratory station equipped with a solar radiation simulator, which showed high agreement, confirming the validity of using these models. Both temperature increment and pressure drop were validated. This chapter also presents the developed and assembled test bench for absorbers comparative research. In the numerical studies, the non-uniform distribution of concentrated heat flux on the absorber surface, consistent with the real conditions, was applied, which increases the accuracy of the calculations against most models presented in the literature. The results obtained demonstrate the validity of the segmented application of twisted tapes, by considering the additional pressure losses and the increased demand to cover installation own needs caused by higher circulating pump demand. A long-term analysis of the specified conditions showed the potential to increase the efficiency of the solar facility by approximately 0.27 percentage points.

Chapter 4 is focused on coatings applied on absorber external surfaces to increase the absorptivity and thus the efficiency of the installation. The main objective of the results presented in this chapter was to determine the possibility of replacing the expensive selective coatings typically used in linear absorbers with cost-effective but highly absorptive no-selective coatings in preliminary absorber sections, with maintaining at least the same efficiency level. To determine the potential of such a design, analyses were performed for parabolic trough collectors with different geometries that reflect the varied nature of their application. To perform the assumed analyses, a detailed heat transfer model in parabolic trough collectors was developed, the calculation procedures of which are presented in the study methodology. Furthermore, the model was developed with special consideration for the separation of the heat flux supplied to the absorber surface into a concentrated and natural form. In parabolic trough collectors with a low concentration ratio, this separation significantly increases the accuracy of the results obtained, due to the higher proportion of natural radiation compared to full-scale parabolic trough systems. The results showed that, due to the lower temperature level of heat transfer fluid, a high potential of the non-selective coatings co-application was indicated. Furthermore, the use of a low-cost non-selective coating can provide a significant reduction in the investment cost of the installation and impact the development potential of concentrating solar power systems.

Chapter 5 deals with an aspect of solar tracking. Parabolic trough collectors, which are one of the technologies based on concentrating solar radiation, require continuous solar tracking due to the utilisation of mainly direct irradiance. As an active component, the solar tracker is characterised by a certain degree of positioning accuracy and is exposed to weather conditions, especially wind. Based on a low-concentrated parabolic trough collector geometry, a series of optical and thermodynamic analyses were conducted to determine the maximum positioning deviations of the solar tracker to avoid reducing its efficiency. Ray tracing analysis and heat transfer model was adopted for this purpose. The results are intended to indicate assumptions for the design of low-concentrated parabolic trough tracking devices. The study also compiled results for another way of reducing the cost and weight of the installation, i.e. not using a glass envelope around the absorber pipe. The increased level of non-uniformity of heat flux on the absorber surface was also discussed, which, because of the tracking error, can cause high-temperature differences on the absorber surface and thus affect its potential damage.

Chapter 6 presents a summary and conclusions.

Chapters 2 to 5 highlight the most significant aspects of Articles I to IV, which are included in the appendix section. Figure 1 shows a graphical visualisation of the thesis scope.

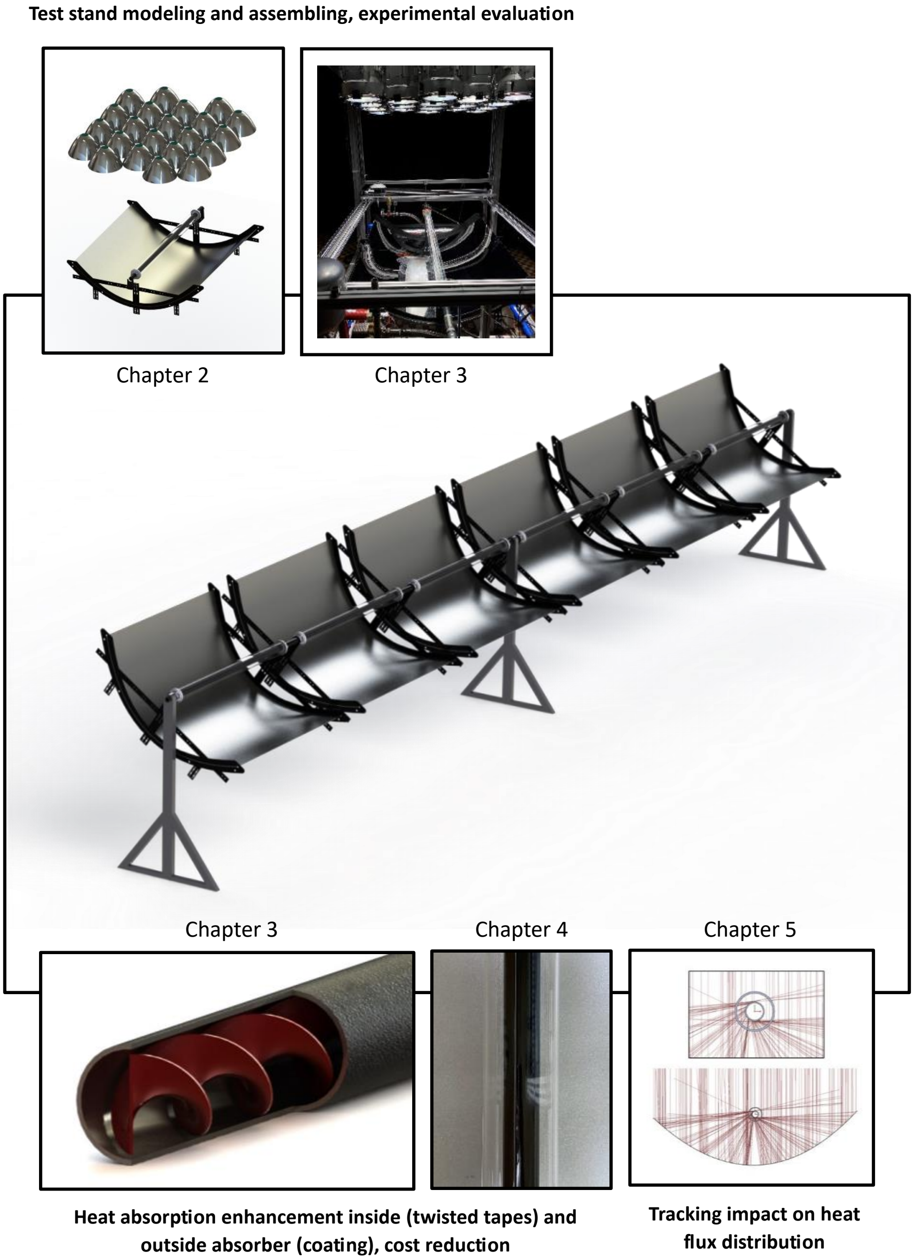


Fig. 1 Graphical visualisation of the thesis scope

3. List of publications

The doctoral thesis consists of 4 monothematic papers listed below.

I. Ł. Bartela, **B. Stanek***, D. Węcel, A. Skorek-Osikowska, *A solar simulator numerical modeling for heat absorption phenomenon research in a parabolic trough collector*, International Journal of Energy Research, Vol. 46, 2021, (**IF**$_{2021}$=**4.672**)

II. **B. Stanek**, J. Ochmann, D. Węcel, Ł. Bartela*, *Study of twisted tape inserts segmental application in low-concentrated solar parabolic trough collectors*, Energies, Vol. 16, 2023, (**IF**$_{2022\text{-}2023}$=**3.252**)

III. **B. Stanek***, W. Wang, Ł. Bartela, *A potential solution in reducing the parabolic trough based solar industrial process heat system cost by partially replacing absorbers coatings with non-selective ones in initial loop sections*, Applied Energy, Vol. 331, 2023, (**IF**$_{2022-2023}$=**11.446**)

IV. **B. Stanek***, D. Węcel, Ł. Bartela, S. Rulik, *Solar tracker error impact on linear absorbers efficiency in parabolic trough collector – Optical and thermodynamic study*, Renewable Energy, Vol. 196, 2022, (**IF**$_{2022}$=**8.634**)

*corresponding author

The author's contribution for each paper was following:

I. **Bartosz Stanek's contribution** was to plan and design the experimental test station, develop a numerical model for ray tracing analysis, carry out a calculation campaign, analyse results, estimate the cost of the solar simulator, prepare and submit the manuscript. According to the author's statement, Bartosz Stanek's contribution was equal to **55 %**.

II. **Bartosz Stanek's contribution** was to prepare the scope of the numerical and experimental analysis, comprehensively design, construct and assemble the experimental test stand, develop the experimental methodology, manufacture twisted tape inserts, execute experimental tests and validate numerical models, perform ray tracing analysis, formulate boundary conditions for CFD analysis, conduct long term analysis, analyse results, prepare the manuscript. According to the author's statement, Bartosz Stanek's contribution was equal to **65 %**.

III. **Bartosz Stanek's contribution** was to formulate research assumptions and methodology, develop a mathematical model of heat transfer, conduct a calculation campaign, analyse the results, prepare and submit the manuscript. According to the author's statement, Bartosz Stanek's contribution was equal to **80 %**.

IV. **Bartosz Stanek's contribution** was to prepare scope and assumptions for optical and thermodynamic analysis, develop Ray Tracing numerical models, conduct a calculation campaign, analyse the results, prepare and submit the manuscript. According to the author's statement, Bartosz Stanek's contribution was equal to **65 %**.

4. Modelling of the solar simulator experimental bench for linear absorbers testing - Paper I

The considered research stand had to be multipurpose enough to be used mainly for testing parabolic trough collectors but also in the future for testing photovoltaic panels, so the main idea was that the light sources would be arranged on one plane surface and illuminate the target below. Due to the high cost of prefabricated solutions that could not be directly adapted to the planned tests, it was decided to carry out a series of optical-numerical studies to perform a preliminary analysis to check the validity of using different light sources and designing the test bench. The objectives were that the illuminated area had to be a minimum of 1 square metre (1x1 m), the radiation as uniform as possible, the spectrum as similar to solar radiation as possible, and the heat flux provided to the absorber surface corresponding to approximately 1000 W/m^2 direct normal irradiance. A visualisation of the test stand with a parabolic trough collector, is shown in Figure 2.

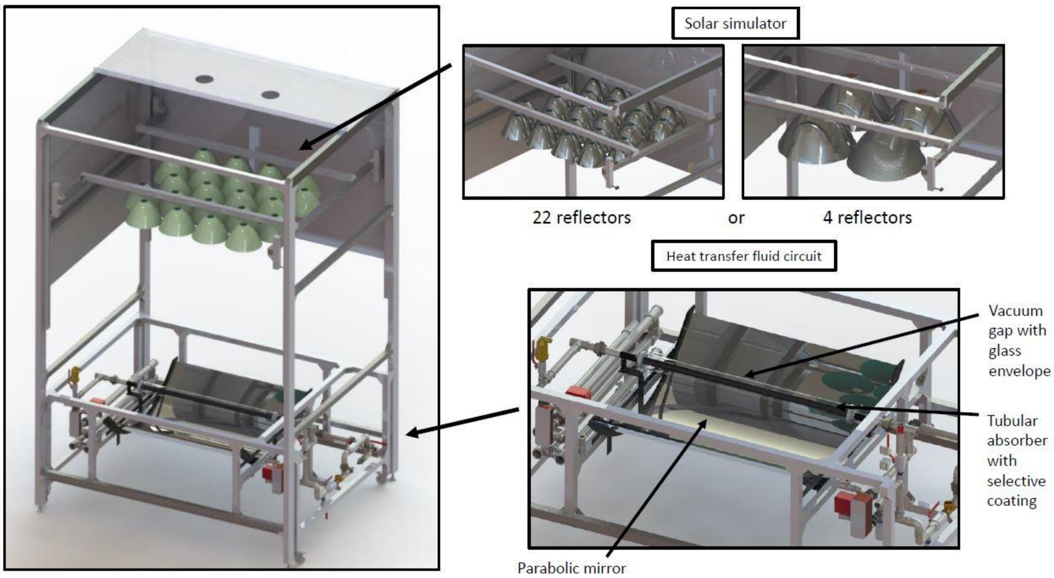


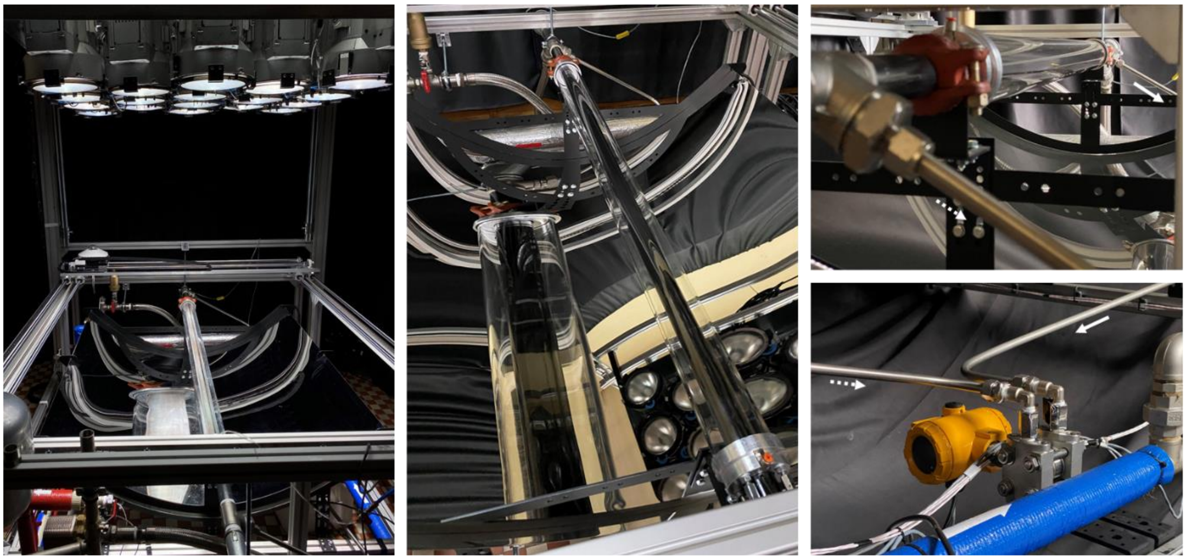
Fig. 2 The design of the solar simulator for testing parabolic trough collectors

The results obtained enabled a comprehensive analysis of the test bench to be carried out and a list of required elements to be determined, which reproduced radiation close to natural one as efficiently as possible.

5. Heat absorption enhancement inside tubular absorber by using twisted tape inserts - Paper II

The first part of this chapter was devoted to experimental test stand, the second one to twisted tape inserts analysis.

The comprehensive assembly of the experimental stand can be divided into many stages, but two main parts were the most demanding: the radiation simulator and the parabolic trough collector. The final stand arrangement consisted of 18 ARRI spotlights, each with an HMI OSRAM source of 575 W configured as shown in Figure 3. All tests were performed under solar simulator stable conditions, following verification of the stability of the radiation emitted by the discharge sources, and with the laboratory shaded to neutralise the influence of outdoor conditions. Measurements of heat flux and its distribution were carried out periodically to determine both the energy input to the absorber surface and the changes associated with source degradation. All tests were performed for a steady state, which required sufficient time for thermal stabilisation of the installation. Data recording was carried out continuously to determine the stability of the measurement. The associated measurement uncertainty, in each case, was calculated according to GUM (Guide to the Expression of Uncertainty in Measurement) objectives.



a) b) c)

Fig. 3 Experimental bench: a) solar simulator and parabolic trough collector, b) linear absorber placed in parabolic trough focal length, c) pressure drop meter and its connections before and after linear absorber

The Application of flow-disturbing inserts inside the tubular absorber is one of the known methods of intensifying heat absorption by the heat transfer medium. The study analysed the use of tabulating inserts in a segmented arrangement along the length of the absorber to identify a combination that maximises heat extraction and does not cause excessive pressure drop. Twisted tapes are characterised by a simple structure and potentially the highest chance of use in a solar loop due to their simplicity of application and manufacturing process. The twisted tape places in linear absorber is presented in Fig. 4, where main geometrical parameters ale marked.

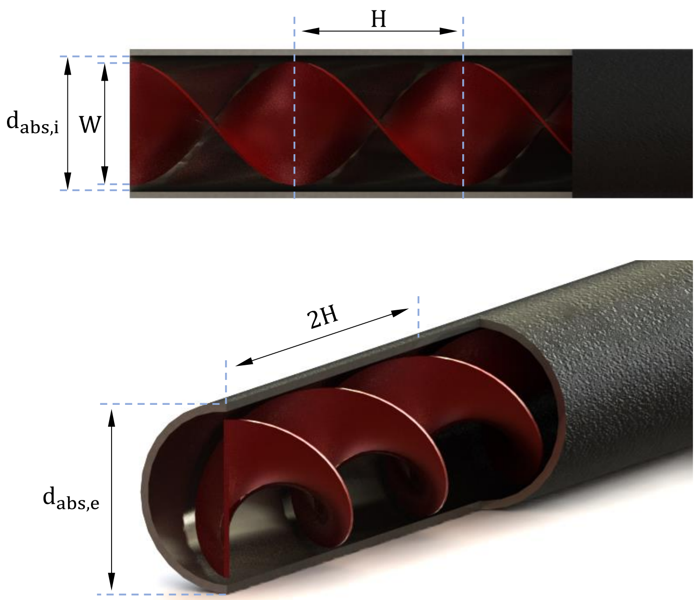


Fig. 4 Linear absorber with twisted tape insert

The impact of twisted tapes on the installation strictly depends on a variety of parameters, which also limits the possibility of performing a broad multi-parametric analysis. In the research conducted, geometries and parameters similar to those of manufactured solar installations which are based on parabolic trough collectors were assumed and for these assumptions, the validity of their use in the particular sequence was presented. Twisted tapes applied inside the absorber loop create a swirl flow, which is characterised by intensive mixing of the fluid and detachment of the near-wall layer, thus intensifying heat absorption. The analysis indicates the correlations of how the Nusselt number increases with decreasing twisted ratio. A reduction in the fluid temperature differential around the absorber circumference has also been demonstrated, potentially extending the operating period of the absorbers and reducing the internal thermal stress of the receiver. In the results, the maximum range of applicability of the inserts in the solar loop analysed was determined, which maximises the efficiency of the installation. The applied solution was tested by performing a long-term analysis, with varying weather conditions based on the NREL weather database.

6. No-selective absorber coating segmental application in solar loop - Paper III

The external surface of serially produced linear absorbers is usually coated with a selective coating, which is a coating with high absorptivity and low emissivity. This is a result of adapting regular parabolic trough collectors to their smaller-scale equivalents and preserving this design feature. However, the lower temperature level occurring in the preliminary sections of low-concentrated parabolic trough collectors loop provides the opportunity to apply significantly cheaper coatings, of a non-selective nature but with extremely high absorptivity, a low price and a simpler application process. An analysis of the potential for applying this previously not considered approach to reduce investment costs and, in some cases, increase installation efficiency was presented in the Paper III. The tool that enabled this analysis was the developed 2-dimensional heat transfer model, especially for low-concentrated ratio parabolic trough collectors.

The advanced mathematical model developed includes parameters such as the geometry of the parabolic collector installation, the materials used and their thermodynamic and optical properties, the atmospheric conditions such as solar irradiance, ambient and sky temperature, sun position and wind speed. The effect of the positioning error, mirror and receiver dirt, type of coating, shading and incidence angle modifier is also included in the model.

The heat transfer model in the receiver includes convection between the inner surface of the absorber and the heat transfer fluid, conduction through the absorber pipe, radiation and convection losses between the external surface of the absorber (including coating) and the internal surface of the glass envelope, conduction through the glass envelope, convection and radiation losses from external glass envelope to ambient and sky. The heat transfer model was presented in Fig. 5.

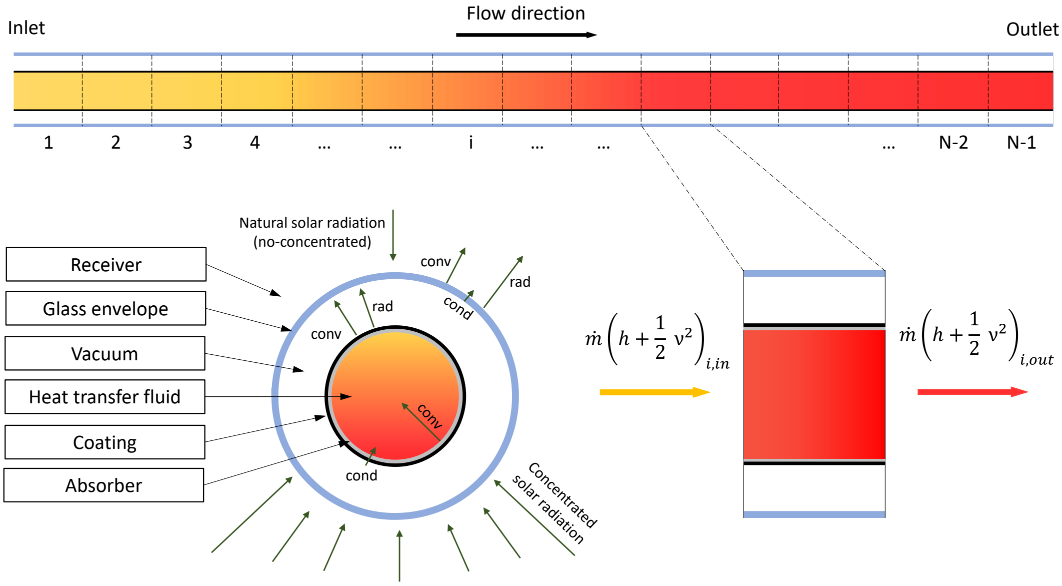


Fig. 5 Two-dimensional model of heat transfer in PTC receiver

The extremely high absorptivity of some non-selective coatings applied to the external surface of the absorber compensates for the radiation losses resulting from the high emissivity, which is dependent on the temperature of the heat transfer fluid and absorber surface. The optimisation of the use of these coatings is highly dependent on the nature of the flow, type of heat transfer fluid, temperature and concentration ratio. Paper III analyses the application potential of this solution for three PTC geometries with different temperature stages, reflecting possible applications in the solar thermal industrial process and one case reflecting a full-scale power plant. The advantage of non-selective coatings such as the Pyromark analysed is the very simple application method, in this case, it is a spray coating. Compared to the multi-step application process of selective coatings, which requires a series of expensive equipment, the potential for a reduction in investment cost seems significant.

The study analysed both the efficiency of the absorber in its length and the efficiency of the entire solar loop, consisting of several absorbers. The first results showed the potential in the application of a non-selective coating up to a heat transfer fluid temperature range of about 115 °C for a single solar loop length of up to 45 metres. At the same time, the results depended mainly on the reference coating and the type of flow adopted, in accordance with the respective industrial installations. Figure 6 shows the results where the inlet temperature to the solar loop was 100 °C and the minimum assumed outlet temperature was 200 °C. The analysis was performed for G_B=800 W/m2 and three different solar loop lengths consisting of 8, 16 or 24 absorbers. To obtain the minimum desired temperature for the same conditions, the corresponding mass flow had to be adjusted. The application of Pyromark in the preliminary absorber sections initially increases the efficiency of the solar loop, but with too many absorbers, the efficiency decreases below the reference value. Points A and B, respectively, determine the operating points that maximise efficiency and maximise the number of absorbers while maintaining an efficiency higher than the reference value. It was demonstrated that, for the conditions analysed, a low-cost non-selective coating could be used in up to 25%, 50% and 62.5% of the absorbers. The results showed the high application potential of this method at the same time demonstrating its high dependence on work parameters.

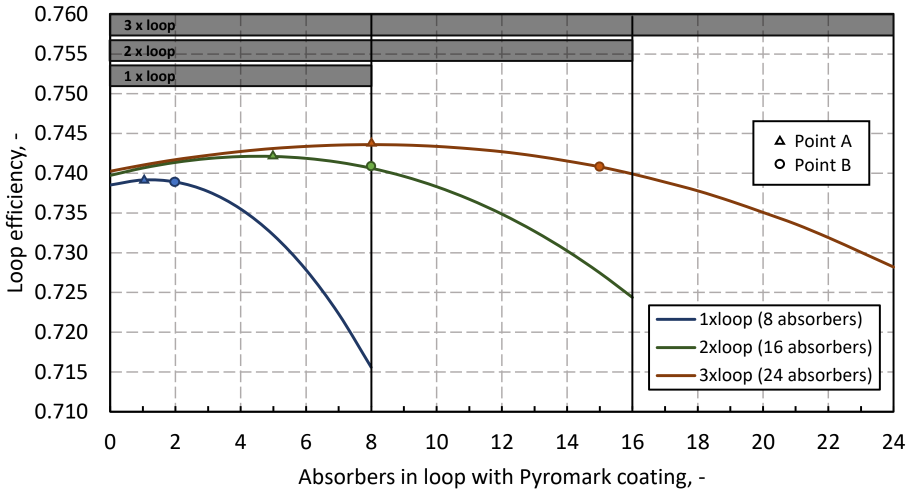


Fig. 6 Solar loop efficiency as a function of number of absorbers with no-selective coating, results for selected case

7. Evaluation of tracking deviation impact on parabolic trough collector efficiency - Paper IV

Since mainly direct solar radiation is utilised in CSP installations, the correct irradiance concentration is a crucial process in achieving high efficiency. Therefore, in the Paper IV, it was decided to analyse this phenomenon and investigate the impact of the potential error that can occur with a solar tracker which is vulnerable to atmospheric conditions, especially wind. This research aims to answer the following question.

- What is the maximum tracker error that does not affect installation operation?
- What is the positioning effect on the low-concentrated parabolic trough collectors' efficiency?
- How does tracking error affect the radiation distribution on the absorber surface?

The impact of solar tracking error was investigated using optical-engineering Monte Carlo ray tracing software APEX, which uses a Bidirectional Reflectance Distribution Function (BRDF) to describe the reflected beam behaviour. This method allows the energy accompanying each ray to be tracked and the total flux and distribution to be calculated on the selected surface, in this instance the outer surface of the absorber. The BRDF function describes the form in which the incident light over a surface is scattered. This method considers the material properties of individual parts, including reflectivity, transmissivity and absorptivity.

Changing the position of the parabolic mirror relative to the direct solar rays shifts the focus point of the absorber axis, in one direction as can be seen in Figure 7. Certain rays are focused unevenly on the surface of the tubular absorber, while others completely miss the surface of the absorber. The selected results graphically visualise path rays that, when reflected from the parabolic mirror, entirely skip the absorber surface for a tracker deviation of 4°. The usual distribution of heat flux on the surface of the absorber generates a non-uniform distribution of radiation, but still, one that has its axis of symmetry. In the studies carried out, it was shown that an error in the position of the tracker generates areas with very high heat flux values.

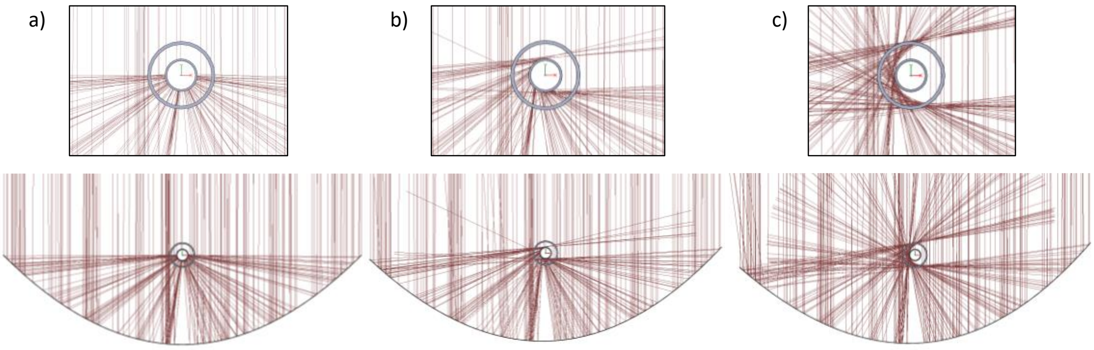


Fig. 7 Solar radiation path for selected tracker error presented in the cross-section, tracker position deviation: a) 0° (ideal), b) 2°, c) 4°

8. Summary and conclusions

The doctoral dissertation is based on the author's four major monothematic publications in the following journals: Paper I - International Journal of Energy Research (*publ. Wiley & Sons*), Paper II - Energies (*publ. MDPI*), Paper III - Applied Energy (*publ. Elsevier*), Paper IV - Renewable Energy (*publ. Elsevier*).

The main objective of this study was to identify the phenomenon of heat absorption in a parabolic trough collector and to determine methods to intensify heat absorption by analysing selected components of PTC. In the thesis, the primary research interest was placed on parabolic trough collectors with low-concentration ratios, which can produce heat with the potential for use in industrial processes.

Research activities which made the objective of the dissertation possible were the development of a model of heat flow in a linear absorber, the description of this model by a set of mathematical equations, the creation of 2 and 3-dimensional models, and the development of an optical model of the phenomenon of radiation concentration on the external surface of a tubular absorber. Validation of the developed designs was possible by conducting a series of experimental tests on a test stand, where a parabolic trough collector with multiple absorbers was tested using a solar simulator. The experimental test stand created as part of the doctoral study was comprehensively designed and manufactured by the author of this thesis.

The research work on analysing the performance of parabolic trough collectors was initiated by conducting two activities simultaneously. The first involved analysing and in-depth comprehension of the process of radiation concentration on the external surface of the absorber and the phenomenon of absorption of this heat in linear absorbers. The data resulting from this analysis directly influenced the parallel research activity, which was the definition of assumptions and the design of an experimental test stand on the previously mentioned heat absorption phenomenon.

In the paper I included in the dissertation, the process of designing the test bench is presented, which began with the analysis and selection of the light source type, considering the spectrum of radiation as well as the operating characteristics.

The analysis considered, three potential sources: tungsten halogen, metal-halide and xenon arc lamp. In terms of, spectral distribution and the nature of the radiative emission, tungsten halogen was rejected and the potential sources metal-halides and xenon arc lamps were adopted for further consideration. At this stage of the research, considering the assumed illuminated area of at least 1 m^2 and the variety of commercially available HMI and Xenon sources, the use and corresponding arrangement of reflectors with different coatings were considered. Two geometries were selected, one for HMI and one for Xenon, taking into account the assumed geometry of the parabolic concentrator and absorber, as well as possible reflectors and their compatibility with the light sources. The subsequent step, was the modelling of the optical system using the optical-engineering software APEX which is based on Monte Carlo Ray Tracing Method. The analysis revealed that for both cases, a portion of the simulated radiation has a scattered nature, and after reflection from the parabolic mirror did not reach the absorber which highlighted the need to oversize the light sources to achieve sufficient heat flux. It was determined that the best conditions for radiation simulation were achieved for the case where 22 units of 400 W HMI were considered. The analysis concludes that the simulation of optical systems depends on many parameters and each of them affects the nature of the simulated radiation. The use of a higher number of smaller reflectors with metal-halide sources allows for a higher energy stream reflected from the mirror of the concentrator and reaching the absorber tube. At the stage of planning the test stand (2019/2020), the cost of the solar simulator was estimated at around 20 000 euros.

The next stage of the work was the comprehensive construction of a test stand, in which the parabolic trough collector, could be tested under constant and repeatable conditions. This was the most time-consuming phase of the work because it took about 3 years in total. Finally, in the stand 18 HMI 575 W sources of the same series of types as those studied in the optical tests presented in the first part of the study were used. Optical analyses were repeated for higher source power and fewer reflectors and confirmed the feasibility of using this configuration. The experimental stand was divided into 2 parts, a solar radiation simulator and a parabolic trough loop. The incident radiation on the outer surface of the linear absorber corresponded to a natural radiation value of 990 W/m^2. The results of the conducted series of analyses were intended to validate numerical models developed simultaneously, describing the process of heat transfer in parabolic trough collectors. The research was carried out for stabilized conditions, where intensification of heat absorption was considered through, for instance, the effect of coatings on absorber efficiency, as well as the application of various inserts inside the linear absorber on the heat transfer fluid side. Validation results showed high agreement between models and experiments.

At the same time, mathematical models of parabolic trough collectors were developed. The proposed mathematical model was specifically adapted to low-concentrated installations by considering concentrated and non-concentrated radiation separately.

Regarding the analysis of heat absorption by the absorber, one can distinguish the work carried out into ones focused on the inner and outer parts of the linear absorber. Inside the absorber, the focus was on the application of twisted tapes, introducing swirl flow, which results in the intensive mixing of heat transfer fluid inside the tubular absorber, and a more intensive collection of heat from the inner walls of the absorber. Twisted tapes with twisted ratios of 1, 2 and 4 were considered, where the diameter of the absorber was corresponding to the installation to heat industrial process applications. The temperature range of the analyses performed was within the assumptions of heat for industrial processes and was in the range between 60 °C and 250 °C. Analyses demonstrated that each of the considered inserts results in an intensification of heat extraction, an increase in efficiency and a reduction in maximum temperature peaks, which reduces stresses in the installation. For the analyzed results, optimization showed that the most optimal is to use an insert with twisted ratio 1 up to 190 °C of thermal fluid, and twisted ratio 2 for higher temperatures. The results of the numerical analysis were applied to a mathematical model to verify the long-term impact of this arrangement on the PTC facility efficiency. The study was performed for southern Spain location to highlight the applicability of low-concentrated PTC for heat industrial processed in locations with extremely high application potential, highlighted in the introduction section. The analysis was performed at a 1-hour frequency, considering changing weather conditions, for a solar loop of 90 meters. Besides the 12-month analysis for the one year period, results for three selected days were presented. The average increase in the system's efficiency was 0.27%, including pressure losses in the installation and the higher power demanded for its own needs. The studies performed are limited to thermodynamic analyses. The study excluded an evaluation of the cost of twisted tapes and the potentially higher cost of purchasing a pump for circulating fluid, which provides the potential for further research into the application of this method of enhancing heat collection. The analysis was conducted for a specific thermal fluid and PTC geometry. Changing certain parameters can significantly affect the optimal applicability of twisted tapes, so in future work, more extensive analysis may be done.

On the outer side of the absorber, the application of previously unconsidered non-selective coating was examined, which is characterized by high absorptivity but also high emissivity. The Pyromark coating, which was also applied to the absorber in the test stand, was used as an example in the study. The motivation for conducting research on coatings was driven by the relatively high cost of selective coatings, which are applied using multi-step methods, which increases their cost and also, because of the potential for using non-selective coatings in preliminary sections of absorber loops. The analysis considered multiple concentration ratios and temperatures to provide a preliminary assessment of the feasibility of using this coating for various applications for facilities producing heat for industrial processes. Preliminary analyses indicated the inability to apply the non-selective coating in full-scale installation, which highlights the reason why such a solution was not considered before. The geometries and operating parameters tested, reflected entirely or were very close to industrially used solutions. For the case where the aperture was 1 meter, the analysis showed that non-selective coating can be applied in the whole solar loop. In that case, the low-temperature range of heat transfer fluid 60 - 120 °C was considered. The PTC system with a medium temperature range and a concentration ratio of 17.3 has shown the possibility of optimization for absorbers where the temperature of HTF is up to 115 °C. Changing the connection of 3 parallel solar loops into 1 series increases the possibility of optimizing the number of absorbers. In the best optimal case (800 W/m^2), 15 of the 24 absorbers can be coated with a Pyromark instead of the reference selective coating. The Pyromark coating price for absorbers was estimated as 12.8 USD/m^2. In future analyses, it is worth considering other non-selective coatings and demonstrating the potential of their application to reduce investment costs.

In this analysis, case studies were performed for an assumption in which mass flow is adjusted according to the parameters of weather conditions to reach a given temperature level. In future work, which has already been done in part as mentioned in the dissertation, a case can be considered where mass flow is constant and the outlet temperature is dependent on weather conditions. Then an additional heat source can be applied, which reheats the given heat transfer fluid to the desired parameters. The application potential of this solution is broad, which also enables a wide range of future research.

An analysis worth consideration in the future is to use both methods at once: segmented positioning of twisted tapes and segmental applied no-selective coating in an absorber loop.

The last parameter considered in the dissertation was aimed at determining the impact of solar tracker deviation on PTC efficiency. The optical-engineering software used enabled the determination of ray propagation paths and analysis of the illuminated surface, considering the influence of individual optical elements and their properties. The maximum angle deviation of the solar tracker positioning for the tested geometry, not significantly affecting the operation of the linear absorber for a diameter of 33.7 mm was reported as 1.5°, for 21.3 mm was reported as 0.9°. Increasing the concentration factor by reducing the diameter of the absorber was found to increase the system's sensitivity to optical errors. For an absorber diameter of 33.7 mm, a tracking deviation of 3° results in a decrease in the irradiance concentration factor from 7.36 to 3.92. For the lower absorber diameter, a reduction from 11.81 to 5.4 was calculated for a 2° defect. The maximum tracking deviation for the 33.7 mm and 21.3 mm diameters and the geometry analyzed was 4.5° and 2.7°, respectively. At higher values, solar rays do not focus on the absorber surface at all. In the parabolic collectors analyzed with higher solar tracking deviation, it is possible to observe greater differences in the values of concentrated heat flux reaching the absorber surface, which can cause greater temperature gradients in the absorber and worse heat transfer from the internal absorber wall to the circulating medium, but also cause high stresses in the absorber material. For 1000 W/m^2 and a tracking deviation of 2°, the highest value of focused irradiance for the 33.7 mm absorber, increases from 17.5 kW/m^2 to nearly 32 kW/m^2.

The results emphasize the need for a highly accurate solar tracking system even for low-concentration solar technologies. Potential future work related to the sun-tracking process could be to optimize the shape of the parabolic mirrors and/or to use a second mirror with an optimal geometry that would eliminate such a high sensitivity of the optical system to deviations in the positioning of the tracker, which could also increase the utilization of non-direct and partially diffuse radiation.

In conclusion, the extensive research reported in this thesis presented methods for analysing parabolic trough collectors, primarily with low-concentration ratios, methods for intensifying heat absorption on the inner and outer sides of a linear absorber, as well as optimization of these methods for selected configurations and the importance of the sun position tracking function in the context of the concentration process. The methodology for the comprehensive design of solar radiation simulators that enable the testing of parabolic trough collectors under constant and repeatable conditions is also presented. The author's experience in relation to the design and construction of solar radiation simulators results in current collaboration with researchers from Solar Group in KTH Royal Institute of Technology, where the author of this thesis is applying the gained experience and co-designing a simulator for testing photovoltaic panels. At the beginning of 2023, the dissertation author also began working with a researcher from the University for Continuing Education Krems. As part of this cooperation, preliminary studies of the solar calcination process were carried out on a test stand. The overall experience gained resulted in the author's commitment to analysis related to energy storage, a topic that is complementary to renewable energy production, which in the future may provide a solid basis for further analysis in this direction.