**archives
of thermodynamics**
Vol. **43**(2022), No. 3, 47–61
DOI: 10.24425/ather.2022.143171

An experimental study on parabolic trough collector in simulated conditions by metal-halide solar radiation simulator

BARTOSZ STANEK*
ŁUKASZ BARTELA
DANIEL WĘCEL
SEBASTIAN RULIK

Silesian University of Technology, Department of Power Engineering and Turbomachinery, Konarskiego 18, 44-100, Gliwice, Poland

Abstract The utilization of solar radiation to obtain high-temperature heat can be realized by multiplying it on the illuminated surface with solar concentrating technologies. High-temperature heat with significant energy potential can be used for many technological purposes, e.g. the production of heat, cold or electricity. The following paper presents the results of the experimental study, on the operation of the parabolic linear absorber in the parabolic concentrator solar system. The parabolic mirror with an aperture of 1 m and a focal length of 0.25 m focuses the simulated radiation onto a tubular absorber with a diameter of 33.7 mm, which is placed in a vacuum tube. The length of the absorber is 1 m. The installation is illuminated by the solar simulator, which allows to carry out tests under constant and repeatable conditions. The simulator consists of 18 metal halide lamps, with a nominal power of 575 W each with a dimming possibility of up to 60%. The paper presents preliminary results of heat absorption by the analysed absorber, temperature increment, collected heat flux, and the pressure drop crucial for the optimization of the absorber geometry.

Keywords: Solar simulator; Parabolic trough collectors; Parabolic trough collectors testing; Concentration solar power

*Corresponding Author. Email: bartosz.stanek@polsl.pl

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

Nomenclature

c_p	–	specific heat capacity, J/(kgK)
L1, L2, L3	–	distances between the simulator and the PTC surface
$\dot{m}$	–	mass flow, kg/s
P	–	power, W
$\dot{Q}$	–	heat flux, W
T, t	–	temperature, K, °C
ΔT	–	temperature difference, °C
$\dot{V}$	–	volumetric flow, m^3/s

Greek symbols

η	–	efficiency
ρ	–	density, kg/m^3

Subscripts

abs	–	absorber
dis	–	dispersion
e	–	external surface
el	–	electricity
g	–	glass
h	–	heat
htf	–	heat transfer fluid
rad	–	radiation
ref	–	reflector
sim	–	simulator

Acronyms

CSP	–	concentrated solar power
HMI	–	metal-halide
PTC	–	parabolic trough collector

1 Introduction

Parabolic trough collectors (PTCs) are devices that enable the production of high-temperature heat using solar radiation, concentrated on their surface. The heat generated can be used directly for heating, electricity generation or cooling [1]. Through appropriately shaped parabolic mirrors, the radiation is focused on their focal point. These solar systems can have 1-axis or 2-axis solar trackers to follow the sun's position during the day. Because PTCs use direct normal irradiance they need to operate precisely and any deviation results in a power and efficiency drop [2].

Although linear concentrators are a quite mature technology, as more than a dozen full-scale solar power plants can confirm, research is still being

www.czasopisma.pan.pl www.journals.pan.pl

conducted to intensify heat collection and increase their efficiency. Among the most important components to be optimised are the linear absorbers. Research is conducted on both the external side (i.e. the radiation-absorbing coatings) and the thermal medium. One method is to provide turbulence flow using twisted inserts which increases the efficiency of heat collection [3]. Another solution is to combine the production of high-temperature heat and electricity by locally covering the pipe with flexible photovoltaic panels [4].

Accurate experimental studies to determine the parameters of individual solutions require constant and repeatable test conditions. Varying solar irradiance over time, temperature or wind direction and strength has a huge impact on the results obtained. It is therefore necessary to test such solutions under laboratory conditions. Solar radiation simulators are used for this purpose.

Several technical solutions of radiation simulators for testing solar technologies can be identified. Some of them are focused on illuminating a surface as large as possible, for example for ageing studies or technology research, where collimation or specific beam profile is not necessary [5, 6]. Sabahi *et al.* [5] analysed the simulator based on 12 metal halide lamps, half of which are 1 kW, while the others are 2 kW. The illuminated area of the test stand is up to 7.56 m^2. An even more extensive field of the working area, namely 17.46 m^2, has a simulator analysed by Meng *et al.* [6]. One hundred eighty eight metal halide lamps were used in the simulator. Radiation intensity regulation in the range from 150 to 1100 W/m^2 can be implemented using a variable number of lamps turned on, and by changing the lamp-to-area distance.

The popularity of photovoltaic panels forced the need to develop special designs of simulators to study the effects of various factors on their operation and the possibility to compare the impact of different technological solutions. These solutions require a high uniformity of an illuminated field, which is why these simulators are often based on LED technology [7, 8]. Some solutions focus mainly on the light source and the appropriate spectrum adjustment. Li *et al.* [9] analysed a multi-source high flux solar simulator. Also popular are high-flux simulators, where the radiation beam is concentrated at a point which provides high power. Such simulators are used for solar thermal research, usually for point tests of concentrators such as solar towers [10]. An interesting solution is the high flux simulator based on the Fresnel lens developed by Wang *et al.* [11].

Simulators for testing parabolic concentrators are not as common as the solutions presented previously. This is due to the need to use very accurate optics, which is associated with a high price. The simulator used to carry out the tests described in this paper was developed as a low-budget device, and the results show its applicability.

2 Methods

Experimental studies on parabolic radiation concentrators have been performed using artificial irradiation emitted by a metal-halide (HMI) solar simulator. The solar simulator test stand is presented in Figs. 1 and 2. The research rig can be classified into two main components. The first one is a radiation source, i.e. a solar simulator (*1*), equipped with air cooling (*2*) from a profiled ventilation hood along with an extraction fan with a capacity of 1500 m^3/h. The second part of the test stand is the parabolic solar concentrator system (*3*). It consists of a thermal fluid circuit and a radiation absorber with a profiled parabolic mirror (*4*). Figure 1 also shows the power supply system for the stand (*5*) and the measurement system (*6*).

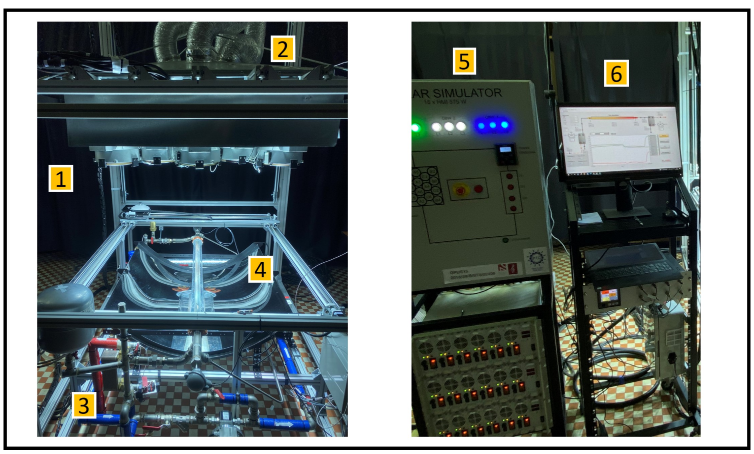

Figure 1: Test stand for parabolic trough collectors testing using a solar simulator.

The solar radiation simulator (Fig. 2) is composed of 18 metal halide lamps arranged in the most efficient configuration for this type of study determined from previous numerical studies [12, 13]. A set of metal halide reflectors (*7*) is placed directly above the investigated solar device on a lift that allows changing the distance of the light source from the illuminated surface. Each reflector (*8, 9*) consists of a metal halide lamp, a reflector, a reflector casing and a lens. The radiation source is the Osram metal halide lamp with a nominal power of 575 W. It is a discharge source which means that radiation is emitted through metal halides and mercury via an electric arc created between the anode and the cathode. This source, compared to incandescent sources, is characterised by a relatively point-like radiation emitter which allows more accurate optical operations to determine the radiation path. For this reason, using appropriately shaped reflectors, such radiation can be directed relatively perpendicularly to the illuminated surface. In the case of the reflector used, it is possible to move the light source further from the focal length of the reflector, which results in greater diffraction of the radiation. This approach makes it possible to investigate photovoltaic panels, but in the PTC testing case, it was most efficient to position the source at the focal point of the reflector. Additionally, specially shaped lenses were used for the study, further collimating the radiation beam. The total power of the floodlight set is 10.35 kW. Using electronic power supplies, this power can be continuously decreased to 60% of the nominal power, which corresponds to 6.21 kW.

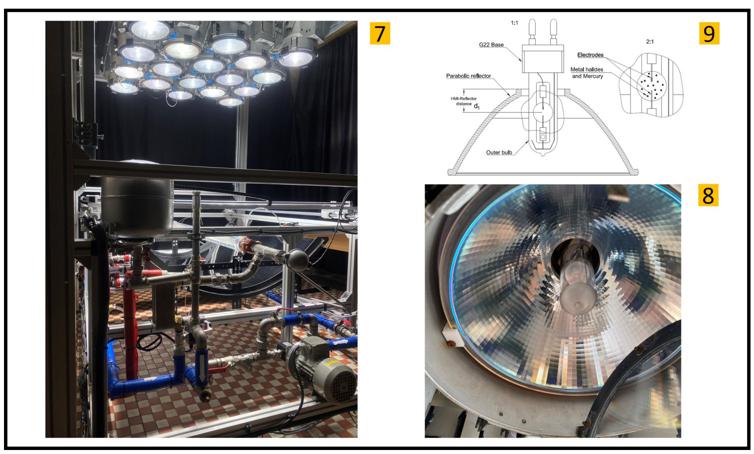

Figure 2: Solar simulator powered by eighteen 575 W metal-halide lamps.

The parabolic linear concentrator loop is composed of a fixed parabolic mirror made of a highly reflective, polished steel sheet with a width and length of 1000 mm and a focal length of 250 mm. The sheet is placed in a laser-cut holder which prevents unwanted displacement from its original position. A tubular absorber is embedded in the focus of the parabolic mirror and surrounded by a vacuum tube. The absorber is made of steel and its characteristic parameters are summarised in Table 1. For the original

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

measurements, the steel absorber was not coated in order to allow future comparisons of the increase in efficiency of the device through the use of various materials. The absorber is surrounded by a transparent cover made of borosilicate glass, which maintains the vacuum to reduce convective losses. Figure 3 shows the geometry of the parabolic radiation concentrator and the basic geometrical parameters are listed in Table 1.

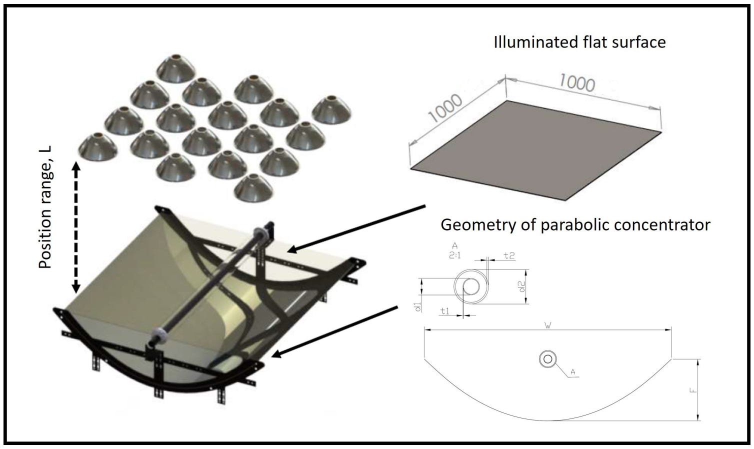

Figure 3: Parabolic concentrator geometry.

Table 1: Specification of the parabolic trough collector geometry.

Width (W), mm	1000
Height = focal length (F), mm	250
Length, mm	1000
Absorber diameter (d1), mm	33.7
Absorber thickness (t1), mm	2
Glass pipe diameter (d2), mm	70
Glass pipe thickness (t2), mm	3.2

To carry out a comprehensive study of PTC technology, the test stand was equipped with a circulating pump, a precise volumetric flow meter, electric heaters enabling the determination of a wide range of temperature at the inlet to the absorber, temperature sensors, including the inlet and outlet from the absorber, heat extraction through water cooling in plate heat exchangers, and pressure drop measurement, necessary to determine the characteristics of individual solutions intensifying heat exchange, as well as with the expansion tank.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

To precisely analyse the phenomenon of heat absorption by the thermal fluid, a LabView [14] program was developed to record measurement data, control parameters, control cooling, to determine the inlet temperature at the absorber and control parameters such as ambient temperature, radiation simulator temperature, flow rate and pressure drop. The results diagram presented in Figure 4 enables the determination of the stabilised state for the phenomenon. The presented characteristics show the stable temperature of the inlet to the absorber and the process of stabilising the heat absorption (i.e. red curve).

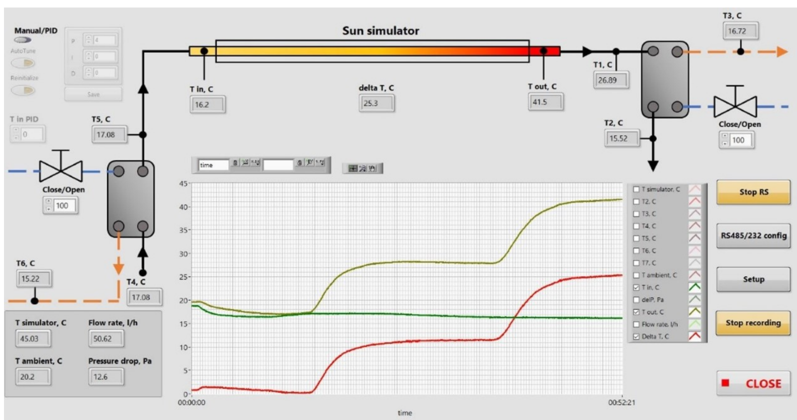

Figure 4: LabView program.

The circulating medium in the test bench is Therminol VP-1, a mixture of biphenyl and diphenyl oxides. The characteristic properties of Therminol-VP1 are shown in Table 2. It is a thermal fluid from petroleum refining by-products and artificial synthesis. Its unique advantage is its high heat-transfer capacity. The maximum temperature for the liquid state can reach up to 400°C, which allows a high utilisation potential. Therminol VP-1 has the highest thermal stability of all organic heat transfer fluids. This

Table 2: Thermal fluid characterization [15].

Max. temperature for industrial applications, °C	400
Density, kg/m^3	$-0.856 \cdot \mathrm{T_{htf}} + 1316$
Specific heat, J/(kg·K)	$2.7137 \cdot \mathrm{T_{htf}} + 761.88$
Thermal conductivity, W/(m·K)	$-1.36 \cdot 10^{-04} \cdot \mathrm{T_{htf}} + 0.1773$
Dynamic viscosity, Pa·s	$250568541 \cdot \mathrm{T_{htf}^{-4.407}}$

medium is often used in full-scale solar power plants. Another heat transfer fluid planned to be used in this installation is water, which has higher heat absorption parameters, but can be used only in a low-temperature range. At this moment, when high-temperature tests are planned, Therminol VP-1 which is a mixture of biphenyl and diphenyl oxides was selected as a thermal medium.

The accuracy of the main measuring devices is summarized in Table 3. Based on the accuracy of the measuring devices, a measurement uncertainty analysis was carried out for each measurement. A-type and B-type uncertainties were determined, as well as the compound uncertainty according to the guide uncertainty measurement (GUM) [16]. Error bars for the corresponding measurement points are shown in the appropriate figures.

Table 3: Accuracy of measurement devices.

Parameter	Measurement equipment	Accuracy
Temperature	Thermocouple type K (NiCr-Ni)	Class 1 (±1.5)
Flow	Flow meter Kobold DON-215HR33H0M0	1%
Pressure drop	Siemens D-76181	0.15%

2.1 Research procedure

Four cases were considered, differing in the power supply of the solar radiation simulator and the distance of the simulator from the surface of the parabolic concentrator. The tests were carried out for a maximum simulator power supply of 10.35 kW (18 · 575 W) and a minimum power equal to 60% of the maximum power of 6.21 kW. The simulator distances from the PTC surface were defined as $L1 = 520$ mm, $L2 = 720$ mm, and $L3 = 920$ mm. For each case, the possible heat absorption of the thermal fluid was investigated by varying the flow rate in the system in the range $1.39 \cdot 10^{-5}$–$6.94 \cdot 10^{-5}$ m^3/s with a step of $6.94 \cdot 10^{-6}$ m^3/s.

- Starting up the thermal fluid circuit (PTC) installation including cooling and stabilising temperature readings throughout the circuit.
- Setting up the solar radiation simulator in a specific configuration ($L1-L3$) and activating the air cooling system.
- Launching the solar radiation simulator, setting the appropriate power and waiting for the simulated radiation beam to stabilise.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

- Awaiting a steady state (as seen in Fig. 4), and starting data recording for that state.
- Saving data for steady state and averaging around 300 measured points as a measurement point.
- Change the thermal fluid flow.
- Perform tests for a different configuration.

2.2 Calculations

The main measurements carried out in the test stand were the temperature increase over the length of the absorber, the pressure drop and the thermal fluid flow rate. To determine the efficiency of the absorbers, the volumetric flow rate was recalculated to the mass flow rate for a given temperature using the formula

$$\dot{m} = \dot{V}\rho \,, \tag{1}$$

where: $\dot{m}$ – mass flow; $\dot{V}$ – volumetric flow, ρ – thermal fluid density.

The heat flux absorbed by the thermal fluid in the absorber was calculated using the temperature measured with K-type thermocouples and the fluid-specific data. The received heat flux was determined by the equation

$$\dot{Q}_{\text{abs}} = \dot{m} c_p \Delta T \,, \tag{2}$$

where: $\dot{Q}_{\text{abs}}$ – heat flux collected by absorber from the simulated radiation; ΔT – temperature difference between outlet and inlet of the absorber, c_p – specific heat capacity, $\dot{m}$ – mass flow.

It is also essential to determine the efficiency of the tested device. In this case, the measurement of the power supplied directly to the absorber was not carried out due to the necessity of its very precise measurement and the need to use precise equipment. The construction of the system to accurately measure the radiation reaching the absorber surface is currently being completed and the results will be evaluated. However, the efficiency of the linear absorber should be calculated as:

$$\eta_{\text{abs}} = \frac{\dot{Q}_{\text{abs}}}{\dot{Q}_{\text{abs,e}}} \,, \tag{3}$$

where: $\dot{Q}_{\text{abs}}$ – heat flux collected by linear PTC, $\dot{Q}_{\text{abs,e}}$ – heat flux reaching the external surface of the collector. The heat flux reaching the external

www.czasopisma.pan.pl www.journals.pan.pl

surface of the linear absorber should be measured in several places along the circumference and length of the absorber by a heat flux meter. To determine the efficiency of a device such as a radiation simulator for testing linear absorbers, the efficiency was calculated on the path: electrical power supply of the simulator – absorber heat flux. The equation defining this correlation is shown below

$$\eta_{\mathrm{el}\to\mathrm{h}} = \frac{\dot{Q}_{\mathrm{abs}}}{P_{\mathrm{sim}}}\,, \tag{4}$$

where: $\eta_{\mathrm{el}\to\mathrm{h}}$ – electric to heat efficiency (solar simulator to absorbed heat), P_{sim} – electric power of solar simulator.

Equation (4) describing the efficiency in the path of electric power of the solar simulator to absorbed heat can be split into individual elements affecting this value, as follows:

$$\eta_{\mathrm{el}\to\mathrm{h}} = \eta_{\mathrm{el}\to\mathrm{rad}}\eta_{\mathrm{dis}}\eta_{\mathrm{ref}}\eta_{g}\eta_{\mathrm{abs}} = \frac{\dot{Q}_{\mathrm{abs}}}{P_{\mathrm{sim}}}\,, \tag{5}$$

where: $\eta_{\mathrm{el}\to\mathrm{rad}}$ – solar simulator efficiency (conversion of electrical energy into useful radiation – directed towards the PTC) that includes metal-halide efficiency, reflector reflectivity, and transmissivity and collimation correction in the lens; η_{dis} – the dispersion efficiency, which determines how much of the emitted and reflected radiation from a parabolic mirror will be directed towards the absorber; η_{ref} – the reflectivity of the surface of a parabolic mirror, which determines how much energy is reflected by the mirror and how much is absorbed; η_{g} – the transmissivity of the borosilicate tube surrounding the absorber; η_{abs} – linear absorber efficiency, including material absorptivity, heat transmission through the pipe, radiation and convection losses from the external surface of a receiver to the ambient, as well as thermal fluid collection efficiency.

Since $\eta_{\mathrm{el}\to\mathrm{rad}} = 0.22$ was determined in previous work [17] by analysing the radiation distribution on a flat surface, modelled numerically and validated, the following relations were determined:

$$\eta_{\mathrm{el}\to\mathrm{rad}} = \frac{\dot{Q}_{\mathrm{rad}}}{P_{\mathrm{sim}}} \tag{6}$$

and

$$\eta_{\mathrm{rad}\to\mathrm{abs}} = \eta_{\mathrm{dis}}\eta_{\mathrm{ref}}\eta_{g}\eta_{\mathrm{abs}} = \frac{\dot{Q}_{\mathrm{abs}}}{\dot{Q}_{\mathrm{rad}}}\,, \tag{7}$$

where: $\dot{Q}_{\mathrm{rad}}$ – simulated radiation heat flux; $\eta_{\mathrm{rad}\to\mathrm{abs}}$ – efficiency on the path, simulated radiation to absorbed heat.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

3 Results and discussion

Figure 5a shows the results of temperature increment as a function of thermal fluid flow rate, where the inlet temperature was constant at 16°C. The calculated Reynolds number was in the range of 187 to 912, which indicates laminar flow. The highest temperature rise observed was 26°C, for position *L2* and the maximum power of the radiation simulator. The temperature in each case analysed decreased with increasing thermal fluid flow. The lowest temperature rise was observed for the *L3* position and the minimum power of the simulator. For position *L3*, a significant difference can be seen between the temperature rise for maximum and minimum power. The temperature increase for position *L1* is higher than for *L3* while maintaining the same radiant power. Studies of temperature increment and power gain as a function of flow rate are aimed at determining the basic characteristics of the absorber. In a later stage of research, where the effect of flow turbulizing inserts will be analysed, the results presented in this article will provide a reference case. The heat flux absorbed by the thermal fluid increases with increasing flow rate, as can be seen in Fig. 5b. From a flow of $3 \cdot 10^{-5}$ m^3/s, the output stabilises at a certain level. Small deviations are visible. The maximum power received by the absorber was over 750 W which indicates a high radiation flux delivered to the absorber. The maximum power received for the greatest distance of the simulator to the PTC

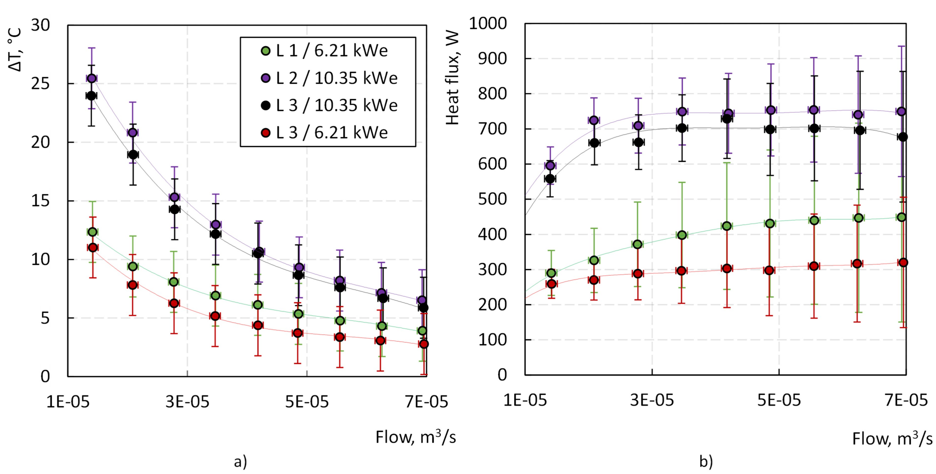

Figure 5: Experimental results: a) temperature increment as a function of thermal fluid flow, b) heat flux absorbed by the thermal fluid as a function of flow rate.

(*L3*) was around 300 W. For position *L3*, the difference in heat flux for the two simulator powers analysed is over 400 W.

Figure 6 shows the efficiency of transmitting the energy from the solar simulator to useful heat in the absorber pipe according to Eq. (6). As with power, efficiency increases up to a certain value and then remains constant. The efficiency of *L1* reaches the maximum for the highest flows, such as the case of *L2* / 10.35 and *L3* / 10.35, this means that the significant approach of the radiation simulator to the parabolic concentrator improves the efficiency of the test set. This may be due to an increase in the reflective efficiency of the radiation at a given angle to the tubular absorber. The lowest efficiency is represented by distance *L3* with minimum power. Changing the emitted power, therefore, improves the efficiency of the simulation. This characteristic shows that to measure the most significant value, i.e. the efficiency of the absorber, it is necessary to measure the radiation incident on the external surface of the tube absorber.

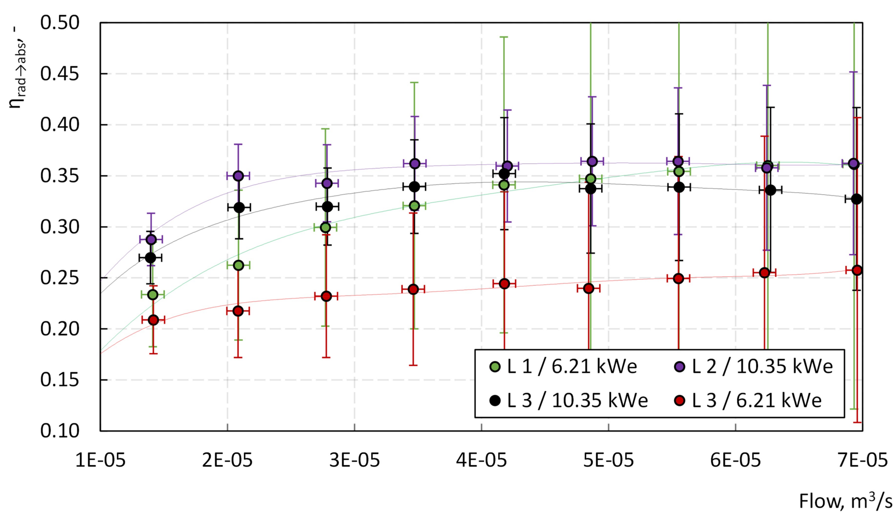

Figure 6: Efficiency as a function of thermal fluid flow.

As part of the study, the pressure drop associated with an increase in the flow rate of the thermal oil medium was also measured. The pressure drop is in the range of 10–100 Pa, as presented in Fig. 7. It increases along with the flow rate. No significant deviation was observed, which could affect the quality of the measurement.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

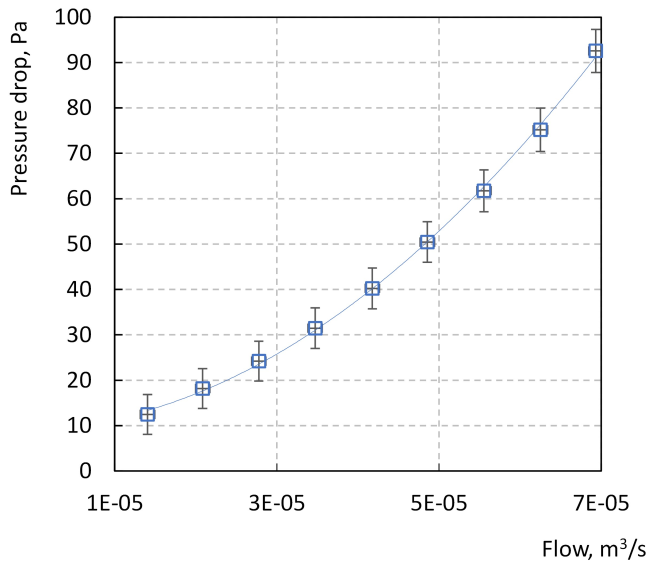

Figure 7: Pressure drop as a function of thermal fluid flow.

4 Conclusions

The preliminary experimental results of heat absorption in a parabolic trough collector, where the solar simulator was a radiation source, have been presented. Tests were conducted for several power configurations and the distance of the simulator from the parabolic trough collector. The following conclusions and observations were drawn from the work:

- the low-cost solar simulator in the presented configuration can be used to simulate solar radiation to study the heat absorption of a linear absorber;
- despite the high radiation losses in the simulator-absorber pathway, a large part of the energy is still supplied to the absorber, which makes it possible to carry out absorption tests;
- varying the power supply to the simulator and the distance from the simulator to the receiver gives the possibility to adjust the power of the useful radiation, but it is more efficient to change the power in the power supply;

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

- changing the distance from the simulator to the parabolic trough collector, for constant power, does not affect the energy delivered so significantly, which may be the result of good beam collimation through the simulator;
- the maximum power received by the absorber was 750 W and the lowest was 300 W;
- the temperature increment in the absorber is at the expected level, a maximum of 25°C/m;
- the power simulated by the device is repeatable, which makes it possible to compare results to optimise the geometry of the absorbers;
- to determine the key indicator which is the efficiency of the absorber, an accurate measurement of the radiation concentrated on the tubular surface of the absorber is necessary;
- it is necessary to carry out tests for a wider range of thermal fluid flow in the absorber and a larger range of cases (power and distance).

Acknowledgements The scientific work is funded by the National Science Centre within the framework of research project no. 2018/29/B/ST8/02406. Bartosz Stanek is a holder of European Union scholarship through the European Social Fund, P4S InterPOWER (grant POWR.03.05.00-00-Z305).

Received 3 March 2022

References

[1] Abd-Elhady M.S., Melad E.B., Abd-Elhaim M., Seif A.A.: *The cooling rate of the heated vapor compression cycle in case of using refrigerants R134a, R22, and R600a*, Arch. Thermodyn. **42**(2021), 2, 11–30.

[2] Stanek B., Węcel D., Bartela Ł., Rulik S.: *Solar tracker error impact on linear absorbers efficiency in parabolic trough collector – Optical and thermodynamic study.* Renew. Energy **196**(2022), 598–609.

[3] Grzywnowicz K., Stanek B., Bartela Ł.: *Increasing the efficiency of the parabolic trough collector under variable solar irradiance by internal flow turbulization – a numerical study.* In: Proc. 34th Int. Conf. on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS21), Taormina, 2021.

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

[4] Stanek B., Grzywnowicz K., Bartela Ł. Węcel D., Uchman W.: *A system analysis of hybrid solar PTC-CPV absorber operation.* Renew. Energy **174**(2021), 635–653.

[5] Sabahi H., Tofigh A.A., Kakhki I.M., Bungypoor-Fard H.: *Design, construction and performance test of an efficient large-scale solar simulator for investigation of solar thermal collectors.* Sustain. Energy Technol. Assess. **15**(2016), 35–41.

[6] Meng Q., Wang Y., Zhang L.: *Irradiance characteristics and optimization design of a large-scale solar simulator.* Sol. Energy **85**(2011), 9, 1758–1767.

[7] Hamadani B.H., Chua K., Roller J., Bennahmias M.J., Campbell B., Yoon H.W., Dougherty B.: *Towards realization of a large-area light-emitting diode-based solar simulator.* Prog. Photovolt: Res. Appl. **21**(2013), 4, 779–789.

[8] Al-Ahmad A.Y., Holdsworth J., Vaughan B., Sharafutdinova G., Zhou X., Belcher W., Dastoor P.: *Modular LED arrays for large area solar simulation.* Prog. Photovolt. Res. Appl. **27**(2019), 2, 179– 189.

[9] Li L., Wang B., Pottas J., Lipiński W.: *Design of a compound parabolic concentrator for a multi-source high-flux solar simulator.* Sol. Energy **183**(2019), 805–811.

[10] Ekman B.M., Brooks G., Rhamdhani M.A.: *Development of high flux solar simulators for solar thermal research.* Sol. Energy Mater. Sol. Cells **141**(2015), 436–446.

[11] Wang W., Aichmayer L., Garrido J., Laumert B.: *Development of a Fresnel lens based high-flux solar simulator.* Sol. Energy **144**(2017), 436–444.

[12] Bartela Ł., Stanek B., Węcel D., Skorek-Osikowska A.: *A solar simulator numerical modeling for heat absorption phenomenon research in a parabolic trough collector.* Int. J. Energy Res. **46**(2021), 10074–10087.

[13] Stanek B., Bartela Ł., Węcel D., Skorek-Osikowska A.: *Research on spatial non-uniformity of power distribution for solar radiation simulation.* In: Proc. 12th Int. Exergy, Energy and Environment Symp. (IEEES-12), 2020, Book of abstracts.

[14] https://www.ni.com/docs/en-US/bundle/labview-docs/page/labview.html (accessed 1 Dec. 2021).

[15] https://www.therminol.com/product/71093459 (accessed 10 March 2022).

[16] https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf (accessed 02 May 2022).

[17] Stanek B., Bartela Ł.: *Numerical and experimental study on 10 kWe metal-halide solar simulator for parabolic-trough collector testing.* In: Proc. 34th Int. Conf. on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS21), Taormina, 2021.