University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 1 January 2025

Semi-Uniform Metal Foam Distribution in Parabolic Trough Collector: An Experimental Approach for Enhancing Thermal Performance Under Iraqi Weather Conditions

Mustafa F. Hasan *, **Mohammed A. Nima**

Department of Mechanical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

ABSTRACT

In the present work, the impact of metal foam (MF) on the thermal efficiency of a parabolic trough collector (PTC) was experimentally investigated using two types of receivers: one with metal foam insertion (MFI) and one without. Tests were conducted with a 30% filling ratio (FR) of copper foam blocks, consisting of 10 discs, each 45 mm thick, semi-uniformly spaced along the receiver pipe. The copper foam had pore densities of 10–40 PPI and porosities of 0.903 and 0.8983. The experiments carried out under ASHRAE 93 standards involved varying volume flow rates from 0.1 to 0.3 LPM, using water as the heat transfer fluid. The experiments took place in Iraq in May 2024, from 9:00 a.m. to 4:00 p.m., under solar radiation conditions. To ensure data reliability, uncertainty analyses were performed on temperature, solar irradiation, flow rate, and pressure drop. The results indicated that the use of metal foam in the receiver improved collector efficiency, with a notable 16.74% increase at 40 PPI and 0.3 LPM. The highest thermal efficiency was achieved with 40 PPI, which raised the PTC outlet temperature to 58 °C at 0.1 LPM, compared to 53 °C for a without MFI pipe. According to performance evaluation criteria, 10 PPI foam outperforms 40 PPI foam. Compared to the denser 40 PPI, the larger 10 PPI pores improve water flow, reduce resistance, and require less energy to pump the heat transfer fluid (HTF). However, the findings found that while metal foam improves heat transfer efficiency, it increases pressure drop, highlighting the importance of balancing these factors in system design.

Keywords: Iraq climate, Filling ratio, Metal foam, Parabolic trough collector, Thermal performance.

1. INTRODUCTION

Currently, severe weather events and the persistent increase in fuel prices due to crude oil shortages compel us to utilize natural resources more effectively and explore alternative, renewable energy options. Solar energy stands out as a valuable renewable resource,

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.01.09

Article received: 13/09/2024
Article revised: 13/10/2024
Article accepted: 27/10/2024
Article published: 01/01/2025

captured when solar radiation reaches the Earth's surface. Solar thermal collectors are essential components of any solar thermal system, as they convert solar energy into heat. A working fluid, such as air, water, or oil, passes through the collector and absorbs this heat. Research has explored several efficient methods to improve thermal performance, particularly by reducing heat losses from the PTC. One approach to lowering the receiver temperature is to increase the heat transfer coefficient inside the receiver pipe. This can be achieved by using twisted tapes inside the receiver, employing nanofluids to enhance the working fluid's thermal properties, or inserting metal foam blocks as a permeable medium, either fully or partially, into the receiver pipes, as examined in this study. Porous media have a high surface area-to-volume ratio and promote strong flow mixing, making them excellent for enhancing heat transfer.

Metallic foams are porous materials that work especially well for structural applications and heat transfer **(Ashby et al., 2000)**. Metallic foam comes in two forms: closed cell and open cell. Open-cell foam has connected pores that allow liquids to flow through, making it ideal for heat transfer applications. Many investigations have looked into how metal foams and other materials can improve the thermal efficiency of solar collectors. **(Zhao et al., 2004)** examined the thermal characteristics of six copper alloy foams by measuring both the heat transfer coefficient and the pressure drop. Their findings show that cell size has a greater impact on overall heat transfer than porosity. They also identified the ideal porosity for balancing pressure drop and heat transfer. **(Naphon, 2005)** looked at how porous foam affected the thermal efficiency of flat-panel solar collectors. The findings revealed that increasing the foam's thermal conductivity is an important factor in improving collector efficiency. When compared to a collector without foam, the efficiency of the foam-based collector increased by 25.9%. **(Albanakis et al., 2009**) evaluated the pressure loss and heat transfer characteristics of a porous foam utilized in a volumetric solar receiver through experiments. The results show that flow conditions and material characteristics affect thermal efficiency. **(Kumar and Reddy, 2009 and 2012)** used a receiver tube with a porous disc insert to perform a computational analysis. The analysis explored the effects of various porous disc-shape characteristics on heat transfer. The results showed that the inclusion of porous discs considerably enhanced heat transfer efficiency. This results in a more uniform temperature gradient throughout the receiver tube. **(Wang et al., 2013)** studied the effect of using porous materials with varying pore sizes and heights on the top and bottom of the receiver tube. Based on their findings, the best thermal performance is achieved when 40 PPI porous foam covers three-quarters of the pipe cross-section. In another experiment, (**Reddy et al., 2015**) investigated PTC's thermal performance in an experimental setting using porous disks of various receiver tube shapes. Using perforated plates as a porous medium, they found that arranging the porous plates along the receiver tube improved the PTC's performance over the previous configuration. However, they also noted that the use of porous materials raises pumping costs due to increased pressure losses.

(Mohammed et al., 2015) conducted an experimental investigation of mixed convection heat transfer in a vertical concentric coil filled with metal porous media. Water is used as a working fluid, and it receives a uniform heat flux. The findings indicate that changes in heat flux and Reynolds numbers influence wall surface temperature. **(Luma, 2015)** numerically analyzed mixed and uniform natural convection flows in a rectangular vented enclosure filled with water-saturated aluminum foam. In this study, the effects of physical parameters on temperature distribution and flow were investigated, as well as variations in the average number of Nusselts. The findings revealed that as porosity increased, the average Nusselt value initially increased and then decreased. **(Abbas and Mohammed, 2016)** conducted an experimental study of convective heat transfer in a horizontal channel made up of metal foams with two different pore densities and partially heated by a steady heat flow. Air was used as a working fluid in the investigation. The findings showed that changes in heat flux and Reynolds numbers significantly impacted the wall temperature in each heated area. The average Nusselt number was over 80% in every test condition, indicating a significant improvement in heat transfer efficiency. **(Abadi and Kim, 2016)** looked at how copper metal foam affects pressure drop and pipe heat transfer. Highly porous metal foams improve heat transfer between the liquid and solid phases, resulting in higher pressure drops and heat transfer coefficients. The findings revealed that both the Reynolds number and the geometry of the metal foam play an important role in these effects. **(Zheng et al., 2017)** studied how the copper foam filling ratio affects the nitrate molten salt's thermohydraulic performance in the receiver pipe using computational techniques. According to their findings, when compared to smooth pipes, the friction factor increased by up to 4000% and the Nusselt number by 380%, with a PEC exceeding 1.5. **(Ali and Mohammed, 2017)** examined how adding eight copper foam blocks could increase the thermal efficiency of flat-plate solar water collectors. They examined solar radiation levels in the Iraqi climate on July 8, 2016, between 9:00 a.m. and 4:00 p.m., with Reynolds numbers ranging from 207 to 625. The results showed that the metal foam blocks increased the collector's outlet temperature by lowering the receiver temperature and improving the heat transfer coefficient.

(Ghasemi and Ranjbar, 2017) used a CFD model with uniform solar heat flux to examine the impact of porous rings on a PTC receiver pipe. They found that the flow pattern was turbulent, and using Siltherm 800 as the HTF improved the performance of the receiver pipe. The results show that placing a porous ring on the inner part of the receiver tube can significantly increase the performance. **(Saedodin et al., 2017)** assessed the performance of solar collectors made of metal foam and flat plates using experimental and numerical methods. The analysis indicated an 18.5% increase in thermal efficiency. **(Jamal-Abad et al., 2017)** tested a PTC pipe with copper metal foam with 30 PPI and 90% porosity for thermal fluid performance. According to the data, there was a 73.4% increase in the Nusselt number and a 130-fold increase in the friction factor. **(Zaversky et al., 2018)** carried out experimental and numerical tests on single- and multi-layer ceramic foams used as solar receivers. The results indicate that increased porosity improves thermal efficiency. **(Tayebi et al., 2019)** conducted a numerical study to examine how partially circular copper metal foam and nanofluid affect the thermal performance of the receiver pipe. They observed that the maximum efficiency was at 34.51%. **(Jenan and Mohammed, 2019)** was evaluated numerically the effect of metal foam on the heat transfer properties of a dual air-water pipe heat exchanger. The spaces between the two cylinders were randomly filled with ten metal foam fins having a porosity of 0.93. The findings showed that the inner pipe wall's temperature was influenced by both the Reynolds number and the incoming water temperature. **(Heyhat et al., 2020)** carried out tests to ascertain the ideal temperature for PTC adsorption. In the receiving pipe, copper metal foam and cupric oxide were used as nanofluids in laminar flow. According to the findings, adding the foam raised thermal efficiency by 26%. **(Bozorg et al., 2020)** achieved an analysis using aluminum ring foam to assess the thermal efficiency of the absorption pipe revealing that the mix of nanofluids and aluminum foam significantly improved performance. A PEC of 1.5 was obtained via a 20% increase in the heat transfer coefficient and a 119% increase in the pressure drop. **(Valizade et al., 2020)** conducted experiment work to assess the impact of using metal foam as a heat transfer improvement method on the performance of direct adsorption PTCs. The results showed that the largest thermal efficiency increases with two configurations: fully porous foam 171.2% and semi-porous foam 119.6%.

(Vahabzadeh et al., 2020) evaluated the effects of annular porous media mixed with synthetic oil and aluminum oxide nanofluid on a PTC receiver. The results showed a 14% increase in overall efficiency. **(Peng et al., 2020)** examined through a numerical study of the impact of gradient metal foam placed within a PTC receiving pipe. The study found that gradient metal foam enhanced the Nusselt number, with increases ranging from 43.7% to 812.6%. **(Peng et al., 2021)** tested inserting porous fins at the bottom of the receiver pipe by the experimental and numerical analysis, which enhanced the PTC efficiency. The Nusselt number increased significantly from 256.3% to 838%. **(Helmi et al., 2022)** conducted a numerical simulation to assess the performance of a solar collector featuring rotating parabolic troughs, porous fins, and nanofluid magnets. According to the findings, a receiver with copper porous fins and 0.97 porosity had a 3.7 times higher heat transfer rate than an empty receiver. **(Esmaeili et al., 2023)** used numerical analysis to examine the effects of mixing hybrid nanofluids and new turbulators on PTC performance. The results indicated a 35.7% increase in heat transfer. **(Heyhat and Khattar, 2023)** run experiments to investigate the effect of various metal foam shapes on the thermal performance of a PTC under laminar flow conditions. The findings revealed that the receiver pipe with porous foam achieved the highest thermal efficiency, reaching 50.8%. **(Esmaeili et al., 2023)** used three distinct foam configurations inside the receiver pipe to experimentally evaluate the effect of MFI on PTC performance. The findings indicated that the periodic array arrangement of metallic foam provided the greatest improvement, increasing thermal efficiency by 14% over the tube without porous media.

According to studies, adding MF to PTCs improves thermal Performance. This study looks at the potential benefits of integrating an MF into the receiver pipe of a PTC. A new PTC model was created to evaluate thermal performance, concentrating on copper foam with porosities of 0.903 and 0.8981 and pore densities of 10 and 40 PPI. Fluid flow rates ranged between 0.1 and 0.3 LPM. Unlike prior studies involving various metal foam compositions, this study discovered that a 30% FR successfully enhances fluid mixing and breaks the thermal boundary layer while not significantly raising pressure drop. This arrangement improves heat conduction and overall system performance by improving heat transfer and reducing flow resistance. The PTC system was evaluated using ASHRAE 93 criteria, considering PEC, friction factor, heat gain, and thermal efficiency, offering a full understanding of how MF improves PTC performance in real-world applications.

2. EXPERIMENTAL METHODS AND TEST PROCEDURES

2.1 An Explanation of The System

The analysis looked at a PTC system with two types of receivers: one included with MFI and one without. **Fig. 1** depicts the experimental setup for the PTC system. As per (**Arasu and Sornakumar, 2007**), the reflector is constructed from steel with a 90° rim angle suitable to efficiently capture solar energy. The receiver pipe is made of copper and coated with black matte paint to maximize solar energy absorption. A Pyrex glass cover surrounds the receiver pipe, creating an evacuated space to minimize convective heat losses and maintain thermal efficiency. The entire system is mounted on a tracking frame that aligns the collector with the sun's movement to ensure maximum solar radiation exposure throughout the day. Key components include:

- Reflector: Constructed from steel for durability and high reflectivity, with a 90° rim angle for optimal solar energy concentration.
- Receiver pipe: Made of copper with an outer diameter of 28 mm, coated with black paint to improve solar absorption.
- Pyrex glass cover: Protects receiver pipe and reduces heat losses through insulation.
- Flow system: Includes a flow meter and pump to regulate the water flow rate between 0.1 to 0.3 LPM, ensuring consistent heat transfer fluid movement through the receiver.
- Mounting and alignment: A polyethylene bushing ensures secure mounting of the receiver, while PTC is oriented in an East-West direction for optimal solar tracking.

This setup is critical for evaluating the thermal performance of the PTC, particularly the impact of MFI on heat transfer efficiency under actual Iraqi weather conditions. **Table 1** includes detailed specifications for PTC's reflector and receiver components.

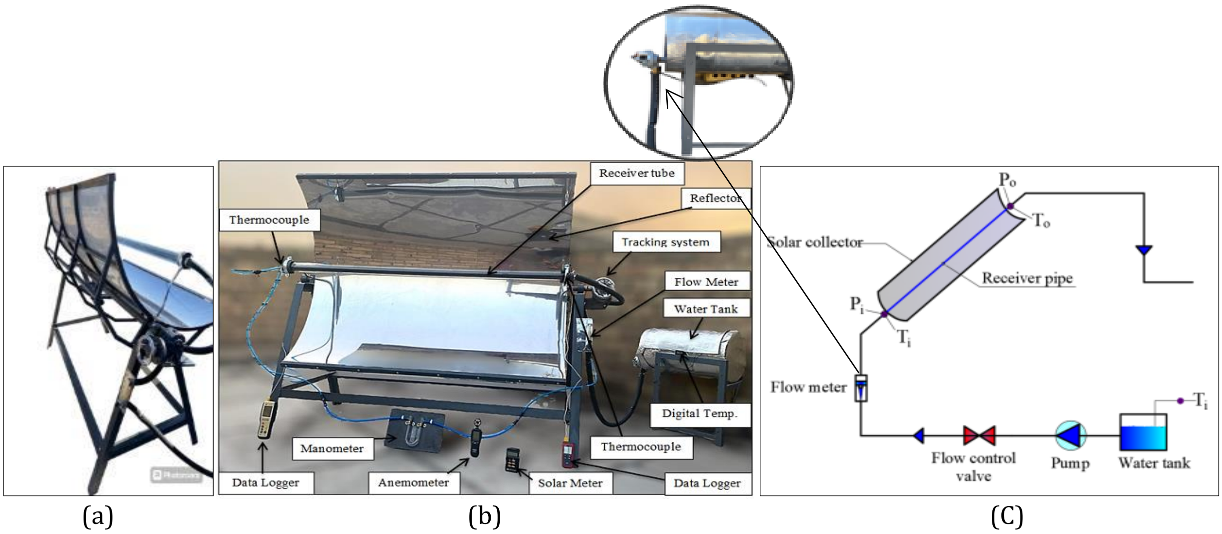

Figure 1. a) Diagram of solar collector's test apparatus; b) PTC utilized in the present study; C) Side view of PTC.

Table 1. Dimensions of PTC and pipes

Parameter	Dimensions	Unit
Parabola Length	1.5	m
Width	1	m
Focal Length	30	cm
Rim Angle	90	degree
Outer Diameter – Copper Receiver	28	mm
Outer Diameter – Pyrex Cover	52	mm
The reflectivity of the Reflector Surface	95	%
Transmissivity of the Glass Pipe	82	%
The emissivity of the Glass Pipe	89	%
Absorptivity of the Receiver Pipe	91	%
The emissivity of the Receiver Pipe	94	%
Concentration Ratio	10.773	-
Inlet Water Temperature	25	°C

2.2 Testing Apparatuses

The experiments are to compare two types of receivers: one with no MFI and one with partial MFI. To accurately measure water temperature, Type-K thermocouples were installed at the test section's inlet and outlet. An anemometer measured the temperature and velocity of the surrounding air. All thermocouples were calibrated before the experiment to ensure their accuracy. Fluid flow within the receiver pipe was measured using a vertically mounted rotameter flow meter range from 0.06 - 0.6 LPM, and solar radiation intensity was measured using a TES1333R solar power meter. A pump (C00855480) with a maximum flow rate of 21 LPM and a power rating of 0.25 kW controlled fluid flow from the storage tank. All experimental procedures followed the ASHRAE 93 standard, resulting in consistent and reliable data collection.

2.3 Metal Foam Arrangement

In this study, copper metal foam was added to a PTC receiver pipe in the form of ten 45-mm discs totaling 450 mm in length, resulting in a pipe volume filling ratio of 30%. The study examined the effects of semi-uniform metal foam configurations with porosities of 0.903 and 0.8981 and pore densities of 10 and 40 PPI. These configurations were compared to the baseline system. Copper foam was selected for its high thermal conductivity, which improves the system's overall thermal performance by efficiently transferring heat from the receiver surface to the heat transfer fluid. Copper is also strong, durable, and mechanically stable, making it an ideal material for long-term solar energy applications. **Table 2** contains a detailed description of the copper metal foams used in the experiment, while **Fig. 2** is a visual representation.

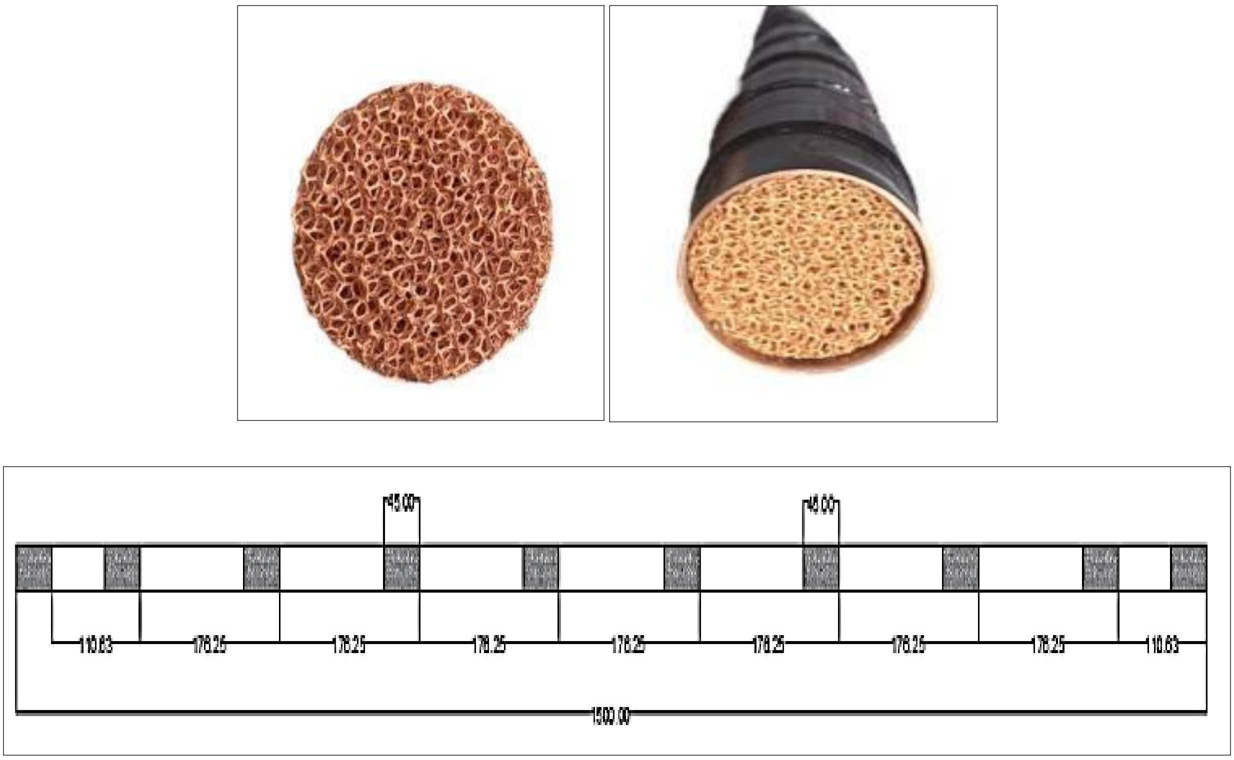

Figure 2. Copper metal foam insertion inside PTC receiver pipe, all dimensions in mm.

Table 2. Geometric and thermophysical characteristics of metal foam (**Abbas, 2016).**

Material		**Copper**
Porosity		0.903, 0.8981
Pore Density		10, 40 PPI
Thickness		45 mm
Number of Disks		10
Diameter of MF		26 mm
Thermal Conductivity		389 W/m.K
Permeability	**10 PPI**	$7.86*10^{-8}$ m^2
	40 PPI	$1.75*10^{-8}$ m^2

3. EXPERIMENTAL PROCEDURES

In May 2024, the PTC was tested under varying environmental conditions in Baghdad, Iraq. To improve system performance, several preparatory and operational procedures were implemented. These procedures ensure that the PTC operates properly and captures data consistently during testing. The main processes used for the experiment are as follows:

A. The PTC guidance system is adjusted to keep the collector in direct alignment with the sun. This guarantees that maximum solar radiation is captured.
B. The solar collector's axis was set for the East-West (E-W) orientation, enabling it to follow the sun's orientation during the day for maximum exposure.
C. Water from the storage tank is transmitted to the PTC system, where a flow meter is mounted behind the pump to precisely monitor the water flow rate across the tube.
D. The inlet valve of the PTC receiving pipe opens to enable water to flow across the receiver to absorb heat.
E. A flow meter continuously measures the flow, and a control valve controls the water flow rate across the receiver pipe to maintain the required experimental conditions.
F. To evaluate the system's functioning, data loggers are used to continuously record temperatures at the inlet, outlet, and pressure.
G. To ensure that every piece of equipment-including the flow meter, data loggers, and thermocouples-is operating as intended, routine checks are carried out.
H. Throughout the tests, key criteria are regularly examined to determine PTC performance. The variables are liquid outlet temperature, ambient temperature, wind speed, HTF pressure, and solar radiation intensity.

These activities offer a methodical way to collect thermal performance data under practical conditions and use PTC.

4. MATHEMATICAL MODEL

The collector's immediate performance is evaluated using steady-state circumstances. As noted by (**Duffie and Beckman, 2013; and Kalogirou, 2013**), equations 1 and 2 specify the thermal efficiency and useful gain of the PTC.

$$Q_u = \dot{m_f}\, c_p\left(T_{f,o} - T_{f,i}\right) \quad (1)$$

$$\eta_{th} = \frac{Q_u}{I_b\, A_a} \quad (2)$$

The ASHRAE model **(Mousavi et al., 2017)** is used to develop the beam solar radiation equation, which is then verified for accuracy against records of global solar radiation.

The procedure described by **(Kalogirou, 2014)** will be used to calculate the absorbed radiation S.

$$S = I_b(\rho_m \tau_g \alpha \gamma) \quad (3)$$

(Young et al., 2002) provide an outline of the friction factor calculation process:

$$f = \left(\frac{\Delta P}{\frac{1}{2}\rho U^2}\right)\left(\frac{D}{L}\right) \quad (4)$$

(Heyhat et al., 2020) studied thermohydraulic performance using PEC:

$$PEC = \frac{Qu/Qu_0}{(f/f_0)^{1/3}} \quad (5)$$

The subscript 0 indicates the receiver pipe without MFI, and the Qu and f stand for the MFI-equipped receiver pipe's useful gain and friction factor, respectively.

The uncertainties of temperature, solar radiation, flow velocity, and pressure drop are shown in **Table 3**. The calculation of uncertainty in friction factors (Eq. 4) and thermal efficiency (Eq. 2) depends on these variables. The process described by (Moffat 1988) is followed in the uncertainty analysis for these variables to calculate the efficiency and friction factor. To estimate the uncertainty U of a determined result R that depends on several measurable factors (x1, x2,..., xn), use the formula below:

$$U_R = \left[\sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i} U_{xi}\right)^2\right]^{1/2} \quad (6)$$

where:

U_R = Uncertainty in the findings

$\frac{\partial R}{\partial x_i}$ = Partial derivative of the result concerning the i-th variable

The uncertainty in thermal efficiency can be calculated as:

$$U_\eta = \eta\sqrt{\left(\frac{U_{Q_u}}{Q_u}\right)^2 + \left(\frac{U_I}{I}\right)^2} \quad (7)$$

The friction factor's uncertainty can be calculated as follows:

$$U_f = f\sqrt{\left(\frac{U_{\Delta p}}{\Delta p}\right)^2 + \left(\frac{2U_u}{u}\right)^2} \quad (8)$$

Uncertainty analysis of thermal efficiency and friction factors is performed using uncertainties in temperature, solar irradiation, flow rate, and pressure drop.

Table 3. Measurement uncertainties related to a specific data point parameter uncertainty.

Solar Irradiance	±32 (W/m^2)
Temperature	±0.1(0C)
Pressure	drop ±50(Pa)

5. RESULTS AND DISCUSSION

The performance of the PTC was evaluated using a receiver pipe partially filled with copper MFI, which was designed to improve heat transfer to the water. In May 2024, experimental tests took place in Baghdad, Iraq (latitude 33.3°, longitude 44.4°). **Table 1** details the geometrical and thermophysical properties of the PTC, as well as the metal foams. The setup included ten copper foam blocks, each 45 mm thick, resulting in a 30% filling ratio within the receiver pipe. Tests were conducted from 9:00 a.m. to 4:00 p.m. to assess the effects of metal foam distribution and varying flow rates on PTC's thermal performance. **Fig. 3** depicts the changes in global solar radiation and ambient temperature throughout the day.

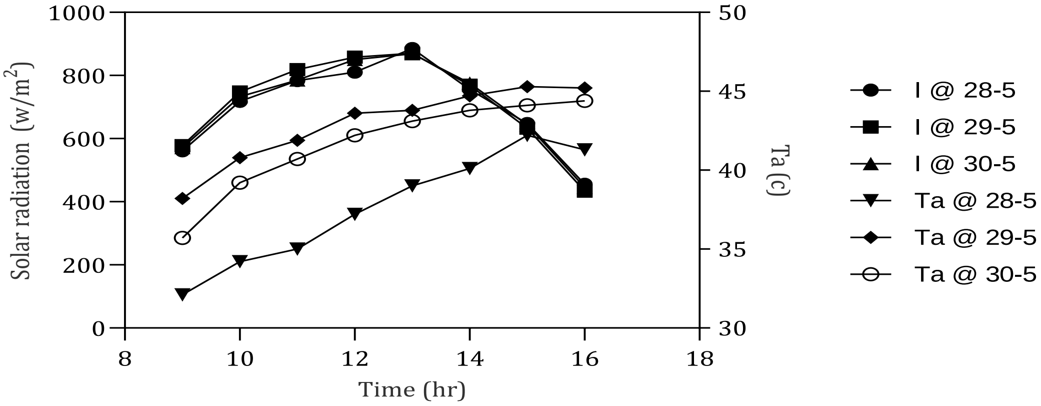

Figure 3. Experimental Measurements of Surrounding Temperature and Solar Radiation Throughout Time on May 2024.

5.1 Impacts of Metal Foams on Temperature Distribution

This study examined how the distribution of MFI influences the outlet temperature of a PTC with varying flow rates while keeping the inlet temperatures constant. **Fig. 4** shows the outlet water temperatures of PTC systems with and without MFI at different flow rates. The findings indicate that PTC systems with metal foam have higher outlet temperatures than those without MFI, particularly at lower flow rates. At lower flow rates, the metal foam greatly improves heat transfer. This occurs because the turbulence generated by the metal foam improves fluid mixing and reduces the thickness of the thermal boundary layer, increasing heat transfer efficiency. The metal foam's porous structure also helps by increasing the surface area for heat exchange between the HTF and the receiver pipe, which improves overall system performance.

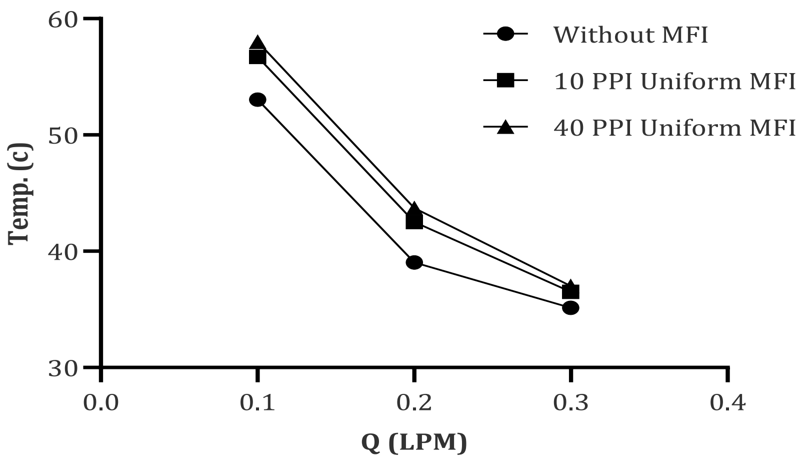

Figure 4. The Variance of Outlet Temperatures at Varied Flow Rates on May 2024.

5.2 Pressure Drop and Friction Factor

Fig. 5 shows that as the flow rate increases, pressure loss decreases. However, adding metal foam to the receiver pipe causes a noticeable increase in pressure loss. This is because metal foam has a larger surface area, increasing resistance and impeding fluid flow. The foam improves contact between the fluid and the receiver pipe, increasing flow resistance and the velocity gradient of the hydrodynamic boundary layer, resulting in more pressure loss.
Fig. 6 shows the relationship between the Reynolds number and the friction factors. Metal foam significantly increases the friction factor, especially in a semi-uniform configuration at 40 PPI. For 40 PPI in Reynolds number 152, the friction factor is approximately 164 times greater than in a without MFI receiver. For PTC with an MFI of 10 PPI, the increases are approximately 40 times. This increase is primarily due to metal foam blocking the flow path, which increases surface area and flow resistance. This disruption alters the velocity gradient of the hydrodynamic boundary layer. Lower PPI foams have fewer obstructions and a smaller surface area, which reduces pressure drops and friction.

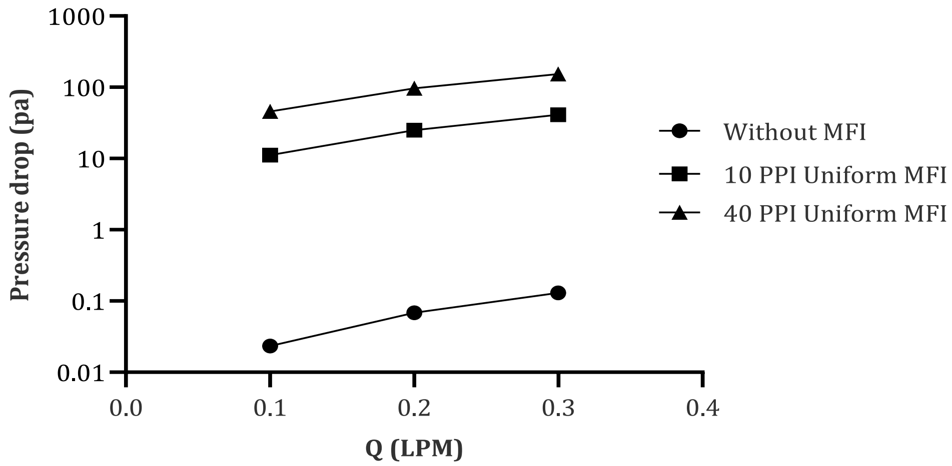

Figure 5. Pressure Drop Variation With Flow Rates on May 2024.

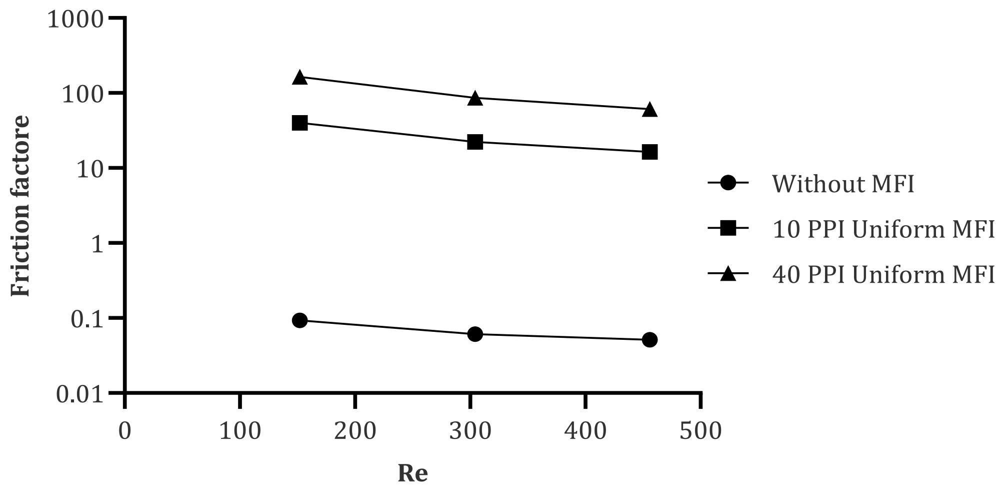

Figure 6. Friction Factor Variation With Reynolds Number on May 2024.

5.3 Useful Heat Gain

Fig. 7 shows the relationship between useful thermal energy output and local time. The figures show hourly thermal energy production for PTC systems with and without MFI on different days in May 2024. Metal foam improves heat transfer and energy output by increasing surface area, improving conductive and convective heat transfer, and lowering thermal resistance. Furthermore, **Fig. 7** depicts how flow rates influence heat gain. The results show a flow rate of 0.3 LPM provides the greatest energy gain when compared to lower flow rates. This suggests that suitable flow rates combined with metal foam improve heat exchange between the receiver and working fluid, resulting in a significant increase in system thermal efficiency.

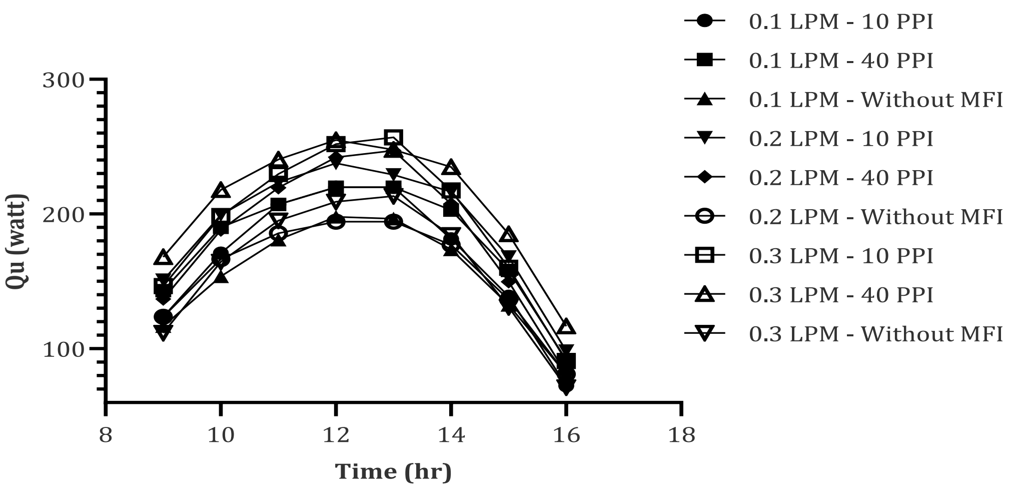

Figure 7. Variation of Useful Thermal Power of the PTC Over Time on May 2024.

5.4 Thermal Efficiency

Fig. 8 depicts variation in thermal efficiency over time as the volume flow rates increase. The data show that higher flow rates improve thermal efficiency, especially in foamed PTC. At flow rates of 0.1, 0.2, and 0.3 LPM, efficiency increases by 9.2%, 10.46%, and 15.12% for the 10 PPI samples, and 12%, 14.7%, and 16.74% for the 40 PPI samples. The 40 PPI sample performs better because of its larger surface area, which promotes heat exchange. Several factors contribute to these enhancements. Copper foam's high thermal conductivity improves heat transfer efficiency; The metal foam disrupts the fluid boundary layer, allowing for more efficient heat transfer from the pipe wall to the fluid. Furthermore, metal foam increases the velocity gradient near the wall, reducing the thickness of the boundary layer and promoting fluid mixing, thereby improving heat transfer within the receiver pipe. These factors work together to significantly improve the PTC system's overall thermal efficiency.

Fig. 9 shows the impact of the different volume flow rates (0.1, 0.2, and 0.3 LPM) on the daily efficiency of the collector. The data clearly indicate that increasing the flow rate improves the collector's efficiency. Additionally, the results show that the 40 PPI foam performs better than the 10 PPI foam, leading to higher overall system efficiency.

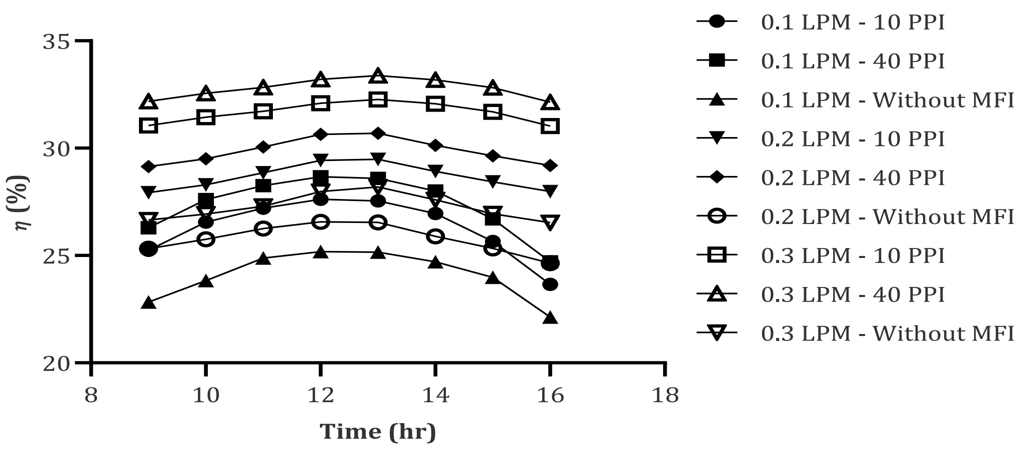

Figure 8. Thermal Efficiency at Varying Flow Rates with Local Time on May 2024.

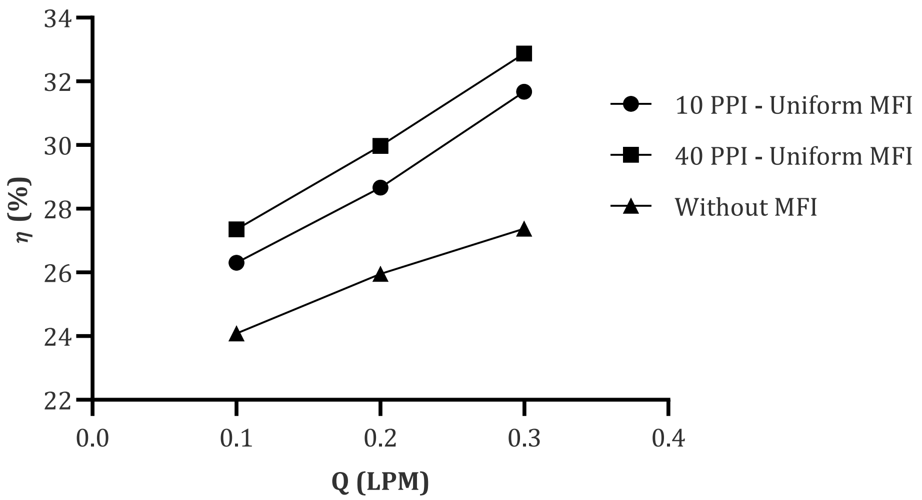

Figure 9. Average Daily Thermal Efficiency at Varying Flow Rates in May 2024.

5.5 The Performance Evaluation Criteria (PEC)

The PEC was calculated to compare the thermohydraulic performance of PTC systems with and without MFI at different pore densities. As shown in **Fig. 10**, the PEC decreases with increasing Reynolds number, owing to the higher pressure drop outweighing the corresponding increase in heat transfer. Specifically, increasing the flow rate from 0.1 LPM to 0.3 LPM reduced PEC by 36% and 34% for systems with 10 and 40 PPI foam, respectively. This shows, that while metal foam improves heat transfer, the associated increase in flow resistance reduces overall thermohydraulic performance at higher flow rates.

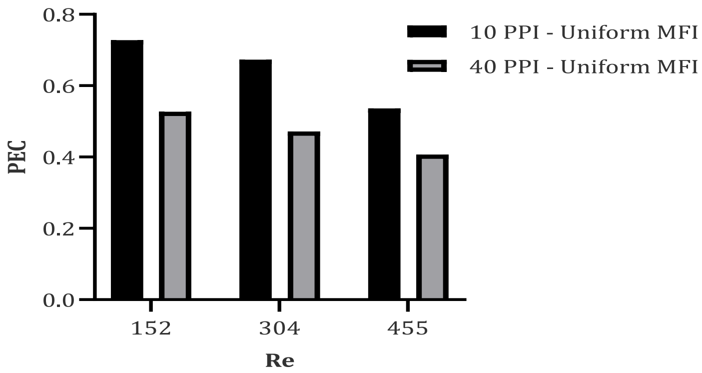

Figure 10. Copper Metal Foam PEC with 10 PPI and 40 PPI at Varying Reynold Numbers.

6. CONCLUSIONS

This study explored the effect of MFI on the receiver tube of a PTC and discovered notable enhancements in thermal efficiency. MFI has been shown to enhance heat transfer rates, making it a useful method for increasing solar thermal systems. Using this method not only lowers pumping power and pressure loss but also increases thermal efficiency. Compared to earlier research that employed a whole MFI system, this makes it a workable way to boost efficiency.

- According to the findings, usable heat gain in PTC receivers is much increased when MFI is used. When the flow rate was adjusted to 0.3 LPM at noon, the results showed a 31% increase.
- The useful heat gain is increased at high flow rates as compared to lower water flows along the day.
- According to the study, adding MF to the receiver pipe greatly enhances thermal efficiency. When compared to a pipe without MF, copper foam with a 30% FR and variable PPI resulted in a significant improvement in thermal performance.
- The experimental findings indicate that the PTC system's thermal performance is enhanced by volume flow rates up to 0.3 LPM.
- Pressure decreases significantly as a result of the foam's porous nature and higher flow resistance. As a result, the amount of pumping power needed increased, going from 0.0007 W in pipes without MFI to 0.79 W at 0.3 LPM in pipes containing metal foam.
- It was discovered that the 10 PPI sample configuration reduced the friction factor, indicating a lower resistance to fluid flow than the 40 PPI. This decrease in friction factor suggests that the 10 PPI sample promotes smoother fluid movement, lowering flow resistance within the receiver pipe.
- Because of the higher pressure drop associated with the 40 PPI sample, the PEC with the 10 PPI was superior. This suggests that, while the 40 PPI sample has a higher heat transfer, the 10 PPI sample has a more balanced trade-off between thermal performance and pressure drop, resulting in a better PEC.

NOMENCLATURE

Symbol	Description	Symbol	Description
A_a	Aperture Area, m^2	ρm	Mirror Reflectance
Q_u	The useful energy gain, w	τ_g	Transmissivity of Cover Glazing
m_f	Mass flow rate, kg/s	α	Absorptivity
C_p	Specific heat, J/kg.K	γ	Collector inclination angle
D	Diameter of receiver pipe, m	S	The Absorbed Radiation, W/m^2
L	Length, m	I	Total incident radiation, W/m^2
$T_{f,i}$	The inlet water temperature, C	**Abbreviations**	
$T_{f,o}$	The outlet water temperature, C	CFD	Computational Fluid Dynamics
η_{th}	Thermal efficiency, %	MF	Metal Foam
I_b	Beam Radiation, w/m^2	MFI	Metal Foam Insertion
f	The friction factor	PPI	Pore Per Inch
Δp	The differential in pressure, pa	PTC	Parabolic trough collector
ρ	Density, kg/m^3	PEC	Performance evaluation criteria
u	Velocity, m/s	HTF	Heat transfer fluid

Acknowledgments

This work was supported by the Department of Mechanical Engineering, College of Engineering, University of Baghdad.

Credit Authorship Contribution Statement

Mustafa Falih Hasan: Writing original draft, validation, and methodology.
Mohammed A. Nima: Review and editing, validation, and proofreading.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Albanakis C., Missirlis D., Michailidis N., Yakinthos K., Goulas A., Omar H , Tsipas D , and Granier B., 2009. Experimental analysis of the pressure drop and heat transfer through metal foams used as volumetric receivers under concentrated solar radiation. *Experimental Thermal and Fluid Science*, 33(2), pp. 246–252. https://doi.org/10.1016/j.expthermflusci.2008.08.007.

Arasu A.V. and Sornakumar T., 2007. Design, manufacture, and testing of fiberglass reinforced parabola trough for parabolic trough solar collectors, *Solar Energy*, 81(10), pp. 1273-1279. https://doi.org/10.1016/j.solener.2007.01.005.

Ashby M.F., Evans A.G., Fleck N.A., Gibson L.J., Hutchinson J.W. and Wadley H.N.G., 2000. *Metal Foams: a Design Guide*. Butterworth-Heinemann, Boston, MA. https://doi.org/10.1115/1.1421119.

ASHRAE Standard 93, 2003. Methods of testing to determine the thermal performance of solar collectors. Atlanta, GA, USA.

Bamorovat A. G., & Kim K. C., 2016. Experimental heat transfer and pressure drop in a metal-foam-filled pipe heat exchanger. *Experimental Thermal and Fluid Science*, 82, pp.42-49. http://dx.doi.org/10.1016/j.expthermflusci.2016.10.031.

Bozorg, M. V., Hossein Doranehgard, M., Hong, K., & Xiong, Q., 2020. CFD study of heat transfer and fluid flow in a parabolic trough solar receiver with internal annular porous structure and synthetic Oil–Al_2O_3 nanofluid. *Renewable Energy*, 145, pp. 2598–2614. https://doi.org/10.1016/j.renene.2019.08.042.

Duffie, J. A., & Beckman, W. A., 2013. *Solar engineering of thermal processes*. New York: Wiley. ISBN:9781118671603.

Esmaeili Z., Akbarzadeh S., Rashidi S., and Valipour M.S., 2023. Effects of hybrid nanofluids and turbulator on efficiency improvement of parabolic trough solar collectors. *Engineering Analysis with Boundary Elements*, 148, pp.114–125. https://doi.org/10.1016/j.enganabound.2022.12.024.

Esmaeili Z., Valipour M.S., Rashidi S., and Akbarzadeh S., 2023. Performance analysis of a parabolic trough collector using partial metal foam inside a receiver pipe: an experimental study. *Environmental Science and Pollution Research*, 30, p. 89794–89804. https://doi.org/10.1007/s11356-023-28732-1.

Ghasemi S.E., and Ranjbar A.A., 2017. Numerical thermal study on the effect of porous rings on the performance of solar parabolic trough collector. *Applied Thermal Engineering*, 82, pp. 807–816. https://doi.org/10.1016/j.applthermaleng.2017.03.021.

Heyhat M.M., and Zahi Khattar M., 2023. On the effect of different placement schemes of metal foam as a volumetric receiver on the thermal performance of a direct absorption parabolic trough solar collector. *Energy,* 266, pp.126428. https://doi.org/10.1016/j.energy.2022.126428.

Heyhat M.M., Valizade M., Abdolahzade S., and Maerefat M., 2020. Thermal efficiency enhancement of direct absorption parabolic trough solar collector (DAPTSC) by using nanofluid and metal foam. *Energy*, 192, pp. 116662. https://doi.org/10.1016/j.energy.2019.116662.

Heyhat M.M.; Valizade, M.; Abdolahzade, Sh.; 2020. Thermal efficiency enhancement of direct absorption parabolic trough solar collector (DAPTSC) by using nanofluid and metal foam. *Energy*, 192, pp. 116662, https://doi.org/10.1016/j.energy.2019.116662.

Jamal-Abad M.T., Saedodin S., and Aminy M., 2017. Experimental investigation on a solar parabolic trough collector for receiver pipe filled with porous media. *Renewable Energy,* 107, pp. 156–163. https://doi.org/10.1016/j.renene.2017.02.004.

Kalogirou S. A., 2013. *Solar energy engineering: processes and systems*. Oxford, OX5 1GB, UK: Academic Press. ISBN–13: 978-0-12-397270-5.

Kalogirou, S., 2024. *Solar Energy Engineering: Processes and Systems*. London: Academic Press, an imprint of Elsevier. ISBN: 9780323993517.

Kumar K.R. and Reddy K.S., 2012. Effect of porous disc receiver configurations on performance of solar parabolic trough concentrator. *Heat and Mass Transfer/ Waerme- Und Stoffuebertragung*, 48, pp. 555–571. https://doi.org/10.1007/s00231-011-0903-8 .

Kumar K.R. and Reddy K.S., 2009. Thermal analysis of solar parabolic trough with porous disc receiver. *Applied Energy*, 86(9), pp. 1804-1812. https://doi.org/10.1016/j.apenergy.2008.11.007.

Ali, L.F., 2015. Natural and mixed convection in a square vented enclosure filled with metal foam. *Journal of Engineering*, 21(11), pp. 60–79. https://doi.org/10.31026/j.eng.2015.11.04.

Moffat R.J., 1988. Describing the uncertainties in experimental results. *Experimental Thermal and Fluid Science*, 1(1), pp.3–17. https://doi.org/10.1016/0894-1777(88)90043-X.

Nima M.A. & Hajeej A.H., 2016. Experimental investigation of convection heat transfer enhancement in the horizontal channel provided with metal foam blocks. *Journal of Engineering*, 22(5), pp. 144–161. https://doi.org/10.31026/j.eng.2016.05.10.

Nima M.A. and Ali M.A., 2017. Numerical study of heat transfer enhancement for a flat plate solar collector by adding metal foam blocks. *Journal of Engineering*, 23(12), pp. 13–32. https://doi.org/10.31026/j.eng.2017.12.02.

Hamzah, J. A. and Nima, M. A., 2019. Numerical investigation of heat transfer enhancement of double pipe heat exchanger using metal foam fins. *Journal of Engineering*, 25(6), pp. 1–18. https://doi.org/10.31026/j.eng.2019.06.01.

Nima M.A., Abdal-Hussein S.A., and Hameed S.S., 2015. Mixed convection heat transfer in a vertical saturated concentric annulus packed with a metallic porous media. *Journal of Engineering*, 21(09), pp. 85–104. https://doi.org/10.31026/j.eng.2015.09.06.

Maleki V., Hizam S., and Gomes C., 2017. Estimation of hourly, daily, and monthly global solar radiation on inclined surfaces: Models re-visited. *Energies*, 10 (1), pp. 134. https://doi.org/10.3390/en10010134.

Naphon P., 2005. Effect of porous media on the performance of the double-pass flat plate solar air heater. *International Communications in Heat and Mass Transfer*, 32(1), pp. 140–150. https://doi.org/10.1016/j.icheatmasstransfer.2004.11.001.

Helmi, N., Nazari, A., Bezaatpour, M., Nateghi, S., & Ghaebi, H.., 2022. Investigation of energy storage in parabolic rotary trough solar collectors using various porous fins with magnetic nanoparticles. *Energy for Sustainable Development*, 70, pp.194–204. https://doi.org/10.1016/j.esd.2022.07.009.

Peng H., Li M., and Liang X., 2020. Thermal-hydraulic and thermodynamic performance of parabolic trough solar receiver partially filled with gradient metal foam. *Energy,* 211, pp.119046. https://doi.org/10.1016/j.energy.2020.119046.

Peng H., Li M., Hu F., and Feng S., 2021. Performance analysis of receiver pipe in parabolic trough solar collector inserted with semi-annular and fin shape metal foam hybrid structure. *Case Studies in Thermal Engineering*, 26, pp. 101112. https://doi.org/10.1016/j.csite.2021.101112.

Reddy K.S., Kumar K. R., and Ajay C.S., 2015. Experimental investigation of porous disc enhanced receiver for solar parabolic trough collector. *Renewable Energy*, 77, pp. 308–319. https://doi.org/10.1016/j.renene.2014.12.016.

Saedodin S., Zamzamian S., Nimvari M.E., Wongwises S., and Jouybari, H.J., 2017. Performance evaluation of a flat-plate solar collector filled with porous metal foam: Experimental and numerical analysis. *Energy Conversion and Management*, 153, pp. 278–287. https://doi.org/10.1016/j.enconman.2017.09.072.

Siavashi M., Vahabzadeh Bozorg M., and Toosi M.H., 2021. A numerical analysis of the effects of nanofluid and porous media utilization on the performance of parabolic trough solar collectors. *Sustainable Energy Technologies and Assessments,* 45, pp. 101179. https://doi.org/10.1016/j.seta.2021.101179.

Tayebi R., Akbarzadeh S., and Valipour M.S., 2019. Numerical investigation of efficiency enhancement in a direct absorption parabolic trough collector occupied by a porous medium and saturated by a nanofluid. *Environmental Progress & Sustainable Energy,* 38(2), pp. 727–740. https://doi.org/10.1002/ep.13010.

Valizade M., Heyhat M.M., and Maerefat M., 2020. Experimental study of the thermal behavior of direct absorption parabolic trough collector by applying copper metal foam as volumetric solar absorption. *Renew Energy*, 145, pp.261–269. https://doi.org/10.1016/j.renene.2019.05.112.

Wang P., Liu D.Y., and Xu C., 2013. Numerical study of heat transfer enhancement in the receiver pipe of direct steam generation with parabolic trough by inserting metal foams. *Applied Energy*, 102, pp. 449–460. https://doi.org/10.1016/j.apenergy.2012.07.026.

Young D.F., Munson B.R., Okiishi T.H., and Huebsch W.W., 2002. *Fundamentals of Fluid Mechanics*. United States of America, Wiley. ISBN 978-0470-26284-9.

Zaversky F., Aldaz L., Sánchez M., Ávila-Marín A., Roldán M.I., Reche J.F., Füssel A., Beckert W., and Adler J., 2018. Numerical and experimental evaluation and optimization of ceramic foam as solar receiver – Single-layer vs multi-layer configurations. *Applied Energy*, 210, pp. 351–375. https://doi.org/10.1016/j.apenergy.2017.11.003.

Zhao C. Y., Kim T., Lu T. J., and Hodson H. P., 2004. Thermal transport in high porosity cellular metal foams, J. *Thermophys. Heat Transfer*, 18 (3) pp. 309–317. https://doi.org/10.2514/1.11780.

Zheng Z.J., Li M.J., and He Y.L., 2017. Thermal analysis of solar central receiver pipe with porous inserts and non-uniform heat flux. *Applied Energy*, 185(2), pp. 1152–1161. https://doi.org/10.1016/j.apenergy.2015.11.039.

توزيع الرغوة المعدنية شبه المنتظم في المجمع المكافئ: نهج تجريبي لتحسين الأداء الحراري في ظل الظروف الجوية العراقية

مصطفى فالح حسن جبر *، محمد عبد الرؤوف نعمة

قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

في العمل الحالي، تم التحقيق تجريبياً في تأثير الرغوة المعدنية على الكفاءة الحرارية لمجمع الطاقة الشمسية ذو القطع المكافئ (PTC) باستخدام نوعين من المستقبلات: واحدة تحتوي على إدخالات من الرغوة المعدنية (MFI) والأخرى بدونها. تم إجراء الاختبارات باستخدام نسبة ملء 30% (FR) من كتل الرغوة النحاسية، تتألف من 10 أقراص، كل منها بسمك 45 مم، موزعة بشكل شبه موحد على طول أنبوب المستقبل. كانت الرغوة النحاسية ذات كثافات مسامية تتراوح بين 10 و40 PPI ومسامية تبلغ 0.903 و0.8983. تمت التجارب وفقًا لمعايير ASHRAE 93، مع تغيير معدلات التدفق من 0.1 إلى 0.3 لتر/دقيقة، باستخدام الماء كوسيط لنقل الحرارة. أجريت التجارب في العراق في مايو 2024، من الساعة 9:00 صباحًا إلى 4:00 مساءً، تحت ظروف إشعاع شمسي. لضمان موثوقية البيانات، تم إجراء تحليلات للشكوك على درجة الحرارة، والإشعاع الشمسي، ومعدل التدفق، وفقدان الضغط. أشارت النتائج إلى أن استخدام الرغوة المعدنية في المستقبل حسن من كفاءة المجمع، مع زيادة ملحوظة قدرها 16.74% عند 40 PPI و0.3 لتر/دقيقة. تم تحقيق أعلى كفاءة حرارية مع 40 PPI، مما رفع درجة حرارة مخرج PTC إلى 58 درجة مئوية عند 0.1 لتر/دقيقة، مقارنة بـ 53 درجة مئوية للأنبوب بدون رغوة. وفقًا لمعايير تقييم الأداء، تتفوق رغوة 10 PPI على رغوة 40 PPI. وبالمقارنة مع رغوة 40 PPI الأكثر كثافة، تعمل مسام 10 PPI الأكبر على تحسين تدفق المياه وتقليل المقاومة وتتطلب طاقة أقل لضخ سائل نقل الحرارة (HTF). ومع ذلك، وجدت النتائج أنه رغم أن الرغوة المعدنية تحسن من كفاءة نقل الحرارة، فإنها تزيد من فقدان الضغط، مما يبرز أهمية موازنة هذه العوامل في تصميم النظام.

الكلمات المفتاحية: الرغوة المعدنية، الأداء الحراري، مجمع القطع المكافئ، نسبة الملء ،مناخ العراق.