

Article

Experimental Studies of the Influence of Microencapsulated Phase Change Material on Thermal Parameters of a Flat Liquid Solar Collector

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Abstract: The article presents the results of preliminary research aimed at determining the possibility of using microencapsulated phase change material (mPCM) slurries as a working fluid in installations with a flat liquid solar collector. In the tests, the following were used as the working fluid: water (reference liquid) and 10% wt. and 20% wt. of an aqueous solution of the product under the trade name MICRONAL[®] 5428 X. As the product contained 43% mPCM, the mass fraction of mPCM in the working liquid was 4.3% and 8.6%, respectively. The research was carried out in laboratory conditions in the range of irradiance $I = 250\text{--}950 \text{ W/m}^2$. Each of the three working fluids flowed through the collector in the amount of 20 kg/h, 40 kg/h, and 80 kg/h. The working fluid was supplied to the collector with a constant temperature $T_{in} = 20 \pm 0.5 \text{ }^\circ\text{C}$. It was found that the temperature of the working fluid at the collector outlet increases with the increase in the radiation intensity, but the temperature achieved depended on the type of working fluid. The greater the share of mPCM in the working liquid, the lower the temperature of the liquid leaving the solar collector. It was found that the type of working fluid does not influence the achieved thermal power of the collector. The negative influence of mPCM on the operation of the solar collector was not noticed; the positive aspect of using mPCM in the solar installation should be emphasized—the reduced temperature of the medium allows the reduction in heat losses to the environment from the installation, especially in a low-temperature environment.

Keywords: flat solar collector; microencapsulated PCM slurry; experimental investigation; thermal operation parameters



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1. Introduction

The interest in acquiring and storing solar energy was started by the energy crisis that took place in the 1940s. Hottel's pioneering works from 1942 constitute the basis for the construction of the most common devices for obtaining solar energy—flat, liquid solar collectors [1]. Additionally, the Dover Sun House, designed in 1948 by architect Eleanor Raymond and the MIT engineer Maria Telkes [2], showed in a practical way the possibilities of storing this heat in special partitions of the building, in which there was a material undergoing phase change [3]. Since then, simultaneous work has been carried out to improve the thermal efficiency of solar collectors and to find new solutions to store large amounts of thermal energy.

Improving the operation of solar collectors is based, among others, on the use of solar radiation concentrators, selective coverage of the absorber surface, modification of the absorber structure, reduction in heat loss from the collector to the environment, optimization of the glazing position in relation to the absorber, use of polymers to reduce the size and weight of the collector, mini channels to intensify heat transfer to the fluid, and modify the properties of the working fluid through the use of additives (e.g., nanoparticles) [4–9]. The current solutions of liquid solar collectors are based on the use of water as the basic

working medium. Hence, the theoretical working range of the collector is between 0 °C and 100 °C. This range can be extended by using water propylene glycol ($T = -25$ – 200 °C) as the working liquid. However, the temperature of the working medium at the level of 50–60 °C already causes problems. These are high heat losses from the solar system to the environment, especially in winter, and sufficiently high intensity of solar radiation is required to maintain/increase the temperature of the working medium [10]. The solution to the above-mentioned problems may be adding to the base liquid particles of the phase change material (PCM).

1.1. Liquids with a Phase Change Material in the Field of Solar Energy

PCM is a substance that is able to absorb (while adding heat) and then release (while cooling it) significant amounts of heat. The heat exchange process is accompanied by a change in the material phase, and it takes place at a constant or variable temperature within a narrow range—the phase transition temperature. The heat absorbed/given off during the phase transition is called latent heat, in contrast to sensible heat, the supply/removal of which results in significant changes in body temperature [11,12].

In the field of solar energy, PCM is commonly used as a heat accumulator in tanks that act as thermal energy storage [13–17]; building partitions as a filling of empty spaces or addition to cement, paint, plaster [18–20] reducing daily room temperature fluctuations; in photovoltaic panels (PV-PCM) as a back layer limiting excessive heating of the module, which reduces its efficiency [21–25]; and as an addition to the working fluid in the integrated photovoltaic thermal system (PVT), cooling the photovoltaic panels and at the same time transferring heat to the storage tanks [26–29].

The liquid with the additive is PCM; it is the so-called Latent Functional Thermal Fluid (LTFT). LTFT is a two-phase working fluid used in heat exchange systems and is characterized, unlike single-phase fluids, by the possibility of transferring more heat (by the value of latent heat). The LTFT group includes ice slurries; emulsions consisting of particles of PCM material added directly to the base liquid; slurries of encapsulated PCM added to the base liquid; clathrate hydrate slurry, where the water molecules form the lattice structures, and the molecules of the other substance fill the lattices; and shape stabilized slurry, where PCM is infiltrated in high-density polyethylene and is dispersed in water to form slurry [30–32]. Encapsulation is the most commonly proposed type of PCM slurry among the five discussed above [33]. Technological progress has made it possible to obtain micro- or even nanometer-sized capsules [31,34,35]. The PCM encapsulation process eliminated one of the disadvantages of PCM (especially commonly used paraffin)—its low thermal conductivity. By washing the PCM capsules with the base liquid, the phase-conversion process can take place in the “full volume” of the PCM since it can start simultaneously in each capsule being washed. Moreover, the addition of nanoparticles of materials with high thermal conductivity to the PCM or base liquid increases the conductivity of the entire slurry [36–38].

The microencapsulated PCM slurry (mPCM) is a potential working fluid in heat systems, thanks to which it is possible to transport large amounts of heat without the need to obtain a high temperature of the medium. This helps to reduce heat losses to the surroundings of the entire installation with solar collectors. Additionally, as it is shown in studies [39–43], which aimed to assess the effect of mPCM addition on the flow and heat transfer characteristics in channels, the use of mPCM increases the value of the heat transfer coefficient, and the power required to pump the slurry, in relation to the heat transported, is lower than in single-phase fluids. It can therefore be presumed that the use of mPCM slurry as a working fluid in systems with solar collectors may reduce heat loss to the environment, increase the heat exchange intensity in the collector and hot water tank, and increase the efficiency of the entire system or reduce the dimensions of the installation.

1.2. Letant Functional Thermal Fluid as a Working Fluid in Solar Installations—Previous Research

While the number of publications devoted to the use of mPCM slurry in heat exchange systems is significant, the subject of the practical use of mPCM slurry as a working fluid in solar collectors is very limited. The few publications on this subject include the work carried out by a team of employees of the DENERG Energy Department from Italy and colleagues. Paper [44] presented and discussed the authors' own concepts of solar systems with PCM slurry as a heat carrier. Article [45] presented a mathematical model of a flat, liquid solar collector. The model was based on the Hottel–Whillier equation, and the MATLAB/Simulink program was used to solve it. The model assumes that the working fluid is, in one case, a 20% aqueous solution of ethylene glycol, and in another, a slurry of microencapsulated PCM-n-eicosane (60% by weight of mPCM in an aqueous solution of ethylene glycol). The analyses showed that the use of mPCM in the base fluid resulted in an approximate 7% increase in the annual efficiency of the collector regardless of the orientation and the tilt angle. In the next article [46], the same authors simulated the work of the collector, wherein one case, the base liquid was a glycol water solution (40% glycol/60% water), and in another case, a 50% mPCM slurry (n-eicosane) in the above-mentioned solution. The simulations were carried out assuming different values of solar radiation, assuming that the outdoor air temperature changes every 5 °C from −15 °C to +40 °C. It was found that the amount of heat obtained by the innovative system is much higher (from 20% to 40% in the “winter season”) compared to the working fluid without mPCM. It was also shown that the temperature of the slurry at the outlet of the collector is always lower than the temperature of the glycol water solution, despite the same amount of energy transported in the working fluid. Paper [47] described the results of simulation analyses according to our own mathematical model in comparison with the results of experimental tests obtained for a prototype installation with a water–glycol solution (without the addition of mPCM) as a working liquid. After successful validation, the mathematical model was used to simulate the influence of the location, orientation of the collector, and the effect of mPCM concentration in the slurry on the thermal efficiency of a flat solar collector installation. It was found that an increase in mPCM share to 60% resulted in an increase in collector productivity to 7–8%. The next study [48] presented a numerical model that enables the analysis of the dynamics of an installation consisting of a collector, heat storage, and control automation. The simulation results were compared with the results of long-term experimental data carried out with a full-scale prototype plant. An aqueous glycol solution with 5%, 10%, and 15% microencapsulated n-eicosane was used as the working liquid. It was found that the liquid temperature at the outlet from the collector, obtained from the simulation, differs from that measured in the experimental conditions by no more than 1.8%, which positively validated the extensive mathematical model.

A study by Feng et al. [49] presented the results of experimental studies data of an evacuated heat pipe solar collector with mPCM slurry as a working liquid. A 50% aqueous slurry of PC210 (Ciba, BASF—Ludwigshafen, Germany) was used. The test results were compared with the results of thermal tests of the collector when water was the working fluid. It was found that the European Standard EN 12 975, on which the measurements made were based, requires modification when the working liquid is mPCM slurry. It was noticed that the research method modified by the authors allows to accurately predict the efficiency of the evacuated heat pipe solar collector when the mPCM slurry is the working fluid. The average efficiency of solar collectors with mPCM slurry was higher than with the use of water. In conclusion, the authors also state that further experiments should be carried out, including the study of mPCM slurry in various types of solar collectors.

Sun et al. [50] investigated experimentally the efficiency of a solar installation for heating water, which included, inter alia, a flat solar collector. As the working liquid, an aqueous paraffin emulsion (paraffin mass 20%) with the addition of graphene was used to improve the thermal conductivity of the fluid. The tests were carried out in laboratory conditions with solar radiations, including 300 W/m², 500 W/m², and 800 W/m². It was

found that the thermal efficiency of the PCM system can reach even 89.67%, which was 14.76% more than when water was used as a working fluid.

The presented literature review clearly shows that the number of publications on the use of mPCM slurry/PCM emulsion in solar installations as a heat transfer fluid is negligible. The studies presented in the worldwide literature are preliminary testing studies, and research is required to carry out detailed analyses of the impact of mPCM on the efficiency of the entire system and its individual components. The subject seems all the more topical as it is possible to improve the thermal conductivity of the slurries by adding nanoparticles of substances with a high thermal conductivity coefficient to the PCM material or the base liquid.

The article presents the authors' own experimental research data on the thermal parameters of a flat solar collector. The tests were carried out in laboratory conditions in the range of solar irradiance of 250–950 W/m². Distilled water and an aqueous mPCM slurry were used as the working liquid. The mPCM slurry was made by mixing the product MICRONAL[®] 5428 X (Moraine, OH, USA) with distilled water. The mass fraction of the product to distilled water was 10% and 20%. As the product itself contains about 43% of microencapsulated paraffin in water, the actual share of mPCM in the working liquid was 4.3% and 8.6%, respectively. The research was carried out for three different values of the mass flow rate of the working liquid through the solar collector.

2. Method and Materials

2.1. Working Fluid

In the tests, distilled and demineralized water (standard liquid) and two aqueous mPCM slurries were used as the working liquid. The base liquid in the slurry was also distilled, and demineralized water and the addition was a product from Microtek Labs under the trade name MICRONAL[®] 5428 X. The main components of the product, according to the manufacturer's data [51], was paraffin wax microencapsulated in a highly crosslinked polymethylmethacrylate polymer wall and water. The mass fraction of mPCM in water is $43 \pm 1\%$ wt. The mean peak of the melting point of paraffin is 28 ± 1 °C, and the heat of fusion is ≥ 160 kJ/kg. The mean particle size of mPCM is 1–5 µm. Working liquids (slurries) were made by adding the original product to the base liquid, and then the whole was mechanically stirred for 15 min. A homogeneous slurry of mPCM was obtained. As the share of mPCM in the original product was on average 43%, and the product was added to water in the amount of 10% and 20% of the mass fraction, working liquids were obtained in which the mass fraction of mPCM was, respectively, 4.3 and 8.6%.

2.2. The Experimental Facility

The tests were carried out in laboratory conditions on the test stand, the diagram of which is shown in Figure 1. Its basic element was a flat liquid solar collector KSH-2.0 by Kospel (Koszalin, Poland). The dimensions of the collector are $1072 \times 2119 \times 90$ mm, and the aperture area $A = 1.98$ m² [52]. The collector was placed on the supporting structure and operated in an upright position.

At a distance of 2 m from the front surface of the collector, a set of infrared heaters with the possibility of regulating their radiation intensity was installed. The radiators were equipped with Philips HeLeN filaments (Diez/Lahn, Germany), the radiation spectrum of which (manufacturer's data) is presented against the spectrum of solar radiation in Figure 2. Due to the fact that the spectrum of the radiation of the filament differs significantly from the spectrum of solar radiation, it is difficult to compare the results of our own research with the results of other authors. For this reason, the results of our own research on the collector's operation, when the mPCM slurry flows through the collector, were compared with the results of our own research, when the standard liquid flows through the collector-distilled and demineralized water.

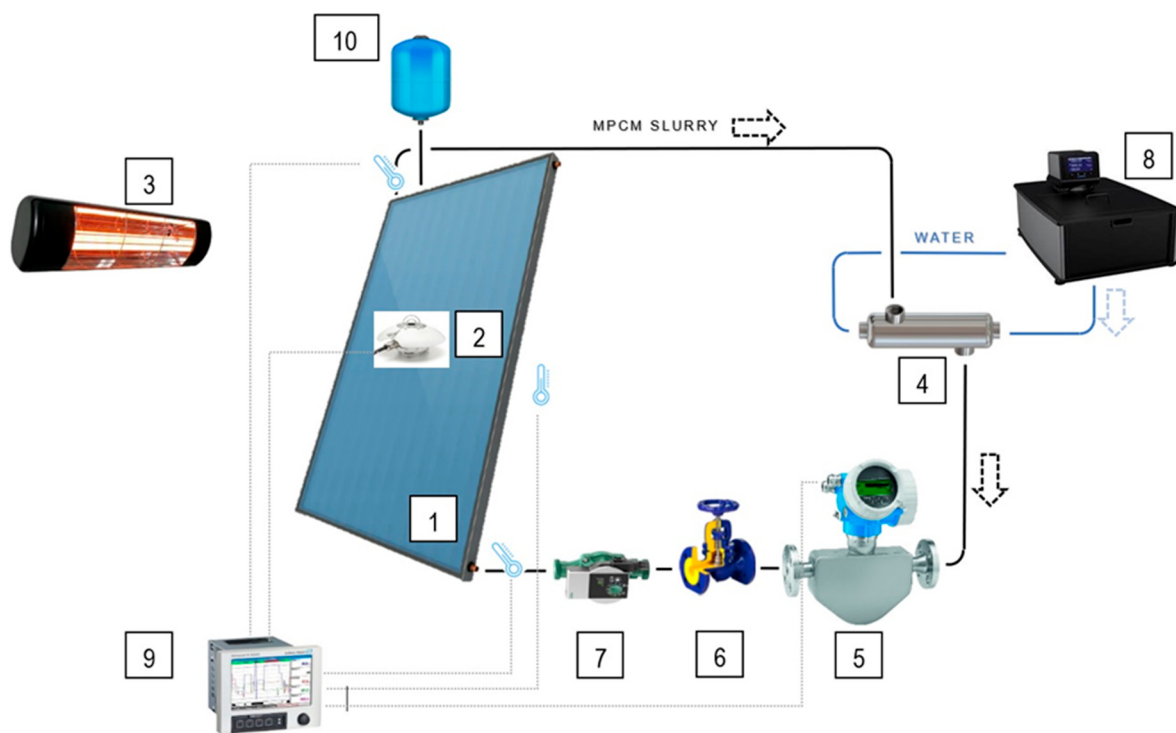


Figure 1. Pictorial diagram of the experimental facility: 1—flat solar collector; 2—pyranometer; 3—infrared heater; 4—heat exchanger; 5—Coriolis type mass flow meter; 6—regulating valve; 7—circulation pump; 8—cryostat; 9—recording device; 10—mPCM leveling vessel.

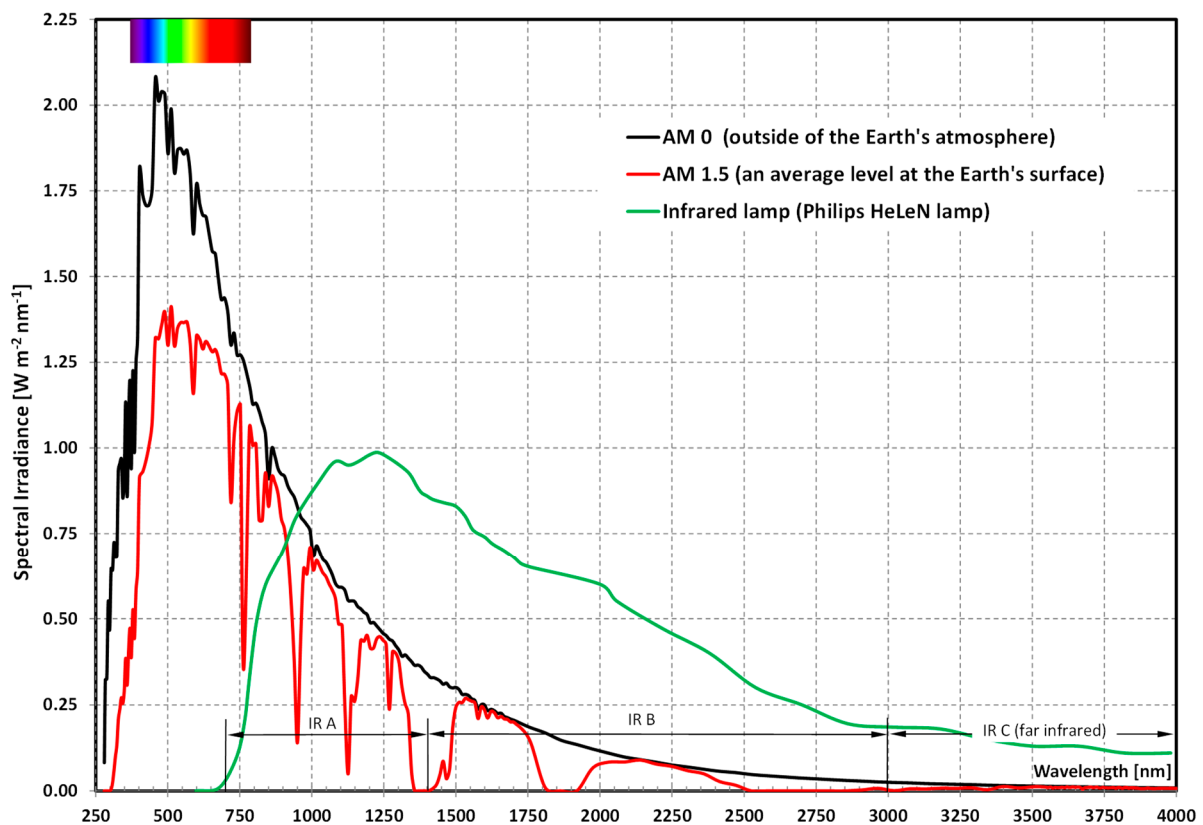


Figure 2. The spectrum of radiation of a Philips HeLeN filament against the spectrum of solar radiation.

The total irradiance reaching the collector surface was measured with a secondary standard CMP11 pyranometer by Kipp and Zonen (Delft, The Netherlands). The value of the radiation intensity was defined as the arithmetic mean of 18 local values of total radiation measured at points evenly distributed on the collector's face. The maximum value of the total irradiance that can be obtained in laboratory conditions was $I = 1000 \text{ W/m}^2$. The accuracy of the determination of the average irradiance was $\pm 4.33 \text{ W/m}^2$.

The movement of the working medium in the test circuit was forced by a centrifugal pump. The pump pumped the working medium through the collector. Then the working medium flow to the heat exchanger. In the heat exchanger, the working medium transferred the heat collected in the collector to the intermediate liquid cooled by the cryostat. The working fluid, at the reduced temperature, was passed through a Coriolis mass flow meter (Promass 80A manufactured by Endress+Hauser; Wien, Austria). The measuring accuracy of this device is $\pm 0.15\%$ of the measured value. The working medium with a defined known flow rate returned through the control valve to the pump suction port.

The ambient temperature, the working medium at the collector inlet, and the temperature of the working medium at the collector outlet were measured using individually made K-type thermocouples. Each thermocouple was individually calibrated (in the range of $10\text{--}80 \text{ }^\circ\text{C}$) in relation to a standard glass thermometer with a $0.02 \text{ }^\circ\text{C}$ graduation. The error in the thermocouple indications did not exceed $\pm 0.2 \text{ K}$. All temperature, flow, and irradiance signals were archived using the RSG40 Memograph recorder by Endress+Hauser.

2.3. Research Procedure and Data Reduction

All measurements were made in steady-state at three different irradiance values. For each irradiance, three measurement series were performed with different flow rates of the working liquid. The mass flow rate of the working liquid was (approximately) 20 kg/h , 40 kg/h , and 80 kg/h . In order to assess the impact of the mass fraction of mPCM on the collector's work, the temperature of the working medium at the collector inlet was kept constant ($T_{in} = 20 \pm 0.5 \text{ }^\circ\text{C}$), and different temperatures of the working medium at the outlet from the collector, for the same conditions of the experiment, were the effect of the physical properties of the working fluid. The ambient temperature was constant and equal to $19 \pm 0.5 \text{ }^\circ\text{C}$.

The heat collected by the water flowing through the collector is defined on the basis of the relationship:

$$Q = \dot{m} \cdot c_p \cdot (T_{in} - T_{out}), \quad (1)$$

where: T_{in} and T_{out} denote the working fluid temperature at the collector inlet and outlet, $\dot{m}$ —mass flow rate of the working fluid, and c_p —specific heat of the working fluid.

The heat received by the mPCM water slurry flowing through the collector was determined on the basis of the relationship:

$$Q = \dot{m} \cdot (h_{in} - h_{out}), \quad (2)$$

where: h_{in} and h_{out} , respectively, denote the specific enthalpy of the slurry at the collector inlet and outlet. Specific heat capacity of water was adopted following the literature data, i.e., $c_p = 4.19 \text{ kJ/(kgK)}$. The specific enthalpy of the mPCM slurry used during the research was determined experimentally. The results were obtained based on the so-called "thermal delay method". It is an improved version of the T-history method, which provides results with less error. The basis for determining the specific heat value is the time-dependent cooling process. The samples of the suspension and the standard liquid (water) were heated to $50 \text{ }^\circ\text{C}$. During their cooling down in a room with a temperature of $10 \text{ }^\circ\text{C}$, the instantaneous temperature that the PCM slurry reaches in relation to the temperature of the standard liquid at the same time was measured. After the conversion, it is possible to determine the specific heat of the slurry and heat of phase transformation. The entire procedure and necessary dependencies are described in detail in the study by

the authors [53]. The influence of temperature on the specific enthalpy of the aqueous mPCM slurry based on MICRONAL[®] 5428 X is shown in Figure 3.

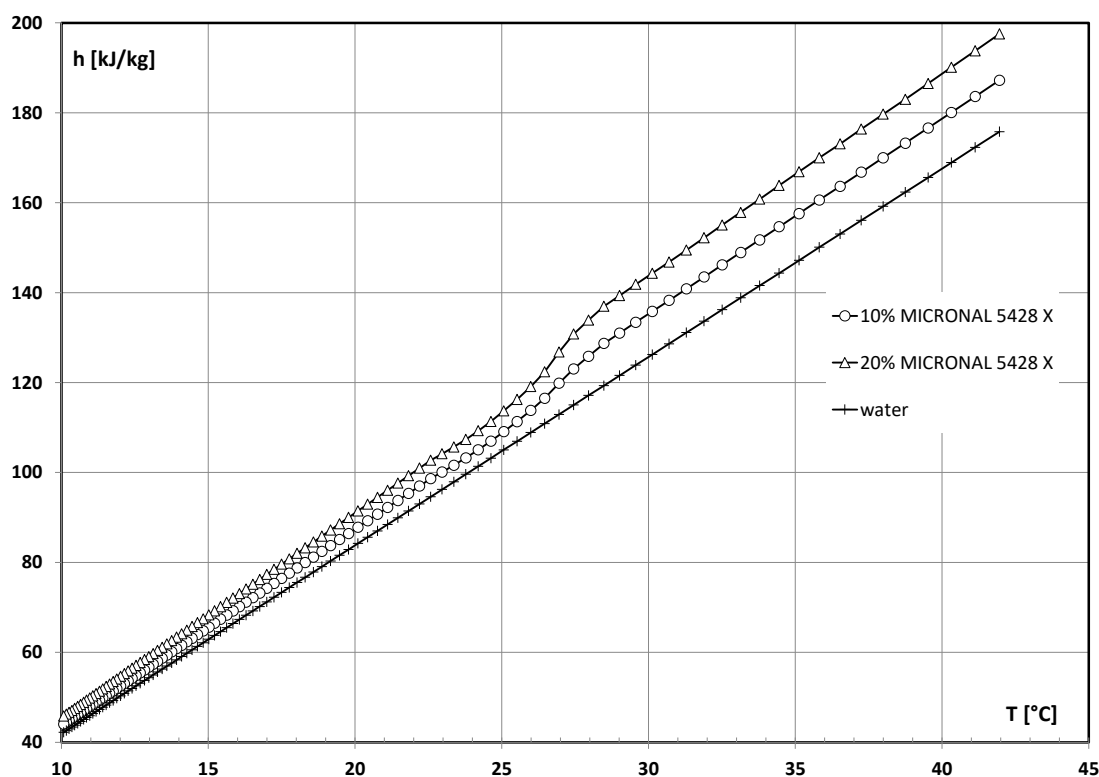


Figure 3. Specific enthalpy of working liquids used during thermal tests of the collector.

3. Results and Discussion

3.1. Test Results of a Solar Collector Supplied with the Reference Liquid–Water

Figure 4 shows the influence of the irradiance on the temperature increase of the reference liquid–water. It was noted that the greater the intensity of radiation reaching the collector surface, the greater the temperature of the working liquid. The three curves apply to the working fluid flow rates of 18.8 kg/h, 39.1 kg/h, and 79.9 kg/h, respectively. It was noted that the greater the working fluid flow through the collector, the smaller the working fluid temperature rise was obtained for each case of irradiance.

The influence of the irradiance reaching the surface of the collector on its thermal power is shown in Figure 5. It was noted that the amount of heat transferred to the medium flowing through the collector increases with the increase in radiation intensity. It was also noted that the greater the mass flow rate of the working fluid, the greater the efficiency of energy conversion and the amount of heat transferred to the medium. The intensity of the heat exchange process between the channel wall and the working fluid may increase with the increase in the velocity of liquid flow through the collector. The obtained relationships, presented in Figures 4 and 5, confirm the results of studies by other authors [54–57], who investigated the impact of both the water flow rate (as the base liquid) and the proposed nanofluids flow rate on the thermal performance of a flat liquid solar collector.

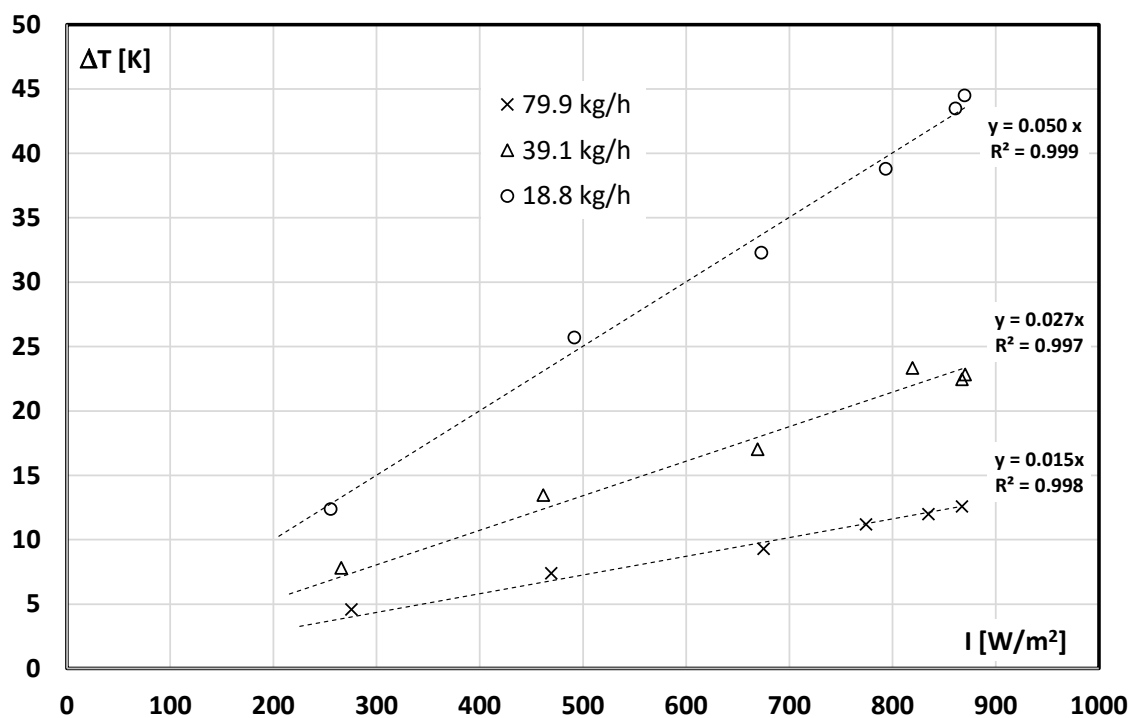


Figure 4. Influence of irradiance on the increase in water temperature in the solar collector.

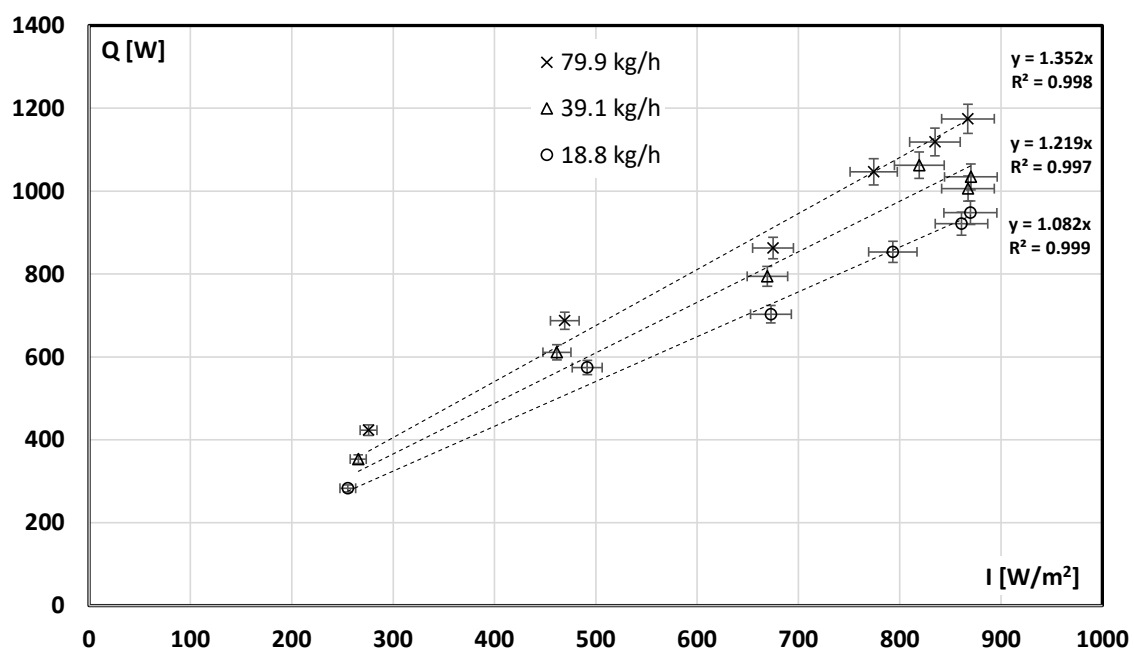


Figure 5. Influence of the irradiance on the amount of heat transferred to the water flowing through the solar collector.

3.2. Test Results for a Solar Collector Supplied with mPCM Slurry

Figure 6 shows the influence of the irradiance on the temperature increase in the liquid flowing through the solar collector (water slurry of 4.3% wt. mPCM). It was noted that the greater the intensity of radiation reaching the collector surface, the greater the increase in temperature of the slurry flowing through the collector. Similarly to the flow of water, the greater the flow rate of the working liquid through the collector, the lower its temperature increase (at the same irradiance).

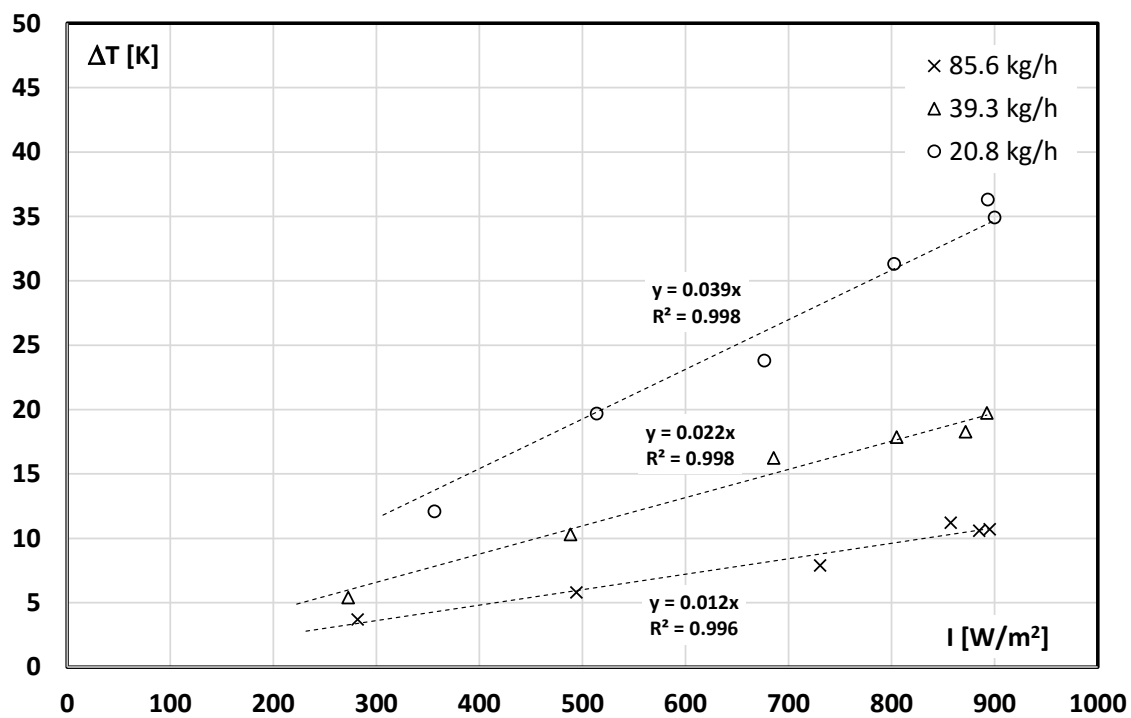


Figure 6. Influence of irradiance on the temperature increase in mPCM water slurry (4.3 wt.%) in the solar collector.

The effect of the irradiance on the collector surface on the value of the heat transferred to the aqueous mPCM slurry is similar to that for water (Figure 7). Both the increase in the radiation intensity and the increase in the slurry flow rate result in an increase in the heat transferred to the working fluid.

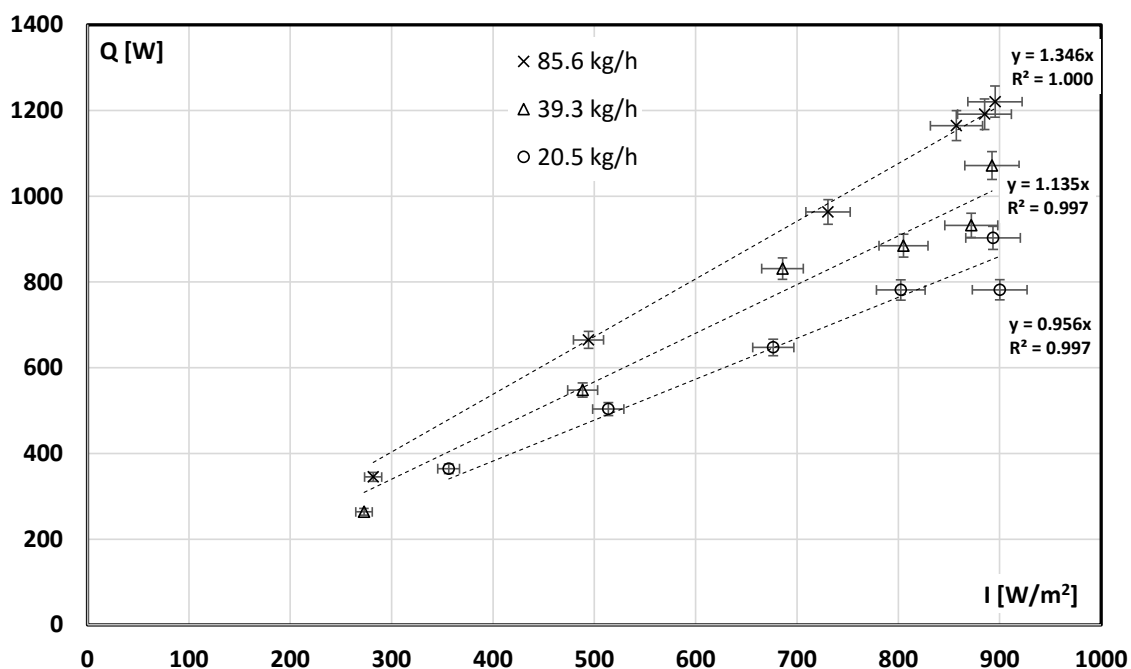


Figure 7. Influence of the irradiance on the amount of heat transferred to the mPCM water suspension (4.3 wt.%) flowing through the solar collector.

It should be mentioned that the relationships (not presented here), as in Figures 6 and 7, were also obtained during the test of the collector through which 8.6% wt. aqueous mPCM slurry.

3.3. The Influence of mPCM in the Slurry on the Results of the Solar Collector Tests

The following figures present the test results obtained for the working liquid flow at the level of ~ 40 kg/h. The results for water, 4.3 wt.% aqueous slurry of mPCM, and 8.6 wt.% aqueous slurry of mPCM were compared. Figure 8 shows the influence of the irradiance on the temperature increase of the working medium. It was noted that the increase in the mass fraction of mPCM in the slurry allows obtaining a lower temperature of the working medium at the outlet of the collector. The temperature of the 8.6% mPCM slurry leaving the collector is lower than the water temperature by about 10 K (at the maximum value of radiation intensity obtained during the tests). It follows that it is possible to use mPCM slurry as a working liquid in the solar collector circuits, which entails a decrease in the temperature of the working liquid.

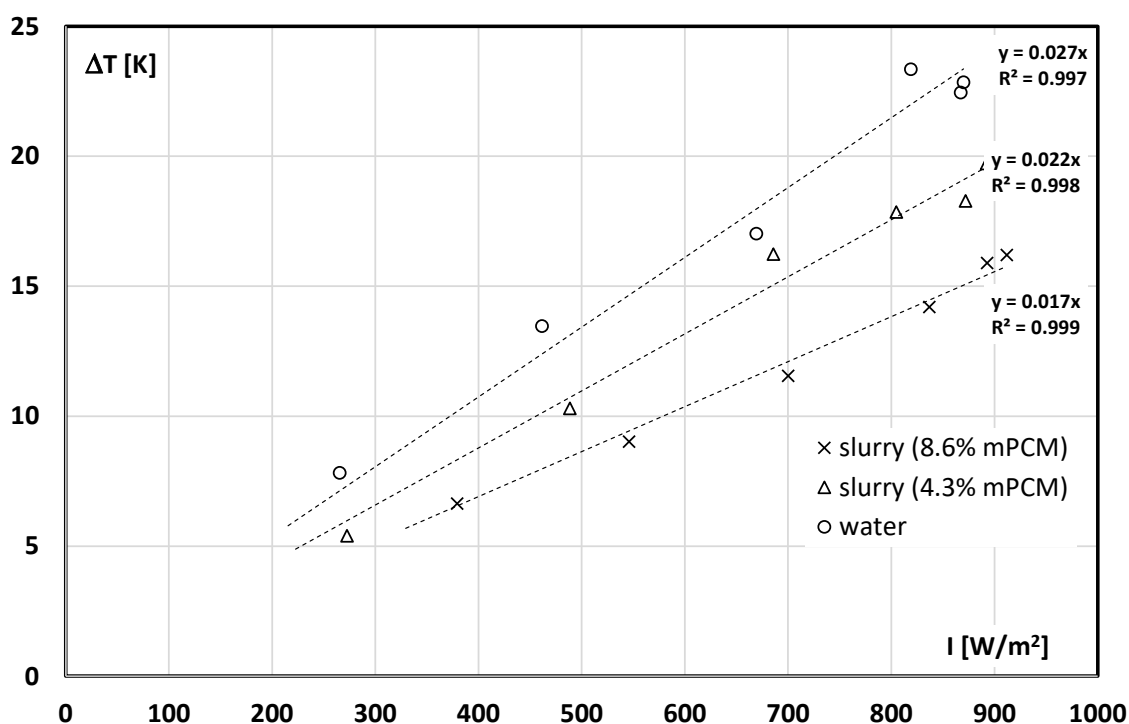


Figure 8. Influence of the irradiance on the increase in temperature of the working liquid ($m \approx 40$ kg/h).

The research was carried out with the use of PCM, the phase change temperature of which is about 28°C . Ultimately, in the installation of a liquid solar collector, a slurry can be used, where the PCM has a phase change temperature, e.g., about 70°C . The advantages of using such a slurry in a solar collector installation are as follows:

- In summer, when hot water consumption is sometimes too low (low demand for hot water, the user has gone on holiday), the water temperature in the tank rises. Then, the temperature of the working liquid flowing through the exchanger also increases. When it reaches the mPCM phase transition temperature, further heat input causes the phase transformation process to start. This is performed at a constant temperature of the working fluid until all PCM in the plant has undergone a phase change. The traditional working fluid may reach boiling point during this time. Then, excessive pressure in the installation causes the safety valve to open and the liquid vapors to be released into the environment. When the working fluid is water, there is no problem, and its deficiency can be easily replenished. However, in temperate regions, due to cold winters, the working fluid is not water but a water–glycol solution. Then, its deficiencies need to be supplemented, and in fact, too high a temperature caused the substance to lose its properties. In this case, all liquid in the system must be replaced;

- In winter, when the temperature of the working liquid is significantly higher than the ambient temperature, the heat losses, including those from the collector, are higher with the higher the temperature of the working liquid in the system. The supply of the same amount of heat to the reservoir with the mPCM slurry at a temperature slightly above the phase transition temperature is more effective than, for example, water, which should have a higher temperature. Reducing heat loss to the environment increases the efficiency of the complete installation.

The influence of the type of working medium on the collector's thermal power is shown in Figure 9. The summary concerns the tests carried out for the flow of working fluids at the level of ~ 40 kg/h. The presented comparison shows that, regardless of the type of working fluid, the collector's thermal power is comparable, regardless of the radiation intensity reaching the collector surface.

It should be emphasized that similar trends were obtained for other values of the working fluid flow rate (~ 20 kg/h and ~ 80 kg/h).

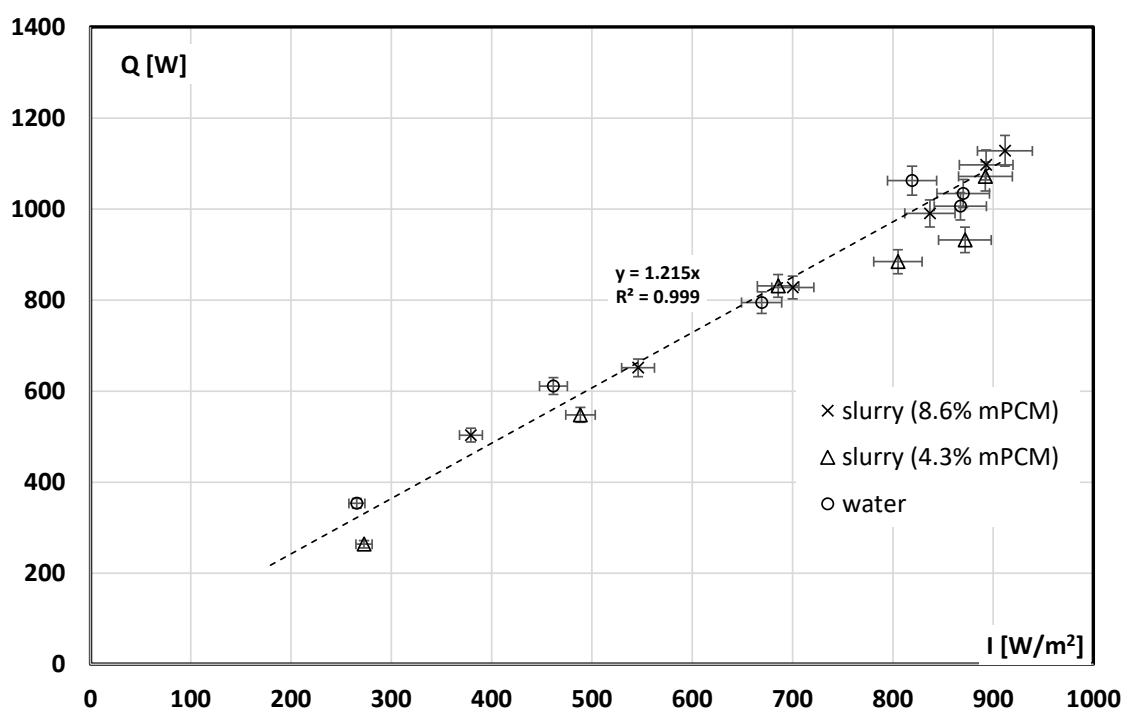


Figure 9. Influence of the irradiance on the heat flux transferred to the working fluid flowing through the solar collector ($m \approx 40$ kg/h).

4. Summary and Conclusions

There are a significant number of publications devoted to the use of nanofluids as a working fluid in the installation of solar collectors. This paper presents one of the pioneering research results regarding the possibility of using microencapsulated PCM (mPCM) slurry in such installations. It should be emphasized that these are the results of preliminary cognitive studies aimed at preliminary assessment of the possibility of using mPCM slurries and their impact on the operation of the liquid solar collector. The tests were carried out in laboratory conditions with the use of a commercial collector with an aperture area of 1.98 m^2 . The tests were carried out with the use of three types of working liquid: water (reference liquid) and aqueous mPCM slurry (4.3% wt. and 8.6% wt.). The working liquid flowed in the amount of ~ 20 kg/h, ~ 40 kg/h, and ~ 80 kg/h. The irradiance on the surface of the collector was varied in the range of $250\text{--}950 \text{ W/m}^2$. In order to assess the influence of the type of medium on the operation of the solar collector, the temperature of the working liquid at the collector inlet was constant, near the ambient temperature,

and amounted to $T_{in} = 20 \pm 0.5$ °C. Based on the research, the following conclusions were obtained:

- The more PCM microcapsules in the working liquid, the lower the temperature of the liquid leaving the collector (for the same irradiance), which results from the use of the latent heat of the PCM material;
- The type of working fluid does not affect the collector's thermal power obtained for analogous conditions of the experiment (irradiance, mass flow of the working fluid);
- It is possible to use mPCM water slurry as a working fluid in solar collector installations without adversely affecting its performance;
- The use of the phase change heat of the PCM material contained in the microcapsules circulating in the working fluid caused its temperature to be lower than that of water without the addition of mPCM when the same amount of thermal energy was transported;
- The reduced temperature of the working liquid may have a positive effect on the operation of the system: In summer—protection of the working fluid against overheating that results in a phase change and pressure increase in the system, or an irreversible change in the physical properties of the working fluid (e.g., based on propylene glycol); In winter—lowering the temperature of the working liquid circulating in the installation reduces heat loss to the environment (especially through the collector), increasing the overall efficiency of the system.

The presented results are preliminary studies on the use of mPCM slurry in liquid solar collectors. The authors of the study intend to carry out detailed research data on the influence of the slurry on the collector's operation, on the basis of which it will be possible to determine the efficiency of the collector as a function of irradiance I and reduced temperature differences $(T_{in} - T_{amb})/I$.

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References

1. Pandey, K.M.; Chaurasiya, R. A review on analysis and development of solar flat plate collector. *Renew. Sustain. Energy Rev.* **2017**, *67*, 641–650. [CrossRef]
2. Raymond, E.; Telkes, M. Dover Sun House, Dover Massachusetts. 1948. Available online: <https://energyhistory.yale.edu/library-item/eleanor-raymond-and-maria-telkes-dover-sun-house-dover-massachusetts-1948> (accessed on 2 March 2021).
3. Pandey, A.K.; Hossain, M.; Tyagi, V.; Rahim, N.A.; Selvaraj, J.A.; Sari, A. Novel approaches and recent developments on potential applications of phase change materials in solar energy. *Renew. Sustain. Energy Rev.* **2018**, *82*, 281–323. [CrossRef]
4. Javadi, F.; Metselaar, H.; Ganesan, P. Performance improvement of solar thermal systems integrated with phase change materials (PCM), a review. *Sol. Energy* **2020**, *206*, 330–352. [CrossRef]
5. Zayed, M.E.; Zhao, J.; Elsheikh, A.H.; Du, Y.; Hammad, F.A.; Ma, L.; Kabeel, A.; Sadek, S. Performance augmentation of flat plate solar water collector using phase change materials and nanocomposite phase change materials: A review. *Process Saf. Environ. Prot.* **2019**, *128*, 135–157. [CrossRef]
6. Khan, M.M.A.; Ibrahim, N.I.; Mahbubul, I.; Ali, H.M.; Saidur, R.; Al-Sulaiman, F.A. Evaluation of solar collector designs with integrated latent heat thermal energy storage: A review. *Sol. Energy* **2018**, *166*, 334–350. [CrossRef]
7. Bohdal, T.; Kruzel, M. Refrigerant condensation in vertical pipe minichannels under various heat flux density level. *Int. J. Heat Mass Transf.* **2019**, *146*, 118849. [CrossRef]

8. Bohdal, T.; Charun, H.; Kruzel, M.; Sikora, M. An investigation of heat transfer coefficient during refrigerants condensation in vertical pipe minichannels. *E3S Web Conf.* **2018**, *70*, 02001. [\[CrossRef\]](#)
9. Kruzel, M.; Bohdal, T.; Sikora, M. Heat transfer and pressure drop during refrigerants condensation in compact heat exchangers. *Int. J. Heat Mass Transf.* **2020**, *161*, 120283. [\[CrossRef\]](#)
10. Serale, G.; Fabrizio, E.; Perino, M. Design of a low-temperature solar heating system based on a slurry Phase Change Material (PCS). *Energy Build.* **2015**, *106*, 44–58. [\[CrossRef\]](#)
11. Wang, Z.; Qiu, F.; Yang, W.; Zhao, X. Applications of solar water heating system with phase change material. *Renew. Sustain. Energy Rev.* **2015**, *52*, 645–652. [\[CrossRef\]](#)
12. Qiu, Z.; Li, P.; Wang, Z.; Zhao, H.; Zhao, X. PCM and PCM slurries and their application in solar systems. In *Advanced Energy Efficiency Technologies for Solar Heating, Cooling and Power Generation*; Springer: Berlin, Germany, 2019.
13. Koohi-Fayegh, S.; Rosen, M. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2019**, *27*, 101047. [\[CrossRef\]](#)
14. Jouhara, H.; Żabnieńska-Góra, A.; Khordehgah, N.; Ahmad, D.; Lipinski, T. Latent thermal energy storage technologies and applications: A review. *Int. J. Thermofluids* **2020**, *5–6*, 100039. [\[CrossRef\]](#)
15. Elarem, R.; Alqahtani, T.; Mellouli, S.; Askri, F.; Edacherian, A.; Vineet, T.; Badruddin, I.A.; Abdelmajid, J. A comprehensive review of heat transfer intensification methods for latent heat storage units. *Energy Storage* **2019**, *3*, e127. [\[CrossRef\]](#)
16. Dutkowski, K.; Kruzel, M. Microencapsulated PCM slurries' dynamic viscosity experimental investigation and temperature-dependent prediction model. *Int. J. Heat Mass Transf.* **2019**, *145*, 118741. [\[CrossRef\]](#)
17. Dutkowski, K.; Kruzel, M. Experimental investigation of the apparent thermal conductivity of microencapsulated phase-change-material slurry at the phase-transition temperature. *Materials* **2021**, *14*, 4124. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Ikutegbe, C.A.; Farid, M.M. Application of phase change material foam composites in the built environment: A critical review. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110008. [\[CrossRef\]](#)
19. Faraj, K.; Khaled, M.; Faraj, J.; Hachem, F.; Castelain, C. A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. *J. Energy Storage* **2020**, *33*, 101913. [\[CrossRef\]](#)
20. Magendran, S.S.; Khan, F.S.A.; Mubarak, N.; Vaka, M.; Walvekar, R.; Khalid, M.; Abdullah, E.; Nizamuddin, S.; Karri, R.R. Synthesis of organic phase change materials (PCM) for energy storage applications: A review. *Nano Struct. Nano Objects* **2019**, *20*, 100399. [\[CrossRef\]](#)
21. Ahmadi, R.; Monadinia, F.; Maleki, M. Passive/active photovoltaic-thermal (PVT) system implementing infiltrated phase change material (PCM) in PS-CNT foam. *Sol. Energy Mater. Sol. Cells* **2021**, *222*, 110942. [\[CrossRef\]](#)
22. Fu, Z.; Liang, X.; Li, Y.; Li, L.; Zhu, Q. Performance improvement of a PVT system using a multilayer structural heat exchanger with PCMs. *Renew. Energy* **2020**, *169*, 308–317. [\[CrossRef\]](#)
23. Kılış, B. Development of a composite PVT panel with PCM embodiment, TEG modules, flat-plate solar collector, and thermally pulsing heat pipes. *Sol. Energy* **2019**, *200*, 89–107. [\[CrossRef\]](#)
24. Chavan, S.V.; Devaprakasam, D. Improving the performance of solar photovoltaic thermal system using phase change material. *Mater. Today Proc.* **2020**, *46*, 5036–5041. [\[CrossRef\]](#)
25. Dutkowski, K.; Kruzel, M.; Zajczkowski, B.; Białko, B. The experimental investigation of mPCM slurries density at phase change temperature. *Int. J. Heat Mass Transf.* **2020**, *159*, 120083. [\[CrossRef\]](#)
26. Akshayveer, K.A.; Singh, A.P.; Singh, O. Effect of novel PCM encapsulation designs on electrical and thermal performance of a hybrid photovoltaic solar panel. *Sol. Energy* **2020**, *205*, 320–333. [\[CrossRef\]](#)
27. Alwaeli, A.H.A.; Kazem, H.A.; Chaichan, M.T.; Sopian, K. Experimental investigation of using nano-PCM/nanofluid on a photovoltaic thermal system (PVT): Technical and economic study. *Therm. Sci. Eng. Prog.* **2019**, *11*, 213–230. [\[CrossRef\]](#)
28. Maatallah, T.; Zachariah, R.; Al-Amri, F.G. Exergo-economic analysis of a serpentine flow type water based photovoltaic thermal system with phase change material (PVT-PCM/water). *Sol. Energy* **2019**, *193*, 195–204. [\[CrossRef\]](#)
29. Alwaeli, A.H.A.; Chaichan, M.T.; Sopian, K.; Kazem, H.A.; Mahood, H.B.; Khadom, A.A. Modeling and experimental validation of a PVT system using nanofluid coolant and nano-PCM. *Sol. Energy* **2018**, *177*, 178–191. [\[CrossRef\]](#)
30. Liu, C.; Ma, Z.; Wang, J.; Li, Y.; Rao, Z. Experimental research on flow and heat transfer characteristics of latent functional thermal fluid with microencapsulated phase change materials. *Int. J. Heat Mass Transf.* **2017**, *115*, 737–742. [\[CrossRef\]](#)
31. Karaipekli, A.; Erdoğan, T.; Barlak, S. The stability and thermophysical properties of a thermal fluid containing surface-functionalized nanoencapsulated PCM. *Thermochim. Acta* **2019**, *682*, 178406. [\[CrossRef\]](#)
32. Hawlader, M.; Uddin, M.; Khin, M.M. Microencapsulated PCM thermal-energy storage system. *Appl. Energy* **2003**, *74*, 195–202. [\[CrossRef\]](#)
33. Chen, L.; Wang, T.; Zhao, Y.; Zhang, X.-R. Characterization of thermal and hydrodynamic properties for microencapsulated phase change slurry (MPCS). *Energy Convers. Manag.* **2014**, *79*, 317–333. [\[CrossRef\]](#)
34. Chai, L.; Shaikat, R.; Wang, L.; Wang, H.S. A review on heat transfer and hydrodynamic characteristics of nano/microencapsulated phase change slurry (N/MPCS) in mini/microchannel heat sinks. *Appl. Therm. Eng.* **2018**, *135*, 334–349. [\[CrossRef\]](#)
35. Alehosseini, E.; Jafari, S.M. Nanoencapsulation of phase change materials (PCMs) and their applications in various fields for energy storage and management. *Adv. Colloid Interface Sci.* **2020**, *283*, 102226. [\[CrossRef\]](#)

36. Usman, M.; Siddiqui, F.; Ehsan, A.; Sadaqat, R.A.; Hussain, A. Improvement of thermal conductivity of paraffin wax, a phase change material with graphite powder. In Proceedings of the 17th International Bhurban Conference on Applied Sciences and Technology (IBCAST), Islamabad, Pakistan, 14–18 January 2020.
37. Wu, S.; Yan, T.; Kuai, Z.; Pan, W. Thermal conductivity enhancement on phase change materials for thermal energy storage: A review. *Energy Storage Mater.* **2019**, *25*, 251–295. [[CrossRef](#)]
38. Lan, W.; Shang, B.; Wu, R.; Yu, X.; Hu, R.; Luo, X. Thermally-enhanced nanoencapsulated phase change materials for latent functionally thermal fluid. *Int. J. Therm. Sci.* **2020**, *159*, 106619. [[CrossRef](#)]
39. Yang, L.; Liu, S.; Zheng, H. A comprehensive review of hydrodynamic mechanisms and heat transfer characteristics for microencapsulated phase change slurry (MPCS) in circular tube. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109312. [[CrossRef](#)]
40. Ghoghhaei, M.S.; Mahmoudian, A.; Mohammadi, O.; Shafii, M.B.; Mosleh, H.J.; Zandieh, M.; Ahmadi, M.H. A review on the applications of micro-/nano-encapsulated phase change material slurry in heat transfer and thermal storage systems. *J. Therm. Anal. Calorim.* **2020**, *145*, 245–268. [[CrossRef](#)]
41. Jia, Y.; Zhu, C.; Fang, G. Performance optimization of a photovoltaic/thermal collector using microencapsulated phase change slurry. *Int. J. Energy Res.* **2019**, *44*, 1812–1827. [[CrossRef](#)]
42. Ran, F.; Chen, Y.; Cong, R.; Fang, G. Flow and heat transfer characteristics of microencapsulated phase change slurry in thermal energy systems: A review. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110101. [[CrossRef](#)]
43. Moshtagh, M.; Jamekhorshid, A.; Azari, A.; Farid, M.M. Experimental and numerical investigation of microencapsulated phase change material slurry heat transfer inside a tube with butterfly tube inserts. *Appl. Therm. Eng.* **2020**, *174*, 115270. [[CrossRef](#)]
44. Serale, G.; Cascone, Y.; Capozzoli, A.; Fabrizio, E.; Perino, M. Potentialities of a low temperature solar heating system based on slurry phase change materials (PCS). *Energy Procedia* **2014**, *62*, 355–363. [[CrossRef](#)]
45. Baronetto, S.; Serale, G.; Goia, F.; Perino, M. Numerical model of a slurry PCM-based solar thermal collector. In Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning, Xi'an, China, 19–21 October 2013.
46. Serale, G.; Baronetto, S.; Goia, F.; Perino, M. Characterization and Energy Performance of a Slurry PCM-based Solar Thermal Collector: A Numerical Analysis. *Energy Procedia* **2014**, *48*, 223–232. [[CrossRef](#)]
47. Serale, G.; Goia, F.; Perino, M. Numerical model and simulation of a solar thermal collector with slurry Phase Change Material (PCM) as the heat transfer fluid. *Sol. Energy* **2016**, *134*, 429–444. [[CrossRef](#)]
48. Prearo, G.; Serale, G.; Perino, M. Numerical model for solar thermal collectors and thermal energy storages based on phase change slurry. In Proceedings of the ISES Solar World Congress 2017 with IEA SHC Solar Heating and Cooling Conference 2017, Abu Dhabi, United Arab Emirates, 29 October–2 November 2017.
49. Fang, W.; Riffat, S.; Wu, Y. Experimental investigation of evacuated heat pipe solar collector efficiency using phase-change fluid. *Int. J. Low-Carbon Technol.* **2017**, *12*, 392–399. [[CrossRef](#)]
50. Sun, L.; Xiang, N.; Yuan, Y.; Cao, X. Experimental investigation on performance comparison of solar water heating-phase change Material system and solar water heating system. *Energies* **2019**, *12*, 2347. [[CrossRef](#)]
51. Microtek Labs. *Micronal ®5428 X*; Microtek Labs: Moraine, OH, USA, 2018.
52. KOSPEL. *Solar Collector—Technical Brochure*; KOSPEL: Koszalin, Poland, 2013. (In Polish)
53. Dutkowski, K.; Kruzel, M.; Zajaczkowski, B. Determining the heat of fusion and specific heat of microencapsulated phase change material slurry by thermal delay method. *Energies* **2020**, *14*, 179. [[CrossRef](#)]
54. Rajput, N.S.; Shukla, D.D.; Rajput, D.; Sharm, S.K. Performance analysis of flat plate solar collector using Al₂O₃/Distilled water nanofluid: An experimental investigation. *Mater. Today Proc.* **2019**, *10*, 52–59. [[CrossRef](#)]
55. Moravej, M.; Bozorg, M.V.; Guan, Y.; Li, L.K.; Doranehgard, M.H.; Hong, K.; Xiong, Q. Enhancing the efficiency of a symmetric flat-plate solar collector via the use of rutile TiO₂-water nanofluids. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100783. [[CrossRef](#)]
56. Sharafeldin, M.; Gróf, G. Experimental investigation of flat plate solar collector using CeO₂ -water nanofluid. *Energy Convers. Manag.* **2018**, *155*, 32–41. [[CrossRef](#)]
57. Sundar, L.S.; Kirubeil, A.; Punnaiah, V.; Singh, M.K.; Sousa, A. Effectiveness analysis of solar flat plate collector with Al₂O₃ water nanofluids and with longitudinal strip inserts. *Int. J. Heat Mass Transf.* **2018**, *127*, 422–435. [[CrossRef](#)]