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PHOTOVOLTAIC-THERMAL SYSTEMS WITH INCORPORATED PHASE CHANGE MATERIALS

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FOTONAPONSKI-TOPLINSKI KOLEKTORI S FAZNO PROMJENJIVIM MATERIJALIMA

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1. INTRODUCTION

The ways of generating, storing, and distributing energy are globally rapidly changing, [1]. Therefore, energy production and trading tend to increase flexibility and reduce costs while taking into account the impact on the environment from the production phase to the final consumer. Fossil energy sources undoubtedly contribute to carbon emissions but also generate other toxic materials harmful to the environment, [2]. Hence, economic fluctuations and climate change require a rapid energy transition to low-carbon power production, [3]. The energy transition to renewable energy sources is driven by a variety of technologies, however, is primarily dominated by wind energy [4] and photovoltaic (PV) systems [5]. The International Energy Agency states that almost half of the installed renewable energy capacities in 2021 (close to 290 GW) were related to photovoltaics, followed by wind and hydropower, [6]. Solar photovoltaic energy sources make up 60% of newly added renewable energy capacities, i.e. according to estimates, in 2021 almost 160 GW of solar photovoltaic systems were installed globally, [6]. According to the International Renewable Energy Agency, installed solar capacity has been growing steadily over the past decade, [7]. But the rate of growth varies considerably across different regions of the world, i.e. 74% of globally installed solar capacities in 2011 were related to Europe, while in 2021 this figure dropped to 22%, with Asia leading the way with a share of 57%, which is a significant increase compared to 13% in 2011, [7]. Overall, photovoltaic technology has been expanding in recent years due to the continuous decline in unit cost, i.e. unit cost ranges from 1.5 €/Wp to 3.5 €/Wp, [8]. The primary limiting factor of all photovoltaic technologies is relatively low efficiency, ranging from 13% to 18% depending on environmental conditions [9] and specific technology, [10]. The overall efficiency of a photovoltaic system can be improved by a cogeneration approach such as photovoltaic-thermal (PVT) systems that generate electricity and useful heat, [11]. The use of PVT collectors can contribute to the acceleration of energy transition, considering that, in addition to electricity generation, they can be used to generate hot water for households, pool heating, air heating, drying, etc., [5]. Currently, there are over twenty manufacturers of PVT collectors globally, of which 48% are uncovered flat plate collectors and 28% are covered, while the rest are air-based, concentrating, and vacuum tube collectors, [5]. PVT collectors are expanding relatively slowly in the market due to high investment costs, mainly between 330 €/m^2 and 900 €/m^2, [5]. The efficiency of PVT collectors, and consequently unit cost, depends on the design itself, where the focus can be on either electrical or thermal efficiency. The expected electrical efficiency of the PVT collector is generally less than 20% while the thermal efficiency depending on the design varies between 40% and 80%, [11]. The thermal component of the system is slightly more sensitive to design so thermal management is needed to maximize electrical production and thermal efficiency. These two tasks conflict with each other, so it is necessary to achieve a balance between the production of electricity and the generation of useful heat. Increasingly, the thermal management of PVT collectors is based on phase change materials (PCM) that serve as a passive heat sink, [12]. In recent years, a lot of research has been done to improve the efficiency of PV systems using PCM materials. Such PV-PCM systems in passive mode achieve an increase in efficiency of up to 20%, with a noticeable higher benefit of PCM in the summer months, [13]. To effectively maintain the fragile balance between electrical and thermal efficiency of the PVT-PCM system, it is necessary to apply various numerical methods extensively in the design phase with the inevitable experimental approach. In general, the numerical approach to PCM modeling is very demanding in terms of basic parameters that affect the phase transition process as well as the complexity of heat transfer mechanisms, [14].

The main objective of this work is to integrally analyze the existing design solutions of PVT-PCM collectors with a regard to the applied PCM materials and the possibilities of numerical modeling of such concepts. Analysis of numerical approaches is necessary to detect the dominant heat transfer mechanisms that occur before, during, and after the phase transition process of PCM materials. A properly modeled phase transition process allows the detection of weak points in the early stages of development of the PVT-PCM concept and optimization of design to maximize the overall efficiency of the system.

2. REVIEW METHODOLOGY

The selection of up-to-date research findings was performed in three steps using Elsevier's Scopus® database, [15], as the source of published articles, Fig. 2.1. The primary selection was made with regard to the relevant keywords and subject area for papers published in English in the period from 2019 to 2022, i.e. last four years. This period was chosen to consider the most recent research findings while having in mind the attractiveness of the field of research and the current state of the art. Primary selection significantly narrowed the field of research, but it was necessary to further narrow the subject of research. Therefore, secondary selection grouped articles according to the main focus of the research. Two groups have been formed, the first dealing with experimental PVT-PCM collector systems and the second being somewhat broader, covering numerical modeling of PCM materials in PVT systems and other engineering applications. In the third step of the review, the first group dealing with experimental research was decomposed to the integration of different PCM materials into PVT systems and different approaches to the design of PVT-PCM collectors. Then, the second group dealing with numerical modeling was decomposed into numerical strategies of PCM enhanced PVT systems and numerical approaches to PCM phase transition to detect all the specifics of different numerical analyzes in the context of phase change materials. In summary, the reviewed papers provide insight into the current state of technology and help to perceive future trends.

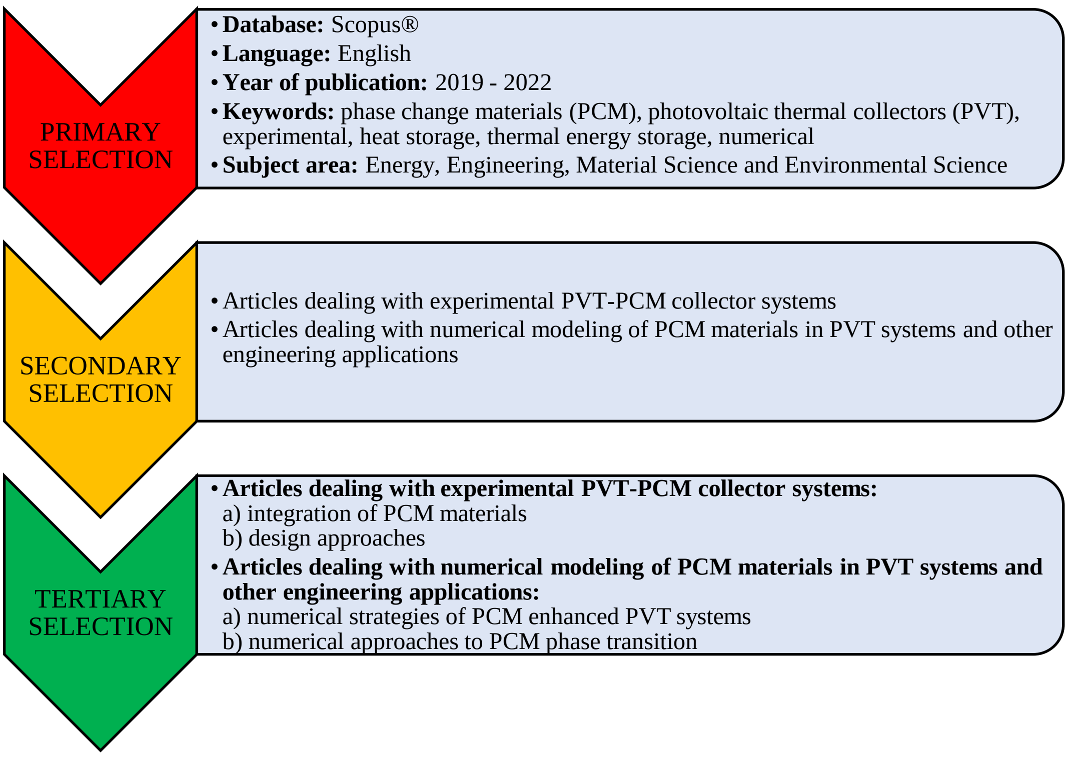


Fig. 2.1. Review methodology approach

3. PVT COLLECTORS: GENERAL FEATURES

The solar potential of a geographical location is not only a function of irradiated solar energy but also depends on the available surface on which energy harvesting systems can be placed. Globally, urban areas are mostly overcrowded with very limited spatial capacity and insatiable energy hunger. Therefore, cogeneration systems that are more efficient in harnessing solar energy per area are being installed. The most prominent solar cogeneration system is photovoltaic thermal (PVT) collectors. PVT collectors combine photovoltaic solar cells that transform insolation into electricity with a solar thermal collector that converts waste heat from the PV system into usable thermal energy. The photovoltaic component of the PVT collector is mainly based on monocrystalline PV cells due to higher nominal electrical efficiency compared to polycrystalline PV cells, but higher nominal efficiency is accompanied by a slightly higher purchase price. Commonly, both silicon photovoltaic technologies sustain significant degradation of electrical efficiency with increasing cell temperature, [16]. This phenomenon causes a collision with the thermal component of the system that tends to higher temperatures to produce hot water. Thus, the key to good PVT collector design is the balance between the opposing natures of the electrical and thermal efficiency of the collector. This integrated solution requires a special heat exchanger that is fixed to the back of the PV panel and together they form a PVT collector, Fig. 3.1. The heat exchanger of a conventional PVT collector usually consists of a copper absorber surface merged with copper pipes thus forming a thermal absorber. The thermal absorber is usually protected from the weather on the underside with thick thermal insulation.

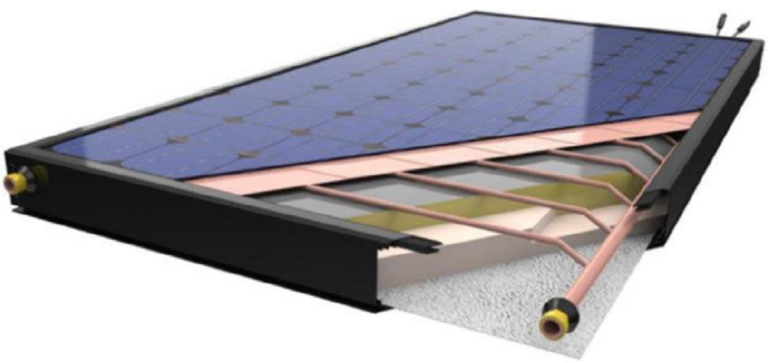


Fig. 3.1. Typical PVT collector layout, [8].

Depending on the heat transfer fluid, PVT collectors can be divided into PVT air and PVT water collectors. Furthermore, they can be distinguished with respect to glazing, i.e. covered, uncovered, and concentrating PVT layouts, [8]. Both heat transfer fluid and glazing type directly affect the operating temperature of the PVT collector. Most conventional PVT collector designs operate at low operating hot water temperatures, i.e. up to 50 °C. The exception is concentrating PVT collectors whose operating temperatures can exceed 80 °C. Most PVT collector designs are a compromise between the electrical and thermal components of the system. Hence, the overall efficiency (η) of the system is the sum of electrical (η_{el}) and thermal efficiency (η_{th}), Eq. (1).

$$\eta = \eta_{el} + \eta_{th} \tag{1}$$

The electrical efficiency of PVT collectors primarily depends on the PV technology, the irradiated solar energy (G), the area (A_{PVT}) of a PVT collector, and the temperature of PV cells that affects the output current (I) and voltage (V), Eq. (2).

$$\eta_{el} = \frac{I \cdot V}{A_{PVT} \cdot G} \tag{2}$$

The thermal efficiency of PVT collectors is somewhat more complex, considering that in addition to the PV technology, irradiated solar energy, and the area of the collector, it also depends on the thermal properties of the heat transfer fluid and its mass flow rate ($\dot{m}$), Eq. (3). The specific heat capacity (C_p) is a characteristic of the selected heat transfer fluid, while the temperature difference (ΔT) is the result of a complex interaction between the design of the PVT collector, heat transfer fluid, and ambient conditions.

$$\eta_{th} = \frac{\dot{m} \cdot C_p \cdot \Delta T}{A_{PVT} \cdot G} \tag{3}$$

Researchers are trying in different ways to manipulate the fragile energy balance of PVT collectors, so in addition to several other technologies such as nanotechnology, different phase change materials are increasingly being implemented, [8]. When implementing any technology, it is necessary to take into account investment costs. Namely, conventional commercially available PVT collectors have a price no less than 300 €/m^2, [17], while for comparison, classic PV panels cost around 200 €/m^2, [8]. Thus, the relatively high price is currently a limiting factor to the wider application of PVT collectors.

4. APPLICATION OF PHASE CHANGE MATERIALS IN PVT SYSTEMS

Phase change materials are increasingly used in the thermal management of various engineering systems, but the bulk relates to thermal energy storage (TES) problems, [18]. Different types of PCM, such as hygroscopic, organic, inorganic, etc., can be found in the literature while the vast majority are commercially available on the market. The selection of a suitable PCM material primarily depends on its characteristics and the desired field of application. The main thermophysical characteristics that must be taken into consideration are density, melting temperature, thermal conductivity, latent heat, specific heat, etc. The role of the favorable properties of PCM can be particularly pronounced in PVT systems by absorbing the heat generated mostly in the photovoltaic part of the system.

4.1 Integration of phase change materials into PVT systems

PVT systems in combination with PCM can produce more electricity and efficiently harvest thermal output with the inevitable stabilization of photovoltaic temperature. PVT systems are mainly designed to operate in the low-temperature range due to the relatively conflicting natures of thermal and electrical efficiency. Therefore, the melting temperature of applied PCM materials ranges from 22 °C to 60 °C, Table 4.1. The most commonly used PCM materials are paraffin-based with relatively low thermal conductivity, i.e. about 0.25 W/mK. Thermal conductivity improvement can be achieved by adding nanomaterials, but this raises the price of PCM with the inevitable negative effects on the environment, given the toxicity of nanomaterials, [19]. According to the literature, Table 4.1, the minimum latent heat is 160 kJ/kg, while the maximum is 250 kJ/kg. The specific heat capacity can vary from 1.7 kJ/kgK to 2.9 kJ/kgK but is usually around 2 kJ/kgK.

The application of PCM in a PVT system can have different repercussions on thermal and electrical efficiency due to the complexity of heat transfer. Thermal management depends on current operating conditions as a result of insolation, convection, conduction in the layers of PVT collectors, and the overall inertness of PCM. Thus, the thickness of the PCM directly affects the thermal and electrical efficiency of the collector. More PCM can absorb more heat but also results in a more inert and more expensive system. The average price of commercially available PCM ranges from 5 €/kg up to 15 €/kg, [37].

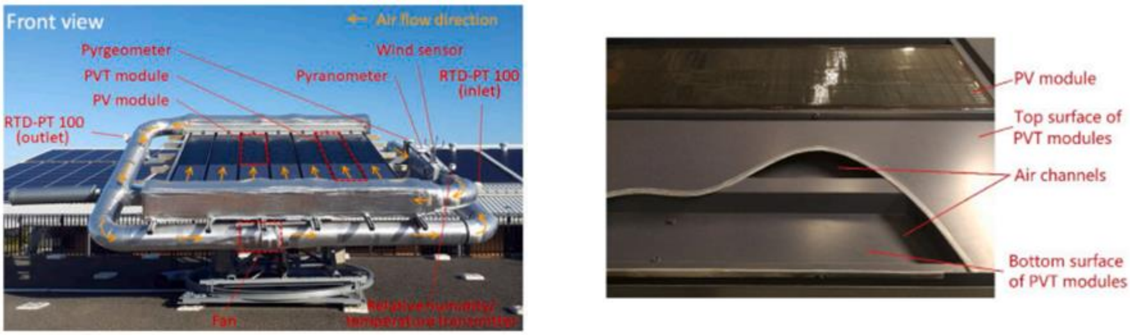
Table 4.1. Summary of applied PCMs in PVT systems

References	PCM type	Melting temperature (°C)	Thermal conductivity (W/mK)	Latent heat (kJ/kg)	Specific heat (kJ/kgK)
[20]	paraffin-coated micro-encapsulated PCM	28	0.34	213.5	1.779
[21]	RT-35	29-36	0.2	160	2
[22]	RT44HC-0.009%f-CNT	ca. 44	-	248.6505	-
[23]	PS-CNT foam encapsulated paraffin	38-47	0.4	124.9	-
[24]	S21	23	0.234	170	2.2
[25]	RT44	41-44	0.2	168	2
[26]	RT35 HC	34-36	0.2	240	2
[26]	RT28HC	27-29	0.2	250	2
[26]	RT25HC	22-26	0.2	210	2
[27]	Merck 107158 (paraffin)	57-60	0.24	220	2.9
[28]	PLUSICE S25	25	0.54	180	2.2
[29]	RT-35HC	35	0.166	240	2.1
[30]	A44	44	0.18	242	2.15
[31]	Paraffin wax	57	0.24	220	2.1
[32]	RT50	50	0.2	160	2.0
[33]	Lauric acid	44-46	0.19	228	1.7
[34]	PCM32/280	32	0.4	186	-
[35]	Octadecane	28	0.21	244	1.9
[36]	Paraffin wax (Merck, 107151)	46-48	0.24	220	2.9

4.2 Design approaches of experimental PVT-PCM collector systems

A well-designed PVT-PCM collector must reconcile opposing electrical and thermal nature at an acceptable investment cost. This opposing nature has resulted in several different design solutions that incorporate a range of technologies.

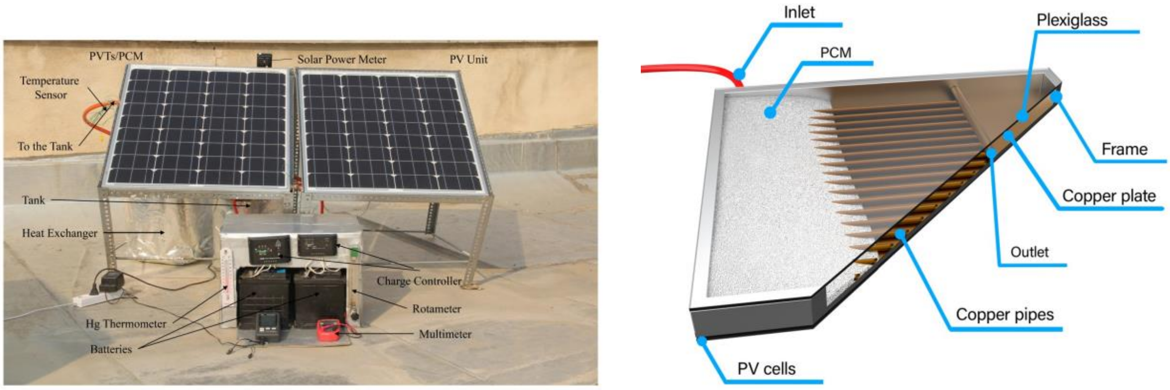
An air-cooled PVT collector with a passive component based on S21 PCM material was tested in a typical Australian oceanic climate, [24]. Air was circulated through straight channels while the thermal energy storage (TES) part of the system was formed with PCM bricks shaped and contained in a metal container, Fig. 4.1. The back of the collector was insulated to minimize heat loss. Simultaneously, to maximize electricity production, the entire PVT-PCM collector system can be rotated around the central axis (360°) with the possibility of varying the slope from 0° to 35°. After optimization, the overall efficiency of the system increased from 37.6% to 40.2% while the daily utilization of the TES system increased from 13.3% to 79.5%. Heat dissipation from the collector could have been better if some other coolant was used instead of a relatively good insulator like air. Air is certainly the cheapest option, but economic and environmental analyses have not been conducted in the described work.



(a) (b)

Fig. 4.1. Experimental rig of air-cooled PVT collector, [24].

A nanofluid-cooled PVT collector with incorporated Merck 107158 PCM was experimentally tested in Iran's cold semi-arid climate, [27]. The combination of water with ethylene glycol enriched with MWCNT nanoparticles (0.1 wt% and 0.2 wt%) took the heat from the collector using straight copper pipes merged with a copper plate while no insulation was applied to the back of the collector, Fig. 4.2. The nanofluid cooling approach compared to the conventional pure water approach increased electrical efficiency by 4.2% and thermal efficiency by 23.5%. The preparation of the nanofluid was very briefly described, with the thermal properties of the nanofluid produced being insufficient for a more detailed analysis. Similar can be observed with the properties of PCM that were given in a relatively wide range which is insufficient to accurately characterize this aspect. Given that nanomaterials were used in the experiment, it was necessary to carry out an environmental impact study and economic analysis of the PVT concept, but unfortunately, none of this was conducted.



(a) (b)

Fig. 4.2. Experimental layout (a) and scheme of PVT-PCM collector (b), [27].

PVT-PCM collector with PLUSICE S25 PCM material was tested in a solar simulator using 500 W halogen lamps, [28]. PCM in different thicknesses (20, 30, and 50 mm) was applied and fins were added to enhance heat transfer. To ensure good thermal conductivity and avoid short circuits, the PCM aluminum container was connected to the back of the PV panel with thermal grease, Fig. 4.3, Adequate air circulation behind the PCM was ensured with a rectangular duct integrated with vertical and horizontal openings. Additional thermal stability of the system was ensured with Celotex insulation on the back. This concept of PVT collector generated up to 10% higher electrical efficiency while the performance with fins resulted in an additional increase of 3%. The lack of testing in environmental conditions is noticeable in the paper since the research is limited exclusively to laboratory conditions. Furthermore, a lack of economic analysis and environmental evaluation is noted.

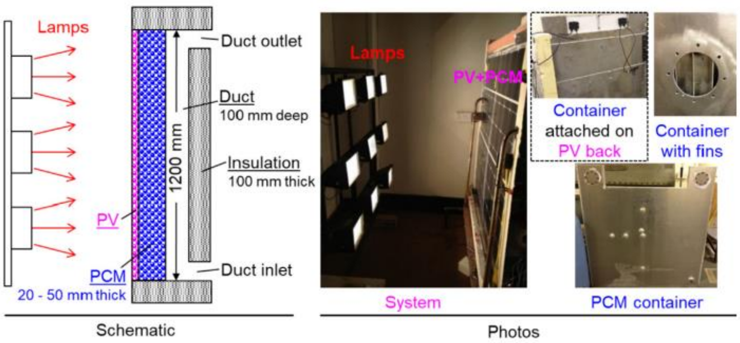
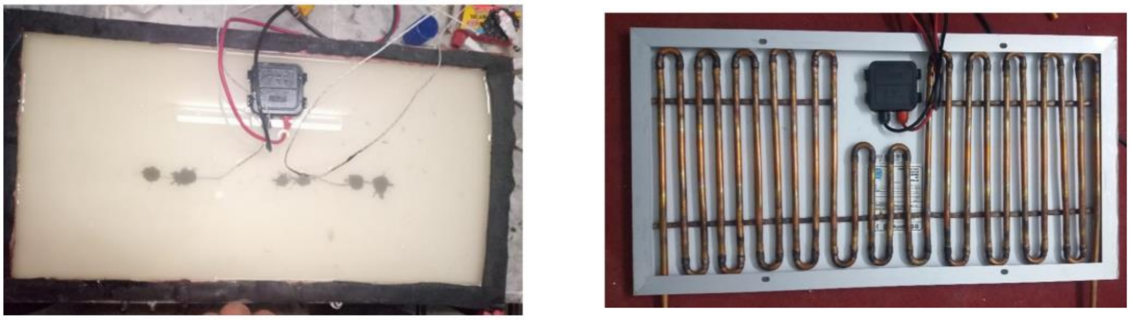


Fig. 4.3. System schematic and experimental rig, [28].

The passive/active cooling concept of the PV panel was tested in the humid subtropical climate of Pakistan, [29]. RT-35HC PCM was applied for passive cooling of PVT collector where the active cooling component was based on the nanofluid. Distilled water was enriched with 0.05 vol% to 0.15 vol% graphene (60 nm) in a two-step mixing process to produce a nanofluid with improved thermal properties. The concept of a PVT collector is relatively simple given that the already existing volume between the back of the PV panel and the aluminum frame was closed to form a PCM container. Serpentine copper pipes with nanofluid were positioned within this volume, Fig. 4.4. In addition, the concept of PVT-PCM collector with exclusively passive cooling was tested. For this case, the contact area of PCM and the system was increased with fins. The largest improvement in electrical efficiency of 23.9% was recorded for the PVT-PCM collector system with nanofluid, while for the exclusively passive system the improvement was only 9.1% compared with the referent PV panel. The system with water as a cooling medium instead of nanofluid was also tested, and the electrical efficiency improvement was 22.7%, however, the thermal efficiency was 17.5% lower than in the case of nanofluid coolant. Overall, the paper does not explain in detail the process of material selection, nor the process of creating the resulting collector design. Design optimization was not executed or at least it was not elaborated in the article. The environmental and economic analysis was not carried out as expected, given that no long-term testing was performed, i.e. the testing was conducted in just a few days.



(a) (b)

Fig. 4.4. Melted RT-35HC in a transparent container (a) and serpentine copper pipes on the backside (b), [29].

A novel PVT collector with A44 PCM in aluminum bags was tested under laboratory conditions, [30]. Serpentine aluminum pipes in a spiral ensured a uniform temperature field since good thermal contact with aluminum bags was achieved thanks to the thermal paste, Fig. 4.5. Better thermal interaction between the pipes and the PCM could be accomplished if the pipes were immersed in the PCM. It was experimentally determined that the maximum electrical efficiency of the system was 12.59% with a total system efficiency of 83.59%. The maximum improvement in electrical efficiency was 12.75%. Neither an economic analysis nor an environmental impact study has been conducted, which is understandable given that no long-term experimental tests have been carried out in real operating conditions.

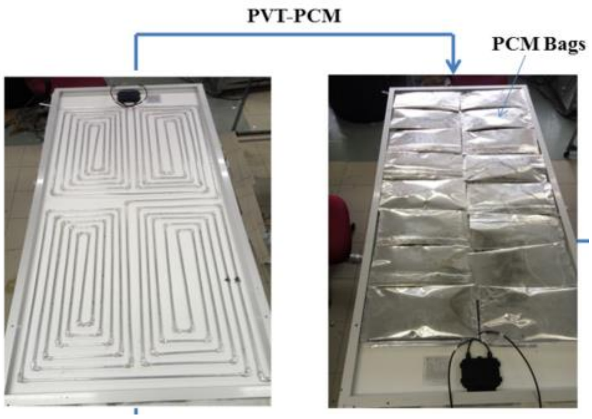


Fig. 4.5. PVT-PCM collector with serpentine aluminum pipes in a spiral, [30].

Experimental testing of the PVT collector with phase change material based on the paraffin wax was conducted in the tropical monsoon climate of India, [31]. A relatively simple cooling concept, with a serpentine copper pipe exchanger immersed in paraffin, was merged to the rear of the collector, Fig. 4.6. The reason for utilizing PCM with a relatively high melting point of 57 °C is not precisely elaborated in the paper. The applied concept yielded 17.3% higher electrical efficiency with an average increase in the overall efficiency of 28.8% compared to the conventional PV panel. The exergo-economic analysis was also conducted, and based on economic analysis, a payback period of 6 years was determined. This assessment should be taken with caution, considering that the experimental research was completed in just a few days.

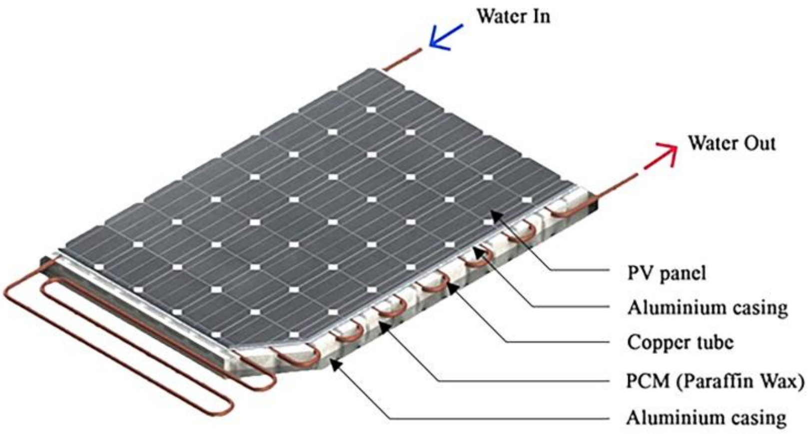
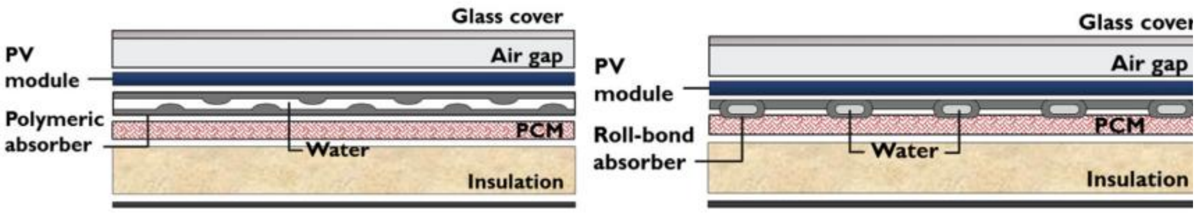


Fig. 4.6. PVT-PCM collector with serpentine copper pipe, [31].

A parallel experimental study of two PVT-PCM concepts was conducted in the semi-arid climate of Spain, [32]. The first PVT-PCM concept integrated a high-density polyethylene absorber with RT50 organic PCM packaged in metallic bags, Fig. 4.7. (a). The second PVT-PCM concept integrated an aluminum roll-bond absorber with inorganic C48 PCM packed in matchbox aluminum foil pouches, Fig. 4.7. (b). These are two very similar designs with identical glass covers, air gap, and rock wool insulation while the PCM materials and absorber geometries are significantly different. The maximum overall efficiency for the first concept was up to 50% while for the second concept it was up to 63% with a thermal efficiency increase of 30% compared to the reference sheet and pipe copper absorber. No significant increase in electrical efficiency was detected, so the concepts considered can be applied in situations where thermal energy is a priority. The importance of the absorber design in the context of the thermal and electrical energy balance and the cost-effectiveness of the PVT system is obvious, but unfortunately, the economic and environmental aspects of the proposed concepts were not elaborated.



(a) (b)

Fig. 4.7. PVT-PCM collector with polymeric absorber (a) and PVT-PCM collector with roll-bond absorber (b), [32].

Experimental testing of the PVT collector with lauric acid PCM was conducted in the tropical rainforest climate of Malaysia, [38]. The PCM was contained in aluminum foil packets while ensuring good thermal contact (thermally conductive paste) with serpentine copper pipes via an aluminum absorber, Fig. 4.8. The PVT-PCM system generated a relatively modest amount of electricity with a maximum efficiency of 11.08% although an increase in efficiency of 11% was observed compared to the conventional PV panel. Nevertheless, the system generated significant amounts of heat with efficiency typically ranging from 75 to 85%. Thus, the concept is suitable for applications where heat generation is a priority. An extensive economic analysis was conducted and a payback period of 4 years was determined. Unfortunately, no environmental evaluation of the PVT-PCM concept was conducted.

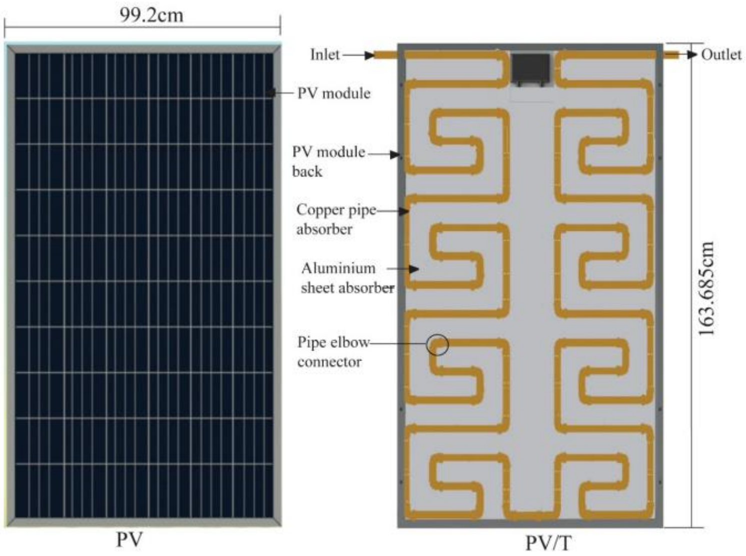


Fig. 4.8. PVT-PCM collector layout with serpentine copper pipes, [38].

An air-cooled PVT system with salt hydrate phase change material (PCM32/280) was tested in the cold semi-arid climate of Iran, [34]. The relatively simple concept of PVT collector with steel absorber plate, PCM, and aluminum layer oxide was subjected to forced convection through the air channel while achieving an electrical efficiency improvement of 9%, Fig. 4.9. Since the generated heat was not harvested, it is more precise to define the system as a hybrid cooled PV panel than a PVT-PCM collector. The lack of an experiment is a relatively short testing period of only two months in which it is not possible to accurately determine possible gains in energy production at the annual level. As expected, no economic and environmental analysis has been carried out, nor has the necessary optimization of the system in terms of PCM selection and geometry.

Fig. 4.9. Air-cooled PVT-PCM system, [34].

Water-based nanofluid and ZnO nanoparticles were used in combination with Paraffin wax (Merck, 107151) PCM for thermal regulation of the PVT collector in the cold semi-arid climate of northern Iran, [36]. The absorber connected to the copper pipe was applied for simultaneous cooling of the PV panel and PCM, but the geometry itself is insufficiently described, so it is not possible to analyze in detail the possible disadvantages and advantages of the concept, Fig. 4.10. However, given the choice of copper as an absorber material, a good thermal management system is to be expected, which is ultimately evident from the average thermal efficiency of about 51.6%. Unfortunately, no economic and environmental analysis was conducted, which is a major shortcoming when considering that the nanomaterials used are certainly a significant factor in terms of economics and especially in terms of environmental aspects.

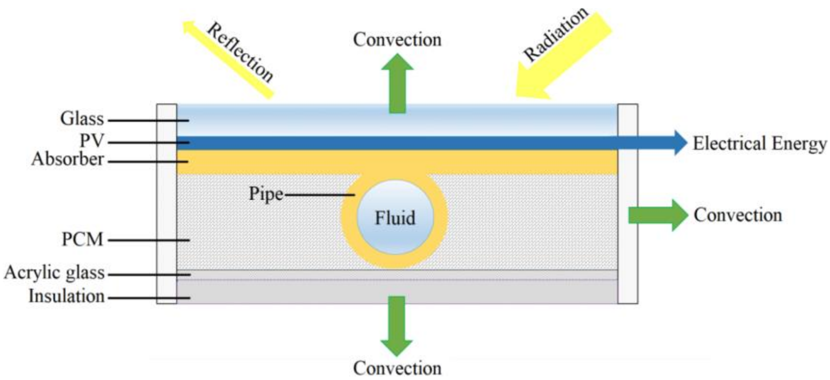


Fig. 4.10. PVT-PCM collector with nanofluid coolant, [36].

The paraffin wax enhanced with SiC nanoparticles was implemented in the PVT system and tested in the tropical rainforest climate of Malaysia, [39]. Galvanized steel sheet was merged with a silicone oil layer on the backside of the PV panel to ensure good thermal contact. Nano-enhanced PCM was contained with another galvanized steel sheet and actively cooled by copper pipes with nanofluid coolant, Fig. 4.11. The concept of the PVT collector incorporating nano boosted PCM actively cooled with nanofluid showed significantly better electrical and thermal properties compared to conventional solutions, i.e. 13.7% electrical efficiency and 72% thermal efficiency. Unfortunately, the paper does not thoroughly consider the economic and environmental repercussions of the application of nanomaterial in the PVT system.

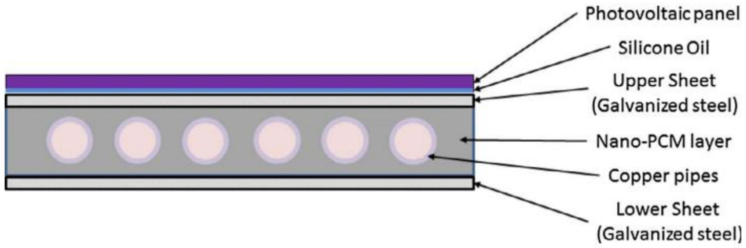


Fig. 4.11. PVT concept with nano boosted PCM and nanofluid coolant, [39].

The PVT collector with paraffin PCM was experimentally tested in the tropical wet and dry climate of Bangladesh, [40]. Paraffin was contained in a case with fins to accelerate heat transfer from PCM to water coolant, Fig. 4.12. The research was conducted in only two months, with the measurement of electrical efficiency of the system excluded from the consideration, probably due to technical reasons. Thermal efficiency ranged from 43% to 65% depending on insolation. The overall efficiency of the system is unknown so it is difficult to evaluate the quality of the system based on half data. Furthermore, neither an economic nor an environmental analysis of the system was conducted.

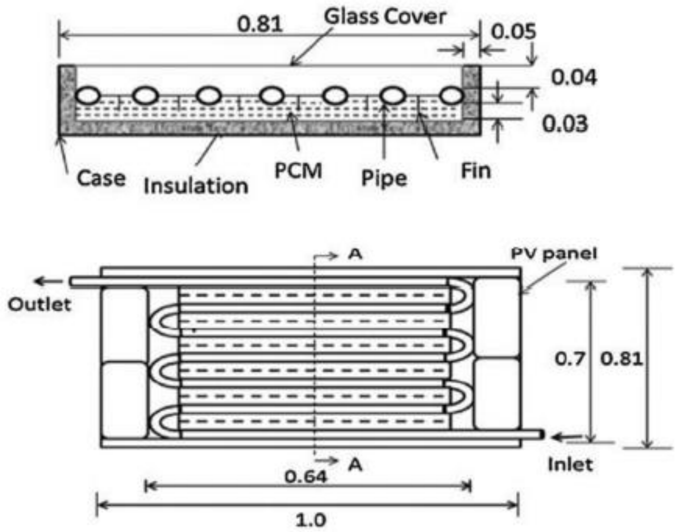


Fig. 4.12. PVT collector with parabolic concentrator, [40].

Building-integrated PVT-PCM collector was tested in the oceanic climate of Australia, [41]. The concept was integrated on the roof surface to obtain low-grade heating/cooling of the building. The specificity of the concept is two layers of PCM in blocks to increase the thermal capacity of the concept, Fig. 4.13. The average electrical efficiency was about 8.3% while the average thermal efficiency was about 13%. Relatively low efficiencies are expected given that this is a passive system and it would be more accurate to classify it as a hybrid cooled PV panel than as a PVT collector. Economic and environmental analyzes would provide an answer to the sustainability and cost-effectiveness of the system but they were not implemented.

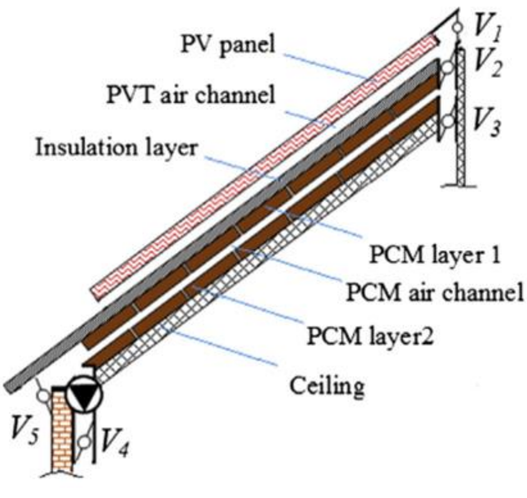


Fig. 4.13. Building-integrated PVT-PCM collector, [41].

The PVT collector with composite PCM material based on OM35 paraffin combined with biochar was tested in the humid subtropical climate of India, [42]. In terms of design, the PVT collector is not a novelty, considering that the serpentine copper pipes on the back of the PV panel were conventionally positioned in the PCM material, Fig. 4.14. What distinguishes this concept from other similar ones is the unusual choice of composite PCM material. In terms of performance, the concept contributed to an improvement in electrical efficiency of 18.4% while the maximum thermal efficiency was 71.2%. Environmental and economic analysis was not conducted which is a pity given that a new composite PCM material was introduced.

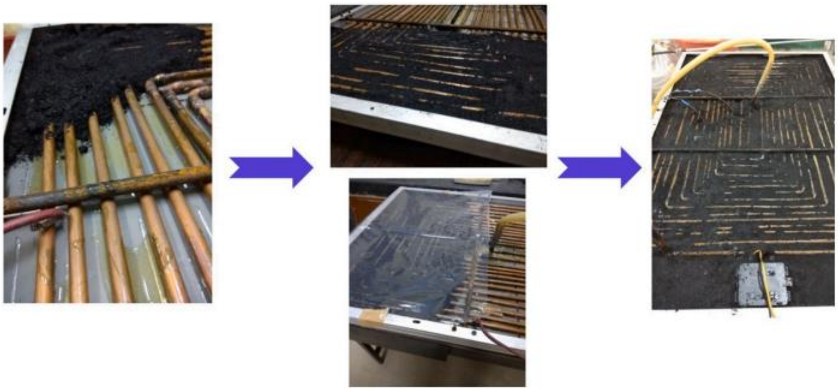


Fig. 4.14. PVT collector with composite phase change material, [42].

4.3 Summary of PVT-PCM design approaches

Based on the overview of existing PVT-PCM collector solutions, the main design elements of individual approaches with the corresponding performance indicators are summarized in Table 4.2. The most commonly used technologies are poly-crystalline and mono-crystalline silicon PV cell types, which is expected given that they are widely represented on the market and are the most affordable. The majority of the PCM materials used are of organic origin and are contained mainly in metal containers which are dominantly made of aluminum due to availability and relatively low weight. The high thermal conductivity of aluminum can adversely affect the thermal management of the rear surface of the PVT collector due to parasitic heat flux from the environment at the rear of the collector. Most designs have solved this problem by adding insulation to the back of the collector. The most commonly used coolant is water that flows through pipes in active operation mode. Due to its high thermal conductivity, copper is mostly used material for pipes, while their shape is mainly serpentine due to the larger contact surface area with phase change material. The increase in electrical efficiency of PVT-PCM collectors is, as expected, more modest than the increase in thermal efficiency compared to conventional PVT collectors. The maximum reported overall efficiency, based on short-term measurements, of the PVT-PCM collector was over 80% which can be misleading as the overall efficiency at the annual level should be calculated. Generally, an efficiency at a yearly level below 50% can be expected.

Table 4.2. Main design elements of PVT-PCM collectors and performance indicators

Ref.	PV cell type	PCM type	PCM container	Coolant /Active cooling rig	Insulation	Efficiency
[24]	Copper indium gallium selenide	S21	Metal	Air/Straight channels	YES	37.6%-40.2% increase in overall efficiency
[27]	Mono-Crystalline silicon	Merck 107158	Thin copper plate	Water-based nanofluids/ Straight copper pipes	NO	4.2% increase in electrical and 23.5% in thermal efficiency
[28]	Mono-Crystalline silicon	PLUSICE S25	Aluminum	Air/ Naturally ventilated duct	YES (Celotex)	10% electrical efficiency improvement and an additional 3% with fin ducting
[29]	Mono-Crystalline silicon	RT-35HC	Aluminum sheet	Water-based nanofluid/ Serpentine copper pipes	YES	Overall efficiency increased from 10.9% to 14.1% while thermal efficiency was up to 45.8%
[30]	Poly-Crystalline silicon	A44	Aluminum bags	Water/ Serpentine aluminum pipes in a spiral	YES (Polyethylene)	83.5% overall efficiency and an increase of 12.7 % in electrical efficiency
[31]	Poly-Crystalline silicon	Paraffin wax	Aluminum	Water/ Serpentine copper pipe	NO	Improvement of electrical efficiency of 17.3%, the thermal efficiency of 26.87%, and the maximum of 40.59% in overall efficiency
[32]	Unspecified type	RT50,	PAKVF4PCA metallic bags	Water/ High-density polyethylene absorber	YES (Rock wool)	Up to 50% overall efficiency
[32]	Unspecified type	C48	Matchbox aluminum foil pouches	Water/ Aluminum roll-bond absorber	YES (Rock wool)	Up to 63% overall efficiency
[38]	Poly-Crystalline silicon	Lauric acid	Aluminum foil packets	Water/ Serpentine copper pipe	YES (Ceramic fiber paper)	Maximum thermal efficiency of 87.72% and maximum

						electrical efficiency of 11.08%
[34]	Mono-Crystalline silicon	salt hydrate (PCM32/280)	Polycarbonate sheet	Air/Channel	NO	9% increase in electrical efficiency
[36]	Mono-Crystalline silicon	Paraffin wax (Merck, 107151)	Acrylic glass	ZnO and water nano-fluid/Copper pipe	YES	11.9 % improvement in electrical efficiency and maximum overall performance of 65.7%
[39]	Unspecified type	Paraffin wax with SiC nanoparticles	Galvanized steel	SiC and water nanofluid/ Serpentine copper pipes	YES (Glass wool)	13.7% maximum electrical efficiency and 72% maximum thermal efficiency
[40]	Unspecified type	Paraffin	Unspecified type	Water/ Serpentine copper pipes with plate	YES (Corkwood)	Overall efficiency ranging from 46% to 63%
[41]	Unspecified type	Unspecified type	Unspecified type	Air/Single channel	YES	Average thermal efficiency of about 13% and average electrical efficiency of about 8.3%
[42]	Unspecified type	OM35+biochar	Plexiglass cover	Water/ Serpentine copper pipes	YES (Polyethylene foam sheet)	Average thermal efficiency of about 60.3% and average electrical efficiency of about 12.6%

5. NUMERICAL MODELING OF PHASE CHANGE MATERIALS

A large variety of PCM materials are frequently used for thermal energy storage applications, passive cooling, waste heat recovery, etc. [43]. A key aspect of PCM-based thermal management is heat transfer optimization given the relatively low thermal conductivity of the majority of PCM materials. PVT-PCM collectors are particularly sensitive to thermal management due to the opposing nature of electrical and thermal efficiency, i.e. if one increases, the other decreases, and vice versa. Therefore, it is necessary to find a balance between electrical and thermal efficiency with regard to current environmental conditions. An additional numerical challenge is the complex mechanism of heat transfer in phase change material that includes conduction, convection, but also phase transition. Thus, numerical analysis of systems involving PCMs such as PVT-PCM collectors should take into account the full spectrum of heat transfer mechanisms.

5.1 Numerical strategies of photovoltaic systems in synergy with PCM

Numerical analysis of heat transfer in the PVT-PCM collector system at insolation of 1000 W/m^2 was performed using COMSOL Multiphysics® software, [30]. A44 PCM was heated under the influence of insolation and a phase transition was induced after which heat was collected by water coolant, thus, thermal management of the system was taken over by the forced convection cooling. Discretization was performed with different mesh ranging from coarser with approx. 1.5 million elements to finer with approx. 7.8 million elements. Unfortunately, although a grid dependency study with four different meshes was conducted it is not clear which one was eventually used. The discretized 3D geometry had an unstructured finite element mesh that could certainly be further optimized, Fig. 5.1. According to the numerical analysis, the maximum overall efficiency of the PVT-PCM system was 84.75%, while for the experimental investigation it was lower, i.e. 76.16%. It is important to emphasize that the numerical results followed the experimental results trend with relatively constant deviation for all coolant flow rates. The phase transition was considered using the enthalpy-based method, [44], where convection in liquid PCM was neglected, i.e. heat transfer in A44 is conduction driven. The enthalpy method of the phase transition process is a generally accepted approach but convection in PCM is often neglected especially when PCM properties, e.g. density and viscosity, are taken as a constant, [41].

Fig. 5.1. Unstructured finite element mesh of PVT-PCM collector concept, [30].

The Enthalpy porosity method was used to simulate heat transfer through a multi-layer window concept, [45], that integrates photovoltaic technology, PCM materials, and air as an insulating layer, Fig. 5.2. In the PCM, the dominant mechanism of heat transfer was conduction, with convection not mentioned at all. Convective heat transfer was described with Boussinesq approximation but for the air cavity. It is explicitly emphasized in the paper that this approximation referred to the air domain which implies that it does not refer to the PCM domain. The discretization of 2D geometry resulted in meshes that had between 15000 and 27000 elements depending on the geometry while the simulation time step was relatively large with a 1 s period. In terms of system performance, window designs with the PV-PCM combination reduced room heat gains by over 90% compared to the design without PCM.

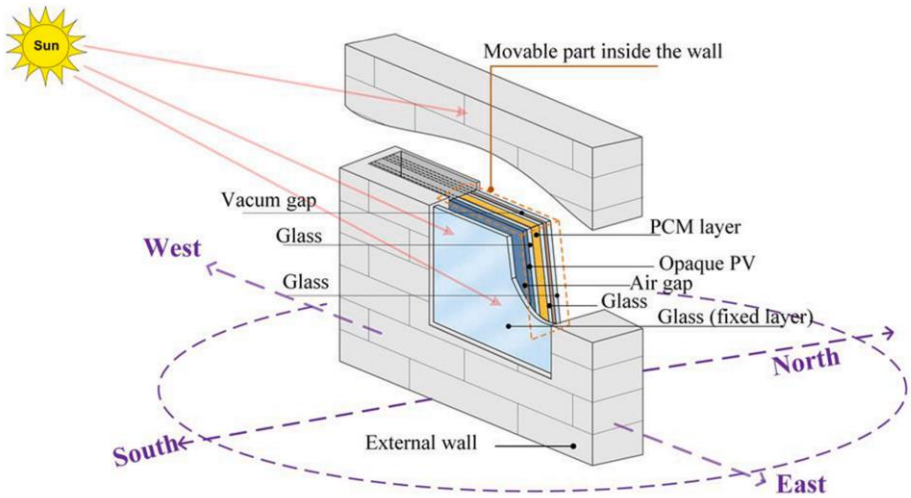


Fig. 5.2. Multi-layer PV-PCM window concept, [45].

An extremely large time step of 500 s is listed in paper [46] where a 2D simulation of a multi-layer PV panel with a PCM layer was performed in Ansys Fluent software. The reason for such a large time step was not elaborated nor is the total number of finite elements clear although the reported mesh is claimed to be completely structured. Ambient conditions such as solar radiation, air temperature, and wind speed as well as radiative heat exchange with the environment are built into the model using User-Defined Functions (UDF), Fig. 5.3. User-Defined Functions of these variables were polynomial time-dependent. Based on the conducted numerical analysis, the authors expect a daily increase in electricity production of over 5% but pointed out the lack of experimental validation of the model as a limiting factor.

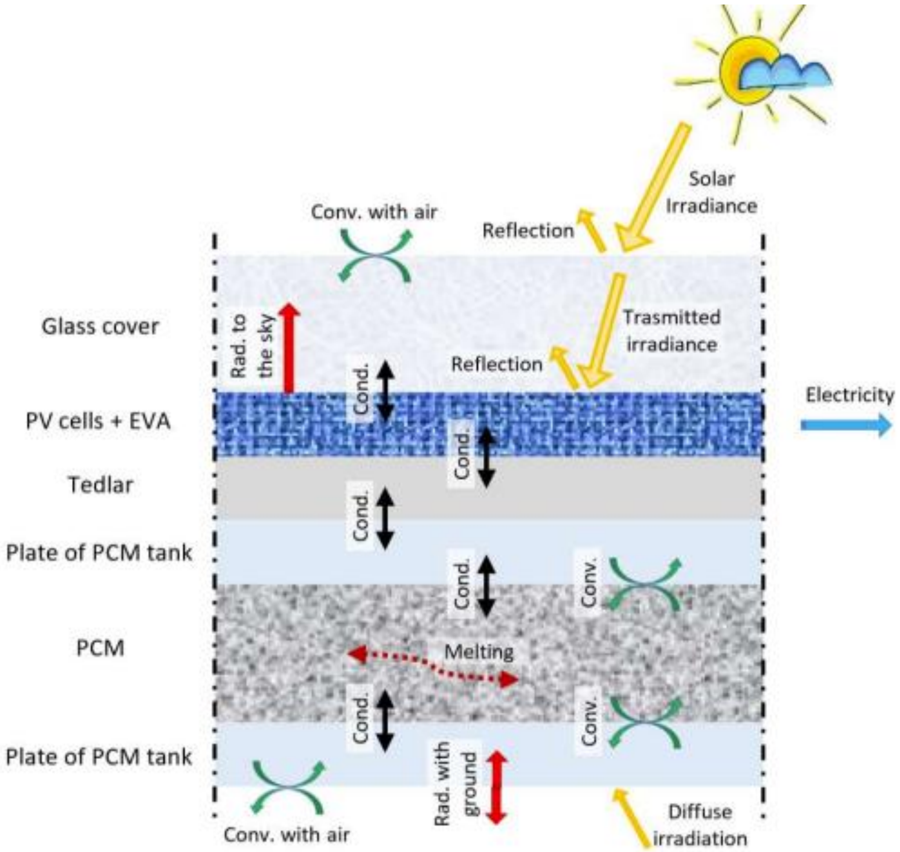


Fig. 5.3. Heat transfer scheme in CFD simulation, [46].

Experimental validation of a similar concept is presented in paper [47] where a CFD analysis of building integrated photovoltaic with incorporated nano-enhanced PCM was conducted. Unlike research [46] the natural convection effect was modeled in PCM, i.e. Navier-Stokes equations were solved. The advantage of the presented approach is that velocity fields in nano-enhanced PCM are obtained by solving Navier Stokes equations for incompressible flows, but probably for that reason, the geometry was reduced to 2D. It is not clear why there is no heat transfer on the rear surface of the PV system, especially since the rear surface is made of aluminum, which has a relatively high thermal conductivity, i.e. symmetry boundary condition was not properly justified, Fig. 5.4. The paper concluded that nanoparticles increase the thermal conductivity of PCM but adversely affect natural convection within PCM, i.e. both conductive and convective mechanisms must be taken into account in heat transfer analysis.

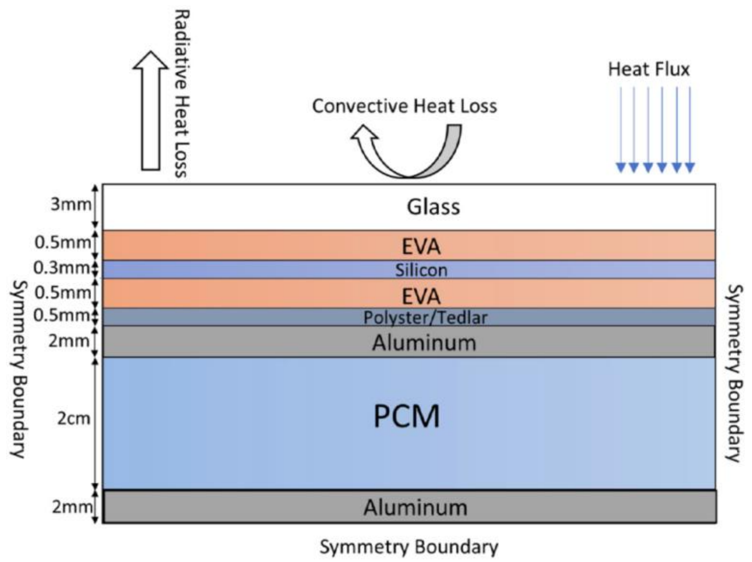


Fig. 5.4. Heat transfer scheme in numerical simulation, [47].

An interesting concept of a photovoltaic system with thermoelectric generators supported by PCM material is presented in paper [48]. The novel concept generated a relatively modest maximum cumulative power increase of 1.86% over 5 hours, but thanks to numerical analysis, the low thermal conductivity of PCM was detected as the main limiting factor together with the expected low efficiency of commercial thermoelectric power conversion devices. For numerical modeling, it was assumed that all solar radiation was absorbed in the silicon layer of the PV panel while the properties of all materials were constant, Fig. 5.5. The contact resistance between the thermoelectric device and the PCM layer was neglected. Inside the PCM heat transfer was guided by a conductive mechanism where convection is not mentioned except for convective heat transfer from the outer surfaces of the PV system. The conventional enthalpy-porosity method was used to model the phase transition.

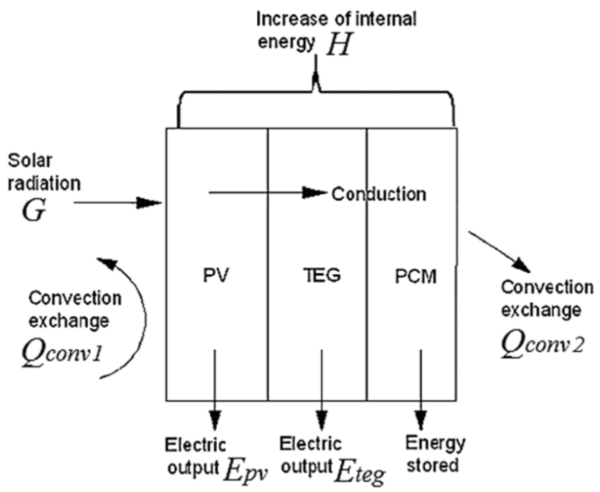


Fig. 5.5. Heat transfer pathway in thermoelectric PV-PCM system, [48].

The same method was applied in paper [49] where numerical analysis of a PVT-PCM collector included forced convection induced active cooling, i.e. water or water-based nanofluid coolant integrated with the copper absorber, Fig. 5.6. A relatively conservative time step of 1 s was used for which a time step dependence study was conducted. For the enthalpy-porosity method application, the importance of the mushy zone morphology constant (C) was emphasized, which should vary between 10^4 and 10^7, i.e. the authors adopted a value of 10^5. This constant describes how quickly the velocity in PCM will decrease to 0 during solidification therefore it has a crucial influence on the duration of the phase change and the overall accuracy of the simulation.

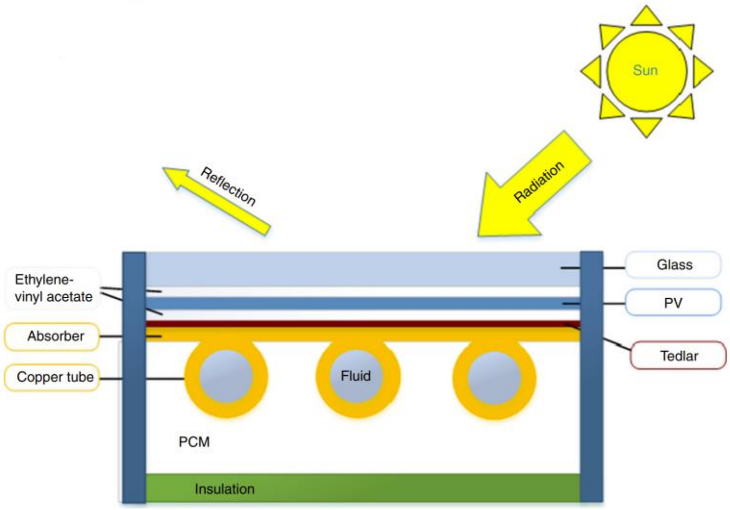


Fig. 5.6. Scheme of PVT-PCM collector, [49].

The same value of 10^5 for mushy zone morphology constant was implemented in paper [50], where the almost identical concept of PVT-PCM collector, Fig. 5.7, was numerically investigated as in [49]. A time step dependency study was not conducted in this paper, so a very large time step of 150 s is not properly justified.

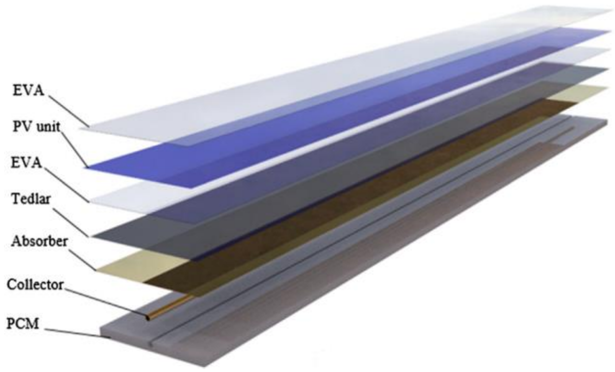
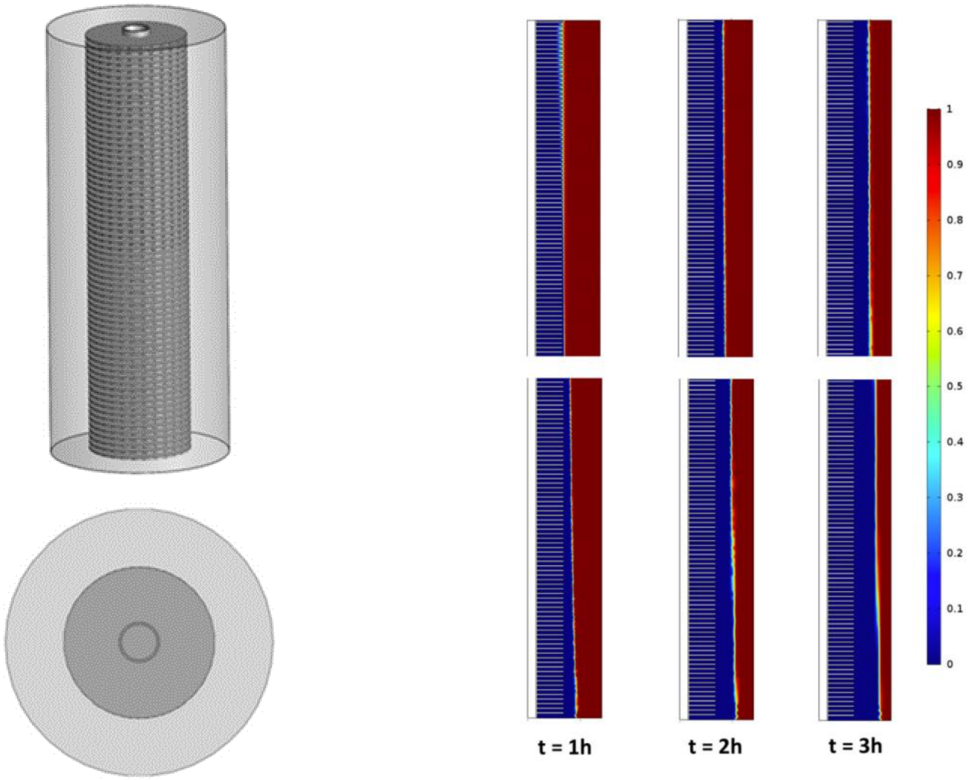


Fig. 5.7. Schematics of PVT-PCM collector with conventional absorber, [50].

5.2 Numerical approaches to PCM phase transition: other applications

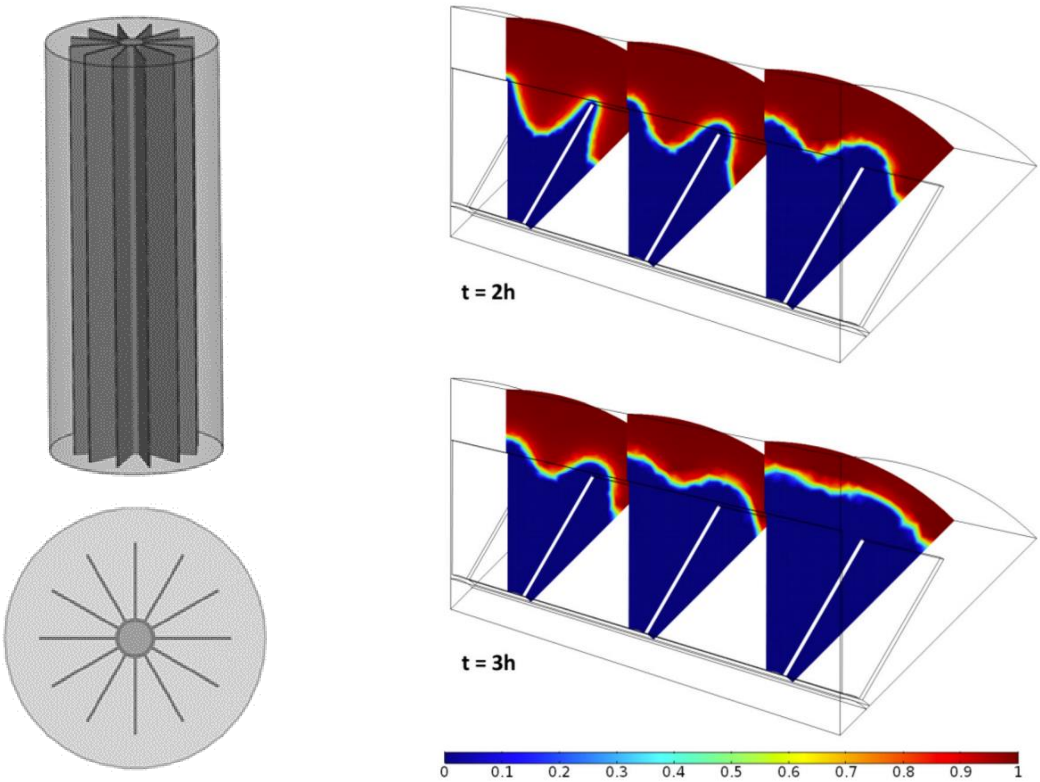
Very few publications deal with the numerical analysis of PV-PCM topic or more precisely PVT-PCM collectors primarily due to the complex multivariable heat transfer between different materials and phases. In addition to the inevitable phase transition in PCM materials, all other heat transfer mechanisms with more or less influence appear. Conduction and radiation are mostly taken into account in one way or another while convection is mostly considered on the outer surfaces of the collector. Thus, convection modeling within PCM is often omitted and mostly without a valid reason. It is most likely a matter of conformism and circumvention of numerically more challenging problems given the complexity of thermal interactions that culminate in modeling phase change materials. To consider the modalities of simulation and the influence of convection on the phase transition of PCM materials, it is necessary to consider other numerical analyzes outside PV-PCM-related matters.

Two different embodiments of heat exchangers with radial, Fig. 5.8, and longitudinal fins, Fig. 5.9, were numerically simulated whereby the 3D and 2D domains of PCM were discretized, [51]. The thermal output of both designs was almost identical, but the longitudinal design required less material consumption. Conduction was the dominant heat transfer mechanism in the CrodaTherm 60 PCM phase transition simulation while convection was completely neglected. Unfortunately, the reason for omitting convection was not adequately elaborated. The paper does not specify the used software, however, a sort of FEM numerical analysis was evidently conducted.



(a) (b)

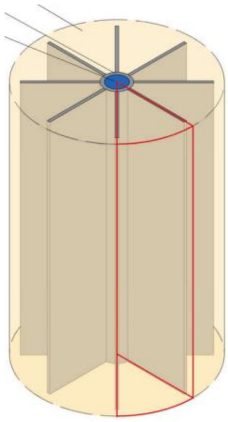
Fig. 5.8. Radial fins heat exchanger geometry (a) and 2D simulation of radial fins heat exchanger (b), [51].



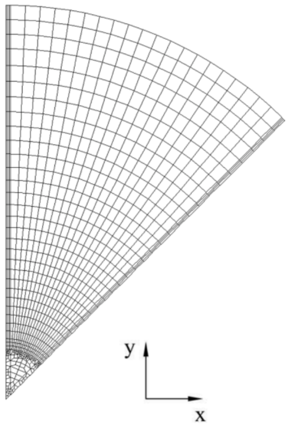
(a) (b)

Fig. 5.9. Longitudinal fins heat exchanger geometry (a) and 3D simulation of longitudinal fins heat exchanger (b), [51].

A similar 3D CFD simulation of the longitudinal fins PCM heat exchanger as in [51] was performed in paper [52], with natural convection being taken into account using the Boussinesq approximation, Fig. 5.10. The Boussinesq approximation is often used to solve the problem of natural convection without completely solving the Navier-Stokes equations if the density variations are relatively small, i.e. faster convergence is obtained since the change in density only affects buoyancy forces.



(a)



(b)

Fig. 5.10. Longitudinal fins heat exchanger geometry (a) and mesh of one-eight of longitudinal fins heat exchanger (b),[52].

A two-dimensional shell and tube TES unit nonisothermal flow was simulated in [53] with induced buoyancy force solved with Boussinesq approximation, Fig. 5.11. It was concluded that in the initial period of the phase transition the conduction heat transfer regime is dominant, after which the crucial role is taken over by convection, which significantly depends on the geometry of the problem.

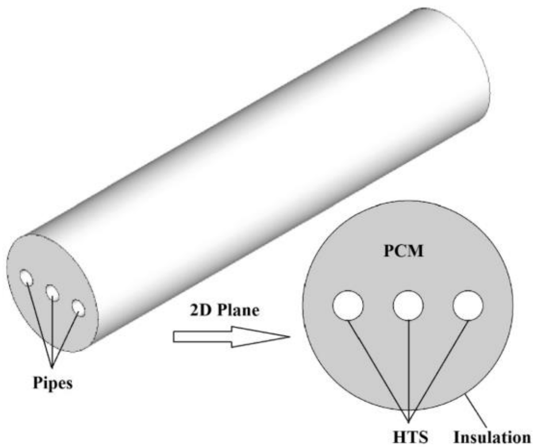


Fig. 5.11. Two-dimensional shell and tube TES domain,[53].

Dominantly, PCM materials are modeled as a homogeneous porous layer with physical properties independent of temperature as in paper [54]. In this case, the effect of natural convection in the solar TES tank was modeled in Ansys Fluent using the Boussinesq approximation to simulate the buoyancy effect at constant paraffin density, Fig. 5.12. Modeling the phase change material as a porous layer is the basis of Fluent's Solidification/Melting model, i.e. the enthalpy-porosity method. Thus, all numerical phase transition analyses performed in this software are based on this method, whereby conductive heat transfer is modeled by default while modeling convective heat transfer requires more complex formulations.

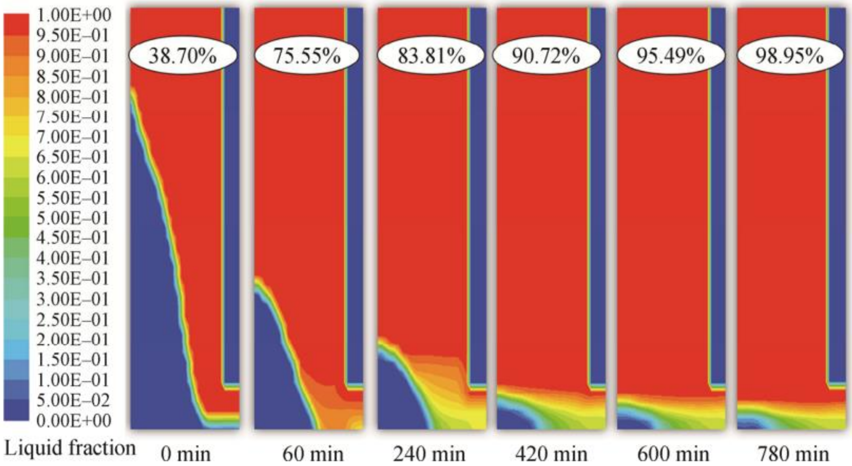


Fig. 5.12. Liquid fraction field during phase transition in solar TES tank,[54].

5.3 Summary of numerical strategies and discussion on critical aspects

Based on selected and reviewed papers, common features were detected, as well as the specifics of individual numerical approaches to simulating solid/liquid phase transition in different engineering applications, Table 5.1. As expected, relatively conservative PCM materials such as paraffin or paraffin-based materials were frequently numerically analyzed, however, nano-enhanced PCMs were also analyzed in several publications. Nano-enhanced PCMs are numerically very demanding due to possible structural inhomogeneity, or more precisely, the tendency of nanomaterials towards agglomeration and sedimentation, [19]. This phenomenon is not adequately addressed in the considered publications, i.e. the isotropy of PCM is assumed and implemented in the numerical investigation as such. The predominant mostly applied numerical software is commercially available CFD Ansys Fluent code which is based on the finite volume method (FVM), followed by COMSOL Multiphysics which is primarily based on the finite element method (FEM). In terms of dimension in computer workspace, i.e. 2D or 3D, both approaches are present where 3D is computationally much more demanding. The 3D approach is surprisingly frequently used, but the authors mostly resort to symmetric geometry. Such geometry is then reduced to a much smaller domain by applying symmetry boundary conditions which consequently decreases computational cost. The symmetry boundary condition mirrors the solution along the surface to which it is applied, which is often non-physical and represents a source of error, especially in comparison with experimental results. The discretization of the numerical domain depends on the geometry and can vary from several thousand elements [54] to several million elements [30], and often the authors do not specify whether they are 3D or 2D cells. Depending on the type of simulation, transient and steady-state solution calculation can be distinguished while the latter is rarely used in the reviewed papers. The steady-state solution was presented in paper [55] followed by transient while in [56] only steady-state simulation was performed resulting in the phase transition process being excluded from the consideration. Transient simulation is more sensitive to mesh quality, so it is numerically much more demanding, with time step size being especially important. The time step dependence study should result in an appropriate time step, but unfortunately, the authors very rarely conduct it. For small time steps of 0.1 s or 1 s, this is not so problematic but for large time steps like 60 s [48], 150 s [50] and 500 s [46] it should be mandatory. The conventional enthalpy-porosity method of phase transition is mainly used since it is embedded in Ansys Fluent Solidification/Melting model. However, the considered numerical approaches in the reviewed papers differ significantly in the formulation of heat transfer within the phase change material. All approaches consider conductive heat transfer, but the convective heat transfer mechanism is often unjustifiably neglected. Conduction is absolutely dominant while PCM is in a solid phase, but as soon as the liquid phase occurs, the convective mechanism gradually begins to act in parallel with conduction. The higher the fraction of the liquid phase in the domain, the greater the influence of convective flows and the associated buoyancy forces. In papers where natural convection in PCM was taken into account, it was mostly solved by Boussinesq approximation instead of solving velocity fields with full Navier Stokes equations for compressible flows. Full Navier Stokes equations are mostly nonlinear, so Boussinesq approximation partially reduces the nonlinearity, i.e. increases the stability of the simulation and the speed of convergence. The Boussinesq approximation is accurate when it comes to small changes in density, therefore, it is necessary to analyze the suitability of the application of this approximation for each PCM with respect to the expected temperature range. Such an analysis was not performed in the reviewed papers, i.e. Boussinesq approximation implementation was not adequately justified and elaborated.

Table 5.1. Phase change materials numerical approaches in various engineering applications

Ref.	PCM	Software	Geometry	Discretization	Simulation type	Heat transfer mechanism in PCM	Accentuated details
[51]	CrodaTherm 60	Unspecified (FEM method)	2D-cylinder and pipe with radial fins 3D-one-eight of cylinder and pipe with longitudinal fins	143000 elements (2D) 71000 elements (3D)	Transient (time step is unspecified)	Conduction (convection was neglected)	Forced convection in coolant was modeled
[52]	RT25	ANSYS Fluent	3D-one-eight of cylinder and pipe with longitudinal fins	268500 elements	Transient (time step set to 0.1 s)	Conduction and natural convection	Natural convection was solved using Boussinesq approximation
[53]	Lauric acid	ANSYS Fluent	2D-cylinder and pipes	16000 elements	Transient (time step set to 0.1 s)	Conduction and natural convection	Natural convection was solved using Boussinesq approximation
[54]	Paraffin	FLUENT 16.0.	3D-quarter of a cylindrical tank and an electric heater	8448 elements	Transient (time step set to 1 s)	Conduction and natural convection	Natural convection was solved using Boussinesq approximation
[55]	Metallic PCMs: MgSi, AlSb, NiSi, and Mg_2Si	ANSYS Fluent	3D-half of cylindrical solar receiver	2322019 elements	Transient (time step is unspecified)	Conduction (convection was not described)	Steady-state simulation was also conducted to analyze individual properties of PCM
[30]	A44	COMSOL Multiphysics®	3D- PVT-PCM collector	Between 1.5 million and 7.8 million elements	Transient (time step is unspecified)	Conduction (convection was neglected)	Enthalpy-based method of phase transition
[45]	RT35HC RT31 RT27 RT42	ANSYS Fluent 19.2	2D-multi-layer PV-PCM window	15000-27000 elements	Transient (time step set to 1 s)	Conduction (convection was not described)	Boussinesq approximation was used for air cavity simulation not PCM
[46]	RT28HC RT35HC	ANSYS Fluent	2D-multi-layer PV panel with PCM layer	Unspecified number of elements	Transient (time step set to 500 s)	Conduction (convection was not described)	Flow in liquid PCM was considered as laminar

[47]	n-Octadacane PCM enhanced with nanoparticles: Al_2O_3, CuO, TiO_2 and Cu	COMSOL 5.0	2D-multi-layer PV panel with PCM layer	1109 boundary elements and 36759 domain elements	Transient (time step is unspecified)	Conduction and natural convection	Velocity fields in nano-enhanced PCM were obtained by solving Navier Stokes equations for incompressible flows
[48]	n-Octadecane	ANSYS Fluent	3D-thermoelectric PV-PCM system	24900 elements	Transient (time step set to 60 s	Conduction (convection was not described)	Enthalpy-porosity method of phase transition
[49]	Paraffin wax	ANSYS Fluent 16.2	3D-PVT-PCM collector with absorber	6417495 elements	Transient (time step set to 1 s)	Conduction (convection was not described)	Enthalpy-porosity method of phase transition
[50]	Unspecified PCM	ANSYS Fluent 16.2	3D-PVT-PCM collector with absorber	2.4 million elements	Transient (time step set to 150 s)	Conduction (convection was not described)	Forced convection in coolant was modeled
[56]	C15, C18, C22 Palmitic acid/Capric acid Sodium phosphate	ANSYS FLUENT/CFX	PVT-PCM collector with sheet-and-tube heat exchanger (Unclear, 2D or 3D)	1528960 elements	Steady-state	Conduction (convection was neglected)	Pointwise software was used to generate mesh
[57]	RT28 PCM with expanded graphite	FLUENT	PV-PCM panel (Unclear, 2D or 3D)	140895 elements	Transient (time step set to 0.5 s)	Conduction (convection was neglected)	Composite PCM was form-stable and convection was neglected

6. CONCLUSIONS

Different approaches to the design of PVT-PCM collectors and ways to balance a system's electrical and thermal performances were analyzed. In general, PVT systems predominantly operate in the low-temperature range due to the fragile balance and opposing nature of electrical and terminal efficiency. PVT systems upgraded with PCM undoubtedly produce more electricity as a result of the stabilization of the collector temperature with a useful heat yield as a by-product. Adequate PCM for thermal management purposes must have appropriate thermophysical properties such as density, melting temperature, thermal conductivity, latent heat, specific heat, etc. The key thermal property is latent heat, which generally ranges from 160 kJ/kg to 250 kJ/kg, as it ensures the autonomy of thermal management in passive mode. Furthermore, a suitable PCM must also have a suitable melting temperature in the low-temperature range, i.e. melting temperature customarily ranges from 22 °C to 60 °C. The thickness of the PCM directly affects the energy balance of the PVT collector, but it is necessary to take into account the price of PCM, which ranges from 5 €/kg up to 15 €/kg. Most of the PCMs used are of organic origin and are found in metal containers made mostly of aluminum. Such containers are positioned on the rear surface of the PV panel and are further insulated. The active component of PVT-PCM collector thermal management is in most cases water-cooled with a serpentine copper pipe immersed in PCM. The overall efficiency of PVT-PCM collectors can be over 80% daily, but at the annual level, significantly lower efficiencies can be expected, i.e. below 50%.

The phase transition of PCM is the most challenging part of PVT-PCM collectors in terms of numerical analysis. Numerically, this problem is principally solved with the conventional enthalpy-porosity method on which the commonly used Ansys Fluent Solidification/Melting model rests. Since phase transition is a time-determined process, transient simulation is necessary to detect heat transfer details and dominant mechanisms. The numerical approaches differ the most in the formulation of heat transfer within PCM. Namely, all papers take into account conduction while convection is often unjustifiably neglected. While PCM is in the solid phase, conduction is dominant, but as the liquid fraction grows, convection takes precedence due to the appearance of convective flows and buoyancy forces. The Boussinesq approximation is commonly used to model natural convection as an alternative to solving velocity fields with full Navier Stokes equations for compressible flows. The Boussinesq approximation reduces nonlinearity thus increasing the stability of the simulation and accelerating convergence, although in the future it is likely to lose importance as computational capabilities grow.

Trends in PVT collector design often involve the implementation of PCM materials therefore a complex heat transfer mechanism must be the result of an iterative approach involving experimental research and numerical analysis. The PVT-PCM collector market is constantly growing, so future designs will need to optimize the fragile energy balance for competitiveness, taking into account investment costs and environmental impact.

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ABSTRACT

Photovoltaic-thermal (PVT) collectors convert irradiated solar energy into electricity while generating useful heat as a by-product. Hybrid PVT collector technology is a form of cogeneration as it combines the characteristics of a photovoltaic panel and a thermal solar collector. A key feature in the design of PVT collectors is the balance between electricity generation and heat generation. The review deals with the possibilities of integrating phase change materials (PCM) into the design of PVT collectors. Experimental PVT-PCM collectors were systematically analyzed to detect suitable PCM materials and passive/active cooling rig design solutions for thermal management purposes. Furthermore, numerical strategies and critical aspects of PCM material integration in PVT collector systems were analyzed, as well as the phase transition of PCMs in general. The importance of proper modeling of the phase transition, and especially the mechanisms of heat transfer, among which convection is often unjustifiably neglected, was emphasized. Numerically, the problem of phase transition was approached in various ways, however, the majority of approaches were based on the enthalpy-porosity method. Future PVT-PCM collectors will need to integrate an experimental and numerical approach for design competitiveness, taking into account investment cost and environmental impact.

SAŽETAK

Fotonaponski toplinski kolektori konvertiraju dozračenu sunčevu energiju u električnu pri čemu se generira korisna toplina kao nusproizvod. Fotonaponski toplinski kolektori predstavljaju jedan vid kogeneracije jer kombiniraju karakteristike fotonaponskog panela i klasičnog solarnog kolektora. Ključna značajka u dizajnu ovakvih hibridnih kolektora je ravnoteža između proizvodnje električne energije i proizvodnje topline. Pregledni rad se bavi mogućnostima integracije fazno promjenjivih materijala u dizajnu hibridnih kolektora. Eksperimentalni fotonaponski toplinski kolektori s fazno promjenjivim materijalom su sustavno analizirani kako bi se otkrili prikladni materijali i dizajnerska rješenja pasivno/aktivne rashladne tehnike s ciljem termalnog menadžmenta. Nadalje, analizirane su numeričke strategije i kritični aspekti integracije fazno promjenjivog materijala u hibridne kolektorske sustave te je provedena analiza fazne tranzicije općenito. Naglašena je važnost pravilnog modeliranja faznog prijelaza, a posebno mehanizama prijenosa topline, među kojima se konvekcija često neopravdano zanemaruje. U pogledu numeričke analize, problemu faznog prijelaza pristupalo se na različite načine, no većina pristupa temeljila se na konvencionalnoj entalpijskoj metodi koja materijal u faznoj tranziciji razmatra kao pseudo porozan medij. Kako bi se postigao tržišno konkurentan dizajn budući fotonaponski termalni kolektori s fazno promjenjivim materijalom morat će integrirati eksperimentalni i numerički pristup vodeći računa o troškovima ulaganja i utjecaju na okoliš.