A REVIEW OF THE APPLICATION OF SOLID-LIQUID PHASE CHANGE MATERIALS IN WATER HEATERS

by

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Review paper
https://doi.org/10.2298/TSCI230311145W

This paper reviews the stability, heat transfer efficiency and photothermal conversion efficiency optimization studies of solid-liquid phase change materials (PCM) applied to water heaters. Suggestions and prospects were proposed. The study shows that the solid-liquid PCM are mostly filled in the water tank, thermal storage devices or solar thermal collector heater system with paraffin wax, and the addition of solid-liquid PCM can significantly improve the water heater performance. Further in-depth research is needed on PCM dosage and system economics of their application in heat pump water heaters, and the application of photothermal conversion PCM in solar water heater systems.

Key words*: PCM, water heater, heat transfer efficiency, performance coefficient, photothermal conversion*

Introduction

Although the power supply in China is relatively stable, the peak-valley electric difference of power load is significant. Especially in recent years, the peak of power consumption caused by climate change have climbed, which has intensified the imbalance between electricity supply and demand in space and time, bringing serious challenges to the power grid peak regulation, domestic and industrial electricity consumption [1]. The electricity consumption of building operation accounts for about 1/4 of the total electricity consumption of society, and the electricity consumption of water heaters is 20-40% of the total household electricity consumption, the annual electricity consumption of water heater reaches 40-60 billion kWh [2, 3], which has great potential for participating in peak regulation of power grid. With the high energy storage density [4], PCM can effectively improve the efficiency of water heaters, reduce operating costs, and alleviate the mismatch of electricity supply and consumption. For the four kinds of PCM-solid-liquid PCM, liquid-gas PCM, solid-solid PCM, and solid-gas PCM, the disadvantages of the latter three kinds of PCM, for instance, small heat storage density, large volume variation during phase change, and high pressure, hinders the application of the three

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kinds of PCM. Thus, solid-liquid PCM are widely used in water heater energy storage [5-7]. The efficacies of PCM in water heaters are thermal storage and photothermal conversion. Stability, thermal storage capacity, thermal storage/discharge rate, and photothermal conversion efficiency are the main optimization points in PCM applications.

For heat pump water heaters (HPWH), solar water heaters (SWH), electric water heaters (EWH), and gas water heaters, PCM are more widely used in the first three types of water heater. The PCM applied in water heaters can not only increase the water temperature of water heaters, extend the heating duration and improve the performance, but also reduce the electricity cost by peak shifting. In recent years, the coupling technology of latent heat storage and photothermal conversion has become a research hotspot in the application of PCM for SWH [8-10], which can effectively solve the mismatch of solar energy supply and consumption. Thus, the photothermal conversion PCM that integrates light absorption, photothermal conversion and heat storage can simplify the application of PCM in SWH, consequently, the system energy efficiency could be improved. In this paper, the modification of PCM and the application of PCM in different types of water heaters are analyzed.

Overview of the application of PCM in water heaters

Figure 1 shows the classification of PCM modification and the application of PCM in water heaters. The research on the performance optimization of PCM mainly focuses on the enhanced stability, heat transfer efficiency and photothermal conversion efficiency. The application of PCM in HPWH solves the problems of low operating efficiency under sever outdoor conditions, long heating time, frost and supply-demand imbalance, while the application of PCM in SWH is classified according to the type of collectors.

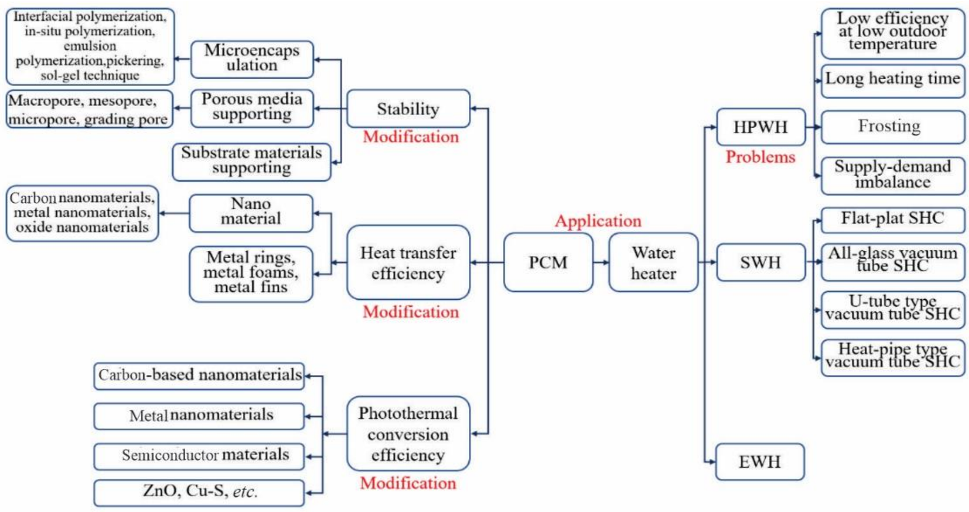

Figure 1. The classification of PCM modification and the application of PCM in water heaters

Functional requirements of PCM for thermal storage units

Although PCM have been widely used in water heaters, it suffers material leakage, volume variation, corrosion, and low thermal conductivity during phase change. Therefore, stability and heat transfer efficiency are two key points for the application of PCM [11-13], while, for photothermal conversion PCM, the photothermal conversion capability also should be evaluated [14]. This section will review the research work of PCM about stability, heat transfer efficiency and photothermal conversion capability improvements at home and abroad.

Stability of PCM in energy storage units

To improve the stability of PCM during phase change, current research has focused on microencapsulation [15], coupling with porous media and substrate materials for support. Microencapsulation means wrapping the particles and liquids of PCM with film-forming materials by physical and chemical methods (interfacial polymerization, in situ polymerization, emulsion polymerization, Pickering and sol-gel, *etc.*), thus the microcapsules of different sizes are proposed [16-20]. After encapsulation, the PCM can be isolated from the surrounding environment, which not only increases the specific surface area for heat transfer, but also avoids risks such as leakage and corrosion, which can improve the stability of PCM in energy storage units.

In terms of encapsulation of PCM, Sanchez-Silva *et al.* [21] compared the situation that styrene, methyl methacrylate, and polymethyl methacrylate (PMMA) serve as shell materials for graphite microencapsulation respectively, the results show that PMMA has more intense reactivity and higher polarity, which is more favorable for graphite microencapsulation. Wang *et al.* [22] compounded PMMA with stearic acid, and the composite was microencapsulated, no leakage exists for microencapsulated PCM material in 500 times of heat storage and release tests, the composite shows good thermal and chemical stability. Wang *et al.* [23] prepared PMMA shells on the surface of *n*-octadecane, the encapsulated microcapsules show good heat storage and release properties and thermal stability in tests. Al-Shannaq *et al.* [24] used PMMA to microencapsulate paraffin wax, and the microencapsulated spheres had a regular shape, smooth surface, the concentration of PCM in the microcapsules was as high as 85.6%. In terms of the composite of PCM and porous media, the porous media that widely used in domestic and international studies arranged by pore size from largest to smallest as [25] macroporous media (>50 nm, foam metal, foam graphite, *etc.*) [26-29], mesoporous media (2-50 nm, silica, carbon nanotubes – CNT) [30-33], microporous media (<2 nm, metal organic frameworks, porous polymers, *etc.*) [34-36], and graded pore media (graded porous polymers, graded porous carbon, *etc.*) [37-39]. In addition to stability promotion, porous media also have large thermal conductivity, which can simultaneously enhance the heat transfer efficiency of PCM. Chen *et al.* [40] composited polyurethane with *n*-octadecane, and the test results show that the composite PCM is easy to shape with lower cost, and has a promising application in solar energy storage. Pandey *et al.* [41] compounded *n*-eicosane with random copolymers, the composite properties remained stable throughout 500 times of heat storage and release cycles.

Heat transfer efficiency of PCM in energy storage units

To improve the heat transfer efficiency of PCM, the main method is adding nanomaterials, metal rings/metal foams/metal fins [42-47] for PCM in studies at home and abroad, while the latter additions will significantly increase the weight and cost of PCM, which is not conducive to the application of PCM. Therefore, in recent years, nanomaterials are mainly used as additives to improve the thermal conductivity of PCM, the most commonly used nanomaterials include carbon nanomaterials, metal nanomaterials, and oxide nanomaterials.

Carbon nanomaterial additives mainly include CNT [48-50], graphene [51, 52], and expanded graphite [53, 54]. The enhancement effect of carbon nanomaterials on the heat transfer coefficient of PCM mainly depends on the specific surface area and dispersion of the material, and the larger the specific surface area and the more dispersed the nanoparticles, the more significant enhancement effect of carbon nanomaterials on thermal conductivity of PCM. Metal nano additives mainly include copper nanoparticles [55, 56], silver nanoparticles [57, 58], and iron nanoparticles [59]. Oxide nanomaterials mainly include SiO_2 [60, 61], TiO_2 [62, 63], CuO [64, 65], and Al_2O_3 [66], among which, TiO_2 has the most significant ability to enhance the heat transfer efficiency of PCM and is the most widely used oxide nano additive with low cost [59]. With the increase of nanomaterial concentration, the thermal conductivity of the PCM generally increases, but it also leads to a decrease in the latent heat of the composite PCM.

Photothermal conversion efficiency of PCM in energy storage modules

For the application of PCM in SWH, the phase change energy storage only has a single function of latent heat storage, the system usually composed by heat collection, energy storage and connection components, the structure is complex. In recent years, some researchers have found that the non-radiative decay process of some materials in sunlight has a photothermal conversion function, after the composition of photothermal conversion material and PCM, thus, the composite PCM integrate three functions of light absorption, photothermal conversion and thermal storage, which can simplify the SWH system and improve the energy utilization efficiency. The widely studied photothermal conversion materials at home and abroad include carbon-based nanomaterials, metal nanomaterials, semiconductor materials, ZnO, and Cu-S [67, 68]. Given that different photothermal conversion materials have differences in absorption wavelengths, the absorption wavelength can be controlled by changing the chemical composition of the composite PCM. Kong *et al.* [69] sprayed C-SiO_2-NT on the surface of paraffin wax, and the results show that the photothermal conversion efficiency of the composite PCM could reach 87.6%. Zhang *et al*. [70] proposed Ag-GNS nanosheets by modifying graphene with Ag nanoparticles, and is was used as a carrier material to load polyethylene glycol (PEG) to prepare composite photothermal conversion PCM, the photothermal conversion efficiency of the composites reaches 88.7-92.0%. Zhang *et al*. [71] added Ti_4O_7 into SiO_2-paraffin phase change microcapsules, the addition of Ti_4O_7 broadened the spectral absorption range of the composite photothermal conversion PCM, the conversion efficiency reaches 85.36%. Ma *et al.* [72] microencapsulated the composite PCM-paraffin with TiO_2/graphene oxide and dispersed it into water to form a suspension with high thermal conductivity, specific heat and light absorption properties, therefore, the energy storage capacity of the SWH was enhanced. The photothermal conversion efficiency of composite photothermal conversion PCM in domestic and international literature is basically above 85%.

Application of PCM in water heaters

The PCM is mainly applied to HPWH and SWH, few studies have also applied it to electric water heaters. Table 1 lists the research on the application of PCM in water heaters.

Applications of PCM in HPWH

The HPWH consists of heat pump and heat storage unit/water tank, which produces heat by heat pump and stores the heat in heat storage unit or water tank, finally, the heat will be supplied to users. Compared with electric water heaters and gas water heaters, HPWH have a longer heating time and low efficiency at low temperature conditions. Given the high energy storage density of PCM, it can be applied to HPWH to realize cold water preheating, shorten heating time, provide heat source for heat pump defrost, and improve system efficiency. The application of PCM in HPWH is to solve the problems of low efficiency, long heating time, frost under low temperature conditions, balancing supply and demand and power peak regulation.

Table 1. Application of PCM in water heaters

Ref.	PCM	Phase change temperature [°C]	Latent heat [$kJkg^{-1}$]	Types	Application position	Conclusion
[73]	Paraffin wax RT35HC	35	240	SWH	In a thick flat plate type thermal storage tank after heat generation by PV panels	The addition of PCM can reduce the 50 L, 75 L, 100 L, and 125 L thermal storage tank volume by 15.3%, 21.2%, 22%, and 21.5%, respectively
[74]	Paraffin wax RT40 + SiO_2 + copper ring	39.7	133	HPWH	Thermal storage tank	The heat transfer efficiencies of PCM were improved, the heat storage time was reduced by 64% and the heat release time was released by 55%
[75]	Paraffin wax RT44HC	43	255	HPWH	In the external annular shell of the heat storage tank	With the same volume of water tank, the addition of PCM increases the heat storage capacity by 14% and reduces the heating time by 13% with the same heating temperature rise
[76]	Paraffin wax RT42 + graphite	43	139.7	SWH	In glass vacuum tube collector, wrapped on the outer wall surface of the water pipe which connected to the tank	Under night operation condition, the water temperatures of water heater with paraffin wax (RT42) + graphite and myristic acid were 6~18 °C and 17~29 °C higher than the water temperature of water heater without PCM, respectively
	Myristic acid	54	189			
[77]	Paraffin wax + expanded graphite	52-54	140	HPWH	Compression molding and filling in the heat exchange unit	When the inlet water flow rate is 0.5 Lpm, outlet water flow rate is 45 °C, the adding of PCM increase the outlet water flow rate by 83.12%, and the water tank volume is reduced significantly
[78]	Paraffin wax 56# + graphite	56.03	254.9	HPWH	In thermal storage tank	After the structural optimization of thermal storage tank with PCM, the average actual COP of the HPWH reaches 3.8
[79]	Paraffin wax + 1 wt.% nano copper	59.6	160.3	SWH	In the plate collector, between the light-absorbing plate and the insulation plate	After 24 hours of operation, the addition of the PCM resulted in a 15.95% increase in the outlet water temperature
[80]	Paraffin wax $C_{26}H_{54}$	56	250	SWH	Inside the glass tube of the heat pipe type vacuum tube collector	By filling half of the collector tubes with paraffin wax ($C_{33}H_{68}$) and the other half with erythritol ($C_4H_{10}O_4$), the efficiency of the SWH filled with dual PCM increased by 26% compared to that with no PCM
	Paraffin wax $C_{33}H_{68}$	72	256			
	Erythritol $C_4H_{10}O_4$	118	339.8			

→

[81]	Paraffin wax C20H42	36.6	237.4	SWH	The inner surface of insulation in flat type collector	When the flow rate is 0.0015 kg/s, the thickness of the PCM is 0.01 m, and the setting temperature is 313 K, the overall cost of the SWH is the lowest
[82]	Myristic acid	54	189	SWH	In the vacuum tube of the glass vacuum tube collector	The addition of 6 wt.% expanded graphite can increase the heat release capacity of the phase change unit and improve the uniformity in the heat transfer process
	Stearic acid + expanded graphite	56-69.9	167.3			
[83]	Stearic acid + carbon fiber	52.52	76.69	SWH	In the vacuum tube of the *U*-tube vacuum tube collector	Composite PCM have better thermal stability and heat transfer efficiency
[84]	PEG + acrylic acid + carboxyl-rich carbon	33.32	143.16	SWH	In the vacuum tube of the glass vacuum tube collector	The composite PCM has higher thermal conductivity (204% higher than PEG), high energy storage density and 93.3% photothermal conversion efficiency
[68]	Galactitol/myristic acid + perlite	43.83	121.13	SWH	-	Good thermal stability, the decay of latent heat value is less than 7% after 1000 times of test
[85]	$Ba(OH)_2 \cdot 8H_2O$ small amount of $BaCO_3$ works as nucleating agent	77.9	193	SWH	In the vacuum tube of the glass vacuum tube collector	The addition of the PCM extended the heating time of the water heater under night operation and delayed the peak temperature in the tank by 1 hours
[86]	$NH_4Al(SO_4)_2 \cdot 12H_2O$	94	269	SWH	In the water tank of the heat pipe type vacuum tube collector water heater	The heat storage/release capacity was increased
	$Ba(OH)_2 \cdot 8H_2O$	78	265			The heat storage/release capacity and system efficiency were increased
[87]	$CH_3COONa \cdot 3H_2O$ Borax as the nucleating agent	55	246	HPWH	In thermal storage unit	The thermal storage capacity was improved
[88]	$CH_3COONa \cdot 3H_2O$	–	250	Solar-assisted HPWH	Encapsulated in cylinders and placed in the upper part of the heat storage tank	The power consumption was reduced by 12.1-13.5%
[89]	Stearic acid + graphite	69	157.5	HPWH	Filled between the outer wall of the heat transfer fluid tube and the hexagonal shell	Heat consumption and heat storage can be performed simultaneously, the flexibility in energy use of the system was enhanced
[91, 92]	$CaCl_2 \cdot 6H_2O$	–	–	HPWH	Filled in the thermal storage unit to compensate for the heat required for defrosting	Compared with reverse-cycle defrost, the COP of frost-free HPWH were increased by 17.9% and 3.4% at –3 °C and 3 °C outdoor temperature, respectively

[92]	$CaCl_2 \cdot 6H_2O$ + 2 wt.% of $SrCl_2 \cdot 6H_2O$	–	–	HPWH	Filled in the thermal storage unit to compensate for the heat required for defrosting	Compared with reverse-cycle defrost, the operation is more stable, when the outdoor temperature rises from –10 °C to 0 °C at a relative humidity of 80%, the average COP increases of 56.2%

In terms of the application of PCM in HPWH, Long *et al.* [78] filled paraffin wax (56#) in the storage tank and simulated the temperature distribution during the thermal storage process by quasi-steady state method, results show that the average COP of the HPWH system could reach 3.08. Zou *et al.* [75] filled paraffin wax (RT44HC) in the external annulus of the thermal storage tank. The addition of PCM increased the heat storage capacity of the HPWH by 14% at the same water tank volume, and reduced the heating time by 13% at the same temperature rise. Wu *et al.* [75] filled the heat exchanger unit with compression-molded paraffin/graphite, when the inlet water flow rate was 0.5 Lpm and the outlet water temperature was 45 °C, the addition of PCM increased the outlet water flow rate by 83.12% and significantly reduced the volume of the water tank. Li *et al.* [93] applied CNT/paraffin composite PCM in a HPWH, the results show that the addition of CNT led to a significant increase in the heat storage rate and discharge rate of the HPWH, moreover, the system operation is stable. Compared with the HPWH without PCM, the addition of composite PCM reduced the volume of the thermal storage unit by 50% in HPWH. As shown in fig. 2, Inkeri *et al.* [89] optimized the structure of heat storage unit, the stearic acid-graphite composite PCM was filled in the middle cavity of the circular tube and the hexagonal shell. Heat consumption and heat storage can be performed simultaneously, the flexibility in energy use of the system was enhanced.

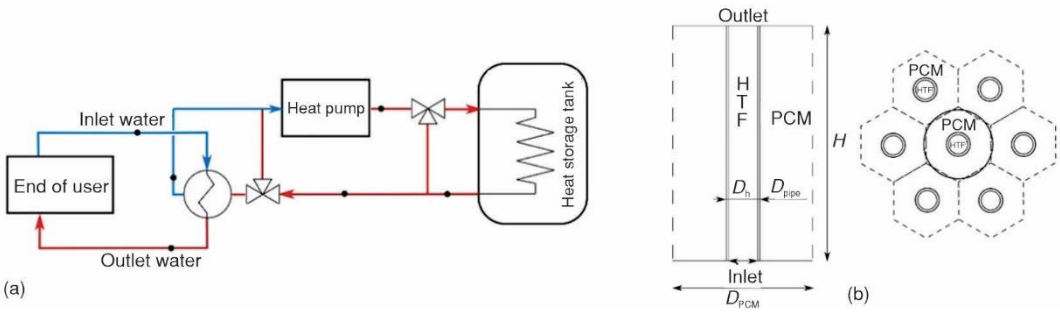

Figure 2. The HPWH system schematic; (a) the HPWH system schematic and (b) the structural schematic of heat storage unit [89]

As shown in fig. 3, Kutlu *et al.* [88] proposed a novel solar energy-assisted HPWH, the sodium acetate trihydrate was encapsulated in cylinders and placed at the top of the heat storage tank, the system energy consumption decreased 12.1%8-13.5% by switching system between different operation modes.

In terms of PCM applied to HPWH defrost, as shown in fig. 4, Wang *et al.* [90, 91] proposed a novel frost-free air-source HPWH with solid desiccant for dehumidification. The condensing heat was recovered by PCM $CaCl_2$ - $6H_2O$ when heating, so that it can be used as a low temperature heat source for desiccant regeneration to ensure continuous operation of the HPWH. Compared with the reverse cycle for defrosting, the COP of the frost-free HPWH was increased by 17.9% and 3.4% at –3 °C and 3 °C outdoor temperature, respectively. Wang *et al.*

[92] used $CaCl_2·6H_2O$ + 2 wt.% of $SrCl_2·6H_2O$ as PCM to provide the heat source for desiccant regeneration in the frost-free air-source HPWH. Furthermore, the performance of the frost-free HPWH was compared with that of the conventional HPWP, the results show that the frost-free HPWH operated more stable, and the average COP of the system increased by 56.2% when the outdoor temperature increased from –10 °C to 0 °C at 80% relative humidity, but further research is needed to enhance the performance of the HPWH under low outdoor temperature conditions.

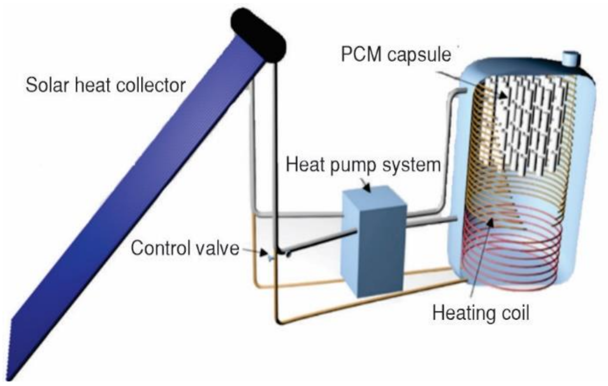

Figure 3. The schematic of the solar energy-assisted HPWH [88]

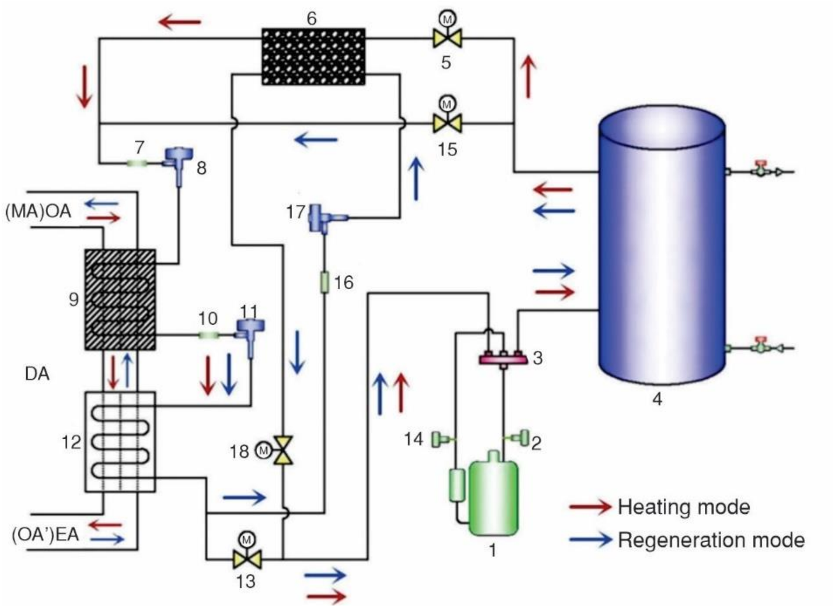

Figure 4. The schematic of the novel frost-free HPWH; *1 – compressor, 2-14 – high/low-pressure protection devices, 3 – four-way valve, 4 – water tank, 5,13,15,18 – solenoid valve, 6 – energy storage device, 7,10,16 – filter drier, 8,11,17 – electronic expansion valve, 9 – heat exchanger coated with a solid desiccant, and 12 – evaporator*

Applications of PCM in SWH

The PCM in SWH are used for thermal energy storage and photothermal conversion, and the application position are generally solar heat collectors and water tanks. For the two types of solar heat collectors-flat plate solar heat collectors and vacuum tube solar heat collectors, the latter has lower heat loss, therefore, vacuum tube solar heat collectors have become increasingly popular in recent years. According to the system structure, vacuum tube solar collectors are generally divided into 3 types: all-glass vacuum tube collectors, *U*-tube vacuum tube collectors, and heat pipe vacuum tube collectors.

Figure 5 shows the schematics of the flat plate solar heat collector, solar radiation is absorbed through the glass plate by the adsorption layer and then converted into heat and conducted to the heat transfer media. As shown in fig. 5(a), Alloihi *et al.* [81] placed a paraffin layer on the surface of the insulation layer in the flat plate solar heat collector, and the working performance of the SWH at different flow rates, PCM thickness and setting temperatures was studied, when the flow rate was 0.0015 kg/s, the PCM thickness is 0.01 m and the setting temperature is 313 K, the SWH has the lowest comprehensive cost. As shown in fig. 5(b), Al-Kayiem *et al.* [79] filled paraffin +1 wt.% nano-copper composite PCM between the adsorption and insulation plates, compared with the working performance of the SWH without PCM, that of the SWH with PCM increases the outlet water temperature by 15.95% after 24 hours of operation.

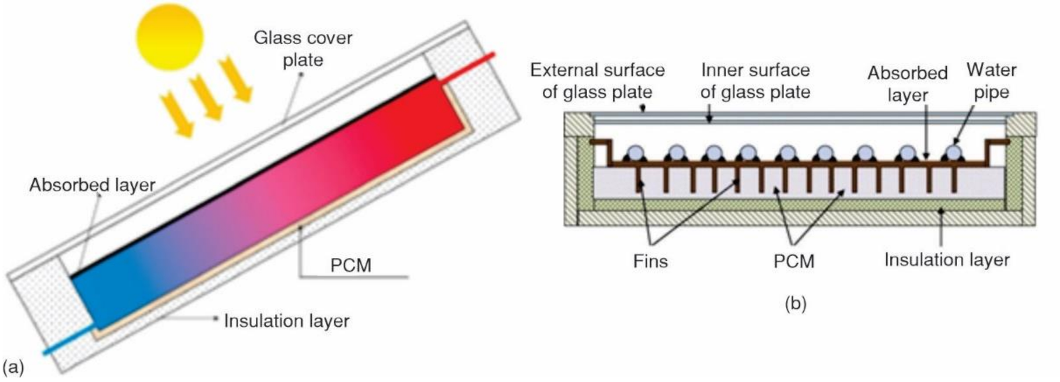

Figure 5. Schematics of flat plate solar heat collector; (a) the PCM covered on the surface of the insulation layer [81] and (b) the PCM filled between adsorption and insulation layer [79]

Figure 6 shows all-glass vacuum tube solar heat collectors, Chaabane *et al.* [76] wrapped TR42-graphite and myristic acid respectively on the outer surface of the water pipe that connected to the tank. The experimental results show that, compared with the case without PCM wrapping, the outlet water temperatures of the SWH were increased by 6~18 °C and 17~29 °C, respectively. Li *et al.* [82] filled the myristic acid + stearic acid composite PCM in the vacuum tube of the solar heat collector, and the composite PCM was modified by adding expanded graphite with different concentrations, the results show that the addition of 6 wt.% expanded graphite could improve the discharge efficiency of the PCM and improve the uniformity during heat transfer process. Yang *et al.* [84] prepared the PEG + acrylic acid + carboxy carbon composite PCM which combines the function of heat storage and photothermal conversion, and the composite PCM was filled into all-glass vacuum tube solar heat collector. The results show that the composite PCM has high thermal conductivity (204% higher than PEG), and has higher energy storage density and 93.3% photothermal conversion efficiency when applied in the all-glass vacuum tube solar heat collector.

Figure 7 shows the schematics of the application of PCM for heat storage in the *U*-tube type vacuum tube solar heat collector. Generally, PCM are filled between the *U*-tube external surface and the inner surface of the vacuum tube type solar heat collector. Xie *et al.* [83] prepared stearic acid + carbon fiber as the composite PCM, and filled the composite PCM in vacuum tubes. After the thermal cycling experiment, the results show that the composite PCM has good thermal stability and heat transfer efficiency. Olfian *et al.* [94] studied the effects of

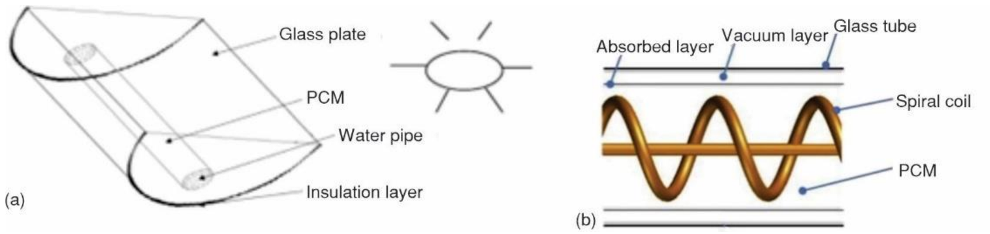

Figure 6. Schematics of All-glass vacuum tube solar heat collector; (a) the PCM covered on the surface of the water tube [76] and (b) the PCM filled in the vacuum tube [82]

PCM on the heat-collecting efficiency at different *U*-tube diameters, and the results show that, compared with the heat-collecting efficiencies of the vacuum tube type solar heat collector at 8 mm and 10 mm *U*-tube diameters, the daily heat-collecting efficiencies increased by 34% and 48.5% when the *U*-tube diameter was 6mm. respectively. Xue *et al.* [85] modified the $Ba(OH)_2 \cdot 8H_2O$ by adding $BaCO_3$ as a nucleating agent to reduce the subcooling degree, the experimental results show that the heating time of the *U*-tube type vacuum tube solar heat collector at night was extended and the peak temperature in the tank was delayed by 1 hours.

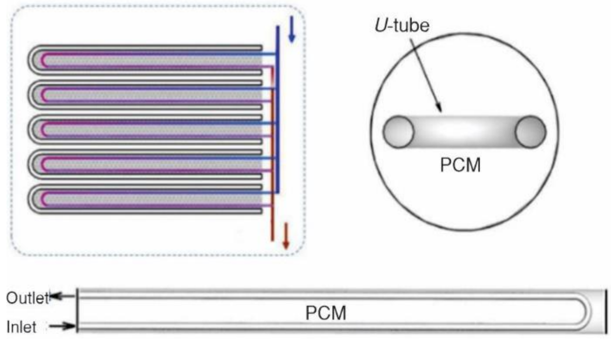

Figure 7. The schematic of the *U*-tube type vacuum tube solar heat collector

Figure 8 shows the schematics of PCM application in heat pipe type vacuum tube collector. The PCM is filled between the inner surface of the vacuum tube and the external surface of the heat pipe, and the solar radiation heat is absorbed by the PCM. One end of the heat pipe is inserted into the PCM and another end is connected to the water channel, thus, the heat can be transferred to water. Papadimitratos *et al.* [80] proposed a novel thermal storage SWH using a dual PCM filling method, half of the vacuum tubes were filled with paraffin and another half of the vacuum tubes were filled with erythritol, the experimental results show that, compared with the efficiency of heat pipe vacuum tube SWH without PCM filling, that of the heat pipe vacuum tube SWH with dual PCM was improved by 26%.

Applications of PCM in electric water heaters

The PCM are generally applied in heat exchanger or insulation layer for electric water heaters [95]. Qu *et al.* [96] modified sodium acetate by adding sodium pyrophosphate as the nucleating agent, the composite PCM was filled in the heat exchanger with finned copper tubes inside, fig. 9(a). The experimental results show that the addition of the PCM improved the heat storage capacity of the electric water heater, furthermore, after the modification for the PCM, the heat transfer efficiency of the heat exchanger increased by 12.23%. Zeng *et al.* [97] compared the economic benefits of thermal storage electric water heaters with water heaters without PCM, the results show that the tank volume of thermal storage electric water heaters could be reduced by 30~50% with the same amount of hot water preparation.

Moreover, the annual operation cost was only 1/3 of that of electric water heaters without PCM. Wu *et al.* [98] studied the effect of PCM (paraffin + 10 wt.% graphite) layers

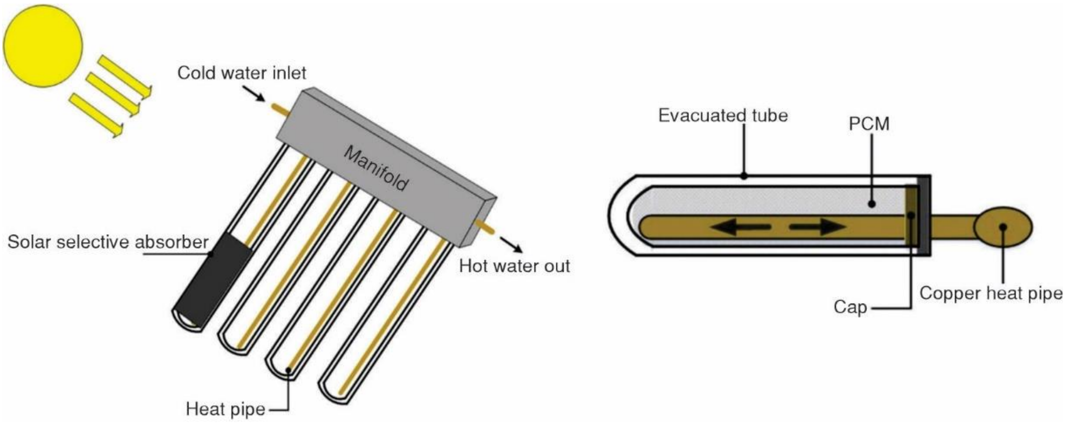

Figure 8. The schematic of PCM applied in heat pipe vacuum tube solar heat collector [80]

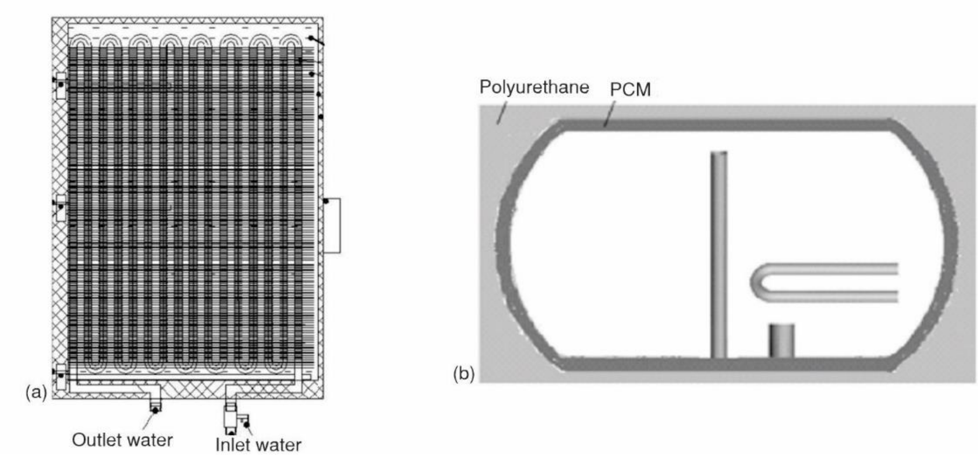

Figure 9. The schematic of PCM applied in electrical water heaters;
(a) application of PCM in heat exchanger [96] and
(b) application of PCM in insulation layer [98]

with different thicknesses in insulation layer on the performance of electrical water heaters, fig. 9(b). The results show that, with the total insulation thickness unchanged, when the insulation time was 36 hours, the PCM layers with thicknesses of 10 mm, 15 mm, and 20 mm were able to increase the outlet water temperature by 6.9%, 8.6%, and 10.6%, respectively.

Conclusions

This paper has reviewed the PCM modification studies in terms of stability, heat transfer efficiency and photothermal conversion efficiency, and the application research of PCM in different types of water heaters. The application of PCM in water heater can enhance the heat storage capacity, improve the operation efficiency, shorten heating time and reduce system operation cost. Which has extensive application prospects. Future work could focus on the following points for in-depth research, so as to promote the innovation and industrial upgrading of thermal storage water heaters.

- At present, paraffin is the most widely used solid-liquid PCM for water heaters. The PCM are generally applied in water tanks, heat storage tanks or solar heat collectors. The research on PCM application at home and abroad mostly focus on material modification in terms of thermal storage capacity, thermal conductivity and stability of materials. The application scenarios and cost of PCM should be taken into consideration, the application economy could be taken as an evaluation index, so as to promote the application and marketization of new PCM.

- The selection and dosage of PCM, selection and design of heat storage units are still under developing in HPWH. In-depth research and development on thermal storage HPWH with high efficiency, energy-saving, reliability and cost advantages are still needed.
- Most of the studies on photothermal conversion PCM focusing on the material modification, the further research of its application in SWH is suggested.
- To promote the efficient consumption of green energy, thermal storage water heaters can be treated as virtual energy storage resources for buildings to participate in power grid demand response. Furthermore, the control strategy for thermal storage water heaters to participate in demand response could be an emerging interdisciplinary research direction.

Acknowledgment

This research was financially supported by the National key research and development plan project (2022YFC3802501).

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Paper submitted: March 11, 2023
Paper revised: March 20, 2023
Paper accepted: May 15, 2023