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

***Chao WANG*[1,2,3], *Xiaoya JIA*[2,3,*], *Peng ZHAO*[2,3], *Liangbing WANG*[2,3], *Liming SHI*[2,3]**

[*1]Beijing University of Aeronautics and Astronautics, Beijing, China 1

[2] Secretariat of National Technical Committee for standardization of household electric appliance, Beijing, China 2

[3] China Household Electric Appliance Research Institute, Beijing, China 3

[*] Corresponding author: jiaxy@cheari.com

*This paper reviews the stability, heat transfer efficiency and photothermal conversion efficiency optimization studies of solid-liquid phase change materials applied to water heaters. Suggestions and prospects were proposed. The study shows that the solid-liquid PCMs 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 PCMs can significantly improve the water heater performance. Further in-depth research is needed on PCM material dosage and system economics of their application in heat pump water heaters, and the application of photothermal conversion phase change materials in solar water heater systems.*

Key words*: phase change material; water heater; heat transfer efficiency; performance coefficient; photothermal conversion*

## 1. 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], phase change materials (PCM) can effectively improve the efficiency of water heaters, reduce operating costs, and alleviate the mismatch of electricity supply and consumption. For the 4 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 kinds of PCM. Thus, solid-liquid PCMs are widely used in water heater energy storage [5-7]. The efficacies of PCMs 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, solar water heaters, electric water heaters and gas water heaters, PCMs are more widely used in the first three types of water heater. PCMs 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 solar water heaters [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 PCMs in solar water heaters, consequently, the system energy efficiency could be improved. In this paper, the modification of PCM and the application of PCMs in different types of water heaters are analyzed.

## 2. Overview of the application of PCM in water heaters

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

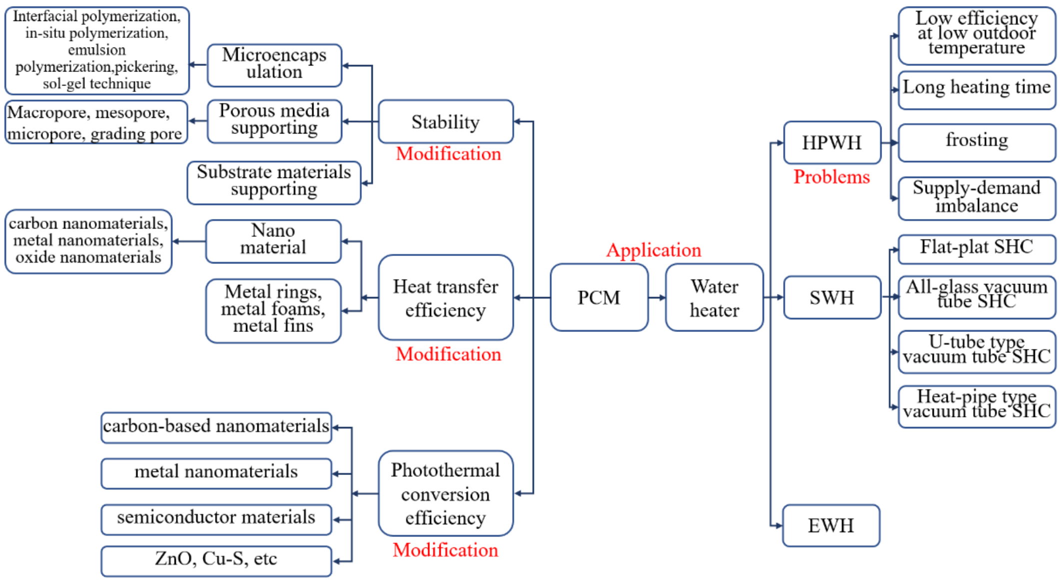



**Fig.1 The classification of PCMs modification and the application of PCMs in water heaters**

## 3. Functional requirements of PCMs for thermal storage units

Although PCMs 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 PCMs [11-13], while, for photothermal conversion PCMs, the photothermal conversion capability also should be evaluated [14]. This section will review the research work of PCMs about stability, heat transfer efficiency and photothermal conversion capability improvements at home and abroad.

### 3.1. Stability of PCMs in energy storage units

To improve the stability of PCMs 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 PCMs 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 PCMs 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 PCMs in energy storage units.

In terms of encapsulation of PCMs, Luz Sanchez 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. Yi 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. Hao 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. Refat Al 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 PCMs 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) [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 PCMs. Keping 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. Kalpana et al [41] compounded n-eicosane with random copolymers, the composite properties remained stable throughout 500 times of heat storage and release cycles.

### 3.2. Heat transfer efficiency of PCMs in energy storage units

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

Carbon nanomaterial additives mainly include carbon nanotubes [48-50], graphene [51, 52], and expanded graphite [53, 54]. The enhancement effect of carbon nanomaterials on the heat transfer coefficient of PCMs 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 PCMs. Metal nano additives mainly include copper nanoparticles [55, 56], silver nanoparticles [57, 58], and iron nanoparticles [59]. Oxide nanomaterials mainly include SiO2 [60, 61], TiO2 [62, 63], CuO [64, 65], and Al2O3 [66], among which, TiO2 has the most significant ability to enhance the heat transfer efficiency of PCMs and is the most widely used oxide nano additive with low cost [59]. With the increase of nanomaterial concentration, the thermal conductivity of the PCMs generally increases, but it also leads to a decrease in the latent heat of the composite PCM.

### 3.3. Photothermal conversion efficiency of PCMs in energy storage modules

For the application of PCMs in solar water heaters, 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 PCMs, thus, the composite PCMs integrate three functions of light absorption, photothermal conversion and thermal storage, which can simplify the solar water heater 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. sprayed C-$SiO_2$-NTs on the surface of paraffin wax, and the results show that the photothermal conversion efficiency of the composite PCM could reach 87.6% [69].Yuan Zhang et al. proposed Ag-GNS nanosheets by modifying graphene with Ag nanoparticles, and is was used as a carrier material to load PEG to prepare composite photothermal conversion PCMs, the photothermal conversion efficiency of the composites reaches 88.7%-92.0% [70]. Zhang et al. 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 PCMs, the conversion efficiency reaches 85.36% [71]. Ma et al [94] 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 PCMs in domestic and international literature is basically above 85%.

## 4. Application of PCMs in water heaters

PCM is mainly applied to heat pump water heaters (HPWH) and solar water heaters (SWH), few studies have also applied it to electric water heaters. Table 1 lists the research on the application of PCMs in water heaters.

Table.1 Application of PCMs in water heaters

| Researcher | PCM | Phase change temperature/℃ | Latent heat /kJ·kg$^{-1}$ | Types | Application position | Conclusion |
|---|---|---|---|---|---|---|
| Colarossi D et al.[72] | Paraffin wax（RT35HC） | 35 | 240 | SWH | In a thick flat plate type thermal storage tank after heat generation by photovoltaic panels | The addition of PCMs can reduce the 50L, 75L, 100L and 125L thermal storage tank volume by 15.3%, 21.2%, 22% and 21.5% respectively |
| WANG Y C[73] | Paraffin wax（RT40）+$SiO_2$+copper ring | 39.7 | 133 | HPWH | thermal storage tank | The heat transfer efficiencies of PCMs were improved, the heat storage time was reduced by 64% and the heat release time was released by 55% |
| Deqiu Zou et al.[74] | 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. |
| Monia et al.[75] | 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℃ and 17~29℃ higher than the water temperature of water heater without PCM, respectively. |
| | Myristic acid | 54 | 189 | | | |
| Jianghong Wu et al.[76] | Paraffin wax + expanded graphite | 52-54 | 140 | HPWH | Compression molding and filling in the heat exchange unit | When the inlet water flow rete is 0.5L/min, outlet water flow rate is 45℃, the adding of PCM increase the outlet water flow rate by 83.12%, and the water tank volume is reduced significantly. |
| Jianyou Long[77] | 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. |
| Hussain et al.[78] | Paraffin wax +1wt% Nano Copper | 59.6 | 160.3 | SWH | In the plate collector, between the light-absorbing plate and the insulation plate | After 24 h of operation, the addition of the PCM resulted in a 15.95% increase in the outlet water temperature. |
| Alexios et al.[79] | 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 PCMs increased by 26% compared to that with no phase change materials |
| | Paraffin wax（$C_{33}H_{68}$） | 72 | 256 | | | |
| | Erythritol（$C_4H_{10}O_4$） | 118 | 339.8 | | | |
| A.Allouhi et al.[80] | Paraffin wax（$C_{20}H_{42}$） | 36.6 | 237.4 | SWH | The inner surface of insulation in flat type collector | When the flow rate is 0.0015kg/s, the thickness of the PCM is 0.01m, and the setting temperature is 313K, the overall cost of the SWH is the lowest. |
| Chuanchang Li et al.[81] | 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 | | | |
| Xie et al.[82] | Stearic acid + carbon fiber | 52.52 | 76.69 | SWH | In the vacuum tube of the U-tube vacuum tube collector | Composite PCMs have better thermal stability and heat transfer efficiency. |
| Huizhi Yang et al.[83] | Polyethylene glycol (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. |
| Shin Ying et al.[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. |

| | | | | | | |
|---|---|---|---|---|---|---|
| H.Shengxue[84] | Ba(OH)2·8H2O（small amount of BaCO3 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 1h. |
| YUAN X Y[85] | NH4Al(SO4)2·12H2O | 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)2·8H2O | 78 | 265 | | | The heat storage/release capacity and system efficiency were increased. |
| WU J H[86] | CH3COONa·3H2O（Borax as the nucleating agent） | 55 | 246 | HPWH | In thermal storage unit | The thermal storage capacity was improved. |
| Cagri et al.[87] | CH3COONa·3H2O | - | 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%. |
| E.lnkeri et al.[88] | 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. |
| F.H.Wang et al.[89, 90] | CaCl2·6H2O | - | - | HPWH | Filled in the thermal storage unit to compensate for the heat required for defrosting | Compared with reverse-cycle defrost, the COPs of frost-free HPWH were increased by 17.9% and 3.4% at -3°C and 3°C outdoor temperature, respectively |
| Zhihua Wang et al.[91] | CaCl2·6H2O +2wt% of SrCl2·6H2O | - | - | 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%. |

### 4.1. Applications of PCMs in HPWH

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, HPWHs 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 PCMs in HPWHs is to solve the problems of low efficiency, long heating time, frost under low temperature conditions, balancing supply and demand and power peak regulation.

In terms of the application of PCMs in HPWHs, Jianyou Long et al [77] 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. Deqiu Zou et al [74] 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. Jianghong Wu et al [76] filled the heat exchanger unit with compression-molded paraffin/graphite, when the inlet water flow rate was 0.5 L/min 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. Xinfang Li et al [92] applied CNTs/paraffin composite PCM in a HPWH, the results show that the addition of CNTs 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, E.lnkeri et al [88] 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.

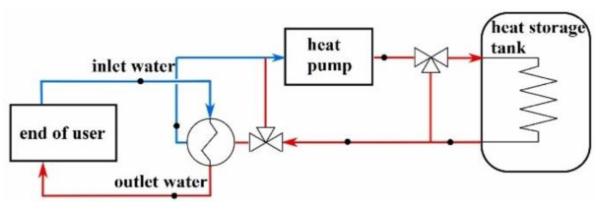



**Fig.2(a) HPWH System schematic**

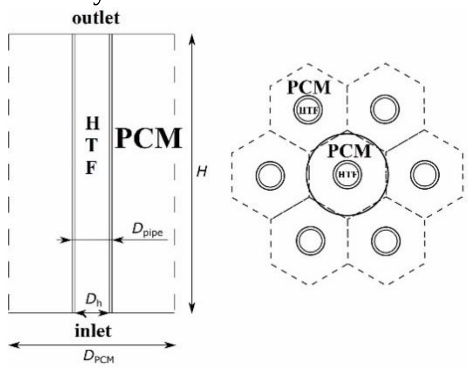



**Fig.2(b) The structural schematic of heat storage unit[88]**

**Fig.2 HPWH System schematic**

As shown in fig.3, Cagri et al [87] 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%-13.5% by switching system between different operation modes.

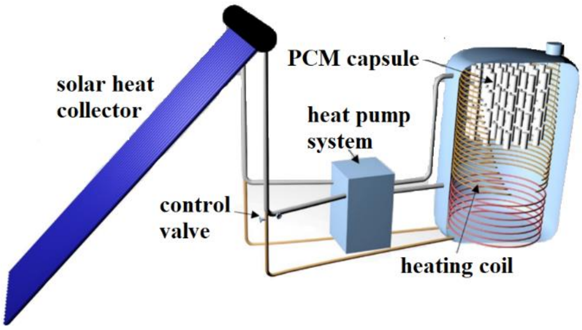
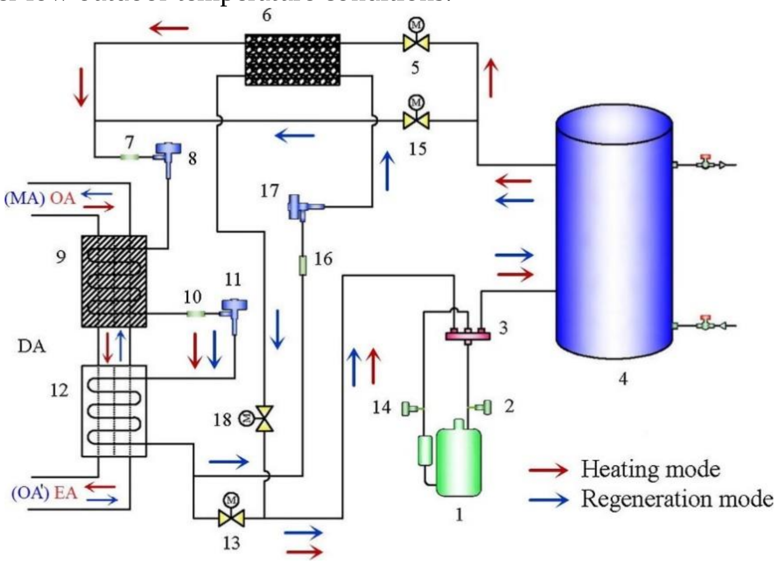



**Fig.3 The schematic of the solar energy-assisted HPWH [87]**

In terms of PCMs applied to HPWH defrost, as shown in Fig.4, F.H. Wang et al [89, 90] 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. Zhihua Wang et al [91] used $CaCl_2{\cdot}6H_2O$+2wt% of $SrCl_2{\cdot}6H_2O$ 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.




**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；12-evaporator**

**Fig.4 The schematic of the novel frost-free HPWH[91]**

### 4.2. Applications of PCMs in SWH

PCMs in SWHs 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 3types: all-glass vacuum tube collectors, U-tube vacuum tube collectors and heat pipe vacuum tube collectors.

Fig.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 [80] 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 0.01m and the setting temperature is 313K, the SWH has the lowest comprehensive cost. As shown in Fig.5(b), Hussain et al [78] filled paraffin+1wt% 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 h of operation.

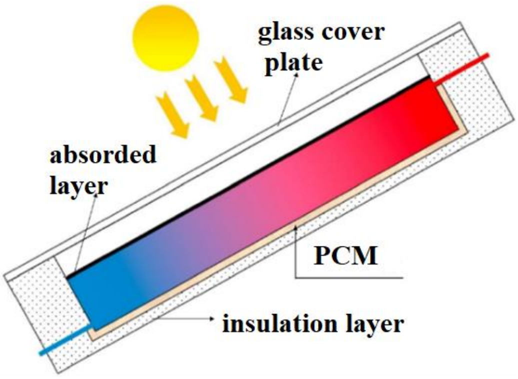



**Fig.5(a) The PCM covered on the surface of the insulation layer[80]**

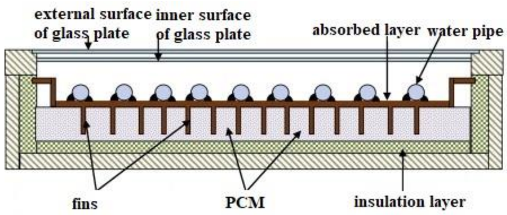
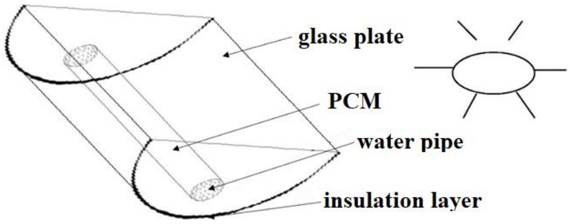



**Fig.5(b) The PCM filled between adsorption and insulation layer[78]**

**Fig.5 Schematics of flat plate solar heat collector**

Fig.6 shows all-glass vacuum tube solar heat collectors, Monia et al [75] 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. Chuanchang Li et al [81] 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. Huizhi Yang et al [83] prepared the polyethylene glycol (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.



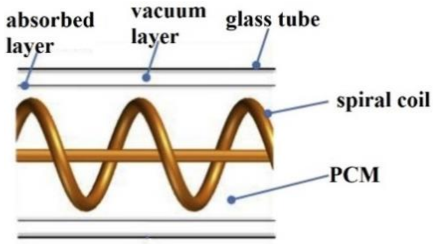




**Fig.6(a) The PCM covered on the surface of the water tube[75]**

**Fig.6(b) The PCM filled in the vacuum tube[81]**

**Fig.6 Schematics of All--glass vacuum tube solar heat collector**

Fig.7 shows the schematics of the application of PCM for heat storage in the U-tube type vacuum tube solar heat collector. Generally, PCMs are filled between the U-tube external surface and the inner surface of the vacuum tube type solar heat collector. Xie et al [82] 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. HassanOlfian et al [93] studied the effects of 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 8mm and 10mm U-tube diameters, the daily heat-collecting efficiencies increased by 34% and 48.5% when the U-tube diameter was 6mm. respectively. H.Shengxue et al [84] 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 1h.

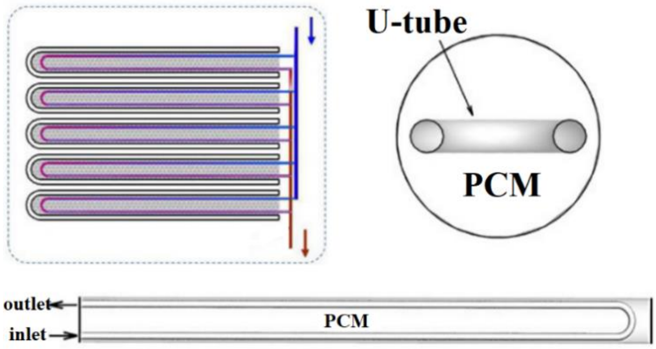



**Fig.7 The schematic of the U-tube type vacuum tube solar heat collector**

Fig.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. Alexios et al [79] 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%.

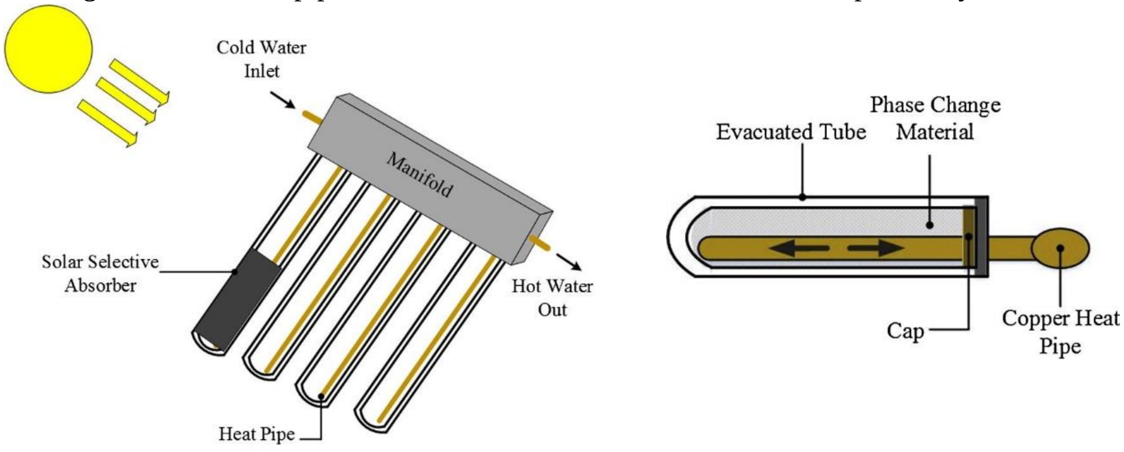



**Fig.8 The schematic of PCM applied in heat pipe vacuum tube solar heat collector[79].**

### 4.3. Applications of PCMs in Electric water heaters

The PCMs are generally applied in heat exchanger or insulation layer for electric water heaters [95]. Qu Renjun 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. 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 Yun et al [97] compared the economic benefits of thermal storage electric water heaters with water heaters without PCMs, 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 PCMs. Wu, L. et al [98] studied the effect of PCM (paraffin + 10 wt% graphite) layers with different thicknesses in insulation layer on the performance of electrical water heaters. The results show that, with the total insulation thickness unchanged, when the insulation time was 36h, 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.

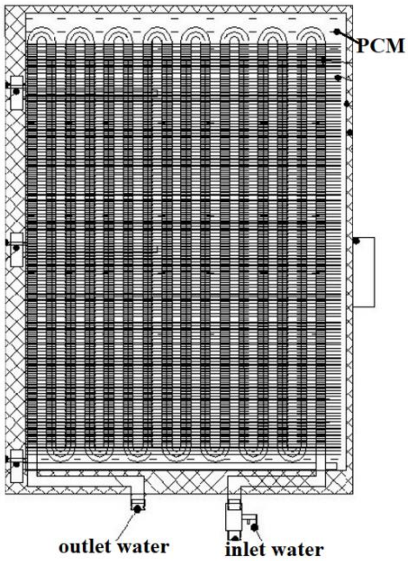



Fig.9(a) Application of PCM in heat exchanger[96]

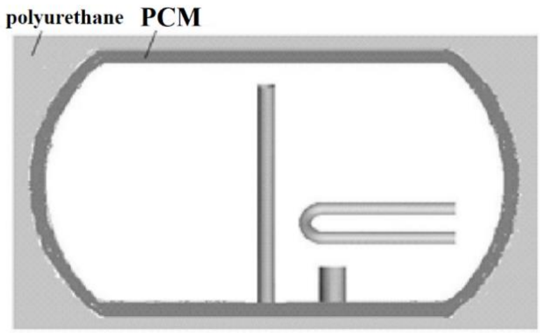



Fig.9(b) Application of PCM in insulation layer[98]

**Fig.9 The schematic of PCM applied in electrical water heaters**

**5. Conclusion**

This paper has reviewed the PCM modification studies in terms of stability, heat transfer efficiency and photothermal conversion efficiency, and the application research of PCMs in different types of water heaters. The application of PCMs 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.

(1) At present, paraffin is the most widely used solid-liquid PCM for water heaters. And PCMs are generally applied in water tanks, heat storage tanks or solar heat collectors. The research on PCMs 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 PCMs 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 PCMs.

(2) The selection and dosage of PCMs, selection and design of heat storage units are still under developing in HPWHs. In-depth research and development on thermal storage HPWH with high efficiency, energy-saving, reliability and cost advantages are still needed.

(3) Most of the studies on photothermal conversion PCM focusing on the material modification, the further research of its application in SWH is suggested.

(4) 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.

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