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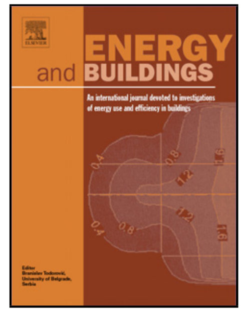

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Author: ZhongBing Liu Ling Zhang GuangCai Gong HangXin Li GuangFa Tang

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Review of solar thermoelectric cooling technologies for use in zero energy buildings

ZhongBing Liu, Ling Zhang * , GuangCai Gong, HangXin Li, GuangFa Tang

College of Civil Engineering, Hunan University, Changsha, China, 410082, P.R. China
Corresponding author: (0086) (0731) 85228641, Fax: (0086) (0731) 88822610, E-mail: lingzhang@hnu.edu.cn

Abstract

Energy crisis and global warming have become more and more serious with the social development. Since buildings account for a significant proportion of the total energy consumption and carbon emissions, it is very necessary and urgent to decrease building energy consumption. Minimizing the need for energy use in buildings through energy-efficient measures and adopting renewable energy are the basic strategies. Zero energy buildings, which only consume solar energy and other renewable energies, have been considered as one solution and have drawn more and more attention in recent years. Solar thermoelectric cooling technologies can be powered directly by a photovoltaic (PV) and cause no harm to the environment, which fully fulfill the demand of ZEBs. This paper reviews solar thermoelectric cooling technologies and proposes a technical route of solar thermoelectric cooling technologies for use in Zero energy buildings. It can be seen that solar thermoelectric cooling systems can minimize the energy demands, increase energy effectiveness and reduce fossil energy consumption in buildings. With the thermoelectric and PV industry‘s development along with the advent of new materials, the solar thermoelectric cooling technologies for use in zero energy buildings are promising.

Keywords: Solar energy; thermoelectric cooling technology; Zero energy building; Active building envelope; Energy recovery; Air conditioner.

● We review about 50 papers to get a clear state of solar thermoelectric cooling technologies for use in buildings.

● We describe main solar thermoelectric cooling systems for use in ZEBs.

●We proposed the technical route of solar thermoelectric cooling technologies for use in ZEBs.

●The review discovers that the solar thermoelectric cooling technologies are promising for use in ZEBs.

1. Introduction

The environment pollution and energy crisis have become the focus of attention all over the world. As the world population increasing and economic development, the world has experienced large increase in energy consumption over the past 30 years. Buildings account for a significant proportion of global energy consumption and carbon emissions worldwide. About 30% of energy consumption in china [1], 40% in USA [2], and 20-40% in developed counties is consumed by buildings and predicted to increase by 34% in the next 20 years [3-4]. Meanwhile, buildings are responsible for about 30% of the global anthropogenic carbon emission in 2004 according IPCC report [5]. In china, buildings contributed up to 1/4 of the total carbon emission in 2007 [6]. Many efforts have been made to find ways to decrease the building energy consumption to help ease the energy crisis by scholars worldwide and Zero Energy Buildings (ZEBs) have been considered and drawn many attentions in recent years.

Zero Energy Buildings are kind of buildings which totally depend on solar energy and other renewable energy and do not consume conventional energy. The basic principles of selecting the technologies used in these buildings are to use the energy resources more efficiently and to reduce building energy consumption and carbon emissions as much as possible. Many countries have adopted or been considering ZEBs as their future building energy targets. For example, EU regulators have published the Energy Performance of Buildings Directive (EPBD)[7].The EPBD mainly focuses on reducing the operational energy consumption of buildings, but it will also establish that by 2020, and it demands that every new building in the EU must be a "nearly-zero" energy building, which means to reduce the building energy demand and to produce energy on building site (or nearby) to balance the building energy demand in a cost-effective way.

In general, ZEBs involve two design strategies: minimizing the need for energy use in buildings through more energy-efficient measures, and adopting renewable energy and other technologies to meet the minimal energy needs [8]. The building industry's advance towards zero energy means the probable integration of additional energy-saving and clean energy producing components and systems. Energy saving in building envelopes, internal design conditions and building service systems are three main measures to minimize the energy demand in ZEBs. As to renewable energy application in ZEBs, the most commonly applied technologies are building integrated PV technology, wind turbines technology and solar thermal technology.

Thermoelectric cooling systems have no mechanical moving parts and do not employ working fluids, which transfer heat from the cold side of the modules to the hot side with consumption of electricity [9]. Due to the advantages such as high reliability, low weight, and flexibility in packaging and integration, thermoelectric cooling systems have been widely used in military, aerospace, instrument, and industrial products [10-14]. Thermoelectric cooling systems can be powered directly by a photovoltaic (PV) without the help of AC/DC inverter, which greatly reduces the costs. Moreover, these systems are Freon free, causing no harm to the environment. Therefore, the thermoelectric coolers and the solar cells combined technologies are beneficial to solar energy using and environment protection, which fully fulfill the demand of ZEBs [15].

Recently researchers have created lots of novel solar thermoelectric cooling systems and improved the systems' performances. In this paper, applications of solar thermoelectric cooling technologies are reviewed and the possibility of their application in ZEBs is discussed. In details, in Section 2, solar thermoelectric cooling system is introduced. In Section 3, technologies of thermoelectric active building envelope including active wall and window system, which both use solar energy active control the thermal flux of building envelope, are introduced. In Section 3, the researches on applications of thermoelectric technologies in waste heat and cold recovery are reviewed, including heat recovery in mechanical ventilation system, thermoelectric air conditioner condense heat recovery, waste water heat recovery, kitchen exhaust heat recovery. In Section 4, solar thermoelectric air conditioners such as thermoelectric radiant air conditioner and solar thermoelectric energy storage air conditioner are presented. In Section 5, summary of solar thermoelectric cooling theologies for use in ZEBs are conducted. finally, conclusions are drawn in Section6.

2. Solar thermoelectric cooling system

In commercial types, the thermoelectric modules consist of P-type and N-type blocks of semiconductor materials. Fig. 1 shows the schematic design of commercial TE modules [16]. When direct current is passed through one or more pairs of P-type and N-type semiconductors, thermoelectric cooling effect occurs. When the thermoelectric cooling system works for space cooling, the cold side temperature decreases and heat is absorbed from indoor environment. At the same time, the temperature at the hot side increases and heat is dissipated to outdoor environment. By controlling the direction of the current, the functions of cooling and heating can be easily achieved.

In solar thermoelectric cooling system, solar radiation energy is converted into electrical energy by means of a photovoltaic unit. Subsequently, the electrical energy is supplied to the thermoelectric cooling system. Solar thermoelectric cooling system uses electron gas to serve as the working fluid and thus causes no harm to the environment. Due to this characteristic, there is an increasing interest in using solar thermoelectric cooling system for domestic refrigeration systems. Moreover, recent progresses in PV and thermoelectric technologies have led to significant reductions in manufacture costs of solar thermoelectric cooling system together with moderate improvements in the system performance. Although the coefficient of performance of solar thermoelectric air conditioner is lower than that of conventional compressor air conditioner, efforts are being made to develop domestic thermoelectric cooling systems which associate the advantages with this solid-state energy conversion technology.

Fig.1. Schematic design of commercial TE modules [16].

3. Application of solar thermoelectric technologies in active building envelopes

Building envelope separates the indoor and outdoor environment of a building, which is the key factor that determines the indoor quality. Building envelope plays an important role in building energy consumption. A large amount of energy is needed to compensate for thermal energy losses or gains that occur in building envelope systems for climate control. Conventional strategies to compensate for thermal energy losses or gains in enclosures rely on passive insulation materials and centralized heating and cooling systems. This space cooling or heating usually consumes electrical energy or non-renewable fossil fuels. In order to reduce building energy consumption, different passive methods such as insulation walls and passive solar building envelopes are used to reduce thermal energy losses or gains in enclosures.

Recently, passive solar building envelopes can be achieved by using solar system which can maximize solar heating gains in heating seasons and minimize heating gains in cooling seasons. Passive solar heating is a well-established concept in cold climates, which mainly includes solar chimney [17], solar room [18], Trombe Wall [19], etc. However, both passive insulated walls and solar walls have disadvantages: (1) Passive insulation cannot effectively control the heat flux and may have a negative influence on building energy consumption in summer [20]. (2) Passive solar technology usually can only be used in winter for heating. But in summer, passive solar envelopes cannot reduce the thermal load of envelope by controlling heat flux. Building envelopes integrated with thermoelectricity offer a new way for heating and cooling which can actively regulates the heat flow and provide both heating and cooling to offset the thermal losses or gains of envelopes. Compared with insulated envelopes and passive solar systems, the thermoelectric active building envelopes convert solar radiation into electrical energy and subsequently use the electrical energy to power a thermoelectric cooling system, which can fulfill active control of the heat flux in building envelopes.

3.1. Active building wall

Active building walls are kind of walls which can actively control the heat flux of the walls with solar energy [21, 22]. Fig.2 depicts the sketch diagram of an active building wall, which is integrated with a photovoltaic (PV) unit and a thermoelectric (TE) unit. The PV forms the external surface of the wall with an airflow channel between it and the inside thermoelectric panel. In the active building wall, the PV unit changes the solar radiation energy into electrical energy while the TE unit changes the electrical energy into thermal energy, as shown in Fig.3. The TE unit can operate in a heating or a cooling mode, depending on the direction of the current supplied by the PV unit. This feature allows for the active building envelope to be used for heating as well as cooling applications. Compared with conventional thermal technologies, the active building walls have advantages as follows: (1) operating with solar energy, (2) consisting of solid state devices and operating silently with no moving parts, (3) using little or no fossil energy sources, and (4) beneficial to environment in the long term.

Fig.2. Active building wall system [22].

A computational analytical model of the thermoelectric cooler and heat sink has been developed to instruct active building wall system design [22]. The analysis results show that the total input power required to operate the TE unit decreases as the distribution density of the TE coolers increase. The thermal resistance of the heat sink plays a key role in determining the optimal number of TE coolers in all of the design configurations. Dessel et al. have developed a finite elements model to calculate the heat transfer for active buildings wall systems [23]. The results of parametric study show that for both heating and cooling mode the optimal systems can be achieved when the smallest TE-modules are being used that are spaced at relative short distances from each TE modules.

Fig.3. Energy flow in active building wall systems [24].

3.2. Active building window

The active building window system is a new window technology which integrates photovoltaic and thermoelectric technologies [24-26]. The schematic of this type of window-system is illustrated in Fig.4. Eight TE modules are mounted on two aluminum tubes and placed on both sides of the window. Each TE module is connected to the external heat sink, which either absorbs/dissipates heat into the air through natural convection. The aluminum tubes are encapsulated with thermal insulation materials on all sides except for the side facing inwards, and they are filled with thermal storage masses (water). The tubes act as a thermal bank for the ABE window-system. They slowly absorb or dissipate heat towards the space surrounding the window. The ABE window system is operated with a stand-alone PV system.

Experimental results show that the system can affect indoor temperature of the testing room with 2-6^{o}C and the ABE window system can provide 35-40W effective energy to control the temperature of the room. The overall efficiency is about 5% in cooling mode and 13% in heating mode [24-26].

Fig.4. Active building window [26].

Fig.5 shows the schematic of a novel type of active thermal insulator (ATI) window [27]. As shown in the Fig.5, the ATI window is composed of the following four parts: (1) the passive window, (2) the PV module, (3) the thermoelectric cooling units, and (4) the heat sinks. The semi-transparent PV module is integrated into the front pane of a passive double-pane window and it is used to power the TE units integrated into the window frame. Finned heat sinks are placed in contact with the TE units to control the heat transfer between the TE units and the ambient environments. Since the direction of the heat flow can be switched by changing the direction of electrical current, the system can work in both heating and cooling modes.

Fig.5. Schematic of the active thermal insulator window [27].

Interactions among subsystems are showed in Fig.6. It can be seen that the PV module not only generates electrical power but also reduces the solar heat gain through the window. The TE units can restrain the heat transfer in the natural direction and therefore reduce the total heat gains or losses through the window. The analysis results show that ATI window can reduce the heat gains by about 67% when the system is powered by incident solar radiation. Moreover, the reduced load on traditional HVAC systems can reduce the economic and environmental cost as well as building energy consumption [27].

Fig.6. Subsystem interactions of the active thermal insulator window [27].

4. Application of solar thermoelectric technologies in energy recovery system

Energy recovery technologies can improve the energy efficiency, which have been widely applied in different energy system. General energy recovery technologies mainly include heat pipe heat exchanger [28], liquid desiccant technology [29], absorption refrigeration [30] and thermoelectric cooling technology [31]. Thermoelectric cooling systems have no mechanical moving parts and do not employ working fluids that are harmful to the environment, which can transfer heat from the cold side of the modules to the hot side with consumption of electricity. And if applying the thermoelectric cooling technologies in building energy recovery system, the temperature difference between the hot side and the cold side of thermoelectric modules would be smaller than the traditional thermoelectric cooling system, thus the energy recovery system can obtain a better performance [32]. In this section, thermoelectric ventilator, solar thermoelectric air conditioner with hot water supply, combined thermoelectric heat pump and heat pipe water heater, and thermoelectric heat pump water heater with exhaust heat recovery will be illustrated respectively.

4.1. Thermoelectric ventilator

Different from market available ventilators with passive heat recovery, thermoelectric ventilator is integrated with a flat fin cross flow sensible heat exchanger and a thermoelectric modules heat exchanger to enhance heat recovery. As shown in Fig.7, the thermoelectric ventilator is composed of two centrifugal fans, an aluminum-made flat-fin cross flow sensible heat exchanger, air duct, a thermoelectric modules heat exchanger made by thermoelectric modules and flat-fin sinks. The cross flow sensible heat exchanger and a thermoelectric modules heat exchanger is made in cubical shape separately. Inlet and outlet air tunnel are connected with air ducts in order to collect condensed water from air and reduce the ventilator’s pressure loss. Air volume of this ventilator ranged from 60 to 70m^3/h. Two centrifugal fans with high pressure were chosen, with standard gauge values: 120 m^3/h, 140Pa, 58W, 0.16a, 2000rpm, and 50db. There were 10 thermoelectric modules with type of 12706[33, 34].

The performances of the domestic thermoelectric ventilator under different operating voltage were investigated in cooling mode and heating mode. The maximum COP was gained with the input voltage of 8V, however, the maximum heating power occurred in 12V.The fresh air temperature and exhaust temperature were also recorded in order to evaluate the performance of the ventilator. The performance of the ventilator was over 2.5 both in cooling mode and heating mode. Moreover, it was proved that the performance could be further improved by optimizing the operating voltage and improving thermal resistances.

Fig.7. Thermoelectric ventilator [33, 34].

In order to improve the performance of the ventilator, a heat pipe exchanger was used in the thermoelectric ventilator [35]. Fig.8 illustrates the system design for a heat pipe thermoelectric ventilator. The ventilator is divided into three parts: the fresh air part, the thermoelectric cooling modes part and the exhaust air part. In summer, the outdoor fresh air is cooled down when it flows through heat pipe exchangers into the indoor environment. At the same time, the exhaust air cools down the heat pipe exchangers on the other side of the thermoelectric cooling modules. In winter, the heating side and cooling side reverse and the system is converted to the heating mode by changing the current direction input to the thermoelectric modules. The outdoor fresh air is heated up when it is pumped into the indoor environment, while the exhaust air is cooled down when it flows through heat pipe exchangers to the outdoor environment. In this way thermal energy of the exhaust air is recovered.

An integrated mathematical model was developed to optimize the performance of the thermoelectric ventilator. Results showed that the cooling rate first increased to the highest point and then decreased when the working current increased, whereas the coefficient of the performance decreased all the time. The maximum COP was 4.78 in summer mode and 4.16 in winter mode. The performance of this heat pipe exchanger was proved to be much better than that of conventional heat exchangers. In addition, the thermoelectric ventilator worked more efficiently with lower fresh air temperature in summer mode and higher fresh air temperature in winter mode.

Fig.8. Heat pipe thermoelectric ventilator [35].

4.2. Solar thermoelectric air conditioner with hot water supply

Condensing heat recovery in vapor compression air conditioning systems has been applied in many engineering projects [36-37]. Similar to vapor compression air conditioning systems, a large amount of heat needs to dissipate when thermoelectric air conditioner works under cooling mode. Fig.9 illustrates a solar thermoelectric air conditioner with heat recovery available for both space cooling and hot water supply. The solar thermoelectric air conditioner with hot water supply (STACHWS) is divided into three parts: (1) the air part, (2) the TEC modules part, and (3) the water part. The TE modules are sandwiched between the hot and cold side of heat exchangers. When an electrical current passes through the junction of dissimilar conductors, heat is either absorbed or released at the junction. Reversing the direction of the current changes the direction of the heat flow. The PV system can provide a constant DC power supply during daytime, while batteries can provide power to the STEACWH system at night. According to the applications, the STEACWH system can be classified in the following operating modes: (1) Space cooling and water heating mode, (2) Space cooling mode, (3) Space heating mode [38].

Fig.9.The working principle of the solar thermoelectric air conditioner with hot water supply [38].

When the system works under space cooling and water heating mode, the water tank is filled with water. The return air is cooled down when it flows through heat exchangers into the indoor environment when DC current is applied to the STEACWH system. At the same time, the water is heated up in the water tank by the heat exchanger on the other side of the TEC modules. In this way, thermal energy of the hot sides of TEC modules is recovered.

The performances of the STACHWS system were investigated under different working mode. Experiment results indicated that the coefficient of performance (COP_{int}) decreased as the water temperature increased. The system had relatively high coefficient of performance (COP_{int}) which could reach up to 4.51 when the water temperature was 20^{o}Cand 2.74 when water temperature was 42^{o}C. A simulation model was set up to optimize the performance of the thermoelectric air conditioner with hot water supply. Results showed that there was an optimum current (I_{op}) that make COP_{int} reach the maximum value. I_{op} was relevant to the water temperature. Higher water temperature led to a higher I_{op} but a lower COP_{int}. When the STACHWS system worked in space cooling and water heating mode, it could be observed that, there was an optimum COP_{int} when electric current was about 0.8 to 1.4A[38].

4.3. Integrating thermoelectric heat pump with heat pipe water heater

An instantaneous water heater has been developed by means of integrating a thermoelectric heat pump with a separating thermosiphon, as shown in Fig.10. Thermoelectric modules are sandwiched between heat exchangers on hot side and the condensing heat exchanger of the thermosiphon on cold side. The separating thermosiphon is composed of an evaporator, a vapor pipe, a condenser and a condensed liquid pipe. The evaporating is embedded in the floor to recover heat from waste hot water [39, 40].

When the system works, the working fluid acetone first absorbs heat from waste water through evaporating heat exchanger, and then rises and passes through the vapor pipe into the condenser, where heat flows into the cold side of the thermoelectric modules. Simultaneously, the supply water on the cold side of thermoelectric modules is heated with power consumed by the TE modules.

Fig.10. Schematic diagram of integrating heat pipe and thermoelectric water heater [39].

The performances of the thermoelectric heat pump were researched under different flow rates of hot water in Changsha. Results showed that increasing flow rate could intensify the heat exchanges, and therefore improve the performance of the water heater. Increasing mean temperature difference of heat mediums resulted in linearly decreasing performance of the water heater, and the decreasing trend was more remarkable in the case of less power input than in the larger power input.

The energy efficiency ratio (EER) of this water heater reached 1.45 or more, even if the water temperature reached 40^{o}C with different flow rates. Compared with the electric water heater with EER of 0.9, the novel water heater can reduce more than 38% of power consumption. In addition, the performance can be further improved by optimizing system design and fabrication on the basis of experiment data.

4.4. Thermoelectric water heater with kitchen exhausts heat recovery

A large amount of exhaust heat in public kitchen needs to dissipate, which causes energy waste as well as thermal pollution. At the same time, the electrical or gas-fired boiler must operate all-day long in order to assure constant kitchen hot water supply. Fig.11 shows a thermoelectric heat pump water heater with kitchen exhausts heat recovery [41]. The working principle of the thermoelectric heat pump water heater is as follows: The exhaust air is pumped into the flue by ventilator, firstly filtrated by oil filter, then cooled by the water required of heating through the thermoelectric heat pump and finally discharged to outdoor. The water is heated by kitchen exhausts through the thermoelectric heat pump in the water tank and then transported into the storage tank. The temperature of water is controlled by the inlet and exit valves. Under an operating voltage of 16V and an exhaust temperature of 36^{o}C, the coefficient of performance decreases from 1.66 to 1.22 when the temperature of water increases from 28 ^{o}C to 46 ^{o}C. In comparison with the conventional electric water heater, thermoelectric heat pump water heater with kitchen exhausts heat recovery is more efficient. Besides, its performance can be further improved by optimizing the design and fabrication on the basis of experiment data. It also has other advantages, such as facility, reliability, no pollution, and so on [41].

Fig.11.Schematic diagram of a thermoelectric water heater with kitchen exhaust heat recovery [41].

5. Solar thermoelectric air conditioners

The air conditioners and refrigerators have become common household appliances around the world. More and more people will need air conditioners as the quality of life that people demand improves. However, the refrigerant of traditional air conditioner, Freon, once leaked, will do irreversibly damage to the ozone sphere and thus cause stronger ultraviolet radiation. Moreover, electric-driven air-conditioning system consumes too much energy. To meet their demands, fossil fuels are burned to generate electricity, which causes greenhouse effect and continuously worsen global warming, and in turn the demand of air-conditioning would further increases. These facts are encouraging manufacturers to seek alternatives to conventional refrigeration technology. One of the alternative refrigeration systems is thermoelectric cooling technology [42, 43].

5.1. Solar thermoelectric radiant air conditioning system

A solar thermoelectric cooled ceiling combined with displacement ventilation system has been developed for space climate control, as presented in Fig.12 [44]. The solar thermoelectric cooled ceiling (STCC) adopts thermoelectric cooler instead of hydronic panels as radiant panels. The solar thermoelectric cooled ceiling (STCC) is burdened with removal of a large fraction of sensible cooling load. The TE modules are connected in series and sandwiched between the aluminum radiant panel and heat pipe sinks in STCC. The heat sinks are used for dissipating heat of TE modules. The fan can provide forced air convection to help the TE modules to release heat more efficiently into the atmosphere. By controlling the direction of the current, the functions of cooling and heating can be both achieved.

The combined system dehumidifies the supply fresh air using a thermoelectric dehumidified ventilation system, as shown in Fig.8 [35]. The thermoelectric dehumidified ventilation system is responsible for removal of a small fraction of sensible cooling load and all latent cooling loads. A 1.8m×0.6m aluminum cooling panel with ten TE modules was tested in an experiment room, and the TE modules were uniformly distributed in the aluminum panel. The size of the TE module is 39×39×3.8mm, with 127 thermoelectric couples of bismuth telluride and ceramic surface, type of 9500/127/060B.

Fig.12.Schematic diagram solar thermoelectric cooled ceiling combined with displacement ventilation system [44].

The performance of the thermoelectric cooled ceiling was investigated under cooling mode and heating mode. Results indicated that increasing the operating voltage increased the total heat flux. The decreasing the temperature difference between ambient temperature and indoor temperature significantly increased the total heat flux and slightly increased the system COP in both cooling and heating mode. The total heat flux of the STCC system in cooling mode was higher than 60W/m^2 and the system COP could reach 0.9 under operating voltage of 5V. In the heating mode, the total heat flux of the STCC system under operating voltage of 4V was over 110W/m^2 and the COP of the system could reach 1.9[44].

5.2. Solar thermoelectric energy storage air conditioner

Thermoelectric air conditioner with heat storage system has been developed as shown in Fig.13. The thermoelectric cooling system primarily consists of a thermoelectric cooling unit, a shell-and-tube PCM heat storage unit, an air-water heat exchanger and a piping system. Heat absorbed from the indoor environment through the thermoelectric cooling unit can be released through the air-water heat exchanger with water as the heat transfer fluid (HTF). The system can realize two operating modes, which are dissipating generated heat to outdoor air through the air-water heat exchanger (mode 1) and releasing heat to the shell-and-tube PCM heat storage unit (mode 2). The two modes can be easily switched over through manually controlling valves [45].

The work principle is as follows: if outdoor air temperature is relatively low, such as in the early morning or late afternoon, the working mode 1 will be in operation and heat generated by space cooling will be dissipated to the outdoor environment. When outdoor air temperature is high, the PCM heat storage unit will be activated and the system will convert to mode 2. At night, the PCM heat storage unit will be discharged by using relatively cool outdoor air. Therefore, PCM with appropriate melting temperature suitable for local weather conditions would be preferred for its advantage of using “free cooling” at night to “regenerate” the PCM.

Fig.13. Schematic diagram of the prototype thermoelectric cooling system [45].

The schematic diagram and photograph of the thermoelectric cooling unit are shown in Fig. 14. It is depicted that the thermoelectric module is sandwiched between the conductive fin and the water tank. Two axial fans are installed at the fin side to enhance convective heat transfer. A finned coil is employed in the water tank to achieve better heat exchanges. The thermoelectric module used in this study was RC12-8. PCM was RT22, which had a melting temperature of 19-23 ^{o}C (with main peak at 22 ^{o}C and heat storage capacity of 200 kJ/kg).

Fig. 14. Schematic diagram and photograph of the thermoelectric cooling unit [45].

The experiment results showed that the average COP of the thermoelectric air conditioners was 0.8, and the maximum COP value was 1.22. The maximum cooling capacity achieved 210W at present. Comparison experimental study showed that 35.3% electrical energy could been saved in the prototype thermoelectric cooling system by using PCM heat storage on the condition that outdoor air temperature was in the range of 30 ^{o}C to 33 ^{o}C and temperature of the conditioned space was set at 24 ^{o}C.

6. Summary

In order to build cost-effective ZEBs, the energy demand should be a minimized, which can be provided only by renewable energy. Therefore, measures that can minimize the building energy demand should be fully considered when design buildings. Fig.15 shows the technical route of solar thermoelectric cooling technologies for use in Zero Energy Buildings. Active solar thermoelectric building envelopes and thermoelectric low-grade energy recoveries are used to restrain the heat losses or gains of buildings and improve energy efficiency and therefore to reduce the building energy demand to a minimum, the small amount of energy need then could be satisfied just by solar thermoelectric air conditioner. In this way only renewable energy is consumed in buildings, which fully meets the demand of ZEBs.

Due to the advantage of inherently reliable, low maintenance, silent, clean, and distributed nature, the solar thermoelectric cooling technologies can be easily integrated with buildings. Besides, the distributed nature of the thermoelectric (TE) heat pumps minimizes overall energy consumption by providing local temperature control and eliminating the energy costs associated with air circulation fans and duct losses. Therefore, applications of active building envelope, energy recovery and solar thermoelectric air conditioner in zero energy buildings are promising.

Fig.15. Technical route of solar thermoelectric cooling technologies for use in Zero Energy Buildings.

Even though the performances of solar thermoelectric cooling technologies and relevant applications cannot compete with vapor compression technologies at present, the performance of solar thermoelectric cooling system can be enhanced by improving and optimizing the heat exchanger structure and the operating parameters, because those aspects significantly affect the efficiency of the whole system. Moreover, the performance of solar thermoelectric cooling system can be improved by selecting TE and PV system with higher performances. As the efficiency of commercial available PV is about 15%-20%, and the products still have a large space to improve compared with the maximum PV efficiency of 39% [46]. Meanwhile, the TE performance is closely related to the figure of merit of thermoelectric materials, ZT, the TE modules used in the present researches have a ZT of about 0.6 to 0.7, which is not high considering the progress of TE technology. It is achievable since the latest quantum well materials have a ZT as high as 2.4 at 300 K [47], and when TE materials have a ZT = 2, the COP of TE coolers can reach to the COP of vapor-compression coolers in climate-control applications [48].

In current studies, the solar thermoelectric cooling technologies were established by bulk components, such as commercially available TE and PV systems. Thermoelectric and PV industry develope rapidly along with the advent of new materials. Recent advances in thin-film TE and PV systems, and emerging researches in the area of organic TE and PV materials, offer opportunities to yield extremely thin, efficient, and low-cost thermoelectric systems. For example, when PV and TE modules are collapsed to very thin sections, the solar thermoelectric technologies might be applied in transparent building materials, such as glass.

7. Conclusions

In order to minimize the energy demands in buildings, increase energy effectiveness and reduce fossil energy consumption, the solar thermoelectric cooling technologies such as active building envelope, thermoelectric energy recovery systems and solar thermoelectric air conditioners are recommended to be used in zero energy buildings.

Active building envelope is a new thermal control technology which integrates TE modules and PV units within building envelope. It can actively control heat flux in wall and compensate for passive heat losses or gains in building envelope by using solar energy. However, it has not been actually used in buildings so far, only theoretical researches and experiment tests of a single system were made, more work should be done for its application in buildings.

Thermoelectric waste heat recovery devices have a high efficiency, such as the coefficient performance of thermoelectric ventilator can reach 4.78 in summer mode and 4.16 in winter mode, which can compete with vapor compression based applications.

The coefficient performance of the solar thermoelectric radiant air conditioning system and solar thermoelectric energy storage air conditioning system can reach 1.9 and 1.22 respectively, which are both more efficient than conventional thermoelectric cooling system with an average coefficient performance of 0.3-0.4. However, the coefficient performance is still relatively low. More efforts should be made to improve the coefficient performance of solar thermoelectric air conditioner systems in order to compete with vapor compression technologies.

The performance of solar thermoelectric cooling system can be improved by selecting TE and PV system with higher performances. The figure-of-merit ZT value of thermoelectric module is only about 0.7 at present. If the ZT factor of the thermoelectric material could be further improved and increased to, for example, 2.0 in the next decade, the COP value and energy saving of this thermoelectric cooling system would be further increased. In the near future, solar thermoelectric cooling system will make a significant contribution, especially in zero energy buildings, in reducing fossil fuel consumption and carbon emissions.

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Abbreviates of parameters:

TE –thermoelectric

ABE window– active building envelope window

COP – coefficient of performance (-)

COPint –the integrated coefficient of performance is defined to estimate the energy utilization of the integrated system

ZT – the figure of merit of thermoelectric materials

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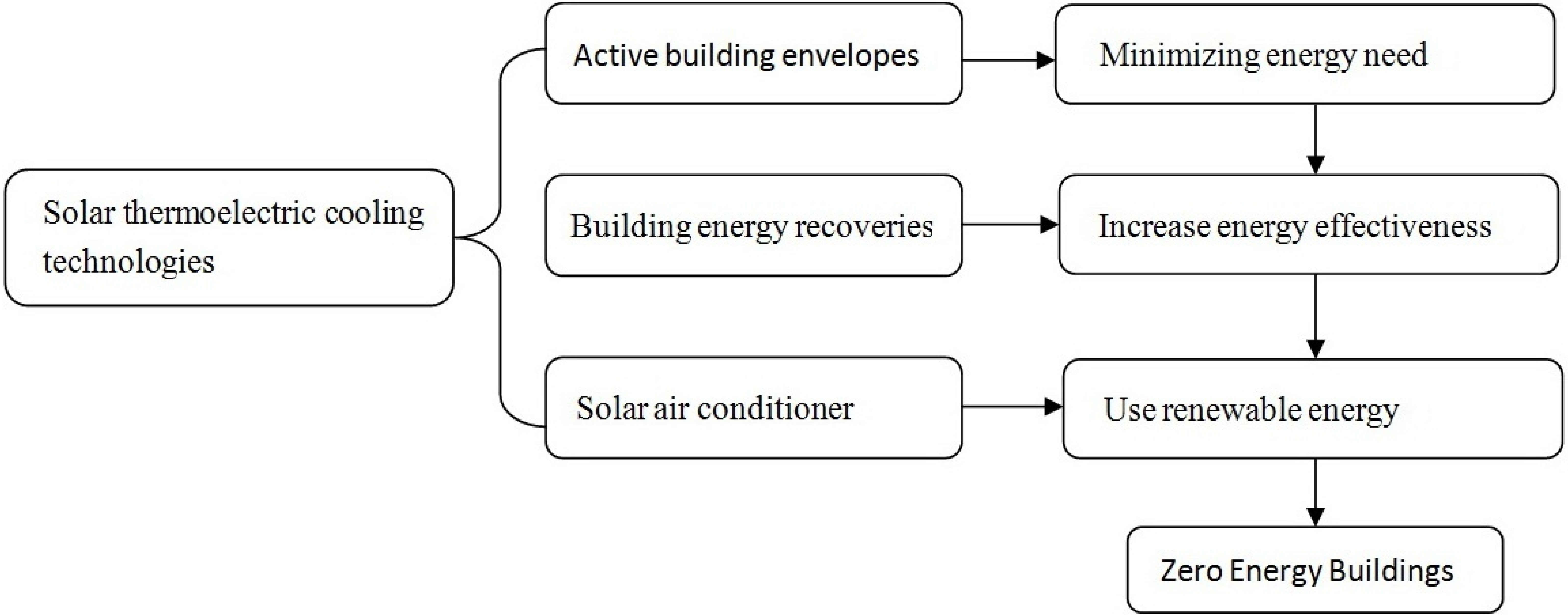
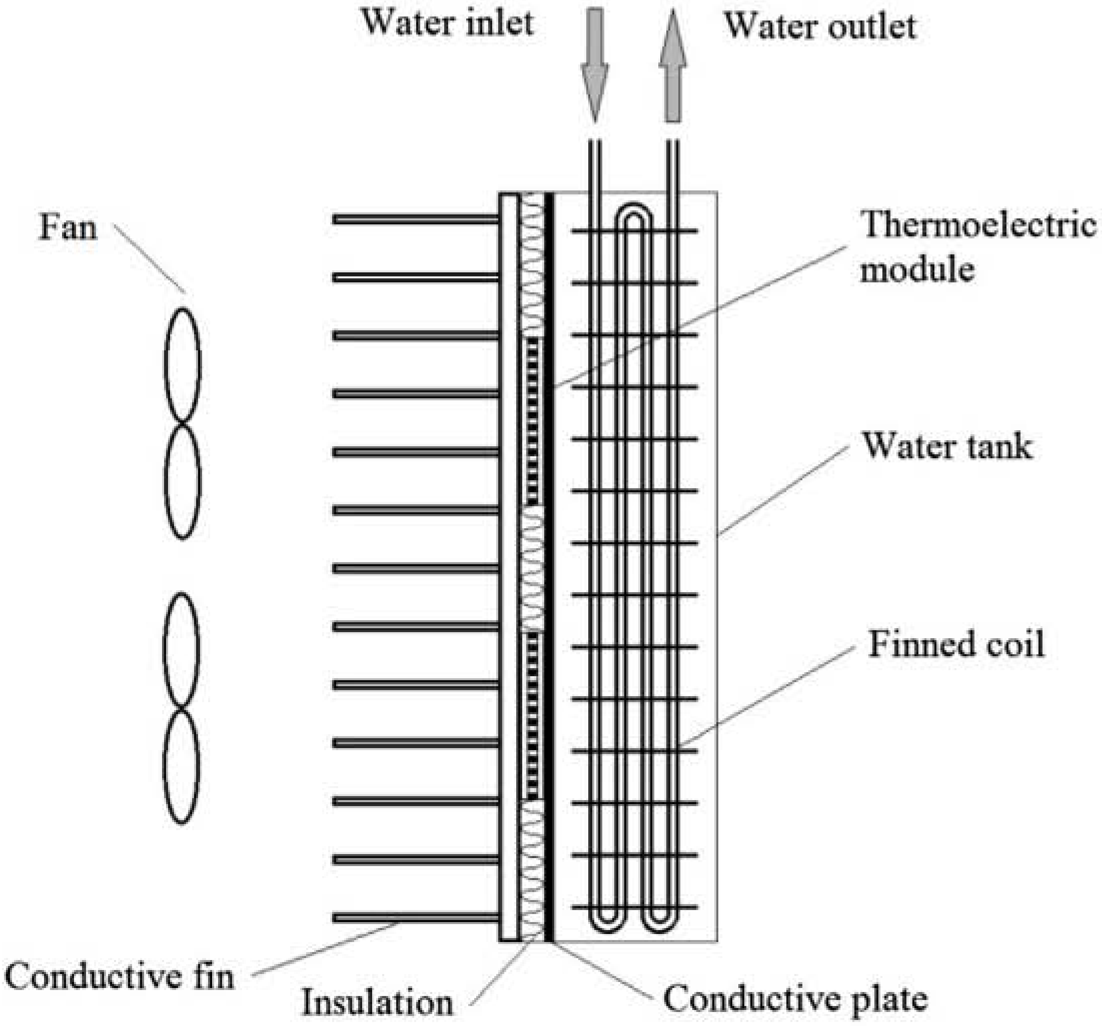
Figures captions

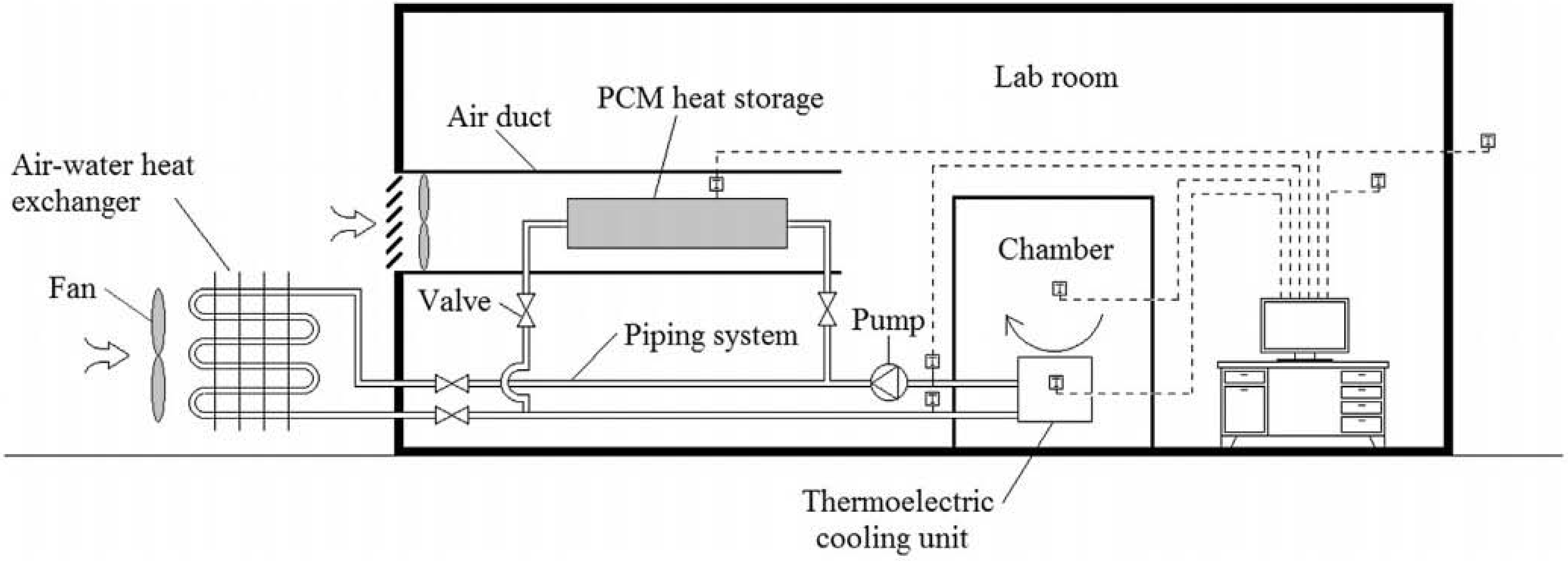
Fig.14. Schematic diagram and photograph of the thermoelectric cooling unit

Fig.15. Technical route of solar thermoelectric cooling technologies for use in Zero Energy Buildings

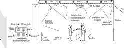

Solar thermoelectric cooling technologies
Active building envelopes
Building energy recoveries
Solar air conditioner
Minimizing energy need
Increase energy effectiveness
Use renewable energy
Zero Energy Buildings

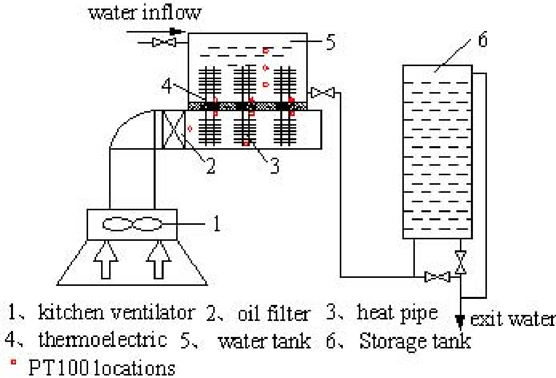


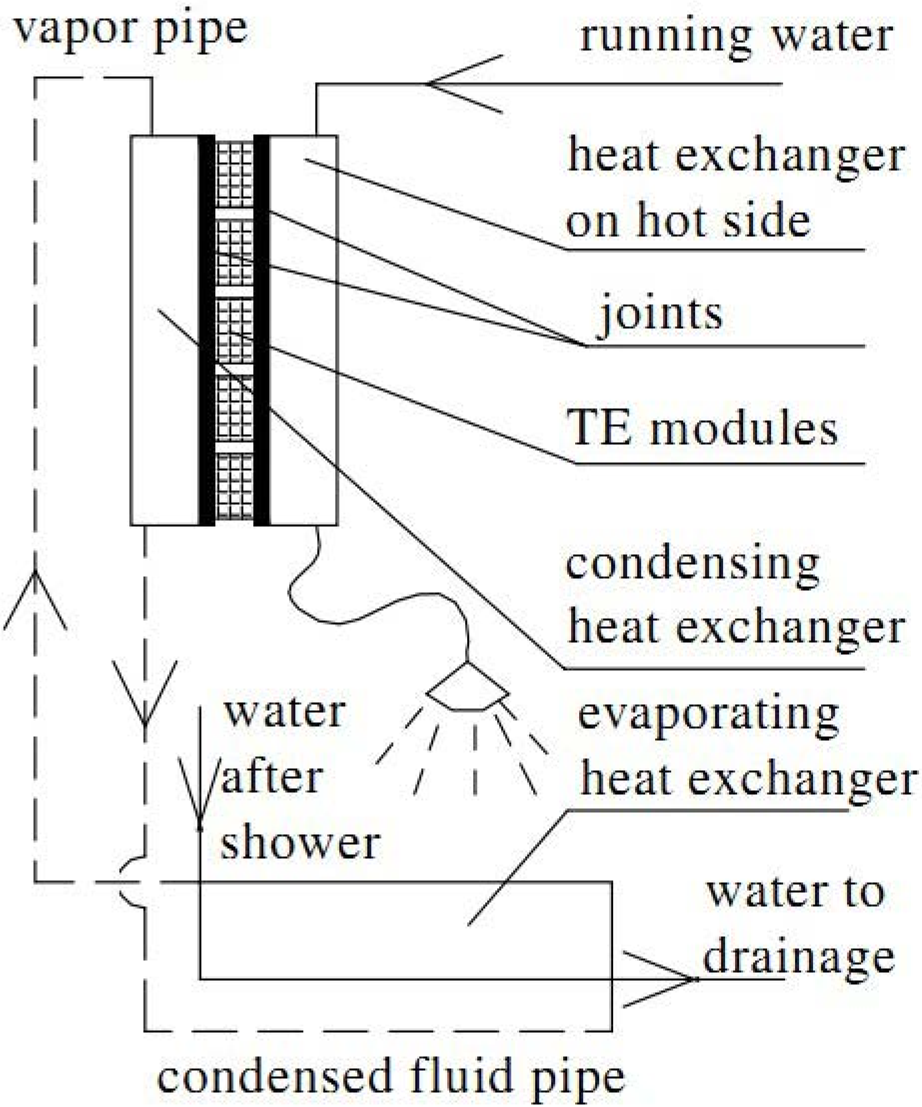
Water inlet
Water outlet
Fan
Thermoelectric module
Water tank
Finned coil
Conductive fin
Insulation
Conductive plate

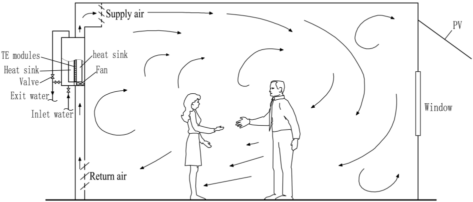

Lab room
PCM heat storage
Air duct
Air-water heat
exchanger
Chamber
Fan
Valve
Piping system
Pump
Thermoelectric
cooling unit

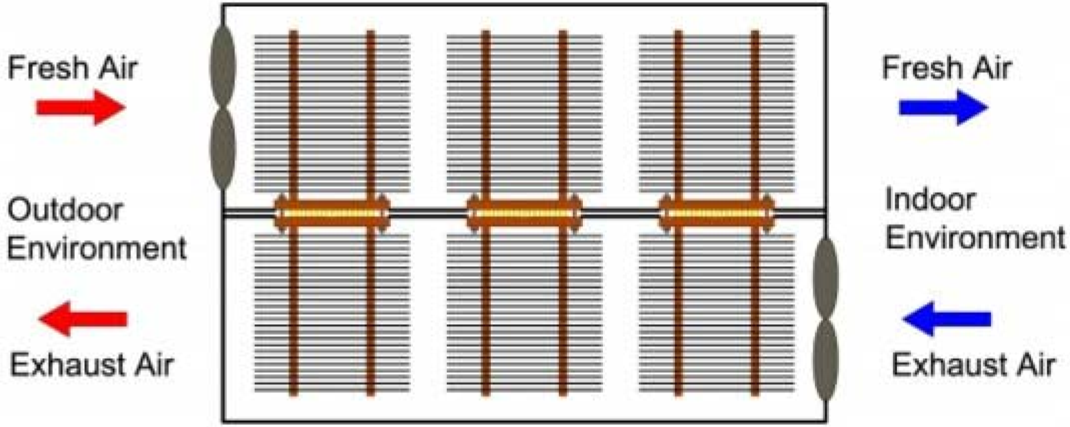
age


Fan
Exhaust
STCC
Heat sink
TE modules
PV
Radiation from walls
Radiation from occupants and other heat sources
Convection from occupants
Radiation from window
Window
Heat sink
TE modules
Exhaust
Fresh air
Fresh air
Thermoelectric dehumidified ventilator
Fresh air
Fresh air

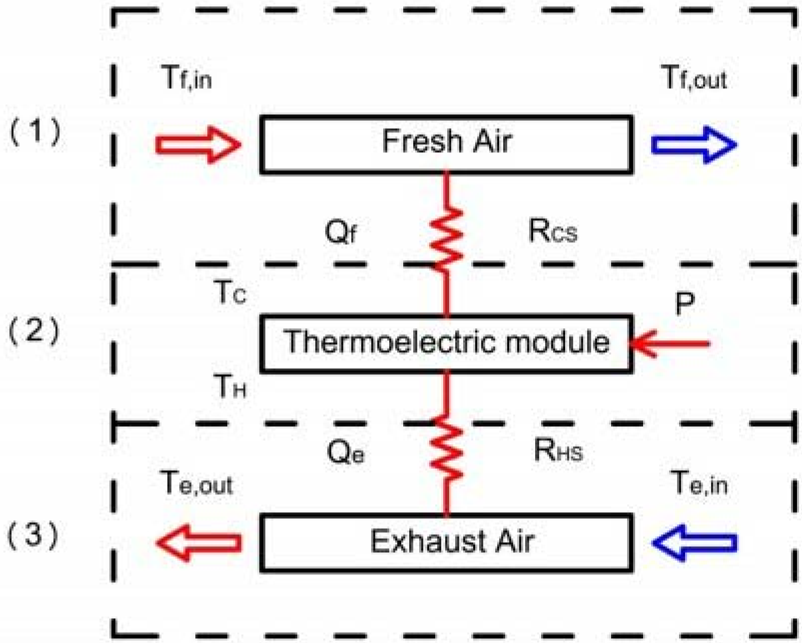

water inflow
5
6
4
2
3
1
exit water
1、kitchen ventilator 2、oil filter 3、heat pipe
4、thermoelectric 5、 water tank 6、Storage tank
PT100 locations


vapor pipe
running water
heat exchanger
on hot side
joints
TE modules
condensing
heat exchanger
evaporating
heat exchanger
water
after
shower
water to
drainage
condensed fluid pipe

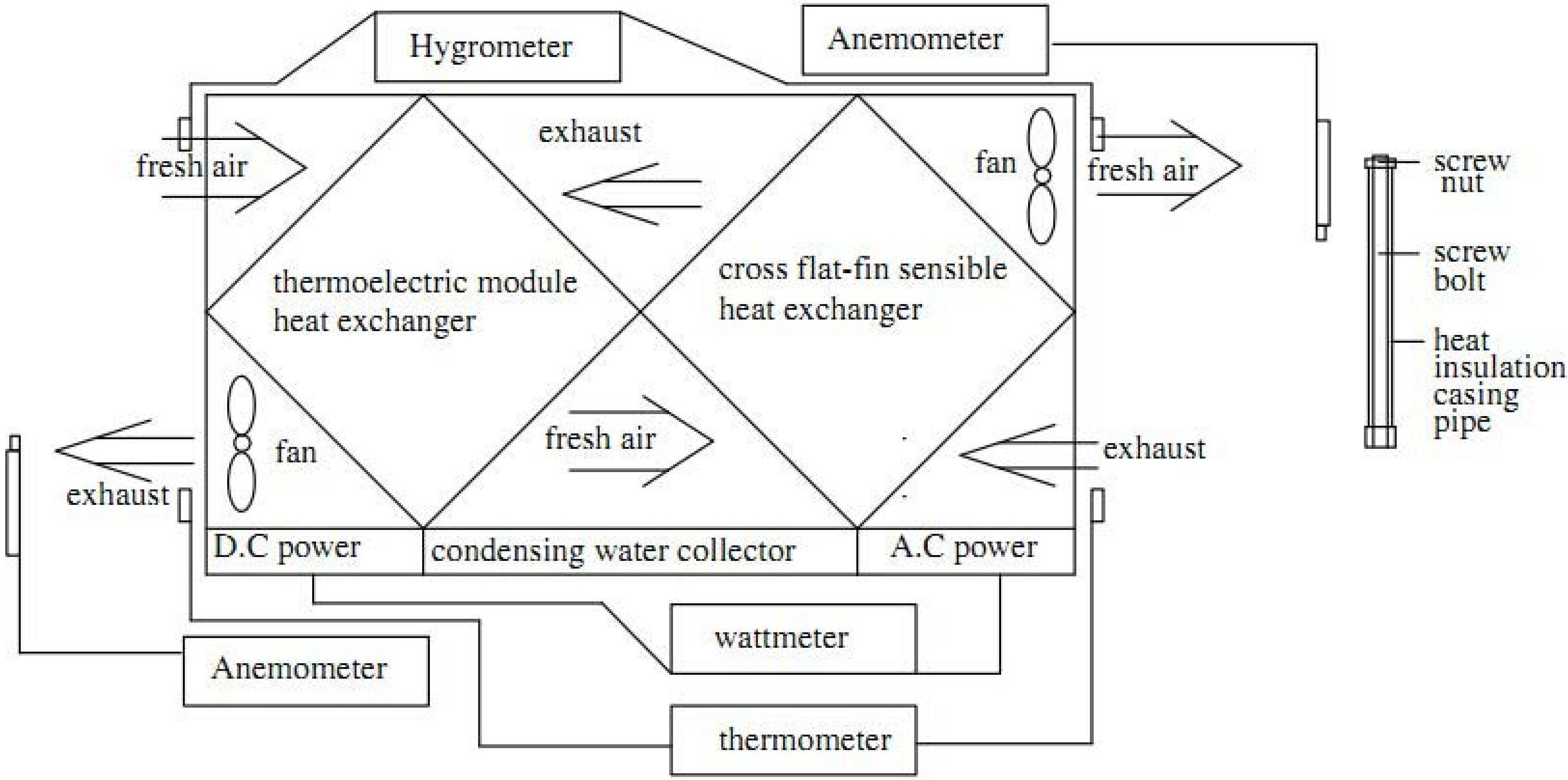

Supply air
PV
TE modules
heat sink
Heat sink
Fan
Valve
Exit water
Inlet water
Window
Return air



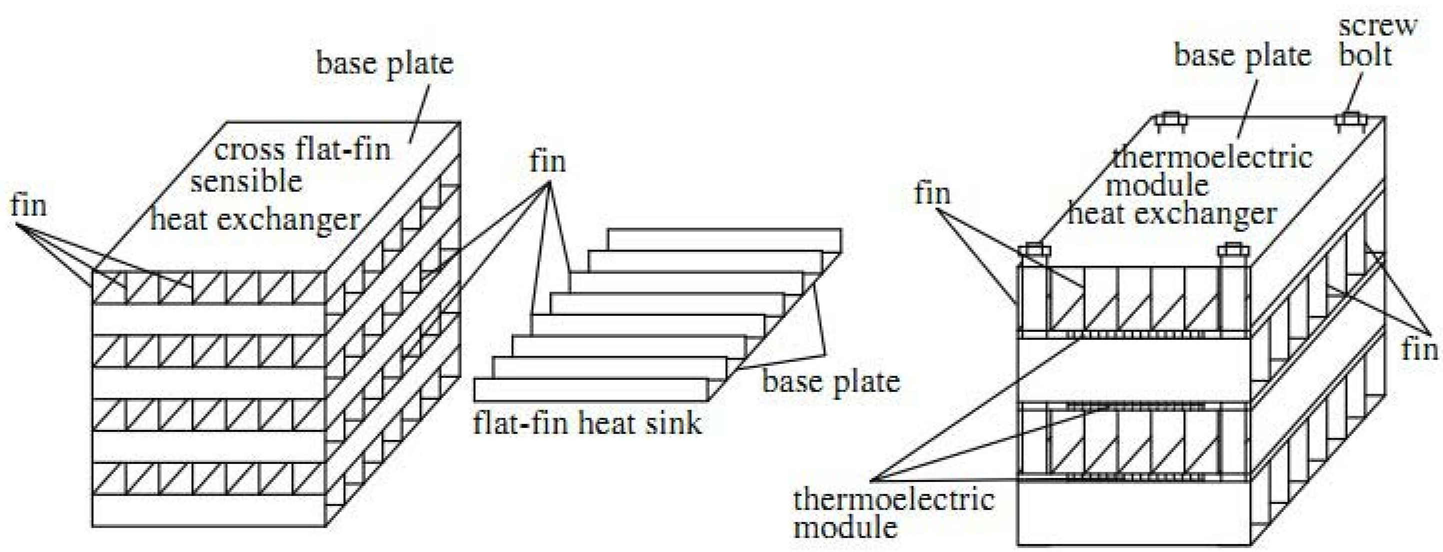
(a) Schematic diagram



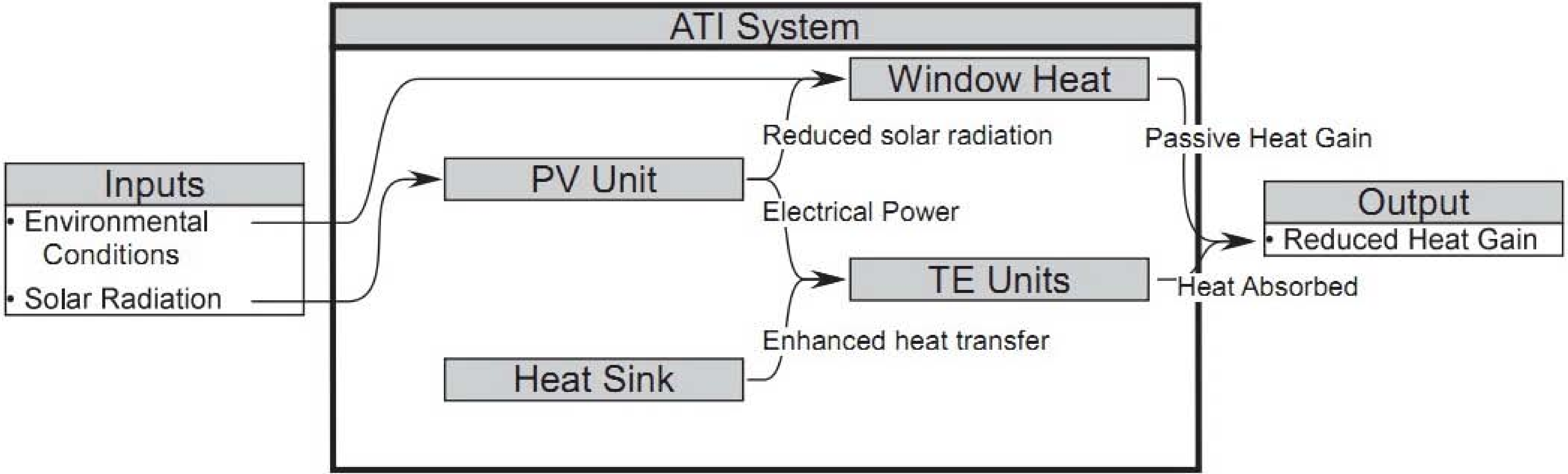
(b) Simplified model

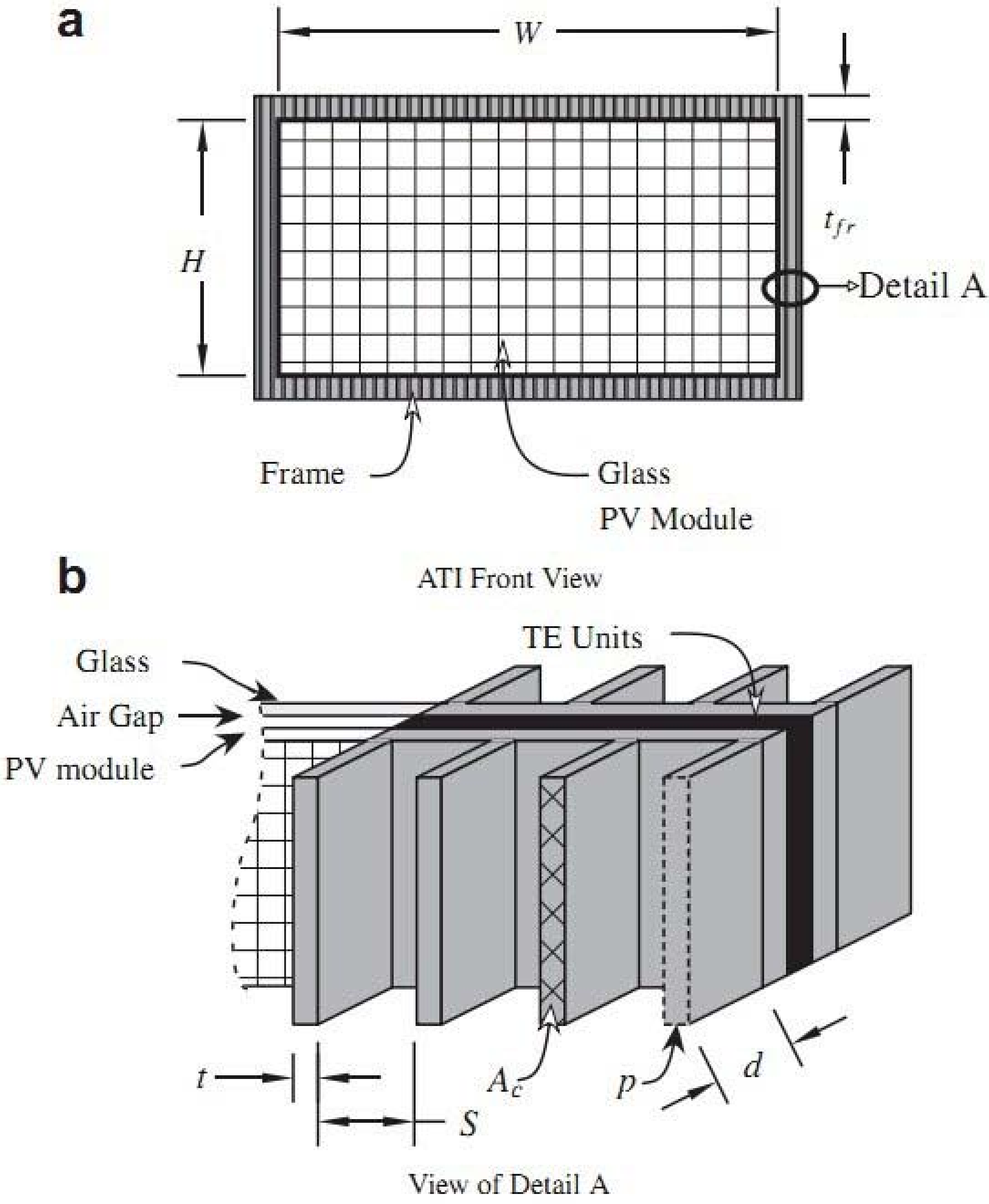


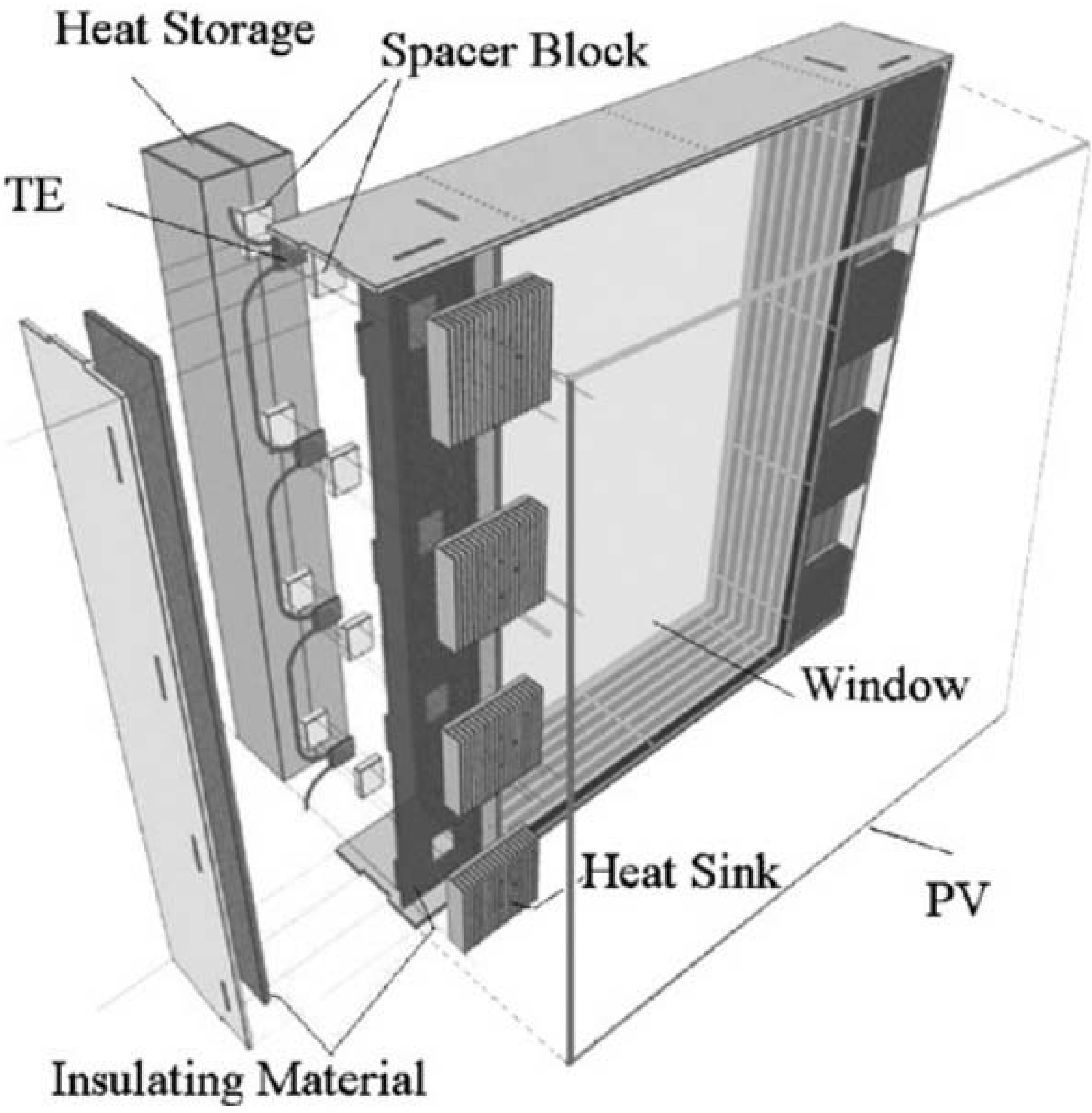
Hygrometer
Anemometer
exhaust
fresh air
fan
fresh air
screw
nut
screw
bolt
heat
insulation
casing
pipe
thermoelectric module
heat exchanger
cross flat-fin sensible
heat exchanger
fan
fresh air
exhaust
exhaust
D.C power
condensing water collector
A.C power
wattmeter
Anemometer
thermometer

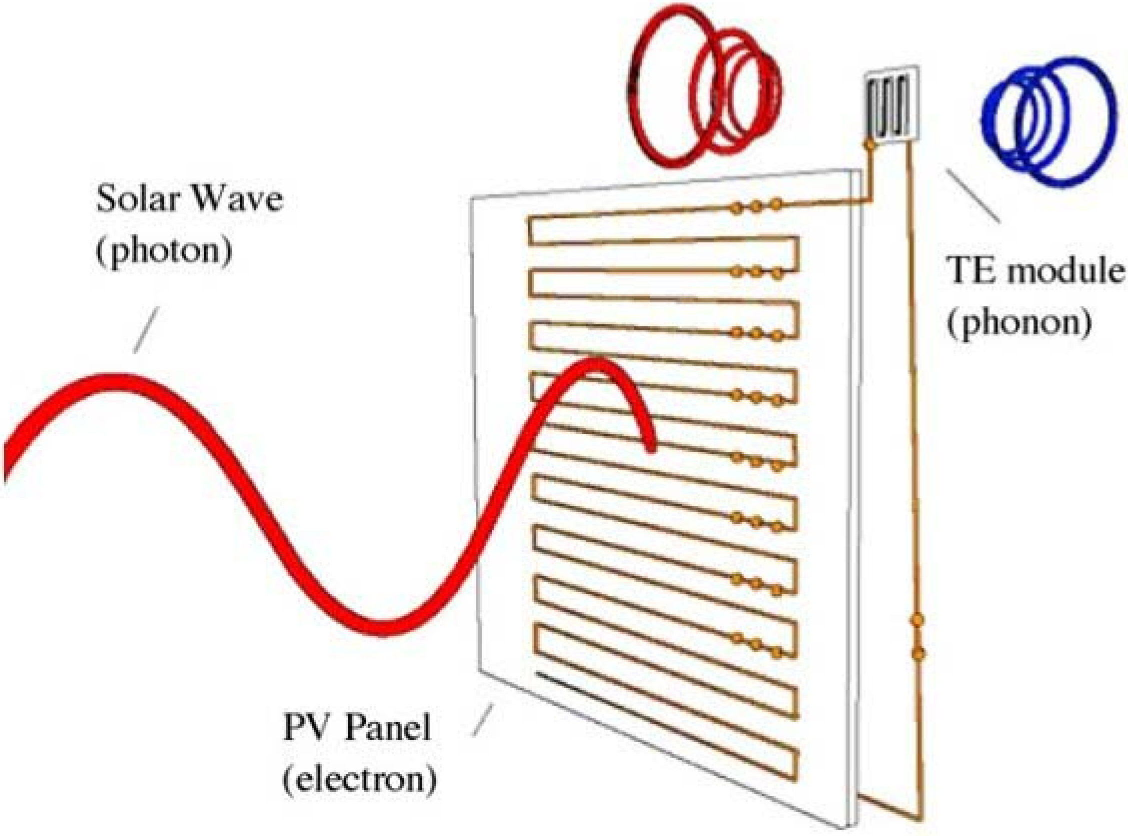


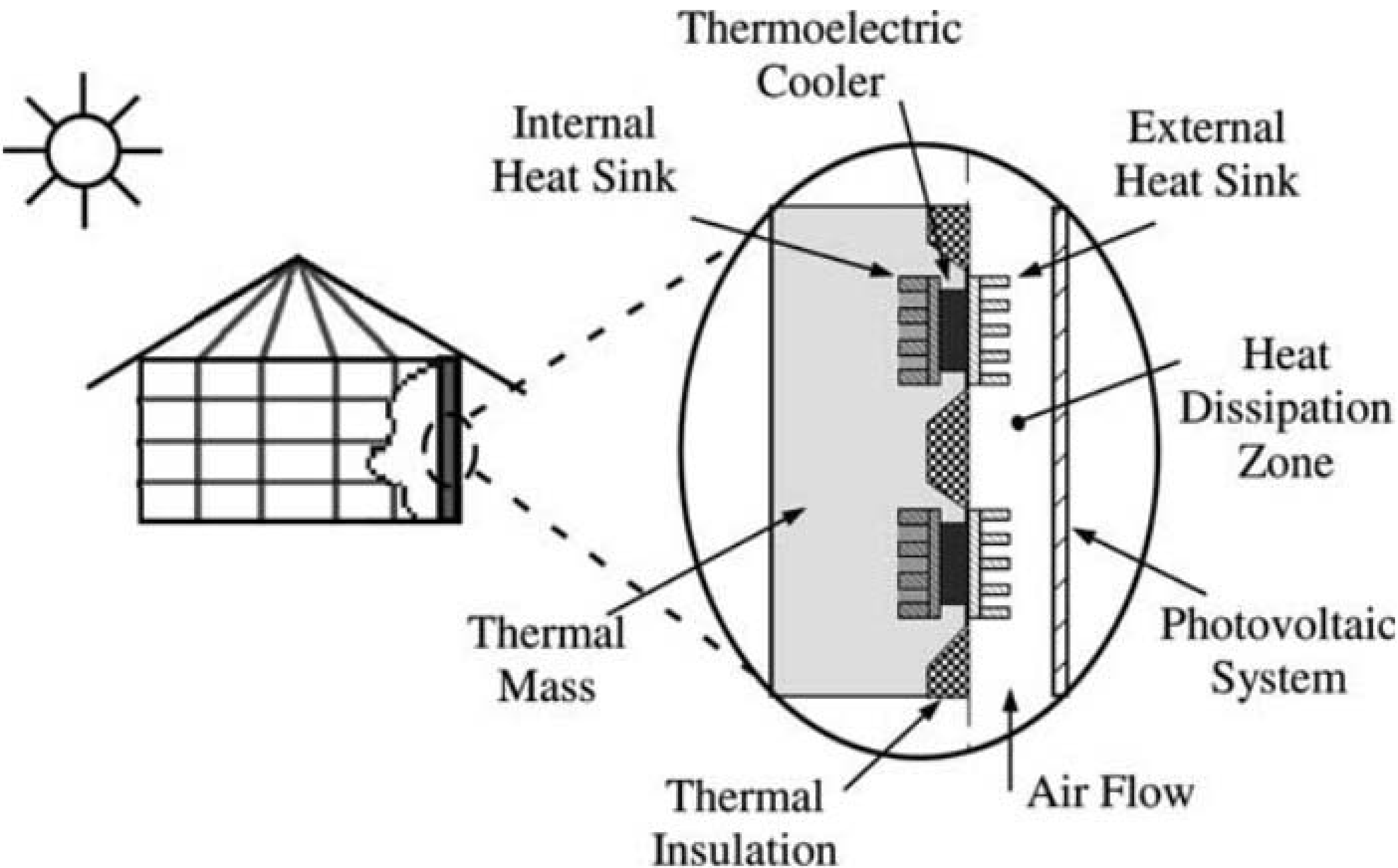
base plate
cross flat-fin
sensible
heat exchanger
fin
fin
base plate
flat-fin heat sink
base plate
screw
bolt
thermoelectric
module
heat exchanger
fin
fin
thermoelectric
module

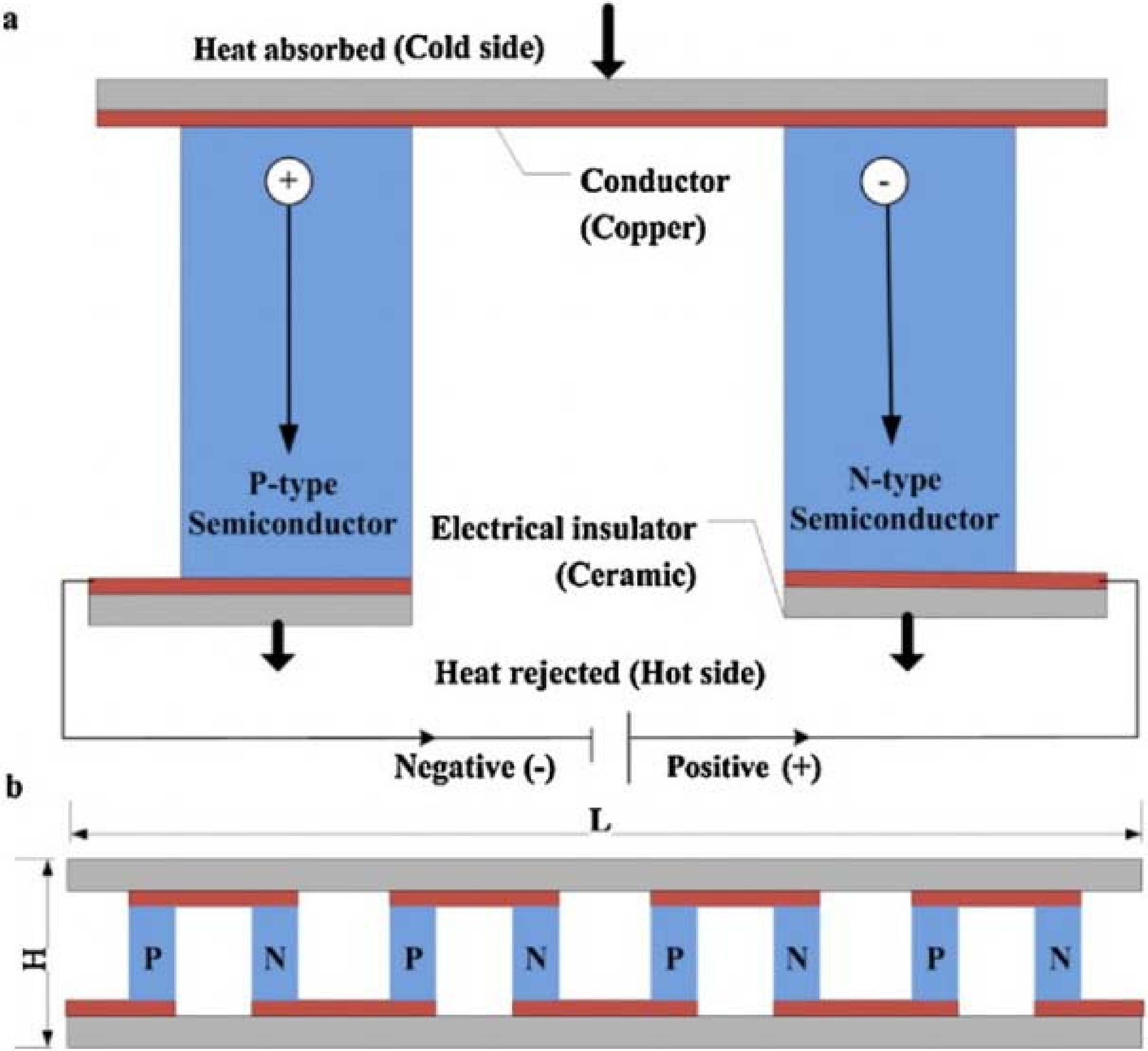

ATI System
Window Heat
Reduced solar radiation
Passive Heat Gain
Inputs
• Environmental Conditions
• Solar Radiation
PV Unit
Electrical Power
Output
• Reduced Heat Gain
TE Units
Heat Absorbed
Enhanced heat transfer
Heat Sink


a
W
H
t_{fr}
Detail A
Frame
Glass
PV Module
b
ATI Front View
TE Units
Glass
Air Gap
PV module
t
A_c
p
d
S
View of Detail A


Heat Storage
Spacer Block
TE
Window
Heat Sink
PV
Insulating Material


Solar Wave
(photon)
TE module
(phonon)
PV Panel
(electron)


Thermoelectric
Cooler
Internal
Heat Sink
External
Heat Sink
Heat
Dissipation
Zone
Thermal
Mass
Photovoltaic
System
Thermal
Insulation
Air Flow


a
Heat absorbed (Cold side)
Conductor
(Copper)
+
-
P-type
Semiconductor
N-type
Semiconductor
Electrical insulator
(Ceramic)
Heat rejected (Hot side)
Negative (-)
Positive (+)
b
L
H
P
N
P
N
P
N
P
N