

REVIEW

Building Integrated Thermoelectric Air Conditioners—A Potentially Fully Environmentally Friendly Solution in Building Services

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The refrigerants used in conventional vapor-compression air conditioning systems have detrimental effects on the global environment. Phasing-down hydrofluorocarbon (HFC) refrigerants for HVAC equipment over the next 20 years has been proposed. A thermoelectric air conditioning system that directly converts electrical energy to thermal energy using a simple solid-state semiconductor device, has the advantages of environmentally friendly, no refrigerant, very compact, high reliability, no moving parts (except for small fans), and it can be easily integrated into the building structure. However, the existing thermoelectric air conditioning systems have the problem of low Coefficient of Performance (COP), which limits its applications for domestic air conditioning. With the development of the thermoelectric technologies, the above problem is prospected to be solved. The paper presents an overview of recent advances in thermoelectric materials, thermoelectric module design and thermoelectric heating and cooling system design which would provide the potential to greatly improve the COP of the thermoelectric air conditioner. In addition, utilizing the waste heat of the thermoelectric system for domestic applications to improve the overall COP of the system would be an ideal way to promote public adoption of the TE air conditioner, which is discussed in this paper. The paper also presents an overview of the existing building integrated thermoelectric air conditioning systems and proposes a novel building integrated thermoelectric system that integrates a thermoelectric heat pump unit into a double-skin ventilated facade to provide heating and cooling, heat recovery ventilation and domestic hot water or drying services for buildings, based on the thermoelectric waste heat utilization. Several building integration methods of the proposed system are presented.

Keywords: Thermoelectric, air conditioner; COP; waste heat utilization; building integration

1. Introduction

Thermoelectrics can enable direct energy conversion between heat and electricity, based on thermoelectric effects, which has been considered as a green and sustainable solution to the global energy dilemma. A thermoelectric module is a simple solid-state device that converts electrical energy into thermal energy or the reverse. As shown in **Figure 1**, it consists of a number of couples of p- and n-type semiconductor strips sandwiched between two ceramic plates, connected electrically in series and thermally in parallel. When supplied with a suitable electric current they can provide either cooling or heating depending on the direction of the current. Heat generation or absorption rates are proportional to the magnitude of the current and also the temperature of the hot and cold side.

The amount of heat removed by the hot side corresponds to the cooling effect and the electrical power input.

The thermoelectric modules are reliable energy converters and have no noise or vibration as there are no

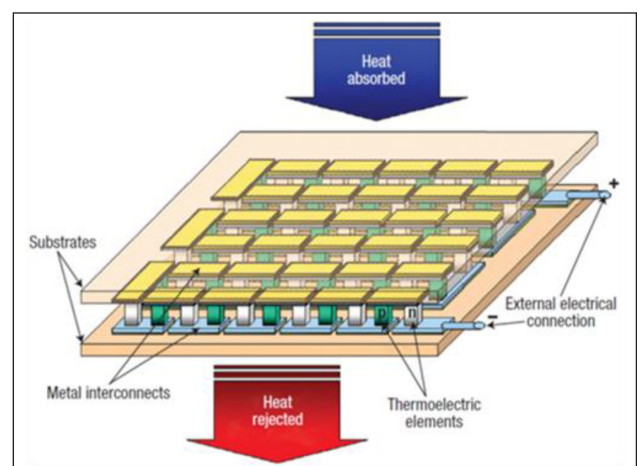


Figure 1: Thermoelectric module.

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mechanical moving parts. They have small size and are light in weight. As heat pumps, they are friendly to the environment as CFC gas or any other refrigerant gas is not used. Due to these advantages, the thermoelectric devices found a large range of applications in recent decades, including cooling electronic devices, refrigerator and air conditioner, power generation and thermal energy sensors, etc (Riffat et al, 2003).

Any thermoelectric device has a given operating temperature range beyond which its operation may cease. For cooling/heating applications, all thermoelectric modules require heat sinks in order to dissipate the energy generated or absorbed at the two junctions. A thermoelectric cooling/heating unit is therefore composed of three basic components, the thermoelectric module, the heat dissipater at the hot side of the module and the cooling component at the cold side of the module, as shown in **Figure 2**.

Conventional mechanical air conditioning systems are energy intensive and currently dominate the HVAC market. The refrigerants used in conventional vapor-compression air conditioning systems have detrimental effects on the global environment. Phasing-down hydrofluorocarbon (HFC) refrigerants for HVAC equipment over the next 20 years has been proposed and the refrigerants are undergoing a massive shift globally (Ortlieb et al, 2017). Although alternative refrigerants with low global warming potential (GWP) will partially solve the problems, a long-term complete solution is to move building HVAC systems away from vapor compression technologies (Tan et al, 2015). In recent years, the thermoelectric (TE) technology has attracted considerable attentions from various research areas, as its ability to directly convert between thermal and electrical energy using a simple solid-state semiconductor device, offering sustainable solution in

various fields (Park, et al, 2016). A TE air conditioning system has the advantages including fully environmentally friendly, no refrigerant and requiring no periodic replenishment, substantially less maintenance, compact in size and light in weight, high reliability, no moving parts (except for small fans) and no noise or vibration, long life span, can stand severe environments, easy to be integrated into the building structure, and more importantly it can be powered by direct current (DC) electric sources, such as photovoltaic (PV) cells and fuel cells. However, the existing TE air conditioning systems have low Coefficient of Performance (COPs) for space cooling that limits its application for domestic air conditioning. Literature review found few researches in the TE building space cooling (Zhao D et al, 2014; Gillott M et al, 2010; He W et al, 2013; Alomair M et al, 2015; Liu Z et al, 2015, Khire R, 2005). Currently the most efficient TE space cooling system in research has an average cooling COP of 0.9, with the maximum cooling COP of 1.22 (Zhao D et al, 2014). A TE cooling system with higher COP of 2.4 can also be found, however, this is achieved using very low temperature water of 12°C as a cooling medium (Liu Z et al).

Generally, the low COPs of the TE air conditioners were caused by a few problems, i.e, low figure of merit (ZT) of the thermoelectric materials, inefficient TE module design and inappropriate cooling system design. With the development of TE materials and TE technologies in recent decade, the above existing problems could be overcome and a highly efficient TE air conditioner is prospected. In addition, recent development in TE material with obviously reduced cost would provide TE air conditioners with greatly reduced cost. Furthermore, utilizing the high density waste heat produced by the TE cooling system for domestic applications would be an ideal way to enhance the overall

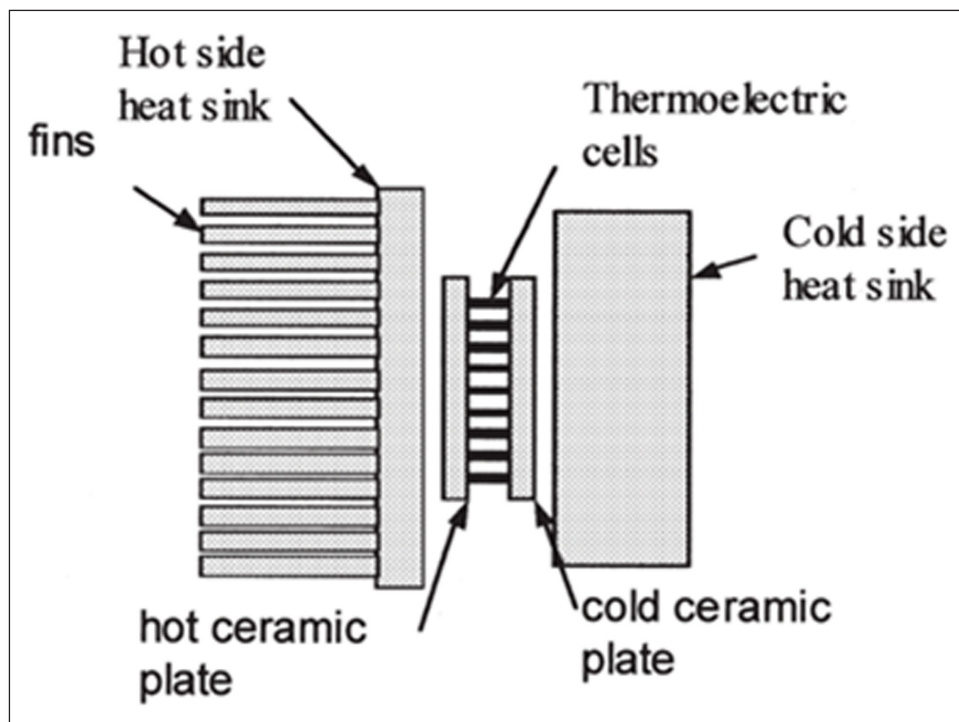


Figure 2: Basic components of a thermoelectric cooling/heating system.

efficiency of TE system operation. However, few researches in utilization of the waste heat of thermoelectric system can be found (He W et al, 2013; Zhao D et al, 2014), and these systems are either in inefficient or no compact.

The paper presents an overview of the current advance of the TE technologies, i.e., TE materials, advanced TE module and system design methods, which would provide a potential to greatly improve the COPs and reduce the costs of the TE air conditioning systems, which would promote the public acceptance of the TE air conditioners.

A TE air conditioner has an advantage of being very compact and small size and therefore it can be easily integrated into the building structure. In the near future, solar thermoelectric cooling system driven by PV will make a significant contribution, especially in zero energy buildings, in reducing fossil fuel consumption and protecting environment (Liu Z et al, 2015).

The paper also presents an overview of the existing building integrated TE air conditioning systems, the drawbacks of the existing systems are analysed and a novel building integrated thermoelectric air conditioning system has been proposed. This system smartly integrates a TE heat pump unit into a double-skin ventilated façade. The system sets multifunction in one, it provides heating/cooling and ventilation for buildings, and the high density waste heat produced in the cooling mode (predicted $>60^{\circ}\text{C}$) is directly utilized to provide domestic hot water or drying (clothing or other goods) services. The system has the capability of performing heat recovery ventilation or recovering heat from domestic waste water and PVT to use as a heat source of the TE heat pump in heating mode. The system with this structure would have the potential of greatly enhanced overall COP, in addition to the advance in recent TE material and TE technology. Furthermore, the proposed system is very compact and easy to be integrated into the building structure without restriction of direction, various methods on integration of the system into buildings are introduced schematically.

2. Optimization of the thermoelectric cooling/heating system design

At present, the COP of a thermoelectric coolers is typically <1 . However, it has been reported that a well-designed (small cooler) system can achieve a COP to be >2 [www.analogtechnologies.com]. The well designed system should have optimum design/selection of the following items according to its operating conditions, include: (1) selection of the optimum TE material (ZT) by balancing its efficiency (judged by ZT), availability and cost. (2) optimization of the geometrics of thermoelectric elements; (3) optimization of the heat dissipate/transport components; (4) optimization of the operating DC current. Recent development in TE material, TE module geometry design, heat removing and dissipating technologies would benefit the TE cooling/heating system design to further enhance the COP of the system.

2.1. Recent advance in thermoelectric material

The material used in construction of a TE cooling system plays an important role in controlling the performance of these devices. The TE performance is closely related

to the figure-of-merit of thermoelectric materials, ZT. A good thermoelectric material should have high primary criterion of merit ZT. A high ZT requires low thermal conductivity but high electrical conductivity [Twaha et al, 2016]. Conventional thermoelectric materials are bulk alloy materials such as Bi_2Te_3 , PbTe, SiGe and CoSb_3 , among which Bi_2Te_3 is the most commonly used one for a long time. They usually process a ZT value less than one (Bell L E et al, 2008).

It was reported that if the average ZT reaches 2, domestic and commercial solid-state heating, ventilating and air-cooling systems using thermoelectric material would become practical (Bell L E et al, 2008). The recent advances in thermoelectric material make it possible to significantly improve ZT factor through nanotechnology. Two primary approaches are bulk samples containing nanoscale constitutes and low dimensional materials. New thermoelectric materials with larger ZT factor values may intruquer a breakthrough in various application areas for thermoelectric devices. It was reported that the best commercial thermoelectric materials recently have ZT values around 1.0 (Zhao D et al, 2014). The highest ZT value in research is about 3, reported by Harman in 2005 (Harman T C et al, 2005). Other best reported thermoelectric materials have figure-of-merit values of 1.2–2.6 at certain temperature (Zhao D et al, 2014; He W et al, 2015), **Table 1** lists a selection of the reported high figure-of-merit thermoelectric materials.

In addition, with the development of the TE material technology, the cost of TE module has become much lower. In 2001, a piece of high quality TE cooling module (CP2-127-06-L1-4.5W) from Melcor, USA [www.melcor.com] costs US \$161, now the cost reduced to be \$59.8, a similar one costs only US \$24 from ATI (USA) [www.analogtechnologies.com]. In China, it is even cheaper, a piece of Tecl-07103 Peltier Thermoelectric Cooling Module costs only US \$5.69 [http://hebeitd.en.made-in-china.com]. Therefore, cost should no longer be a problem for development of TE heating/cooling system.

2.2. Recent advance in thermoelectric module geometry and system design

The parameters that affect the performance of TE modules can be physical or nonphysical. The most important optimization parameters for TE modules include TE element leg length, leg area ratio between n- and p-type legs, fill fraction, load resistance and module spacing (Twaha S et al, 2016). Thermal stresses in the legs and temperature distributions and their influence on module performance under designed operating conditions need to be investigated (Rabari R et al, 2014). Finite element can be used to solve such complexity using selected TE materials (Erturun U, 2014). The Math model has been developed for the thermodynamics and thermal stress analysis of TE system to optimum design or selection of the optimum module for the designed operating conditions (Al-Merbaty S et al, 2013). Optimum thermoelement and module geometry can be determined by a compromise between the COP and heat pumping capacity to optimum design of the TE module for a specific application.

Table 1: A selection of high figure-of-merit thermoelectric materials.

Material	Type	ZT value	Temperature
Bi-doped PbSeTe/PbTe (QDSL)	n-type	3	550K
$\text{In}_{0.2}\text{Ce}_{0.15}\text{Co}_4\text{Sb}_{12}$ Skutterudite	n-type	1.43	800K
$(\text{Bi}_{0.25}\text{Sb}_{0.75})_2\text{Te}_3$	p-type	1.27	298K
$\text{Bi}_2(\text{Te}_{0.94}\text{Se}_{0.06})_3$	n-type	1.25	298K
$\text{K}_{0.95}\text{Pb}_{20}\text{Sb}_{1.2}\text{Te}_{22}$	n-type	~1.6	750K
PbTe-SrTe	p-type	1.7	~800K
Binary crystalline $\text{In}_4\text{Se}_{3-6}$	n-type	1.48	~705K
$\text{AgPb}_m\text{SbTe}_{2+m}$	n-type	~2.2	800K
$\text{Bi}_2\text{Se}_{0.5}\text{Te}_{2.5}$		1.28	Room temperature
$(\text{Bi,Sb})_2\text{Te}_3$		1.41	Room temperature
$\text{Bi}_2\text{Te}_{2.7}\text{Se}_{0.3}$		1.27	Room temperature
$\text{Bi}_{0.4}\text{Sb}_{1.6}\text{Te}_3$		1.26	Room temperature
$(\text{Bi}_2\text{Te}_3)_{0.25}(\text{Sb}_2\text{Te}_3)_{0.75}$		1.80	723
$\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}$		2.38	773
$\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$		1.93	693
$(\text{Bi}_2\text{Se}_3)_x(\text{Bi}_2\text{Te}_3)_{1-x}$		1.87	713
$\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}$	p-type	1.86	693
$\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$		2.4	300
SiC/B4C+PSS		1.75	873
SnSe single crystal		2.6 ± 0.3	923

The standard simplified energy equilibrium model or zero dimensional model has been widely used for TE cooler and air-conditioning analysis and design (Riffat S B et al, 2004, Fraisse G et al, 2013). However, its accuracy is limited due to gross simplifying assumptions: 1) thermoelectric material properties are temperature independent; 2) half of the Joule heat goes to the hot side while the other half goes to cold side. This assumptions could result in up to 10% error. One-dimensional thermoelement model solves detailed temperature distribution along thermoelement length. In one-dimensional model, temperature dependent parameters bring in two considerations. One is the temperature dependent Thomson effect. The other is that Thomson effect, Joule heat and heat conduction have to be considered together since the temperature distribution is no longer linear through the thermoelement (Huang M J et al, 2005; Mitrani D, 2009; Reddy B V K et al, 2013). Although a three-dimensional modelling captures temperature distribution both along and across the thermoelement, thus, it performs better than one-dimensional modelling, it is very computationally expensive and complicated (Wang X D et al, 2012). Therefore, one-dimensional thermoelement model should be an ideal tool for TEC analysis and design at present.

Commercially, a large amount of different types of modules are available, some of them are most suitable for heating/cooling applications, such as thermal cycling series module in ATI (USA) and CP series module (Lairdtech USA)

for large heat pumping applications [www.lairdtech.com/products/cp14-31-045-11-w45].

2.3. Recent advance in heat removal/dissipate systems

The power of the heat exchanger heat sinks in the hot and cold side of the TE modules, especially the hot side heat sink that is used to remove the high heat flux, is very important for enhancing the efficiency of the TE cooling/heating system. Researches can be found to investigate the heat sinks' geometry allocation of the heat transfer area and heat transfer coefficients of hot and cold side heat sinks (Zhou Y et al, 2012; Zhu L et al, 2013; Pan Y et al, 2007). The results obtained is useful for the optimal design and manufacture of heat sinks for TE cooling/heating systems.

Figure 3 shows some current commercial available high power TE heat sinks for electronic device cooling.

3. Thermoelectric cooling system waste heat utilization and predicted COPs

During the operation the thermoelectric cooling mode produces large amount of high density waste heat. Utilizing the waste heat for domestic hot water/drying services would be an ideal way to enhance the overall efficiency of thermoelectric system operation and promote public adoption of the thermoelectric air conditioner. Researches in utilization of the waste heat of thermoelectric system is rare as mentioned in Introduction section.

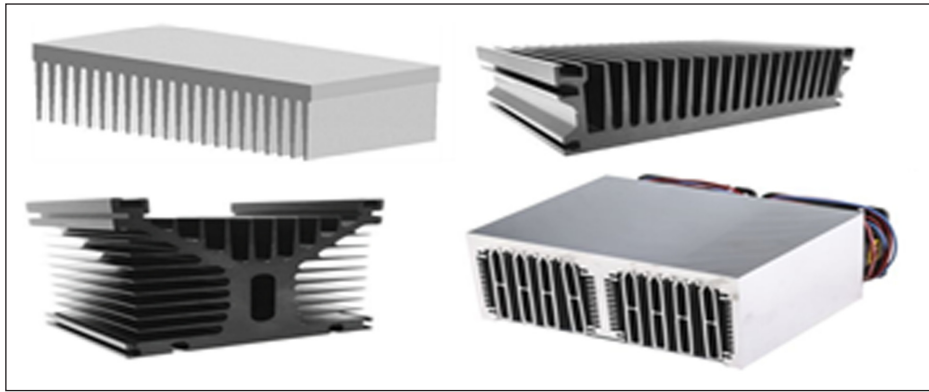


Figure 3: Various configurations of high power hot side heat sinks.

However, utilization of the waste heat for domestic applications has great potential to highly enhance overall COP of the thermoelectric system. The waste heat produced in the cooling mode of the thermoelectric system is high density, and for building applications our previous work found it has a suitable temperature of 60–70°C for producing domestic hot water (Riffat S B et al, 2004; Ma X, 2004).

Use of the microencapsulated phase change material slurry (MEPCM slurry) would be an ideal technology for effectively utilization of waste heat produced in the thermoelectric cooling system. A MPCM slurry can fulfil the three functions simultaneously in the thermoelectric space cooling system, i.e, heat absorption from the hot side of the TE modules, heat transportation through liquid cold plate and pipelines and heat storing in the heat storages. Furthermore, the high energy content of the slurry allows significant reductions to be made in the size of pipes, pumps and storage tanks. To keep the pump energy consumption low, it is important to choose a MEPCM slurry with good energy transportation capability, good heat transfer ability and lower pumping power requirement. The concentration of the MEPCM slurry will also affect the above aspects (Ma X et al, 2009).

In a thermoelectric cooling system, the waste heat produced on the hot side can be assessed by the second thermodynamics law, i.e.,

$$Q_h = Q_c + Q_E \quad (1)$$

Where, Q_h is the waste heat produced on the hot side; Q_c is the cooling energy produced on the cold side; Q_E is the electrical energy input;

The Coefficient of Performance (COP) of the system for cooling is expressed as:

$$COP_c = Q_c / Q_E \quad (2)$$

The overall COP of the system when the waste heat is utilized in cooling mode can be expressed as:

$$COP_{overall} = (Q_h + Q_c) / Q_E = 2 \times COP_c + 1 \quad (3)$$

As aforementioned in Introduction section, the current most efficient TE space cooling system in research has an average cooling COP of 0.9, with the maximum cooling

COP of 1.22 (Zhao D et al, 2004). If the waste heat produced in the system can be utilized for domestic hot water service, the overall average cooling COP can be 2.8, with the maximum overall system COP of 3.44, which could be competitive to the traditional vapour compression air conditioner system with a COP of 2 to 3. If a thermoelectric space cooling and heating system are well designed based on current advanced TE material, module and system design, the cooling COP could reach 2, heating COP could reach 3, by utilizing the waste heat the overall COP can reach 5, which would be competitive to the traditional one regarding to the energy efficiency.

4. Size and cost of the thermoelectric air conditioning system

The TE air conditioner system is a compact flat unit. Previous work found that a 0.38 m² of TE unit (with a cooling COP of 0.6 and heating COP of 1.12), which is smaller than a common room heating radiator, can satisfy the heating/cooling requirement of a 15 m² room based on Scotland weather conditions (Ma X, 2004). With the development of the TE air conditioning technology, the cooling COP of the system would reach 2, as mentioned in section 3 (whereas the heating COP would be 3), the TE unit would be much smaller and the above mentioned TE unit for a 15 m² room in Scotland would have an area of only 0.11 m².

5. Integration of the thermoelectric air conditioning system into the building structure

The TE air conditioning system is very compact and easy to be integrated into the building structure. Some researches in building integrated TE air conditioning system can be found, as are presented in this section. Although many efforts have been made in this aspect and the progress is obvious, as presented in section 5.1, great improvements are still needed. Drawbacks of these systems are analysed in section 5.2.

5.1. Existing building integrated thermoelectric air conditioning systems

Figure 4 shows an active solar thermoelectric radiant wall system with a dimension of 1580 × 810 mm (Liu, Z et al, 2015). The system from the outside to the inside mainly consists of photovoltaic system, airflow channel, and thermoelectric radiant cooling system. The PV forms an envelope

surrounding the external wall with an airflow channel maintained between the thermoelectric radiant panel and the PV unit. The TE modules are connected in series and sandwiched between the aluminium radiant panel and the heat sinks. The heat sinks are used to dissipate heat for TE modules. The fan can provide forced air convection to help the TE modules to release heat more efficiently into the airflow channel. In order to reduce energy dissipated into the airflow channel, insulation material was pasted at the back of the radiant aluminium pane. The direction of the heat flow of the wall can be achieved by controlling the direction of the operating current. This feature enables the system useable for different climates. The wall system was installed in a testing room of 3 m × 3 m × 3 m. Experi-

mental results showed that use of this wall system has reduced the traditional air conditioning system requirements.

Figure 5 shows an active building envelope system (Khire R et al, 2005). This system is comprised of two basic components: a photovoltaic unit (PV unit) and a thermoelectric heat pump unit (TE unit), which are integrated within the overall building enclosure. The PV unit forms an envelope surrounding the external wall such that a gap is maintained between the wall and the PV unit. This gap acts as an external heat dissipation zone for the TE unit. The external walls of the system consist of two layers, the external layer (facing the PV unit) is made of a thermal insulating material, and the internal layer is made of a material with high heat storage capacity. As shown in **Figure 5**, the thermal insulation and thermal mass pertain to the external and the internal layers of the external wall, respectively. The TE coolers are dispersed inside the openings that are provided in the insulating layer. Each TE cooler consists of two heat sinks, the internal heat sink either absorbs or dissipates heat to the thermal mass layer and the external heat sink either dissipates or absorbs heat from the surrounding air through natural or forced convection, in cooling and heating modes respectively.

Figure 6 shows a solar thermoelectric air conditioner with heat recovery available for both space cooling and hot water supply (Liu, Z et al, 2015). The solar thermoelectric air conditioner with hot water supply 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 system at night. The system has three working modes (1) space cooling and hot water mode; (2) space cooling mode; (3) space heating mode;

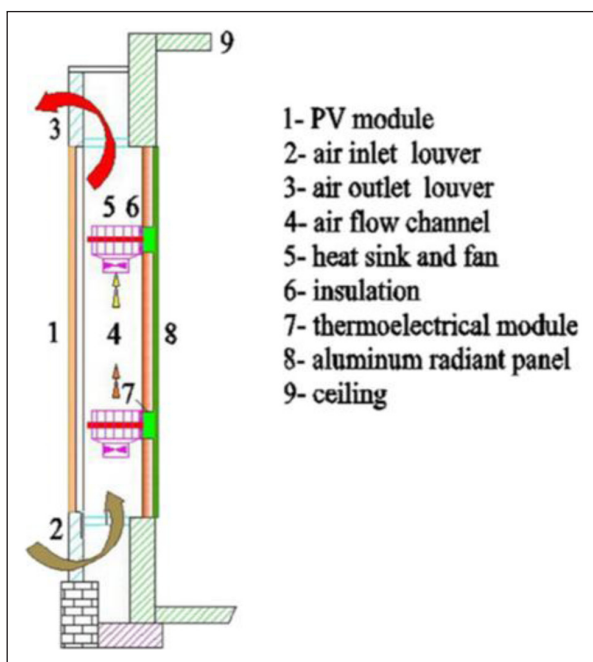


Figure 4: Active solar thermoelectric radiant wall system.

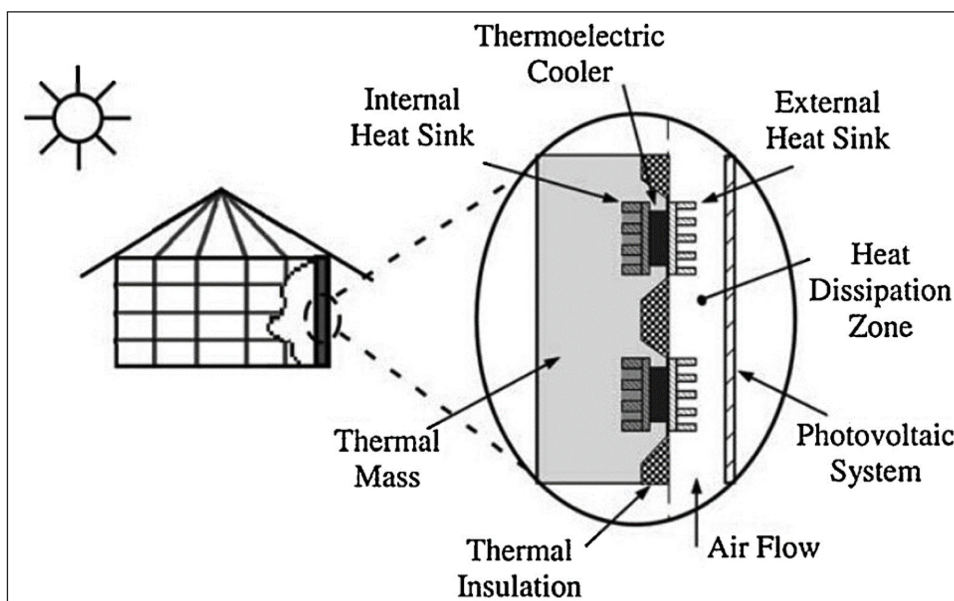


Figure 5: Active building envelope system.

As shown in **Figure 6**, this system is a water source heat pump when it works in heating mode, when it works in cooling mode, the water flow acts as a coolant to cool the hot side of the TE unit, when hot water is required in cooling mode, i.e., in space cooling and hot water mode, the water stops flowing and is warmed up in the water tank.

Experiment results showed the system had relatively high overall coefficient of performance in cooling and hot water mode, the overall COP (cooling energy plus energy for hot water over power input) could reach up to 4.51 when the water temperature was 20°C and 2.74 when water temperature was 42°C. The heating COP can be reached at 3.05 when the water inlet temperature is 24°C. The maximum cooling COP of the system is 2.4 when the system works stably under the water inlet temperature of 12°C.

As shown in **Figure 7**, a solar thermoelectric cooled ceiling combined with displacement ventilation system proposed for space climate control (Liu Z, 2014). In this system, the solar thermoelectric cooled ceiling adopts thermoelectric cooler instead of hydronic panels as radiant panels, which is burdened with removal of a large fraction of sensible cooling load. The TE modules are connected in series and sandwiched between the aluminium radiant panel and heat pipe sinks in solar thermoelectric cooled ceiling. The

heat sinks are used to dissipate heat for 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 easily achieved.

The combined system dehumidifies the supply fresh air using a thermoelectric dehumidified ventilation system. The thermoelectric dehumidified ventilation system is responsible for removal of a small fraction of sensible cooling load and all latent cooling loads. As shown in **Figure 7**, the dehumidified ventilation system was composed of a thermoelectric modules heat exchanger made by thermoelectric modules, fans, and flat-fin heat sinks. In summer, the fresh air side behaves as cold side, while the exhaust air side is hot side. The fresh air is cooled down when it flows through heat sink into the indoor. At the same time, the exhaust air cooled down the heat sink on the other side of the TE modules. In winter, reverse the cold side and hot side by changing the direction of the current. The fresh air is heated up and while the exhaust air is cooled down. Therefore, thermal energy can be recovered from the exhaust air and the fresh air could be handled in high energy efficiency. The system COP can reach 0.9 in cooling mode and 1.9 in heating mode.

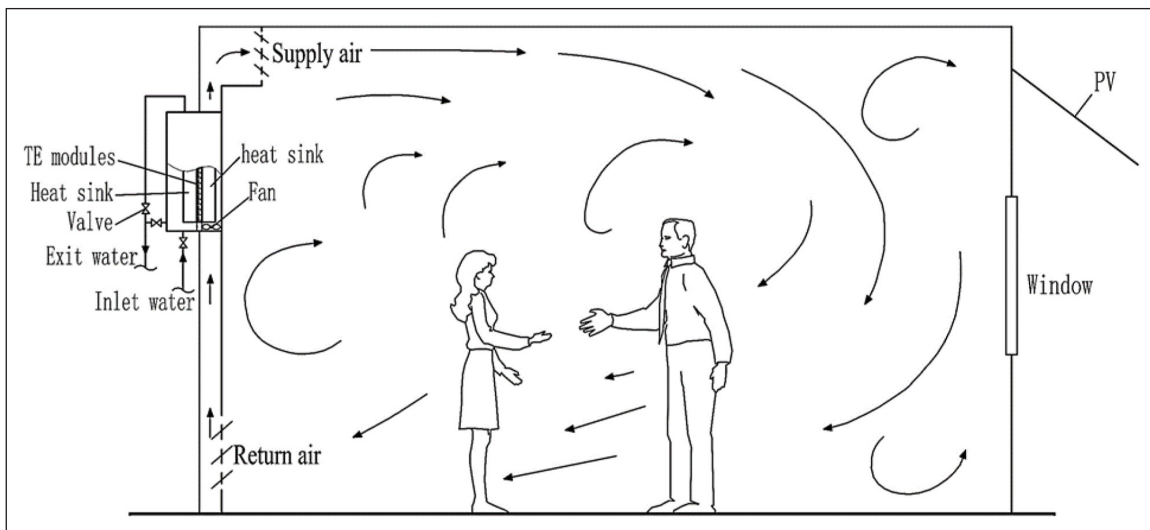


Figure 6: Solar thermoelectric air conditioner with hot water supply.

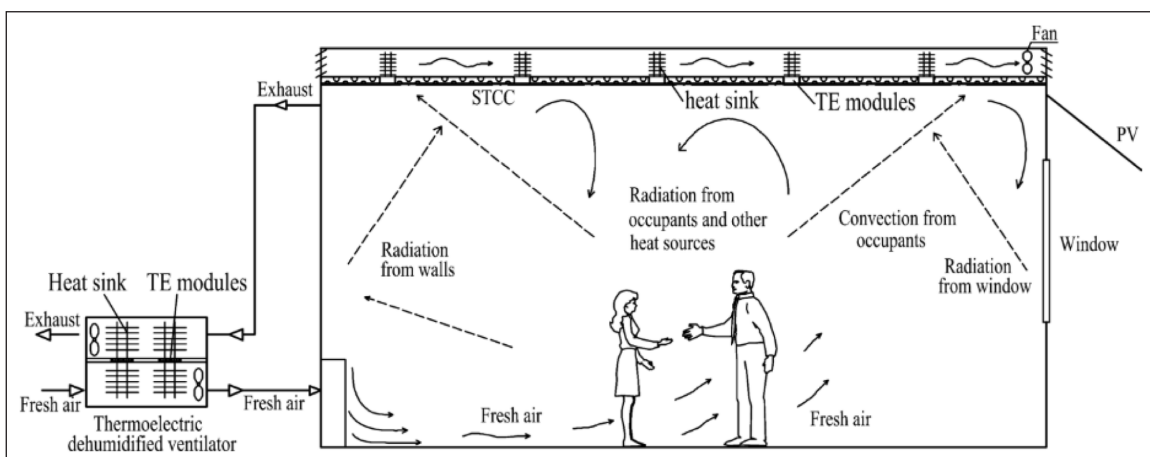


Figure 7: Solar thermoelectric cooled ceiling combined with displacement ventilation system.

A thermoelectric air conditioner with heat storage system has been developed as shown in **Figure 8** (Zhao D et al, 2014) 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. 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. The experiment results showed that the average COP of the thermoelectric air conditioners was 0.8, and the maximum COP value was 1.22.

5.2. Drawbacks of the existing building integrated air conditioning systems

Although many efforts have been made to integrate the TE air conditioning system into the building structure and the progress is obvious, as presented in section 5.1, improvements are still required. The disadvantages of the existing systems are stated as follow.

The systems showing in **Figures 4** and **5** dissipates the thermal energy provided by the TE units to the live room by only radiating and natural convection, which is not efficient as the TE system produces high density energy and forced convection is required, the radiating systems therefore will need more TE units. In addition, The TE units in the systems showing in **Figures 4** and **5** are arranged in series in an air flow channel, which is not very effective for removing the waste heat produced by the TE units in cooling mode as if many TE units are required in these system, the air flow heated up by the TE units in the lower part of the channel may not remove the waste heat from the units in the upper part of the channel, vice versa in heating mode. The similar problems exists in a ceiling system shown in **Figure 7**, in which TE units are arranged in series in a ceiling channel.

In the system shown in **Figure 7**, the forced convection inside the room is provided by a TE dehumidified

ventilator that can also dissipate the thermal energy provided by the TE units in the ceiling to the live room, however, this system is not compact and aesthetic as the TE dehumidified ventilator system need to be located outside the building or a utility room close to the external wall of the building. Although the system shown in **Figure 6** can provide forced convection in the room side of TE unit by circulating the room return air through the TE unit to dissipate the thermal energy produced by TE unit, there is no fresh air added to the room regarding to the ventilation. In addition, this system (**Figure 6**) uses water as a cooling medium or heat source in cooling and heating mode respectively, which can increase the COP of the system as the liquid cooled TE systems are usually more efficient than air cooled system, however, a highly efficient water circulation system using air to water heat exchanger is needed to dissipate the heat to the environment in cooling mode or absorb heat from the environment in heating mode, the system is therefore complex. The system shown in **Figure 8** is also a water cooled TE system that uses the air to water heat exchanger as a circulation system, which is complex. In addition, the TE unit in this system occupy the live space, which is not aesthetic.

Furthermore, except for the system shown in **Figure 5**, none of the systems has a thermal storage integrated into the system to store the extra thermal energy produced by the solar driven TE systems for night time and low isolation period use, which is not economic, although the system shown in **Figure 6** uses battery to store the PV electric energy, however, the battery is too expensive.

Besides, except for the system shown in **Figure 8**, none of systems has a thermal storage to store the high density waste heat for domestic applications. For a PV powered TE system with high density waste heat, storing extra thermal energy produced by TE units and utilization of waste heat from the TE units are essential to enhance the overall performance of the system and allow the system running more economically, which will promote public acceptance of the TE air conditioning system.

This paper proposes a novel building integrated thermoelectric air conditioning system that overcomes all the disadvantages of the above existing systems and is very

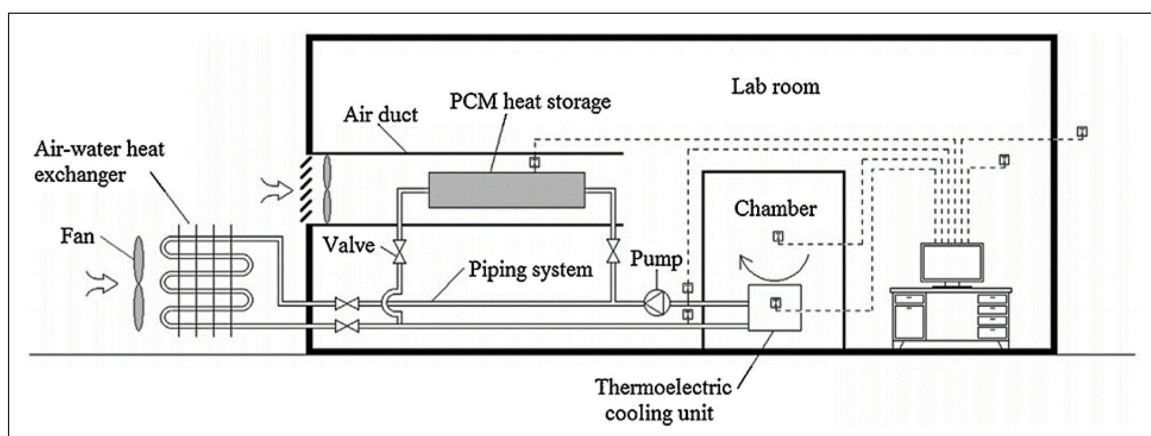


Figure 8: Thermoelectric air conditioner with heat storage system.

simple and compact. The details of the proposed system are presented in section 6.

6. A novel building integrated thermoelectric system proposed

The proposed novel system smartly integrates a flat TE heat pump unit into a double-skin ventilated façade and sets multifunction in one, it provides heating/cooling and ventilation for buildings, and the high density waste heat produced in the cooling mode (predicted >60°C) is directly utilized to provide drying (clothing or other goods) services (Option 1, **Figure 9**,) or domestic hot water services (Option 2, **Figure 10**). The flat TE heat pump unit is composed of three components, (1) the TE modules (TE unit); (2) the finned encapsulated phase change material (PCM) attached on one side (the side face to the room) of the TE modules as a heat dissipater and a heat storage of extra cooling/heating energy output from TE modules,

the stored thermal energy will be used in the night time (when driven by PV) or high peak electricity period (when driven by mains power) (**Figures 9** and **10**); (3) a high power heat sink (**Figure 9**, Option 1) or a micro encapsulated phase change slurry heat dissipating, transportation and storage system (PCS system) (**Figure 10**, Option 2) on another side (the side face to the façade gap) of the TE modules to remove the waste heat produced in cooling mode and to provide the heat source in heating mode.

The details of the operations of the two different components of the two Options are described as follow: In Option 1 (**Figure 9**) in cooling mode, cold room exhaust air mixing with outdoor air flowing through the façade gap can effectively remove the TE waste heat dissipated on the high power heat sink and bring it to drying chamber for drying services; in heating mode, warm indoor exhaust air mixing with outdoor air flows through the heat sink and dissipates heat to the heat sink to provide a heat

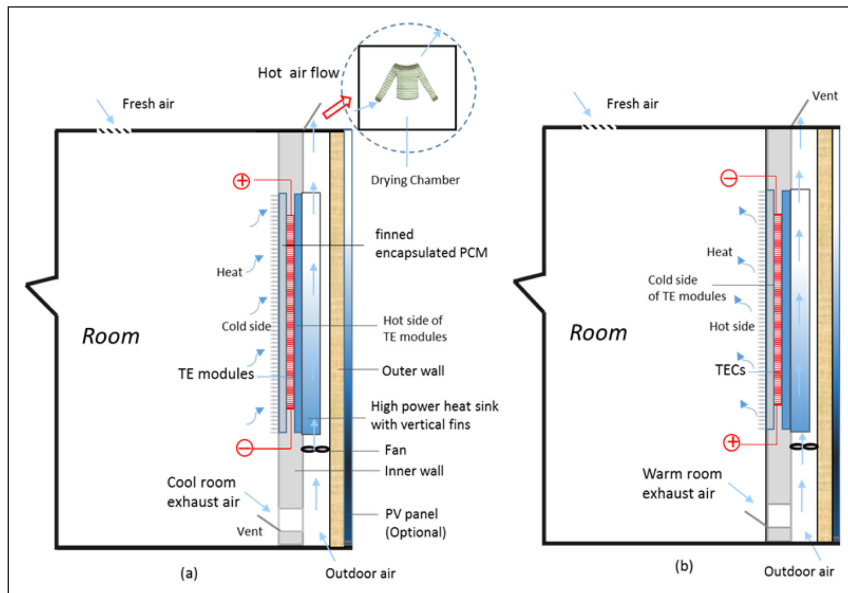


Figure 9: TE façade system-option 1 (a) cooling mode (b) heating mode.

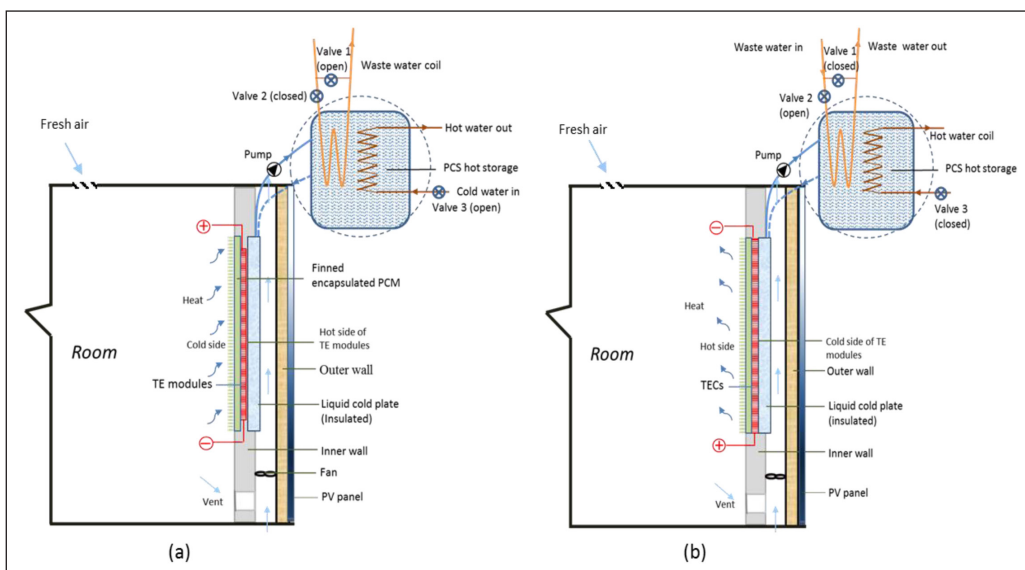


Figure 10: TE façade system-option 2 (a) cooling mode (b) heating mode.

source for the TE heat pump, these actually achieve the heat recovery ventilation. In Option 2 (**Figure 10**) in cooling mode, the PCS system has the capability to effectively remove, transport and store the waste heat for domestic hot water serves, in heating mode, it can store and transport heat from domestic waste water to provide the heat source for the TE heat pump. As shown in **Figures 9** and **10**, in both Options, the room ventilation is performed through the façade gap by a ventilation fan mounted in the gap of the double-skin façade, and the ventilation air movement inside the room can also promote the heating and cooling energy dissipating from the finned encapsulated PCM to the room. For the TE unit, a number of TE modules can be arranged to be one or more matrixes to form TE sub-units, with the partition in between to form the air flow channels in the façade gap (**Figure 11**). The number of the TE modules and the dimension of the matrix can be optimized regarding to the air flow channel size and air flow temperature at the channel outlet to optimize the heat dissipating efficiency. PV panel can be installed on external wall of the façade (as an option) in case the system is driven by PV.

The innovative façade system has the capability of performing heat recovery from room ventilation air and use the recovered cooling/heating energy as a part of cooling medium (in cooling mode) or heat source (in heating mode) of the heat pump (Option 1, **Figure 9**), or recovering heat from domestic waste water to use it as a heat source of the TE pump in heating mode (Option 2, **Figure 10**), these can greatly reduce the temperature difference between hot and cold sides of TE modules, which is an important action to enhance the COP of the TE system. In addition, a high power heat sink (**Figure 3**) and a PCS system are firstly used as a heat dissipater in Option 1 and 2 respectively instead of conventional heat sink and water cooling system, which would therefore further greatly enhance the

COPs of the system. Furthermore, owing to the effective utilization of high density waste heat of TE heat pump for drying or domestic hot water services in cooling mode, the overall COP of the TE system would be higher.

The novel building integrated multi-functional TE air conditioning system can be used for residential and commercial buildings, for both new buildings and retrofitting buildings. The system can be driven by mains power or directly driven by solar PV panel or fuel cells, without need of converter, and so it would also have a large promising market for small mobile spaces, such as mobile field office, by forming a stand-alone façade system driven by PV.

The above system is under investigation based on recent advances in TE technologies (TE material, module design and system design), heat sink and PCM/PCS technologies. The expected energy and economic performance will be superior to the existing TE air conditioning systems.

The proposed TE air conditioner unit can be easily integrated into the building structure due to the small flat shape, compact structure and no direction restriction. Different methods for integration of the proposed TE air conditioning unit into building structure are investigated. Except for integration into a double skin façade (**Figures 9** and **10**), the TE unit can be integrated into the ceiling, fireplace chimney and window frame. **Figure 12** shows the integration of the TE air conditioning unit into ceiling. **Figure 13** shows the integration of the TE air conditioning unit into fireplace chimney for retrofitting the buildings. **Figure 14** shows the integration of a small TE air conditioning unit into window.

7. Conclusions

Recent advances in TE technologies would provide a potential to greatly improve the COPs and reduce the costs of the TE air conditioning systems. This would promote the public acceptance of the TE air conditioners. The TE

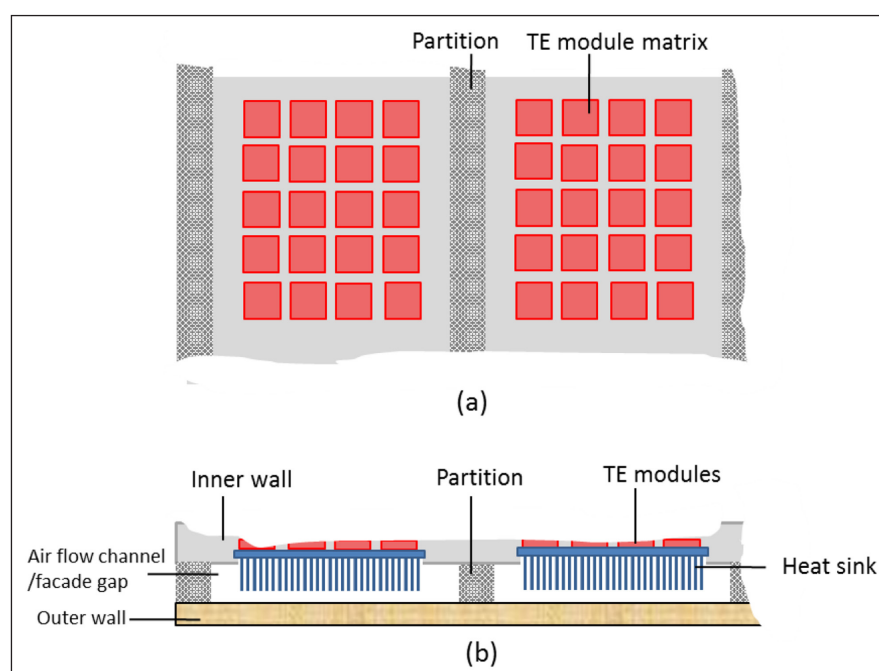


Figure 11: Arrangement of TE modules in the façade.

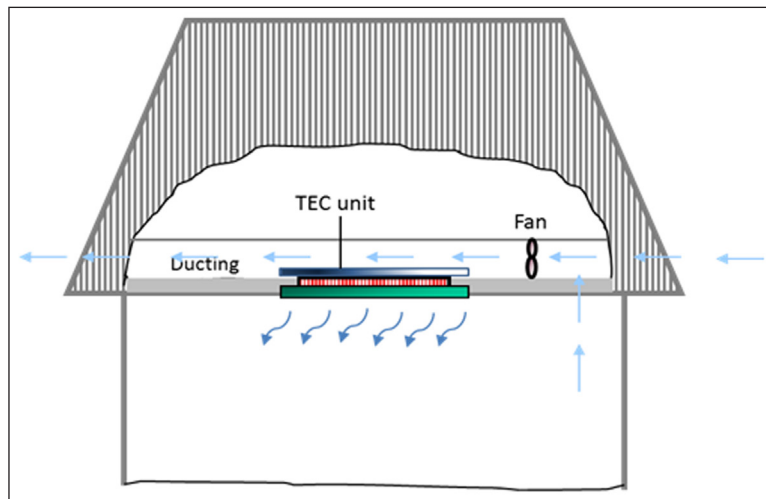


Figure 12: Integration of TE unit into ceiling.

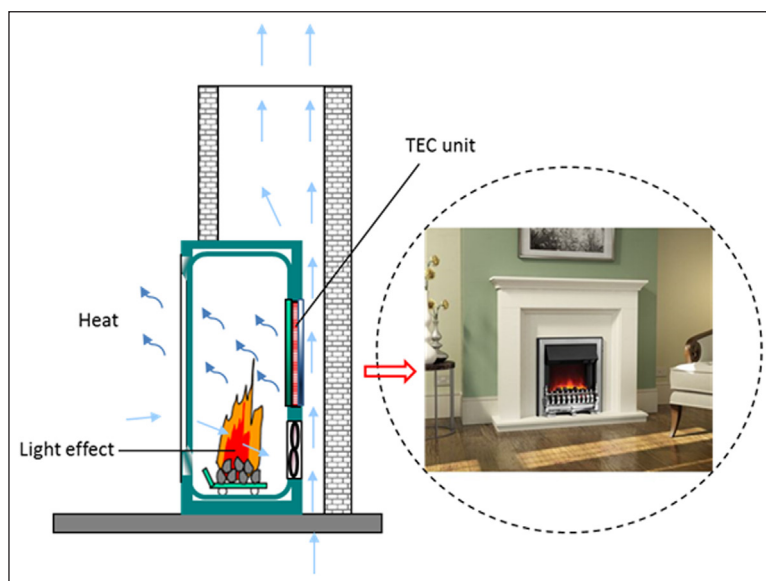


Figure 13: Integration of TE unit into fireplace chimney.

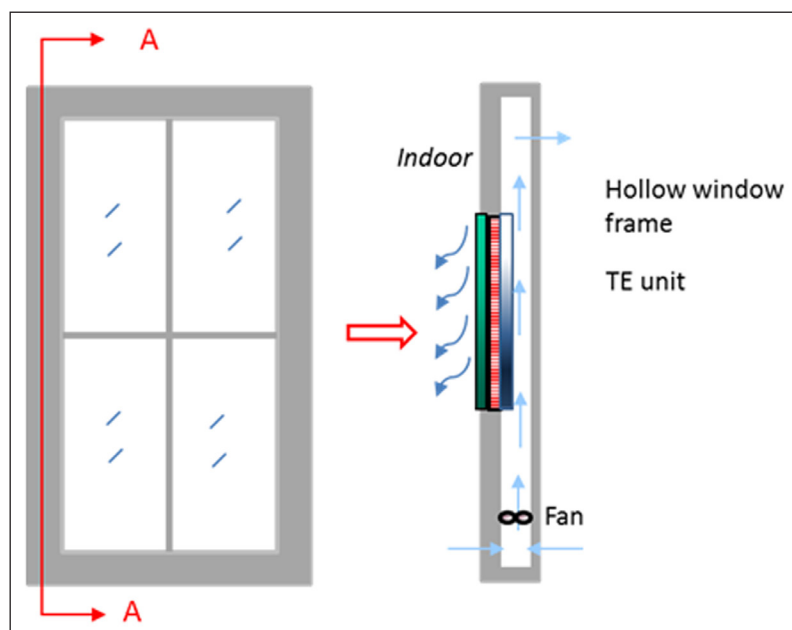


Figure 14: Integration of TE unit into window frame.

materials with higher Figure of merit have been reported, which would make domestic TE air conditioning system become practical. Furthermore, the advanced analytical models will provide an effective tool for optimum design of the TE modules and TE systems. In addition, effective utilization of the waste heat produced in cooling mode will greatly improve the overall COP of the TE system. It is prospected that the TE air conditioner would be competitive and superior to the conventional vapour compression one regarding to the energy efficiency. The TE system has the advantage of easy integration into the building structure, which can also bring the benefit of heat recovery ventilation. The drawbacks of the existing building integrated TE air conditioning systems have been analysed, finally a novel building TE façade system is proposed, alternative methods of integration of the proposed TE air conditioning unit into building structure are presented.

Competing Interests

The authors have no competing interests to declare.

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