Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Experimental study and performance analysis of solar-driven exhaust air thermoelectric heat pump recovery system

Zhongbing Liu\textsuperscript{a,b}, Weijiao Li\textsuperscript{a,b}, Ling Zhang\textsuperscript{a,h}, Zhenghong Wu\textsuperscript{a,b}, Yongqiang Luo\textsuperscript{a,b}

\textsuperscript{a} College of Civil Engineering, Hunan University, Changsha, China, 410082, P.R. China

\textsuperscript{b} Key Laboratory of Building Safety and Energy Efficiency of the Ministry of Education, Hunan University, Changsha 410082, China

A R T I C L E   I N F O

Keywords: Heat recovery Photovoltaic Thermoelectric Fresh air Coefficient of performance

A B S T R A C T

Exhaust air heat recovery is of great significance for building energy conservation. Since passive heat recovery systems use temperature or enthalpy difference between outdoor air and indoor air to drive the system, the temperature of fresh air supply cannot meet indoor requirements and the exhaust heat is not fully recovered. In this study, a solar-driven exhaust air thermoelectric heat pump recovery (SDEATHP) system is tested and evaluated for its ability to recover thermal energy from exhaust air to cool or heat fresh air. An experimental platform was established to test its performance. Results show that the SDEATHP system can obtain higher fresh air supply temperature in winter and lower fresh air supply temperature in summer. The system requires only 3.12 W of power for the fans, and the average relative cooling coefficient in summer and the average relative heating coefficient can reach 50.6 and 57.9, respectively. The optimal operating current and voltage of TE modules and photovoltaic system is analyzed, and then the number and types of electrical connections for the TE modules in SDEATHP system are discussed. The SDEATHP system provides a new method for building energy recovery and fresh air supply.

© 2019 Elsevier B.V. All rights reserved.

1. Introduction

With the intensification of global warming and the increasing building energy consumption, building energy efficiency has become the focus of attention worldwide [1,2]. Buildings account for 30% of China’s total social energy consumption which has become the largest energy consumption entity in China [3]. Reducing energy use through more energy-efficient measures has become a common concern for researchers [4]. Fresh air supply in buildings is of great benefit to indoor air qualities and peoples’ health, and has become a concern due to the sick building syndrome (SBS) and the outbreak of the severe acute respiratory syndrome (SARS) in 2003 [5]. Due to the large temperature or enthalpy difference between the outdoor fresh air and the indoor air, the handling of fresh air requires a large amount of building energy consumption. Research showed that fresh air systems consume about 20–40% of the total energy consumption of the air-conditioning systems [6]. Therefore, development of fresh air equipment and systems to reduce the energy consumption of fresh air is of great significance to building energy conservation.

Heat recovery systems include passive and active heat recovery systems, which are environmentally friendly and energy efficient. Passive heat recovery systems do not have energy-driven refrigeration equipment, and what it needs is only fan or pump energy consumption so that it can obtain higher energy efficiency by recycling exhaust heat for heating or cooling fresh air. In recent years, various forms of passive heat recovery systems have been widely used in buildings, including heat pipe heat exchangers, flat plate heat exchangers, rotary wheel heat exchangers and liquid coupled run around energy recovery systems [7–9]. However, since these passive waste heat recovery systems use the temperature or enthalpy difference between the outdoor fresh air and indoor air to drive the system, the temperature of the fresh air supply from the passive heat recovery systems are always higher in summer and lower in winter than the indoor temperature. Active energy recovery systems can recover latent heat of the exhaust air and active control of fresh air temperature and humidity. The heat pump heat recovery system is a kind of active energy recovery system, which is based on thermal cycle operation and uses exhaust air instead of outdoor air as a heat source [10]. But, it requires additional power to drive the compressor, and the system is complex and only suitable for buildings that have a large demand for fresh air.
Thermoelectric cooling systems have the advantages of simple structure, no moving parts, no refrigerant, and have been applied in the fields of building waste heat recovery, air conditioning systems and hot water systems [11,12]. Lu et al. developed and tested an instantaneous thermoelectric heat pump water heater, and the energy efficiency ratio (EER) of this water heater reached 1.45 or more [13]. Kim et al. developed a thermoelectric heat pump to heat buildings, and studied three cases on the optimal number of TEMs and the current [14]. Li et al. investigated a thermoelectric ventilator, which was integrated with a flat fin cross flow sensible heat exchanger and a thermoelectric modules heat exchanger to enhance heat recovery, and the performance of the ventilator was over 2.5 in both cooling and heating mode [15]. Cai et al. analyzed a thermoelectric heat recovery unit first and then developed a cost-performance model considering the relationship between system performances and operating cost. The results indicated that the operating cost of a thermoelectric heat recovery system could be lower than 0.025 $/kWh under the optimal parametric conditions [16].

Thermoelectric cooling systems can be directly connected with photovoltaic (PV) systems, which provide a new method for solar energy applications in buildings [17–20]. Some solar thermoelectric cooling systems have been investigated in recent years. Liu developed a photovoltaic-thermal compound thermoelectric ventilator (PVT-TEV) system, in which photovoltaic thermal (PVT) collector generates electricity in winter and simultaneously preheats the fresh air to achieve comprehensive utilization of solar energy [19–20]. Xu et al. tested a PV thermoelectric window system and the coefficient of performance of the system is about 2.5 for the heating mode [21]. Sabah et al. conducted a research on a solar thermoelectric system, and the results showed that the hot and cold side temperature of the thermoelectric (TE) modules have an important effect on the system performance [22]. Cheng et al. tested a solar-driven thermoelectric cooling system. The system utilizes the waste heat of the photovoltaic and the hot side of the thermoelectric modules to obtain hot water, and simultaneously uses the cold side of the thermoelectric modules to cool the indoor [23]. Roonak and Yavar studied a photovoltaic thermoelectric cooling-heating system and the coefficient of performance of the system was about 1 when the voltage were 12 V [24]. Kashif et al. developed and studied a thermoelectric air duct system assisted by a photovoltaic wall for space cooling in tropical climates. The coefficient of performance of the system increases from 0.67 to 1.15 and the cooling power increases from 101.34 to 517.24 W, with an increase in input current from 2 A to 6 A [25]. Liu et al. studied an active solar thermoelectric radiant wall system, and the results showed that the system can actively control the temperature of the wall [26]. It can be seen that there are many researches on thermoelectric systems in the application of waste heat recovery in buildings, but there is no research on solar photovoltaic direct connection thermoelectric heat pumps for waste heat recovery.

To overcome the shortcomings of the passive waste heat recovery systems and the active compressed waste heat recovery systems, this study proposes a solar-driven exhaust air thermoelectric heat pump recovery (SDEATHP) system. In the SDEATHP system, a solar photovoltaic converts solar radiation into electrical energy, which is subsequently used to power the exhaust air thermoelectric heat pump recovery (EATHP) system to recover the exhaust heat energy for fresh air heating or cooling, realizing the aim of active control of fresh air. The system has no power consumption except for the fans because it uses solar energy to drive the thermoelectric cooler. Moreover, with its power generation in situ and used in situ, and with no battery or inverter, the SDEATHP system can save the investment in power grid and reduce the loss of power transmission and distribution. In order to prove the feasibility of the SDEATHP system, the solar-driven exhaust air thermoelectric heat pump recovery (SDEATHP) system is tested and evaluated for its ability to recover thermal energy from exhaust air to cool or heat fresh air. In details, in Section 2, the working principle of the SDEATHP system was introduced. In Section 3, the system experimental test platform was established. In Section 4, the performance of the system was analyzed and discussed. In Section 5, the coupling characteristics of photovoltaic direct-connected exhaust air thermoelectric heat pump recovery system are analyzed and discussed. Finally, conclusions and recommendations are drawn in Section 6.

2. Working principle of the system

Fig. 1 depicts the prototype solar-driven exhaust air thermoelectric heat pump (SDEATHP) system. The SDEATHP system mainly consists of exhaust air thermoelectric heat pump recovery system (EATHP) and solar photovoltaic (PV) system. The PV system is installed above the window as a fixed shading device in buildings. The EATHP system is composed of fresh air fan, fresh air side heat sink, thermoelectric modules, exhaust air side heat sink and exhaust air fan. The thermoelectric modules are installed between the fresh air side heat sink and the exhaust air side heat sink. The EATHP system is directly connected to and powered by the PV system.

As shown in Fig. 2, the EATHP system has two working modes: cooling in summer and heating in winter. In summer, outdoor fresh air flows through the heat sink of the cold side (fresh air side) under the pressure of fresh air fan. Driven by direct current generated by photovoltaic system, the temperature at cold side of thermoelectric modules in EATHP system decreases and the heat is absorbed from the fresh air so that the fresh air is cooled down. At the same time, the heat generated by the hot side of the thermoelectric modules passes through hot side heat sink and is taken away by indoor exhaust air.

In winter, the SDEATHP system works in heating mode by changing the current direction of the photovoltaic system input thermoelectric modules. As shown in Fig. 2(b), fresh air is heated up by the fresh air side heat sink, and exhaust air is cooled down by the exhaust air side heat sink. In this way, the SDEATHP system realizes waste heat recovery of exhaust air. The thermoelectric heat pump has the function of active cooling and heating, and sob the system can achieve active control of fresh air. The SDEATHP system has no power consumption except that for the fans because it uses solar energy to drive the EATHP system. In addition, with power generation in situ and used in situ, and with no battery or inverter, the SDEATHP system is low in cost.

3. Experiment investigation

3.1. Experiment setup

The prototype SDEATHP system was built and installed at the Changsha, China. The annual solar radiation of Changsha is about 1163–1393 kWh/m² [27]. Twelve TE modules were used in the SDEATHP system, and three times four TE modules (4 × 3 TE modules) were connected in series, with both series connected to the PV system in a parallel, as can be seen in Fig. 3. Every two TE modules were equipped with two heat pipe sinks, one for each side of the TE modules. The heat pipe sinks were commercial ones. A fan was installed on the fresh air and exhaust air outlets respectively and powered by a DC power. The power of each fan was 1.56 W (the operating voltage was 12 V), and the air flow of the fan was 61m³/h. The dimensions of the EATHP system were 420 × 265 × 340 mm, and the EATHP was made of fiberglass with a thickness of 11 mm. The diameter of fresh air and exhaust air duct was 168 mm. The fiberglass was covered with insulation material.
that is 27 mm in thickness and 0.002 W/m•K in thermal conductivity.

The dimensions of the PV were 1640 × 992 mm, and its rated power output was about 270 W. Other parameters include short-circuit current ($i_{PV-ss} = 9.34 A$), open-circuit voltage ($u_{PV-oc} = 38.7 V$), and maximum power ($u_{PV-max} = 31.4 V$, $i_{PV-max} = 8.6 A$). The PV panel faces south and its installation angle was 30°. The type of TE module is 9500/127/060 B and its size is 39 × 39 × 3.8 mm, which is produced by FERROTEC Corporation [28]. Table 1 shows the properties of the TE modules. The experiment was carried out in the laboratory and the room size was 3 m x 3 m x 3 m.

### Table 1

| TE module       | Number of elements N | $\Delta T_{max}$ (°C) | $Q_{max}$ (W) | $S^*$ (V/K) | $R^*$ (Ω) | $K^*$ (W/°C) |
|-----------------|----------------------|------------------------|---------------|-------------|----------|-------------|
| 9500/127/060 B | 127                  | 72                     | 57            | 0.05        | 2.36     | 0.51        |

*a At the average temperature of 20 °C*

### 3.2. Test method

The temperature values mainly included ambient temperature ($T_a$), inlet fresh air temperature of EATHP ($T_{in}$), outlet fresh air temperature of EATHP ($T_{out}$), and indoor temperature ($T_{ind}$). They are tested and recorded with a PT100 temperature sensor and a paperless recorder. The locations of the major temperature sensors are
shown in Fig. 1. The solar radiation was measured by pyranometers, which was placed at the same angle as the PV modules. The sensitivity of the pyranometer was 9.731 μV/Wm². The voltage and current of the PV system were recorded by a digital multimeter. Air velocity was measured by a digital anemometer thermal wind speed tester air flow meter (AR866). The relative humidity of the inlet and outlet fresh air was measured by humidity sensors (HIH-4000-003).

3.3. Theoretical analysis of the system

The PV electrical power (P) and electrical efficiency (ηel) are calculated with the following equation:

\[ P = U \times I \]  
\[ \eta_{el} = \frac{U}{I} \times \frac{A_{	ext{PV}}}{G} \]

where \( I \) is the current of the PV module (A), \( U \) is the voltage of the PV module (V), \( A_{	ext{PV}} \) is the PV collector area (m²), and \( G \) is the solar radiation (W/m²).

The cooling capacity in cooling mode \( (Q_c) \) and heating capacity in heating mode \( (Q_h) \) of SDEATHP system are calculated by [15]:

\[ Q_c = CM(h_{fin} - h_{fout}) \]  
\[ Q_h = CM(h_{foul} - h_{fin}) \]

where \( h_{fin} \) is the enthalpy of inlet fresh air (kJ/kg), and \( h_{fout} \) is the enthalpy of the outlet fresh air (kJ/kg), \( C \) is the specific heat capacity of air, which is 1.01 kJ/(kg•K), and \( M \) is the mass flow rate of fresh air (kg/s).

According to the temperature and humidity of the fresh air, the enthalpy of fresh air can be calculated by Eqs. (5)–(7) [29]:

\[ P_v = 611.2e^{(18.678-234.5T_R)/(T_R+257.14)} \]  
\[ d = 0.6219 \left( \frac{0.01H_RP_v}{101325 - 0.01H_RP_v} \right) \]  
\[ h = 1.01T_d + (2500 + 1084T_d) \]

where \( P_v \) is the steam saturation pressure, \( T_d \) is the dry bulb temperature of the fresh air, \( h \) is the relative humidity of the fresh air, and \( h \) is the enthalpy of the fresh air.

The system coefficient of performance (COP) and the relative coefficient of performance (COPf) of the SDEATHP can be calculated by Eqs. (8)–(11) [15]:

\[ \text{COP}_c = \frac{Q_c}{(P + W)} \]  
\[ \text{COP}_h = \frac{Q_h}{(P + W)} \]  
\[ \text{COP}_{cf} = \frac{Q_c}{W} \]  
\[ \text{COP}_{hf} = \frac{Q_h}{W} \]

where \( P \) is the electric power provided by PV system, and \( W \) is the power consumption of the fan. \( \text{COP}_c \) is the system coefficient of performance of the SDEATHP in cooling mode and \( \text{COP}_h \) is the system coefficient of performance of SDEATHP in heating mode. \( \text{COP}_{cf} \) is the relative coefficient of performance of the SDEATHP in cooling mode and \( \text{COP}_{hf} \) is the relative coefficient of performance of SDEATHP in heating mode.

4. Results and discussion

4.1. Test results

The system was tested in both cooling and heating modes under actual climatic conditions. Figs. 4 and 5 show the variations of voltage, current and solar radiation on the test day in cooling and heating modes, respectively. It can be seen that the voltage and current increase as solar irradiation increases. In cooling mode, the current is 1.9A and the voltage is 8V when the solar radiation is 236W/m². When the solar radiation is increased to 1177W/m² in cooling mode at 12:45, the current and voltage reach the maximum values of 6.31A and 28.1V respectively. In heating mode, the maximum current and voltage of the SDEATHP system are 28.2V and 6.14A respectively, and when the solar radiation is 878W/m² at 12:25 on the test day, the current and voltage decrease with the decrease of solar radiation.

Figs. 6 and 7 show the electrical power of the SDEATHP in relation to solar radiation on the test day in cooling and heating modes, respectively. It can be observed that increase in irradiation intensity leads to increase in the electric power of the SDEATHP system. The maximum electric power is about 177W at the solar radiation value of 1176W/m² in cooling mode, and in heating mode, the maximum electric power is about 173 W at the solar radiation value of 876W/m². It can also be seen from Figs. 6 and 7 that the electrical efficiency of the PV system is also affected by solar radiation because the thermoelectric cooling modules are directly connected to the PV system without maximum power point tracking. The maximum electrical efficiency is 13.7% when the solar radiation is 736W/m², and the minimum electrical efficiency is only 1.1% when the solar radiation is 330W/m² in heating mode.

In cooling mode, the maximum electrical efficiency is 15% when the solar radiation is 640 W/m² and the minimum electrical efficiency is only 2.8% when the solar radiation is 111 W/m².

Fig. 8 shows the variations of inlet fresh air temperature (Tfin), outlet fresh air temperature (Tfout) and indoor temperature (Ti) in cooling mode. It can be seen that the temperature of the outlet fresh air is maintained at 26.4°C to 29.3°C, which is 5.4–9.9°C lower than the inlet fresh air temperature of 32.7°C to 37.9°C. During the test, the indoor air temperature is maintained at 23°C to 26°C, and the outlet fresh air temperature is only 0–6°C higher than it.

Fig. 9 shows the relative humidity of inlet fresh air and outlet fresh air in cooling mode. The relative humidity of outlet fresh air is between 77%–79% while the relative humidity of inlet fresh air is between 44%–61%. This is because the lower the fresh air temperature is, the lower the relative humidity is, and so the relative humidity of the outlet fresh air is greater than the relative humidity of the inlet fresh air.

Fig. 10 shows the variations of inlet fresh air temperature, outlet fresh air temperature and indoor temperature in heating mode. It can be seen that fresh air supply temperature is lower than indoor temperature when the system starts to work, and as the solar irradiation increases, the temperature of outlet fresh air gradually increases from 13.8°C to the maximum value of 31.8°C at 12:05. Meanwhile, the fresh air supply temperature is about 12°C higher than the indoor air temperature. After 2:30 pm, the fresh air supply temperature gradually decreases from 29.1°C to 21.2°C at 16:30. The maximum temperature difference of outlet fresh air and inlet fresh air is 14.7°C when the solar radiation is 852W/m² and the indoor temperature is controlled within 18–22°C most of the time.

Fig. 11 shows the variations of the cooling capacity, COPc and voltage of the SDEATHP system in cooling mode. Due to changes in solar irradiation, the cooling capacity of the system fluctuates greatly, with values between 52 W and 295 W. The cooling capacity
reaches the maximum value of 295 W when the voltage is 26.2 V, but when the voltage reaches the maximum value of 27.6 V, the cooling capacity is just 216 W. This is because the cooling capacity of the SDEATHP system is affected by the voltage and other factors, such as inlet fresh air temperature and exhaust air temperature. As shown in Fig. 11, the COPc of the SDEATHP system decreases as the operating voltage increases. The maximum COPc can reach 14.2 at 15:40, and the minimum COPc is only 0.51 at 13:10. This is because the larger the voltage is, the larger the temperature difference between the hot and cold sides of the thermoelectric modules is, resulting in lower COPc.

Fig. 12 shows that the heating capacity, COPh, and voltage of the SDEATHP system vary with time. It can be seen that after the system starts working, the heating capacity gradually increases from
38.7 W to 300.8 W at 11:40, and then gradually decreases because of solar radiation. It can be observed that the heating capacity drops rapidly after 12:05, but the voltage remains at around 28 V. This is because the temperature of the inlet fresh air increases and the indoor temperature decrease at the same time, and the sharp increase of the temperature difference between the cold and hot sides of the thermoelectric cooling system leads to sharp decrease of heating capacity. As shown in Fig. 12, the COP of SDEATHP system is affected by the voltage, and the larger the voltage is, the larger the COP is. The system can obtain a larger heating factor before 10:00 and after 15:40 because the operating voltage is small. The maximum heating coefficient is 5.6 (9:10), and the minimum heating coefficient is 1.29 (10:00).

4.2. System performance analyses and discussion

To determine the SDEATHP system’s ability to recover heat from exhaust air, we tested the performance of the SDEATHP system in summer and winter operating conditions. The experimental results are shown in Figs. 4–12. It can be seen that the SDEATHP system shows a different performance under different solar radiation, inlet fresh air temperature and exhaust air temperature. In this part, we use the test data of the solar radiation, temperatures and voltage to compute the performance of the SDEATHP system, including average cooling capacity, average electrical efficiency of PV and average system COP of the SDEATHP system.

The amount of average solar radiation is calculated according to the test results (Figs. 6 and 7). The average solar radiation received by the PV system during the testing day is 641.3 W/m² in summer and 583.7 W/m² in winter. As can be seen from Table 3, the average electrical power of the PV system is 102 W in summer and 104.6 W in winter. Overall, the average electrical efficiency of the PV is 9.4% in summer and 11% in winter. According to Figs. 11 and 12, the average SDEATHP cooling capacity and heating capacity are 158 W and 180.8 W, respectively. According to the average
electrical power and average electrical efficiency of the PV, the average system COP of the SDEATHP system is about 1.50 in cooling mode and 1.68 in heating mode. However, since the SDEATHP system uses photovoltaic to drive the thermoelectric cooling system, the system requires only 3.12 W of power for the fans. If the fan power is used as the input power of the system to calculate the performance of the system, the average relative cooling coefficient can reach 50.6 and 57.9, respectively. Improvement in the performance of the SDEATHP system can be achieved by improving heat dissipation conditions, especially the hot side of the thermoelectric modules. Moreover, the performance can be further improved by selecting higher performance of TE modules and the PV system [30].

Using solar energy to drive the thermoelectric cooler, the SDEATHP system has no power consumption except that for the fans. As can be seen from Figs. 8 and 10, the indoor temperature is 23 °C to 26 °C, and the outlet fresh air temperature is only 0–6 °C higher than it is in cooling mode. In heating conditions, the outlet fresh air temperature gradually increases after the SDEATHP system starts to work, and becomes higher than indoor temperature, reaching the maximum value of 31.8 °C at 12:05. At this time, the outlet fresh air temperature is about 12 °C higher than indoor air temperature. It indicates that the SDEATHP system can obtain higher outlet fresh air temperature in winter and lower fresh air supply temperature in summer and can achieve full recovery of exhaust air heat. However, traditional passive heat recovery systems are driven by temperature difference or enthalpy difference between fresh air and exhaust air. The temperature drop of fresh air supply temperature in summer and the temperature rise in winter are smaller, and the system cannot obtain fresh air temperature that is lower in summer and higher in winter than indoor temperature.

When there is no solar energy on rainy day or at night, the alternating current (AC) power can be converted to direct current (DC) to drive the SDEATHP system, thus achieving a continuous supply of fresh air for buildings. In addition to working in summer and winter, the SDEATHP system can also handle fresh air in swing season. Because of the decrease in outdoor fresh air temperature and in photovoltaic cell temperature in swing season, the photovoltaic cell power generation efficiency increases as compared with that in summer. In addition, the SDEATHP system can obtain lower fresh air supply temperature because of the lower temperature of fresh air inlet.

Compared with active heat pump waste heat recovery system, the SDEATHP system shows many advantages. It has no mechanical moving parts, no working fluids and is Freon free. At present, the SDEATHP system is relatively bulky. It can be reduced in size by application of more compact heat exchanger to the EATHP system. With its power generation in situ and used in situ, and with no battery or inverter, the SDEATHP system is simple and can save...
investment in power grid and reduce loss of power in transmission and distribution.

5. Discussion on photovoltaic and TE modules connection strategy

In this section, we have a theoretical discussion on photovoltaic and TE modules connection strategy of the SDEATHP. There are different options for performance simulation of photovoltaic cells [31]. In this study, the single diode $R_T$-model (five-parameter method) is selected to calculate the performance of the photovoltaic. The $I-U$ characteristic of the PV module is as follows [32]:

$$ I = I_{ph} - I_0 \frac{U + IR_T}{V_t} - 1 - \frac{U + IR_T}{R_p} $$

where $I_{ph}$ is photo current (A); $I_0$ is diode saturation current (A); $V_t = N_e n_0 k T / q$ is diode thermal voltage (V); $T$ is the temperature of the junction (K); $N_s$ is the number of solar cells in series; $n_0$ is the diode ideality factor; $k$ is Boltzmann’s constant ($1.380653 \times 10^{-23}$ J/K); $q$ is the absolute value of electron's charge ($1.60217646 \times 10^{-19}$ Coulomb); $R_p$ is the parallel resistance (Ω); $R_s$ is the series resistance (Ω). The model was called five parameters model because there are five unknown parameters of $I_{ph}$, $I_0$, $R_p$, $R_s$ and $V_t$, which can be extracted by differential evolution (DE) method [32] with the data from the manufacturer.

Based on Eq. (12), the $I-U$ curves of the photovoltaic cells at any solar radiation and temperature can be obtained. For a PV cell under actual operating conditions, the PV cell output current value is determined by the resistance value of the connected load. When photovoltaic cell is directly connected to thermoelectric modules, the specific operating point of the thermoelectric system can be determined in the $I-U$ curves of the photovoltaic cell according to the electrical characteristics of the thermoelectric cooling system.

For each connection strategy Fig. 13, the relationship between voltage and current can be calculated by Eqs. (13)–(16):

$$ V = x V_{TE} $$

$$ I = y I_{TE} $$

$$ P_{TE} = \frac{V^2}{R_{TE}} + a T_{TE} \Delta T = V_{TE} I_{TE} $$

$$ I = y \left(\frac{V}{x} - a \Delta T / R_{TE}\right). $$

where $I$ is the total current of the EATHP system, and $V$ is the total voltage of the EATHP system. $I_{TE}$ is the current of the single thermoelectric module, $V_{TE}$ is the voltage of the single thermoelectric module, $P_{TE}$ is the power consumption of the single TE modules, $x$ is the number of the TE modules in series, and $y$ is the number of the TE modules in parallel, $a$ is the Seebeck coefficient, $R_{TE}$ is the module's electrical resistance, and $\Delta T$ is the temperature difference of the cold side and hot side of the TE modules. In order to calculate the power input of the TE modules, the $\Delta T$ is assumed to be 15 °C, and the parameter value of $R_{TE}$ is 2.36Ω, according to the product information of TE modules.

In order to get outstanding performance, the SDEATHP system requires that: (1) the current of each TE module should be maintained at the current point of the maximum COP; (2) the thermoelectric modules should work within allowable working voltage range; (3) Photovoltaic cells should work as close to the point of maximum efficiency as possible. As shown in Fig. 13, there are some connection strategies for the TE modules and PV system. According to Eq. (16), we can get the $I-V$ curves of the thermoelectric modules under different connection diagrams. Moreover, when the $I-V$ curves of thermoelectric modules were added to those of the PV system, we can identify the TE and PV system working points, as shown in Fig. 4.

Fig. 14 shows the operating voltage and current curves of thermoelectric cooling modules under different connection strategies. From the $I-U$ curves of the photovoltaic cells under solar radiation of 200 W/m², 400 W/m², 600 W/m², 800 W/m², and 1000 W/m², we know that the maximum efficiency operating point of the photovoltaic under different solar radiation is between 30–38.5 V. In addition, according to our previous research, when a single TE module has a current between 1.2 and 2.2 A, it can achieve excellent performance [13]. Therefore, we can reach the following conclusion about the strategies of connecting the TE systems to the PV system for current SDEATHP system. From Fig. 14, (1) when using a $3 \times 4$ TE module, the photovoltaic cell has lower power generation ef-
6. Conclusions and recommendations

In this study, a solar-driven exhaust air thermoelectric heat pump system is tested and evaluated for its ability to recover energy from exhaust air to cool or heat fresh air. The SDEATHP system uses solar energy to drive thermoelectric heat pump, and has no power consumption except for the fans. An experimental test platform was established under actual climatic conditions to analyze its performance. The fresh air temperature can reach the maximum value of 31.8 °C, which is about 12 °C higher than the indoor air temperature in winter, and the outlet fresh air temperature is 0–6 °C higher than indoor temperature when it is 23 °C to 26 °C in summer, which indicates the SDEATHP system can effectively heat the fresh air in the winter and cool the fresh air in the summer. The average cooling and heating coefficient of performance is about 1.50 and 1.68, respectively. The system requires only 3.12 W of power for the fans and the average relative cooling coefficient in summer and the average relative heating coefficient can reach 50.6 and 57.9, respectively, which indicates the system can achieve active recovery of heat from the exhaust requiring only a minimal amount of additional energy.

Due to the fluctuation of solar radiation intensity, the fresh air temperature of the system has certain fluctuations. In the future, energy storage technologies can be used to control fresh air temperature. For example, using a battery to store electrical energy of photovoltaic cells, we can control the fresh air temperature by changing the voltage of thermoelectric modules. In addition, we can use phase change material to store the thermal energy of SDEATHP system to balance the cooling or heating needs of fresh air handling. The performance of the SDEATHP system can be further improved by optimizing the connection strategy between the TE modules and the PV system and by improving the heat dissipation conditions, especially the hot side of the thermoelectric modules. Moreover, using higher performance TE and PV systems also can improve the performance of SDEATHP system.

Declarations of interest

None.

Table 2

| Abbreviates of parameters | Symbols |
|---------------------------|---------|
| PV collector area | A_{pv} |
| system Coefficient of Performance of SDEATHP in cooling mode | COP_c |
| system Coefficient of Performance of SDEATHP in heating mode | COP_h |
| relative coefficient of performance of the SDEATHP in cooling mode | COP_{cd} |
| relative coefficient of performance of SDEATHP in heating mode | COP_{ch} |
| the solar radiation (W/m²) | G |
| relative humidity of fresh air (%) | H_r |
| the enthalpy of fresh air before being handled (kJ/kg) | h_{fin} |
| the enthalpy of fresh air after being handled (kJ/kg) | h_{fout} |
| input electric power(W) | P |
| cooling capacity of SDEATHP system in summer mode (W) | Q_c |
| heating capacity of SDEATHP system in winter mode (W) | Q_h |
| voltage (V) | U |
| the temperature of inlet fresh air (°C) | T_{in} |
| the temperature of outlet fresh air (°C) | T_{out} |
| the indoor temperature (°C) | T_{in} |
| temperature difference of thermoelectric module (°C) | ΔT |
| the specific heat capacity of air, which is 1.01 kJ/(kg·K) | C |
| the electrical efficiency of PV(%) | η_{el} |
| power consumption of fan(W) | W |
| the electrical resistance of thermoelectric module's (Ω) | R |
| the Seebeck coefficient of thermoelectric modules (VK⁻¹) | K |

Acknowledgements

The work described in this study is sponsored by the National Natural Science Foundation of China (Grant Number: No. 51708194, No. 51578221 and No.5150714), and the National Natural Science Foundation of Hunan province China (Grant Number: No. 2015JJ4002) and the China Scholarship Council (NO.201706135009). And we also want extend our great gratitude to a associate professor Nanyi Zhou, for her particular language help during the entire process of paper composing and revising.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.01.017.
References

[1] Yan Zhou, Evaluation of renewable energy utilization efficiency in buildings with energy analysis, Appl. Therm. Eng. 137 (2018) 430–439.

[2] Ping Wang, Guangcai Gong, Ying Wang, Long Li, Thermodynamic investigation of combined energy efficiency for building retrofit, Energy Build. 77 (2014) 139–148.

[3] X. Kong, S. Lu, Y. Wu, A review of building energy efficiency in China during eleventh five-year period, Energy Policy 41 (2012) 624–635.

[4] Li Lan, Zhiqiang (John) Zhai, Zhixue Lian, A two-part model for evaluation of thermal neutrality for sleeping people, Build. Environ. 132 (2018) 319–326.

[5] Zhongbing Liu, Wei-Jiao Li, Yazhen Chen, Yongqiang Luo, Ling Zhang, Review of energy conservation technologies for fresh air supply in zero energy building, Appl. Therm. Eng. 148 (2019) 544–556.

[6] L.Z. Zhang, Total Heat recovery: Heat and Moisture Recovery from Ventilation Air, Nova Science Publishers, New York, 2008.

[7] A. Mardiana-Idayu, S.B. Rifat, Review on heat recovery technologies for building applications, Renew Sust. Energ. Rev. 16 (2012) 1241–1255.

[8] Cheng Zeng, Shuli Liu, Ashish Shukla, A review on the air-to-air heat and mass exchanger technologies for building applications, Renew. Sust. Energ. Rev 75 (2017) 753–774.

[9] M.M. Ardehali, S. Torfi, Simulation modeling for analysis of effectiveness and prime movers electrical energy demand of liquid coupled energy recovery systems, Energy Convers. Manag. 47 (2006) 2431–2440.

[10] Xiao Hao, Zi-Yang Zhang, Chun-Lu Zhang, Yue Yu, Comprehensive analysis of exhaust air heat pump heat recovery efficiency in dedicated outdoor air system, 12th IEA Heat Pump Conference, 2017.

[11] Zhongbing Liu, Ling Zhang, Guangcai Gong, et al, Review of solar thermoelectric cooling technologies for use in zero energy buildings, Energ. Build. 102 (2015) 207–216.

[12] Yongqiang Luo, Ling Zhang, Zhongbing Liu, Yingzi Wang, Jing Wu, Xiaqiang Wang, Dynamic heat transfer modeling and parametric study of thermoelectric radiant cooling and heating panel system, Energ. Convers. Manag. 154 (15) (2016) 504–516.

[13] Q. Luo, G. Tang, Z. Liu, J Wang, A novel water heater integrating thermoelectric heat pump with separating thermosiphon, Appl. Therm. Eng. 25 (14-15) (2005) 2193–2200.

[14] Y.W. Kim, J. Ramousse, G. Fraisse, P. Dalicieux, Optimal sizing of a thermoelectric heat pump (THP) for heating energy-efficient buildings, Energ. Build. 70 (2014) 106–116.

[15] Tao Li, Guangta Tang, Guangcai Gong, Guangqiang Zhang, Nianping Li, Lin Zhang, Investigation of prototype thermoelectric domestic-ventilator, Appl. Therm. Eng. 29 (2009) 2016–2021.

[16] Yang Cai, Shun-Jun Mei, Di Liu, Fu-Yun Zhao, Han-Qing Wang, Thermoelectric heat recovery units applied in the energy harvest built ventilation: Parametric investigation and performance optimization, Energ. Convers. Manag. 171 (2018) 1163–1176.

[17] Zhongbing Liu, Ling Zhang, Guangcai Gong, Yongqiang Luo, Fangfang Meng, Evaluation of a prototype active solar thermoelectric radiant wall system in winter conditions, Appl. Therm. Eng. 89 (5) (2015) 36–43.

[18] Zhongbing Liu, Ling Zhang, Guangcai Gong, Experimental evaluation of a solar thermoelectric cooled ceiling combined with displacement ventilation system, Energ. Conver. Manag. 87 (2014) 559–565.

[19] Z.B. Liu, L. Zhang, Y.Q. Luo, Y.L. Zhang, Z.H. Wu, Performance evaluation of a photovoltaic thermal-compound thermoelectric ventilator system, Energ. Build. 167 (2018) 23–29.

[20] Zhongbing Liu, Yelin Zhang, Ling Zhang, Yongqiang Luo, Zhonghong Wu, Jing Wu, Yingde Yin, Guoqing Hou, Modeling and simulation of a photovoltaic thermal-compound thermoelectric ventilator system, Appl. Energy 228 (15) (2018) 1887–1900.

[21] Xi Xu, Steven Van Dessel, Evaluation of a prototype active building envelope window-system, Energ. Build. 40 (2) (2008) 168–174.

[22] Sahab A, Abdul-Wahah, Ali Elkameth, Ali M. Al-Damkhi, et al, Design and experimental investigation of portable solar thermoelectric refrigerator, Renew. Energ. 34 (1) (2009) 30–34.

[23] Tsung-chieh Cheng, Chin-Tsing Cheng, Zhu-Zin Huang, et al., Development of an energy-saving module via combination of solar cells and thermoelectric coolers for green building applications, Energy 36 (1) (2011) 133–140.

[24] Reonak Daghigh, Yavar Khaleedian, Effective design, theoretical and experimental assessment of a solar thermoelectric cooling-heating system, Solar Energy 162 (2018) 561–572.

[25] Khashif Ishad, Kairutil Habib, Firdaus Basrawi, Biduyat Baran Saha, Study of a thermoelectric air duct system assisted by photovoltaic wall for space cooling in tropical climate, Energy 119 (2017) 504–522.

[26] Zhongbing Liu, Ling Zhang, Guangcai Gong, Experimental evaluation of an active solar thermoelectric radiant wall system, Energ. Conver. Manag. 94 (2015) 253–260.

[27] Qijin Wang, Zonghong Li, Application Technology of Solar Energy, China society press, Beijing, 2005.

[28] Ferrotec. The datasheet of 1303958716. http://www.ferrotec.com.cn/sharefile/1303958716.pdf.

[29] Rong Jianwei, Calculation and application of wet bulb temperature, Refrigerat. Technol. 4 (2008) 38–40.

[30] P. Heremans, Low-Dimensional Thermoelectricity, Acta Phys. Polonica A 108 (2005) 609–634.

[31] V.J. Chin, Z. Salam, K. Ishtaque, Cell, modelling and model parameters estimation techniques for photovoltaic simulator application: a review, Appl. Energy 154 (2015) 500–519.

[32] W. Cong, Z. Cai, Parameter extraction of solar cell models using repaired adaptive differential evolution, Solar Energ. 94 (2013) 209–220.