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Thermoelectric system applications in buildings: A review of key factors and control methods

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ABSTRACT

A low coefficient of performance (COP) limits the development of thermoelectric (TE) systems in buildings. However, considering their good integration with solar systems and budling structures, there is good application potential for TE systems in buildings. In many previous works, control systems indeed help TE systems to improve their performance. Therefore, the objective of this work is to analyze and summarize key factors in the control process and control methods for designing and optimizing the control systems for TE systems in buildings. This work reviews relevant publications from 2000 to 2022 on control applications of TE systems in different fields and groups them into key factors and control methods. The analysis of the key factors indicates the power strength of Peltier cells, the number of working Peltier cells, the temperature difference between the cold and hot sides, and the temperature difference between the object side and the indoor space as significant factors. Additionally, the most relevant control methods for the operating voltage or current are also classified. It is crucial to appropriately adjust these key factors using suitable control methods to achieve improved COP. Regarding the control application of TE systems in buildings, this is an issue that has not been studied with specific attention. Therefore, the analysis of key factors and control methods is meaningful for control systems to improve the performance of TE systems in buildings, especially under dynamic operating conditions of the built environment.

Abbreviations

Nomenclature

AI	Artificial intelligent
ANN	Artificial neuro network
COP	Coefficient of performance
COP_c	Coefficient of performance for cooling
COP_h	Coefficient of performance for heating
e(t)	Error between reference and output
FL	Fuzzy logic
HDO	Heat disturbance observer

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HVAC	Heating, ventilation, and air conditioning
IoT	Internet of things
K_p	Proportional tuning constant
K_i	Integral tuning constant
K_d	Differential tuning constant
m	Mass flow rate (kg/s)
MPC	Model predictive control
N	Number of working Peltier cells
N_{opt}	Optimal number of working Peltier cells
NF	Neuro fuzzy
P	Power (W)
PI	Proportional integral
PD	Proportional differential
PID	Proportional integral differential
PSO	Particle swarm optimization
PWM	Power width modulation
r(t)	Reference
SMC	Sliding mode control
T_c	Temperature at cold side (K or °C)
T_h	Temperature at hot side (K or °C)
T_i	Indoor temperature (K or °C)
T_o	Outdoor temperature (K or °C)
TE	Thermoelectric
TEM(s)	Thermoelectric module(s)
u(t)	control signal
y(t)	Output
ΔT_{hc}	Temperature difference between the hot and cold sides (K or °C)
ΔT_{io}	Temperature difference between indoors and outdoors (K or °C)
ΔT_{si}	Temperature difference between the object side and the indoor space (K or °C)

1. Introduction

Buildings account directly and indirectly for 30% of global energy consumption, including nearly 55% of global electricity consumption [1]. As a result, the development of more energy-efficient systems for building draws wide concern worldwide. In this context, this article pays special attention to the utilization of thermoelectricity in buildings, a system that comes from other fields and has been studied for years for its implementation in buildings. Several application cases of thermoelectric (TE) systems in buildings offer notable advantages, such as easy assembly and installation with buildings, potential performance, space-saving benefits, and compatibility with the direct current produced by renewable energy sources [2].

Ibáñez-Puy et al. [3] analyzed the performance of a TE system under building conditions using an adiabatic box prototype. The targeted temperature could be achieved at approximately 20 °C with a coefficient of performance for cooling (COP_c) of 1.4 under an ambient temperature of 25 °C. Similarly, a coefficient of performance for heating (COP_h) of 2.7 under an ambient temperature of 15 °C was achieved. Martín-Gómez et al. [4] presented a TE wall prototype capable of regulating indoor temperature with a COP_c of 0.79–1.78 in cooling mode and with a COP_h of 1.02–1.91 in the heating mode depending on the input voltages. Xu et al. [5] designed a TE window system prototype for temperature control. The hot-side temperature could reach 60 °C in the heating mode while the cold-side temperature could reach 15 °C in the cooling mode, under an ambient temperature of approximately 20 °C. Furthermore, TE systems could be installed on the ceiling [6] or roof [7] as well as integrated into the ventilation system [8]. For instance, Luo et al. [9] indicated that their TE ceiling system could generate a cooling capacity ranging from 48.6 W/m^2 to 104.1 W/m^2 with COP_c ranging from 1.06 to 2.29 depending on the working current ranging from 2 A to 3 A.

However, compared to COP_h ranging from 3.5 to 5.6 [10] and COP_c ranging from 2.54 to 4.56 [11] of conventional heating, ventilation, and air conditioning (HVAC) systems, the lower performance of TE systems limits largely the application of TE systems in buildings. Nevertheless, due to their good integration with solar energy systems and building structures, general TE systems still have considerable potential for application in buildings. To enhance the performance of TE systems, reducing thermal resistance and using heat recovery units are helpful [12]. For instance, the installation of heat sinks with a thermal conductance of 30 W/K can increase both the COP and thermal capacity of the TE system [13]. Martín-Gómez et al. [4] also emphasized the importance of fans and heat sinks in improving the system performance. Additionally, Hagenkamp et al. [14] suggested that incorporating an additional heat recovery system can benefit the TE system with fewer Peltier cells.

In addition to these improvements from strengthening heat transfer or incorporating heat recovery units, and utilizing high-performance thermoelectric materials such as metal material [15,16], nanocrystal material [17] etc., and effective ceramic structures consisted of ceramic material [18–20], the control system plays a crucial role in optimizing system parameters under various working conditions [21] for optimal performance [22,23]. However, designing a robust and sensitive control system becomes challenging due to dynamic heat disturbance [24] from the ambient and system nonlinearity resulting from the dependency on several parameters of TE systems. Therefore, it is essential to analyze and summarize relevant key factors and control methods of TE systems in various fields to design appropriate control strategies for control systems under specific conditions.

In various fields, there are different application demands for the accuracy, response, and robustness of the control system. As a result, the key factors considered, and the control methods employed for the control system vary accordingly. In the electronics field, for instance, electronic components exhibit high temperature sensitivity, necessitating a greater emphasis on response and accuracy. Thakor et al. [25] applied PID control to adjust the input power to Peltier cells, achieving a target temperature with a mere overshoot of 0.069 °C after approximately 178 s. In the medical field, precise temperature control is of importance for organ conservation or blood-free surgical procedures, thereby requiring control systems with robustness and accuracy. Hakan et al. [26] developed a TE control system using P control which successfully attained the target temperature with an error of ±0.3 °C and reliably maintained the temperature for a determined duration.

In the building field, similar considerations of accuracy, response, and robustness are also necessary to control systems, but the requirements for controlling indoor set points are generally more permissive compared to the fields of electronics or medicine. An experiment conducted on cyclic fluctuating air temperature showed that the thermal dissatisfaction rate for controlling air temperature between 26 °C and 28 °C in a cyclic manner is lower than that for maintaining a constant air temperature control at 26 °C [27]. This suggests that there is a more permissive demand for accuracy and stability in indoor temperature control. In terms of response, Yu et al. [28] found that the temperature drop rate ranges from 1.8 °C/h to 2.4 °C/h in the height range of 0.7 m–1.5 m from the ground using a radiant TE cooling ceiling set at 16 °C–18 °C. Hence, while high accuracy, robustness, and response are not necessarily critical for indoor temperature control in common buildings, maintaining an appropriate level of accuracy, robustness, and response is important to meet indoor set point while also saving energy.

To improve the performance of TE systems in buildings, it is meaningful to analyze and summarize control factors and control methods for TE systems utilized in different fields. This analysis can then be used to design optimal control strategies for TE control systems in buildings, considering uncertainties and dynamic disturbances to achieve desired indoor set point under specific ambient conditions. However, a comprehensive investigation of control factors and methods for TE systems in buildings is currently lacking, despite its potential usefulness in designing control strategies for various control processes.

Therefore, the objective of this work is to analyze and summarize control factors and methods for TE systems utilized in different fields, with a particle focus on their applicability in buildings. Then TE systems in buildings can be related to different control possibilities so that the weaknesses and strengths of each option allow new development options to be proposed.

The structure of this paper is as follows: Section 2 presents the methodology employed for collecting relevant literature and establish categorization criteria. Section 3 describes and analyzes key factors involved in the control process, specifically in relation to building applications. Section 4 groups different control methods for efficiently adjusting key factors to meet set points. Section 5 presents a discussion of the findings and further compares all the analysis results, and the final section presents the conclusions drawn from the discussion.

2. Methodology

As shown in Fig. 1, building TE systems consist of TE modules and heat dissipation components (heat sinks, fans, etc.), which adjust indoor temperature by controlling the power strength of working TE modules and the operations of fans by controllers. Despite the significance of these control processes, a comprehensive review analyzing and summarizing control factors and methods specific to TE systems in buildings has not been reported thus far. This paper aims to fill this gap by providing a focused review of the state-of-the-art control factor and methods. The analysis and summary of relevant references serve as the basis for identifying optimal control strategies for TE systems in buildings.

2.1. Search queries

The authors focus on applications of thermoelectricity in buildings for heating or cooling space in the field of control systems. Therefore, research related to control factors, parameters, strategies, or methods for TE systems from 2000 to 2022 has been gathered through two online journal databases: Scopus and Web of Science (WOS). The development of TE generators and TE materials is not considered in this study. As shown in Table 1, the search parameters are used. The query strings used for Scopus and WOS are “(ABS (thermoelectricity OR Peltier) AND ABS (heat* OR cool*) AND NOT ABS (generat*)) AND PUBYEAR > 1999 AND PUBYEAR < 2023”

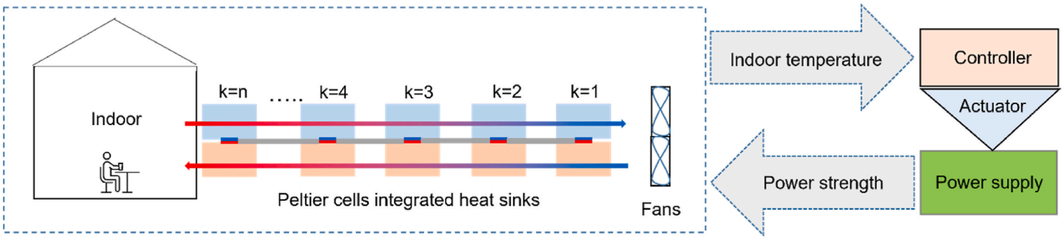

Fig. 1. Concept of TE control systems in buildings.

Table 1
Search conditions.

Publication years			01/01/2000-31/12/2022
Topic	Keywords (ABS)	Databases	Documents
TE applications for heating and cooling	thermoelectricity OR Peltier And heat* OR cool* AND NOT generat*	Scopus WOS	2237 2237
Development of control systems of TE systems for heating and cooling	thermoelectric* OR Peltier AND control* AND method* OR strateg* OR factor* OR parameter* AND heat* OR cool* AND NOT generat*	Scopus WOS	308 316

for TE application for heating and cooling, and further "(ABS (thermoelectricity OR Peltier) AND ABS (control*) AND ABS (method* OR strateg* OR factor* OR parameter*) AND ABS (heat* OR cool*) AND NOT ABS (generat*)) AND PUBYEAR $>$1999 AND PUBYEAR $<$2023" for the development of control systems of TE systems for heating and cooling.

All the searched publications have been analyzed and filtered. As shown in Fig. 2, the number of publications related to TE applications has considerably increased in recent years (indicated by the red tendency line). Among these publications, the research on TE control also correspondingly increases (indicated by the blue tendency line). This upward trend in control systems of TE systems including applications in buildings highlights the need for a comprehensive review article that explores control factors and methods for TE control systems in buildings.

2.2. Classification criteria

As shown in Table 2, the main keywords extracted from the literature have been filtered and classified into six groups. This review focuses on the groups of key factors and control methods for TE control systems.

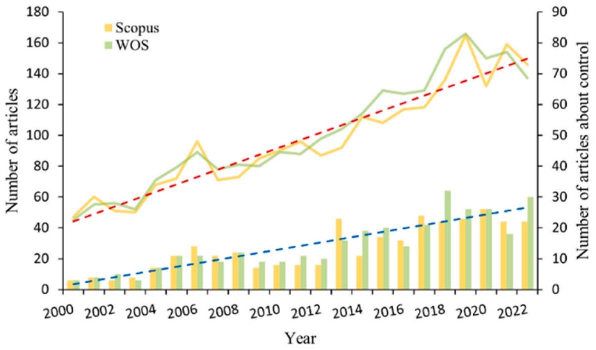

Fig. 2. The linear graphs correspond to the number of relevant articles published (left axis) and the bars correspond to the number of articles published specifically about control (right axis).

Table 2
Keywords about applications of TE control systems within the search range.

Control system					
Fields	Types	Control methods	Control factors	Improvement targets	Demands
Aerospace	AI control	Adaptive PID control	Electric power	COP	Accuracy
Building	Closed loop control	ANN control	Flow rate	Cost effectiveness	Durability
Electronics	Linear control	Fuzzy control	Indoor temperature	Energy efficiency	Response/Sensitivity
Industrials	Nonlinear control	Machine learning	Operating current	Heat leakage	Robustness/Stability
Mechanics	On-line control	MPC	Operating voltage	Ohmic resistance	
Medicine	Optimal control	PID control	Outlet temperature	Parameter optimization	
	Precise control	PWM	Surface temperature	Power loss	
	Real-time control	SMC	Temperature difference	Seebeck coefficient	
	Robust control		Thermal capacity	Thermal resistance	

In the group of control factors, this work has further defined thermal capacity, electric power, operating voltage, and operating current as indicators of the power strength of Peltier cells and the number of working Peltier cells. This is because the thermal capacity is influenced not only by the input voltage or current but also largely affected by the number of working Peltier cells. Furthermore, factors such as temperature difference, flow rate, and surface temperature are associated with the temperature difference between the cold side and the hot side. Additionally, the surface temperature, the indoor temperature, and the temperature difference were defined as the temperature difference between the object side and the indoor space. Consequently, the control factors have been summarized as the power strength of Peltier cells, the number of working Peltier cells, the temperature difference between the cold side and the hot side, and the temperature difference between the object side and the indoor space.

In terms of the control methods, a variety of control applications for TE systems have been identified, as illustrated in Table 2. After conducting statistical analysis, this work has classified the main control methods used in TE systems as PID control, Adaptive PID control, and Fuzzy logic control. To visually depict the statistical findings, a keywords analysis has been made using the software VOSviewer [29], as shown in Fig. 3. The analysis reveals that the main keywords associated with control methods include PID control, Fuzzy logic control, and Fuzzy PID (Adaptive PID control). Finally, the conceptual structure of the classification could be shown in Fig. 4.

3. Analysis of key factors

A certain number of Peltier cells are employed in TE systems, and their operating voltage or current could be changed to adjust thermal capacity due to Peltier effect [30]. This allows for adapting to different indoor thermal demands to achieve the desired indoor temperature. Consequently, there are temperature differences between the cold and hot sides as well as between the object side and the indoor space. In the working process, these key factors classified in the session of classification criteria significantly influence the system performance and the effectiveness of indoor conditioning.

A summary of these key factors proposed in literature can be found in Table 3. It has been demonstrated that by appropriately adjusting the power strength of Peltier cells, the number of working Peltier cells, the temperature difference between the cold and hot

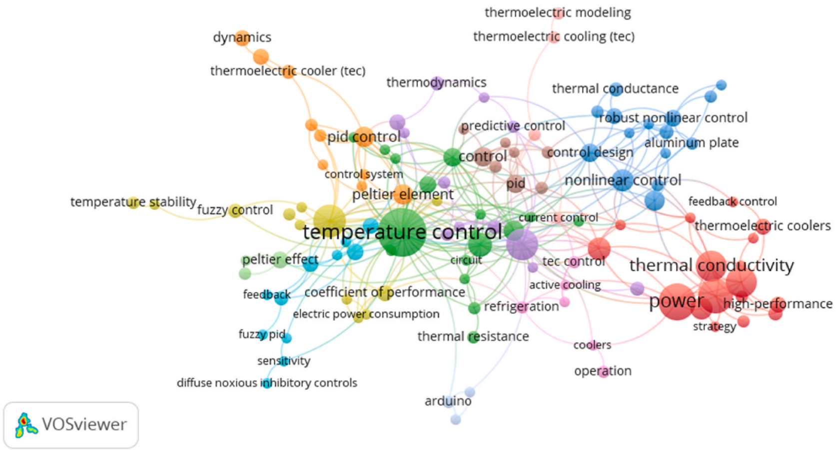

Fig. 3. Scientific analysis map with co-occurrence clusters of keywords based on TE control system.

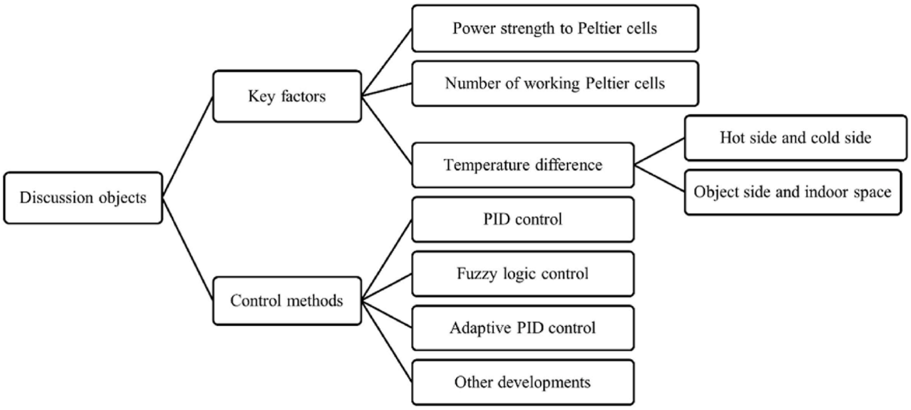

Fig. 4. Conceptual structure of discussion objects based on the classification according to the literature found.

Table 3
Summarization of key factors in control process of TE systems considered in the literature by chronological order.

Ref.	Factors				Working conditions	COP_h	COP_c	Control methods
	P	N	ΔT_{hc}	ΔT_{si}				
2005 [31]	600 W	10–60			T_o of 38 °C; T_i of 20 °C		1.1–1.2	
2007 [5]	3–7 V	8	15–30 °C		T_o of 23 °C; T_i of 30–50 °C and 15–18 °C	1.4–2.4	0.5–1.4	Step change
2010 [32]	1–3 A	3	5–14 °C	1–5 °C	T_o of 30 °C; T_i of 25–27 °C		0.45	
2013 [33]	1.1–2.3 A	5–100			T_o of −10 °C; T_i of 20 °C	1.2–2.5		
2014 [8]	1–5 A	12	5–20 °C	12–26 °C	T_o of 30–36 °C and 6–14 °C; T_i of 26 and 20 °C	4.2	4.8	
2015 [34]	0.7–2 A	50–250	5–40 °C		T_o of 2–6 °C; T_i of 15 °C	2.0–2.5		
2015 [35]	2–7 A	24			T_o of 30 °C; T_i of 25 °C		0.4–0.7	
2017 [36]	4–9 V	3	18–24 °C	2–3 °C	T_o of 2–4 °C; T_i of 19–24 °C	2.0–2.6		
2018 [37]	36 W; 144 W	2			T_o of 28–31 °C; T_i of 22 °C			On-Off control
2018 [38]	114 W		22 °C	5 °C	T_o of 27 °C; T_i of 19 °C		0.4	
2018 [22]	4–12 V	6	14–35 °C		T_o of 10–13 °C; T_i of 24–50 °C	1.1–2.1		
2019 [39]	8.5–12 V	2–6			T_o of 25–60 °C		0.2–2.4	
2020 [21]	720 W	24			T_o of 28–35 °C; T_i of 26–28 °C		0.8–1.2	IoT-based control
2021 [40]	3–12 A		10–40 °C		T_o of 30 °C; T_i of 25–27 °C	1.4–4.0	0.4–3.0	
2021 [41]	100–2000 W	1–50			T_o of -10-19 °C; T_i of 25–27 °C	0.9–3.0		
2021 [13]	0.5–1.5 A	4	10–15 °C	7–15 °C	T_o of 15 and 29 °C; T_i of 20 and 24 °C	1.0–8.0	2.0–7.0	
2022 [12]	100–1000 W	1–100			T_o of 0–10 °C; T_i of 20 °C	1.6–3.3	0.5–3.0	
	50–420 W				T_o of 30–40 °C; T_i of 25 °C			

side, and/or the temperature difference between the object side and the indoor space, a higher COP can be achieved while reaching the desired indoor temperature.

3.1. Power strength of peltier cells

By increasing the operating current or voltage, the thermal capacity of TE systems can be enhanced [21]. However, this also leads to an increase in the temperature difference between the cold and hot side, subsequently resulting higher heat conductance and a reduction in overall efficiency. Han et al. [8] simulated that the COP increases (or decreases) as the power strength of Peltier cells decreases (or increases). In experimental studies, Zuazua-Ros et al. [22] tested a TE system integrated with walls and observed that the COP_h decreased from 2.1 to 1.0 as the power strength of Peltier cells increased. Similarly, Mainil et al. [38] noted that the COP_c decreased from 0.8 to 0.4 with an increase in thermal capacity from 50.5 W to 113.64 W. Furthermore, a reduction in indoor temperature can be achieved from 3 °C to 5.3 °C when Irshad et al. [35] operated the TE system under an operating current of 6 A. However, when the operating current exceeded 6 A, they observed a decline in cooling performance.

Hence, taking into account the daily variation in ambient temperature, the power strength of Peltier cells can be modulated dynamically to achieve the desired indoor temperature and enhance system performance. In response to the ambient variation, Peltier cells can be operated at various levels of partial load by changing the operating current [42]. In a study conducted by Haryanti et al. [37], a TE system was designed with multiple working modes, allowing for switching between high mode and low mode by adjusting the power strength of Peltier cells based on the actual cooling load variation. Similarly, Wang et al. [36] operated a TE system at a lower voltage to achieve a higher COP under ambient temperatures above 10 °C, while a higher voltage was utilized to meet the necessary thermal capacity with a lower COP under ambient temperatures below 10 °C.

Moreover, Luo et al. [43] applied specific operating currents to Peltier cells under specific thermal conditions. This approach ensured that the surface temperature of integrated TE walls matched the indoor temperature, thereby achieving a zero gain/loss envelope. And Seyednezhad et al. [40] implemented individual control over Peltier cells to adapt various operation conditions with different operating voltages.

3.2. Number of working peltier cells

As mentioned above, increasing the power strength of Peltier cells leads to a decrease in COP [4]. However, TE systems are required to provide significant thermal capacity with high power strength to achieve the desired indoor temperature under a large temperature difference between indoors and outdoors. Irshad et al. [21] adjusted the cooling capacity by aligning and disassociating Peltier cells based on the data input of indoor and outdoor temperature. In their study, during the initial and final phases of operation, the outdoor temperature is lower, the operations of two columns of Peltier cells were deactivated. However, during peak hours, all the columns are connected in parallel to utilize the maximum cooling capacity, thereby improving the performance.

Additionally, Kihre et al. [31] proposed a multi-objective optimization method and concluded that a small number of working Peltier cells would result in a uniform distribution of heat transfer. However, the enhancement of the COP from the decreasing total input power as the distribution density of Peltier cells increases through the addition of more working Peltier cells. Hagenkamp et al. [41] found that the efficiency improves with a higher number of modules in the system. Furthermore, Dizaji et al. [39] tested the cooling characteristics of TE systems of 2-joined, 4-joined, and 6-joined thermoelectric module (TEM) while maintaining the same cooling capacity by decreasing the power strength of each Peltier cell as the number of working Peltier cells increased. The results indicated that 6-joined TEM provides a COP approximately 100% higher than 2-joined TEM, despite having the same total input current. These findings suggest that employing more working Peltier cells with lower power strength can provide the required thermal capacity while improving the COP.

However, it is important to consider the economic implications when increasing the number of Peltier cells in TE systems [31]. What's more, it has been observed that there is an optimal number of working Peltier cells for achieving the best performance, and exceeding this optimal value can lead to a decrease in COP [12]. To determine the optimal number of working Peltier cells in TE systems for different heat loads, Díaz-de-Garayo et al. [12] tested their TE heat pumps with different numbers of module. Based on their experimental results, COP increased with an increasing number of working Peltier cells up to the optimal value. However, the COP started to decreases when the number of working Peltier cells increased beyond the optimal value. In a simulation study conducted by Allouhi et al. [34], a TE system with Peltier cells ranging from 50 to 250 was examined. It was found that when the number of working Peltier cells was below 150, the COP increased as the working Peltier cells increased, while the COP decreased as the working Peltier cells increased beyond 150.

In addition, it is crucial to consider the optimal number of working Peltier cells when adjusting thermal capacity in different working mode. Kim et al. [33,44] explored the optimal number of working Peltier cells under different total power strengths (thermal capacities). They discovered that the optimal number of working Peltier cells at the maximal COP point decreased as the power strength increased. A similar relationship between the optimal number of working Peltier cells and power strength can be also observed in other TE heat pumps [12]. Therefore, it is easier to exceed the optimal number of working Peltier cells by adding more cells when the heat load increases. Considering the economic cost, it is important to consider the increased investment required for each additional cell when determining the number of installed Peltier cells. Therefore, the decision regarding the number of Peltier cells to be installed should be based on the optimal number required to handle the heat load during periods of high frequency of use.

3.3. Temperature difference

3.3.1. Temperature difference between the cold and hot sides

Thanks to the Peltier effect, when Peltier cells are applied with the operating voltage or current, one side starts to absorb heat for cooling while another side releases heat for heating. This creates a temperature difference between the cold and hot sides, which leads to thermal conductance within the Peltier cell itself and then a reduction of thermal capacity at both sides. Allouhi et al. [34] compared the hourly COP with a fixed current and a constant number of working Peltier cells in scenarios involving large and small temperature difference between the cold and hot sides (referred to as high mode and low mode). Their findings indicated that a higher COP can be gained under a smaller temperature difference. In another experiment, the temperature difference between the cold and hot sides increased from 3.79 °C to 18.48 °C, the COP_h decreased by 19.13% [36]. Therefore, reducing the temperature difference between the cold and hot sides of Peltier cells could enhance the overall COP of the system [40,45].

As mentioned above, increasing the power strength of Peltier cells to meet indoor thermal demand is always accompanied by an increase in temperature difference between the cold and hot sides. To reduce the temperature difference between the cold and hot sides, one approach is to decrease the power strength of Peltier cells. Xu et al. [5] found that adjustments to the power strength of Peltier cells had minimal impact on the cold-side temperature (less than 2 °C in cooling mode). However, they observed a significant effect on the hot-side temperature with a difference of 5 °C–10 °C for each step change in operating voltage. It is important to note that adjusting the power strength of Peltier cells to decrease the temperature difference between the cold and hot sides also decreases the thermal capacity, which can consequently impact the effectiveness of the indoor air conditioning.

To address this issue, various heat sinks with different structures, materials, and shapes are employed to strengthen heat dissipation and decrease the temperature difference between the cold and hot sides [46,47]. Even if the power strength of Peltier cells increases, a relatively better COP can be achieved by utilizing heat sinks which strengthen the heat transfer between Peltier cells and air flows. Wang et al. [13] used heat sinks to increase the thermal conductance of the TE wall. They observed that both COP_c and cooling capacity per unit area increased as the thermal conductance of the heat sink increases. However, beyond a thermal conductance of 30 W/K, both COP_c and thermal capacity per unit area reached a stable state. In another TE prototype [5], increasing the performance of the heat sink also improved the overall performance of the TEMs during the summer season.

Moreover, the use of fluid machines facilitating the fluid flow to strengthen thermal convection can further improve heat transfer between Peltier cells and flows, thereby reducing the temperature difference between the cold and hot sides and enhancing the system performance [48]. Mohammad et al. [49] presented an optimization framework to find the optimal operating current and fan rotation speed that minimizes the overall power consumption while achieving the desired temperature. Mironova et al. [50] adjusted the power strength of fans installed on the hot side to achieve the lowest possible cold-side temperature. In another study [37], a motor fan was controlled to operate at high speed in high mode and at low speed in low mode, maintaining an appropriate temperature difference between the cold and hot sides.

3.3.2. Temperature difference between the object side and the indoor space

Supply air is heated up or cooled down by the heat released from or absorbed by the object sides of Peltier cell. The supply air temperature serves as an intermediate variable between the object side and the indoor space, enabling the adjustment of the indoor temperature to meet the desired set point. With a constant flow rate and stable ambient temperature, a higher object-side temperature leads to a higher supply air temperature [12]. Consequently, this results in a higher indoor temperature and vice versa. However, higher object-side temperature (in heating mode) or lower object-side temperature (in cooling mode) always consumes more energy and can potentially lead to indoor overheating or overcooling. To prevent such issues, TE control systems should understand the relationship between object-side temperature and the desired indoor set point.

Wang et al. [36] tested a TE system with an operating voltage ranging from 4 V to 9 V under an ambient temperature of 2 °C–4 °C. The experimental results demonstrated that the temperature difference between the object side and the indoor space remained at 2 °C–3 °C. The indoor temperature increases from 18 °C to 24 °C as the operating voltage increased. These results indicated that sufficient thermal comfort can be achieved by the TE system with a temperature difference between the object side and the indoor space of 2 °C–3 °C, considering that occupied areas require a suitable temperature range of 18 °C–21 °C and transient occupancy areas require a range of 16 °C–18 °C [51].

In a study conducted by Maneewan et al. [32], the results showed that the indoor temperature ranged from 25.8 °C to 27.5 °C with an object-side temperature of 22 °C under an average ambient temperature of 30 °C. It was found that a relatively small temperature difference between the object side and the indoor space ranging from 4 °C to 6 °C was sufficient to meet indoor cooling demand, particularly under low ambient temperature conditions. Similarly, Mainil et al. [38] tested a TE cooler box and found that the temperature inside the box can be remained at 19 °C with an object-side temperature of 14 °C (a temperature difference between object-side temperature and desired temperature of 5 °C) under an ambient temperature of 27 °C.

Wang et al. [13] analyzed the performance of a TE wall for heating and cooling and demonstrated that the TE system was able to achieve an indoor temperature ranging from 24 °C to 26 °C in summer, with a temperature difference between the object side and the indoor space of 8 °C. In winter, the system created an indoor temperature of 20 °C, with a temperature difference between the object side and the indoor space ranging from 6 °C to 15 °C. There is a larger temperature difference between the object side and the indoor space. It should be understood that these variations in temperature difference can be attributed to difference in system structure, experimental scale, and working conditions in these studies. Nonetheless, a common observation from these studies is that the temperature difference between the object side and the indoor space tends to increase as the indoor thermal demand increases, resulting in a decrease in the COP [8].

As analyzed in section 3, TE systems have the flexibility to operate at different power strengths, allowing for various working modes under different working conditions. This enables the system to achieve the desired indoor temperature in a dynamic ambient environment by adjusting the power strength of Peltier cells accordingly. However, as the power strength of Peltier cells increases to meet higher thermal demand, the temperature difference between the cold and hot sides also increases. This leads to a decrease in the COP due to the larger heat conductance between the cold and the hot sides. To address this challenge, there are two main approaches. Firstly, sharing the total thermal demand with more working Peltier cells can realize the improvement of the overall COP. By increasing the number of working Peltier cells, they can be operated at lower power strength for the same thermal demand. Secondly, installing heat sinks of high conductance and fluid mechanical devices can enhance the efficiency of heat transfer from Peltier cells to flows. This helps to decrease the temperature difference between the cold and hot sides. By implementing these solutions, the indoor temperature can be adjusted with a lower temperature difference between the cold and hot sides as well as between the object side and the indoor space, leading to enhance the COP.

However, it is not sufficient for an effective control system only to understand the relationships among these key factors. It is equally important to implement an appropriate control method that can modulate key factor. A well-designed control system with a suitable control method can significantly improve the performance compared to those without control methods [52]. However, only a limited amount of research, as shown in Table 3, has explored the use of the control method in TE systems to enhance the COP. Therefore, another review analysis for control methods in TE systems is essential for the development of optimal TE control systems [22].

4. Analysis of control methods

The key factors can be modulated by adjusting the operating current or voltage of Peltier cells in response to the actual working conditions. However, the actual working conditions of TE systems are often unstable due to the dynamic thermal disturbance from other system components, occupants' behavior, and ambient temperature variations [53]. Therefore, various types of control systems have been developed to address these diverse working conditions, as shown in Table 2. To optimize performance, each TE control system requires the implementation of appropriate control methods for better performance [54]. A summarization of the control methods reviewed in this paper can be found in Table 4.

4.1. PID control

Proportional integral differential (PID) control are widely used in over 95% of closed-loop systems and can be implemented using hardware with various amplifiers or software tools [25]. As shown in Fig. 5, the PID controller outputs a control signal to the actuator based on the error between the real-time value and the set point. The effectiveness of the PID controller is influenced by the tuning of control parameters such as K_p, K_i, and K_d. Firdaus et al. [72] employed PID control to regulate the operating current of Peltier cells. In their study, a TE control system consists of the controller, Peltier cells, and sensors.

TE systems employing PID control can adjust relevant factors to meet the desired indoor temperature with better COP in a faster, more precise, and stable manner. Sundayani et al. [76] demonstrated that PID control enabled reaching a desired temperature three times faster compared to systems without PID control. Bazzo et al. [74] proposed a precise temperature control system based on PI control, achieving a maximum error of ±0.1 °C and reducing temperature fluctuation by 92. Saifizi et al. [81] designed a PD temperature control system, maintaining the object temperature at 4 °C with an error of only 0.21 °C as the ambient temperature increases. And Du et al. [71] employed PID control to adjust the operating voltage of Peltier cells, successfully maintaining the object temperature at the desired temperature with a fluctuation of ±0.5 °C within 20 min.

The performance of a PID control system relies on the control parameters chosen, which encompass response speed, robustness, accuracy, and stability. Boubaris et al. [80] applied PI control with fixed control parameters to maintain the temperature difference

Table 4
Summarization of control methods for TE systems considered in the literatures by chronological order.

Methods	Fields	Objectives	Results	
			Benefits	Drawbacks
Individual control [55,56]	Electronics	Optimize COP	Against non-uniform heat distribution	Complex system
FL [57]	Prototype	High stability	Steady state error of ±0.005 °C	Fuzzy rules and functions
FL [58,59]	Industrials	High response and accuracy	Reach 29 °C within 4 min	Fuzzy rules and functions
NF [60]	Medicine	Robustness, response, accuracy	Keep 30 °C within 10 min	Heavy calculations
MPC [61]	Prototype	High robustness	Reach 25 °C within 200–300 s	Model dependency
ANN-PID [62,63]	Building	High robustness and response	Achieve 18 °C without overshoot within 340 s	Heavy calculations and data learning
PID/FL [26]	Medicine	Accuracy	Reach 15 °C within 5–8 min	
HDO [64–67]	Prototype	Compensate for current	Against thermal disturbance	Add complexity
FL [68]	Electronics	High robustness	Reach −20 °C with error of ±3%	
FL-PID [69]	Mechanics	High robustness and accuracy	High dynamic response	Add complexity
NF- PID [70]	Mechanics	High robustness and accuracy	Dynamic response without overshoot	Heavy calculations
PID [71]	Aerospace	High accuracy	Reach set point with error of ±0.5 °C	Low dynamic response
PID [25]	Electronics	High accuracy	Reach 25 °C around 180 s	
PID [72]	Electronics	Save energy		Low dynamic response
FL [73]	Medicine	High response	Reach set points within 5 min	Set of data base
PI [74]	Electronics	High accuracy	Temperature ripple of ±0.1 °C	Model-dependent
SMC [24,50]	Mechanics	Against thermal disturbance	Compensate for thermal disturbance	Model-dependent
Pulse operation [48]	Building	Higher COP	High response and accuracy	
Adaptive PI [75]	Mechanics	High robustness	Optimize stability	Model-dependent
PID [76]	Prototype	Higher response	3 times faster	Fixed control parameters
HDO [77]	Prototype	Higher response	High response and stability	Add complexity
ANN [78]	Electronics	Higher COP	High response and stability	Data learning
PSO-PID [79]	Prototype	High stability	Simply thermal process	Model-dependent
PI [80]	Prototype	Higher COP	High response	
PD [81]	Electronics	High robustness	Steady-state error of 0.4 °C	Fixed control parameters
PID [82]	Electronics	High accuracy and stability	Less fluctuation of temperature	Manual tuning
PID [83]	Industrials	High accuracy and stability	High response and stability	Fixed control parameters
FL [84]	Prototype	Flexible control	Oscillation of about 2 °C	Fuzzy rules and functions
PID/FL [52]	Electronics	High response and accuracy	Better effectiveness	

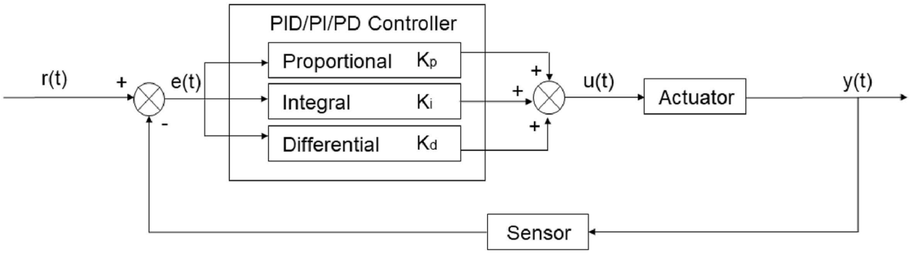

Fig. 5. Flow chart of the PI/PD/PID controller [25].

between the cold and hot sides by controlling the operating current of Peltier cells and fans. However, PID control with fixed control parameters always exhibits suboptimal performance in nonlinear TE system due to dynamic thermal disturbance [60]. The performance of the PID control system always deteriorates when the operating condition deviate from the operation condition used to tune the control parameters [85]. Therefore tuning the control parameters of PID control is critical when operating in dynamic working ambient. Arman et al. [82] manually optimized control parameters to control the PWM signals and found that the tuned control parameters of K_p 90, K_i 30, and K_d 80 showed the best performance in minimizing temperature error. However, Singgin et al. [83] tested different PID control systems with various control parameters and evaluated that the systems with the control parameters of K_p 5.53, K_i 8, and K_d 2 have a better performance. Hence, the optimal control parameters vary for different TE control systems and depend on the specific working conditions.

4.2. Adaptive PID control

As mentioned previously, conventional PID control often exhibits a low performance in dynamic ambient conditions [60]. To address this limitation, adaptive PID control, which dynamically tunes control parameters based on ambient variations, would significantly improve the performance of the control system. Song et al. [62] designed a TE temperature control system. The control system can adapt ambient variations and compensate for nonlinear loss by tuned control parameters which are adjusted according to the fuzzy rules, as shown in Fig. 6. In the study, the response time for cooling down by 18 °C is around 340 s with good stability. In another study, Song et al. [63] proposed an artificial neural network (ANN) PID control system that combines the learning ability of the neuro network and the decision-making ability of the fuzzy logic to tune the control parameters of the PID controller against dynamic

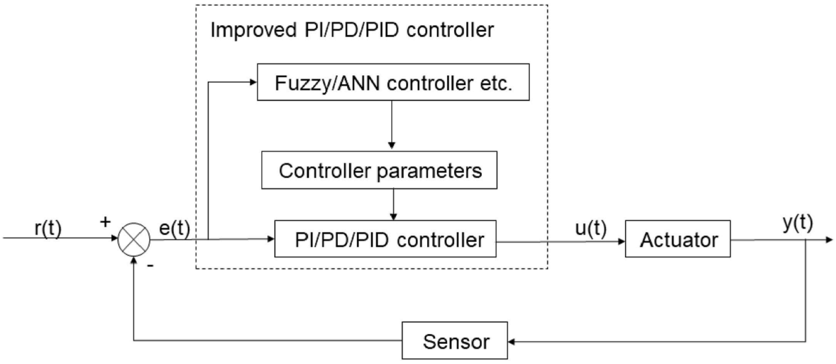

Fig. 6. Flow chart of the improved PI/PD/PID controller [62].

conditions. This hybrid approach demonstrates improved performance compared to conventional PID control, thanks to its successful performance in many systems [68].

Uncertainties and dependency on system parameters make TE systems nonlinear. Thanana et al. [69] developed fuzzy PID control to automatically tune control parameters, leading to improved dynamic response in a nonlinear TE system. However, TE systems still easily overshoot or undershoot under transient dynamic response conditions. To overcome this issue, Thanana et al. [70] proposed a neuro-fuzzy PID, which dynamically fine-tunes the PID control parameters online, effectively preventing overshooting and maintaining accurate temperature tracking in the steady state.

Besides, several other adaptive PID control methods have been employed in TE systems. To attenuate the oscillating behavior of the temperature control and achieve a fast response simultaneously, Mironova et al. [75] introduced a feedforward regulation-based model for tuning control parameters of the PI control and used an anti-windup scheme to enhance the stability of the PI control over a long time. Osawa et al. [77] introduced a heat disturbance observer for the PD control against nonlinear characteristics of the system, such as Joule heat and thermal conductance. The method showed an improvement in robustness by reducing modeling errors. Hu et al. [79] used particle swarm optimization (PSO) algorithm-based PID control to adjust object temperature. Their results showed that the PSO-PID control system has less overshoot and better stability than the conventional PID control.

4.3. Fuzzy logic control

Fuzzy logic control can not only assists in tuning control parameters but also independently work well in TE systems without the need for the precise mathematical modeling [59]. Indiketiya [52] made a comparative study on the performance of the TE temperature control system employing on-off control, PID control, and fuzzy logic control. The results indicated that PID control showed better performance on response and accuracy than on-off control due to its high control effort at initial time and adjustment based on real-time feedback. Furthermore, fuzzy logic control performs better than PID control due to its robust adaption on system nonlinearity. Similarly, Hakan et al. [26] compared the performance of the PID control with the fuzzy logic control in TE temperature control and observed that fuzzy logic control not only achieved energy saving but also minimized temperature fluctuation.

Fuzzy logic control can compensate for nonlinear errors, and reduce steady-state errors [59]. Hakan et al. [58] employed fuzzy logic control to achieve robust and accurate maintenance of the optimal temperature at 15 °C by adjusting the duty cycle of pulse width modulation (PWM) based on fuzzy rules. In their study, when the object temperature increases, the duty cycle is increased, thereby increasing the power strength of working Peltier cells. Similarly, fuzzy logic control is also employed in other studies to determine the duty cycle of PWM for temperature control purposes [73,84].

However, as shown in Fig. 7, the implementation of the fuzzy control requires careful consideration of the initial membership functions and fuzzy rule to handle system dynamics and uncertainties [60]. Ayman et al. [57] examined the fuzzy control using different membership functions for variable cooling loads. The results showed that the cold-side temperature can be maintained at a nearly

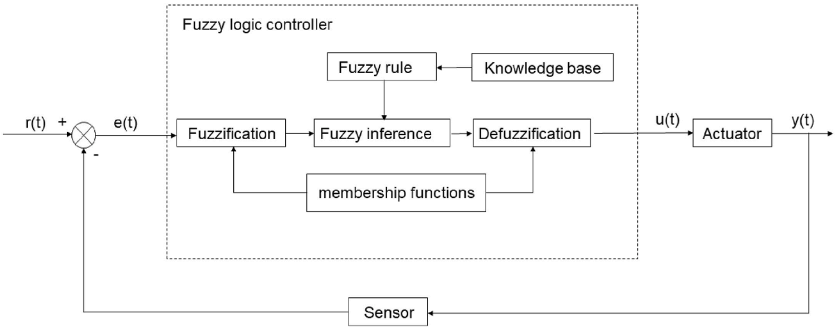

Fig. 7. Flow chart of the Fuzzy logic controller [57].

constant temperature with high stability and the trapezoidal membership function provides the minimum steady-state error. Similarly, Nurul et al. [68] employed fuzzy logic control to maintain the object temperature under changing ambient conditions and indicated that fuzzy rules can be customized for the input and output of the fuzzy control. In another study, considering the benefits of the learning and defining of ANN, Ahiska et al. [60] proposed a neuro-fuzzy control system to automatically adjust and identify optimal linguistic terms and membership functions required for fuzzy logic control.

4.4. Related developments

In addition to the control methods mentioned above, there are some other specific control methods for TE systems.

In the case of individual control, in some studies [55,56], the power strength of individual couples of the Peltier cell is sensed and controlled to address the non-uniform heat load. The results showed that the operation can improve the performance. In another study, Bermejo-Busto et al. [86] explored the use of beehive strategies to design a TE temperature control system. This approach created a good environment in the air cavity by the decentralized computational control of the equipment based on theoretical analysis.

Regarding intelligent control, Daisuke et al. [61] applied nonlinear model predictive control to a TE system, which demonstrated high accuracy and robustness against variations in heat loads. The control system can reach the desired temperature of 25 ˚C within 200–300 s under heat loads of 20 W, 30 W, and 50 W. In another study [78], an array of random set points within the minimum and maximum temperature range was generated. Then the control system sent the controller each set point, which retrained an ANN using the new data, thereby correlating desired temperature with the input voltage of Peltier cells.

To mitigate thermal disturbances, Morimitsu et al. [64–67] employed a heat disturbance observer to compensate for the thermal disturbance arising from joule heat or ambient, and parameter identification error during the signal transmission. Additionally, Mironova et al. [24,50] designed sliding mode control based on Lyapunov's approach to reduce the thermal disturbance during operation. Simulation results showed that the stable cold-side temperature of −10 ˚C was maintained through the adjustment of the operating current.

The operating voltage or current of Peltier cells can be modulated by adjusting the duty cycle of PWM. Sanver et al. [87] used a microcontroller to drive Peltier cells through the PWM technique. MOSFET was employed as a switching component to manage the cooling capacity by changing the duty ratio. The experiment [88] showed that the desired temperature was set at either high or low, but a duty cycle of 80 resulted in the shortest time delay for reaching set points. In a building TE system, the pulse width and shape of the control signal were modified to adjust cooling capacity. The results showed that cooling power increased by 23.3% and COP increase by 2.12% with specific pulse width and shape [48].

In section 4, as presented in Table 4, different control methods have been discussed for their applications in TE systems, targeting different objectives such as robustness, response speed, accuracy, stability, and simplicity. While there is no perfect method that suits for all control systems, it is possible to find an appropriate method for specific working condition that can enhance system performance. PID control is a widely used method due to its simplicity and adaptability to diverse working conditions. However, the tuning of control parameters is essential to the control performance. Adaptive PID control offers the advantages of automatically tuning control parameters, resulting in a better dynamic response against ambient variations. Fuzzy logic control, which does not rely on precise mathematical models, exhibits good dynamic response, but the performance is largely dependent on the set of its fuzzy rules and functions. Furthermore, certain control methods, despite being less commonly employed, can still provide significant benefits to TE control system.

5. Discussion

5.1. Key factors

The total power strength of Peltier cells can be adjusted by modulating the operating voltage or current of each Peltier cell. Fig. 8 shows the linear graphs diagram of the COP and the temperature difference between indoors and outdoors corresponding to the oper-

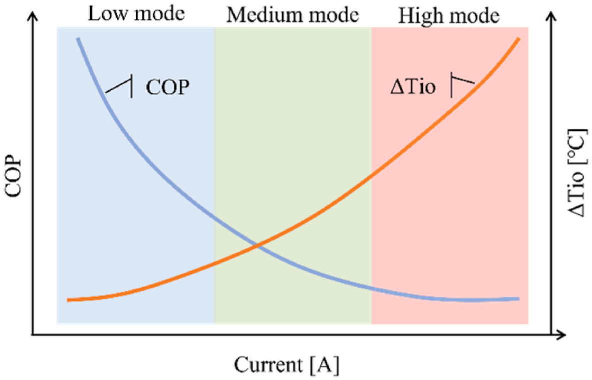

Fig. 8. The linear graphs diagram of the COP and the temperature difference between indoors and outdoors correspond to the operating current in different working modes.

ating current in different working modes. The working modes are categorized based on the total heat load, with higher modes corresponding to larger heat loads. As the heat load increases, the TE system should provide greater thermal capacity by increasing operating current or voltage, operating in a higher working mode. However, this also leads to an increased temperature difference between the cold and hot sides, resulting in a lower COP, as shown in Fig. 8. Depending on the specific working conditions, the system can adjust the power strengths in different working modes to improve the COP and save energy.

In this case, on the one hand, the total power strength can be increased by increasing the equal operating voltage or current of each Peltier cell at the same time. Then as the fresh flow passes along the heat sink, the temperature difference between the object side and the flow decreases, which means the actual heat released into or absorbed from the flow decreases along the heat sink. On other hand, the total power strength can also be increased by increasing the operating voltage or current of each Peltier cell at different levels, while maintaining an equal temperature difference between the object side and the flow as the fresh flow passes along the heat sink. This ensures that the actual heat released into or absorbed from the flow remains constant. And it would be interesting to explore which approach yields better results under certain working conditions.

In addition to increasing the operating voltage or current of Peltier cells, greater thermal capacity can also be achieved by increasing the number of working Peltier cells. Fig. 9 shows the linear graphs diagram of the COP corresponding to the number of working Peltier cells in different working modes. It can be observed, firstly, for the same number of working Peltier cells, operating the system in a higher mode result in a lower overall COP. Secondly, in a certain working mode, activating more working Peltier cells up to the optimal number of working Peltier cells allows the total heat load to be distributed among a larger number of Peltier cells. This leads to a reduction in the power strength required of each Peltier cell and then a decrease in the temperature difference between the cold and hot sides of each Peltier cell. As a result, the overall COP enhances. Moreover, operating Peltier cells under partial working load helps protect them from the high load. Besides, the specific distribution of working Peltier cells also affects the efficiency of heat dissipation.

However, the optimal number of working Peltier cells for the maximal overall COP is different in various working modes. The optimal points of the number of working Peltier cells are marked by the green dots in Fig. 9. The optimal number decreases as the power strength increases, which can be observed in several experiments [12,33,44]. It is important to understand the optimal number of working Peltier cells under different working conditions. If the number of working Peltier cells increases beyond the optimal value, the COP remains stable or decreases, while the initial investment of the system increases. Considering the distribution of Peltier cells, the limitation of the installation space, the initial investment, and the variations in the heat load in buildings, further research is required to explore the adjustment of the number of working Peltier cells for achieving better performance.

Strengthening the heat transfer between Peltier cells and flows is an effective approach to reduce the temperature difference between the cold and hot side. Fig. 10 shows the linear graphs diagram of the COP and the temperature difference between the cold and hot sides corresponding to the device configurations. The compared scenarios include the TE system without heat sinks and fans, the TE system with heat sinks and without fans, and the TE system with heat sinks and fans. As shown in Fig. 10, for a given heat load, the temperature difference between the cold and hot sides of the TE system without heat sinks and fans initially increase and then stabilize, resulting in a drop in the COP, which also reaches a stable state.

To address this issue, on the one hand, installing heat sinks with high thermal conductivity can significantly strengthen thermal conductance, leading to a reduction in the temperature difference between the cold and hot side. The use of heat sinks results in an increase in the COP, as shown in Fig. 10. When selecting heat sinks, there are requirements on size (to fit within installation space limitations), weight (to ensure lighter components), heat resistance (to enable efficient high conductivity), shape (to optimize heat transfer efficiency), etc. achieving improved heat transfer and integration with building structures. On other hand, controlling the fans or pumps to strengthen the thermal convection by increasing the flow rate can further decrease the temperature difference between the cold and hot sides and increase the COP, as shown in Fig. 10. Fans or pumps not only help to decrease the temperature difference between the cold and hot sides but also modulate one-side temperature under certain temperature difference between the cold and hot sides to create an extreme object-side temperature. However, at the same time the increased power consumption and working noise associated with the operation of fans or pumps can have a negative impact on the COP.

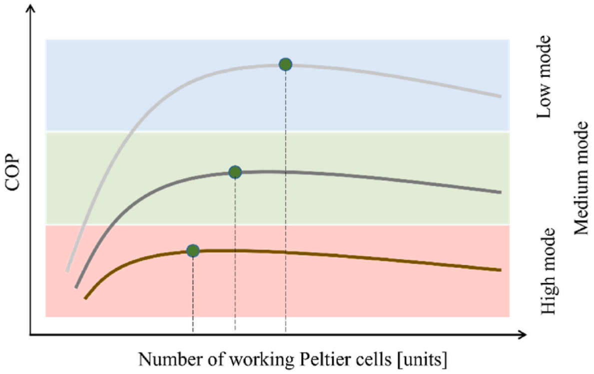

Fig. 9. The linear graphs diagram of the COP corresponds to the number of working Peltier cells in different working modes (the dots mean the optimal points).

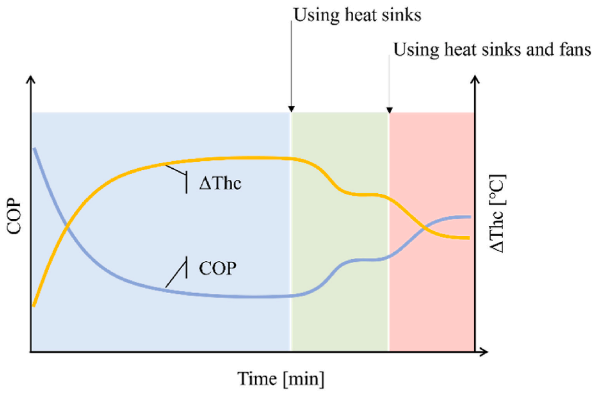

Fig. 10. The linear graphs diagram of the COP and the temperature difference between the cold and hot sides correspond to the device configurations.

The object-side temperature of Peltier cells can serve as a control parameter due to its direct relationship with the power strength. It is also important to understand the relationship between the object-side temperature and the indoor temperature. In a higher working mode, namely a larger temperature difference between indoors and outdoors, the TE system needs to maintain a higher or lower object-side temperature to achieve the indoor set point, considering a certain flow rate and a certain number of working Peltier cells. Consequently, there is a larger temperature difference between the object side and the indoor space for the same indoor set point, leading to a higher supply air temperature. While this decreases the time to reach the set point, it also results in nonuniform indoor temperature distribution. And larger temperature difference between the object side and the indoor space also means a lower COP due to a higher object-side temperature. Therefore, the temperature difference between the object side and the indoor space has the similar trend to the temperature between indoors and outdoors corresponding to the operating current, as shown in Fig. 8.

In conclusion, effective manipulation of key factors under various working scenarios, as depicted in Table 5, can indeed enhance performance in TE systems.

When faced with an increased heat load, the thermal capacity demand must be increased. As discussed previously, increasing the power strength of Peltier cells for greater thermal capacity results in a larger temperature difference between the cold side and the hot side, as well as between the object side and the indoor space. While this enhances the response speed in reaching the set point, it decreases the COP. To improve the COP, several approaches can be adopted. Firstly, increasing the power strength while simultaneously increasing the air flow rate and utilizing the return air system can decrease the temperature difference between the cold and hot sides. This approach strengthens heat transfer and reduces heat loss from the exhausted air, thereby improving COP. Secondly, activating additional Peltier cells with lower power strength (if the number of working Peltier cells is less than the optimal number) is another method to enhance COP. This approach results in smaller temperature differences between the cold and hot sides for each Peltier cell. However, if the number of working Peltier cells exceeds the optimal number, deactivating some Peltier cells until the optimal number can improve COP by reducing total power consumption.

Under the same heat load, maintaining the same power strength while increasing the air flow rate with the return air system, and selectively activating or deactivating Peltier cells with lower or higher power strength can optimize performance based on the relationship between the number of working Peltier cells and the optimal number.

Furthermore, when the heat load decreases, the thermal capacity should also be reduced to prevent overheating or overcooling. Decreasing the temperature difference between the cold and hot sides by using Peltier cells with lower power strength improves COP. To minimize the impact on supply air temperature, reducing the air flow rate and utilizing the return air system can enhance COP by reducing power consumption of the fans and heat loss from the exhausted air. Additionally, considering the relationship between the

Table 5
Interrelationships among key factors for enhancing performance in various scenarios.

Scenarios	Variations	Solutions	Results		
Heat load ↑	P ↑	–	ΔT_{hc} ↑	ΔT_{si} ↑	COP ↓
	P ↑	m ↑ plus return air system	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↓	N ↑ (if $N < N_{opt}$)	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↑	N ↓ (if $N > N_{opt}$)	ΔT_{hc} ↑	ΔT_{si} ↑	COP ↑
Heat load -	P -	m ↑ plus return air system	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↓	N ↑ (if $N < N_{opt}$)	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↑	N ↓ (if $N > N_{opt}$)	ΔT_{hc} ↑	ΔT_{si} ↑	COP ↑
Heat load ↓	P ↓	–	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↓	m ↓ plus return air system	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↓	N ↑ (if $N < N_{opt}$)	ΔT_{hc} ↓	ΔT_{si} ↓	COP ↑
	P ↑	N ↓ (if $N > N_{opt}$)	ΔT_{hc} ↑	ΔT_{si} ↑	COP ↑

↑: increase; ↓: decrease; -: do not change.

number of working Peltier cells and the optimal number, adjusting the number of working Peltier cells can further enhance performance.

5.2. Control methods

Achieving optimal performance in TE systems relies on the coordinated control of these key factors. It is critical to use appropriate control methods for TE systems to modulate these key factors, considering the ambient variations and the nonlinearity of the system.

Compared to simple on-off control, PID control offers better performance by modulating the operating voltage to achieve accurate temperature control based on the error between the set point and the real value. It is widely applied to energy systems in buildings and other fields due to its practicality, user-friendliness, and stability. However, PID control systems are susceptible to the influence of dynamic conditions. The performance of PID control systems would degrade if the operating conditions deviate from the conditions used for tuning control parameters of PID control [85]. The variations and time delay of indoor space and outdoor ambient, as well as the complexity of TE systems, further complicate the application of PID-based TE systems.

In building applications, adaptive PID control such as fuzzy-PID control, which employs fuzzy rules to automatically tune PID control parameters, offer improved dynamic response and adaptability compared to conventional PID control. Auto-tuning of PID control parameters based on dynamic conditions can effectively reduce the overshoot or undershoot in buildings. Fuzzy-PID control conjuncts with a set of fuzzy rules to tune PID control parameters online, allowing it to be applied in different working ambient [89]. However, defining the range of membership functions still relies on expert experience, and obtaining an exact model for adaptive PID control is also a challenging task [81].

Fuzzy logic control uses a simple mathematical model, operates based on fuzzy rule resembling human knowledge, and has a better adaptability compared to PID control in nonlinear systems [57]. However, it is a challenging task to generate effective fuzzy rules for TE systems. Moreover, to achieve enhanced accuracy, many membership functions are required, leading to an exponential increase in the number of fuzzy rules. ANN can learn from the data given for training or initial experience and continually improve its optimization or production over time. It can automate the process of tuning parameters. Therefore, the neuro-fuzzy control could help develop optimal fuzzy rules and determine appropriate membership functions [90]. However, neural networks heavily rely on the availability of the training data and the learning process is computationally intensive and time-consuming [91].

As analyzed above, all the control methods exhibit various performances in terms of accuracy, response speed, stability, robustness, and simplicity, as shown in Fig. 11. Each control method has different performance levels namely low, medium, and high (L, M, and H), across these perspectives. Specifically, the PID control stands out as the simplest option with a better response speed compared to Fuzzy logic control [92]. Thanks to its ability to automatically tune control parameters in dynamic conditions, the adaptive PID control demonstrates improved robustness [69] and accuracy [63] compared to the conventional PID control. Due to the linguistic rules based on professional experience and data training, the fuzzy logic control exhibits a better robustness in dynamic conditions [92] and a higher accuracy [26].

In the field of buildings, the demands of the temperature control on accuracy, response speed, stability, robustness, and simplicity of control systems are more permissive compared to those in the fields of electronics or medicine. However, it is important to consider the adaptability of these control methods to the specific requirements of different types of buildings, particularly in terms of indoor temperature fluctuation. For low-demand buildings, such as residential and commercial buildings with a modest indoor temperature fluctuation of ±0.5 °C, PID control proves to be more suitable due to its simplicity in implementation, acceptable stability, and response speed. On the other hand, medium-demand buildings like laboratories and hospitals, which require a higher level of accuracy and robustness with an indoor temperature fluctuation of ±0.1 °C, can benefit from the adaptability of adaptive PID control, offering dynamic tuning capabilities. For high-demand buildings, such as highly sensitive research laboratories with an indoor temperature fluctuation of ±0.01 °C, fuzzy logic control emerges as a favorable option, providing superior accuracy, robustness, and stability.

6. Conclusions

In recent years, there has been a significant increase in research about TE systems that involved buildings. This growing highlights the need for a systematic review article to explore the key factors and control methods associated with TE systems in buildings. There-

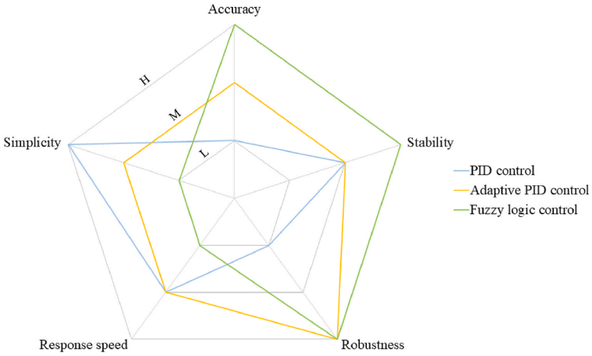

Fig. 11. The general schematic diagram of the comparison of main control methods.

fore, the objective of this work is to provide a state-of-the-art of TE systems proposed in different fields and to offer a thorough examination of the key factors and control methods employed in thermoelectric systems, contributing to a better understanding of their practical implementation in various fields. To accomplish this aim, previously published relevant papers have been categorized into two main groups: key factors and control methods.

Especially, this work further analyzes and discusses the key factors and control methods specifically from the perspective of building applications. This perspective adds depth and relevance to the findings, making them more applicable to thermoelectric building systems. Main conclusions are as follows:

- **The larger total power strength of Peltier cells for the higher thermal capacity always means the lower COP.** To improve the system performance, multimode control and individual control can be applied to adapt to different working conditions. Under various heat loads, the TE system can operate in different modes. Additionally, specific parts of the TE system can work in different modes to mitigate the non-uniform distribution of the heat load.
- **Sharing the total heat load among a greater number of working Peltier cells (up to the optimal value) can improve COP.** Under a specific heat load, more working Peltier cells (up to the optimal value) can work with lower power strength, resulting in a smaller temperature difference between the cold and hot sides of each Peltier cell and higher overall COP. However, when the working Peltier cells exceed the optimal number, the COP maintains stable or decreases.
- **Strengthening heat transfer between Peltier cells and flows can effectively decrease the temperature difference between the cold and hot sides, thus improving COP.** Installing heat sinks with high conductivity can strengthen thermal conductance and increasing the flow rate can strengthen thermal convection by controlling fans or pumps.
- **A larger temperature difference between the object side and the indoor space results in a higher object-side temperature and a lower COP.** The larger temperature difference between the object side and the indoor space leads to a higher temperature of the supply flow. While this decreases the time required to reach the set point, it also increases the non-uniform indoor temperature distribution.

Further, the research includes a comprehensive comparison of the key factors and control methods used to enhance system performance. This comparative analysis helps identify the interrelationship between these key factors in the control process and illustrates the relative strengths and weaknesses of different control methods, providing valuable insights for designing control strategies and systems for thermoelectric building systems. Main conclusion are as follows:

- To enhance the performance of TE control systems, the control strategy should consider the interrelationships among the key factors. Considering the variations in working conditions, a well-designed control strategy should carefully balance and optimize the key factors. By understanding and effectively modulating these interrelationships, TE control systems can achieve improved performance and better adaptability to varying operating conditions.
- For low-demand buildings, PID control proves to be more suitable due to its simplicity in implementation, acceptable stability, and response speed. On the other hand, medium-demand buildings, which require a higher level of accuracy and robustness, can benefit from the adaptability of adaptive PID control, offering dynamic tuning capabilities. For high-demand buildings, fuzzy logic control emerges as a favorable option, providing superior accuracy, robustness, and stability.

Furthermore, we would like to present some points that can help to enhance the performances of TE systems in buildings:

- Explore the effect of imposing power strength on each Peltier cell at the same level or different levels on the overall COP.
- Understand the optimal number of working Peltier cells in different working modes.
- Optimize the structure of the system to enhance the heat transfer efficiency.Evaluate control methods under various scenarios in buildings to identify the practical and effective control methods for TE systems.
- Develop the optimization system for automatically modulating key factors under dynamic ambient conditions.

In the future, with more and more attentions to energy efficiency, automation, and economic cost in building services, there will be a greater potential for the application of TE systems combined with control systems. Implementing appropriate control strategies for TE systems can not only better meet occupants' demands based on parametric analysis with other systems but also minimize the building energy consumption or economic cost by predicting and planning system operations. Thus, we would like to bring up three considerations for TE control systems in buildings around energy efficiency, automation, and economic cost.

- Energy efficiency. Solar-TE systems present a good integration and promising application potential. By utilizing TE systems, the direct current generated by solar systems can be converted into heating or cooling capacity, thus promoting energy sustainability. Integrated control systems play an essential role in enhancing the COP of TE systems through the implementation of appropriate strategies. Moreover, the control systems maximize energy productivity by tracking maximum power point and facilitate the utilization and storage of the produced energy.
- Automation. Intelligent control systems for TE systems are driven by exact computational models or trained using real data, such as process parameters (operating voltage or current, surface temperature, indoor temperature, ambient temperature, unit status, etc.), occupants' behavior, and personalized parameters. These control systems enable a more precise, efficient, and automated response to meet occupants' thermal demands.
- Economic cost. TE systems integrated with energy storage systems can utilize conserved energy generated through renewable energy systems or electric grids. Control systems predict thermal demands and ambient conditions and then plan the electricity

storage based on the utilization conditions of renewable energy systems or the real-time electric price from the electricity grids, to minimize the economic consumption and optimize the overall energy utilization of TE systems.

Declaration of competing interest

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Data availability

The authors are unable or have chosen not to specify which data has been used.

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