Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: xxxx

Thermal diode bridge for the temperature control in built environment

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ABSTRACT

In this paper, we proposed a novel concept of using thermal diode bridge (TDB) and phase change materials (PCMs) to control the temperature in the built environment continuously without any external energy consumption. In the daytime, the solar energy was efficiently harvested and stored in the PCMs so the indoor temperature was significantly reduced. At night, the thermal energy stored in the PCMs was used to heat the room. A thermodynamic model was established to evaluate the performance of the system. It was found that the temperature as well as the temperature variation in the built environment can be significantly reduced with zero energy consumption and green gas emission.

Keywords: Built environment, temperature control, thermal diode bridge, solar energy

NONMENCLATURE

Abbreviations	
PCM	Phase change material
TDB	Thermal diode bridge
Symbols	
C_p	Thermal capacity
h	Convective heat transfer coefficient
K	Heat tansfer coefficient
T	Temperature
t	Time

1. INTRODUCTION

Integrating phase change materials (PCMs) with the walls, ceilings, and floors of buildings to capture and store solar energy for the built environment temperature control represents an essential direction of the low energy building design [1-7]. In the daytime, the PCMs integrated into the building envelope can effectively absorb the solar energy hit on the walls, reducing the temperature in the built environment. At night, the energy stored in the PCMs was released to maintain a stable and comfortable temperature in the built environment. The appropriate PCMs for the building application should have suitable melting points (around 37 ℃), high thermal capacity, and low thermal expansion coefficients during phase change transition, and excellent chemical stability.

In recent years, using PCMs to stabilize the temperature in the built environment had become a hot research topic. However, there are still some problems that should be solved before the PCMs can be practically applied in the real building construction. Because of the heat exchange between the PCMs and the ambient at night, a significant partition of the heat stored in the PCMs was lost into the atmosphere rather than used for heating purposes. There is an urgent demand to develop a high-efficiency energy management system to use better the energy stored in the PCMs.

Thermal diode (TD) is a unique thermal element that can rectify heat flux. In this paper, we proposed using the TDB to control the temperature in the built environment with zero energy consumption. Due to the unique characteristic of one-way heat transfer, in the cold weather, the TDB let the solar energy enter the built environment, but cut off its way back to the ambient. Thus the solar energy could be effectively harvested for heating purposes. In the hot weather, solar energy can be blocked by the TDB, so the energy required for the cooling use can be significantly reduced. It is the first time that the TDB is proposed and studied for the temperature control of the built environment. A comprehensive mathematical model was established to study the temperature control performance of the TDB. The TDB concept proposed in this paper represented a lot of opportunities for the design of next-generation green buildings with zero energy consumption and carbon emission.

2. MATHEMATICAL MODEL

2.1 The concept of the thermal diode

Similar to the electrical diode, the TD is a unique thermal element that can rectify heat flux for specific applications. The characteristic of a typical TD is shown in Fig. 1. At a particular temperature of reference, the magnitudes of heat fluxes going through the thermal diode for the positive and negative temperature gradients differ significantly. The performance of this device is characterized by the rectification ratio [8], which is defined as

$$\phi = \left||Q_{Forward}| - |Q_{Reverse}|\right|/|Q_{Reverse}| \quad (1)$$

Due to the nonlinear thermal conductivity of the TD, for the same temperature gradient magnitude, the forward heat flux is much higher than the reverse heat flux. The unique function of the TD makes it very useful in the case where a one-way heat transfer is required.

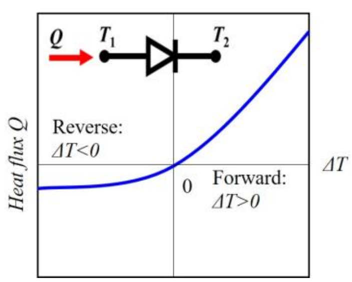

Fig 1. The working principle of the TD

The simplest way to construct a thermal diode is to combine two materials with highly nonlinear temperature-dependent thermal conductivities [9]. In the forward mode, both materials have high thermal conductivities, and the heat flux going through the thermal diode is high. On the contrary, in the reverse mode, both materials have much smaller thermal conductivities and the heat flux is very small. The PCMs were often used for the construction of the thermal diode because their thermal conductivities change significantly during the phase transition. Some TDs which could be integrated into the building envelope for the temperature control of the built environment were shown in Fig. 2. The future applications of the TD in the building temperature control represents a lot of opportunities for energy saving.

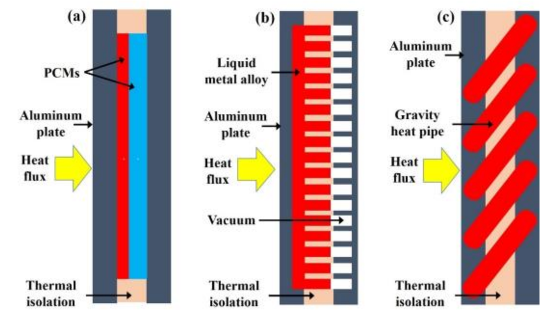

Figure 2. The TDs which could be integrated into the building envelope: (a) PCMs-type; (b) thermal expansion type; (c) gravity heat pipe type.

2.2 Energy management in the built environment

A TDB designed for the built environment temperature control is demonstrated in Fig. 3 with the thermal network shown in Fig. 4. There are four critical components in the TDB: transparent thermal isolation layer, the solar radiation absorption surface, the TD, and the PCMs (the thermal capacitor in Fig. 4). The solar radiation absorption surface is used to harvest solar radiation energy efficiently. The aerogel with ultralow thermal conductivity is used to cover the solar radiation absorption surface, which could reduce the thermal energy loss to the minimum level. According to a recent paper published by Zhao et al. [10], a solar receiver covered with ultra-low thermal-conductivity aerogel could harvest more than 80% of the solar radiation energy. To the back of the solar radiation absorption surface, the PCMs are connected to the surface with a thermal diode. In the daytime, when the temperature of the solar radiation absorption surface is higher than the PCMs ($T_1 > T_2$), the thermal diode operates in its forward mode. The heat absorbed by the solar receiver is effectively stored in the PCMs. At night, the thermal diode works in the reverse mode due to $T_1 < T_2$, the heat released by the PCMs is used to maintain a stable temperature within the built environment. In this way, the TDB stabilizes the temperature in the built environment using solar energy. If the energy management system is well designed, it is possible to maintain a stable and comfortable temperature in the built environment without any electric energy consumption.

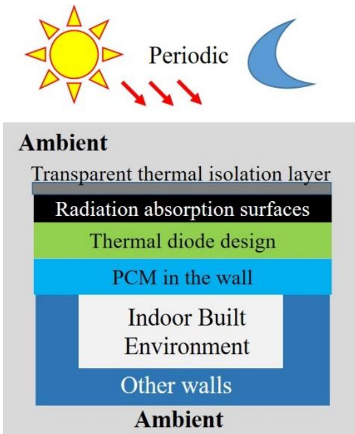

Fig 3. TDB designed for the built environment temperature control

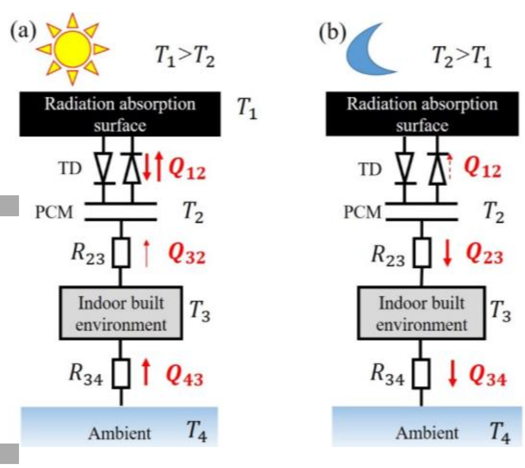

Fig 4. The thermal network in the TDB: (a) daytime mode; (b) night mode

2.3 Basic equations

The variation of ambient temperature in a day can be expressed by Fourier series:

$$T_4 = T_{avg} + \sum_n a_n \sin w_n t + \sum_n b_n \cos w_n t \quad (2)$$

The temperature of the PCMs can be:

$$T_2 = T_p \quad (3)$$

$$T_p < \frac{1}{24}\int_0^{24} T_3\, dt + \frac{A_{rad}\varepsilon R_{23}}{24}\int_0^{24} q_{rad}\, dt \quad (4)$$

The temperature in the environment is given by:

$$T_3 = \frac{C_1 T_p + C_2 T_{avg}}{C_1 + C_2} + \sum_n A_n \sin w_n t + \sum_n B_n \cos w_n t \quad (5)$$

2.4 Parameters used for the model

the diurnal temperature and solar radiation intensity varations [1] in the ambient can be fitted by the Fourier series. More Fourier series terms are required to fit the original data better. In this paper, for simplification, the Fourier series with two terms are used to fit the original data with the fitting parameters.

The average convective heat transfer coefficient on the walls depends on the surface temperature difference. It varies from 2.27 $W/(m^2 \cdot K)$ to 3.39 $W/(m^2 \cdot K)$ with a wall temperature difference ranging from 1.0 to 5.0 ℃ [11]. In the reference model, the average convective heat transfer coefficient on the internal building surface is set to be 2.5 $W/(m^2 \cdot K)$. The phase change temperature of the paraffin mixtures can be adjusted by change the composition. The phase change temperatures of heptadecane, octadecane, eicosane, 46 "paraffin, 48" paraffin, and their mixtures are between 20 ℃ and 50 ℃, which is ideal for the temperature control of the built environment. The parameters and their corresponding values used for the baseline scenario are listed on Table 1.

Table 1. The parameters and corresponding values used in the modeling

Air density	$\rho = 1.225\ \ kg/m^3$
Air thermal capacity	$c_p = 1{,}004\ \ J/(kg \cdot K)$
Area of the house	$A_{house} = 10 \times 10\ \ m^2$
Hight of the room	$H = 3.5\ \ m$
Wall area	$A_{wall} = 3.5 \times 10\ \ m^2$
K of the wall	$K_{wall} = 1.5\ \ W/(m^2 \cdot K)$
Window to wall ratio	$r = 0.1$
K of the window	$K_{win} = 1.4\ \ W/(m^2 \cdot K)$
Roof area	$A_{roof} = 100\ \ m^2$
Building shape coefficient	$\chi = 0.4$
K of the roof	$K_{roof} = 1.0\ \ W/(m^2 \cdot K)$
h on building surface	$h_0 = 2.5\ \ W/(m^2 \cdot K)$
Total solar radiation obsorption coefficient	$\varepsilon = 0.2$
Temperature control range of the TDB	$[T_c, T_h] = [15, 30]$ ℃

2.5 Results

In the baseline scenario, it is assumed that the ambient temperature varies throughout the day with a average temperature of 28.59 ℃ [1]. The lowest temperature happens around 3:00 am with a peak value of 24.15 ℃. And the highest temperature happens around 13:10 pm with a peak value of 34.04 ℃. The diurnal temperature fluctuation amplitude is 9.89 ℃. According to the mathematical model developed above, to maintain a approporate temperature in the built environment, the phase change temperature of the PCMs should be in the range of [24.15, 26.30] ℃, which is quite narrow. When the phase change temperature of the PCMs is set as 25 ℃, the temperature profiles of the ambient and built environment are compared in Fig. 5. For the regular building envelope, the thermal isolation provided by the walls, ceiling, and windows reduces the temperature fluctuation amplitude in the built environment. However, the improvement is not significant, as the temperature fluctuation amplitude is still as large as 9.8 ℃. The building envelope with the TDB integrated, on the other hand, reduces the temperature fluctuation amplitude to about 4.7 ℃ with zero energy consumption. It is also observed that the phases of the temperature profile in the built environment lags behind the ambient temperature. For the regular building envelope, the phase difference between the built environment and ambient is about 14 minutes. For the building envelope with the TDB integrated, the phase difference between the built environment and ambient is about 33 minutes. The TDB can maintain a stable and comfortable temperature in the built environment without any electrical energy consumption.

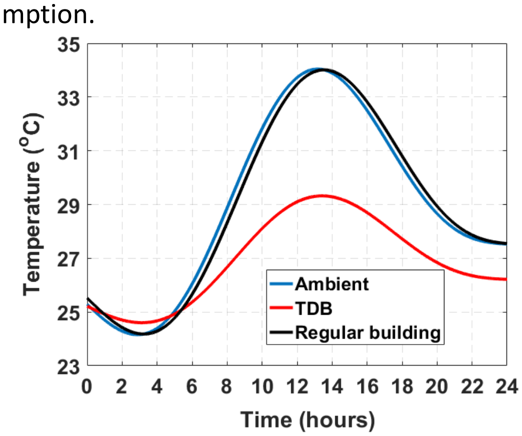

Fig 5. The temperature variations in the built environment when $T_p = 20$ ℃.

The thermal isolation performance of the building envelope could significantly affect the temperature in the built environment. The temperature in the built environment could be better controlled by adopting walls and windows with lower heat transfer coefficient and reducing the window to wall ratio. Fig. 6 showed the temperation variations in the built environment when the the heat transfer coeffient of the walls is reduced from 1.5 $W/(m^2 \cdot K)$ to 0.45 $W/(m^2 \cdot K)$ and the window to wall ratio is reduced from 0.1 to 0.05. It is observed that the temperature fluctuation amplitude in the built environment is significantly reduced when the thermal isolation performance of the building envelope is improved. For the regular house, the peak temperature in the built environment is slightly reduced with better thermal isolation. Also, the phase difference between the temperature profiles in the ambient and built environment is enlarged. This trend is more clearly observed when the TDB is implemented. For the building envelope with the TDB integrated, the better thermal isolated building can reduce the temperature fluctuation amplitude from 4.7 ℃ to 2.2 ℃. The thermal isolation performance of the building envelope played a key role in the control of the temperature in the built environment.

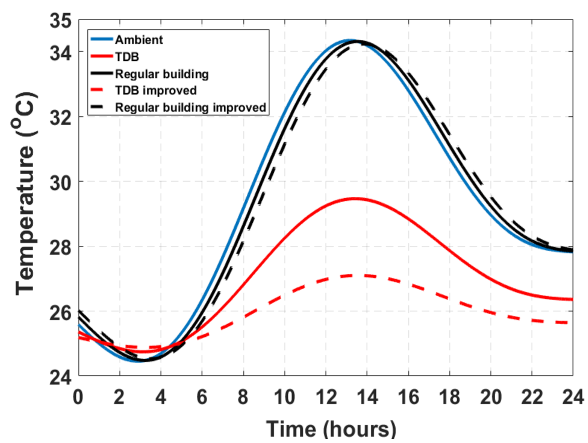

Fig 6. Temperature variations in the built environment with improved thermal isolation

The shape coefficient can significantly affect the building energy consumption. The larger the surface area corresponding to unit building area is, the greater the heat transfer loss and energy consumption are. Building shape coefficient is one of the important factors that affect the heat consumption index of buildings, and it is also an important index of building energy-saving design. The influence of the building shape coefficient on the temperature control performance of the TDB is discussed in this section.

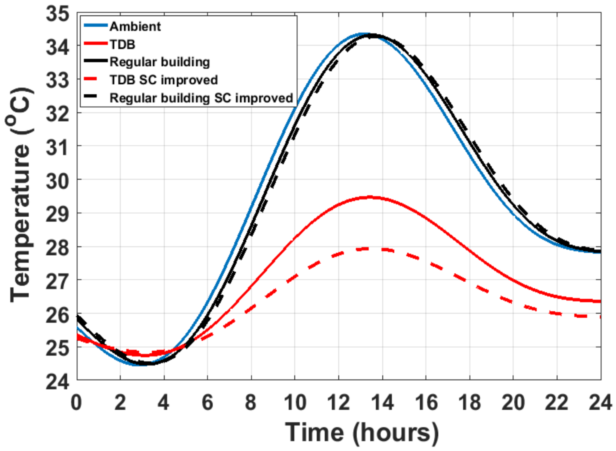

Fig 7. Temperature variations in the built environment with improved thermal isolation

The building shape coefficient is adjusted by changing the area of the building. When the area of the building is changed from 100 m^2 to 300 m^2, the shape coefficient is reduced from 0.4 to 0.2. As shown in Fig.7, for the building envelope with TDB integrated, the temperature fluctuation amplitude in the built environment is significantly reduced with smaller the shape coefficient. With the shape coefficient changing from 0.4 and 0.2, the the temperature fluctuation amplitude reduced from 4.7 ℃ to 2.8 ℃. Meanwhile, the shape coefficient has very small impact on the temperature variation in the built environment for the regular house. The the shape coefficient of building can significant influence the control performance of the temperature variation in the built environment.

ACKNOWLEDGEMENT

This research was supported by the National Natural Science Foundation of China (Grant No. 51778511), Hubei Provincial Natural Science Foundation of China (Grant No. 2018CFA029), and Key Project of ESI Discipline Development of Wuhan University of Technology (Grant No. 2017001).

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