Theoretical Study on Thermal Performance of Dynamic Composite Envelope (DCE)

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Abstract
The Dynamic Composite Envelope (DCE) mainly refer to building envelope with heat source layer, which can fully utilize low-grade renewable energy and adjust thermal insulation level by itself. There are many kinds of DCEs, while design guidelines for thermal performance improvements need further study. This paper the general heat transfer model for an ideal DCE with uniform temperature heat source layer is set up, and the influence of environmental factors, structural factors and heat source factors on the transient thermal characteristics and comprehensive energy saving potential of DCE is discussed by parameter-sensitivity analysis. It is found that the heat source temperature and location are the key parameters and the thickness of heat storage layer and insulation layer affects the energy utilization efficiency.

Highlights
- Heat source layer of the dynamic composite envelope is a good thermal barrier for indoor and outdoor environment.
- Heat source temperature and location are the key influencing parameters.
- The thickness of heat storage layer and insulation layer affects the energy utilization efficiency.
- The heat source layer should be placed in the inner side of the heat storage layer, and adding insulation layer outside the envelope helps to improve energy utilization efficiency.

Introduction
The biggest difference between DCE and traditional envelope is whether there is a built-in heat source layer. The traditional envelope is static in different climate conditions, unable to adjust its own thermal characteristics according to outdoor environment. Even if the thermal resistance is improved by using high-performance insulation materials or increasing the thickness of insulation layer, it cannot meet the opposite needs of heat preservation and heat dissipation in different seasons. In contrast, the DCE has good climate adaptability due to its adjustable heat source layer. The internal heat source of DCE comes from low-grade energy in nature, including geothermal energy, industrial wastewater, solar hot water and so on. The temperature of these low-grade energy sources is usually 10 – 40 °C, which is not enough to be used as a traditional indoor heating or cooling energy source. But it is suitable for application in enclosure. Therefore, the DCE not only has better energy saving potential, but also can improve the utilization efficiency of low-grade energy.

The DCE can be divided into three categories, including air-based, solid-based and liquid-based thermal activated wall. Air-based thermal activation system includes inner air layer wall, permeable wall, etc (CHEN Sarula, Chang T, et al, 2022). Liquid-based thermal activation system includes embedded tube wall, evaporative wall, etc. Solid-based thermal activation system mainly integrates the thermoelectric module into the envelope design.

Some scholars have compared and analyzed the thermal characteristics of the ideal building model under two heating modes (one is the indoor heat source, the other is the DCE), and found that in the case of intermittent heating, the DCE can create a more stable indoor thermal environment (Zhuang Z, Guo W, et al, 2017). At the same time, many scholars have carried out corresponding theoretical or experimental research on specific forms of heat source. Zhuang Z et al. (2022) proposed an air-based DCE and found that the key influencing factors in summer are the thickness of air layer and air supply velocity, and the key factors in winter are the thickness of heat storage layer and insulation layer. Based on a zero-energy experimental building, Zhang H (2011) found that the adjustment of the internal air enclosure structure formed warm wall and cold wall effects in winter and summer respectively. Xu X and Zhu Q (2015, 2016) put forward a series of thermal analysis models for the heat transfer of the built-in tubular enclosure structure, including frequency domain finite difference, semi-dynamic model and dynamic simplified model and found that the built-in tubular enclosure structure can greatly reduce the indoor cooling and heating load. Li X and Shen C (2016, 2017) analyzed the dynamic heat transfer process of the embedded tube wall through comprehensive numerical model simulation and experimental test, and found that the indoor cooling and heating load could be greatly reduced by using cold or warm water. Martin S et al. (2018) proposed two control modes for the embedded pipe wall (heating mode and thermal barrier mode), and studied the influence of water supply temperature, buried pipe location, buried pipe spacing and other parameters on the heat transfer and temperature distribution of the wall. Yang Y et al. (2021) studied the influence of design variables (pipe spacing, diameter, etc.), control variables (heat source temperature, indoor setting temperature,
heating duration), material properties (thermal conductivity of embedded layer) and other factors on wall performance. Liu Z et al. (2015) proposed an active solar thermoelectric radiation cooling and photovoltaic (PV) technology and found that this new system has the ability to control the heat flux of envelope by using solar energy.

In general, most current research on DCEs focuses on the thermal characteristics of the envelope under specific heat source conditions. However there are many kinds of DCEs, and design guidelines for thermal performance improvements need further study. This paper the general heat transfer model for an ideal DCE with fixed temperature heat source layer is set up, and the influence of environmental factors, wall structure factors and heat source factors on the transient thermal characteristics and comprehensive energy saving potential were discussed, and the design method of DCE in different climate was summarized.

Methods

Theoretical modeling

According to relevant specification (General code for energy efficiency and renewable energy application in buildings, GB 55015-2021), the prototype of the DCE is designed as reinforced concrete heat storage layer + EPS insulation layer + heat source layer (as shown in Figure 1). The heat transfer process of DCE includes the heat exchange between indoor and outdoor environment and the envelope as well as the heat conduction between the different material layers.

![Figure 1: Prototype of dynamic composite envelope.](image)

In this study, the heat source layer is idealized as a structural layer with uniform temperature distribution and infinite thickness close to thin surface. The heat transfer balance equations for the DCE are listed as follows:

(1) Outdoor and indoor conditions

Outdoor air temperature fluctuates periodically for 24h. According to relevant literature studies (Kontoleon K J and Bikas D K, 2007), its governing equation is as follows:

\[ T_{o,av}(t) = T_{o,av}^{\text{start}} + \frac{T_{o,\text{max}} - T_{o,\text{min}}}{2} \sin(\omega t + \phi) \]  

(2) Heat transfer of DCE

The envelope model is simplified into a one-dimensional unsteady heat transfer model. According to Fourier's law and energy conservation law, the governing equation of the envelope is obtained.

\[ \frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial x^2} + \frac{q}{\rho c} \]  

(3)

To facilitate calculation, formula (3) is discretized in space and time, and the following formula is obtained.

\[ t_{n+1}^i = \frac{\Delta \tau}{\alpha \Delta x^2} (t_{n+1}^i + t_{n-1}^i) + (1 - 2 \frac{\Delta \tau}{\alpha \Delta x^2}) t_n^i \]  

(4)

Where, \( t_{n+1}^i \) represents the temperature of the n layer wall at time \( i + \Delta \tau \); \( \Delta \tau \) represents the time step, s; \( x \) represents the space step size, m; \( \alpha \) is thermal diffusivity.

The unsteady conduction process of the envelope conforms to the third type of boundary conditions, and its mathematical expression is as follows:

Left boundary condition:

\[ -\lambda \frac{\partial T(x, \tau)}{\partial x} \bigg|_{x=0} = h_i (t(0, \tau) - T_{sa}) \]  

(5)

Right boundary condition:

\[ -\lambda \frac{\partial T(x, \tau)}{\partial x} \bigg|_{x=\delta} = h_i (t(\delta, \tau) - T_{sa}) \]  

(6)

Initial conditions:

\[ t(x, 0) = T_{\text{start}} (0 \leq x \leq \delta) \]  

(7)

Where, \( T_{sa} \) is outdoor comprehensive air temperature, K; \( T_{\text{start}} \) is indoor air temperature, K; \( h_i \) and \( h_o \) are respectively the convective heat transfer coefficient of indoor and outdoor air and their adjacent wall surfaces , W/(m²·k); \( t(x, \tau) \) represents the temperature at time \( \tau \) and at position \( x \), K; \( T_{\text{start}} \) is the wall surface temperature at the initial time, K; \( \delta \) represents the total thickness of the DCE, m.

Performance evaluation index

Since this study simulated the heat transfer characteristics of the envelope under unsteady working conditions, the inner wall temperature \( T_i \) and the inner wall heat flux \( q_i \), which changed periodically in 24 h, were used as the evaluation indexes to evaluate the transient heat transfer characteristics of the envelope. The equivalent thermal resistance \( R_{eq} \) and the daily cumulative heat flow \( Q_{eq} \) are adopted as the comprehensive evaluation indexes. Their formulas are as follows:

\[ R_{eq} = \frac{q_i}{Q_{eq}} \int_{0}^{24} \frac{T_i(t) - T_j(t)}{q_i(t)} dt \]  

(8)

\[ Q_{eq} = \int_{0}^{24} q_i(t) dt \]  

(9)

Where, \( T_i \) and \( T_j \) are the inner and outer wall temperatures at time \( j \) of the enclosure structure, K,
respectively. $q_{ij}$ is the heat flux density of the inner and outer walls of the envelope at time $j$, W/m².

In addition, in order to evaluate the heat source utilization efficiency of the active composite enclosure system, the percentage of 24 h energy supply efficiency $\varepsilon$ was used as the evaluation index, and its calculation formula was as follows:

$$\varepsilon = \frac{\int_{0}^{24h} (q(y)_{ij} - q(n)_{ij}) \, dt}{\int_{0}^{24h} (q(y)_{ij} + q(n)_{ij}) \, dt} \times 100\% \quad (10)$$

Where, $q(y)_{ij}$ and $q(n)_{ij}$ are respectively the inner wall and outer wall heat flux of the DCE at time $j$, W/m²; $q(n)_{ij}$ and $q(n)_{ij}$ are the heat flux of the inner and outer walls at time $j$ corresponding to the traditional envelope, W/m².

**Case Validation**

In order to verify the accuracy of the model, the existing DCE experimental platform was used for testing and comparison (Figure 2). The experimental environment was set as follows: the outdoor ambient temperature varied periodically from 15 °C to 20 °C, and the indoor air temperature was maintained at 28 °C. The heat source layer was an embedded tube structure and its temperature was maintained at 28 °C during the experiment.

By comparing the cyclic variation process of wall temperature and heat flux in 24h, the simulation results of the DCE are basically consistent with the measured data(Figure 3). The equivalent thermal resistance of the composite wall is 0.07 m² • K/W and 0.09 m² • K/W, respectively, which is within the allowable error range. Therefore, the heat transfer model established in the study is reliable.

**Results and Discussion**

In summer, the benchmark indoor temperature is 26 ℃, and outdoor environment is set as the summer solstice of Shanghai. In winter, the indoor temperature is set 18 ℃, and outdoor environment is set as the winter solstice. The reference envelope and its material from outside to inside are: 10 mm plastering mortar, 55 mm EPS insulation mortar, 10 mm interface mortar, 200 mm reinforced concrete heat storage layer, 10 mm plastering mortar.

**Environmental conditions**

The variation of the performance of the envelope after the change of the outdoor environment is compared in figure 4. In summer, the inner wall temperature of DCE is 3.09 ℃ lower than traditional enclosure structure. In winter, the inner wall temperature of DCE is 3.74 ℃ higher than traditional enclosure structure. Besides, the inner surface temperature and heat flux of the former has smaller fluctuations. Thus, the DCE shows better thermal performance in both summer and winter. When the external environment changes, the reaction time of the DCE required for the inner wall temperature to stabilize is shorter. The equivalent thermal resistance of the traditional envelope is the same in winter and summer, while that of the DCE is significantly different under different environmental conditions. It shows that the DCE has good climate adaptability and can be adjusted according to the changes of the external environment. The correlation between the outdoor temperature and the inner wall temperature of the DCE is also analyzed. The R square in summer and winter is both 0.07, which is far less than 1. Thus, the change of outdoor environment has no obvious effect on the thermal performance of the DCE.

**Thermal storage layer thickness**

The thermal performance of the envelope with different heat storage layer thickness is compared in Figure 5–6. The inner wall temperature and heat flux density of the
traditional envelope show periodic changes consistent with the outdoor environment, while that of the DCE finally reach a stable state.

In summer, the inner wall temperature of the DCE increases with the increase of the heat storage layer thickness, and the absolute value of the inner wall heat flux decreases. The inner surface temperature of the DCE with 300 mm thermal storage layer thickness is 0.48 °C higher than that of the DCE with 200 mm thermal storage layer thickness, and is 1.37 °C higher than that of the DCE with 100 mm thermal storage layer thickness. At the same time, the inner heat flux absolute value of the DCE with 300 mm thermal storage layer thickness is 4.13 W/m² less than that of the DCE with 200 mm thermal storage layer thickness, and is 11.95 W/m² less than that of the DCE with 100 mm thermal storage layer thickness. With the decrease of the heat storage layer thickness, the temperature of the inner wall decreases and the indoor heat dissipation increases. Comparing the equivalent thermal resistance of the enclosure system with different heat storage layer thickness, the equivalent thermal resistance of traditional envelope structure increases with the increase of heat storage layer thickness, while that of DCE changes a little.

In winter, the temperature and heat flux density of the inner wall of the DCE decrease with the increase of the heat storage layer thickness, and the heating reaction time of the wall increases. The equivalent thermal resistance of the DCE increases with the increase of the heat storage layer thickness, and the daily accumulated heat flux decreases at the same time. Thus, the thinner the heat storage layer is, the more heat the interior space gets.

**Insulating layer thickness**

In Figure 7–8, the thermal performance of the envelope with or without internal heat source is compared when the thickness of the insulating layer is 0, 55 mm and 100 mm respectively. In summer, the change of insulation thickness has little effect on the inner wall temperature and heat flux density of the DCE. Comparing the comprehensive energy saving potential of the enclosure system, the daily cumulative heat flux of the DCE under different insulation thickness is almost the same. While the energy utilization efficiency of the composite system without insulation layer, with 55 mm and 100 mm insulation layer thickness is 16.58 %, 27.11 % and 33.84 % respectively. Thus, the increase of the insulation layer thickness has little effect on the thermal performance of the DCE, but it affects the energy efficiency.
In summary, for the DCE, although the increase in the insulation layer thickness has no significant effect on the thermal performance of the wall, it improves the energy efficiency of the DCE. Therefore, it is necessary to appropriately increase the heat preservation outside the heat source layer.

**Heat source temperature**

In summer, the thermal performance of the envelope with or without internal heat source is compared when the temperature of the heat source layer is 24 °C, 26 °C, 28 °C and 30 °C, respectively (Figure 9). When the heat source temperature is lower than the indoor air temperature, the heat flux density of the inner wall is negative, and the DCE provides cooling to the room. When the temperature of the heat source layer is equal to the indoor air temperature, the heat flux of the inner wall is 0, and the outdoor heat almost does not enter the room through the envelope. When the heat source temperature is higher than the indoor air temperature and lower than the temperature of the material layer at the same position of the traditional envelope, the internal wall temperature and heat flux density of the composite envelope are lower than that of the traditional envelope, indicating that the thermal insulation performance of the envelope under the action of the heat source layer is improved compared with that of the traditional wall. When the heat source temperature is higher than the temperature of the material layer at the same position of the traditional envelope, the existence of the heat source layer has an adverse effect on the envelope. Comparing the comprehensive energy saving potential of the envelope, the equivalent thermal resistance of DCE at heat source temperature of 24 ℃, 28 ℃, 30 ℃ is -0.43 m²·k/W, 0.49 m²·k/W, 0.26 m²·k/W, respectively, while the equivalent thermal resistance of traditional enclosure is 0.30 m²·k/W. This means the temperature of the material layer at the same position of the traditional envelope is lower than 30 °C. The daily accumulated heat flux of DCE at different heat source temperature are -0.14 kWh/㎡, 0, 0.14 kWh/㎡, 0.28 kWh/㎡ respectively. Thus, when the temperature of the heat source layer decreases, the comprehensive performance of the DCE is improved. When the heat source temperature is lower than that of indoor air, the DCE enclosure provides cooling for indoor space.
In winter, the thermal performance change rule of the envelope with or without internal heat source is compared when the heat source layer temperature is 6 °C, 12 °C, 18 °C, 24 °C respectively (Figure 10). When the temperature of the heat source layer is equal to the temperature of the indoor air, the heat flux of the inner wall is 0, and the indoor heat is almost not lost through the wall. When the heat source temperature is higher than the indoor air temperature, the heat flux is positive, and the DCE supplies energy to the room. When the heat source temperature is lower than the indoor air temperature and higher than the material temperature at the same position of the traditional envelope, the temperature of the inner surface of the DCE is higher than that of the traditional envelope, and the absolute value of the heat flux on the inner wall is lower than that of the traditional envelope, indicating that the thermal insulation performance of the envelope under the action of the heat source layer is improved compared with that of the traditional envelope. When the heat source layer temperature is lower than the material temperature at the same position of the traditional envelope, the overall performance of the DCE is worse than that of the traditional envelope. Comparing the comprehensive energy saving potential of the envelope, the absolute value of the equivalent thermal resistance of the composite wall under the heat source condition of 12 °C is greater than that of the traditional enclosure structure, and the daily cumulative heat flow on the inner wall surface is lower than that of the traditional enclosure structure. As the heat source temperature increases, the equivalent thermal resistance and the daily cumulative heat flow gradually decrease, and finally heat conduction direction changes.

In summary, the temperature of the heat source layer and the temperature difference between the heat source layer and the indoor air are the key factors affecting the performance of the DCE. By adjusting the temperature difference between the indoor air temperature and the heat source temperature, the energy transfer state of the envelope can be adjusted. When the heat source temperature in summer is lower than the material temperature at the same position of the traditional envelope, and the heat source temperature in winter is higher than the material temperature at the same position of the traditional envelope, the comprehensive performance of the DCE is better than that of the traditional envelope. Considering the performance of the enclosure structure and the energy utilization rate, the heat source temperature can be set close to the indoor air temperature under the heating condition in winter and lower than the indoor air temperature in summer. The heat source forms that can be considered include solar energy, industrial waste water, river water, air conditioning condensate water, geothermal energy and so on.

Heat source location
The thermal performance of the envelope under different heat source positions is compared in Figure 11~12. The heat source is placed in five different material layers, and its position from the inner wall side to the outer wall side is marked as 1~5. At position 5, the insulation layer is
located inside the heat source layer, and at position 1−4, the insulation layer is located outside the heat source layer. In summer, the temperature of the inner wall surface gradually increases with the increase of the distance between the heat source layer and the inner wall surface, and the absolute value of the heat flux density of the inner wall surface gradually decreases. When the heat source layer is located outside the heat storage layer, the change of its position has relatively little effect on the temperature and heat flux of the inner wall. The energy utilization efficiency of the DCE at position 1−5 is 74.64 %, 50.87 %, 27.11 %, 19.68 %, and 12.25 %, respectively.

In winter, the inner wall temperature and heat flux decrease with the increase of the distance between the heat source layer and the inner wall. However, when the heat source layer is located outside the heat storage layer, the increase of the distance between the heat source layer and the inner wall has almost negligible effect on the inner wall. The energy efficiency of the DCE under location 1−5 is 74.21%, 49.93%, 25.65%, 18.06%, 10.48%, respectively.

**Conclusion**

Through theoretical research, this paper compares and analyzes the influence of environmental factors, wall structure parameters and heat source parameters on the thermal performance of the DCE. The main findings are as follows: (1) The heat source layer is a good thermal barrier for indoor and outdoor environment, and the change of outdoor environment has no obvious effect on the thermal performance of the DCE. (2) The variation of the heat storage layer thickness has a great influence on the thermal performance. When the heat source layer is located outside of thermal storage layer, the thinner the heat storage layer is, the better the thermal performance of the DCE enclosure in winter and summer is. (3) The thickness of the insulation layer has little effect on the inner wall temperature and heat flux of the DCE, but it significantly affects the energy utilization efficiency of the heat source system. The thicker the insulation layer is, the higher the energy utilization efficiency is. The energy utilization rate of the DCE with insulation is significantly higher than that without insulation. (4) The heat source temperature is a key parameter affecting the thermal performance of the envelope. In winter, when the heat source temperature is higher than the material temperature at the corresponding position of the traditional envelope, the thermal performance of the DCE increases with the increase of the heat source temperature. In summer, when the heat source temperature is lower than the material layer temperature of the corresponding position of the traditional envelope, the thermal performance of the DCE increases with the decrease of the heat source temperature. (5) The position of the heat source layer affects the energy-saving effect of the wall. When the heat source layer is located in the inner side of the heat storage layer, the comprehensive thermal performance of the envelope and the utilization efficiency of the energy system are better. Besides, adding insulation layer outside the envelope helps to improve energy utilization efficiency.

**Nomenclature**

Ti-Y: Inner surface temperature of DCE
Ti-N: Inner surface temperature of traditional envelope
qi-Y: Inner surface heat flux of DCE
qi-N: Inner surface heat flux of traditional envelope

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References


