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# A new insight into opaque envelopes in a passive solar house: Properties and roles

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## HIGHLIGHTS

- A new insight into the opaque envelopes of a passive solar house was gained.
- Five parts of envelopes, i.e., roof, south/east/west/north walls, were discussed.
- Each part of envelopes were analyzed separately rather than treated as a whole.
- Ideal properties of materials for each envelope are diverse from one another.
- Differences are related to the envelopes' leading roles as a heater or a cooler.

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## ABSTRACT

Passive solar houses are effective solutions for minimizing the operating energy of buildings. The building envelopes of passive solar houses exert a significant influence on the degree of indoor thermal comfort. The focus of this study was the construction of high-performance opaque envelopes, i.e., the roof and walls, for a passive solar house, and a new conception of the envelopes from the perspective of the relation between the properties and roles was provided. The discussion was conducted based on a comprehensive range of envelope materials that were distinguished by the thermal conductivity and volumetric heat capacity. For the first time, each part of the envelopes was analyzed separately rather than considered as an entire envelope. By analyzing each envelope individually, the optimum properties of each envelope were found to be distinct from each other. The distinctions are determined by the dominant role of each envelope, which is associated with the location and absorbed solar irradiation. For summer or hot climate applications, when the dominant role is a cooler, the envelope, e.g., the south wall, should consist of materials with high thermal conductivity and large heat capacity; if a heater is the dominant role, the envelope, e.g., the roof, should consist of materials with low thermal conductivity. For winter or cold climate applications, the envelopes with a leading role of a heater or a cooler require materials with high or low thermal conductivity, respectively. Under the guidance of the results, a discussion on the construction of a high-performance opaque envelope with the current materials was also provided.


## 1. Introduction

The building sector is responsible for 30–40% of the primary energy used in developed countries and is also one of the main sources of carbon dioxide emissions, which produces widespread public concern about global warming. Therefore, developing energy-efficient buildings is an urgent requirement for a sustainable and environmentally friendly society. Among advanced buildings, zero-energy buildings (ZEBs) receive continuous attention [1–4] as obliged regulations, e.g., Energy Independence and Security Act of 2007 (United States) and Directive on Energy Performance of Buildings (European Union), have promoted the application of ZEBs. There are different types of ZEBs for different definitions and calculation methodologies [5]. A passive solar house, which is not equipped with active heating, ventilation, and air conditioning (HVAC) systems, may be considered a special type of ZEB due to the fact that the operating energy is almost negligible.

The passive solar house meets the needs of thermal comfort through several passive building components [6] such as thermal storage walls (Trombe walls) [7] and solar chimneys [8]. Despite those components, building envelopes should be the prerequisite and foundation for passive solar houses. Building envelopes can be further sorted into two groups, transparent and opaque parts. The transparent part mainly encompasses windows, while the

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**Nomenclature**

| | |
|---|---|
| $A$ | area of the surface [$m^2$] |
| ACH | air changes per hour |
| $C_V$ | volumetric heat capacity [J/$m^3$·K or kJ/$m^3$·K] |
| $c_p$ | specific heat capacity at constant pressure [J/kg] |
| $h_{i\text{-air}}$ | convection heat transfer coefficient between surface $i$ and air [W/$m^2$·K] |
| $k$ | thermal conductivity [W/m·K] |
| $R_{i\text{-}j}$ | thermal resistance for radiation between surface $i$ and $j$ [K/W] |
| $r_{vent}$ | ventilation rate [ACH] |
| $S'$ | solar irradiation absorbed by the wall per unit area [W/$m^2$] |
| $T$ | temperature [K or °C] |
| $\Delta t$ | time interval [s] |
| $V$ | volume [$m^3$] |
| $\Delta x$ | spatial interval [m] |

*Greek letters*

| | |
|---|---|
| $\rho$ | mass density [kg/$m^3$] |

*Subscripts*

| | |
|---|---|
| air,i | indoor air |
| air,o | outdoor air |
| e | envelope |
| e,$i$ | $i$th node of the envelope |
| $j$ | surface in a room |
| $m$ | surface of outdoor surroundings (e.g., the sky, the ground) |

opaque part includes the floor, roof, and walls. All parts of the envelopes, e.g., the windows, walls, and doors, can be used for passive cooling [9,10]. Many researchers have investigated windows for thermal transmittance performance [11,12] and regulation capacity for radiation [13,14], providing approaches for energy-efficient transparent envelopes. In this study, we focused on opaque parts for the purpose of constructing high-performance envelopes for a passive solar house. First, we must examine by what means the envelopes, specifically their thermophysical properties, influence the degree of indoor thermal comfort for the house.

Some studies on the thermophysical properties have already been reported by researchers. Cabeza et al. improved the envelopes of high internal thermal inertia in Mediterranean climates through a set of experiments [15,16], and Stazi et al. emphasized the efficiency of envelopes with external insulation in the same climate [17,18]. These case studies are effective for giving a direct comparison among particular cases, but only involve limited types of materials, which means that a comprehensive investigation including extensive types of envelope materials is needed. In addition to the case studies, Zhang and his group provided theoretical studies using an inverse problem method [19–21] and an optimization method based on the concept of entransy [22] to determine the ideal thermophysical properties of walls. Within these studies, all of the envelopes, which contained four walls and a roof, were treated as a whole. However, differences among the envelopes exist because of differences in location and the resulting distinctions in the solar irradiation absorbed. Such differences are inherent and may lead to the respective role of each envelope in a house, indicating that the influence of the properties on indoor thermal comfort should not be analyzed equally without a distinction between the envelopes.

Considering the inevitable limitations of case studies and the intrinsic diversity of the building envelopes, we provide a new insight into the relation between the degree of indoor thermal comfort of a passive solar house and the envelope materials. Most of the common materials, either a single material or multilayers, are included, and each part of the envelopes is analyzed separately. The optimum properties of the envelope materials were established to be closely related to the dominant roles that an envelope has on the indoor air. Based on the results, several combinations of envelopes were constructed and compared.

## 2. Model and methods

A passive solar house, as shown in Fig. 1, was studied. The house is 3 m, 4 m, and 5 m in height, width, and length, respectively. All of the opaque envelopes, i.e., the walls and the roof, are exposed directly to the outdoor environment. The transparent part of the envelopes, specifically the window, is located in the center of the south wall and has a size of 1.8 × 1.8 $m^2$. The window is installed with a single-layer plain glass whose solar transmittance, solar absorptivity and long-wave thermal emissivity are 0.77, 0.16 and 0.84, respectively. Although the properties of the opaque envelope

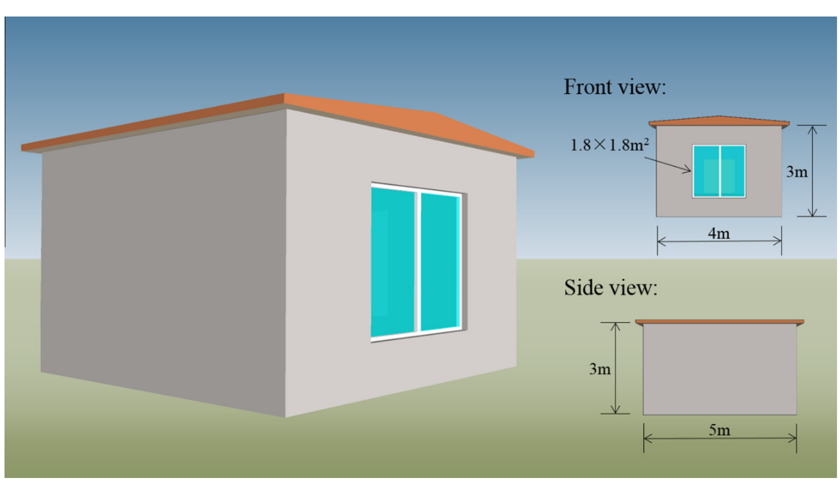


**Fig. 1.** Schematic diagram of a passive solar house.