Energy and exergy analysis of building envelope with different sustainable insulation materials

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Abstract - Sustainable insulation materials have demonstrated potential for enhancing building energy efficiency while maintaining thermal comfort. Traditionally, the energy efficiency of buildings and the insulating effects of these materials on the building envelope have been evaluated through energy analysis, which mainly focuses on quantifying total energy consumption. However, the application of exergy analysis offers a more comprehensive evaluation of the building envelope's energy efficiency. Therefore, this study analyzes the energy and exergy performance of the building envelope with different sustainable insulation materials on the Winter period for 24-h using MATLAB. The results indicate that sustainable insulation materials significantly improve the energy efficiency of the building envelope. This study provides a more comprehensive insight into evaluating the energy efficiency of building envelopes, not only by measuring energy use but also by assessing the effectiveness and quality of the insulation.

Nomenclature

U_i	thermal transmittance in i surface, W.m^{-2}.K
d_j	thickness of j layer in envelope, m
k_j	thermal conductivity of j layer, W.m^{-1}.K
$\dot{Q}_T$	transmission heat loss rate, kW
A_i	area in i surface, m^2
U_{door}	thermal transmittance of door, W.m^{-2}.K
A_{door}	area of door, m^2
F_{xi}	correction factor for specific temperature
T_{in}	indoor temperature, K
T_{out}	outdoor temperature, K
$\dot{Q}_V$	ventilation heat loss rate, kW
c_p	specific heat capacity, J.kg^{-1}.K
ρ	density of the air, kg.m^{-3}
V	volume of the building, m^{-3}
n_d	air exchange rate
$\dot{Q}_S$	solar heat gain rate, kW
I_s	solar irradiance on window, W.m^{-2}
F_f	frame factor
A_w	window area, m^2
g_j	g-value of window
F_{sh}	shading coefficient
F_{no}	orientation factor
$\dot{Q}_0$	heat gain rate due to person, kW
$\dot{Q}_0^{*}$	heat emission per person, kW
n_o	number of people
$\dot{Q}_L$	heat gain rate due to artificial lighting, kW
p_l	power rating, kW
A_N	net floor area, m^{-2}
$\dot{Q}_D$	total heat demand rate, kW
$\dot{E}x_{dest}$	exergy destruction rate, kW
$\dot{Q}$	the rate of heat transfer, kW
$\dot{E}x_{in}$	exergy input, kW
$\dot{E}x_{out}$	exergy output, kW

1. Introduction

The rapidly increasing demand for building has generated a massive amount of energy usage. According to the European Commission [1], buildings accounted for approximately 40% of energy consumption and 36% of energy-related greenhouse gas emissions within the European Union (EU) before 2021. As a result, the construction sector plays a critical role in energy use and greenhouse gas production. Energy within buildings is primarily consumed for heating, cooling, lighting, and ventilation [2,3]. Consequently, enhancing thermal regulation in buildings to improve energy efficiency and reduce consumption has become a focal point of

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attention. The building envelope, acting as the primary interface between the interior and exterior environments, plays a crucial role in thermal regulation beyond mere separation.

Innovatively, recycling biomass-based material for the building envelope is considered a promising strategy for reducing energy consumption [4]. In particular, straw has significant potential for insulation due to its abundant yield and superior insulating properties [5,6]. However, its application still faces some challenges due to the structure. Recent proposals have suggested using cob, a mixture of raw earth and straw, as an insulation material to address these issues [7]. Some researchers have confirmed that the mechanical and thermal properties of the cob can be improved compared the raw earth and straw through experimental methods [8,9].

Despite the interest in sustainable insulation material within building envelopes, there are limited methodologies on the selection of such materials, mainly energy analysis [10]. This gap in the literature underscores the necessity for a novel research direction that combines energy and exergy analyses. Thus, in this study, a numerical simulation to analyze the energy and exergy performance of various sustainable insulation materials in the building envelope is developed using MATALB. The study aims to explore and compare the energy savings and insulated effects of these materials on the building envelope.

2. Methodology

2.1. The studied envelope system

The envelope system studied was implemented in a small building with a floor area of 19.8 m² and a volume of 55.44 m³. A door area of 1.89 m² was set on the west wall. And a small openable window was set on the south wall to allow the real influence of solar radiation on the indoor environment. The indoor air temperature was set to 23 °C to achieve thermal comfort. The building was simulated without a heating system. The standard wall consisted of brick covered with plaster on both the inner and outer sides. In addition, the external side was covered with different sustainable insulation materials: (1) clay; (2) straw; (3) a composition of 95% clay and 5% straw. The schematic of the whole system is shown in Figure 1.

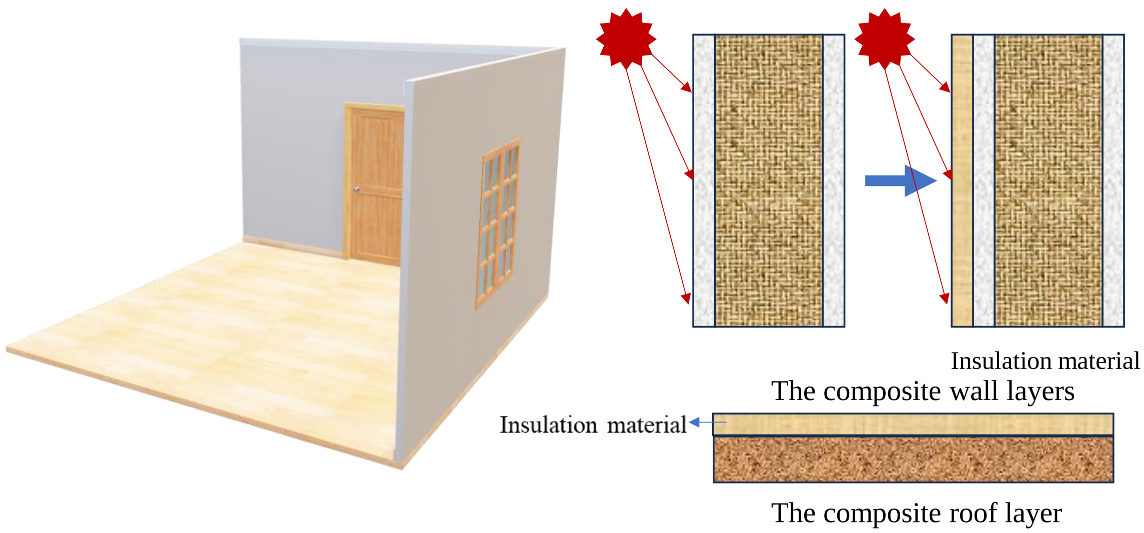


Figure 1: *The different cases studies of building envelope*

Furthermore, this study investigated four envelopes with different types of sustainable insulation materials, as presented in Table 1. Among them, the calculated U value of different cases can be calculated by Eq. (1). The air films can be ignored in this study.

$$U_i = \frac{1}{\sum_{j=1}^{n} \frac{d_j}{k_j}} \quad \textbf{(1)}$$

		Place	*Thickness*	*Thermal conductivity*	*Calculated U value*
		-	m	$W.m^{-1}.K$	$W.m^{-2}.K$
1	Standard wall (without insulation)	Plaster	0.0254	0.72	2.5770
		Brick	0.2286	0.72	
		Plaster	0.0254	0.72	
	Standard roof	Cast-concrete	0.2286	1.13	4.9431
2	Clay wall	Clay	0.03	0.457	2.2041
		Plaster	0.0254	0.72	
		Brick	0.2286	0.72	
		Plaster	0.0254	0.72	
	Clay roof	Clay	0.03	0.457	3.7327
		Cast-concrete	0.2286	1.13	
3	Straw wall	Straw	0.03	0.058	1.1046
		Plaster	0.0254	0.72	
		Brick	0.2286	0.72	
		Plaster	0.0254	0.72	
	Straw roof	Straw	0.03	0.058	1.3899
		Cast-concrete	0.2286	1.13	
4	Clay-straw wall	Clay-straw	0.03	0.259	1.9846
		Plaster	0.0254	0.72	
		Brick	0.2286	0.72	
		Plaster	0.0254	0.72	
	Clay-straw roof	Clay-straw	0.03	0.259	3.1437
		Cast-concrete	0.2286	1.13	

Table 1: *Property for the building envelope [4,9,11]*

2.2. The weather conditions

The simulation was conducted over a 24-hour on Winter period in Strasbourg, located in eastern France (Latitude: 48.573405°, Longitude: 7.752111°). The hourly measurement data of ambient temperature and solar radiation were sourced from the national meteorological service (Meteo) presented in Figure 2. These data reflect the comprehensive integration of diurnal variations in solar irradiance, which inherently consider the Earth's rotation and axial tilt.

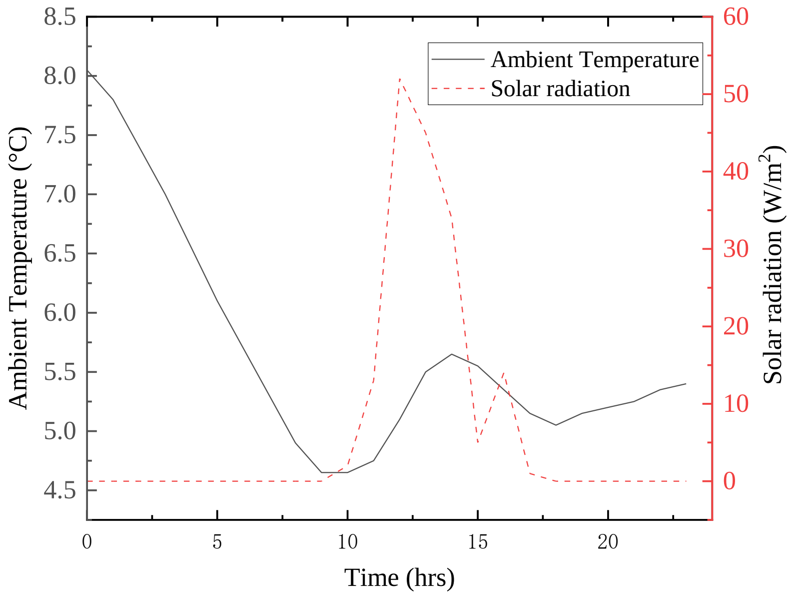


Figure 2: *The weather data of winter period for 24-h*

2.3. The theory analysis

Based on the first law of thermodynamics, the heat loss through transmission, ventilation losses, passive solar heat gain, internal heat gain, and other uses of electricity were taken into consideration in the energy analysis.

In this study, the thermal bridge was neglected. Most importantly, unlike walls and roofs, floors typically have less exposure to external climatic conditions, particularly in multi-story buildings where only ground floors might directly contact the ground. Thus, considering the objectives of this study, the thermal transmission through the floor was deemed to have a negligible impact on the overall energy performance and was therefore excluded from the detailed analysis. The rate of the transmission heat loss through a given envelope area can be calculated as [12]:

$$\dot{Q}_T = \sum\left(U_i \cdot A_i \cdot F_{xi}\right)\cdot\left(T_{in} - T_{out}\right) + U_{door} \cdot A_{door} \cdot \left(T_{in} - T_{out}\right) \quad \textbf{(2)}$$

The rate of ventilation heat loss can be calculated as [12]:

$$\dot{Q}_V = \left(C_p \cdot \rho \cdot V \cdot n_d\right)\cdot\left(T_{in} - T_{out}\right) \quad \textbf{(3)}$$

The rate of solar heat gain through the window can be calculated as [12]:

$$\dot{Q}_S = \sum\left(I_s \cdot \left(1 - F_f\right)\cdot A_{w,j} \cdot g_j \cdot F_{sh} \cdot F_{no}\right) \quad \textbf{(4)}$$

The rate of internal heat gain due to the presence of two people can be calculated as [12]:

$$\dot{Q}_0 = \dot{Q}_0'' \cdot no_o \quad \textbf{(5)}$$

The rate of internal heat gain due to artificial lighting can be calculated as [12]:

$$\dot{Q}_L = p_l \cdot A_N \quad \textbf{(6)}$$

The total heat demand rate following the energy balance can be calculated as [12]:

$$\dot{Q}_D = \dot{Q}_T + \dot{Q}_V - \left(\dot{Q}_S + \dot{Q}_O + \dot{Q}_L\right) \quad \textbf{(7)}$$

Based on the second law of thermodynamics, the ambient temperature can be used as reference temperature in this study. The exergy destruction rate can be expressed as [13]:

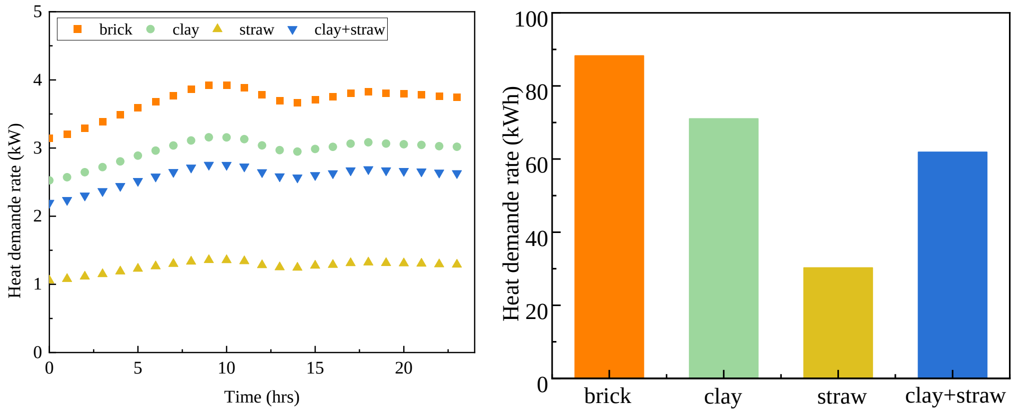
$$\dot{E}x_{dest} = \dot{E}x_{in} - \dot{E}x_{out} + \dot{Q} \cdot (1 - \frac{T_{out}}{T_{in}}) \quad \textbf{(8)}$$

Especially, the exergy destruction rate due to thermal losses from transmission and ventilation was quantified in this study, significantly contributors to overall energy inefficiency in buildings. Therefore, assuming balanced exergy inputs and outputs apart from these losses, focusing on the heat lost through the building envelope and necessary ventilation, a simplified expression for exergy destruction rate was derived as [10,12]:

$$\dot{E}x_{dest} = \left(\dot{Q}_T + \dot{Q}_V \right) \cdot \left(1 - \frac{T_{out}}{T_{in}} \right) \quad \textbf{(9)}$$

3. Results and discussions

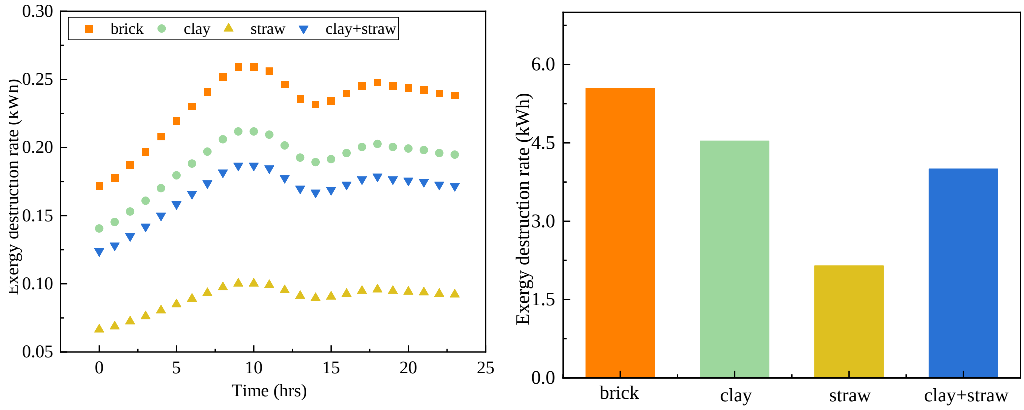
The total heat demand rate results for all cases throughout the day are shown in Figure 3. It is evident that envelopes equipped with sustainable insulation materials exhibit a significantly reduced total heat demand rate compared to buildings lacking insulation. This observation implies that the implementation of sustainable insulation materials can lead to further reductions in the energy consumption of buildings. Furthermore, when comparing the insulation effects of different materials, it appears that the order of total heat demand rate from highest to lowest is clay, composite material (clay + straw), and straw. Consequently, utilizing straw as an insulation material in envelopes results in the lowest energy consumption among the options considered, thereby optimizing thermal comfort more efficiently. Moreover, the use of composite materials, specifically clay combined with straw, presents a viable alternative, suggesting that the integration of traditional and biomass-based materials can optimize building insulation.



(1) The hourly total heat demand rate (2) Sum up the total heat demand rate over the 24-h

Figure 3: *The total heat demand rate*

Figure 4 presents the combined transmission and ventilation heat loss rates of exergy destruction for each case, across all hours considered. Materials demonstrating lower rates of exergy destruction are deemed more effective in minimizing energy consumption. Notably, straw insulation exhibits the lowest rates of exergy destruction, both hourly and daily, making it the most efficient material for retaining heat within buildings during winter. This reduces the necessity for additional heating. Such findings are consistent with those from energy analysis above, highlighting a congruence between the efficiency and energy conservation benchmarks identified through both evaluative methods. This parallel further underscores the effectiveness of straw as an insulation material, reinforcing its potential for enhancing energy efficiency in building design.



(1) The hourly exergy destruction rate (2) Sum up the exergy destruction rate over the 24-h

Figure 4: *The heat loss rate of exergy destruction*

4. Conclusion

Numerical simulations of the building envelope with different sustainable insulation materials have been conducted in this study, with the aim of investigating the energy and exergy performance on Winter period for 24-h. The results indicated that the effectiveness of insulation in the building envelope, from best to worst, is straw, composite material (clay + straw), and clay. Compared to a standard envelope (without insulation material), the envelope insulated with straw exhibited a 65.72% reduction in the total heat demand rate and a 61.79% reduction in the heat loss exergy destruction rate, achieving thermal comfort. This study can serve as a reference for selecting sustainable insulation materials aimed at improving the energy efficiency of buildings. However, in future studies, special focus should be given to economic analysis. This recommendation stems from the observation that using straw envelope does not provide optimal outcomes in terms of both structural strength and economic advantages associated with recycling. Alternatively, incorporating straw and clay into envelope is purported to maximize benefits. Economic analysis should be combined with energy and exergy analyses for a more comprehensive assessment.

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