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IMPACT OF GREEN ROOFING ON THE ENERGY PERFORMANCE OF A DETACHED PASSIVE RESIDENTIAL BUILDING WITH A TROMBE WALL

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Abstract: Implementing passive systems in detached residential buildings helps reduce the use of conventional energy-generating products for heating and cooling. Such buildings require special design, because their efficiency depends on the factors such as climate, terrain, terrain inclination, distance from other buildings, orientation, greenery, shading, and so on. Use of passive systems in detached residential buildings reduces the energy required for heating. Green roofing on such buildings has numerous environmental and energy-related benefits. Trombe wall passive systems are used for passive heating of buildings. This paper examines the impact of different green roof types on the energy properties of a detached residential building with a Trombe wall. The method applied is dynamic simulation using the EcoRoof simulation model within the EnergyPlus™ software package. The location of the analyzed building is the city of Niš, Serbia. The results indicate that the use of extensive green roof type in the analyzed model building with a Trombe wall reduces the total energy required for cooling by 3.45%.

Keywords: green roof, detached residential building, Trombe wall, energy properties

1. INTRODUCTION

Construction industry accounts for approximately 40% of the total energy consumption, while also being responsible for about 36% of CO_2 emissions [1]. Increased greenhouse gas emissions and the resulting negative environmental effects have urged architects worldwide to reinvestigate the technology of bioclimatic architecture as well as passive solar systems. The use of solar energy in solar and bioclimatic architecture is justified both economically and environmentally [2]. Implementing passive systems in detached residential buildings helps reduce the use of conventional energy-generating products for heating and cooling. Such buildings require special design, because their efficiency depends on the factors such as climate, terrain, terrain inclination, distance from other buildings, orientation, greenery, shading, and so on.

2. PASSIVE SYSTEM WITH A TROMBE WALL

In 1967, Félix Trombe used the patent for a massive solar wall to build a passive system into a detached residential house in Odeillo in the Pyrenees, which was later named Trombe wall (TW). The Trombe wall consists of a massive wall painted a dark color, made of a material with excellent thermal storage properties, most commonly brick or concrete. The exterior of the wall is shielded with glass forming an air gap of 2-10 cm. When penetrating the glass, sunlight hits the Trombe wall and heats it [3]. The maximum temperature on the inside of a Trombe wall is usually reached after six to eight hours of sunlight exposure. During the night, the Trombe wall releases heat and heats the indoor space. Heat is transferred to the building's interior by means of conduction and the heat transfer rate depends on the wall material and thickness. To improve heat transfer to the building's interior, ventilation openings may be added to the Trombe wall.

The most common variants used in practice are Trombe wall without the ventilation openings or with ventilation openings at the base and at the top. To prevent reversible heat transfer and uncontrolled heat loss during the night or during cloudy periods, the top and bottom ventilation openings need to be closed. The front air space between the glass and the wall may be vented outward by installing air vents, which prevents overheating during the summer [4].

The advantage of a Trombe wall passive system over a direct passive system is smaller indoor temperature fluctuation. A Trombe wall can also be a load-bearing structural element. The disadvantages of Trombe wall passive systems include wall overheating during daytime, slow heat transfer to the building's interior due to conduction, water vapor condensation on the glass, reduced space flexibility, and blocked view of the outdoor surrounding [4]. Figure 1 shows the cross-section of a Trombe wall passive system with the basic elements.

Trombe wall passive systems are used for passive heating of buildings. A review of the studies discussed in Kostikov et al. showed that the heating energy savings when using a Trombe wall amounted to 30% during the coldest months and up to 50% during the moderately cold months [2]. In the climate of Portugal, the contribution of Trombe walls in the total heating energy consumption balance is 16% [5].

Recent studies of Trombe wall passive systems also investigated the periods of building cooling in the summer months to prevent indoor overheating. The studies conducted in Mediterranean countries showed that the external temperature of a Trombe wall can reach up to 60°C if no shading system is used [5, 6].

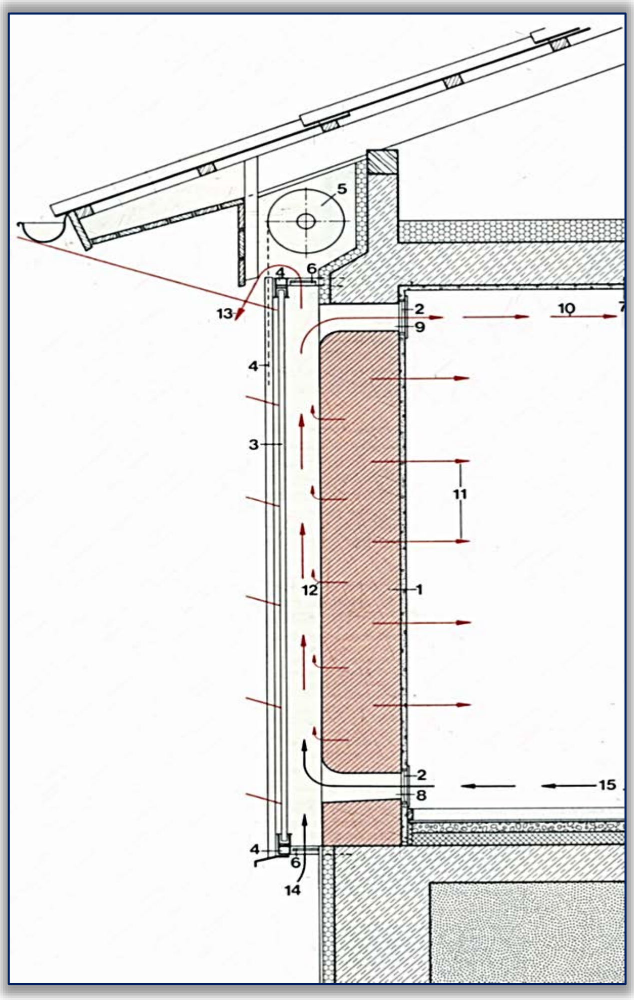

Figure 1. Schematic of the basic operating mode of Trombe wall and its elements [4]: 1. Massive wall made of material with high thermal storage capacity, dark colored on the exterior; 2. Ventilation openings; 3. Double glazing; 4. Glass bearing structure; 5. Blind – temporary sun protection; 6. Air vents; 7. Floor structure; 8. Opening for letting out cold air from the room; closed at night; 9. Opening for letting in warm air; closed in the summer; 10. Warm air flow directly into the room; 11. Delayed release of accumulated energy; 12. Cooling during the summer through dissipation of heat accumulated in the wall; 13. Ventilation of the space between the wall and the glass;14. Fresh air intake

Lohman and Santos found that using Trombe walls in administration buildings can achieve heating energy savings of up to 27%. They also found that the increase of air vents in the Trombe wall can improve its overall functioning [1].

Other studies explored the influence of using phase change and composite materials on Trombe wall heating efficiency [7, 8].

However, the review of previous studies suggests that no studies have examined the influence of green roofing on the efficiency of detached passive buildings with a Trombe wall.

3. METHODOLOGY

This paper examines the influence of green roofing on the energy properties of a residential building with a Trombe wall in a humid continental climate in the city of Niš, Serbia. An analysis is performed of the required energy for heating and cooling of a building with a Trombe wall with extensive, semi-intensive, and intensive green roofing (Table 1). The method used to determine the building's energy properties is dynamic simulation by means of EnergyPlus™ software.

— Green roof model

A green roof is an open space or garden built as a com plex biophysical structure allowing vegetation to grow over a roof structure. Depending on substrate thickness, vegetation type, maintenance, irrigation, and construction cost, green roofs are classified into extensive, semi-intensive, and intensive green roofs (Table 1) [9].

The EnergyPlus™ dynamic simulations were carried out using the *EcoRoof* simulation model to examine the energy performance of a model building with a Trombe wall passive system and a green roof [10]. *EcoRoof* considers the heat exchange inside the plant canopy, the influence of plant canopy on heat transfer, evapotranspiration, and heat storage in the substrate. The input parameters for the simulation model include substrate thickness and thermal properties, plant canopy volume, plant height, plant moisture transpiration, substrate moisture, and irrigation. The basic input parameters for the green roof model variants MODEL GR1, MODEL GR2, and MODEL GR3, defined in EnergyPlus™, are given in Table 2. The green roof surface area is 92.16 m^2.

Table 1. Green roof types with basic characteristics [9]

	Green roof type		
	Extensive	Semi-intensive	Intensive
Load [kg/m^2]	60-150	120-200	250-1000
Substrate thickness [cm]	Up to 15	Up to 15	15-100
Vegetation type	Moss, sedum, grasses	Grasses, shrubs	Perennials, shrubs, and woody plants
Cost	Low	Medium	High
Maintenance	Rare	Occasional	Frequent
Irrigation	Rare	Occasional	Regular
Compatible roof type	Flat or inclined roof	Flat roof	Flat roof
Accessibility	Only accessible for maintenance	Accessible for use to a certain extent	Fully accessible for use (most often for rest and recreation)

Table 2. EnergyPlus™ input parameters of the green roof over the model building with a Trombe wall [9]

Parameter	MODEL GR1	MODEL GR2	MODEL GR3
Green roof type	Extensive	Semi-intensive	Intensive
Vegetation height (parameter range 0.01-1.0 m)	0.15 m	0.50 m	1.0 m
Leaf area index (LAI) (parameter range 0.001-5.0)	2	3.5	5
Leaf albedo	0.22	0.22	0.22
Emissivity of leaves	0.95	0.95	0.95
Stomatal resistance (parameter range 50.0-300.0 s/m)	150	150	150
Thickness	0.15 m	0.35 m	0.50 m
Substrate albedo	0.14	0.14	0.14
Substrate emissivity	0.90	0.90	0.90

— Model of a detached passive building with a Trombe wall and a green roof

The reference model of a detached passive building with a Trombe wall has only the ground floor, with a floor surface area of 92.16 m^2. The floor base is 14.4 m long and 6.4 m wide. The building height is 3 m.

The Trombe wall is made of 0.2 m thick concrete and shielded with air filled double glazing placed 0.10 m in front of the wall. The Trombe wall covers the entire length of the south-facing façade (14.4 m). The wall also contains top and bottom ventilation openings with the dimensions 0.5x0.2 m. The window-to-wall ratio of the east-, west-, and north-facing façades is WWR=20%. Figure 2 shows the geometry of the model building with a Trombe wall.

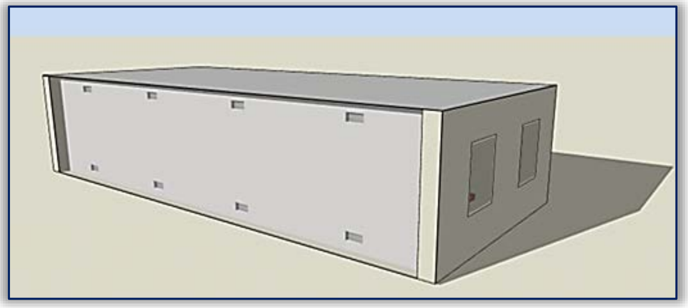

Figure 2. 3D representation of the detached building model with a Trombe wall

Table 3 shows the heat transfer coefficients U for the façade walls, floor and roof structures, and windows of the model building.

Table 3. Coefficient U for the defined thermal envelope elements of the building [9]

Building elements	U [W/m^{2}K]
Façade wall	0.29
Base floor	0.28
Windows	1.50
Flat roof	0.15

The analyzed model building with a Trombe wall is located in Niš, Serbia (43°19' N latitude, 21°54' E longitude, 202 masl). The heat transfer coefficient for all structures in the model's thermal envelope meet the criteria defined in the Rulebook on Energy Efficiency of Buildings [11]. The design temperatures are 22°C for the heating system and 25°C for the cooling system. Air infiltration in the analyzed model variants is 0.700 ac/h.

Three variants of the reference model were developed, each containing one of the green roof types shown in Table 2. The detached building model variants (MODEL GR1, MODEL GR2, and MODEL GR3) differ from the reference model only in that they contain a green roof.

4. RESULTS, ANALYSIS AND DISCUSSION

EnergyPlus™ dynamic simulations were carried out and energy properties for the heating and cooling periods were determined for the defined reference model building with a Trombe wall without a green roof and for its green roofed variants (MODEL GR1, MODEL GR2, and MODEL GR3). The simulation results for the annual and monthly heating and cooling energy requirements for the climate of Niš are shown in Tables 4 and 5, respectively.

Table 4. Total annual heating and cooling energy requirements of the model building with a Trombe wall and without a green roof and of its green roofed variants MODEL GR1, MODEL GR2, and MODEL GR3

	Energy required for heating [kWh]	Reduction of energy required for heating [%]	Energy required for cooling [kWh]	Reduction of energy required for cooling [%]
Reference model (without a green roof)	6064.13	Ref.	3155.26	Ref.
MODEL TWGR1	6064.13	0%	3155.26	0%
MODELTWGR2	6073.332	+0.15%	3105.94	-1.56%
MODELTWGR3	6100.03	+0.59%	3046.29	-3.45%

Based on the simulation results, a comparative analysis was performed of the energy properties of the Trombe wall building with different green roof types. Those results indicate that the use of an extensive green roof produced no changes in the heating and cooling energy requirements. When a semi-intensive green roof was used, the total annual heating energy requirements increase by 0.15%, whereas the total annual cooling energy requirements decrease by 1.56%. The biggest decrease of the total annual cooling energy requirements (3.45%)

was registered when an intensive green roof was used. However, the intensive green roof increased the total annual heating energy requirements by 0.5%. With regard to cooling energy requirements, the improved efficiency of the intensive green roof over the other two types is influenced by substrate thickness and the type of vegetation, which is characterized by its height and its leaf area index (LAI).

Table 5. Total monthly heating and cooling energy requirements of the model building with a Trombe wall and without a green roof and of its green roofed variants MODEL GR1, MODEL GR2, and MODEL GR3

	Reference MODEL TW (without a green roof)		MODEL TWGR1		MODEL TWGR2		MODEL TWGR3	
	Energy required for heating	Energy required for cooling	Energy required for heating	Energy required for cooling	Energy required for heating	Energy required for cooling	Energy required for heating	Energy required for cooling
	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
January	1513.23	6.64	1513.23	6.64	1511.26	6.67	1511.08	6.66
February	1191.36	15.58	1191.36	15.58	1192.94	15.52	1195.30	15.45
March	696.32	36.09	696.32	36.09	699.34	35.67	702.85	35.26
April	212.55	109.32	212.55	109.32	216.01	107.54	220.93	105.19
May	14.47	288.67	14.47	288.67	16.07	281.52	18.11	273.44
June	0.01	566.12	0.01	566.12	0.02	554.35	0.05	541.46
July	0.00	796.99	0.00	796.99	0.00	783.36	0.00	766.75
August	0.00	774.67	0.00	774.67	0.00	765.98	0.00	755.58
September	11.29	353.22	11.29	353.22	11.99	348.81	13.05	342.16
October	193.92	176.05	193.92	176.05	196.62	174.67	201.86	172.83
November	716.39	31.20	716.39	31.20	717.29	31.13	722.18	30.80
December	1514.60	0.70	1514.60	0.70	1511.80	0.71	1514.62	0.71

5. CONCLUSION

This paper presented a comparative analysis of the energy properties of a detached passive residential building with a Trombe wall and the addition of different green roofing types (extensive, semi-intensive, and intensive). It was determined, using the method of dynamic simulation, that the use of extensive green roofing did not improve the energy properties of the building. In addition, the heating energy requirements when using semi-intensive and intensive green roofing were higher compared to the reference model without green roofing. The biggest changes in the energy properties were found when intensive green roofing was used, as it reduced the cooling energy requirements by 3.45%.

The study considered a detached passive building with a Trombe wall made of concrete and shielded with air filled double glazing. The analyzed wall also contained ventilation openings for air circulation. Further research should focus on the efficiency of green roofing with Trombe walls made of other, modern materials. It would also be beneficial to examine the use of phase change materials in Trombe walls in order to determine whether they help decrease the cooling energy requirements for buildings.

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References

[1] Lohmann, V., Santos, P., Trombe Wall Thermal Behavior and Energy Efficiency of a Light Steel Frame Compartment: Experimental and Numerical Assessments, Energies, 13 (2020), 11
[2] Sergei, K., et al., A Review of the Current Work Potential of a Trombe Wall, Renew. Sustain. Energy Rev., 130 (2020), October 2019, pp. 109947
[3] Radosavljević J. Urbana ekologija. Fakultet zaštite na radu u Nišu, Niš. 2009. [Urban Ecology]
[4] Mila Pucar: Bioklimatska arhitektura - zastakljeni prostori i pasivni solarni sistemi, IAUS, Beograd, 2006
[5] Brito-Coimbra, S., et al., Building Façade Retrofit with Solar Passive Technologies: A Literature Review, Energies, 14 (2021), 6
[6] Simões, N., et al., Energy Performance of Solar and Trombe Walls in Mediterranean Climates, Energy, 234 (2021)
[7] Leang, E., et al., Impact of a Composite Trombe Wall Incorporating Phase Change Materials on the Thermal Behavior of an Individual House with Low Energy Consumption, Energies, 13 (2020), 18, pp. 1-32
[8] Oluah, C., et al., Selection of Phase Change Material for Improved Performance of Trombe Wall Systems Using the Entropy Weight and TOPSIS Methodology, Energy Build., 217 (2020), pp. 109967
[9] Vukadinović, A., et al., Impact of Green Roofing on The Energy Performance of a Residential Building with a Sunspace, Tehnika, 76 (2021), 3, pp. 281-287
[10] Energy, U.D. of, Engineering Reference, EnergyPlus™ Version 9.1.0 Documentation, 2019
[11] ***, Pravilnik o energetskoj efikasnosti zgrada, Službeni glasnik RS, 061/2011. [Rulebook on Energy Efficiency of Buildings]