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BUILDINGS WITH DYNAMIC FAÇADES: THE ENERGY PERFORMANCE OF A BUILDING WITH E.T.F.E. AIR CUSHIONS

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Abstract: *The paper is analysing the energy performance of a building that uses ETFE air cushions for the glazed surface of the façades. The dynamic envelope system adapts itself to the external conditions through: the variation of thermal transmittance by inflating and deflating the air chambers of the ETFE cushion and the variation of the shading degree by overlapping two printed ETFE foils. The paper presents a comparative study on the energy performance of the building described above and of a similar building with curtain walls, demonstrating that the dynamic façade saves up to 60% of the required cooling and heating energy. Moreover, by integrating photovoltaic cells within the ETFE air cushion, the cooling and heating energy can be halved.*

Key words: *energy performance, renewable energy, ETFE cushions*

1. Introduction

The introduction of ETFE membrane in buildings was set by Frei Otto at the construction of the Olympic Stadium in Munich, Germany in 1972. ETFE (*ethylene tetrafluoroethylene*) is a lightweight material, increasingly used in constructions due to the light transmittance of 94-97% and its potential in energy saving.

When used as an envelope, the ETFE membranes are often assembled as pneumatically pretensioned air cushions consisting of two or more layers of film, joined to the edges in order to reduce the total load on structure, while offering high thermal insulation. Being a lightweight material with high strength, large surfaces can be obtained, allowing the design of large open spaces and unlimited variety of form, see: [2].

The raw ETFE material does not consist of a petrochemical derivative, but a substance of Class II, according to the Montreal Protocol, a low-energy material. Due to the low weight, the ETFE membrane transport requires less energy (about 90%) than with glass. At the end of the period of use, the system can be dismantled and recycled by melting the membranes and reusing them for the production of new ETFE membranes. The most important aspect in terms of sustainable design is the ability of the system to become a catalyst element for holistic sustainable design, offering natural ventilation, reducing structural weight and controlling light transmission for natural lighting, see: [5].

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Comparison of thermal conductivity and total solar energy transmission factor for glass façades and ETFE air cushions envelope [3] Table 1

	Thermal conduction U (W/m^2K)	Total solar energy transmission factor g
Monolith glass 6 mm	5.9	0.95
Double glass 6-12-6 mm	2.8	0.83
Double glass with high performance 6-12-6 mm	2.0	0.35
2 layers ETFE cushion	2.9	0.71-0.22 (with foil printing)
3 layers ETFE cushion	1.9	0.71-0.22 (with foil printing)
4 layers ETFE cushion	1.4	0.71-0.22 (with foil printing)

Regarding the optical and thermal properties, table 1 shows the thermal conduction (*U*) and the total solar energy transmission power (*g*) of glazing compared to ETFE air cushions.

Typically three layers of ETFE foil are used, as this system conveys an optimal ratio between thermal performance and optical transparency. Thermal and optical properties of ETFE air cushions can be significantly improved by applying other layers, printing and geometry. An example of changing the flow of energy through an ETFE air cushion is to apply a reflective film to the intermediate cushion membrane. The intermediate cavities may be closed or opened, allowing or preventing the penetration of light and heat into the interior space. Application of a low-emissivity film can reduce heat loss during winter nights or reduce the effect of overheating during the summer, see: [1].

A key parameter of ETFE air cushion performance is the presence of a printed intermediate layer for the introduction of shading and the reduction of solar energy transmitted to the interior spaces. Light transmission may vary depending on the number of printed membranes that can be adjusted to combine the shading effect.

The ETFE multifunctional modules (ETFE-MFM) highlight the additional functionalities of photovoltaic modules that can optimize the energy performance of buildings that use integrated photovoltaic system applications. These modules include ETFE air cushions, photovoltaic technology, lighting systems and flexible integrated circuits to generate new lighting possibilities for a sustainable building with thermal, acoustic, lighting performance for the glazed surfaces and renewable energy sources. See: [4].

2. Energy Performance of an Office Building with ETFE Air Cushions

The objective of this case study is to determine the energy performance of a building with ETFE air cushions that allows the dynamic adjustment of the building's envelope to the exterior environment in order to increase energy efficiency. The case study considers the degree of shading and thermal transmittance of the transparent envelope as variable parameters, in order to establish the optimum performance parameter values, the periods of time in which they should have certain values and when they need to change. Different data were introduced to simulate the energy performance of an ETFE air cushion building: compared to the same building with curtain wall; inflating and deflating the ETFE multi-layered air cushions; changing the degree of shading by printing two layers of the ETFE air cushion.

2.1. Calculation Hypotheses – Case Study: the Office Building

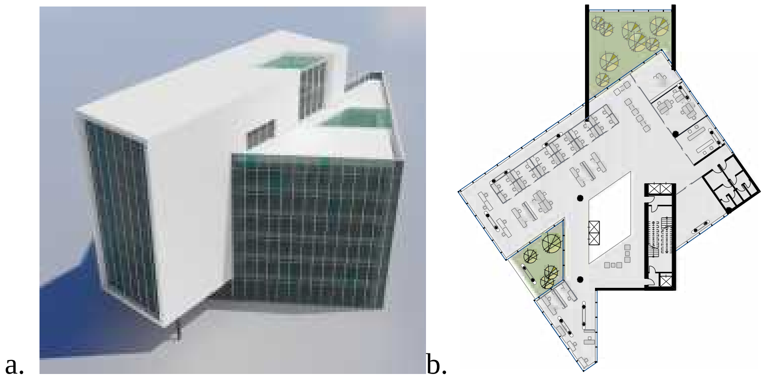


Fig. 1. a. *3-D representation of the office building;* b. *current floor*

In order to generate results as close to reality as possible, a 3D model of an office building of average dimensions was designed in the modelling program Archicad [6] (Figure 1), choosing as location the city of Iasi, Romania, to provide specific climatic parameters. The defined properties of the component elements, the specific interior functions and the occupancy schedule are introduced into the simulation programme PHPP [7]. The opaque-transparent ratio is in favour of the transparency (glazing ratio: 60.9%), to best highlight the problems and the possibilities for optimizing this type of buildings.

In terms of floor number and height, the building fits in the average buildings typology for Europe, USA and China, with 8 levels and 30 m high. The structure of the outer walls consists of a layer of high thermal mass inside (brick or reinforced concrete) and a layer of thermal insulation outside. The construction details of the envelope elements are designed to achieve low thermal transmittance values:

- exterior walls U=0.13 W/m^{2}K;
- roof terrace U=0.10 W/m^{2}K;
- floor on ground U=0.10 W/m^{2}K.

2.2. Variation of Thermal Transmittance and Shading Degree

Simulations will be made for different values for the thermal transmittance and the solar energy transmittance of the ETFE air cushions, taking into consideration the conditions of the interior and exterior environment. These values can be changed by printing two of the layers of ETFE foil so that when both chambers are inflated with air, the shading degree is minimal, and when one of them deflates, the two printed layers overlap by blocking a large amount of the solar input.

Thus, in the PHPP program separate scenarios will be created for a system with:

A. two air chambers: U = 1.5 W/m^{2}K and g = 0.71 (in winter);
B. one air chamber: U = 2.0 W/m^{2}K and g = 0.22 (in summer days);
C. airless: U = 5.6 W/m^{2}K and g = 0.22 (in summer nights).

2.3. Identifying the Moments in which the Envelope Parameters Should Vary

Based on the results for the scenario A (Figure 2) and B (Figure 3), the moment of changing the envelope parameters between the closed or open position of an air chamber are determined. In order to obtain minimum average values for both, heating and cooling, the October-March period is chosen for scenario A and April-September period for scenario B (Figures 4 and 5). The results show a heating energy demand of 153.9 kWh/m^{2}year and 100 kWh/m^{2}year cooling energy demand. Table 2 shows that, although in the combined scenarios A and B the energy demand for heating increases compared to scenario A and the cooling energy decreases compared to scenarios B, the total energy demand is diminished.

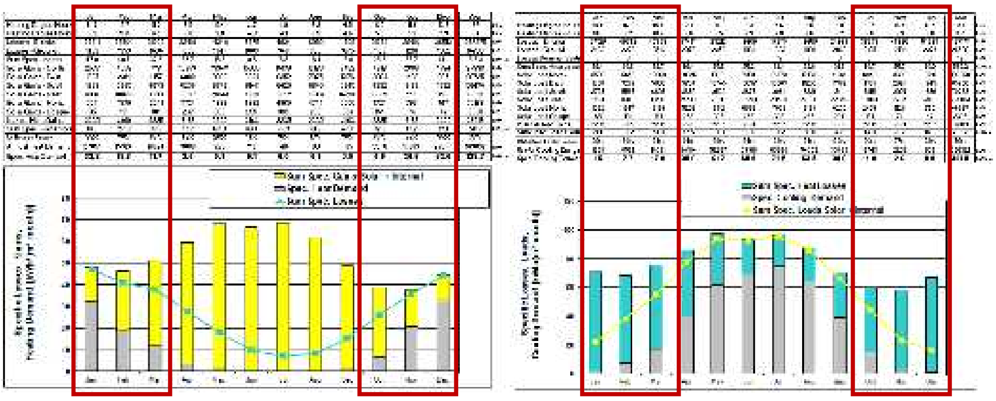


Fig. 2. *Energy performance results for scenario A*

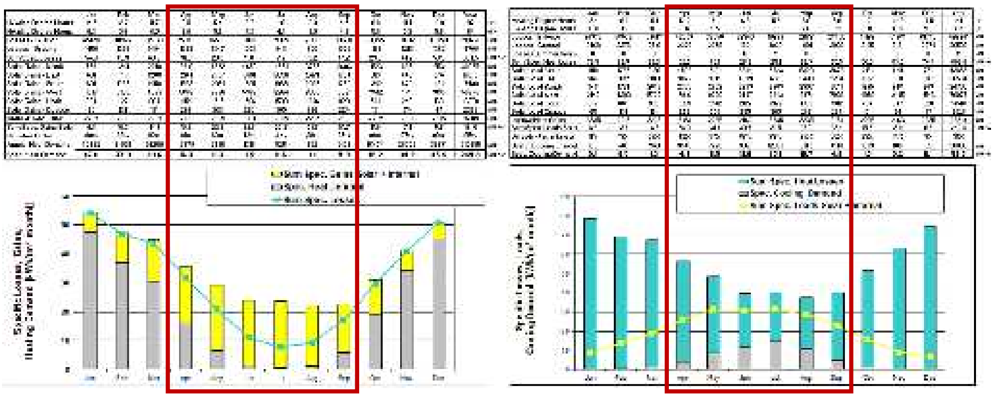


Fig. 3. *Energy performance results for scenario B*

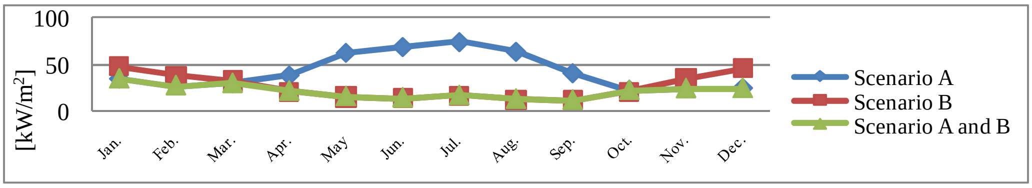


Fig. 4. *Annual energy demand for heating and cooling for scenarios A, B and combined*

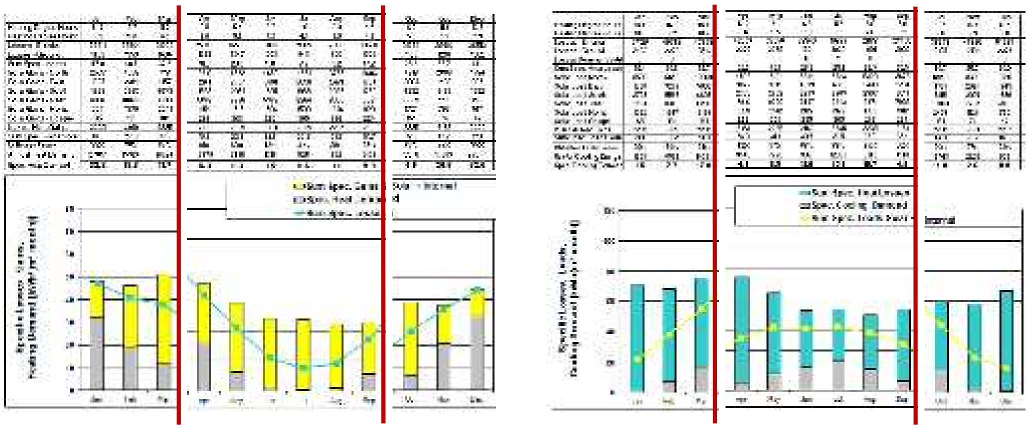


Fig. 5. *Energy performance results for combined scenarios A and B*

Annual energy demand for scenarios A, B and combined Table 2

	Annual heating energy demand [kWh/m^{2}year]	Annual cooling energy demand [kWh/m^{2}an]	Total [kWh/m^{2}an]
Case A	128	392	520
Case B	246	58	304
Case A and B	153.9	100	253.9

Monthly energy reduction for cooling by applying scenarios A, B and C Table 3

	Heat losses to exterior [kKh]	Heat losses to ground [kKh]	Specific heat losses – scenario A and B [kWh/m^2]	Specific Heat losses – scenario C [kWh/m^2]	Difference between specific heat losses [kWh/m^2]	Cooling energy demand – scenario A and B [kWh/m^2]	Reduction in energy demand for cooling [kWh/m^2]
Jan.	57129	2468	69.42	249.4	179.98	1.5	1.5
Feb.	49742	2276	60.59	217.2	156.61	7.7	7.7
Mar.	47879	2516	58.7	209.4	150.7	17	17
Apr.	42509	2378	52.28	163.9	111.62	4.1	4.1
May	32050	2359	40.08	124.1	84.02	8.5	8.5
Jun.	22340	1961	28.3	86.8	58.5	11.6	11.6
Jul.	19636	1932	25.12	76.5	51.38	15.1	15.1
Aug.	21188	1881	26.87	82.4	55.53	10.7	10.7
Sep.	28400	2038	35.45	110.1	74.65	4.8	4.8
Oct.	36248	2165	44.74	158.9	114.16	14.8	14.8
Nov.	45630	2191	55.7	199.4	143.7	2.6	2.6
Dec.	54323	2374	66.04	237.2	171.16	0.8	0.8

Taking into account the possibility of total deflation of chambers during summer nights, the energy saving by reducing the cooling demand will be calculated. Table 3 demonstrates that there is the possibility of reducing the energy requirement for cooling (from 100 kWh/m^{2}year) when the ETFE air cushion system follows the case scenario A, B and C (Figure 6). Therefore, the combined application of scenarios A, B and C for the periods identified above, would be the solution for an optimal performance of the ETFE air cushion system: 153.9 kWh/m^{2}year for heating and 0 kWh/m^{2}year for cooling.

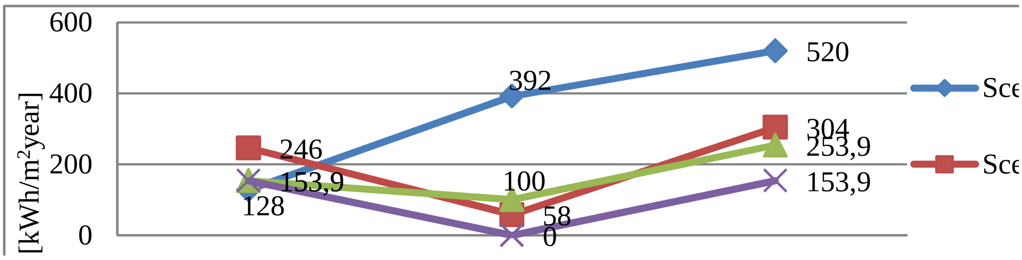


Fig. 6. *Annual energy demand for heating and cooling by applying scenarios A, B and C*

2.4. Integration of Renewable Energy Sources

Considering a solar energy transmission of 0.71 for the October-March period and 0.2 for the April-September period, which can be made to vary by inflating and deflating the air cushions with photovoltaic cells on two foil layers, the objective of this case study is to calculate the energy collected for each period from the south-west façade. It is considered that the photovoltaic cells cover 0.29% of the exterior foil surface and 0.51% of the next foil surface surface and have 90° inclination, being in the plane of the façade. For the periods of time in which the ETFE cushion has two air chambers, the PV cells in the second foil are shaded by the ones on the exterior one, therefore their performance is negligible. The annually collected energy sums up to 45161.42kWh (Table 4), contributing to the reduction of heating energy consumption by 52.64 kWh/m^{2}year.

If photovoltaic cells are also integrated into the south-east ETFE air cushions of the building (Figure 7), the collected energy is 15 761.44 kWh, which is reducing the energy demand with 18.37 kWh/m^{2}year.

The results generated by SolarPro[8] for photovoltaic cells on ETFE air cushion membranes on the south-west façade of the office building Table 4

	Surface covered by PV cells	Collected energy AC [kWh]
Ian.	0.29%	1759.37
Feb.	0.29%	1989.18
Mar.	0.29%	2633.82
Apr.	0.8%	5197.64
May	0.8%	5972.76
Jun.	0.8%	5904.51
Jul.	0.8%	6031.00
Aug.	0.8%	5930.08
Sep.	0.8%	5309.34
Oct.	0.29%	2128.89
Nov.	0.29%	1148.25
Dec.	0.29%	1156.72

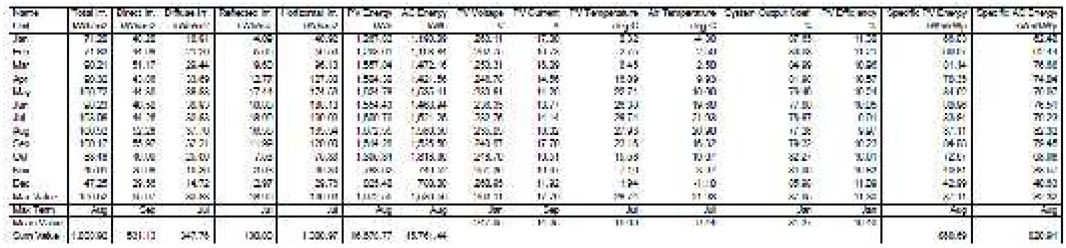


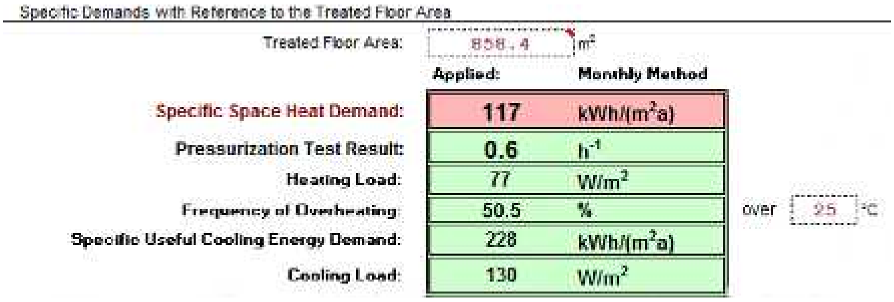
Fig. 7. *Generated results in SolarPro for the PV cells on the ETFE air cushion foils on the south-west façade of the office building*

3. Comparative Analysis of the Energy Performance of the Case Study Building and a Similar, Traditionally Equipped Building

This chapter is presenting a comparative study between the energy performance of the office building with ETFE air cushions and a similar building where the transparent part of the envelope consists of a curtain wall defined by the following characteristics:

- Triple-layer curtain wall iPlus 3 CE - Interpane g = 0.47, Ug = 0.49 W/m^{2}K
- Internorm frame with "Thermix" spacer Uf = 0.63 W/m^{2}K, ϕ_{spacer} = 0.043 W, $\phi_{installation}$ = 0.040 W
- Global thermal insulation coefficient G = 0.474 W/m^{2}K

3.1. Heating Energy Demand



Specific Demands with Reference to the Treated Floor Area

Treated Floor Area:	858.4	m^2	
	Applied:	Monthly Method	
Specific Space Heat Demand:	117	kWh/(m^{2}a)	
Pressurization Test Result:	0.6	h^{-1}	
Heating Load:	77	W/m^2	
Frequency of Overheating:	50.5	%	over 25 °C
Specific Useful Cooling Energy Demand:	228	kWh/(m^{2}a)	
Cooling Load:	130	W/m^2	

Fig. 8. *The annual heating and cooling energy demand and the overheating frequency*

For the traditional building, the heating and cooling energy demand is 345 kW/m^{2}year (Figure 8), 4.16 times bigger than the heating and cooling energy of the ETFE air cushion building with integrated PV cells, of 83 kW/m^{2}year, due to:

- 52.64 kWh/m^{2}year reduction by applying photovoltaic cells to the SW façade;
- 18.37 kWh/m^{2}year reduction by applying photovoltaic cells to the E façade.

3.2. Cooling Energy Demand

The energy saving is important, as for the traditionally equipped building the cooling energy demand is 228 kW/m^{2}year, while for the one with dynamic ETFE air cushion the value decreases to 22.3 kWh/m^{2}year. Therefore, the traditional building uses 10 times more energy for cooling. Also the overheating frequency for the traditional building is 50.5%, while for the ETFE air cushion one this value is 16.3%.

3.3. The Ratio of Energy Consumption from Non-renewable to Renewable Sources

While the traditional building does not use any renewable energy sources, the ETFE air cushion one has integrated PV cells which collect enough energy to reduce the energy demand for heating and cooling, of 153.9 kW/m^{2}year, with 71.01 kW/m^{2}year (46.14%), the rest of 53.86% being supplied from non-renewable sources.

4. Conclusions

Figure 9 shows the heating and cooling energy demand for the traditionally equipped building compared to a similar one in which the glass curtain wall is replaced with ETFE air cushions. The study outlines the energy savings for a building with a dynamic envelope consisting of ETFE air cushions, especially when photovoltaic cells are integrated into the ETFE foils. Due to the possibility of varying the degree of shading and thermal transmittance of the air cushions, the office building with a considerate transparent envelope surface reduces the heating and cooling energy demand from 345 kW/m^{2}year to 153.93 kW/m^{2}year (44.62%), half of which can be supplied from renewable energy sources (i.e. PV cells).

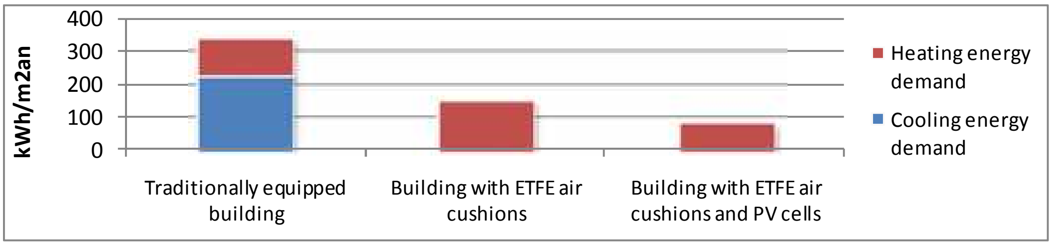


Fig. 9. *Heating and cooling energy demand comparison between case studies*

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