Innovative Systems for Energy Efficient Building Envelopes
Applications at middle latitudes (temperate/mesothermal climates)

MONICA ROSSI

ABSTRACT: This research intends to verify the thermal performance of innovative lightweight building envelope systems using dry construction techniques that were originally developed in continental climates (e.g. Central Europe), and to test their potential application in office buildings at middle latitudes (e.g. Southern Europe), using thermodynamic simulations. Their energy performance in use (annual, winter and summer) was evaluated in three Italian climate zones and possible problems were identified. As a result a proposal for improving the analyzed building envelope was developed, energy performance in use of the optimized building envelope was verified and design criteria for the applications in building at middle latitude were derived.

Keywords: building envelope, thermal comfort, thermal inertia, dry construction, mesothermal climates.

INTRODUCTION
Considering the building envelope as a dynamic interface between the surrounding and the internal environment, its primary role is to contribute to guarantee internal comfort, whilst limiting the use of non renewable energy sources. As a result, this research has identified a number of building envelope systems that can be assembled off-site and combine their lightweight structure with a high energy performance [1], particularly with respect to reduced thermal transmittance and increased thermal inertia. Following a detailed analysis of the products that have been developed in Central Europe in recent years, three groups of innovative products - not yet available or applied in Southern Europe (middle latitudes) - have been identified with respect to satisfying those needs / requirements: VIP (Vacuum Insulation Panels), TIM (Transparent Insulation Materials) and PCM (Phase Changing Materials). These products in fact show interesting energetic characteristics, which are difficult to be found in other materials used in the construction of building envelopes across Southern Europe:
- VIP can combine a high thermal resistance with an extremely reduced weight and thickness, due to their evacuated condition [2];
- TIM also feature a high thermal resistance combined with reduced weight and thickness. If attached to an opaque wall, they can greatly increase its thermal storage capacity [3];
- PCM can greatly increase the thermal inertia of a non-massive structure due to their capacity of changing phase.

CASE STUDIES AND BUILDING ENVELOPES
With the intention to evaluate the applicability of those products in Southern Europe, a number of existing central European buildings, characterised by the use of VIP, TIM or PCM, were selected. As a result of the analysis of their performance (monitored for at least one year), the buildings identified to be particularly innovative and energy efficient are:
- a single family house (Fig. 1-2) in Neumarkt (Germany) using VIP. The house with its longitudinal axis in east-west orientation is characterized by a highly insulated northern facade and metal balconies at its southern side. The balconies provide sun protection during summer and are not attached to the structure of the house in order to prevent thermal bridges;
- an office building (Fig. 3-4) in Erfurt (Germany) using cellulose honeycomb TIM. This project is an energetic retrofit of an already existing 6 floor building. The load-bearing structure of beams and columns in reinforced concrete was kept, whereas the building envelope was completely substituted within only three months;
- the “Haus der Gegenwart” (Fig. 5-6) in Munich (Germany), using gypsum panel with PCM. The house is a prototype for “current” collective housing, developed during a competition. The private rooms are located at the ground floor with independent access ways. The common rooms are located on the first floor, where the building envelope was analyzed.
Other than their innovative energy efficient light dry construction envelope (Tables 1, 2 and 3), the three selected buildings share an energy concept that considers the building as a unitary thermodynamic system [4]. The energy performance of each building depends not only on the envelope but also on all aspects of decisions made during the design / planning process at different scales and planning phases: orientation towards cardinal points, prevailing wind direction, window-to-wall ratio, etc.
VERIFYING ENERGY PERFORMANCE IN USE

In order to verify the potential application of the selected building envelope systems at middle latitudes, the systems were evaluated with respect to the current Italian design regulations [5]. This standard defines an upper limit for the thermal transmittance of a façade based on the climatic zone of the building and imposes a minimum “superficial mass” (kg/m²) for the external vertical surfaces. According to the Italian design regulations, thermal transmittance [U] has to be lower than 0.33 W/m²K for the coldest climate zone in Italy and the superficial mass [M_s] has to exceed 230 g/m² for the warmer climate zones. In case the value for M_s falls below this limit, an experimental verification is necessary to prove that the thermal inertia is equivalent to that of an envelope characterised by the value required. As the selected building envelope systems show a very low value of thermal transmittance compared to the design standard - yet their kg/m² value is lower than the minimum required (Tables 1, 2 and 3) - it has been necessary to simulate their thermal inertia, here intended as phase delay and reduction of the amplitude of the heat transmission.

- Envelope type 1: U= 0.120 W/m²K, M_s= 90 kg/m².
- Envelope type 2: U= 0.330 W/m²K, M_s= 16 kg/m².
- Envelope type 3: U= 0.230 W/m²K, M_s= 135.34 kg/m².

Given that the design standard does not define a methodology to verify the energetic performance in use, this research has developed an experimental procedure, which simulates the application of the selected building envelope systems in three different Italian cities located in diverse climatic zones: Milan (North Italy), Ancona (Central Italy) and Catania (South Italy) (Fig. 7, Table 4).

The energy performance in use of the three selected building envelope systems has been verified by means of thermodynamic simulations using the software package “Energy Plus” applied to a virtual test room (Fig. 7) in those three cities. The virtual test room has a floor surface of 22.5 m² and a height of 3 m. The room has been simulated as an office space (internal thermal load of 380 W) oriented towards the south and with a window-to-wall ratio of 30% (Fig. 8).

Figure 7: Three test locations and 3D view of the test-room.

By means of the simulations, not only the static energy performance parameters imposed by the Italian legislation (U and M_s) were checked, but also two dynamic energy performance parameters defined especially for non-massive structures [1] (time shift $\phi$ and decrement factor $\phi$) were calculated. The time shift is the period of time (hours) between the maximum amplitude of a cause and the maximum amplitude of its effect. In this case, the time shift is the period of time between the maximum value of external surface temperature and the maximum value of internal surface temperature. The decrement factor is the reduction of the amplitude of the heat transmission. Additionally, the annual energy demand necessary to ensure the internal comfort (21°C in winter and 26°C in summer [7]) was calculated assuming a heating system powered by natural gas and an electric cooling system. The annual energy demand is expressed in terms of kWh, € and CO₂ produced [8] (Table 5).

Table 5. Method of calculating costs and produced CO₂

<table>
<thead>
<tr>
<th></th>
<th>Milano</th>
<th>Ancona</th>
<th>Catania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of the heating system</td>
<td>90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy produced per m² of natural gas</td>
<td>9 kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price of natural gas per m³</td>
<td>0.65 €</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions per kWh produced</td>
<td>0.20 kg CO₂</td>
<td>0.20 kg CO₂</td>
<td></td>
</tr>
<tr>
<td>1 kWh for heating</td>
<td>0.08 €</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 kWh for cooling</td>
<td>0.05 €</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EER: Energy Efficiency Ratio

|                     | 3.3 W/W |        |         |
| Price of electric energy mix per kWh | 0.19 € |        |         |
| CO₂ emissions per kWh produced | 0.58 kg CO₂ |        |         |
| 1 kWh for heating | 0.05 € |        |         |
| 1 kWh for cooling | 0.16 kg CO₂ |        |         |

Figure 8: Section and floor plan of the virtual test-room.
The numeric results of the simulation of these three systems were compared with those of a reference façade system (Fig. 9) that is commonly used in buildings in Italy.

- Reference envelope: \( U = 0.33 \, \text{W/m}^2\text{K} \) and \( M_s = 31 \, \text{kg/m}^2 \) (Table 6).

**Figure 9: Section of reference envelope, scale 1:5.**

**Table 6: Technical data of the reference envelope.**

<table>
<thead>
<tr>
<th>Material</th>
<th>( s ) [m]</th>
<th>( \lambda ) [W/mK]</th>
<th>( \rho ) [kg/m³]</th>
<th>( R ) [m²K/W]</th>
<th>( C ) [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>plaster</td>
<td>0.015</td>
<td>0.900</td>
<td>1800</td>
<td>0.016</td>
<td>910</td>
</tr>
<tr>
<td>big honeycomb brick</td>
<td>0.120</td>
<td>0.500</td>
<td>800</td>
<td>0.240</td>
<td>840</td>
</tr>
<tr>
<td>plaster</td>
<td>0.015</td>
<td>0.900</td>
<td>1800</td>
<td>0.016</td>
<td>910</td>
</tr>
<tr>
<td>insulation panel</td>
<td>0.070</td>
<td>0.30</td>
<td>100</td>
<td>2.300</td>
<td>670</td>
</tr>
<tr>
<td>small honeycomb brick</td>
<td>0.080</td>
<td>0.250</td>
<td>700</td>
<td>0.320</td>
<td>840</td>
</tr>
<tr>
<td>plaster</td>
<td>0.015</td>
<td>0.350</td>
<td>1200</td>
<td>0.042</td>
<td>1010</td>
</tr>
<tr>
<td>hi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.123</td>
</tr>
</tbody>
</table>

Since this research was not only intended to verify the selected façade systems against the design standard, but also to simulate their energy performance, an in-depth analysis was performed, changing the orientation of the test room in the four orientations (north, west, south and east) and the window-to-wall ratio (20%, 30% and 50% respectively, corresponding to dimensions of 2.00 x 1.35 m, 3.00 x 1.35 m and 4.10 x 1.56 m respectively) of the tested façade. In all the simulations, the energy demand was compared to the one of the reference envelope and was evaluated in terms of energy demand [kWh], energy costs [€] and CO₂ produced, aiming at establishing also the economic and “environmental” applicability of the considered building envelope systems. The applied methodology comprises the following phases:

1. Climatic analysis of three Italian cities in three different climate zones.

2. First set of thermodynamic simulations: Monitoring of the thermal performance of a traditional façade and three innovative envelope systems in these cities during one year.

3. Calculation of the annual energy demand [kWh], costs [€] and CO₂ produced [kg] for heating and cooling - first set of simulations. Calculation of the annual energy demand [kWh],

4. Evaluation of the simulation results and comparison of the energy performance in use of the reference and the tested façade systems.

5. Second set of thermodynamic simulations - sensitivity analysis:
   - variation of orientation towards 4 cardinal points,
   - variation of the window-to-wall ratio for the test system.

6. Calculation of the annual energy demand [kWh], costs [€] and CO₂ produced [kg] for heating and cooling - second set of simulations.

7. Evaluation of the results of the second set of simulations.

8. Elaboration of proposals for improving the analysed building envelope systems.

9. Definition of design guidelines for the application of the analysed building envelope systems in buildings in Southern Europe (middle latitudes).

**RESULTS OF THE SIMULATIONS**

The simulations provide the possibility of determining the values of time shift (\( \varphi \)) and decrement factor (\( f_a \)) of the building envelopes as well as the overall annual energy demand during one year (winter and summer) (Fig. 10).

- Reference envelope: \( \varphi = 7 \, \text{h}, f_a = 0.10 \).
- Envelope type 1: \( \varphi = 9.5 \, \text{h}, f_a = 0.02 \)
- Envelope type 2: \( \varphi = 2.5 \, \text{h}, f_a = 0.11 \)
- Envelope type 3: \( \varphi \) and \( f_a \) can not be determined due to the nature of PCM

**Figure 10: Example of the calculation of time shift and decrement factor of the reference envelope system.**

The results of the thermodynamic simulations show not only a good thermal performance and energy saving potential of the new building envelopes, but also their liabilities, particularly when using those systems in buildings in Southern Europe. The tested building envelopes showed good results during the course of one year, especially in winter. During the summer period, on the other hand, only a minimum energy saving potential was detected (e.g. envelope type 2 in Catania was less efficient than the reference envelope) (Fig. 11).
These results depend on two main factors:
- The analysed building envelopes were developed for the climatic conditions of central Europe (continental climate), where, in contrast to Italy, energy saving mainly means limiting the energy losses towards the surrounding environment during winter period.
- The used test room is considered to be an office room, meaning that significant internal thermal loads are present. In this case, also building envelope systems with a very good energy performance can not reduce the energy demand for cooling purposes during summer. The use of building envelopes with a big time shift and decrement factor contributes to limiting the impact of the external thermal load on the internal climate. At the same time, they can’t influence the temperature increase due to the internal thermal load and the solar irradiation through the windows.

Based on the above considerations, two different approaches can be derived to solve the two problems:
- Proposals to improve the analysed building envelope systems for their application in southern Europe.
- Criteria for their application at middle latitudes considering not only the building envelope but the entire energy concept of the building in which the envelope is used.

**PROPOSALS FOR IMPROVING**
In order to improve the energy performance of the tested envelope systems for their application in the climate zones of Southern Europe suggestions for improvement were developed for manufactures as well as potential users.

**Envelope type 1 (VIP):** the VIP envelope system shows good energy performance and no further modifications are considered necessary. In order to further improve the energy performance of a building realized with this building envelope system, strategic-functional choices have to be approached during the design process rather than changing the stratification, thickness and materials of this system.

**Envelope type 2 (TIM):** a good energy performance was observed for this envelope type during winter. Nevertheless, excessive energy demand for cooling in summer was determined. This depends essentially on a reduced value of time shift of 2.5 hours, meaning that changes in external temperature arrive inside the room only 2.5 hours later. As a result, four suggestions for improvement were developed (Table 7), all of which include a new panel of various materials inserted between TIM and a PAVATEX panel.

<table>
<thead>
<tr>
<th>Proposal</th>
<th>s [m]</th>
<th>λ [W/mK]</th>
<th>ρ [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal 1</td>
<td>0.08</td>
<td>1.35</td>
<td>1000</td>
</tr>
<tr>
<td>Proposal 2</td>
<td>0.12</td>
<td>1.50</td>
<td>2400</td>
</tr>
<tr>
<td>Proposal 3</td>
<td>0.12</td>
<td>0.036</td>
<td>90</td>
</tr>
<tr>
<td>Proposal 4</td>
<td>0.051</td>
<td>0.010</td>
<td>200</td>
</tr>
</tbody>
</table>

The optimized envelope systems have the following characteristics:
- Proposal 1: $U=0.329$ W/m²K, $M_s=93$ kg/m².
- Proposal 2: $U=0.327$ W/m²K, $M_s=301$ kg/m².
- Proposal 3: $U=0.158$ W/m²K, $M_s=23.8$ kg/m².
- Proposal 4: $U=0.124$ W/m²K, $M_s=23.2$ kg/m².

The performance of the optimized building envelope systems were analyzed and verified in terms of thermodynamic simulations. The results of thermodynamic simulations did not reveal positive results for the first two proposals, but significant outcomes for the second two proposals (Table 8).

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Milano</th>
<th>Ancona</th>
<th>Catania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal 1</td>
<td>51,85 kWh</td>
<td>24,70 kWh</td>
<td>-8,12 kWh</td>
</tr>
<tr>
<td>Proposal 2</td>
<td>50,90 kWh</td>
<td>25,48 kWh</td>
<td>-5,76 kWh</td>
</tr>
<tr>
<td>Proposal 3</td>
<td>50,49 kWh</td>
<td>26,38 kWh</td>
<td>-3,56 kWh</td>
</tr>
<tr>
<td>Proposal 4</td>
<td>91,76 kWh</td>
<td>55,15 kWh</td>
<td>6,57 kWh</td>
</tr>
</tbody>
</table>

These results highlight that a reduction of the thermal transmittance of the envelope corresponds directly to a
reduction of the energy demand. An increased superficial mass, on the other hand, does not necessarily mean an improved energy performance, as proposed by the Italian design regulations [5].

**Envelope type 3 (PCM):** the envelope system containing PCM has a good energy performance during summer. In order to further improve its energy performance during the summer period in hotter climate zones two proposals for improvement were developed. Both of them utilize a PCM with a higher melting temperature (28°C and 30°C) in contrast to the original envelope type 3 (26°C). The simulation results (Table 9) of the optimized envelope system type 3 proved that an increasing melting temperature of the PCM has an energy saving effect only in the hottest of the three Italian cities considered.

**Table 9: Energy saving potential for the optimized building envelope in comparison with the reference system.**

<table>
<thead>
<tr>
<th></th>
<th>Milano</th>
<th>Ancona</th>
<th>Catania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope type 3 (26°C)</td>
<td>88,13 kWh</td>
<td>74,49 kWh</td>
<td>37,30 kWh</td>
</tr>
<tr>
<td>Proposal 1 (28°C)</td>
<td>80,89 kWh</td>
<td>74,33 kWh</td>
<td>40,98 kWh</td>
</tr>
<tr>
<td>Proposal 2 (30°C)</td>
<td>79,90 kWh</td>
<td>66,54 kWh</td>
<td>43,01 kWh</td>
</tr>
</tbody>
</table>

The results further demonstrate that using materials that have the ability of changing their thermal performance with changing temperature (PCM) requires an a priori accurate climatic analysis of the desired construction site in order to optimize their energy performance. Using PCM without knowing the average daily and monthly temperature - and especially the range of temperature fluctuation during one day - can not be energetically and economically efficient.

**DESIGN CRITERIA FOR THE APPLICATION AT MIDDLE LATITUDES**

Based on the results of the simulation it was further possible to identify the reasons that determine the overall energy demand of a building (Fig. 12).

The orientation and the variation of the window-to-wall ratio of the test facade influence considerably the calculated annual energy demand (Fig. 13). Based on the sensitivity analysis, it can be stated that - e.g. for an office building at middle latitudes - the most energy efficient orientation is northwards and the window-to-wall ratio should not exceed 20%. Nevertheless, window size can be increased, if sufficient shading is provided. The potential user of these criteria are architects and engineers.

**CONCLUSION**

This research has demonstrated that non-massive building envelopes with a reduced superficial mass can have a lower energy demand compared to massive building envelopes, also if used at middle latitudes. However, in order to meet this goal it is necessary that the design of a building is based on a consistent energy concept that addresses all aspects of decisions during the design process at different scales.

**REFERENCES**

3. Association for Transparent Insulation (FVTWD e.V.), [Online], Available: http://umwelt-wand.de/ [2008].