Investigation of the envelope’s thermal transmittance influence on the energy efficiency of residential buildings under various Mediterranean region climates

A C Karanafti1,2 and T G Theodosiou1

1Laboratory of Building Construction and Building Physics, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece

2akaranaf@civil.auth.gr

Abstract. Improving the energy efficiency of residential buildings is of outmost importance for reducing their environmental footprint. Recent studies demonstrate that a highly insulated building envelope may burden the building’s performance during the cooling period, especially in regions with hot summers. In this study, the energy performance of a residential building in different Mediterranean regions (Jordan, Greece, Iraq, Egypt, Syria, Morocco, Cyprus, Saudi Arabia, Libya, and Spain) is investigated. Two thermal transmittance values are applied to the building shell, a scenario with a very low one and a scenario with a higher one, to examine under which conditions the cooling performance is improved. A dynamic insulation configuration is also implemented, and its operation is studied for the cooling period of each city. It is concluded that in Southern European and Northern African regions building envelopes with lower thermal resistances perform better, while in even Southern regions an increased thermal resistance may prevent the heat from entering the building more effectively. With the switching insulation system, a great reduction in the cooling demands was reported, which reached up to 50% in Spain, and it was shown that in the southern regions the configuration’s operation should be customized to the ambient conditions to optimize its performance.

1. Introduction

According to the European Commission, the building sector is one of the most energy-intensive and is responsible for about 40% of the total energy consumption and 36% of the total CO₂ emissions in the European Union [1]. Thus, the demands for energy efficient buildings have led to the belief that super-insulated building envelopes provide thermal comfort to the occupants and reduce the energy loads for heating and cooling. However, recent studies reveal that a building shell with very low thermal transmittance may have increased cooling loads, as the excess thermal energy is trapped inside the building and cannot be discharged to the ambient environment during the night. Rodrigues et al. examined 96,000 different residential building geometries in 8 regions around Europe and concluded that the reduction of the thermal transmittance coefficient U contributes to cooling energy mitigation in Northern regions, while in southern regions leads to higher cooling loads [2]. Likewise, Fernandes et al. examined 192,000 building geometries in regions around the Mediterranean sea and concluded that in the southern regions a higher U-value is preferable [3]. D’ Agostino et al. investigated the optimal thermal insulation thickness for an office building located in Milan, Palermo, and Cairo for
different internal loads, and found that for Milan the optimal thickness is 8-10 cm, for Palermo 2-4 cm, and for Cairo an absence of thermal insulation is optimal, otherwise the cooling loads increase [4].

To avoid overheating in the cooling period many researchers have created dynamic insulation configurations that allow the building envelope to have different thermal transmittances according to the ambient conditions. Dabbagh and Krarti developed a dynamic insulation system where the insulation layers can be rotated through an actuator and provide lower thermal resistances, up to 50% reduction, of the building envelope when needed [5]. Alderucci et al. improved an existing dynamic insulation system consisted of an air gap separating the insulation system by the wall that can be ventilated or not, by exploiting Internet of Things technologies [6]. Koenders et al. developed a closed-loop forced convective dynamic insulation system that sets the insulation air-permeable when needed to increase thermal transmittance of walls and achieved a significant reduction of the cooling loads of a residential building [7]. Park et al. investigated the potential energy mitigation of buildings in the U.S.A. by integrating dynamic insulation materials in the external walls. The savings for heating energy were up to 10% and for cooling energy up to 39% [8].

In this study, the building shell’s thermal transmittance influence on the energy performance of a residential building is examined. In more detail, a typical storey of an apartment building, located in cities of 10 different countries around the Mediterranean Sea, is simulated in EnergyPlus and is analyzed with emphasis on its cooling loads. A low and a high U-value scenario is investigated by applying the respective thermal insulation thicknesses. Then, a dynamic insulation system is implemented and customized for the climatic conditions of each city, and its effects on the cooling energy demands are examined.

2. Methodology

2.1. Building description

The examined building is a typical floor of a multi-storey residential building, located in a suburban area. It consists of an apartment with a total area of 99.80 m², load-bearing structure of reinforced concrete, filling masonry from perforated bricks, and external thermal insulation protection, while there are no other buildings or obstacles around it. On the east side, the apartment is in contact with the staircase, which is unheated, and the biggest part of its south and west façade is shaded by the upper floor’s balcony as well as the north-east side of the apartment that is shaded by the semi-sheltered space of the upper floor. Doors and windows have a frame of PVC and double glazing, with a total U_w=2.6 W/(m²K). The building has also a heating and a cooling system, the first one operates from 1/1 to 30/4 and from 1/10 to 31/12 and the second one can operate during the whole year if the internal mean air temperature is over 26°C. The building’s energy performance was analyzed in 10 cities of the Mediterranean region: Amman in Jordan, Athens in Greece, Baghdad in Iraq, Cairo in Egypt, Damascus in Syria, Marrakech in Morocco, Nicosia in Cyprus, Riyadh in Saudi Arabia, Sebha in Libya, and Seville in Spain (figure 1). In table 1 the Heating and Cooling Degree Days for each city are presented.

Figure 1. Investigated cities.
Table 1. Heating and Cooling Degree Days for the examined cities.

| City         | HDD  | CDD  |
|--------------|------|------|
| Amman        | 1181 | 119  |
| Athens       | 1230 | 154  |
| Baghdad      | 1136 | 718  |
| Cairo        | 390  | 270  |
| Damascus     | 1547 | 52   |
| Marrakech    | 638  | 259  |
| Nicosia      | 746  | 237  |
| Riyadh       | 305  | 1420 |
| Sebha        | 519  | 1062 |
| Seville      | 916  | 145  |

Two scenarios of building envelope thermal transmittances were investigated; scenario 1 for $U=0.6\text{W/(m}^2\text{K})$ and scenario 2 for $U=0.15\text{W/(m}^2\text{K})$. The respective thicknesses of the thermal insulation material, which in this case was extruded polystyrene, are presented in table 2, as calculated to achieve the exact $U$-value for each scenario. For the elements in contact with the unheated place, in both scenarios, the thicknesses corresponding to scenario 1 were implemented, for the filling masonry and the reinforced concrete, respectively.

Table 2. Thermal insulation thickness for each examined scenario.

| Building element     | Thermal insulation thickness (m) | Scenario 1 | Scenario 2 |
|----------------------|----------------------------------|------------|------------|
|                      | To ambient air | To unheated space | To ambient air | To unheated space |
| Filling masonry      | 0.039           | 0.039        | 0.214         | 0.039          |
| Reinforced concrete  | 0.048           | 0.048        | 0.223         | 0.048          |

2.2. Dynamic thermal insulation

For all the examined cities the case of implementing switchable thermal insulation, which modified the envelope’s thermal resistance during the cooling period according to the ambient conditions, was investigated. In more detail, the days of the whole year where cooling demands are detected were recorded initially, as presented in table 3. Then, for these periods a dynamic insulation system was applied, so during the night, the effect of the insulation material was eliminated. In the case of filling masonry, the thermal resistance was modified from $R=1.667(\text{m}^2\text{K})/\text{W}$ for scenario 1 and $R=6.667(\text{m}^2\text{K})/\text{W}$ for scenario 2 during the daytime, to $R=0.538(\text{m}^2\text{K})/\text{W}$ during night hours, and in case of the reinforced concrete elements from $R=1.667(\text{m}^2\text{K})/\text{W}$ and $R=6.667(\text{m}^2\text{K})/\text{W}$ for scenarios 1 and 2 respectively, to $R=0.293(\text{m}^2\text{K})/\text{W}$. However, in some of the examined regions, there are significant high temperatures in the summer period, even during the night hours. In these cases, the operation of the variable insulation was adjusted to the ambient temperatures, and its use was limited to parts of the cooling periods that were favorable, i.e., the nocturnal ambient temperatures were below the maximum allowable for thermal comfort, as shown in table 3. As a result, the energy efficiency of the dynamic insulation was optimized.

Table 3. Operating periods of the dynamic insulation system.

| City     | Constant Operation | Optimized Operation |
|----------|---------------------|---------------------|
| Amman    | 7/4 – 31/10         | 7/4 – 12/6 and 3/8 – 31/10 |
| Athens   | 4/5 - 24/10         | -                   |
| Baghdad  | 6/4 – 31/10         | 6/4 – 16/6 and 1/9 – 31/10 |
| Cairo    | 28/3 – 29/11        | -                   |
| Damascus | 3/5 – 25/10         | -                   |
| Marrakech| 17/3 – 23/11        | -                   |
| Nicosia  | 2/5 – 1/11          | 2/5 – 11/6 and 2/9 – 1/11 |
| Riyadh   | 24/2 – 4/12         | 24/2 – 30/4 and 1/10 – 4/12 |
| Sebha    | 13/3 – 28/11        | 13/3 – 19/5 and 9/9 – 28/11 |
| Seville  | 6/5 – 31/10         | -                   |
2.3. Simulation model
The apartment was simulated in EnergyPlus where the materials and elements’ properties were defined. Its geometry is presented in figure 2. The apartment’s floor and ceiling were imported as adiabatic surfaces since it is considered that it is a typical storey and the upper and the subjacent apartments are heating spaces too. Four occupants were defined in the dwelling, being reduced to two from 7:00 to 17:00. Concerning the heating system, it is regulated to operate from 7:00 to 24:00, when needed, while the cooling system may operate from 10:00 to 23:00. The thermostat being used is activated by the internal air temperature. The rest of the parameters are defined according to EN 15251:2012 (i.e., lighting, ventilation rates for IAQ etc.).

![Figure 2. 3D view of the examined dwelling.](image)

In the case of the switchable wall insulation, an air gap was imported between the filling masonry or the reinforced concrete and the external insulation, while the latter’s thicknesses were modified appropriately so that in every case the U-values remained constant. During the night hours, which were previously presented for each city, when the absence of the insulation layer acts positively on the apartment’s performance, the air gap turns fully ventilated from 23:00 to 8:00, while the rest hours of the year the ventilation openings are closed, and the air inside the gap is stagnant.

3. Results and Discussion

3.1. Normal insulation
The increased thermal resistance in scenario 2 resulted in almost zero heating demands in most of the cities, as shown in figure 3, keeping in mind that the initial demands were not significant. More specifically, in Amman a 79.74% reduction was recorded, in Athens, the respective amount was 63.95%, in Baghdad 58.49%, in Cairo 99.96%, in Damascus 58.56%, in Marrakech 100%, in Nicosia 91.01%, in Riyadh 100%, in Sebha 100% and Seville 88.12%. Concerning the cooling loads, in some cities were reduced in scenario 2, while in others they were increased by the more insulated envelope, as shown in figure 4. In particular, 5.68% lower cooling demands were observed in scenario 2 for Baghdad, 7.85% for Riyadh, and 4.75% for Sebha. This is due to the high ambient nocturnal temperatures occurring in summer, which provoke cooling needs even during night hours. On the other hand, the cooling demands recorded increased in the 2nd scenario, for Amman of 7.32%, 3.62% for Athens, 0.62% for Cairo, 5.7% for Damascus, 7% for Marrakech, 2.34% for Nicosia, and 8.59% for Seville.

In figures 5-8 the mean daily ambient temperatures for some of the examined cities are presented. It is obvious that the daily temperature range in all these cities is important, about 15°C or more, with the cities located near the sea having the lowest ranges. It can also be noted that the nocturnal temperatures in Baghdad and Amman are constantly high, over 26°C, resulting in a heat flux across the building envelope towards the internal environment. Thus, the more insulated scenario reduces this heat flux leading to less cooling demands. In Amman and Seville on the contrary, the nocturnal temperatures fall way below the maximum allowable thermal comfort temperature, so at night the heat...
flows towards the external environment. Thus, the extra thermal insulation prevents the excess heat from being discharged, resulting in higher cooling demands.

3.2. Dynamic insulation
The implementation of a switching insulation system, so that at selected periods during the night the heat flux across the building shell occurs unimpeded and the excess heat concentrated inside the apartment is discharged to the ambient environment, resulted in a significant reduction in the cooling demands in most of the examined cities. However, in some cases, the constant use of the dynamic insulation during the whole cooling period led to a slight increase in the cooling loads. By the optimized use of it although, a noteworthy reduction in the cooling loads in all cities was recorded.
Moreover, it was observed that for scenario 2 the decrease in the cooling demands was greater for all the regions.

In more detail, for scenario 1, in Amman, a reduction of 11.94% was recorded by the variable insulation operation compared to the cooling demand that occurred with the existence of normal insulation, while the respective amount for the optimized use of the configuration was 15.07%. For Athens there was no need for optimized use of the dynamic insulation thickness and the decrease in the cooling loads occurred was 18.4%. In Baghdad, the corresponding percentage was 10.61% for the constant use and 12.77% for the optimized use. In Cairo, in the case of the switching insulation, the cooling demands were lower of 20.29%, in Damascus of 36.59%, and in Marrakech of 29.2%. In Nicosia, by implementing the dynamic insulation system the cooling demands lowered by 8.92% in comparison with the ones with the normal insulation, while they were recorded 11.43% lower with the optimized use. In Riyadh, the constant use of the switching insulation system caused an increase in the cooling demands of 0.9%, but the optimized operation led to a decrease of 7.79%. In Sebha, the constant use of the variable insulation thickness reduced the cooling loads by 3.55% and the optimized use by 9.89%. Finally, in Seville, only a constant use was required that led to 41.57% lower cooling demands. The relevant demands are presented in figure 9.

Figure 9. Cooling demands with normal and dynamic insulation for scenario 1.

Figure 10. Cooling demands with normal and dynamic insulation for scenario 2.

For scenario 2 the dynamic insulation system operation resulted in even lower cooling demands than those that occurred for scenario 1. In most of the examined cases, the cooling loads were reduced with the variable thermal transmittance configuration, in comparison with those recorded for the normal insulation existence, as presented in figure 10. The optimized use of the switching insulation system performs better, likewise happened in scenario 1. More specifically, in Amman, the constant use of the dynamic insulation leads to 22.85% reduced cooling demands, while the optimized use to 25.42% savings. In Athens, where just the constant use was investigated, 27.07% lower cooling loads were recorded. In Baghdad, 14.79% fewer cooling demands were achieved with the constant use and 19.05% reduced loads were recorded, compared with the initial loads for the normal insulation configuration. Furthermore, the constant operation during the cooling period of the switching insulation system resulted in 28.99% reduced cooling demands in Cairo, 49.98% in Damascus, and 41.12% in Marrakech. In Nicosia, fewer cooling loads of 13.92% were recorded for the constant use and of 17.08% for the optimized use, while in Riyadh the constant operation of the dynamic insulation during the cooling period increased the cooling demands by 1.67% compared with those that occurred from the normal insulation, but the optimized operation resulted in 12.5% lower cooling demands than the initial ones. In Sebha, 5.5% fewer cooling loads were recorded for the constant use of the variable thermal transmittance configuration and 15.07% for the optimized use, and finally, in Seville the achieved reduction in the cooling demands was up to 51.99% for the constant use.

The implementation of a switching insulation system in the building shell resulted in lower cooling demands, with the recorded reduction being maximum for its optimized operation when needed. The
reductions accomplished are higher for scenario 2, i.e., when at daytime the insulation protection is increased. The system is more efficient in Seville with its constant use during the cooling period, achieving 41.57% reduced cooling demands for scenario 1 and 51.99% for scenario 2. However, what has been observed is that in Riyadh, the existence of high external temperatures during summer nights, leads to increased cooling loads with the constant use of dynamic insulation, even if this increase was of negligible amount.

4. Conclusions
In this research, the influence of the envelope’s thermal resistance on the energy performance of a building in different cities across the Mediterranean region was examined. After investigating under which circumstances a highly insulated building envelope results in increased cooling demands than a less insulated one, the implementation of a dynamic insulation system was studied, with a constant operation during the whole cooling period, and with an optimized operation period. Considering the results, it is shown that:

- A building envelope with high thermal resistance acts negatively on cooling when a high daily ambient temperature range exists and simultaneously the ambient temperatures at night fall below the one considered as the maximum allowable for comfort. Under these circumstances, a high thermal resistance during the night prevents the excess heat accumulated inside building elements from being discharged. This condition applies mainly to southern European and northern African regions, while in even southern regions nocturnal temperatures are over the maximum allowed for comfort for a long time during the cooling period, so a high insulated envelope prevents heat from entering the building more effectively, reducing the cooling demands.

- A switching insulation system is effective mainly in southern European and northern African regions when its operation is constant during the cooling period. In even southern regions with higher ambient nocturnal temperatures than the maximum allowable for thermal comfort, an adaptive operation is required. The dynamic insulation configuration should be used during the periods when the nocturnal temperatures allow the heat across the building envelope to flow outwards and discharge the building.

- The implementation of a variable insulation system performs better when during daytime the envelope is highly insulated, as heat entering the building is lower and can be easily discharged at night.

References
[1] European Commission. Sustainable buildings for Europe’s climate-neutral future [Internet]. 2019. Available from: https://ec.europa.eu/easme/en/news/sustainable-buildings-europe-s-climate-neutral-future
[2] Rodrigues E, Fernandes MS, Soares N, Gomes Â, Gaspar AR and Costa JJ 2018 The potential impact of low thermal transmittance construction on the European design guidelines of residential buildings Energy and Build. 178 379–90
[3] Fernandes MS, Rodrigues E, Gaspar AR, Costa JJ and Gomes Â 2019 The impact of thermal transmittance variation on building design in the Mediterranean region Appl. Energy 239 581–97
[4] D’Agostino D, de’ Rossi F, Marigliano M, Marino C and Minichielo F 2019 Evaluation of the optimal thermal insulation thickness for an office building in different climates by means of the basic and modified “cost-optimal” methodology J. of Build. Eng. 24
[5] Dabbagh M and Krarti M 2020 Evaluation of the performance for a dynamic insulation system suitable for switchable building envelope Energy and Build. 222
[6] Alderucci T, Patrono L, Rametta P and Munafo P 2018 The effectiveness of an Internet of Things-Aware smart ventilated insulation system Therm. Sci. 22 909–19
[7] Koenders SJM, Loonen RCGM and Hensen JLM 2018 Investigating the potential of a closed-loop dynamic insulation system for opaque building elements Energy and Build. 173 409–27

[8] Park B, Srubar WV and Krarti M 2015 Energy performance analysis of variable thermal resistance envelopes in residential buildings Energy and Build. 103 317–25

[9] European Committee for Standardization 2012 EN 15251: Indoor environmental parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics