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Aerogel-based coating for energy-efficient building envelopes

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ABSTRACT

In the building sector, space heating and domestic hot water remain the most important energy users. Buildings' renovation has a high priority in France.

In this paper, we present a recently patented insulating coating based on silica aerogels. Then, we present a simulation-based rapid assessment tool designated for architects, building engineers, and non-expert users to examine the effect of adding this coating on the energy consumption and thermal comfort. All the building construction types representing the different construction periods of France are considered. Also, all these are examined under the different climates of France. The output of this tool is the house energy load with and without the coating. As an inverse problem, the user can enter the required energy load and the output will be the coating thickness. Moreover, the tool provides a thermal comfort assessment based on different thermal comfort models. Results show that applying this coating is very interesting for buildings under rehabilitation. For very well insulated new houses, adding the coating may allow reaching the new thermal regulations (French RT 2012) levels of the low energy buildings. However, this coating may increase the risk of overheating during summer, especially for the Mediterranean climate, which could be overcome by adopting proper shading and night ventilation.

Keywords: Silica Aerogel insulating coating; rapid assessment tool; efficient envelopes; energy simulation; building rehabilitation; thermal comfort

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1. Introduction

In France, the share of the building sector is about 43% of the total energy consumption and 25% of carbon dioxide emission [1]. France has already adopted the objective of reducing its

energy consumption and greenhouse gas emissions by a factor of four to five by the year 2050 as a part of its national strategy for sustainable development, introduced in June 2003, and its climate plan, introduced in July 2004. The new thermal regulations (RT 2012) limits the primary energy consumption for new buildings to 50 kWh/m² per year and requires a better thermal comfort through limiting overheating during the summer season. Thus, it is crucial to find solutions to reduce energy consumption and enhance thermal comfort. Super-insulating materials, such as silica aerogels and vacuum insulation are promising techniques to be used in building envelopes to obtain the desired objectives.

For existing buildings, renovation has a high priority in many countries, and France is one of them, because these buildings represent such a high proportion of energy consumption and they will be present for decades to come. Several studies [2-4] have shown that the most efficient way to curb the energy consumption in the building sector (new & existing) remain the reduction of the heat losses by improving the insulation of the building envelope (roof, floor, wall & windows). A step beyond the current thermal performance of building envelope is essential to realize the intended energy reduction in buildings. For retrofitting and even for new buildings in cities, the thickness of internal or external insulation layers becomes a major issue of concern. For systems (such as domestic hot water) the reduction of thickness is essential. Therefore, there is a growing interest in the so-called super-insulating materials (SIM), such as Aerogels.

Silica aerogels are silica-based dried gels having very low weight and excellent thermal insulation performance. Specifically, they have high porosity (80-99.8%), low density, and low thermal conductivity (14mW/(m.K)) [5]. Silica Aerogels are an innovative alternative to traditional insulation due to their high thermal performance, although the costs of the material remain high for cost-sensitive industries such as the building industry. Research is continuing to improve the insulation performance and to decrease the production costs of aerogels. The unique properties of aerogels offer many new applications in buildings [6]. The extraordinary low thermal conductivity of aerogels as well as its optical transparency allows its use for insulating building facades and insulating window panes. Two different types of silica aerogel-based insulating materials are being used in the building sector. The first is the opaque silica aerogels-based materials and the second is the translucent insulation materials.

Aerogel blankets/panels begin to be used to insulate building walls, grounds, attics, etc. Aspen Aerogels Inc. [7] has developed an insulation blanket based on silica aerogels, Spaceloft[®] [8], having a thermal conductivity of 13.1mW/(m.K). Spaceloft[®] was used to convert an old mill house in Switzerland into an energy saving passive house. A case study was done in the United Kingdom where a number of governmental housing units were retrofitted by adding Spaceloft[®] insulation layer at the interior wall surfaces [9]. A 44% reduction in the U-value, a 900 kWh/year energy reduction, and a 400 kg/year carbon emissions reduction were obtained.

In another study, thermal performances and experimental tests were performed on walls and roofs using aerogel insulation [10]. Hot box measurements on wall assemblies containing aerogels showed that the R-value of wood framed walls is improved by 9% and that of a steel framed wall by 29%. Finite difference simulations performed on steel-framed wall assemblies using 0.6cm thick aerogel strips showed that aerogel can help in reducing the internal surface temperature differences between the center of the cavity and the stud location from 3.2°C to only 0.4°C. For roof structures, hot box measurements performed on the fastened metal roof insulated with aerogel strips showed an increase in the overall roof R-value by about 14%.

Another type of silica aerogel-based materials used in buildings is the translucent insulation materials type. These materials have the advantage to combine a low thermal conductivity along with high transmittance of solar energy and daylighting. Research has been conducted in the last decade on the development of highly insulating windows based on granular aerogel and monolithic aerogel. A new glazing element based on granular silica aerogel was developed at ZAE Bayern, Germany [11, 12]. The glazing consists of 16mm double skin sheet made of polymethylmethacrylate filled with granular silica aerogels separated by two gaps filled with krypton or argon and installing glass panes at the ends. Three window systems were developed. The first is a daylighting system with a total solar transmittance between 0.33 and 0.45, and a U-value having a range of 0.44-0.56 W/m²K. The second system is a sun protecting system developed by applying a lower emissivity (0.03) to the glass panes. A U-value of 0.37-0.47 W/m²K, a visible transmittance in the range 0.19 and 0.38, and a solar transmittance between 0.17 and 0.23 were achieved. The third is a solar collector by placing a heat exchanger between a layer of aerogels and the two glass panes.

In the European projects, HILIT and HILIT+, a monolithic aerogel based window was developed [13] on the basis of the patent of [14]. They obtained a total heat transfer coefficient for the window (U-value) of 0.66 W/m²K and a solar transmittance of 0.85 using a 13.5mm thickness of aerogel. Vacuum glazing technology was also used in developing this window. A case study was done for the Danish climate, where a triple glazed window filled with argon was replaced by this aerogel based window for a house built according to the passive house standards. 19 and 34% energy savings were achieved for 13.5 and 20mm aerogel thickness respectively.

In this study, we present a recently patented insulating coating based on silica aerogels. We call it, hereafter, “Aerogel-Based Coating” (ABC). Thermal insulating coatings or plasters represent an attractive way to improve the thermal performance of building envelopes. Traditional solutions exist; however, the ABCs represent a bigger innovative step [15]. Then, we present a simulation-based rapid assessment tool designated for architects, building engineers, and non-expert users to examine the effect of adding this coating on the energy consumption and thermal comfort. We start with a brief description of the buildings’ construction history in France. Depending on the construction period, different window-to-wall ratios, interior insulation thicknesses, wall structures, etc. are considered. Also, all these are examined under the different climates of France. The output of this tool is the house energy load with and without the coating. As an inverse problem, the user can enter the required energy load and the output will be the coating thickness. Moreover, the tool provides a thermal comfort assessment based on different thermal comfort models.

2. History of Buildings’ Construction in France¹

Until the year 2009, the residential building sector in France counted around 32.2 million housing units with an annual energy consumption of about 494 TWh [19]. Figure 1 shows the number of individual and collective houses for three significant periods in building construction for the different climatic zones in France [20].

¹ References [16-18]

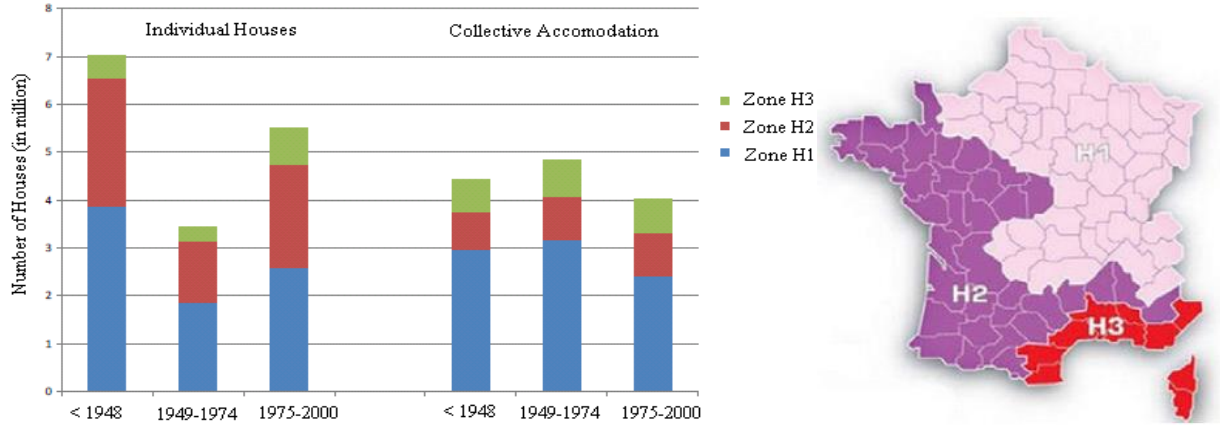


Figure 1: Number of houses in France per climatic region (source: [20])

In the Building Sector, space heating and domestic hot water remain the most important energy users, as presented in Figure 2 [21]. Since the first oil crisis, the implementation of building thermal regulations (RT 1974) through a combination of higher efficiencies of equipment and improved thermal performance of building envelope has led to a significant reduction in the per capita energy requirement for space heating.

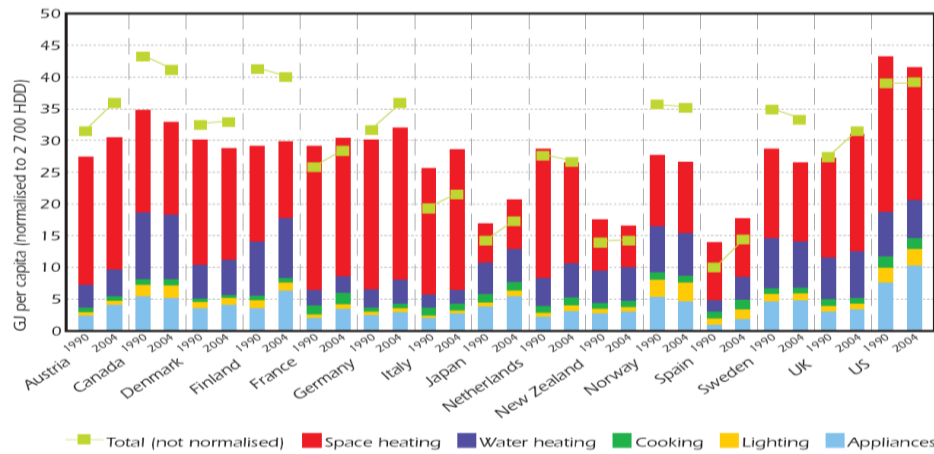


Figure 2: Household energy use per capita (source: [21])

2.1. Traditional Way till the World War 2

This period can be divided into two periods: the first one, before 1914, includes the very old buildings where the construction was based on local materials such as millstone, with little professionalized implementation. The second (1914-1948) represents the period where some manufactured materials started to be used in building construction such as cement, solid bricks, interlocking tiles, etc. These houses consume around 214 kWh/m² (final end-use energy) per year for space heating. Exterior walls are composed of one of the following materials: stone rubble (sandstone, limestone, granite...), mud-brick, solid bricks, timbered structure with soil, brick, or mixed filling. For the ceiling and roofs, the construction is wood with a final coating based on local materials. Windows are simple glazed with wooden joinery, and the window-to-wall ratio is around 10%. No specific thermal insulation was used.

2.2. Construction Strategy after World War 2

At the end of the World War 2, there was an urgent need to rebuild the devastated country. For many, traditional tools and techniques seem somewhat obsolete; they cannot meet the very important and urgent reconstruction needs. Thus, during the reconstruction period, it was vital to experience different construction techniques. Here came the necessity to apply the methods used in industry to the building construction sector: serial, mass, and standard production (construction). That was then called “Building Industrialization”. Prefabricated homes were the solution because their construction was rapid and standard. For individual houses, the construction material for exterior walls was hollow concrete blocks or hollow bricks. For collective (community) houses, the construction material was reinforced concrete.

For houses between the years 1948 and 1967, the space heating energy for house is approximately 226 kWh/(m².year). The ceiling, floor and roof are composed of wood with interlocked tiles. Windows are simple glazed and the window-to-wall ratio varies between 20-27%. No thermal insulation is used.

For houses between the years 1968 and 1974 the space heating energy for house is approximately 177 kWh/(m².year). The ceiling and roof are composed of wood with interlocked tiles or concrete shingles as final coating. It's in these years where insulation started to enter the building industry; however, its implementation was still low. Some of these houses have insulation (4-10cm glass wool) below the ceiling or below the pitch roof. The floor is composed of concrete slab or terracotta. Two types of window glazing are used: simple or double, and the window-to-wall ratio is approximately 37%. No specific thermal insulation is used in exterior walls.

2.3. Interior Insulation: A Reaction after the Oil Crisis in 1970

After the increase in oil prices in 1970, the French government set a policy encouraging energy conservation by improving the performance and efficiency of heating systems and by using thermal insulation in the building fabric. In 1974, the first thermal regulation (RT 1974) was launched forcing buildings to have thermal insulation. Also, the petrochemical industry diversified its markets by producing large amounts of glass wool insulation and polystyrene facilitating the entry of insulation into the building sector.

For this period we distinguish two periods: the first one is between 1975 and 1981, and the second is between 1982 and 1989. Houses in the first period (1975-1981) have exterior walls composed of either: masonry blocks, hollow brick, or stone, with thermal insulation having an R-value of 2.3 (m².K)/W. Energy consumption for space heating is approximately 142 kWh/(m².year). The ceiling/roof is composed of wood with cement finishing. Also, thermal insulation ($R = 4.8(\text{m}^2.\text{K})/\text{W}$) is added below the pitched roof. Windows are simple or double glazed and the window-to-wall ratio is around 25%. The floor is composed of concrete slab or terracotta with thermal insulation ($R=1 (\text{m}^2.\text{K})/\text{W}$).

The majority of the houses in the second period (1982-1989) have exterior walls composed of concrete hollow blocks (67%) with interior insulation having an R-value of 2.4 (m².K)/W. Others (15%) have walls composed of hollow bricks with interior insulation. In addition, other materials are also used such as solid bricks, wood, cellular concrete. Energy consumption for space heating is approximately 106 kWh/(m².year). The ceiling/roof has insulation of $R = 4.8(\text{m}^2.\text{K})/\text{W}$. Windows are simple or double glazed and the window-to-wall ratio is around 25%.

The floor is composed of concrete slab or terracotta with thermal insulation having an R-value of 0.8 (m².K)/W for ground floor or R=1.9 (m².K)/W for crawl spaces.

2.4. Exterior Insulation: The New Approach

For homes built after 1990, exterior walls are, majorly, composed of concrete blocks with thermal insulation having an R-value of 3 (m².K)/W. New kind of hollow bricks (such as brick monomur) are also used possessing a higher energetic performance than those used in previous periods. Ceilings and roofs have insulation of R = 6 (m².K)/W. Floors also have thermal insulation (R = 3 (m².K)/W) below the concrete slab. The installed windows are at first simple glazed, and then become double glazed. The window-to-wall ratio is around 20%. Energy consumption for space heating is approximately 95 kWh/(m².year).

During these last two decades, the rehabilitation of existing buildings introduced the concept of exterior insulation. It is difficult to choose between interior and exterior insulation. Moreover, thermal regulations in force today still don't give recommendations on the best way to insulate buildings. This technique of building insulation has its advantages and its drawbacks:

Advantages of Using Exterior Insulation:

- reduces heat losses through thermal bridges
- enhances thermal comfort through increasing the thermal inertia near the inside of the building
- preserves the usable area of the living space
- conducts the work without the necessity for inhabitants' displacement (for existing buildings); thus, facilitates rehabilitation
- decreases the possibility of condensation
- avoids polluting the interior air due to the insulating materials used
- modifies/improves the aesthetic of buildings (especially old ones; not convenient with some ornamented or heritage buildings)

Drawbacks of Using Exterior Insulation:

- causes a problem when we have balconies and parapets
- high inner thermal inertia may not be suitable in some cases (intermittent heating/cooling)
- should be protected from outside conditions
- generally, more difficult to install than interior insulation
- can't be used when ornamented or heritage facades are to be preserved

2.5. Summary

Table 1 summarizes the construction types of French houses.

Table 1 : Houses' Construction in France during the different periods

		period					
		< 1948	1948 - 1967	1968-1974	1975-1981	1982-1989	1990-2000
Space Heating	Final energy use for space heating	214 (kWh/m ² /year)	226 (kWh/m ² /year)	177 (kWh/m ² /year)	142 (kWh/m ² /year)	106 (kWh/m ² /year)	95 (kWh/m ² /year)
Opaque wall	Construction	- Stone rubble: (such as sandstone, limestone, granite...) - mud-brick - solid bricks - timbered structure with soil, brick, or mixed filling	- hollow concrete blocks - hollow bricks - reinforced concrete	- hollow concrete blocks - hollow bricks - reinforced concrete	-masonry blocks -cellular concrete -hollow brick - stone	- concrete hollow blocks (67% of houses) - hollow bricks (15%)	- concrete blocks - more energy efficient hollow bricks (such as brick monomur)
	Thermal Insulation	Non	Non	Non	R = 2.3 (m ² .K)/W	R = 2.4 (m ² .K)/W	R = 3 (m ² .K)/W
Roof/ceiling	Construction	wood with a final coating based on local materials	wood with interlocked tiles or asphalt shingles	wood with interlocked tiles or concrete shingles	wood with cement finishing (wood with cement finishing (Concrete insulated beam
	Thermal Insulation	Non	Non	Some houses start to have insulation (4-10cm glass wool)	R = 4.8 (m ² .K)/W	R = 4.8 (m ² .K)/W	R = 6 (m ² .K)/W
Floor	Construction	Wood (on arcs) or slab on ground	Wood	concrete slab or terracotta	concrete slab or terracotta	concrete slab or terracotta	Concrete slab
	Thermal Insulation	Non	Non	Non	R= 1 (m ² .K)/W	R = 0.8 (m ² .K)/W for ground floor or R=1.9 (m ² .K)/W for crawl spaces.	R = 3 (m ² .K)/W
Window	Construction	Simple glazed	Simple glazed	Simple / Double	Simple / Double	Simple / Double	Simple then Double
	Window to wall ratio	10 %	20 - 27%	37 %	25 %	25%	20%

3. The New Insulating Coating

A recently patented insulating coating based on the (super)-insulating materials silica aerogels has been developed (Figure 3) [22-24]. The invention is a light mortar that can be applied to the external surface of a building to produce a thermally insulating coating. It consists of water, a mineral and/or organic hydraulic binder, an insulating filler comprising a powder or granules of hydrophobic silica aerogel, a structuralizing filler (option), and additives (option). This coating has a thermal conductivity of 0.0268 W/(m.K), a density of 150 kg/m³, and a specific heat of 990 J/(kg.K). It has been developed mainly for exterior wall surface insulation of buildings and can be used for new building as well as old ones.



Figure 3: The new aerogel-based coating

The coating's application on building's facades can be done manually or using the ordinary techniques well-known by technicians and builders such as plastering. It is

simple, easy to install, and compatible with the traditional masonry facades techniques. It is flexible with respect to unevenness, allows a continuous thermal insulation, and can fill gaps or other difficult access areas. The ease of implementation of this coating facilitates the buildings' rehabilitation.

Its thermal conductivity is measured by means of guarded hot plate and heat flow meter according to the NF EN 12677 standard [25]. Its specific heat is measured by means of differential scanning calorimeter (DSC) according to NF EN 1159-3 standard [26]. Its density is measured according to the NF EN 1602 standard [27].

4. Rapid Assessment Tool

4.1. The Tool's Features

The objective is to develop a rapid assessment tool designated for architects, building engineers, and non-expert users to examine the impact of applying the aerogel-based coating (ABC) on the buildings' external facades of buildings. It addresses the following:

Direct: How much energy reduction (annual heating load) is achieved when adding the coating?

Inverse: What is the needed coating thickness if a certain heating load is required?

Comfort: What is its effect on thermal comfort?

Simulations are carried out for the different construction periods and under the different climates of France: Mediterranean, Oceanic, and Semi-Continental. A two-story house with an attic and crawl space is modeled using the whole building energy simulation program EnergyPlus [28]. Depending on the construction period, different window-to-wall ratios, wall, roof, and ground insulation thicknesses, air change rates, wall structures, etc. are considered. The tool is based on EnergyPlus simulation results and is developed using the MATLAB's [29] graphical user interface (GUI). More than 15,000 simulation runs are carried out.

First, you choose the construction period: before 1948, 1948-1967, 1968-1974, 1975-1990, or after 1990.

Second, you choose between the Direct and the Inverse calculation. The Direct calculation gives the annual heating load for a given coating's thickness while the Inverse calculation gives the coating's thickness for a given annual heating load.

Third, you select the construction inputs (note that these change with the different construction periods).

Fourth, you enter the coating thickness (Direct) or the annual heating load (Inverse). Finally, you run the case and obtain the outputs. The tool will estimate the heating load with and without the coating. Also, it will generate a curve showing the variation of the annual heating load as a function of the coating thickness. In addition to the energy calculations, a thermal comfort assessment is performed when clicking on the "Thermal Comfort Analysis". In this latter, you can choose among different assessment criteria. These are:

- ASHRAE standard 55 [30] simple comfort diagrams: the output is the percentage of occupied time where comfort is met for winter and summer

- Percentage of occupied time heating is not needed (for winter): in addition to this output the degree.hour is also calculated to show how far the room temperature is from the set-point value.
- Fanger's PMV index [31]: the output is the percentage of occupied time where comfort is met ($-0.5 \leq PMV \leq 0.5$)
- ASHRAE standard 55 adaptive thermal comfort model (for summer): it shows the percentage of occupied hours where overheating is probably to occur for different satisfaction levels 90% and 80%, and also its degree.hour.
- EN 15251 adaptive thermal comfort model [32] (for summer): it shows the percentage of occupied hours where overheating is probably to occur for the different satisfaction levels 90%, 80%, and 65%, and also its degree.hour.

In addition to these, three options can be chosen: increase the heating set-point to 21°C, increase the night ventilation rate in summer to 2ach (air-change-per-hour), or increase it to 5ach.

Screen shots for the Rapid Assessment Tool are provided in Appendix 1.

4.2. Building Model

4.2.1. Geometrical Description

The considered house consists of two air-conditioned zones, ground (GF) and first (1F) floors of 50m² floor area with a height of 2.7m, and two unconditioned zones (Attic and crawl space). The envelope construction materials for the different construction periods correspond to those of Table 1.

4.2.2. Internal Loads

A scenario for people occupancy and equipment usage simulating a real case has been modeled. For people, 4 inhabitants are considered. The load of each person is taken as 80W when sleeping, 120W when seated at rest, and 160W when doing a light activity. The occupancy schedule is different between weekdays and weekends and it also differs between the ground and first floors. Figure 4 shows the occupancy schedule for both floors for week days and for weekends. Figure 5 shows the equipment schedule for both floors for week days and for weekends.

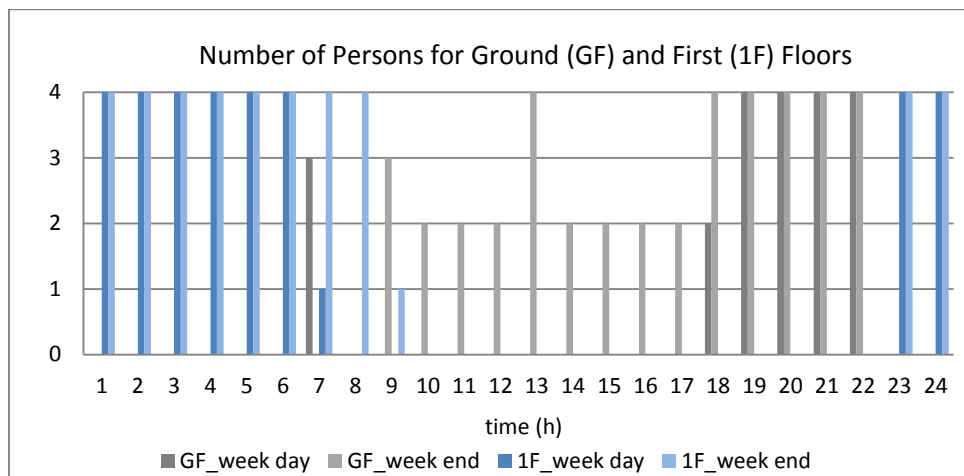


Figure 4: Occupancy schedule for ground and first floors for week days and weekends

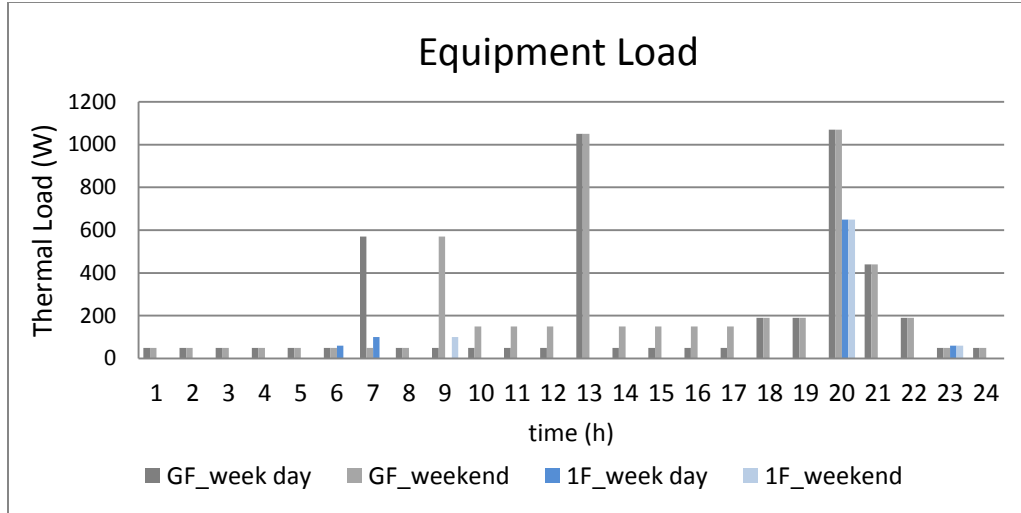


Figure 5: Equipment load schedule for ground and first floors for week days and weekends

4.2.3. HVAC System

An Ideal HVAC system is chosen in EnergyPlus which maintains the interior air temperature of the conditioned spaces constant and equals to 19°C during the heating season. The air change rate (ACR) is set to 0.8ach and 0.4ach for the new and the old houses, respectively, and it is kept "ON" during all time.

4.3. Curve Fitting and Inverse Modeling

It is very difficult and time consuming to simulate all cases; i.e. to vary the coating's thickness from 0cm to 15cm and to simulate all these cases. So what we did is taking some values of the coating thickness which are 0, 0.5, 1.5, 3, 7, 10, and 15cm, simulating the different cases, and then performing a curve fitting for the heating load as a function of the "ABC" thickness. Figure 6 shows an illustration of this for a randomly chosen case. The variation of the energy load against the coating thickness can be fitted by a power curve function having an equation of the form:

$$y = a * x^b \quad (1)$$

where x is the coating thickness and y is the annual heating load.

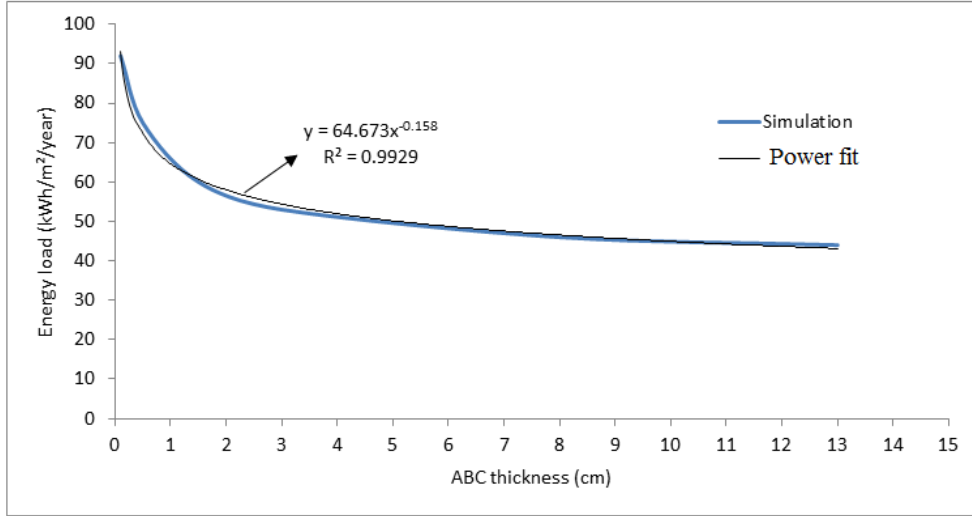


Figure 6: Energy load versus ABC thickness power curve fit

Thus, for each of the different cases, a curve fitting is done, and the coefficients “*a*” and “*b*” are determined. The above equation serves as a direct method to determine the energy load having been given the “ABC” thickness. For the inverse calculation, we want to know the “ABC” thickness when a certain value of the energy load is required; equation (2) is used. This latter is obtained through linearizing and inverting equation (1)

$$x = e^{\frac{(\ln(y) - \ln(a))}{b}} \quad (2)$$

5. Results and Discussion

5.1. Energy Load

Figure 7 shows the house’s energy load without the ABC and with 5cm ABC on the exterior facades for the different construction periods and for the different climates. For the period 1968-1974, we modeled two different houses: the first one “1968-1974(1)” has simple glazed windows with no insulation in the roof; the second one “1968-1974(2)” has double glazed windows with 6cm thermal insulation in the roof. Also, for the period after 1990, we distinguish two cases: the first one, >1990(1), has the exterior walls composed of concrete structure with 10cm internal thermal insulation and the second one, >1990(2), has the exterior walls composed of 42cm of brick-monomur with no internal insulation.

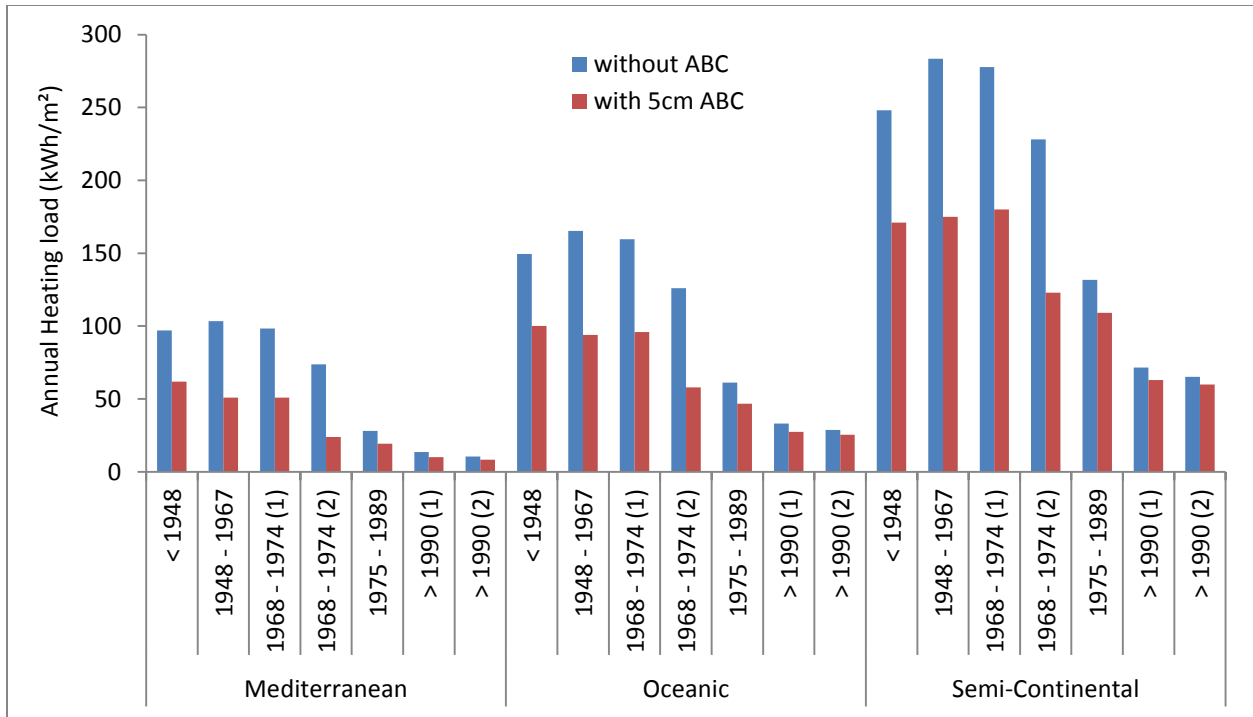


Figure 7: Annual heating load for the different climates and the different construction periods with and without the coating

From this figure, it is shown that for the old houses built before 1974, the percentages of energy reductions are between 40 – 68% for the Mediterranean climate, 37 – 55% for the oceanic climate, and 33 – 46% for the Semi-Continental climate. For the houses built in the period 1975-1989, the reductions are 32%, 23%, and 17% for the Mediterranean, Oceanic, and Semi-Continental climates. Lower reductions are achieved in the new houses, 23%, 14%, and 10% for the three climates, respectively. Since the new houses have already thermal insulation in the exterior envelope, adding the ABC will not decrease a lot the annual load; however, this reduction is still needed to reach the low energy house thermal regulations (RT 2012). To examine this more, the variation of the energy load with respect to the coating thickness for 3 cases: without interior insulation, with 5cm interior insulation, and with 10cm interior insulation is shown in Figure 8.

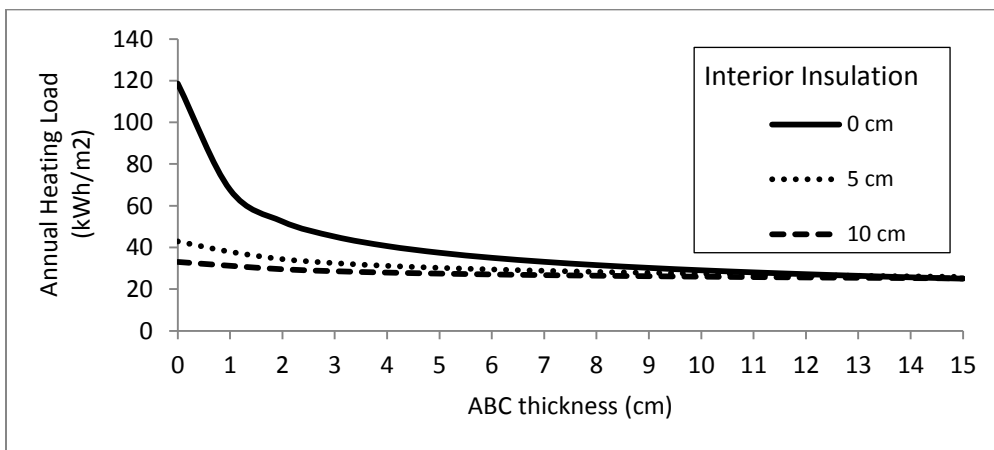


Figure 8: Heating load as a function of the coating thickness for different interior insulation thicknesses

From this figure, we can conclude that this coating is very interesting and beneficial for buildings under rehabilitation, especially the uninsulated houses, where a small thickness can reduce extensively the energy load, which also means conservation of the house's livable area. For a medium level insulated house, adding the coating also has a good advantage. For very well insulated houses, adding the coating will still reduce the energy load, but certainly its importance lies in achieving more and more energy efficient houses to reach the new thermal regulations (RT 2012) levels of the low energy buildings.

5.2. Thermal Comfort

To more accurately characterize the thermal discomfort in the building, the house's occupation is taken into account in the results. In summer (July and August), the building is considered as uncomfortable when the operative temperature falls out of the comfort range in condition that the house is being occupied. This comfort range is based on the adaptive thermal comfort temperatures according to ASHRAE 55 and EN 15251 standards.

In winter and inter-seasons (October till April), the assessment factor is the percentage of occupied time where heating is not needed. The implementation of the coating contributes in increasing this percentage.

5.2.1. Winter and Inter-seasons

The percentage of occupied time where heating is not needed for different coating thicknesses for the old house is shown in Figure 9. As the coating thickness increases, the number of hours where heating is not needed increases. Taking the 5cm as an illustration, the percentage increases by 10%, 6%, and 3% for the Mediterranean, Oceanic, and Semi-Continental climates, respectively.

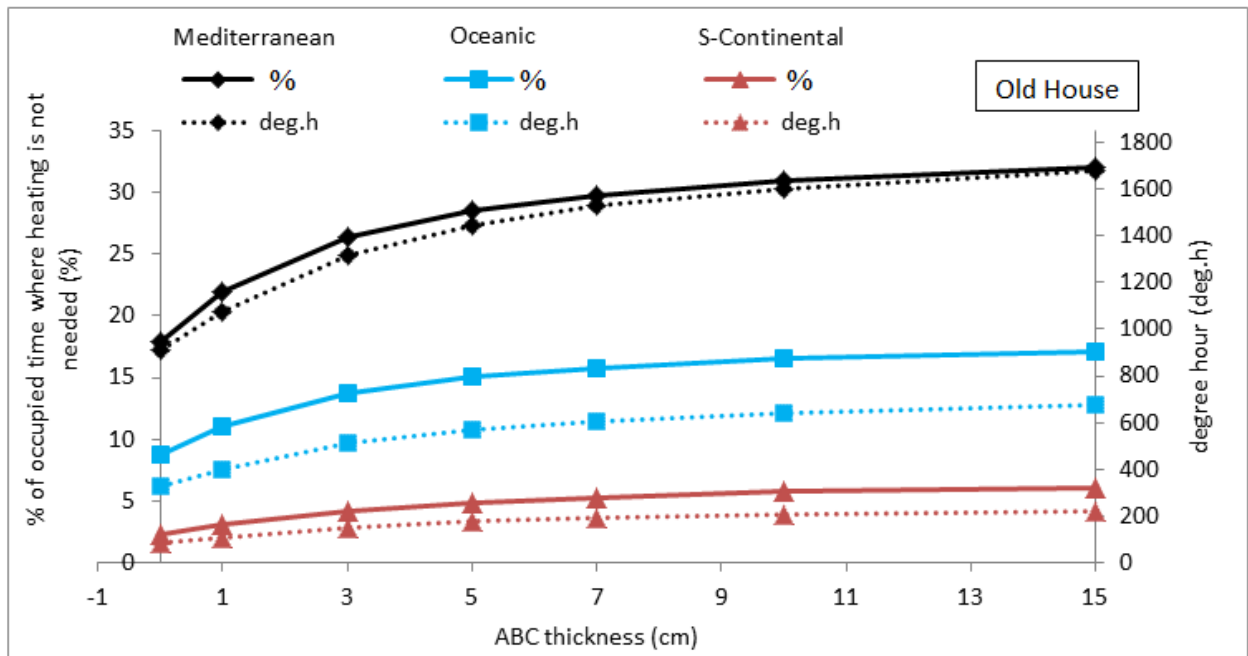


Figure 9: Percentage of occupied time where heating is not needed and its degree-hour for different coating thickness and different climates, old house

Figure 10 shows the percentage of occupied time where heating is not needed for the new house for 0, 5, and 10cm interior insulation. The black curves are for the Mediterranean climate, the blue ones are for the Oceanic climate, and the red ones are for the Semi-Continental climate. For the cases with no interior insulation, applying 5cm of the coating increases the percentage by 28%, 17%, and 10% for the Mediterranean, Oceanic, and Semi-Continental climates. For the houses with 5cm interior insulation, adding 5cm coating on the exterior facades increases the percentage by 12%, 6%, and 4% for the different climates. For the houses with 10cm interior insulation, the increase is about 6%, 3.5%, and 2.5%, respectively.

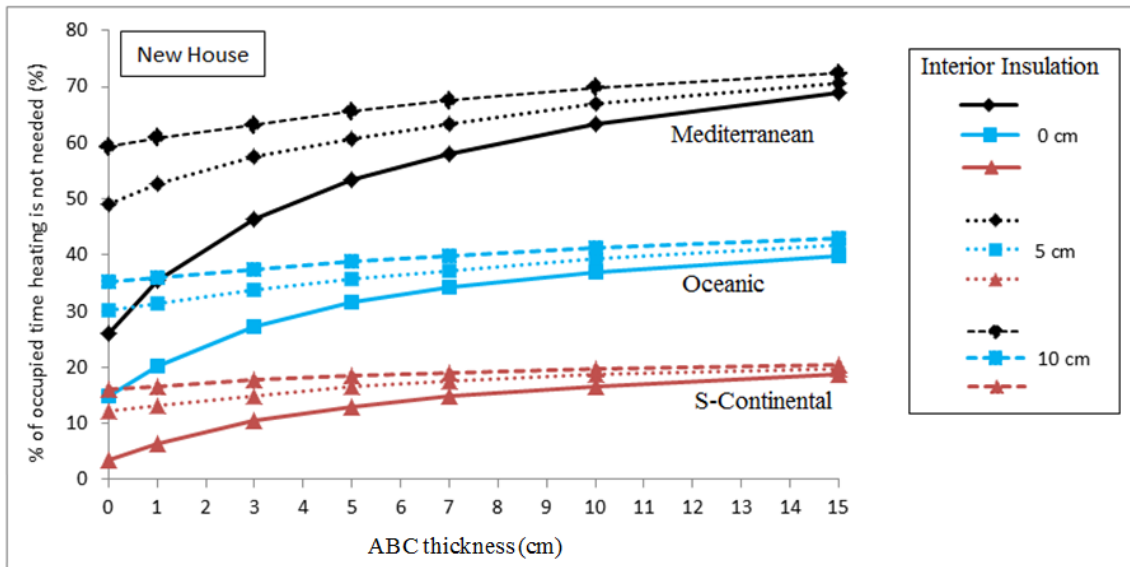
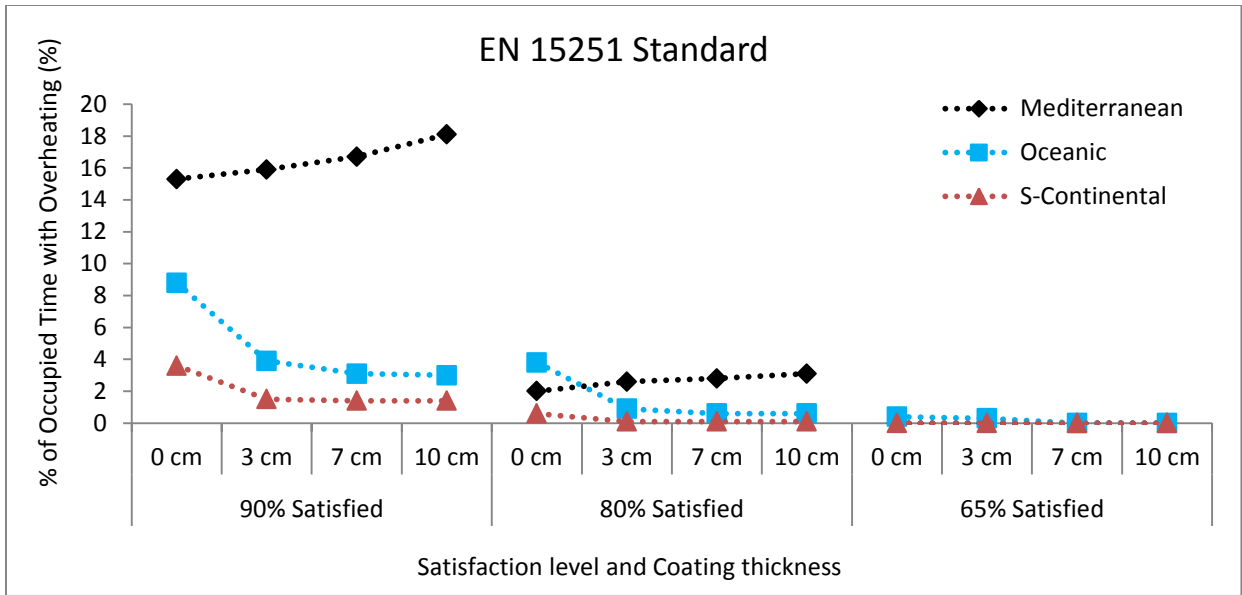


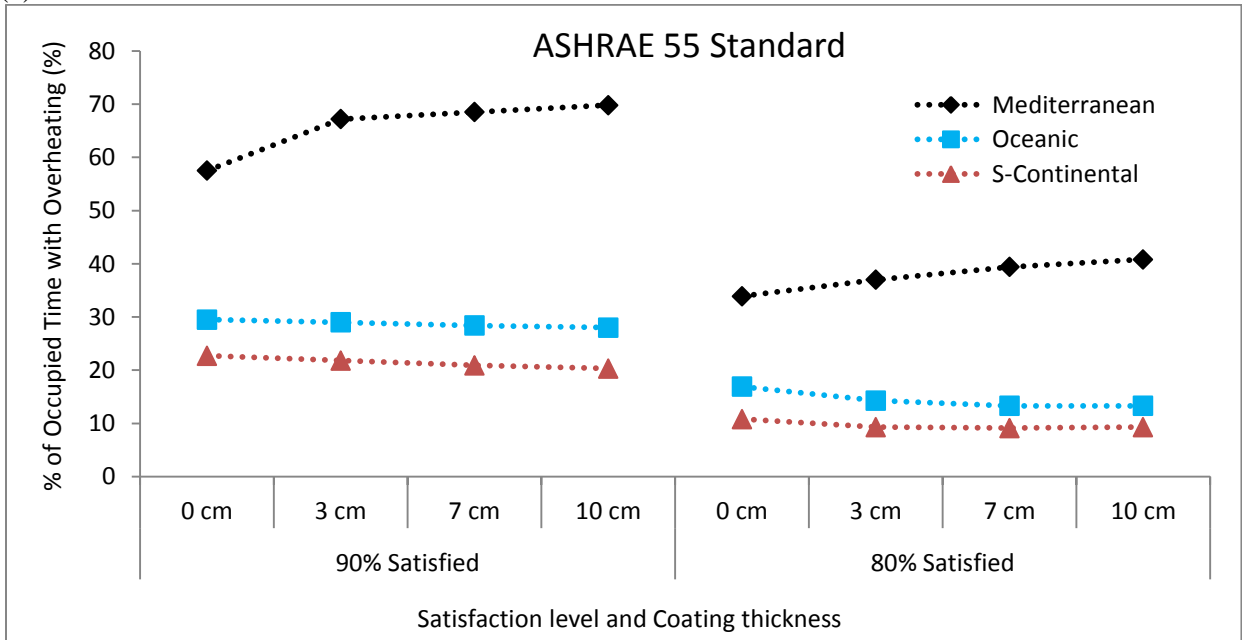
Figure 10: Percentage of occupied time where heating is not needed its degree.hour for different coating thicknesses and different climates, new house

5.2.2. Summer Old House

Figure 11 shows the percentage of occupied time where overheating will probably occur according to (a) EN 15251 adaptive comfort model and (b) ASHRAE 55 adaptive comfort model for different levels of satisfaction. According to the EN standard, it is shown that the house with no coating has a discomfort time percentage of 15%, 9%, and 4% for the Mediterranean, Oceanic, and Semi-Continental climates for 90% of occupants satisfied. For 80% and 65% satisfaction, the overheating percentage decreases to less than 3% for all the climates. For Mediterranean climate, adding the coating increases the discomfort hours with respect to the uninsulated house from 15% to approximately 17% (90% satisfaction level). However, for oceanic and semi-continental climates, adding the coating decreases the discomfort hours from 9% and 4% to about 3.5% and 1.5%, respectively. The same conclusions are derived when using the ASHRAE 55 standard. However, in this latter, the discomfort hours are more than those calculated using the EN standard because the thermal comfort requirements of ASHRAE 55 are more strict; thus, occupants can tolerate higher operative temperatures according to EN 15251 standard.



(a)



(b)

Figure 11: The percentage of occupied time where overheating will probably occur according to (a) EN 15251 adaptive comfort model and (b) ASHRAE 55 adaptive comfort model for different levels of satisfaction, old house

Conclusion 1 (old house):

The conclusions are based on the EN 15251 adaptive thermal comfort standard.

- In the Mediterranean climate, for an old house initially with no coating, there is not so much risk of overheating where the percentage of occupied time thermal comfort is not met does not exceed 2% and 16% for 80% and 90% of occupants satisfied, respectively. Applying the coating does not have a significant effect on this percentage. This latter increases by about 1% when a 7cm layer of the coating is added on the exterior facades.

- For the Oceanic climate, the discomfort time is about 4% and 9% for 80% and 90% of occupants are satisfied, respectively. Adding a 7cm layer of the coating decreases the percentage of discomfort time to less than 1%
- For the Semi-Continental region, no overheating is observed during the occupied hours in the summer period.

New House

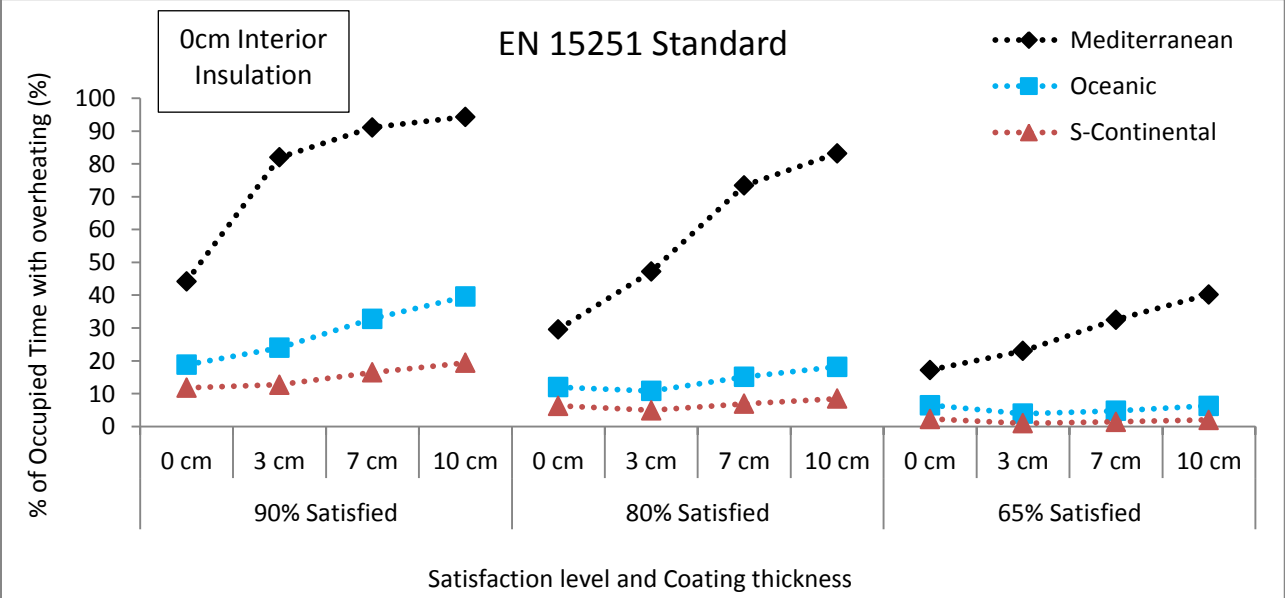
Figure 12 shows the percentage of occupied time where overheating occurs for a new house having (a) no interior insulation, (b) 5cm interior insulation, and (c) 10cm interior insulation. Let us take the case where 80% of occupants are satisfied for a house situated in the Mediterranean region. Initially, when no coating is applied, the percentage of discomfort time is about 30%, 53%, and 72% for 0, 5, and 10cm interior wall insulation, respectively. When a 3cm layer of the coating is applied on the exterior facades, the discomfort time percentage is increased to 47%, 70%, and 80% for the three interior insulation thicknesses, respectively. When a 7cm layer of the coating is added, the percentage increases to 73%, 81%, and 85%, respectively.

To overcome this risk of overheating, night ventilation can be adopted as the outside air temperature drops at night time. This is illustrated in Figure 13, where it shows the percentage of discomfort time for a house situated in the Mediterranean region for no increased ventilation at night and for increased night ventilation to 2ach and 5ach.

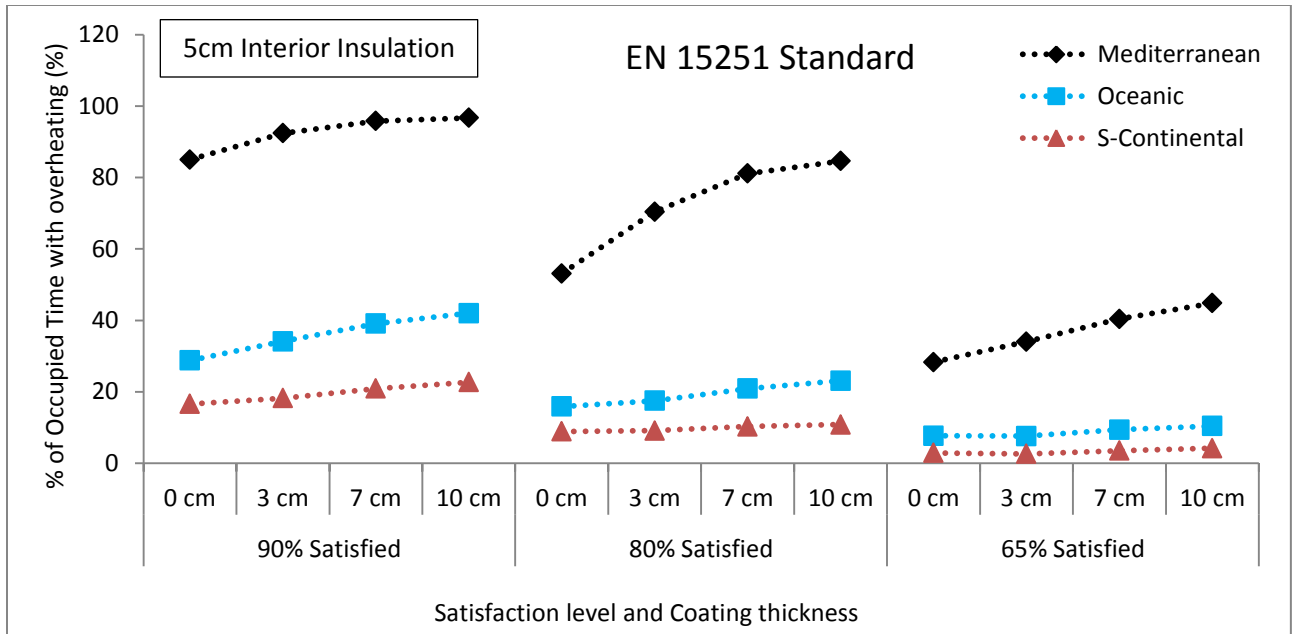
Note that as mentioned earlier, the rapid assessment tool has options to increase the ventilation rates during summer nights.

For the oceanic climate, the percentage of discomfort time during occupied period is approximately 12%, 16% and 20% for 0, 5, and 10cm interior insulation, respectively. These percentages increase by about 4% when a 7cm coating layer is added.

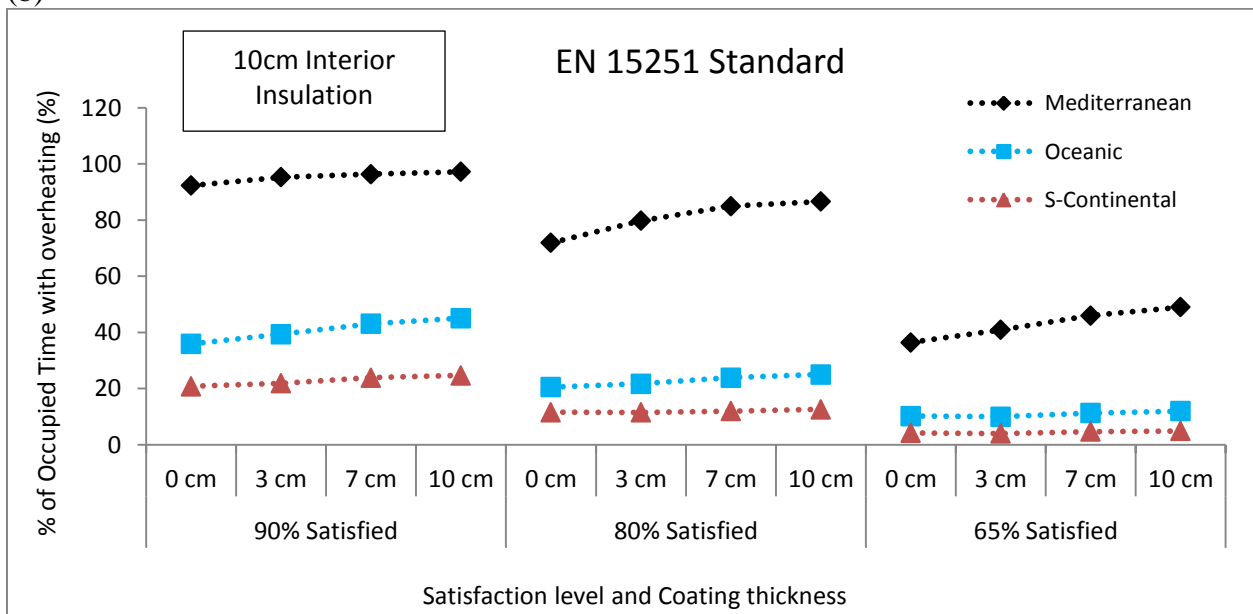
For the Semi-Continental climate, the discomfort time stays below 10% for all the cases. Also, adding the coating doesn't have a significant effect on the discomfort time percentage.



(a)



(b)



(c)

Figure 12: The percentage of occupied time where overheating occurs for a new house having (a) no interior insulation, (b) 5cm interior insulation, and (c) 10cm interior insulation

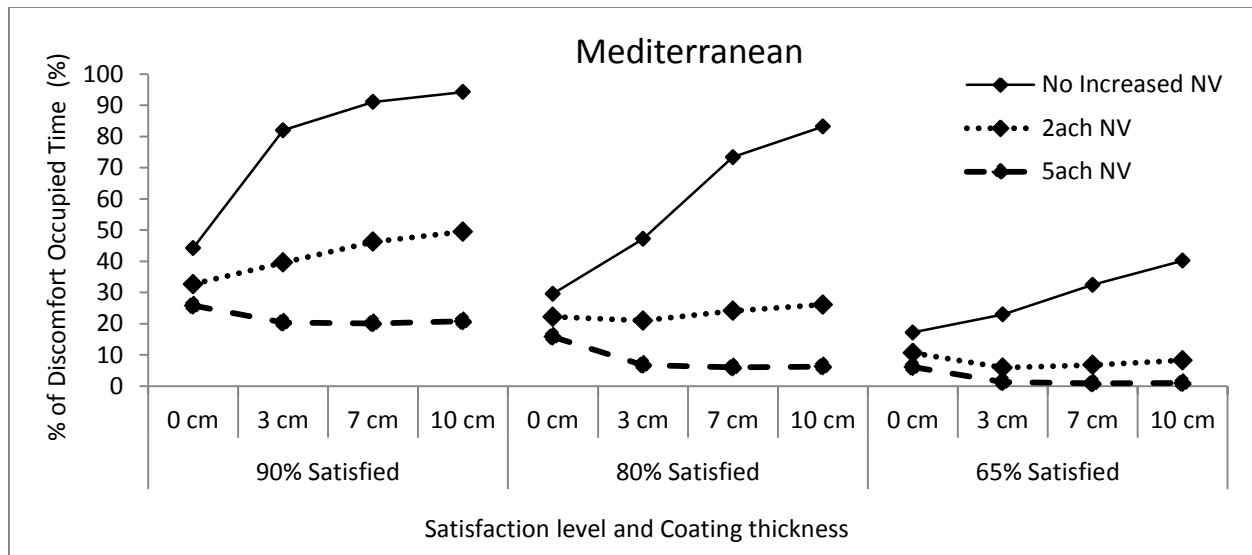


Figure 13: Percentage of discomfort time for different night ventilation rates for a new house in a Mediterranean climate

Conclusion 2 (New house):

The conclusions are based on the EN 15251 adaptive thermal comfort standard.

- In the Mediterranean climate, for a new house initially with no coating, there is a risk of overheating especially for very well insulated envelopes. The percentage of occupied time when thermal comfort is not met can reach 30% for the case of 0cm wall's interior insulation and 70% for 10cm wall's interior insulation. This is due to the fact that the dissipation of the heat inside the house to the outside environment becomes more difficult when the envelope is more insulated. Applying the coating increases significantly the risk of overheating for the house having un-insulated or medium-insulated (5cm) walls. For houses with highly insulated walls (10cm), the effect of applying the coating on the overheating discomfort time is not significant. To overcome this high risk of overheating, night ventilation should be adopted.
- For the Oceanic and Semi-Continental climates, the discomfort time remains below 20% and 10%, respectively, for the different interior insulation thicknesses. Also, the addition of the coating slightly increases these percentages.

Summary

A new insulating coating based on silica aerogels has been developed. The coating's application on building's facades can be done manually or using the ordinary techniques well-known by technicians and builders such as plastering. It is simple, easy, and compatible with the traditional masonry facades. The ease of implementation of this coating facilitates the buildings' rehabilitation. In this paper, we present a simulation-based rapid assessment tool designated for architects, building engineers, and non-expert users to examine the effect of adding this coating on the energy consumption and thermal comfort. All the building construction types representing the different construction periods of buildings in France are considered. Depending on the construction period, different window-to-wall ratios, interior insulation thicknesses, wall structures, etc. are considered. Also, all these are examined under the different climates of France. The output of this tool is the house energy load with and without the coating. As an

inverse problem, the user can enter the required energy load and the output will be the coating thickness. Moreover, the tool provides a thermal comfort assessment based on different thermal comfort models. Results show that applying this coating is very interesting for buildings under rehabilitation. For very well insulated new houses, adding the coating may allow reaching the new thermal regulations (RT 2012) levels of the low energy buildings. However, this coating may increase the risk of overheating during summer, especially for the Mediterranean climate, which could be overcome by adopting night ventilation.

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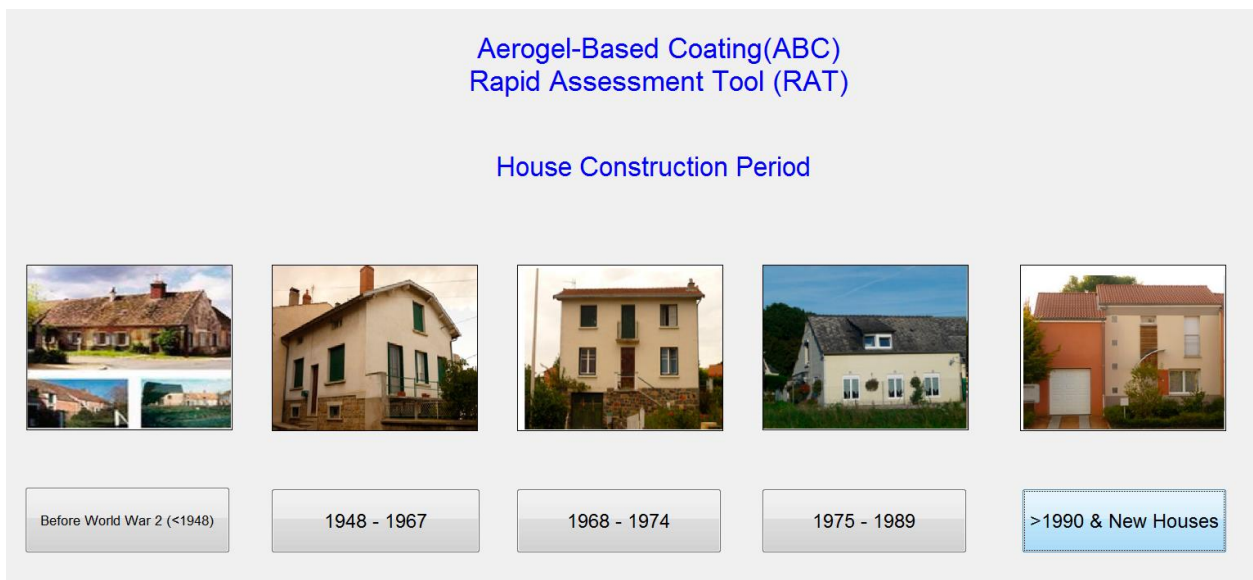
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Appendix 1

Rapid Assessment Tool (RAT) Graphical User Interface



House Construction Period 1968 - 1974



Direct Calculation

Inverse Calculation

Input: Aerogel-Based Coating Thickness
Output: Annual Heating Load

Input: Annual Heating Load
Output: Aerogel-Based Coating Thickness

Rapid Assessment Tool (RAT): Direct "ABC" Thickness -----> Energy Load

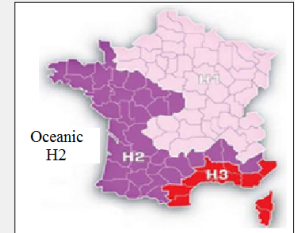
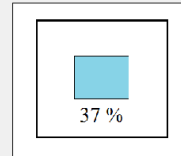
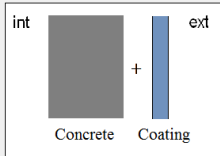
* ABC = Aerogel-Based Coating

Construction Period: 1968-1974

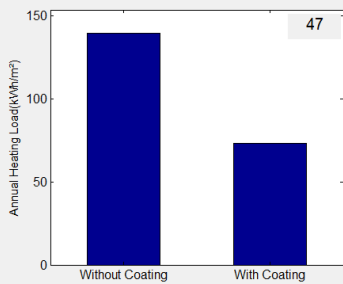


Inputs

Exterior Walls Construction: Concrete
Window Glazing: Single
Air Change per Hour: medium
Window to Wall Ratio: 37 %
Insulated Ceiling: Yes
Climate: Oceanic
"ABC" Thickness (cm): 5



Energy Load with and without the coating



47 %
Reduction in
Energy Consumption

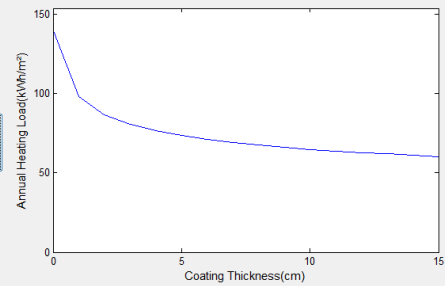
Single Run

Curve Generation

Thermal Comfort Analysis

Outputs

Curve representing Energy Load as a function of Coating Thickness

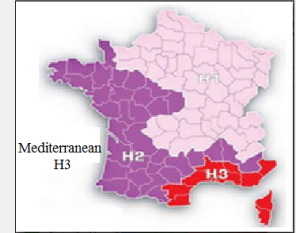
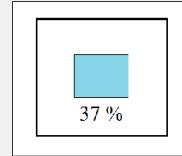
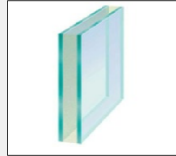
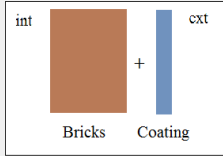


Construction Period: 1968-1974

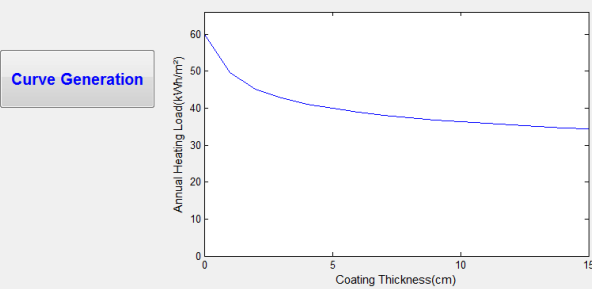


Inputs

Exterior Walls Construction: Bricks
 Window Glazing: Double
 Air Change per Hour: medium
 Window to Wall Ratio: 37 %
 Insulated Ceiling: No
 Climate: Mediterranean



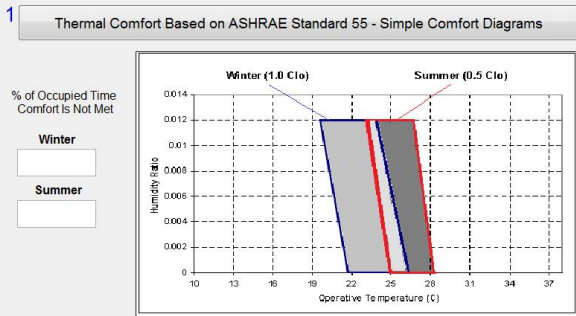
Curve representing Energy Load as a function of Coating Thickness



Input: Heating Load (kWh/m²/year)
 40
 Run
 Output: ABC thickness (cm)
 4.9

Thermal Comfort Analysis

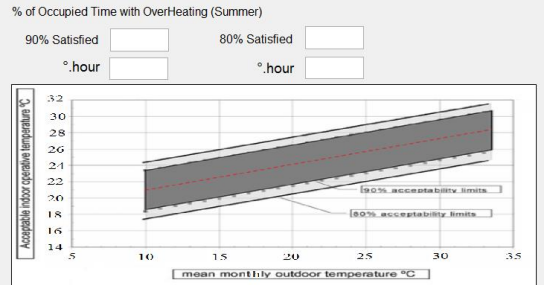
Choose Coating Thickness (cm):
 Increased Heating Setpoint (19°C ----> 21°C)
 Increased Summer Night Ventilation 2 ACH
 Increased Summer Night Ventilation 5 ACH
 RUN CALCULATIONS



2 % of Occupied Time where Heating Is Not Needed and its Degree.Hour
 % of Occupied Time (Winter): °.hour

3 Thermal Comfort According To Fanger PMV Index
 % of Occupied Time Comfort Is Met -0.5 < PMV < 0.5

4 Thermal Comfort Based On ASHRAE 55-2010 Adaptive Comfort Standard



5 Thermal Comfort Based On EN 15251-2007 Adaptive Comfort Standard

