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Effect of thermal diffusivity of insulating materials on room free-float temperature with façade external insulation

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Abstract: External insulation of building façade is widely used to reduce heating energy demand in buildings. Usually, its design concerns only thermal transmittance, while transient thermal behaviour is commonly addressed only as dumping factor or time lag of outdoor heat wave. During summer, in many mild climates, outdoor daily mean temperature is close to comfort temperature. Yet, even though mean heat transfer through building envelope is null, heating during daytime may lead to positive cooling loads or discomfort temperatures in non-conditioned rooms. In residential buildings internal loads are usually very low, so the most relevant loads are heat transfer though outer facades. Moreover, where there is no cooling, wall dumping factor is not meaningful to evaluate the thermal performance of wall insulation, as it is referred to constant indoor temperature. In this framework, a model of a room with a single outer wall has been developed to study the effect of insulating material on free-float temperature. Transient heat transfer through the envelope as well as through inner walls is considered to model indoor air temperature. Different localities in Italy and commonly used insulating materials are considered.

Keywords: Overheating, Thermal comfort, Night cooling, Dynamic effect of thermal insulation, multi-layered walls

Introduction

External insulation of building façade is widely used to reduce heating energy demand in buildings. Actually, in conventional buildings, heating energy demand is mostly due to heat transfer through the building envelope. So, increasing thermal resistance of outer walls by applying thermal insulation reduces heat transfer rate. In order to avoid interstitial moisture condensation and to reduce thermal bridges, insulating panels are often applied outside.

Besides, in many parts of Europe, in summer, climate is quite mild so that heat transfer is from inside to outside during the night as outdoor temperature decreases under indoor comfort temperature. Moreover, in non cooled rooms, indoor temperature fluctuates as a result of inner loads, solar loads and heat transfer through building envelope. So, even during daytime, heat transfer is often from inside to outside. Therefore, insulation of outer walls reduces outgoing heat transfer through building envelope, leading to an increase of indoor temperature.

The risk of overheating in highly insulated dwellings have been pointed out in a number of reports concerning different European Countries (Isaksson & Karlson, 2006; Schmitt et al., 2007; Janson, 2010; Larsen & Jensen, 2011; McLeod et al., 2013). These finding suggests that the thermal insulation of outer walls reduces heating energy demand but may provoke an increase in cooling demand, urging the application of cooling systems.

Anyhow, even in this case, the new cooling energy demand is usually quite low, so yearly energy balance is positive.

As stated, during summer heat transfer through an outer wall may be either inwards or outwards, changing direction during the same day. Thus, transient behaviour of each layer is relevant for indoor temperature behaviour, including insulating layer.

In this framework, different materials, commonly used in outer insulation of building envelope, are analyzed in order to highlight their effect on indoor temperature, presuming there is no cooling. A standard apartment bedroom is considered.

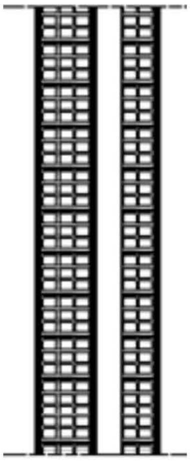
Mathematical Formulation and Computational Procedure

The room is considered to be 5 m wide and 4 m deep with a 3 m height. Only one wall is outfacing in which there is a 1.25 m^2 window. Other walls, the roof and the floor are supposed to adjoin rooms that are almost at the same temperature, so that heat transfer through them may be neglected. In order to evaluate their contribution to indoor heat capacity they are modelled assuming that the midplane is adiabatic.

The outer wall is the type known as "a cassetta", made of two layers in bricks and a wide hollow-space, that is the most common one among reinforced concrete skeleton buildings built between the end of WWII and the arising of the energy crisis in mid '70s. The composition of the wall is sketched in fig. 1. In the cavity, heat transfer occurs by natural convection and radiation at the same time. As radiation heat transfer is prevalent and its thermal capacity per unit volume is much lower than other layers, for calculation purpose it may be treated as a homogeneous layer made of an opaque material with an equivalent conductivity evaluated from eq. 1:

$$k_{eq} = h \cdot s_{cavity} \tag{1}$$

where , *k* stands for thermal conductivity, *h* for combined convection and radiation heat transfer coefficient in the cavity, *s* for thickness.



Material	Thickness mm	Thermal conductivity W/m×K	Density kg/m^3	Specific heat capacity J/kg×K
Plaster	15	0.9	1800	1000
Bricks	120	0.4	750	836
Cavity	60	0.3	1.2	1000
Bricks	80	0.4	750	836
Plaster	15	0.8	1400	1000

Figure 1. Outer wall composition. Data are outside to inside

The window is made of two glass layers with low emissivity inside coating (0.1 emissivity), Argon filling, and is assumed to be completely shaded from direct sunlight.

An energy renewal intervention by application of 60 mm thick insulating panel on the outer face is considered. Expanded polystyrene (EPS), Expanded polyurethane (EPU), and a double density Mineral wool panel (MWP) are considered, with properties stated in table 1, together with insulated wall thermal transmittance.

Table 1. Properties of insulating materials

Material		Thickness mm	Thermal conductivity W/m·K	Density kg/m^3	Specific heat capacity J/kg·K	Thermal diffusivity m^2/s x10^6	Thermal transmittance W/m^2·K
EPS		60	0.036	18	1450	1.38	0.39
EPU		60	0.028	35	1464	0.55	0.33
MWP	outer layer	20	0.031	120	1030	0.25	0.37
	bulk layer	40	0.035	70	1030	0.49	

Thermal field equation in each wall layer is described by a Cartesian one-dimensional Fourier's equation for conducting fields:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \times \frac{\partial T}{\partial \tau} \tag{2}$$

where, T for temperature, α for thermal diffusivity, and τ for time. At layer junction, heat flux conservation is given by:

$$k_a \left.\frac{\partial T}{\partial x}\right|_a = k_b \left.\frac{\partial T}{\partial x}\right|_b \tag{3}$$

where subscripts *a* and *b* stand for the two neighbour layers. Outdoor boundary condition is combined convection and radiation heat transfer coefficient:

$$h_o \cdot (T_{outdoor} - T) + a \cdot W = -k \frac{\partial T}{\partial x} \tag{4}$$

where h_o is outdoor heat transfer coefficient, a is absorption coefficient of solar radiation, and W is solar radiation specific power. Indoor boundary condition is convection heat transfer to room air, and radiation heat transfer to the other surfaces of the room, evaluated through its mean radiant temperature:

$$-k \frac{\partial T}{\partial x} = h_i \cdot (T - T_{room}) + h_r \cdot (T - T_{mr}) \tag{5}$$

where h_i is indoor convection heat transfer coefficient, h_r is indoor radiation heat transfer coefficient, T_{room} is room air temperature, and T_{mr} is mean radiant temperature, defined from eq. 6:

$$T_{mr} = \frac{A_o \cdot T_o + A_i \cdot T_i + A_w \cdot T_w}{A_o + A_i + A_w} \tag{6}$$

where subscripts *o, i* and *w* stand for outer wall, inner wall and window, respectively. Room air temperature is assumed to be uniform and calculated through energy equation:

$$V \cdot \rho_a \cdot c_{p_a} \frac{dT_{room}}{d\tau} = \\ = h_i \cdot A_i \cdot (T_i - T_{room}) + h_i \cdot A_o \cdot (T_o - T_{room}) + h_i \cdot A_w \cdot (T_w - T_{room}) + \dot{Q}_{\iota} + \dot{Q}_V \tag{7}$$

where V is room volume, ρ_a is room air density, c_{pa} is room air isobaric specific heat, $\dot{Q}_i$ *is* inner loads due to people, lighting and appliances, and $\dot{Q}_V$ is ventilation heat transfer, given by eq. 8:

$$\dot{Q}_V = n \times V \times \rho_a \times c_{p_a} \times (T_{outdoor} - T_{room}) \tag{8}$$

where subscripts n is room ventilation rate (air changes per unit time). In the window, conduction heat transfer is neglected, assuming each glass to be isothermal.

Governing equation, along with boundary and initial conditions stated above, are solved through a control-volume formulation of the finite-difference method. A second-order backward scheme is used for time stepping. Auxiliary temperature nodes at materials interfaces are used. The discretized equations lead to a linear system that has been solved with Thomas algorithm with a specifically developed Matlab code.

The code was checked against reference simple analytic solutions found in (Carslaw & Jaeger, 1959) to get the optimal mesh-size and time step. In order to assure that the error to the analytic solution is less than 10^{-3}, 30 s time step with an x-wise step given from eq. 9 has been found to be a good balance between calculation time and solution accuracy.

$$\Delta x = s\sqrt{\frac{1.5}{\alpha \times \Delta\tau}} \tag{9}$$

Results and discussion

Simulations with typical year outer climate in different cities in Italy with usual ventilation and inner loads, as well as with 24 hours sinusoidal solicitation response are performed. While the former simulations provide data close to effective use conditions, the latter are useful to understand the phenomenon. All simulations are performed assuming 0.3 vol/h continuous air change rate.

Sinusoidal solicitation - 24 hours period

A 24 hours long sinusoidal variation of outdoor temperature is considered with 24°C minimum and 34°C maximum. No sunlight nor inner loads are introduced in the calculation. Simulation is reiterated up to periodic regime with a maximum variation of any temperature lower than 10^{-3} K. Periodic regime is reached after 15 to 25 periods.

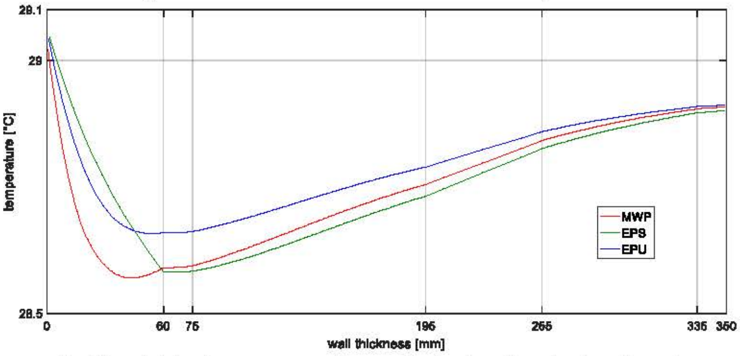


Figure 2. Temperature fields within the outer wall at solicitation beginning (outdoor temperature 29°C)

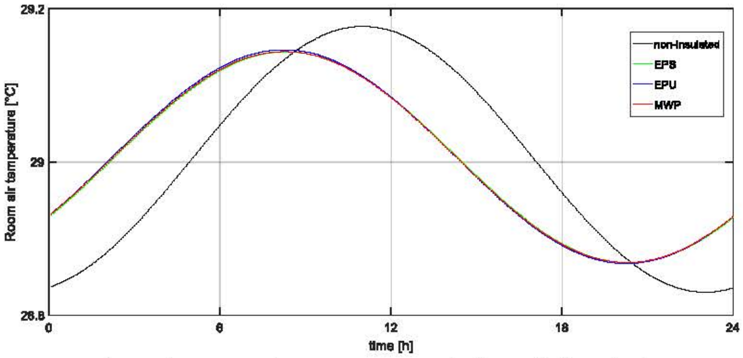


Figure 3. Room air temperature during a full period

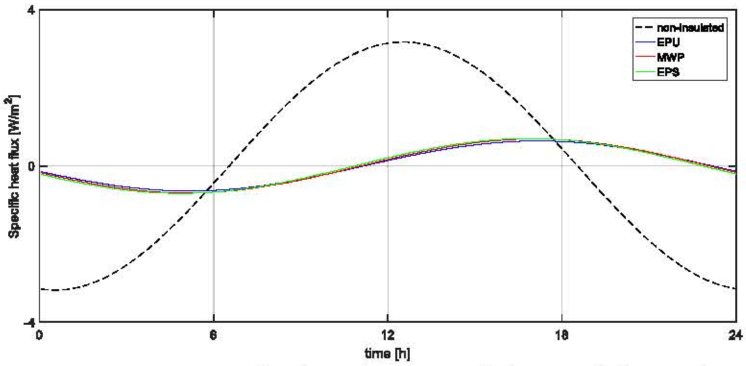


Figure 4. Heat transfer through outer wall during a full period

Temperature fields with the three different insulating materials after 4 minutes from solicitation beginning, when outdoor temperature is equal to the mean 29°C, is shown in fig. 2. Temperature fields in the bricks show a lower gradient in EPU than in the other two. This is clearly due to the higher thermal resistance introduced by this insulating material that is due to its lower thermal conductivity. Besides, MWP show a thermal inertia that lead to a delay in heat wave crossing, so that it is still cooling the outer bricks, while in EPU and EPS panels heat transfer direction is already fully inverted.

As far as the effect on indoor air temperature is considered, the differences between insulating materials smooth down, almost vanishing as shown in fig. 3. All insulating materials share almost the same behaviour. It might be surprising that insulating the outer wall leads to a reduction in heat wave time lag with respect to non-insulated outer wall. It must be considered that room air temperature is due to the combined effect of heat transfer through the outer wall altogether with heat transfer through the window and by ventilation. Insulating the wall reduces its contribution to room temperature, so the effect

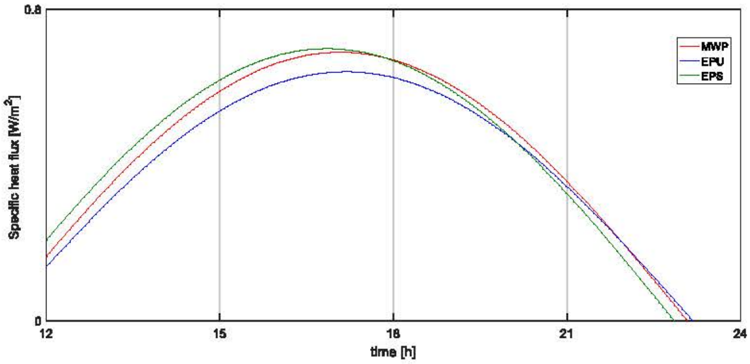


Figure 5. Highlight of peak heat transfer through outer wall for different insulating materials

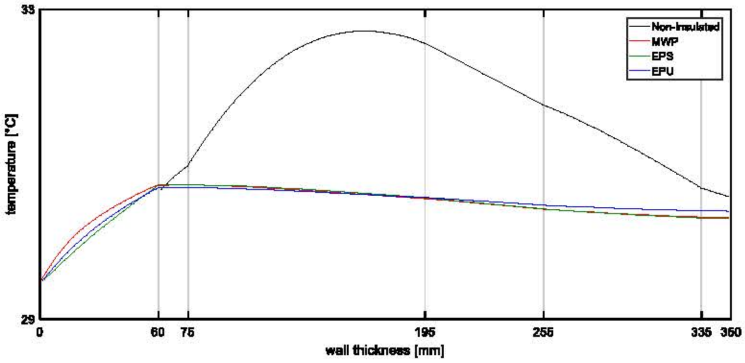


Figure 6. Temperature fields within the outer wall on the hottest day in Rome at 8 p.m.

of the other two heat transfer modes, that share a negligible time lag, take effect earlier, bringing forward the temperature maximum.

Considering solely heat transfer through the outer wall, as shown in fig. 4, the effect of outside insulation is highlighted. Outer wall contribution to heat transfer is strongly reduced, increasing its time lag from almost 7 hours to almost 11 hours. Focusing on the behaviour of different materials it may be seen from fig. 5 that while MWP and EPU share the same time lag, while EPS time lag is one hour shorter.

Data show quite clearly that insulating materials contribution to time lag is mainly due to their thermal resistance. Yet, using materials with lower thermal diffusivity (like MWP) increases time lag further.

Typical year climate

Summer period in a typical year is considered for Milan, Rome, Naples and Palermo, whose mean outdoor temperatures in July and August are given in table 2. The outer wall is assumed to be South facing. Inner loads are assumed to be equal to 150 W from 10 p.m. till 7 a.m. Simulations are performed from 1st May till 30th September to simulate the whole summer period.

Table **2**. Monthly mean temperatures

	Milan	Rome	Naples	Palermo
July	22.3°C	24.1°C	24.6°C	25.6°C
August	21.8°C	24.4°C	24.4°C	26.2°C

Temperature fields in the outer wall for different insulating materials on the hottest day in Rome at 8 p.m. show a decrease in inwards heat transfer rate with some residual thermal inertia in MWP insulating, as shown in fig. 6.

In order to compare the influence of insulation and differences between insulating materials, cumulative indoor temperature distributions are generated, as shown in fig. 7, illustrating the cumulative time in which it is higher than the temperature on the abscissa. It is evident that insulating the outer wall increases indoor temperature as in non air conditioned rooms mean heat transfer direction is outwards. Thus, wall insulation implicates a higher indoor temperature to restore heat transfer rate.

The influence of climate on performance of different insulating materials may be highlighted by comparing cumulative time in which indoor temperature is higher than 28°C,

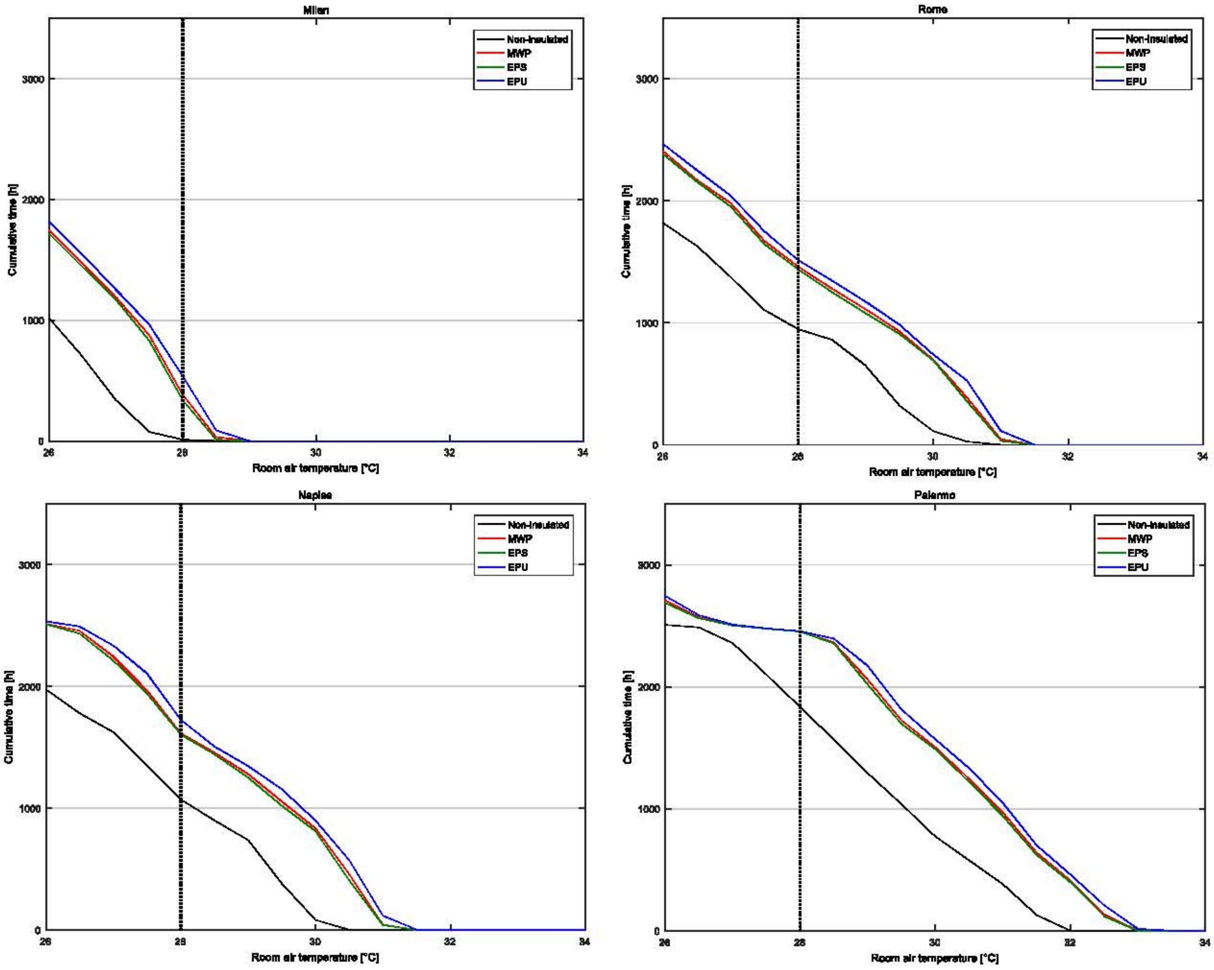


Figure 7. Outer cumulative indoor temperature distributions

that may be chosen as indoor distinctive temperatures for summer, as depicted in fig. 8. It is evident that in Palermo all insulating materials perform in the same way with a 33% increase in cumulative hours with indoor temperature higher than 28°C. As Palermo has a quite hot climate in summer, heat transfer through the outer wall is less relevant on overall behaviour. In Rome and Naples, that have milder summer climate, the higher insulation provided by EPU increases room overheating, especially in Naples in which July is even hotter than August. The overheating due to MWP and EPS, slightly lower in Naples than in Rome, suggests that their effect may be more relevant on a peak period of outdoor temperature rather than on a high mean value.

Conclusions

Simulations of temperature fields and indoor air temperature for a sample room has been performed with a finite difference formulation of heat transfer equations.

Sinusoidal solicitation show that outer insulation modifies indoor temperature evolution reducing room temperature time lag as heat transfer due to ventilation and windows become more relevant. Yet all insulating materials provide almost the same increase in wall time lag, slightly lower for EPS insulation. Mineral wool shows a higher thermal inertia, although it is not enough to change wall behaviour, it may compensate a slightly lower thermal resistance.

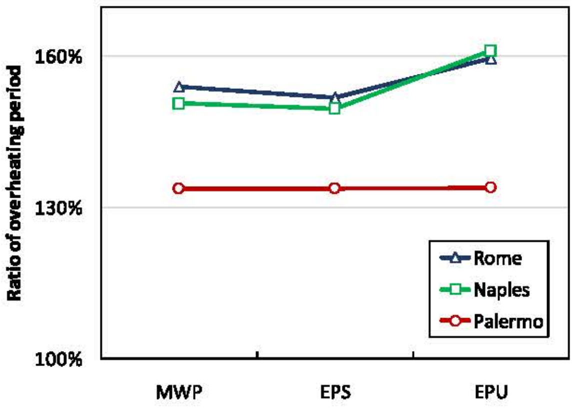


Figure 8. Cumulative time in which indoor temperature is higher than 28°C, ratio to non-insulated wall

Typical year simulations for different climates in Italy with common inner loads show a pronounced overheating, especially in the least hot climate. In Naples and Rome, although monthly mean temperatures are similar, the effect of different insulating materials is not the same. The higher thermal resistance provided by EPU lead to a longer overheating, while MWP and EPS provide a longer overheating in Rome than in Naples, although July monthly mean temperature is lower.

References

Carslaw H.S., Jaeger J.C., (1959) *Conduction of Heat in Solids*, Clarendon, 1959

Isaksson C, Karlson F. (2006) Indoor climate in low energy houses e an interdisciplinary investigation. *Building and Environment*, Volume 41, December 2006, Pages 1678-1690

Janson U. (2010) *Passive houses in Sweden e from design to evaluation of four demonstration projects.* Report EBD-T-10/12, ISBN 978-91-85147-46-5. Lund University, Faculty of Engineering LTH. Available at:, http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Doc_avhandling_UJ_Bok_webb.pdf

Larsen T.S., Jensen R.L., (2011) Comparison of measured and calculated values for the indoor environment in one of the first Danish Passive houses. In: *Proceedings of building simulation 2011: 12th conference of international building performance simulation association*, Sydney, Australia, 14-16 November

McLeod R.S., Hopfe C.J., Kwan A. (2013) An investigation into future performance and overheating risks in Passivhaus dwellings, *Building and Environment*, Volume 70, December 2013, Pages 189-209

Schmitt Y, Dal Savio S, Sparber W. (2007) Monitoring of a multi family passive house in South Tyrol, Italy. In: *Proceedings of 11th international conference on passive houses 2007.* 13-14 April Bregenz, Austria