HYGROTHERMAL ANALYSIS ON THE USE OF INTERNAL THERMAL INSULATION SYSTEMS IN PORTUGUESE RESIDENTIAL BUILDINGS

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ABSTRACT

In Portugal, the external thermal insulation systems (ETIS) are nowadays a current technical solution in residential buildings, contrasting with the rarely used internal thermal insulation systems (ITIS).

In this paper, a quantitative analysis on ITIS is done based on three hygrothermal façade requirements: interstitial condensations, thermal bridges, and temperature variations across the external wall.

Computer simulation was used as research tool. The selected software applications were in compliance with the available European standards, particularly for the interstitial condensations and thermal bridges.

The effect of distinct external climate conditions was evaluated, taking also into account the typical indoor hygrothermal characteristics of Portuguese residential buildings, namely temperature and ventilation rate.

The results of this study quantitatively shows, for the analised hygrothermal requirements, that the ITIS option should not be disregarded at design stage, provided that some proper measures are guaranteed.

KEYWORDS

Internal thermal insulation systems, hygrothermal requirements, residential buildings, sustainability.

INTRODUCTION

The internal thermal insulation systems (ITIS) are an unusual solution in Portuguese residential buildings, despite the several advantages that justify their use when compared to external systems (ex. ETICS), like lowest cost, highest durability, increased airborne sound insulation (limitation of flanking transmission via facade, and also higher external noise insulation, specially when there are no windows), possibility to integrate several equipments (ex. water supply pipes) without damaging the masonry, and maintenance of façade appearance in ancient buildings rehabilitation interventions, among others (Ferreira 2006).

On the other hand, some common disadvantages referred in literature are hygrothermal-related defects on the building envelope originated by interstitial condensations, thermal bridges and high temperature amplitudes on external wall, and also indoor thermal discomfort related with the risk of overheating during summer months.

Since the middle of the 1990 decade the Portuguese construction sector has been gradually changing the traditional construction technique of the residential buildings façade – masonry cavity wall partially filled with a thermal insulation material – to a single leaf wall insulated (almost always) with an ETIS.

The growth foreseen in Portugal for the rehabilitation sector when compared with the new construction market, along with more demanding building thermal regulations (RCCTE 2006), motivated a quantitative research analysis on ITIS behaviour using computer simulaton methods, both for the above-mentioned hygrothermal façade requirements, and also for the indoor thermal comfort conditions.

In this paper the first set of results, concerning the three hygrothermal topics, are presented.

SIMULATION METHODS AND ANALYSIS CRITERIA

Computer simulation was used as research tool. The selected software applications were in compliance with the available European standards, particularly for the interstitial condensations and thermal bridges (respectively EN ISO 13788 and EN ISO 10211-1/2).

In all simulations a typical ITIS design (Figure 1) was considered, consisting of a hollow brick masonry wall rendered on the external surface, and with a thermal insulation material (TIM) protected with a gypsum plasterboard layer on the internal side.

The main thermal and hygric parameters of all the materials used in simulations are shown in Table 1.

The external climate data (monthly mean values) selected for the interstitial condensations and thermal bridges simulations is representative of Portuguese three winter climatic zones (Table 2).

In Table 3 the chosen boundary conditions (surface heat transfer coefficient, h_i and h_e) are summarized, with the internal value (h_i) varying according to the different calculation standards guidelines.

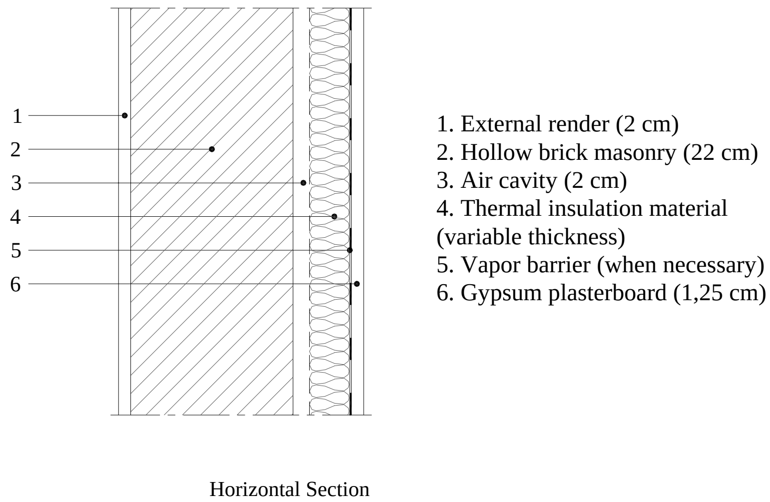

Figure 1 Scheme of the studied internal thermal insulation system.

Table 1 Main thermal and hygric properties of the materials used in simulations (λ – thermal conductivity; c – specific heat capacity; ρ – density; π – water vapor permeability).

Material	λ [W/(m·ºC)]	c [J/(kg·ºC)]	ρ [kg/m^3]	π [g/(m·h·mmHg)]
External render	1.150	840	1900	400×10^{-5}
Hollow brick masonry (22 cm)	0.478	510	775	550×10^{-5}
Concrete	1.750	1080	2400	-
Gypsum plasterboard	0.180	840	820	1200×10^{-5}
Thermal insulation material (characteristic value)	0.040	1400	30	-
Mineral wool (MW)	0.040	-	-	7500×10^{-5}
Polyurethane (PU)	0.030	-	-	200×10^{-5}
Expanded polystyrene (EPS)	0.040	-	-	300×10^{-5}
Extruded polystyrene (XPS)	0.035	-	-	70×10^{-5}
Cellullar glass (CG)	0.050	-	-	0
Aluminium foil (25 μm)	-	-	-	350×10^{-10}

Table 2 Representative monthly mean values of external air temperature (θ_e) and relative humidity (RH_e) for the three Portuguese winter climatic regions (only for $\theta_e \leqslant 13$ºC) (Wouters et al. 2003).

Portuguese Winter Climatic Regions	Climate Data	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Winter I1	θ_e (ºC)	-	12.5	11.8	12.4	-	-
	RH_e (%)	-	80	81	78	-	-
Winter I2	θ_e (ºC)	12.2	9.4	8.8	9.7	11.9	-
	RH_e (%)	80	82	81	77	77	-
Winter I3	θ_e (ºC)	9.3	6.2	5.7	6.9	9.5	12.2
	RH_e (%)	80	83	82	77	72	67

Table 3 Boundary conditions for the distinct hygrothermal topics (according to calculation standards).

Surface	Surface heat transfer coefficient [W/(m^2·ºC)]	Hygrothermal Topic
Internal	4.0	Interstitial Condensations / Thermal Bridges (f-value)
	7.7	Thermal Bridges (ψ-value) / Temperature Profiles
External	25	Interstitial Condensations Thermal Bridges Temperature Profiles

Interstitial Condensations – Research Basics

The assessment of interstitial condensations risk was performed using the Glaser methodology for the reference ITIS with diverse TIM characteristics, combining both its nature (fibrous or cellular) and thickness. It should be reminded here that although simplified, Glaser method allows the prediction of conservative results based on few (and available) thermal and hygric parameters as input data, as emphasized by EN ISO 13788.

The simulation was performed with CONDENSA 2000 (1998), a Portuguese software which can be applied according to the standardized calculation procedure (EN 13788). The calculation was limited to the winter coldest months (monthly mean value of external air temperature less than 13 ºC). The climate data required (namely internal and external air temperatures, external relative humidity and hygrometry) were considered on a monthly mean basis (EN 13788). Due to the unsteady internal air temperatures in Portuguese buildings, largely due to the lack of heating habits, four situations were considered for the mean monthly value: 14ºC, 16ºC, 18 ºC and 20 ºC.

For each situation the critical hygrometry (g/m^3) to avoid interstitial condensations was computed and compared with a reference value of 3 g/m^3, which may be considerered a representative value for a well-ventilated situation (Wouters et al. 2003). Yet in some Portuguese residential buildings (with high occupancy and/or poor ventilation) the higrometry may even exceed 5 g/m^3, and so this fact should be pondered when designing any building solution.

Thermal Bridges – Research Basics

Although thermal bridges are inevitable when using ITIS, one should evaluate the consequences of their occurrence in residential buildings, because not all thermal bridges are problematic if their unfavorable effects are limited to acceptable proportions.

Thermal bridge assessment was performed under two distinct topics: the increase of the heat losses through building envelope (sustainability), and the risk of condensation and mould growth resulting from the lower surface temperature at the thermal bridge area (habitability). Although these two topics are related, it is very convenient to anlayse them separately, to reach more specific conclusions.

Only two-dimensional thermal bridges were studied (often called “linear thermal bridges”), as the three--dimensional thermal bridges, occurring when an insulated wall is perforated by an element with high thermal conductivity (point thermal bridge) or in three dimensional corners, may be overlooked in ordinary residential buildings (Wouters et al. 2003).

Two parameters were used to describe sustainability and habitability topics, respectively linear thermal transmittance (ψ, W/(m·ºC)) and temperature factor at the internal surface (f_{Rsi}, adimensional).The ψ--value represents the extra heat loss as a result of the thermal bridge, while the f_{Rsi}-value quantify the temperature decrease on the surface of the inside face of the thermal bridge area.

The simulation was performed using Kobra v2.0 (2002), a European renowned software for the thermal bridges asessment based on the approach established by ISO 10211-2 (2002), using a finite difference method under steady-state conditions.

Typical Portuguese residential building details were studied for the following junctions: external wall--roof slab (J1); external wall-internal floor slab (J2); external wall-external floor slab (J3); external wall--internal wall (J4). The position and dimension of structural components (columns, beams and slabs) match the ones typically found in Portuguese residential buildings (Corvacho 1996).

The selected cases are in agreement with previous studies concerning thermal bridges assessment in Portuguese residential buildings, representing the worst situations using ITIS (Corvacho 1996) and which may be easely tackled with ETICS. For each situation only two values for the TIM thickness were adopted (3 and 8 cm), after it was found, during the first set of simulations, that the thickness variation of the TIM was not so significant to the the thermal bridges analysis as for instance to the interstitial condensations one.

The evaluation criteria regarding the consequences of thermal bridges occurrence must be different for the sustainability and habitability cases.

For the sustainability case, the analysis was based on the relative importance of ψ-values (Table 4), accounting for the thermal bridge length (as a large ψ-value does not inevitably denote an important thermal bridge). Hence, it is proposed that for a vertical thermal bridge (ex. J4), which usually has a smaller length (room height), a correction strategy is “fundamental” for class C4 and “desirable” for C3 (according to Table 4). In a horizontal case (ex. J2) the maximum classes should decrease to C3 and C2. Internal dimensions were used to quantify the ψ-value, in harmony with the Portuguese building thermal regulations (RCCTE 2006).

Concerning the habitability requirement, f_{Rsi}-value analysis depends of the internal and external air temperatures, and the higrometry. If a residential building is properly heated and ventilated then the critical f_{Rsi}-value may be lower than for the opposite case. In the present study, the following criteria was adopted: for an internal air temperature of 18 ºC and relative humidity between 50-70%, the internal surface temperature cannot be lower than the dew point of the internal air, ie, surface condensation risk must not exist. In this case thermal bridge correction becomes “fundamental”.However, if that risk only exists for a higher moisture content, then we considered that correction is only “desirable”.

Table 4 Classification of thermal bridge effect under the sustainability (heat loss) criteria (Wouters et al. 2003).

Class	ψ-value [W/(m·ºC)]	Effect
C1	$\psi_i < 0.10$	Negligible
C2	$0.10 \le \psi_i < 0.25$	Poor
C3	$0.25 \le \psi_i < 0.50$	Important
C4	$\psi_i \ge 0.50$	Very Important

Temperature Variations – Research Basics

Higher temperature amplitudes in a masonry wall is often the cause for defects like cracking of external finishing and, in worst situations, even of the wall itself, potentially leading to rainwater penetration through the masonry. This is one of the most-quoted disadvantages of ITIS use when compared to ETIS (Ferreira 2006).

The temperature profiles across the masonry wall were determined with a finite difference method (Corvacho 1996) for typical summer and winter temperatures and solar radiation values, with the main purpose of quantifying the maximum value of temperature amplitude on a dayly and annual basis.

Hourly values for external air temperature and solar radiation were used to simulate severe external climate conditions (for a summer and winter day) to an hypothetical vertical external wall located at the city of Porto (available from LFC, Buiding Physics Laboratory, Faculty of Engineering, University of Porto), with varying orientation (N, S, W). Some average values are presented in Table 5 to illustrate the climate conditions considered. For the internal temperature a constant value of 20 ºC was assumed.

Two situations were considered regarding the solar absorption coefficient of external finishing, a darker solution with a 0,70-value and a lighter one with a 0,30-value (more typical in Portugal). For the TIM thickness, again only two values (3 and 8 cm) were considered. However in this case an ETIS solution (similar to the ITIS, only with the relative position of TIM changed) was also used, to allow for comparison between the two systems.

Table 5 Illustrative values of the external climate conditions considered (severe winter and summer day in Porto) for temperature variations simulation.

External Climate Parameters	Summer	Winter
Max. Air Temperature (ºC)	33.3	15.0
Min. Air Temperature (ºC)	16.6	5.1
Max. Radiation, N (W/m^2)	129.8	76.5
Max. Radiation, S (W/m^2)	415.2	579.8
Max. Radiation, E (W/m^2)	612.0	238.7
Max. Radiation, W (W/m^2)	705.0	181.7

DISCUSSION

Interstitial Condensations – Main Findings

The TIM water vapor resistance greatly influences the risk of interstitial condensations. The data presented in Table 6 shows that when using mineral wool (MW) as TIM, the risk increases with its thickness, ie, the maximum hygrometry value that, for a specified internal air temperature, originates interstitial condensations, decreases.

On the contrary, when using PU, EPS, XPS or CG, the increase of the TIM thickness is a positive factor (Table 7). This conclusion confirms the usefulness of some general design rules established by DTU 20.1 (1985), and allows extending their range of application to the Portuguese climate characteristics and typical indoor hygrothermal environment (air temperature and hygrometry). Nevertheless, the increase of the TIM water vapor resistance must be complemented with an appropriate ventilation rate to prevent superficial condensations.

The interstitial condensations risk is, as expected, higher in the more severe winter climatic regions, in particular I3 region. One should also note that it is in this same region that the TIM thickness should be higher – therefore the use of MW with ITIS under severe climate conditions is not recommended. If MW is to be used in such conditions, a water vapor retarder layer should then be implemented.

The internal air temperature had the greatest relative effect on the interstitial condensation risk, although if the water vapor resistance of the TIM is high (all materials except mineral wool) the critical value of hygrometry is always greater than 3,0 g/m^3, which is not a problem for well-ventilated dwellings with low occupancy. If these conditions are not assured, ITIS use will of course bring a higher interstitial condensation risk than other systems.

Thermal Bridges – Main Findings

The simulated results, analyzed according to the established criteria, are summarized in Table 8. One first immediate conclusion is that if suitable indoor hygrothermal conditions are provided (temperature and relative humidity), the ψ_i-value is a much more demanding parameter than $f_{0,25}$-value (which is only significant for region I3, with a more severe winter). Hence, ITIS use in mild climate regions (like I1 and I2 in Portugal) will not probably cause surface condensation and mould growth.

When applying the sustainability criteria, thermal bridge correction becomes critical for junctions J1 to J3, and only desirable for junction J4. However, if simple correction details are planned, basically extending the TIM along the low-insulated building elements (Abreu 2002), the extra heat-loss due to the thermal bridge will no longer be harmful to the energy-efficiency purpose.

In fact, after correction, ψ_i-values less than 0,25 were obtained by simulation for all junctions, which may be classified as a “poor” effect (Table 4).

Temperature Variations – Main Findings

From the several simulation hypotheses combining orientation, TIM thickness and solar absorption coefficent, only the worst ones (for ITIS behaviour, and attending to the purpose of this particular topic) were considered. This was specially true for winter conditions, because the results previously obtained for summer conditions were already considered when choosing the most relevant cases to analyse. Figure 2 shows a resume of the most important simulation results.

For both systems (ITIS and ETIS), wall orientation is a decisive factor, with North and West being the most extreme cases in summer (respectively less and most severe), and South in winter. The North is a favorable orientation for ITIS, with a maximum amplitude of 19 ºC even with a α-value (solar radiation absorption coefficient) of 0,70.

With the increase of the TIM thickness from 3 cm to 8 cm, although the maximum amplitude in ITIS remains approximatly constant, there is an increase of the masonry thickness exposed to that amplitude. In ETIS the increase of the TIM thickness is always favorable (thus decreasing temperature amplitude).

Considering the worst summer conditions for ITIS, the decrease of α-value from 0,70 to 0,30 implies a decrese of the maximum temperature amplitude of 10 ºC for ITIS and 3 ºC for ETIS.

Under winter conditions the performance of ITIS is acceptable, even for the less favourable orientations (South), providing that the α-value remains low.

The known fact of ETIS better performance in this hygrothermal topic is again confirmed by these results. However a single look to the annual worst ITIS results (45 ºC vs. 13 ºC with α = 0,70, 35 ºC vs. 10 ºC with α = 0,30), certainly overemphazises the magnitude of the potential problem.

If external finishing solutions with α-values ≤ 0,30 are used, then only annual temperature variations will be problematic under Porto climate conditions. But even for this cases some additional measures may minimize their harmful effect like the reduction of incident solar radiation during Summer (ex. with vegetation) or an independent or reinforced external covering (ventilated façade, fibre-glass reinforced render, etc.), among others (particularly structural reinforcement of the masonry including connections to structural elements, and a suitable elasticity behaviour of masonry and mortar).

Further studies are needed in order to evaluate the potential pathologies of masonry walls under high temperature variations in consequence of ITIS use.

CONCLUSION

Regarding the hygrothermal topics analysed, there were not found quantitative reasons to unable ITIS use (or to unconsider this option at design stage), not only in rehabilitation interventions, but also in new construction of residential buildings, providing that some proper measures are guaranteed.

In adition, the use of ITIS may contribute to a lower thermal insulation cost in residential buildings with an expected higher durability when compared to ETIS, thus assuring the solution sustainability.

When using ITIS the internal thermal conditions will also change (the results of that part of the study will be published shortly), with thermal inertia playing a decisive role to prevent overheating.

Further developments of this work should include more detailed simulation tools, and specially field monitoring of ITIS use in real buildings to check for the validity of the simulated results.

ACKNOWLEDGMENT

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Table 6 Maximum hygrometry values (g/m3) to avoid interstitial condensations for the Portuguese three winter climatic regions (I1, I2 and I3). Values below 3.0 g/m3 are highlighted since they represent the worst cases. Mineral wool (MW) used as thermal insulation material.

MW Thickness (cm)	Internal Air Temperature (ºC)											
	14	16	18	20	14	16	18	20	14	16	18	20
3	**2.6**	3.1	3.6	4.1	**2.7**	**3.1**	3.6	4.0	**2.7**	3.1	3.5	3.9
4	**2.6**	3.0	3.4	3.9	**2.6**	**2.9**	3.3	3.7	**2.5**	**2.9**	3.2	3.6
5	**2.5**	**2.9**	3.3	3.7	**2.5**	**2.8**	3.2	3.5	**2.4**	**2.7**	3.0	3.3
6	**2.5**	**2.9**	3.2	3.6	**2.4**	**2.7**	3.1	3.4	**2.3**	**2.6**	**2.9**	3.1
7	**2.5**	**2.8**	3.1	3.5	**2.4**	**2.7**	3.0	3.3	**2.2**	**2.5**	**2.7**	3.0
8	**2.5**	**2.7**	3.1	3.4	**2.3**	**2.6**	**2.9**	3.2	**2.2**	**2.4**	**2.6**	2.9
Climatic Region	Winter I1				Winter I2				Winter I3			

Table 7 Maximum hygrometry values (g/m^3) to avoid interstitial condensations for the Portuguese three winter climatic regions (I1, I2 and I3), with distinct thermal insulation materials ordered with increasing water vapor resistance: EPS (expanded polystyrene); PU (polyurethane) XPS (extruded polystyrene); CG (cellular glass).

Thicknes s Thermal Insulation Material (cm)	Internal Air Temperature (ºC) Thermal Insulation Material																Climatic Region
	14				16				18				20				
	EPS	PU	XP S	CG	EPS	PU	XP S	CG	EPS	PU	XP S	CG	EPS	PU	XP S	CG	
3	3.1	3.2	3.2	3.1	3.7	3.9	4.6	4.5	4.3	4.5	6.1	5.9	4.9	5.0	7.4	7.5	Winter I1
8	3.3	3.3	3.3	3.2	4.2	4.7	4.8	4.7	4.6	5.1	6.5	6.3	5.1	5.6	8.4	8.1	
3	3.2	3.3	3.3	3.3	3.7	3.8	4.7	4.6	4.2	4.3	6.2	6.0	4.8	4.8	7.1	7.5	Winter I2
8	3.4	3.5	3.4	3.4	3.9	4.3	5.0	4.8	4.3	4.7	6.6	6.5	4.6	5.1	8.5	8.2	
3	3.2	3.2	4.5	4.4	3.6	3.7	5.4	5.6	4.1	4.1	6.1	7.0	4.6	4.5	6.8	8.5	Winter I3
8	3.2	3.6	4.8	4.7	3.6	3.9	6.3	6.1	3.9	4.2	7.9	7.7	4.2	4.5	8.5	9.4	

Table 8 Thermal bridges severity assessment for typical residential buildings details in Portugal.

Thermal Bridge Effect	Thermal Bridge Type (External Wall / … Junction)			
	Roof Slab (J1)	Int. Floor Slab (J2)	Ext. Floor Slab (J3)	Internal Wall (J4)
Habitability ($f_{0,25}$-value)	F (in I3 region)	D (in I3 region)	F (in I3 region)	D (in I3 region)
Sustainability (ψ-value)	F (in I1, I2 and I3 regions)	F (in I1, I2 and I3 regions)	F (in I1, I2 and I3 regions)	D (in I1, I2 and I3 regions)

F – Thermal bridge correction is *Fundamental*
D – Thermal bridge correction is *Desirable*
I1, I2. I3 – Portuguese winter climatic regions

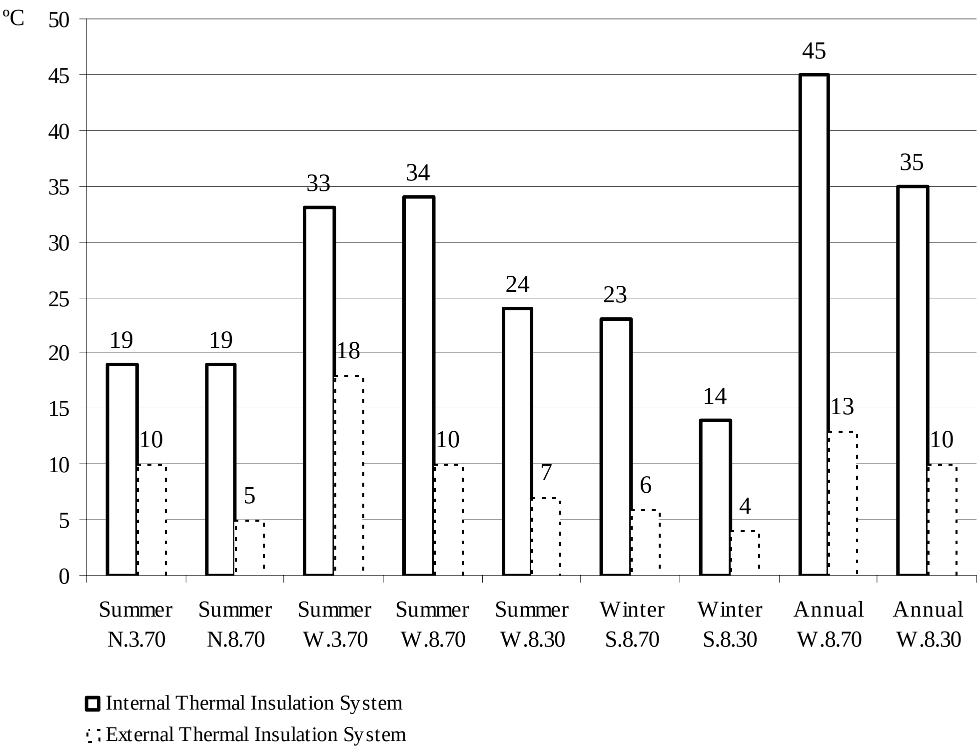

Figure 2 Maximum temperature amplitude across the external masonry wall with external and internal thermal insulation systems, under severe summer, winter and annual Portuguese climate conditions (city of Porto) (each column represent a different combination of wall orientation (N, S, or W), thickness of thermal insulation material (3 or 8 cm) and solar radiation absorption coefficient (0.70 or 0.30).