# COMBINING THERMAL INERTIA, INSULATION AND VENTILATION STRATEGIES FOR IMPROVING INDOOR SUMMER THERMAL COMFORT

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## ABSTRACT

A good level of thermal insulation and an adequate thermal capacity of the building envelope are essential to achieve good energy performance. Many studies have been conducted about this topic, mostly focused on the reduction of energy losses, peak load control and energy savings. Nevertheless, very few studies were realized addressing both insulation and inertia of the building envelope in a thermal comfort perspective, and taking into account the combined effect of different ventilation strategies.

What is the right combination of insulation thickness, heat capacity and night ventilation, in order to achieve better thermal comfort? How to exploit effectively the passive energy potential of the envelope? Of course the answer is not unique since too many parameters influence the building dynamic response under real weather condition. Nevertheless, in this paper a number of simulated results will be reported showing, for a real building with concrete walls, the combined effect of wall thickness, insulation level and outdoor ventilation rates on thermal comfort. These simulations were run under continental climate conditions (UK), and the results show the synergic effect of some strategies to achieve thermal comfort as well as their individual impact on it.

## KEYWORDS

Thermal inertia, thermal comfort, ventilation strategies, dynamic simulation, insulation

## 1 INTRODUCTION

Although the definition of the insulation thickness that is necessary to comply with European or national standards is relatively easy, the management and the exploitation of the thermal inertia of a building is a much harder task, since this is influenced by many factors, linked not only to the thermal properties of the walls, but also to other boundary conditions (weather, heat gains, duration of the heating/cooling cycle).

The heat capacity of the building envelope has inspired many studies since dynamic numerical simulation became accessible and time-cost acceptable. Most of these works are based on an energy saving perspective for HVAC: as an example, see (Aste et al., 2009), (Orosa et al., 2012), (Ozel, 2011) and the works written by Tsilingiris. All these studies report

the thermal behaviour of different heavy walls in simple case studies, under particular boundary conditions and for energy or economic purposes.
However, there are very few works that take into account the actual potential of the thermal capacity of the building envelope, as well as its combination with the level of insulation, in a thermal comfort perspective. In fact, as long as the building is treated as being coupled with an HVAC system, its transient behaviour will be under-exploited and its potential for passive cooling masked or distorted.
In the present work some results concerning the design of new heavy-weight energy-performing houses through numerical simulation will be presented. A parametric analysis has been performed in order to understand the effect of the thermal capacity of concrete walls on indoor thermal comfort in the warm season, when coupled with different insulation thickness or ventilation strategies. To this aim, the building has been simulated in a free-running mode, which exalts the transient behaviour of the envelope as well as its potential for passive cooling.

## 2 METHODOLOGY

The main goal of this paper is to show the role of the thermal capacity of the building envelope, the insulation layer and the ventilation strategies for improving summer thermal comfort in buildings. To this aim, a parametric approach was followed in order to explore not only the individual contribution of each technical solution, but also possible synergic effects.
The results of the simulations were interpreted through the calculation of some indicators, recently introduced in (Sicurella et Evola, 2012), namely the *Intensity of Thermal Discomfort* (ITD) and the *Frequency of Thermal Discomfort* (FTD). The ITD represents the time integral of the difference between the current operative temperature and a threshold value that defines the upper limit for comfort; on the other hand, the FTD is the percentage of time during which thermal comfort is not accomplished, as the previously mentioned threshold value is exceeded.
In this study, the definition of the threshold value is based on the adaptive approach, as described in (EN Standard 15251, 2007); in particular, the threshold operative temperature corresponds to the upper limit of Category I, that is the most restrictive one. The threshold value is not constant in time, but it should be determined daily as a function of the running mean outdoor air temperature. In order to use these indicators, the building is simulated in a free-running mode so as to obtain the time profile of the indoor operative temperature, i.e. the main parameter associated with thermal comfort according to the adaptive approach (Nicol et al., 2002). As the building is supposed to be used for residential purposes, the calculation of the indicators is based on the 24-h profile of the operative temperature.
Thanks to this approach, the comparison between the different design solutions will be based on physical and measurable parameters, thus allowing an easy but comprehensive identification of the best strategies needed to achieve summer thermal comfort.

## 3 CASE STUDY

The methodology described in the previous paragraph was applied during the design stage of real two-storey houses for residential use (see Fig. 1), whose construction is in progress near London (UK). Each house is about 65 $m^2$ in surface and has two floors: the ground floor hosts the living room, a kitchen, a hall and a WC, whereas in the first floor there are a landing, two bedrooms and one bathroom. The main façades are due north and south.
One of the objectives of the project was to understand the real potential of massive constructions to achieve both energy savings and thermal comfort. The results concerning the energy demand are presented in (Sicurella and Tanasiev, 2012): a correct design of the

envelope allowed reducing the specific energy demand for heating by only 2%, whereas the cooling demand could be reduced by approximately 10%, in coherence with other previous works.

Anyway, the present paper wants to focus on thermal comfort, and therefore to investigate on the individual contribution of each technical solution (thermal inertia, insulation, ventilation) as well as their synergic effects. As a reference configuration, in order to achieve excellent winter performance, the massive exterior wall (200 mm concrete) was covered with 300 mm of extruded polystyrene. For the ground floor, that is made by 250 mm of concrete, a 300-mm layer of extruded polystyrene was added, while the roof was composed of tiles, extruded polystyrene (300 mm) and plywood. Table 1 reports the main physical characteristics of the opaque envelope. As concerns the windows, they have a triple glazing with a wooden frame. Their U-value is 1.32 $W \cdot m^{-2} \cdot K^{-1}$, and the g-value is 0.48.

The house is a residential building, whose internal gains (occupancy, lighting, electric equipment) have an average value of 3.06 $W \cdot m^{-2}$, that is typical for new high-performance buildings. The weather data used for the simulations are those of London Gatwick; the simulations were run by using Energy Plus 6.1, through the interface Open-Studio for Google SketchUp and a time step of fifteen minutes was set.

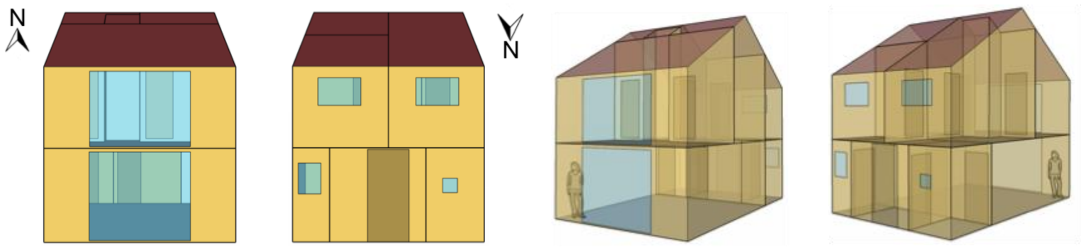


Figure 1: Waterford house, exterior (north view) and interior view (south view)

Table 1: Main features of the simulated building envelope (reference configuration). The materials are listed from the outer to the inner layer.

| | **Components** | **Thickness [cm]** | **ρ $[kg \cdot m^{-3}]$** | **$c_p$ $[J \cdot kg^{-1} \cdot K^{-1}]$** | **λ $[W \cdot m^{-1} \cdot K^{-1}]$** | **U $[W \cdot m^{-2} \cdot K^{-1}]$** |
|---|---|---|---|---|---|---|
| *Exterior walls* | Lime sand render | 3 | 1600 | 1000 | 0.8 | 0.11 |
| | Extruded polystyrene | 30 | 35 | 1400 | 0.034 | |
| | Concrete | 20 | 2300 | 880 | 1.8 | |
| *Ground floor* | Sand and gravel | 5 | 1950 | 1045 | 2 | 0.11 |
| | Polyethylene | 0.01 | 920 | 2200 | 0.33 | |
| | Extruded polystyrene | 30 | 35 | 1400 | 0.034 | |
| | Polyethylene | 0.01 | 920 | 2200 | 0.33 | |
| | Concrete | 25 | 2300 | 880 | 1.8 | |
| | Ceramic | 2 | 2300 | 1000 | 1.3 | |
| *Roof* | Tiles | 2.5 | 1602 | 1464 | 1 | 0.11 |
| | Extruded polystyrene | 30 | 35 | 1400 | 0.034 | |
| | Polyethylene | 0.01 | 920 | 2200 | 0.33 | |
| | Plywood | 1.8 | 700 | 1420 | 0.15 | |
| *Internal walls* | Concrete | 10 | 2300 | 880 | 1.8 | 3.27 |

## 3.1 Parametric analysis

A parametric analysis was performed in order to understand how the insulation of the envelope, the thickness of the concrete slab and the ventilation rate might influence the summer thermal comfort.

To this purpose, seven different solutions for the opaque envelope were considered, by varying the thickness $L_c$ of the concrete slab (for walls and ground floor) from 100 mm to 300 mm, and the thickness $L_{in}$ of the insulation layer from 150 mm to 300 mm. For the sake of comparison, only one case without insulation was considered, but actually this solution is not practically feasible as it would lead to great disadvantages in winter.
For each envelope solution, Table 2 reports the U-value and the values of two dynamic transfer properties, i.e. the *decrement factor* (f) and *the time shift* (φ): they respectively measure the attenuation and the time delay of the thermal wave transferred into the building, if compared to the thermal wave acting on the outer surface of the building. The calculation is conducted according to (ISO 13786, 2007).
As concerns the ventilation of the building, several scenarios were considered, characterized by different values and different time profiles for the air change rate *n*. In any case, ventilation is supposed to be provided through mechanical means.
All the combinations defined in this parametric analysis are reported in Table 3.

Table 2: Main transfer properties for the envelope solutions considered in the parametric analysis.

| **Concrete slab** | **Insulation** | **U** **[$W \cdot m^{-2} \cdot K^{-1}$]** | ***f*** **[-]** | **φ** **[h]** |
|---|---|---|---|---|
| $L_c$ = 200 mm | $L_{in}$ = 0 mm | 3.14 | 0.46 | 6.1 |
| $L_c$ = 100 mm | $L_{in}$ = 150 mm | 0.21 | 0.40 | 7.1 |
| $L_c$ = 100 mm | $L_{in}$ = 300 mm | 0.11 | 0.28 | 11.0 |
| $L_c$ = 200 mm | $L_{in}$ = 150 mm | 0.21 | 0.19 | 9.4 |
| $L_c$ = 200 mm | $L_{in}$ = 300 mm | 0.11 | 0.13 | 13.2 |
| $L_c$ = 300 mm | $L_{in}$ = 150 mm | 0.21 | 0.10 | 11.7 |
| $L_c$ = 300 mm | $L_{in}$ = 300 mm | 0.11 | 0.07 | 15.5 |

Table 3: Combinations used in the parametric analysis.

| **Case nr** | **Concrete slab thickness** | **Insulation thickness** | **Ventilation rate** | **Time schedule for ventilation** | **Comments** |
|---|---|---|---|---|---|
| 1 | 200 mm | 0 mm | $n = 0\ h^{-1}$ | 00:00 – 24:00 | *Role of the insulation* |
| 2 | 200 mm | 150 mm | $n = 0\ h^{-1}$ | 00:00 – 24:00 | |
| 3 | 200 mm | 300 mm | $n = 0\ h^{-1}$ | 00:00 – 24:00 | |
| 4 | 100 mm | 150 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | *Role of the slab thickness ($L_{in}$ = 150 mm)* |
| 5 | 200 mm | 150 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | |
| 6 | 300 mm | 150 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | |
| 7 | 100 mm | 300 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | *Role of the slab thickness ($L_{in}$ = 300 mm)* |
| 8 | 200 mm | 300 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | |
| 9 | 300 mm | 300 mm | $n = 2\ h^{-1}$ | 00:00 – 24:00 | |
| 10 | 200 mm | 300 mm | $n = 0.5\ h^{-1}$<br>$n = 2.0\ h^{-1}$ | 06:00 – 22:00<br>otherwise | *Mechanical ventilation only at night (two schedules)* |
| 11 | 200 mm | 300 mm | $n = 0.5\ h^{-1}$<br>$n = 2.0\ h^{-1}$ | 08:00 – 20:00<br>otherwise | |

## 4 RESULTS AND DISCUSSION

### 4.1 The role of the insulation and the thermal mass

The results of the simulations for all the cases listed in Table 3, in terms of Intensity of Thermal Discomfort (ITD) and Frequency of Thermal Discomfort (FTD), are shown in Fig. 2. As discussed in the following, many elements can be drawn from the analysis of this graph.
First of all, the comparison between cases nr. 1 to nr. 3 suggests that, when no ventilation is allowed ($n = 0\ h^{-1}$), an increase in the insulation thickness implies a considerable worsening of the thermal comfort perceived by the occupants. In fact, the overall ITD in summer grows from 10100 °C·day$^{-1}$ to 13500 °C·day$^{-1}$, when increasing the insulation thickness from 0 mm (case nr. 1) to 300 mm (case nr. 3). This means that the intensity of the thermal discomfort in the sample building, i.e. the average overheating beyond a comfort threshold, increases up to 30% due to the positioning of a thick insulation layer.
The room overheating occurring in case nr. 3 can also be observed in Fig. 3a, where for each day in July the hourly operative temperatures in a representative room during the occupancy period are reported. As one can observe, the operative temperature ranges from 28°C to 32°C, and never falls within the acceptable range for comfort, included between the solid lines. As a consequence, the Frequency of Thermal Discomfort in this case is FTD = 100% (see Fig. 2).
Here, one can understand that the very low thermal transmittance determined by the envelope insulation ($U < 0.21\ W\cdot m^{-2}\cdot K^{-1}$) prevents the heat generated by internal and solar gains from being effectively transferred to the outdoors, especially at night, when the outer temperature is likely to be lower than the indoor temperature. This problem is emphasized by the absence of ventilation. However, even if case nr. 1 presents better results, it is not practically feasible, as the absence of insulation implies a very high thermal transmittance ($U = 3.4\ W\cdot m^{-2}\cdot K^{-1}$), that would strongly affect the energy performance in winter.
In addition, when looking at cases nr. 4 to nr. 6 in Fig. 2, it is possible to remark that an increase in the thickness of the concrete slab from 100 mm to 300 mm, while keeping the same insulation layer (150 mm) and a constant ventilation rate ($n = 2\ h^{-1}$), determines a reduction in the ITD of about 7% (from 11500 °C·day$^{-1}$ to 10700 °C·day$^{-1}$). The same trend emerges through cases nr. 7 to nr. 9, i.e. when the insulation thickness is 300 mm: in this case, the potential reduction in the ITD due to a thicker concrete slab amounts to about 11% (from 15600 °C·day$^{-1}$ in case nr. 7 to 13900 °C·day$^{-1}$ in case nr. 9).
These results testify the importance of thermal mass for improving the response of the building to both internal heat gains and outdoor thermal waves in summer. This is also highlighted in Table 2, where the cases with a higher slab thickness are also those that present lower values of the decrement factor $f$ and higher values of the time shift $\varphi$.

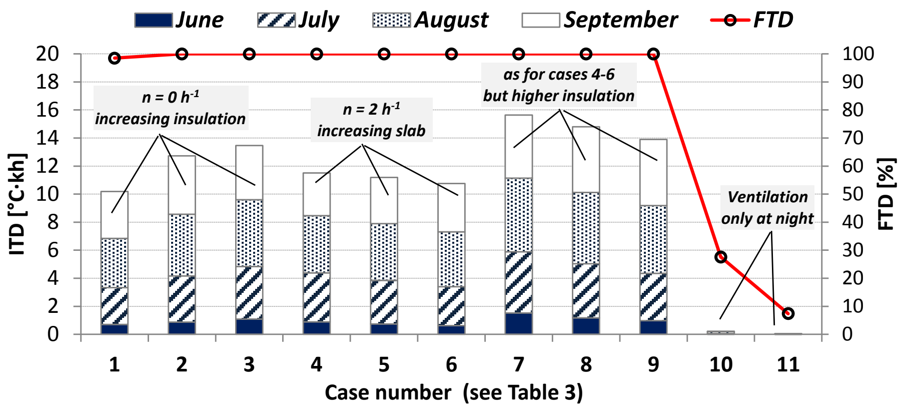


Figure 2: Values of the ITD and the FTD for all the cases considered in the parametric analysis.

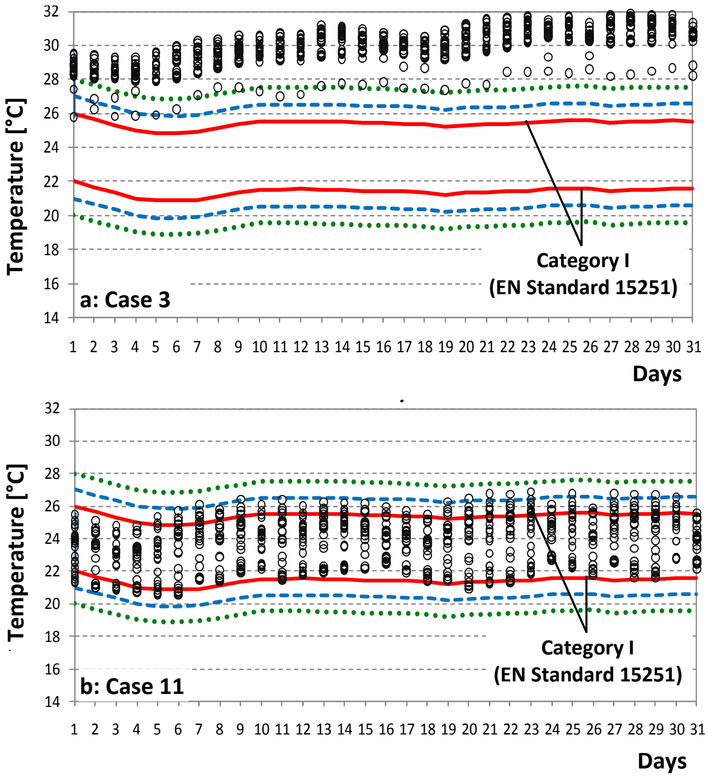


Figure 3: Distribution of the operative temperature in July (a: case 3; b: case 11)

Furthermore, if one compares in Fig. 2 the cases having the same concrete slab but different insulation thickness, it is evident that a higher insulation determines a lower thermal comfort. As an example, ITD = 11200 °C·day-1 in case nr. 5 (200 mm of concrete and 150 mm of insulation) and ITD = 14800 °C·day-1 in case nr. 8 (200 mm of concrete and 300 mm of insulation): thus, the installation of a very thick insulation introduces an increase of 24% in the ITD. This confirms what already remarked form case nr. 1 to case nr. 3, that is to say the negative effect of an excessive envelope insulation on the dissipation of heat gains in summer.

### 4.2 The role of ventilation: definition of appropriate strategies

Now, what is not fully explained by the results shown in Fig. 2 is the role of ventilation. Actually, if one compares case nr. 2 ($n$ = 0 $h^{-1}$) to case nr. 5 ($n$ = 2 $h^{-1}$), that present different ventilation rates but the same thickness of concrete slab (200 mm) and insulation (150 mm), it seems that the higher ventilation rate adopted in case nr. 5 determines better comfort conditions. Indeed, the ITD drops from 12700 °C·day-1 in case nr. 2 to 11200 °C·day-1 in case nr. 5 (-12%). However, a different message emerges if comparing case nr. 3 ($n$ = 0 $h^{-1}$) to case nr. 8 ($n$ = 2 $h^{-1}$), where the thickness of insulation is 300 mm. In this case, it seems that higher ventilation rates should imply worse comfort conditions.

The reason for this behaviour is most likely due to the fact that an intense ventilation during the daytime, i.e. when the outdoor temperature is usually higher than indoor temperature, may have negative effects on the room comfort. This is more likely to occur if the insulation layer is thick, since in this case the operative temperature tends to be high, as already discussed in the previous section.

This remark introduces the need to choose an appropriate ventilation strategy for massive buildings. This issue has been tackled through cases nr. 10 and nr. 11: here, starting from the

configuration of case nr. 8 (200 mm of concrete, 300 mm of insulation), the ventilation of the building was limited to a specific time interval at night. In particular, case nr. 10 implies an air change rate $n = 2\ h^{-1}$ from 22:00 to 06:00, whereas during the daytime mechanical ventilation is switched off, and a low air change rate ($n = 0.5\ h^{-1}$) is considered to describe infiltration through leaks. On the other hand, in case nr. 11 mechanical ventilation is kept for a longer period at night (12 hours, from 20:00 to 08:00).
As shown in Fig. 2, in both cases the seasonal value of the ITD is now close to 0, whereas the Frequency of Thermal Discomfort is very low (FTD = 27.6% for case nr. 10 and FTD = 7.4% for case nr. 11). This proves that these ventilation strategies are very effective for improving summer thermal comfort in the sample building. Further proof of this statement comes from Fig. 3b: here, one can observe that throughout the whole month of July the operative temperature for case nr. 11 lies very frequently within the comfort range defined by Category I of the international standard EN 15251.
In conclusion, the results presented in this section illustrate the need of practising an intense ventilation of the building only at night, when the outdoor temperature is low, hence the potential for discharging the heat released by the thermal mass is high. On the contrary, ventilation during the daytime should be limited to a minimum rate for hygienic purposes, since it is likely to produce a room overheating.

### 4.3 Other remarks on the role of the thermal mass

The results presented in Section 4.1 show the importance of thermal mass for improving the thermal response of the building in summer, especially in terms of comfort for the occupants.
However, it is also interesting to remark that the role of thermal mass is far less significant in winter. Indeed, other simulations were run in order to calculate the energy demand for space heating while varying the thickness of the concrete slab from 100 mm to 300 mm (with 50 mm step). The results show that the specific energy demand for heating decreases very weakly from 35.4 to 34.8 $kWh \cdot m^{-2} \cdot y^{-1}$ (less than 2%) and reveal that, for a well-insulated envelope, the effect of the thermal mass of the walls is almost negligible

Table 4: Thickness of the concrete slab vs. energy demand for space heating ($L_{in}$ = 300 mm)

| Slab thickness | 100 mm | 150 mm | 200 mm | 250 mm | 300 mm |
|---|---|---|---|---|---|
| Energy needs for heating [$kWh\ m^{-2}\ y^{-1}$] | 35.4 | 35.3 | 35.1 | 35.0 | 34.8 |

## 5 CONCLUSIONS

The exploitation of the building thermal mass and of appropriate ventilation strategies have often been treated in an energy saving or economical perspective, while few studies have been made in order to understand their individual and synergic effect on thermal comfort.
In the present work the effect of ventilation strategies, insulation thickness and thermal capacity of the envelope on thermal comfort was investigated by means of dynamic simulations for a real sample building in continental climate.
The results underline the major role played by night ventilation, that is essential to discharge the heat released by the opaque envelope, thus keeping a comfortable indoor temperature. On the contrary, ventilation should be avoided during the daytime, as it might be responsible for room overheating.
Moreover, an excessive thickness of the insulation layer, despite being very effective for reducing energy needs in winter, is a cause of overheating and thermal discomfort in summer.

Hence, a good compromise should be determined for the thickness of the envelope insulation, with the support of dynamic simulations.
As concerns the thermal capacity of the building envelope, in this case study it seems to have a slight effect on thermal comfort if not assisted by an appropriate ventilation strategy; in addition, a heavier structure seems more effective for improving thermal comfort when coupled with a smaller insulation layer. In any case, the role of the thermal capacity is secondary to that of ventilation.
Further investigations are in progress in order determine the combined effect of solar shadings, ventilation and thermal inertia on thermal comfort for historical buildings located in the Mediterranean area. The results will be reported in future papers.

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