The effect of thermal mass on the cooling load in dwellings in a moderate climate

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ABSTRACT

To obtain thermal comfort in a moderate climate, dwellings were traditionally provided with a heating system, but few had cooling systems. The heat in summer was kept out of the building by an appropriate building design. Since larger windows and less compact buildings have become more fashionable, overheating in summer is more problematic. Currently, cooling systems are increasingly installed to improve thermal summer comfort. As a reaction to this increase, producers of building materials with a high thermal capacity have promoted their products for the ability to create a more stable indoor temperature. The use of these materials is therefore assumed to contribute to a more comfortable summer situation.

In this paper the results of a parametric study of dwellings in the context of Belgium are presented, analysing the effect of thermal mass on the cooling load. For the analysis, dynamic energy simulations are executed in EnergyPlus. The influence of a number of parameters such as dwelling type, orientation, glazing, insulation level and ventilation patterns on the cooling load is analysed. This is done both for dwellings with and without thermal capacity to investigate the importance of the latter.

In this paper the results of the parametric study are shown. Thermal capacity proved to improve thermal comfort in summer conditions in a moderate climate like Belgium and in combination with ventilation it can avoid the need for cooling. In winter situation however, some first simulations indicated that thermal capacity leads to a higher energy demand for an intermittent heating schedule. The most important findings are summarized and some aspects remaining for further investigation are highlighted.

1. AIM AND METHODOLOGY

The aim of this paper is to investigate the importance of thermal mass in dwellings to avoid overheating in summer in a moderate climate. A parametric study was executed for two types of dwellings based on dynamic energy simulations. Starting from a reference dwelling, different parameters were changed one by one to analyze the influence in detail. The relative values are thus more important than the absolute values for this comparative parametric study.

Both the number of hours and the number of degree hours above 27 °C (= hours x (temperature – 27) °C) were analyzed as indicators of overheating. Since a detailed discussion on thermal comfort and appropriate indicators is not the topic of this paper, this will not be elaborated in detail.

The indicators were chosen based on two articles by Olesen (Olesen and Parsons, 2002; Olesen, 2007). Category C from table three in the former article (pp. 542) was chosen to ensure no overestimations were made. This means that more than 10% but less than 15% of the people will feel uncomfortable at the chosen set points. From table three in the latter article (pp. 742) the temperature of 27°C is derived for residential buildings in the chosen category C.

2. REFERENCE DWELLINGS

The reference dwellings are a terraced and detached house. The former has a five meter wide façade, is ten meters deep and consists of three floors. The total floor area is 150 m2 (Fig. 1). The ground floor consists of an entrance,

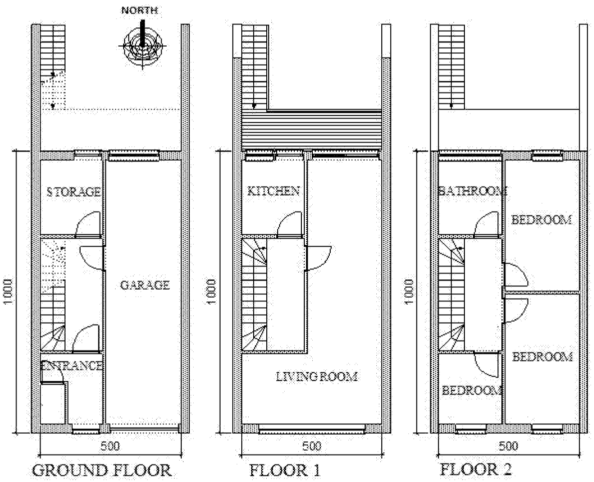

Figure 2. Terraced house: floor plans.

toilet, garage and storage, while the living room and kitchen are situated on the first floor and the bathroom and three bedrooms on the second. The dwelling has an inclined roof with an unused attic.

The neighboring dwellings are assumed to have the same height and inclination of roof. The glazed area in the front façade is rather limited (9 % of the total front facade) while a larger amount of glazed openings is foreseen in the back façade (20 % of the back facade). Important to remark is that the former percentages are percentage of glazing. The percentage of windows is respectively 11 % and 24 %. For the reference dwelling the back façade (garden) is oriented to the north as is indicated on figure 1. However, orientation is one of the parameters in the analysis. There are no shading devices.

The detached house consists of only a ground level and has also a floor surface of 150 m2 (Fig. 2). It has a 17,20 meter wide façade and a depth of 8,7 m and is also foreseen of an inclined roof with unused attic. The dwelling consists of the same rooms as the terraced house, but all are situated at ground level. Also for this dwelling, the back (garden) is situated at the north in the reference case. The back façade consists of 20 % glazing (25 % window), the left façade (bedrooms) of 6 % glazing (8 % window), the front façade of 3 % (4 % window) and the right façade (living room) of 12 % glazing (13 % window). The analysis of this dwelling will not

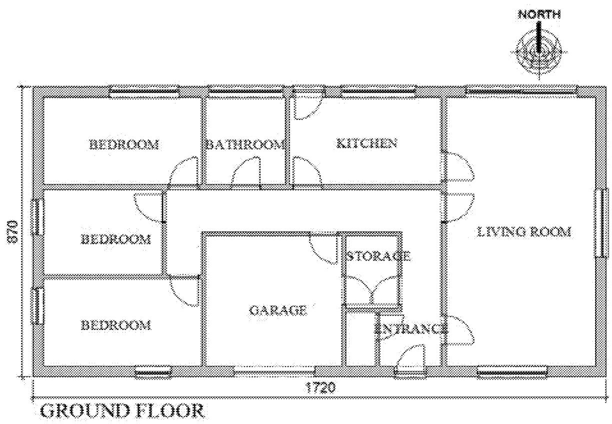

Figure 1. Detached house: floor plan.

be elaborated in detail, but the main results will be summarized and compared with these of the terraced house.

3. SIMULATIONS

EnergyPlus version 1.2.3 was used for the simulations, while the monthly average ground temperature were calculated with an auxiliary program provided by EnergyPlus (www.eere.energy.gov/buildings/energyplus). The test reference year (TRY) of Brussels was used for climatic data input.

For the terraced house, the shared walls are assumed adiabatic, since the neighboring dwellings are considered to be heated as well. This was simulated by assuming the surface temperature at the other side of the wall equal to the surface temperature at the inside of the wall. The thermal capacity of the walls is thus considered in the simulations. The floor plans are simplified for the simulations: the ground floor is subdivided in four zones: toilet, staircase (height = three levels), storage and garage, while both the first and second floor are modeled as one zone; even so the attic. The floor plan of the detached house was simplified in a similar way.

3.1. Element composition

For the building elements, such as walls, roof and floor, a commonly used solution within the Belgian context is chosen. The inner layer of the outer walls and the inner walls are altered in the parametric study. The floor and roof remain unchanged. The shared walls (of the terraced house) are assumed to consist of bricks and remained unchanged since it is prohibited in Belgium to construct shared walls of wood skeleton. For the windows, two alternatives are considered. The first is an aluminum frame with normal double glazing, while the second consists of an aluminum frame with thermally improved glazing.

3.2. Parametric study

All combinations of the parameters listed in table 1 have been simulated, resulting in 120 (4 orientations x 3 material types x 5 insulation levels x 2 glazing types) simulations. However, for the wood skeleton variants, the not insulated combination was not included since this is an unrealistic combination.

Table 1. List of parameters

Case	Orientation	Building material	Insulation	Glazing
reference	0° (north)	brick	not insulated	normal double glazing
case 1a	90° (east)			
case 1b	180° (south)			
case 1c	270° (west)			
case 2a		concrete block		
case 2b		wood skeleton		
case 3a			outer wall: 6 cm roof: 12 cm	
case 3b			outer wall: 6 cm roof: 20 cm	
case 3c			outer wall: 9 cm roof: 20 cm	
case 3d			outer wall: 12 cm roof: 20 cm	
case 4a				improved double glazing

This means 112 simulations instead of 120 were finally executed. For these combinations, we assumed that the dwelling was not heated nor cooled (free running). The effect of ventilation was investigated by simulating the combinations with and without ventilation. Therefore two times 112 simulations were executed. The effect of shading devices has not been investigated in this research, but is of course another important parameter in terms of overheating.

Four inhabitants are assumed whereof both parents are working and both children are going to school. An activity schedule for the whole year was imposed. The internal heat gain of the inhabitants, lighting and electrical appliances equals 14.173 MJ/year for the living room and 5.637 MJ/year for the bedrooms.

The results are shown for the summer season since cooling is the focus of this paper.

3.3. Results

The results for the terraced house are shown in the graphs below. The first graph (Fig. 3) represents the results for the simulations without ventilation.

On the vertical axes the two indicators as mentioned before are plotted. The primary axis represents the number of hours the operative temperature rises above 27 °C, while on the secondary axis the number of degree hours is plotted.

For each orientation, the results are shown for the brick, concrete and wood skeleton variants. The concrete variants have the highest thermal capacity, the wood skeleton the lowest.

For each material, the alternatives are shown from the least to the best insulated case (from left to right). At the utmost left, the reference case is represented. The second dot represents the same dwelling but with thermally improved glazing (case 4a). The great noticeable change (from second to third dot) represents the step where the building skin without thermal insulation is foreseen from a minimal insulation level described in table 1 (case 3a).

From figure 3 we can conclude that overheating is highest for the wood skeleton variants, followed by the brick alternatives. Overheating is lowest for the concrete block variants. For all variants, overheating is highest

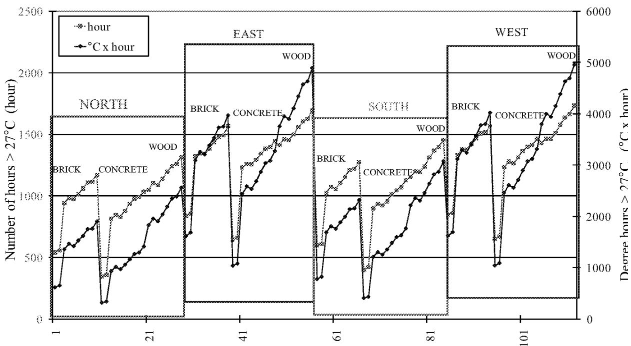

Figure 3. Terraced house: number of hours the operative temperature is above 27 °C (▩, left) and number of degree hours above 27 °C (◆, right) for the living room without ventilation.

for the east and west orientation, meaning that the garden is oriented to the east or west. Moreover the best insulated variants are leading to the highest overheating.

Although the results are not shown for the bedroom, we summarize the findings. The number of times the operative temperature rises above 27 °C on the second floor was higher than on the first floor for all variants except for the not insulated ones. However the number of degree hours above 27 °C was lower for the second floor than for the first floor for all cases except for the well insulated wood skeleton walls. The same exception was noticed for the well insulated brick variants in the north orientation.

It appears that the hours of overheating occurred during daytime. Locating the bedrooms at a higher and the living area at a lower level in the dwelling thus seems to be a good choice for most of the variants considered.

The same analysis has been done for the dwelling with ventilation. The ventilation rates are assumed to be in accordance with the minimum ventilation requirements in Belgium for dwellings (NBN D50-001, table 1, pp. 4). This means that the air in each room is completely refreshed every hour. The results are presented in figure 4, structured analogous to figure 3.

From the graph we can conclude that the highest overheating occurs for the wood skeleton variants, followed by the brick. The lowest overheating is noticed for the concrete variants. Again the highest overheating occurs

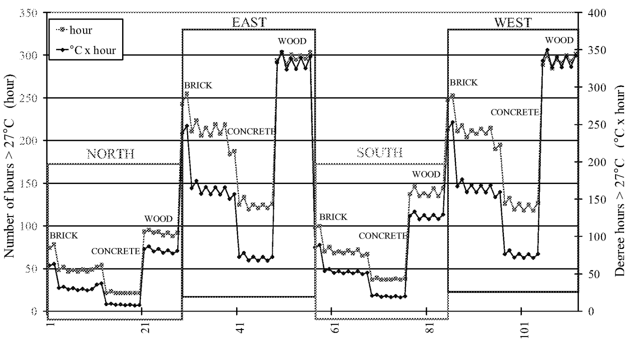

Figure 4. Terraced house: number of hours the operative temperature is above 27 °C (■, left) and number of degree hours above 27 °C (◆, right) for the living room with ventilation.

for the east and west orientation. In contradiction to the dwelling without ventilation however, the insulation level has an opposite (but minor) influence on overheating.

Comparison of figures 3 and 4 shows that ventilation is important to reduce overheating. The number of hours of overheating has reduced from a maximum of 2000 to a maximum of 300 and the number of degree hours has reduced from a maximum of 5000 to 350. The highest reduction is achieved for the concrete variants, followed by the brick and lowest for the wood skeleton variants.

Although ventilation reduces the overheating phenomenon, figure 4 shows that overheating is not completely solved when minimum ventilation is foreseen. From the figure we can see that for the worst orientations (east and west) there are still around 350 degree hours above 27 °C per year for the wood skeleton variants, around 175 degree hours for the brick variants and around 75 for the concrete variants.

For the north orientation (best), we still notice approximately 80 degree hours above 27 °C per year for the wood skeleton variants. However for the brick variants this is only around 40 degree hours and for the concrete only 10. Increasing the ventilation in summer could therefore solve the overheating problem completely for the variants with thermal capacity.

Extra simulations showed that increasing the ventilation rate to the maximum allowed values according to the current standard for ventilation systems for housing in Belgium (NBN D50-001, table 1, pp. 4) could reduce overheating further. However, overheating could not completely be avoided, even not for the most capacitive variants.

In summer, higher ventilation rates are presumable. An adaptation of the Belgian requirements, currently limiting the ventilation to this maximum, could be advantageous to avoid overheating. However this would lead to the risk of ventilating the rooms too extensive in winter conditions.

The overheating in the bedrooms was also investigated for the simulations with ventilation, but proved to hardly occur. Remarkable was however that overheating in the bedrooms was highest for the not insulated brick and concrete variants, followed by the insulated wood skeleton. For the insulated brick and concrete variants, no overheating occurs in the bedrooms.

For the detached house, the same trends were noticed, but overheating was less. Simulating the detached house with the maximum allowed ventilation rates, showed that overheating could completely be avoided for most brick and all concrete variants, while this was not the case for the wood skeleton variants.

4. WINTER CONDITIONS

Finally an analysis of the winter situation was added to the analysis and a year-round evaluation was made. However a more elaborated analysis is needed to investigate more parameters and take more profound conclusions. Nevertheless, it seems important to formulate already some remarks based on these first simulations.

4.1. General analysis

The results presented in figure 5 show the yearly heating demand for the 112 simulations with the minimum required ventilation. The horizontal axis of the graph is again structured in an identical way as the former ones.

The figure shows that the orientation has hardly any influence on the energy demand for heating, but the south orientation leads to a slightly lower energy demand.

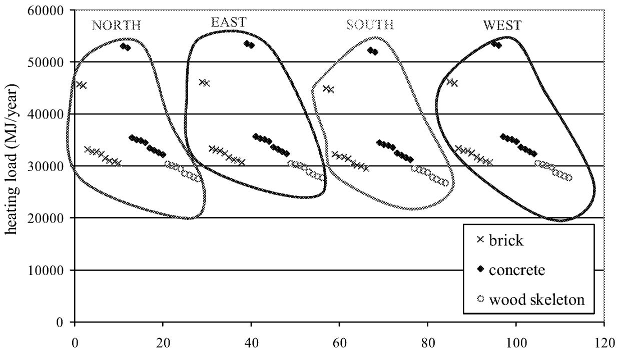

Figure 6. Terraced house: yearly heating demand for the 112 variants with minimal ventilation.

The figure also clearly indicates that the first centimeters of insulation are very important to reduce the heating demand. A further increase of the insulation layer leads to a further decrease of energy demand, but to a lower extent.

The figure moreover shows that the concrete variants are leading to the highest energy demand, followed by the brick variants and ending with the wood skeleton. We can therefore conclude that for the assumptions made, the energy demand for heating is larger for the dwellings with a higher thermal mass.

4.2. Analysis of a specific day

To understand these results, a particular winter day is discussed more in detail. Figure 6 represents both the average indoor air temperature in all heated rooms (primary vertical axis) and the heating energy (secondary vertical axis) for the first of January. Since 75 warm up days were run for the simulations, the analysis of the first day of the year is justified.

The figure clearly indicates that when the heating is switched of, the indoor air temperature decreases more slowly for the variants with thermal capacity. Therefore we would presume that thermal mass is beneficial for the heating demand. However, the graph also shows that more energy is needed to maintain the required indoor air temperature of 21°C during the heating hours.

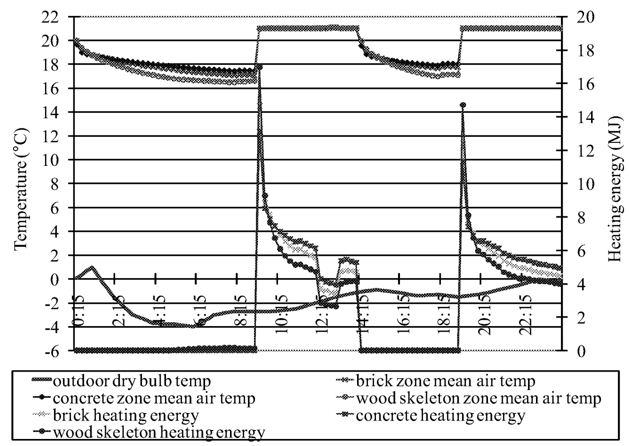

Figure 5. Terraced house: mean air temperature (left, × = brick, ◆ = concrete, ○ = wood skeleton) and heating energy (right) on the first of January for the best insulated variant of the three materials with ventilation.

One of the explanations could be that for the wood skeleton variants the inner walls are insulated for acoustical reasons. This means that the inner walls of the garage are insulated as well, while this is not the case for the brick and concrete variants.

Therefore some extra simulations were executed to investigate the latter. Insulating the walls to the unheated spaces, like the garage, resulted in a smaller difference between the variants with and without capacity, however the wood skeleton still led to the lowest heating demand.

Finally the heating schedule was changed to permanent heating, leading to no difference of energy demand for the variants with and without thermal capacity.

The same trends were again seen for the detached house.

4.3. Yearly energy demand

Finally both a heating and cooling system was installed to investigate if thermal capacity is beneficial on a year-round base. For the alternatives considered and the assumptions made, the variants with a higher thermal capacity led to a higher total energy (heating and cooling) demand. The higher heating demand in winter is thus not compensated by the lower cooling demand in summer.

5. CONCLUSIONS

From the simulations of the terraced and detached house, we can conclude that thermal capacity is important in summer in a moderate climate like Belgium. It improves thermal comfort in summer conditions and in combination with ventilation it can avoid the need for cooling. In winter situation however, some first simulations indicated that thermal capacity leads to a higher energy demand for an intermittent heating schedule. When permanent heating is required, thermal capacity has no influence on the energy demand for heating assuming an identical insulation value, ventilation rate (and air tightness) and behavior of the inhabitants.

Important to remark however is that the energy simulations in this research were primarily executed to analyze the importance of thermal capacity for cooling in summer. The analysis of the winter conditions was an additional first exploration to analyze the influence of thermal capacity on the heating demand in winter. The latter requires more simulations for a more profound understanding of the different influencing parameters.

6. FURTHER RESEARCH

It seems a very interesting challenge to investigate more in detail for which conditions thermal capacity is beneficial for the heating demand in winter and for which not. The dwelling characteristics, such as layout, zoning, compactness, glazing area together with their orientation, behavior of the inhabitants, internal gains, ventilation and insulation value should therefore be analyzed in detail.

Besides dwellings, the same analysis should be done for other functional buildings, such as offices, schools and hospitals to investigate for the different heating schedules when thermal mass is beneficial.

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