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Impact of opaque building envelope configuration on the heating and cooling energy need of a single family house in cold climates

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Abstract

The building envelope plays a crucial role in reducing operational energy demand. The two main properties of the building envelope to look at in this perspective are thermal transmittance (*U*, W/m^2K^1) and thermal inertia, which is often expressed by a metric called periodic thermal transmittance (Y_{ie}, W/m^2K^1). These two properties are also traditionally connected to two different energy demands: while thermal transmittance is crucial to reduce heating energy demand, thermal inertia has an impact on energy demand for cooling. However, a question may rise about the impact of each property on the other demand – i.e. the impact of thermal insulation on the cooling energy demand and the impact of thermal inertia on the heating demand.
A parametric analysis on the influence of the thermal inertia on the energy performance of a single family house in a Nordic climate has been carried out to answer to this question. "Ideal envelopes" have been modelled and simulated, meaning that used thermophysical properties do not represent any specific configuration, but the entire spectrum of technological configurations.
The results show that the influence of the thermal inertia on the heating energy need is very limited. Solutions characterized by very high thermal inertia do not allow heating energy demand to be sensibly decreased. Periodic thermal transmittance has instead an impact on the heating load. The impact of the thermal inertia is also assessed in the warmer season, and the results show that this parameter does not significantly contribute to a better behavior (especially when the upper limit of the indoor air temperature is controlled). Limitations to value of thermal transmittance are also pointed out to avoid non-energy effective conditions when the total (heating plus cooling) annual performance is considered.

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1. Introduction and aim of the research activity

The role of the building envelope in reducing operational energy demand is well-established and good-practice must always rely on well-designed building envelopes. The two main functions that need to be addressed in an energy saving perspective are: *(a)* preventing heat loss from the indoor environment; and *(b)* managing solar gain.

As far as the first function is concerned, the main property of the building envelope to look at is the thermal insulation capability, usually expressed by the *thermal transmittance* (*U*, [W/m^{2}K]) [1]. As far as managing solar gain is concerned, the main property of the building envelope to look at is the thermal inertia, and a fairly accepted metric for this property is called *periodic thermal transmittance* (Y_{ie}, [W/m^{2}K]) [2].

Y_{ie} is defined as the ratio of the complex amplitude of the density of heat flow rate through the surface of the building envelope component adjacent to the indoor environment to the complex amplitude of the outdoor temperature (periodic boundary conditions), assuming constant indoor air temperature. This parameter relates the heat gain though the envelope to the external (periodic) thermal stress, thus taking into account the inertial effects of the component. A building envelope component characterized by low thermal inertia presents high values of periodic thermal transmittance, while a highly inertial component has a low value of periodic thermal transmittance.

The two above mentioned functions are also traditionally connected to two different energy demands: thermal insulation is crucial to reduce heating energy demand, thermal inertia has an impact on energy demand for cooling.

In the Norwegian building context, lightweight wood construction is the most common technology used in small buildings. These constructions are characterized by relatively highly insulation properties, but fairly low thermal inertia – in the entire building structure. Nowadays, the question whether building technologies characterized by higher thermal inertia may or not improve the energy performance of the building during the heating season – and, to some extent, during the warmest part of the year – is a hot-topic in the industry and research sector.

The influence of thermal inertia on the energy performance of buildings is studied since years in different climatic contexts than the Nordic one, and its potential in avoiding overheating and reducing cooling load and cooling demand is the most investigated topic. However, energy saving potentials reported in literature, based on numerical simulations, are very variable, (from very low percentage to almost 80%). A dedicated analysis [3] in Southern European climate conditions estimated the maximum possible saving, due to a high thermal inertia to be around 10% and 20%, for the heating and cooling demand respectively. More recent studies [4,5] have considered the impact of both the periodic thermal transmittance and of the internal areal heat capacity, κ_I [kJ/m^{2}K], showing that the latter metric has a significant role too. It is also worth mentioning that the role of the thermal insulation on the summer energy demand was also investigated [6], highlighting the limited influence of the opaque envelope on both energy demand for cooling and the maximum cooling load, due to the fact that internal (and solar) load are dominant.

Given the lack of dedicated research activities that focus on the Nordic climate conditions, a parametric analysis on the influence of the thermal inertia on the energy performance of a single family house in Oslo climate (59°57′N; 10°45′E) has been carried out and results are herewith presented.

2. Research methodology

2.1. Building envelope configurations and parameters

Given the very general approach to the problem, it was chosen to analyse the opaque building envelope without assuming *a priori* a specific building technology or building materials. Therefore, it was chosen to model and simulate an *ideal* opaque envelope, i.e. a building envelope which does not represent any actual configuration, but is made of just one homogeneous layer of an ideal material, characterized by certain values of *U* and Y_{ie}.

The two parameters are considered independent variables. Though this assumption is correct in theory, it can sometimes be tricky to realize in practice all the possible combinations, due to limitations in building technology and materials. It is worth mentioning that the only theoretical relationship between the two variables is: $Y_{ie} \leq U$. Moreover, is should also be mentioned that Y_{ie} equals *U* only when materials have no heat capacity (and it is thus of little physical meaning). Ten values of *U* and of Y_{ie} are adopted (1.00; 0.80; 0.60; 0.40; 0.25; 0.15; 0.10; 0.05; 0.03; 0.01 W/m^{2}K) and, given the above mentioned limitation, this approach leads to a total of 55 simulations of a building with 55 sets of the two variables.

Aside from the ideal envelope approach for the opaque components, the remaining part of the building envelope is kept constant and modelled assuming specific building technologies and materials. In particular, the thermal transmittance of the triple glazed units with low-e coating (center of the glass panes) was calculated to be 0.66 W/m^{2}K, visible transmittance 0.62, SHGC 0.41, and frame conductance set to 0.65 W/mK. South-exposed windows are equipped with external venetian blinds activated automatically when indoor air temperature exceeds 26 °C. The floor of the ground floor of the building (ground contact) is also kept constant and designed to have a thermal transmittance of 0.13 W/m^{2}K and a periodic thermal transmittance of 0.01 W/m^{2}K. A normalized thermal bridge value of 0.03 W/m^{2}K, in accordance with Norwegian passive house standard NS 3700 [7], is assumed.

2.2. Building model and operation

The case study building is a two storey single-family house, designed to be generic enough to represent an "average" single family house in Norway. The building footprint is 8 m × 10 m, with a heated floor area for each floor 80 m^2, giving a total area of 160 m^2. The total area for windows and door area is 36 m^2 (windows/door to floor area ratio little less than 25%). Details about the plans layout and elevations cannot be herewith given for the sake of brevity, but information can be found in [8]. The total area of interior partitions is 150 m^2.

The lighting system is assumed to be a very energy efficient one combining LED spotlights and LED lighting fixtures, controlled by presence control. The average power demand and heat load from lighting in the normalized 16 hours of operation [9] is 1.3 W/m^2 (which corresponds to an annual energy demand for lighting of 7.6 kWh/m^2). Other internal gains due to occupancy are set equal to 1.45 W/m^2 (daily average) and appliance load for the normalized 16 hours operation is 2.5 W/m². The mean (over 24 hours) ventilation air flow rate is set 1.2 m^3/hm^2 and a heat recovery system with efficiency of 85% is adopted. The two floors are modeled as independent thermal zones with no mass exchange between the two zones. Air flow rate due to infiltration is set 0.08 m^3/hm^2, correspondent to one tenth of the value (N50 < 0.3 ACH @ 50 Pa) required by the Norwegian standard for passive house [7]. The relationship between the standardized N50 value and infiltration rate is based on a simple linear correlation [10] and a more conservative option is chosen (one tenths in place of one twentieth).

Two scenarios have been considered as far as the indoor air temperature control is concerned. In one scenario (building with heating and cooling systems), a lower and an upper limit to the indoor air temperature are set. Set-point for heating is 21 °C (night set-back 19 °C) during the winter time and 18 °C (night set-back 16 °C) during the summer time; cooling set-point is 26 °C throughout the whole year. In the second scenario, there is not an upper limit to the indoor air temperature, which is let free to reach high values (building with only heating system). In this case, the total amount of hours during the year when the indoor air temperature exceeds 26 °C is calculated. In both cases, night ventilation is applied to cool down the building (when the indoor air temperature is higher than 19 °C and the outdoor air temperature is in the range 15 to 26 °C); an ACH = 2 1/h is hypothesized for these conditions. Moreover, passive cooling is also achieved through an increased outdoor air flow rate (up to ACH = 5 1/h) when there is a cooling load and the outdoor air temperature is below the zone exhaust air temperature.

The building is supposed to be located in Oslo, whose climatic conditions are representative for a large part of the Norwegian building stock, on a flat and open terrain without surrounding obstacles.

2.3. Simulations and data analysis

The software tool *EnergyPlus* (v. 7.2) [11] was used to carry out the dynamic simulations. Conduction Transfer Function (CTF) method was adopted for solving conduction in components (twenty time-steps per hour).

Through a post-processing of data, the annual energy need for heating (E_H [kWh/m^2]), the maximum heat flow rate (Φ_H [kW]) on hourly basis, the annual energy need for cooling (E_C [kWh/m^2]), the maximum cooling flow rate (Φ_C [kW]) on hourly basis, and the number of hours when the indoor air temperature exceeded 26 °C are finally calculated. Fifty-five simulations were carried out for each scenario (with and without cooling system) by varying the set of $U;Y_{ie}$, while all the other parameters were kept constant. Moreover, assuming that efficiency of system(s) in heating and cooling mode is similar (e.g. for a small size, 5 kW geothermal heat pump with fix speed compressor: COP_{B0W35} = 4.20; EER_{B30W7} = 4.50), that distribution, emission and regulation losses are similar too, the total energy need for heating and cooling (E_{H+C}) is also calculated as the arithmetic sum of E_H and E_C.

3. Results and discussion

Outcomes of the simulations (Fig. 1a) reveal that periodic thermal transmittance (and therefore the thermal inertia) has an almost negligible impact on the annual energy need for heating, especially compared to that of the thermal transmittance. On the contrary, the maximum annual heat flow rate (Fig. 1b) can be, to some extent, influenced (Φ_H can be reduced by max. 20%) by the adoption of envelopes with higher thermal inertia – when U is in the range 1.00 to 0.25 W/m^{2}K, while for more insulated building the impact of Y_{ie} on Φ_H is smaller. This show that opaque envelope's thermal inertia can be, to some degree, used to reduce heating load, but over the entire year its effect is not significant and U is the dominant parameter. When the value of U moves from 1.00 to 0.25 W/m^{2}K, the reduction of the annual heating need is almost constant (approx. −10 kWh/m^2 each 0.1 W/m^{2}K); when the opaque envelope becomes more and more insulated (U < 0.25 W/m^{2}K) the possibility to further lower Q_H decreases and it is not anymore proportional to the reduction of the thermal transmittance. It is herewith worth noting that U-values required by law/norm in the Nordic countries are in the range 0.20-0.15 W/m^{2}K.

When a building with cooling equipment is considered (Fig. 2a), it is shown that the annual cooling need increases when the thermal transmittance value decreases. This time, contrary to the heating energy need, the rise is not proportional to the increase of U, but exponential. Thermal inertia has no influence on the cooling energy need – the parametric U curves are almost constant along the entire Y_{ie} domain, with the exception of the first step in Y_{ie}, (i.e. from an envelope with no thermal inertia with one characterized by little thermal inertia). There seems to be a certain impact of the periodic thermal transmittance on the maximum cooling load, especially in case of poorly insulated envelopes (chart is not shown for the sake of brevity). However, the range of Φ_C values is rather small and, in practise, it seems not be a meaningful strategy to act on the periodic thermal transmittance to reduce cooling load: in fact, Φ_C appears to be more depend on the thermal transmittance than on Y_{ie}.

The results can be explained considering that the largest part of the cooling load and cooling demand is not due to solar/heat gain through the opaque envelope – where thermal inertia plays indeed a role. Internal heat gain and (to a lower extent, due to the adoption of shading systems), solar gain through the transparent envelope are responsible for the largest share of cooling energy use. This findings are in line with those of a previous study in a different climate [6]. In this context, other variables such as κ_I (internal areal heat capacity) can be investigated to improve the potentials of reducing energy need through opaque envelope design.

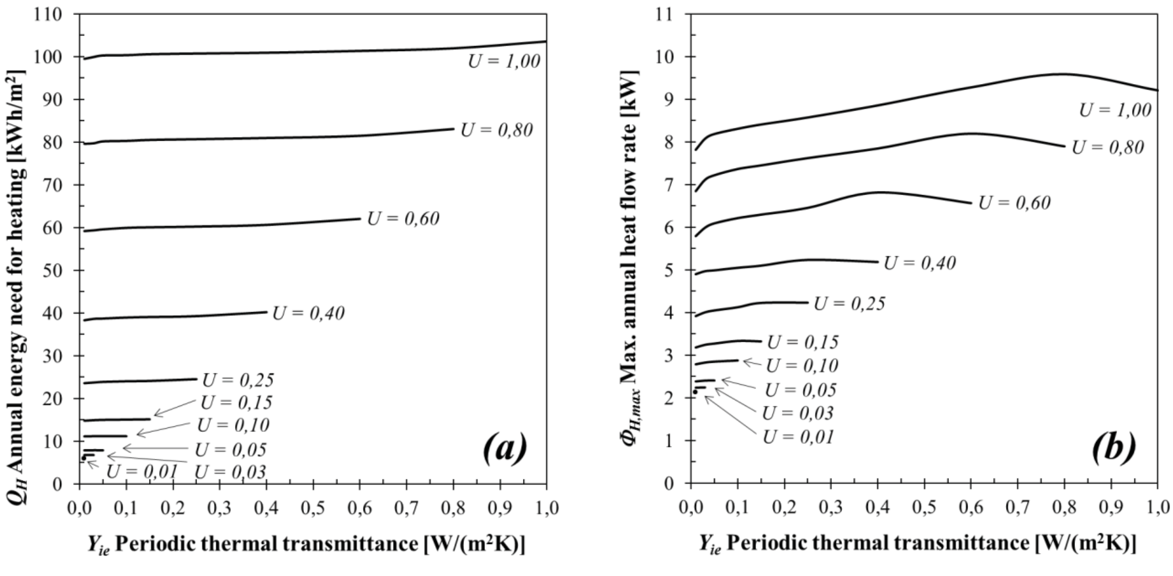

Fig. 1. (a) annual energy need for heating as a function of U and Y_{ie}; (b) maximum annual heat flow rate for heating as a function of U and Y_{ie};

Assuming that the efficiency in energy conversion and that energy loss due to distribution, emission and regulation are similar for both heating and cooling equipment, it is possible to analyse the behaviour of the building during the entire year with the use of just one parameter, the sum of heating and cooling need.

In Fig 3 the whole year performance of the building as a function of U and Y_{ie} is resumed. In the left-hand chart the Pareto front of the simulated cast study is shown, pointing out how a reduction in heating demand due to a lower *U-value* is always accompanied by an increase in cooling energy need. The strategy to insulate more and more the opaque envelope is therefore profitable only until certain values of thermal transmittance values – area highlighted in Fig. 3a, points *F–G*, $U = 0.15 \div 0.10$ Wm^2K. In this range, the annual total (heating plus cooling) energy need is minimized (Fig.3b), while more insulated envelopes (down to $U = 0.01$ W/m^2K) are not energy-effective, over the entire year, due to the increase in the cooling need. It is important to point out again that Y_{ie} has a very little influence (max potential energy reduction of 2%) and *U-value* is the main design parameter to look at.

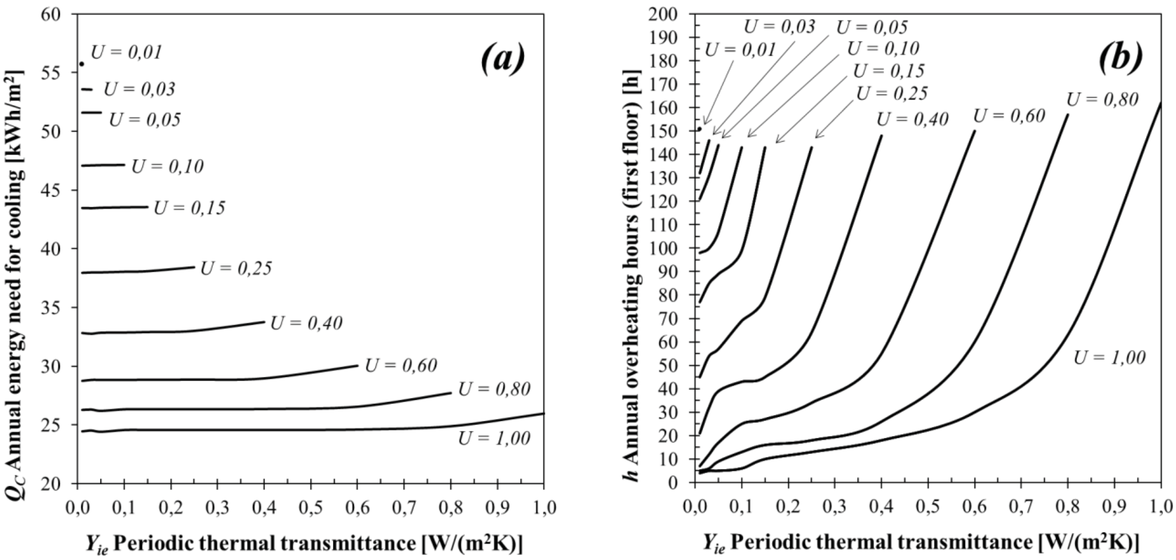

Fig. 2. (a) annual energy need for heating as a function of U and Y_{ie}; (b) annual overheating hours as a function of U and Y_{ie} (first floor only);

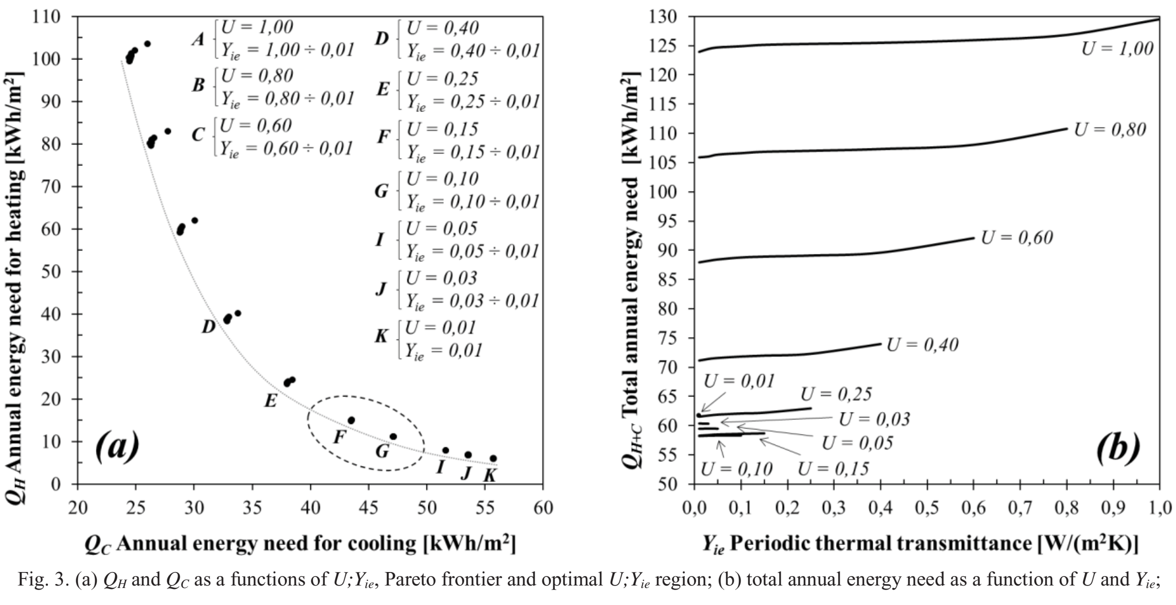

Fig. 3. (a) Q_H and Q_C as a functions of $U;Y_{ie}$, Pareto frontier and optimal $U;Y_{ie}$ region; (b) total annual energy need as a function of U and Y_{ie};

When a building without cooling installation is simulated, the number of hours of overheating (indoor air temperature higher than 26 °C) is used as a parameter to assess the impact U and Y_{ie} on the indoor environment. In Fig. 2b the hours of overheating for the first floor only are plotted vs. the periodic heat transmittance (the ground floor shows a very similar chart). It is possible to see that the more the thermal inertia, the shorter the overheating period. However, it can also be noticed that the lower the thermal transmittance, *(a)* the higher the number of hours of overheating for a corresponding Y_{ie}; and *(b)* the higher the minimum numbers of hours in overheating conditions. In this perspective, it is also important to point out the relationship between thermal inertia and reduction of overheating is not linear: the higher the thermal inertia of the building envelope, the smaller is the decrease of the overheating period compared to the immediately previous Y_{ie} value. Moreover, it can also be observed that the biggest reduction is seen in the step from $Y_{ie} = U$ (i.e. no heat capacity, which is of little significance) to the configuration with a very small value of heat capacity.

4. Conclusions

Data derived from simulations on different opaque building envelope configurations (various combinations of U and Y_{ie}) shows that, in a cold climate like in Oslo, periodic thermal transmittance (a parameter related to the heat capacity and thermal inertia) cannot be used as an efficient mean to reduce the annual heating energy need, regardless of the nature of the building envelope. By modifying the value of Y_{ie} it is possible to decrease the maximum heating load: the biggest reductions are seen for low insulated building envelopes, while for state-of-the-art solution (e.g. $U = 0.15$ W/m^{2}K) the impact of thermal inertia on the heating load is quite small.

The investigation points out that the thermal transmittance is the dominant parameter, with deep implication on both heating and cooling energy need. In particular, it is proved that for a building with cooling equipment, it can be not energy-efficient to increase thermal insulation beyond certain limits: for $U < 0.10 \div 0.15$ W/m^{2}K the total (heating and cooling) energy need over the entire year can be higher than for less insulated envelopes.

When a building not equipped with cooling systems is investigated, overheating is used as a metric to assess the impact of the opaque building envelope configurations. For this case, the impact of the periodic thermal transmittance is limited too, with non-linear decrease of overheating time when more inertial envelopes are adopted.

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