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Impact of the optimization criteria on the determination of the insulation thickness

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ABSTRACT

From the sustainable perspective, the optimum thickness calculations of the buildings envelope insulation materials published in scientific journals suffer a number of notable shortcomings. The most relevant are the short amortization time periods and the prevalence of economic criterion. The work presented shows that an increase from 20 to 50 years in the amortization time period involves, in some cases, to double the value of the optimum thickness. Moreover, the thicknesses calculated applying energetic or environmental criteria for the optimization give, in some cases, results 10 times higher than the ones obtained using the economic argument. The type of insulation materials (especially their different characteristics at the manufacturing stage) and the calculation conditions (e.g. Degree-Days zone) also affect optimum thicknesses determination.

1. Introduction

Among all the solutions proposed to the energy problems in buildings, experts agree that building insulation is the least-cost option for reducing energy consumption and CO_2 emissions [1–4].

As a consequence, the determination of the optimum thickness of the building insulation materials has been a subject of interest for many years amongst the scientific community [5]. The optimum insulation thickness depends on a large number of parameters. The scientific studies are primarily focused on analyzing the effect of the climatic parameters [6–11], the orientation [12,13], the thermal mass [14], the fuels [8,10,15,16], and other parameters [9,17,18].

The calculations of the energetic losses of the buildings are based principally on single analytical models, but also, in some cases, on dynamic methods [13,15].

The optimum thickness is straightforward determined through a life-cycle assessment (LCA), basically balancing the initial investment (insulation materials purchase and installation costs) with the savings that can be made (lower running costs due to lower transmission losses).

A first major drawback of these studies is the amortization time period used for the calculations. The insulation does not wear out, does not require maintenance and does not require replacing. But the studies take values lower or equal to 30 years, with an elevated number of them using a lifetime of 10 years [8–10,13,16,17,19]. This is not consistent with the guaranteed material lifetime neither with the lifetime of the buildings, defined as 50 years by most national building laws [20].

The second major drawback of these studies is that the optimization criterion applied to determine insulation thickness is, in most cases, the economic one. Even in the papers where energy savings and/or the reduction of CO_2 emissions [21–25] are included, the optimum thickness is calculated considering only economic arguments. Nevertheless, the planet is facing huge environmental and energetic problems and the energy needs of the buildings are one of the responsible of this situation. Indeed, an analysis of the final end use of energy in the EU-27 in 2010 shows three dominant categories: transport (31.7%), households (26.7%) and industry (25.3%) [26]. A Life-Cycle Assessment (LCA) of the materials used in the building, and specifically the insulation ones [27], allow calculating the optimum insulation thickness from the environmental and energetic point of views. Furthermore, calculating the optimum insulation thickness with respect to the emissions of CO_2 is consistent with the EU directives on the energy performance of buildings [28], which calculate the energy qualifications as a function of this parameter.

Within this framework, Ostermeyer et al. [29] adapted without major changes the simplified method presented by Petersdorff et al. [30], originally designed to calculate the optimum insulation thickness from the economic point of view, in order to consider environmental parameters. The authors showed that the insulation

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Nomenclature

A	area (m^2)
C_f	economic cost of the fuel (€/J)
CO_2	cost in emissions of CO_2 (kg of CO_2)
Cp	heat capacity (J/kg K)
E	cost in energy (J)
f_u	use factor
HDD	annual Heating Degree Days (°C day)
i	intermittence factor
K_f	environmental cost of the fuel (kg CO_2/J)
N	lifetime (years)
q	annual heat losses (J)
R	thermal resistance (m^2 K/W)
ren	air change rate (ren/h)
T	temperature
U	thermal transmittance (W/m^2 K)
V	volume of the building (m^3)
V_{ins}	volume of the insulation material (m^3)
VR	ventilation rate (m^3/s)
x	insulation thickness (m)

Greeks

ρ	density (kg/m^3)
λ	heat conductivity of the insulation material (W/mK)
η	efficiency

Symbols

€	economic cost (€)

Subscrits

a	annual
b	base, comfort
air	air
cow	complete opaque walls
ins	insulation material
LCA	Life Cycle Assessment; Fabrication and installation phase of the materials
max	maximum
min	minimum
ow	opaque walls, without the insulation layer
u	unity of insulation material (m^3)
USE	use phase of the building
$vent$	ventilation
w	windows
y_0	inversion in the insulation material and installation at year 0

thicknesses obtained from the environmental criterion of optimization, taking into account the life cycle of the materials, are much higher than the ones obtained from the economic criterion optimization method, that only consider the use phase of the building. Their study is limited to mineral wool insulation material. So the impacts, on the optimum thickness, of the parameters related to the fabrication of the insulation materials, such as the energy embedded and the emissions of CO_2 related to this process, are not included.

The present authors believe that the issues mentioned above deserve more attention. Therefore, this work is written with the following objectives:

- To show the relevance of the building and materials lifetime when the optimum insulation thickness is determined.
- To show that the economic optimum thickness values disagree with optimum thicknesses based on energetic or environmental criteria.
- To check the impact of some relevant parameters, including the ones related to the fabrication process of the insulation materials, in the determination of the optimum insulation thicknesses.

2. Methodology

When considering the economic optimization of the insulation thickness, the only properties of the materials needed are the thermal ones (thermal conductivity and, for some methodology of calculation, heat capacity), which influence in the use phase of the building and their running cost. When assessing the whole life-cycle of the building for the calculation of the optimum insulation thickness from the energetic or environmental point of view, it is necessary to take into account the energy embedded in the insulation materials and the emissions of CO_2 related to the fabrication process. In this paper, with the aim of making easier the understanding of the results, the environmental impact is only evaluated through the CO_2 emissions, although some building materials database give more parameters associated to this criterion.

The main goal of this study is not to calculate highly accurate optimum insulation thicknesses but to demonstrate the limitations of the usual way of doing it in relation to, on the one hand, the insulation materials and buildings lifetime and, on the other hand, the optimization criterion selected. In order to focus the work on this objective, the simplified analytical procedure described below was applied and the studied conditions were voluntarily limited. So the results may not be evaluated by themselves, but in comparison with values obtained by the other insulating materials.

The hypotheses used for the model are the following:

- House dimensions $9 \times 6 \times 2.5\ m^3$
- Floor and ceiling adiabatic (dwelling located vertically between two equal housing characteristics and occupation).
- Optimum insulation thickness determined by the building heating demand.
- Ventilation losses included
- Solar gains and internal heat sources not included
- Efficiency of 90% for both biomass and gas space heating systems
- The global warming potential of the greenhouse gases emissions during the fabrication process of the insulation materials is expressed trough the carbon dioxide emissions, as the data bases do not offer the total greenhouse gases mixture for all the considered insulation materials.

In order to evaluate the optimum thicknesses of insulation materials, the methodology determines the balance depending on optimization criterion, for different working conditions (Fig. 1).

On the one hand, the annual costs associated with the use phase of the building are calculated. For this, it is necessary to assess the annual costs in terms of energy during this phase, which is the annual energy consumption (E_{USE}):0

$$E_{USE} = \frac{q}{\eta} \tag{1}$$

where η is the efficiency of the heating system and q is the annual heat losses, which take into account the losses through the complete opaque walls (q_{cow}) and the windows (q_w), and the ones due to ventilation (q_{vent}).

$$q = q_{cow} + q_w + q_{vent} \tag{2}$$

with

$$q_{cow} = U_{cow} \cdot A_{cow} \cdot HDD \cdot f_u \cdot i \cdot 86,400 \tag{3}$$