Energy and Buildings 68 (2014) 203–212

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Cost-optimal insulation thickness in dry and mesothermal climates: Existing models and their improvement

Paris A. Fokaides [a,*], Agis M. Papadopoulos [b]

[a] School of Engineering and Applied Sciences, Frederick University, 7 Y. Frederickou Str., 1036 Nicosia, Cyprus
[b] Laboratory of Heat Transfer and Environmental Engineering, Department of Mechanical Engineering, Aristotle University Thessaloniki, Thessaloniki 54124, Greece

ARTICLE INFO

Article history:
Received 4 November 2012
Received in revised form 30 August 2013
Accepted 2 September 2013

Keywords:
Cost-optimal insulation thickness
Degree days
Insulation materials
Energy performance of buildings

ABSTRACT

The establishment of a methodology for the calculation of the cost-optimal insulation thickness of building elements has been a subject of interest for some years. Many studies have been conducted on the ideal insulation thickness and been based on specific assumptions and approaches. The introduction of the Energy Performance of Buildings Directive recast (2010/31/EC) in May 2010, leads to the compulsory implementation of a specific methodology for this purpose by all European Union member states (Article 5, EPBD recast). Therefore, a study on this subject was conducted, to evaluate the results of previous studies and the strengths and weaknesses of the previous methodologies and to determine how the methodologies should be further developed to provide more reliable results. Additionally, a derived model was validated by a parametric study that examined all possible aspects that could potentially affect the end results. The minimum requirements of the insulation thickness for three selected European cities were also compared to the results of the proposed model applied to these cities. The results show that the proposed model provides a better compromise between simplicity and accuracy, leading at the same time to significantly lower *U*-values and therefore to improved energy efficiency of the buildings.

1. Introduction

It is an established fact, that buildings are responsible for 36% of CO_2 emissions and 40% of energy consumption in the EU as well as that improving the energy efficiency of the building sector is a key area in order to achieve the EU's climate and energy objectives. The EU has therefore set a goal to reduce primary energy use by 20% by 2020, which is one of the five headline targets of the European 2020 Strategy [1]. The improvement of the energy performance of buildings is a cost-effective way of mitigating climate change consequences and improving the security of energy supply, while also creating important job opportunities in the building sector.

The directive on the energy performance of buildings was the first legislative instrument, introduced in 2003, to improve the energy performance of buildings in the Europe Union [2]. It obliged the member states to set minimum requirements for the energy performance of new buildings, to enforce the use of cleaner energy sources, to establish the energy performance certification schemes for new and existing buildings and to introduce regular inspections of boilers and air conditioning systems. The EPBD recast, introduced in 2010 moves a step further and states that all new buildings must present nearly zero energy balance by 2020 [3]. According to this directive, the calculation of the cost-optimal levels of minimum energy performance requirements will be established by means of a comparative methodology framework for buildings and building elements. This comparative methodology will take into account usage patterns, the building category, outdoor climate conditions, investment costs, maintenance and operating costs, earnings from produced energy and disposal costs. The implementation of the methodology is centered around, and is depending on, relevant European standards, described in the CEN standard umbrella document [4].

2. On the optimal thickness of thermal insulation: reviewing the literature

There is plenty of literature on the calculation of the optimal insulation thickness for the various building elements, focusing mainly on Northern and Central Europe, that is for continental and oceanic climatic conditions, which is reasonable given the size of the building stock of this region. As a result, as early as the mid-2000s there were practical guidelines published on this subject [1,5]. There are however not so many studies for the Mediterranean and the Middle East region, that is for mesothermal and dry climates of groups Bsh, Bsk and Csa according to the Köppen scale [6]. It is

* Corresponding author. Tel.: +357 22394394; fax: +357 22438234.
E-mail address: eng.fp@frederick.ac.cy (P.A. Fokaides).

0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.09.006

Nomenclature

Symbols

A	constant
α	annuity factor
C	cost [€]
c	end to primary energy conversion factor
CO_2	carbon dioxide
d	insulation thickness [m]
E	energy consumption [kWh/(m^2 a)]
f_P	overall profit function [€]
h	heat convection coefficient [W/(m^2 K)]
i	interest rate [%]
m	number of building element's layers
n	building lifetime [years]
Q_{SOL}	total solar radiation [W/m^2]
P	profit [€]
R	overall thermal resistance [m^2 K/W]
T	temperature [K]
U	overall heat transmittance coefficient [W/(m^2 K)]

Abbreviations

AC	air conditioning
CDD	cooling degree days [Kd]
CDH	cooling degree hours [Kh]
CEN	Comité Européen de Normalisation
COP	coefficient of performance
DD	degree days [Kd]
DH	degree hours [Kh]
EPBD	Energy Performance of Buildings Directive
EU	European Union
HDD	heating degree days [Kd]
HDH	heating degree hours [Kh]
HVAC	heating ventilation and air conditioning
GDP	gross domestic product
SEER	seasonal energy efficiency ratio

Greek symbols

α	absorptivity
Δ	difference operator
ε	emissivity
∂	partial derivative notation
η	efficiency [%]
λ	thermal conductivity [W/(m K)]
σ	Stefan–Boltzmann constant = 5.67×10^{-8} [W/(m^2 K^4)]

Indices

1–5	constant indices
ADD	additional
AIR	air
AMB	ambient
BAL	balance
C	cooling
CDD	cooling degree days
E	energy
EX	external
F	fixed
ε	emissivity
H	heating
IN	internal
INS	insulated
P	profit
SKY	sky
SOL	solar
UNINS	uninsulated

therefore a worthwhile exercise to discuss in detail the findings of those studies.

In Table 1 are listed the reviewed studies, with respect to the locations considered and the methodologies applied for the quantification of the thermal and cooling loads. All examined studies were carried out after 2000; therefore, the technological status of heating, ventilation and air conditioning equipment, the insulation materials and the cost factors of energy and the materials can be considered to be valid in present terms [7]. The degree-days (DD) method was adopted by almost all studies for the quantification of the heating and cooling loads, as it is considered to be a simple, effective and intuitive way of estimating the building's annual energy consumption [8]. The DD method is a steady-state approach, and it is based on constant indoor conditions during the heating or cooling season. This may introduce some inaccuracy, as one would need a detailed efficiency curve for the heating or cooling systems to enable the determination of the systems' efficiency; such curves are however rarely available. In these studies, the assumed base temperature varied from 18 to 26 °C, with the variance having a direct impact on the energy consumption of buildings for cooling and heating, as higher temperature differences result in higher loads.

The financial projection assumptions for the presented studies are provided in Table 2. The average building's lifetime is considered to be between 10 and 30 years, which is a problem that will be discussed extensively in Section 4. The increase of a building's lifetime has a direct impact on the savings on heating and cooling energy consumption. Therefore, in cases where a building's lifetime was increased, the cost-optimal insulation was found to be thicker. A large deviation in inflation and interest rates values was also observed, depending on the assumptions for the boundary conditions [9].

A large variation of the energy prices applied can be found in the aforementioned studies (Table 3). This is reasonable, because market prices are directly related to the GDP index of the country for which the study was performed. With respect to the buildings' energy performance, one has to keep in mind that it depends to a great extent on the primary energy used, as according to the EPBD buildings are evaluated in terms of their primary energy demand. The energy conversion factor, from final to primary energy, is therefore a dominant figure, with respect to the heating and air-conditioning consumption. This conversion factor can vary strongly from country to country, depending on the primary energy sources used and the development in each country's energy mixture; it is therefore a varying parameter that has to be reconsidered periodically [10,11].

Information regarding the construction and insulation of buildings is given in Table 4. The majority of the examined building elements involved masonry, whereas roofs were also examined in some studies. In all cases, windows were excluded because the methodology concerns conduction-oriented heat transfer. Several different insulation materials were examined, including expanded and extruded polystyrene, glass wool, stone wool and polyurethane foam plates, covering hence to a satisfactory extent the materials dominating the market [12]. The building elements considered are depicted in Fig. 1. Different types of construction were investigated in the studies considered and the optimal insulation thickness was found to vary from 3 cm, in cases where a limited heating demand was covered by rather inefficient heating systems and energy costs were low, as in some Mediterranean countries before the recent economic recession, to 25.9 cm [13], in admittedly marginal cases where demand and energy pricing parameters were extremely high.