Energy and Buildings 110 (2016) 79–93

Contents lists available at ScienceDirect

Energy and Buildings

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

The potential of lightweight low-energy houses with hybrid adaptable thermal storage: Comparing the performance of promising concepts

P. Hoes*, J.L.M. Hensen

Building Physics and Services, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form 14 October 2015
Accepted 15 October 2015
Available online 23 October 2015

Keywords:
Thermal energy storage
Adaptable
Thermal mass
Lightweight buildings
Building performance simulation

ABSTRACT

The international community set clear goals regarding the reduction of CO_2 emissions and energy demand in the built environment. This drives research and building practice to search for solutions and new building concepts that contribute to achieving these goals. The work presented in this paper should be seen in that context. This research focuses on a building concept that makes use of the thermal energy storage capacity of materials and buildings. The concept combines the thermophysical benefits of low and high thermal mass buildings by adapting (on demand) to the most optimal thermal capacity. The main objective of this research is to identify if this so-called hybrid adaptable thermal energy storage (HATS) approach shows potential to reduce the energy demand of new lightweight residential buildings in the Netherlands and maintain or improve thermal comfort. This paper gives an overview of various HATS concepts and discusses the predicted performance of three HATS concepts. This research shows that the HATS approach is able to reduce the heating energy demand compared to a lightweight and heavyweight reference case. Furthermore, it shows that the HATS approach is able to improving thermal comfort compared to the lightweight reference case and maintain thermal comfort compared to the heavyweight reference case.

1. Introduction

1.1. Reduction of energy use and CO_2 emissions

According to the International Energy Agency, the building sector must reduce its total CO_2 emissions by 60% in 2050 in order to limit global temperature rise to 2 °C [1]. Reduction of the use of fossil fuels in the built environment is an important step to meet these CO_2 emission goals. Therefore, the EU introduced the Energy Performance of Buildings Directive (EPBD) in 2002 [2]. The EPBD demands EU countries to reduce the energy use in buildings. This resulted in strict energy performance regulations. For example, the Dutch government introduced the EPC (energy performance coefficient) for new (residential) buildings to enforce energy saving measures; low EPC values correspond to highly energy efficient buildings. The EPC was set to 0.6 in 2011 and lowered to 0.4 in 2015, which forces building designers to use high levels of thermal insulation (R_c values of at least 3.5 m^{2}K/W for floors, 4.5 m^{2}K/W for walls and 6.0 m^{2}K/W for the roof) and high energy efficient boilers. In addition, detached and semi-detached houses require solar collectors to (pre)heat domestic hot water or ground source heat pumps [3]. The goal of the Dutch government is to reach energy neutral dwellings in 2020; therefore, the EPC will be set to 0.0 in 2020. This means that these future dwellings need to be very energy efficient. Moreover, a large portion of the remaining energy demand should be covered with renewable energy. These stricter energy requirements are a great challenge for the building industry.

The EPC focuses only on energy use in the operational phase of buildings, however the construction and demolition phase of buildings also contribute to the total energy use and CO_2 emission of buildings. To this purpose green building rating tools (e.g. BREEAM [4] and LEED [5]) are developed; these tools assess the sustainability of the whole building lifecycle. For instance, most of these tools also evaluate the reuse of building materials and management of waste materials at the construction site [6]. In the Netherlands, the use of these rating tools is not enforced by the building codes; nonetheless, their use is increasing among building designers. As a result, these designers need to reconsider conventional building concepts, since it might be more sustainable to use an alternative concept. Therefore, research and building practice are searching for solutions or new building concepts that contribute to achieving the mentioned energy and CO_2 emission goals.

The work presented in this paper should be seen in the same context. The work focuses on new building concepts that make use

* Corresponding author. Tel.: +31 0 40 247 2273.
E-mail address: p.hoes@tue.nl (P. Hoes).

http://dx.doi.org/10.1016/j.enbuild.2015.10.036
0378-7788/

of the thermal energy storage capacity of materials and buildings. The scope of this research is narrowed down to solutions for residential houses in the Netherlands; the new building concept is discussed next.

1.2. Hybrid adaptable thermal energy storage

The thermal energy storage capacity of a building is closely related to the chosen material of the structural frame. Various materials can be used for the structural frame of a building; the most common materials are steel, wood, brick and concrete. Steel and wood are generally categorized as lightweight constructions with a construction weight of around 100 kg/m^2 floor surface area, while brick and concrete are categorized as heavyweight constructions with a weight of around 500 kg/m^2 floor surface area. From a thermophysical perspective the main difference between lightweight and heavyweight constructions is the difference in *effective thermal mass*; the effective thermal mass describes the effective thermal energy storage capacity of the materials used in a building. In general, buildings with lightweight constructions have a lower effective thermal mass than buildings with heavyweight constructions. This difference in effective thermal mass influences building performance regarding heating energy demand and thermal comfort:

- Buildings with low effective thermal mass show a fast response to temperature and heat flux excitations. This fast response shortens the pre-heating period of buildings compared to buildings with higher effective thermal mass. This results in lower heating energy demands when the building needs to be heated to a higher temperature. However, due to their fast response, buildings with low effective thermal mass are also sensitive to overheating. Though, it is possible to reduce this sensitivity through proper building design, e.g. blinds, overhangs.
- Buildings with high effective thermal mass show a slow response to temperature and heat flux excitations. This slow response delays and reduces peak temperatures, which reduces the risk of overheating. However, this also means that it requires more time to heat the building to a higher temperature, which results in higher heating energy demands when the building cools down due to intermittent building use.

A solution to reduce the risk of overheating in lightweight low thermal mass buildings is to increase the building's thermal energy storage capacity (from here on *effective thermal mass* is referred to as *thermal mass*). This can be done by adding thermal energy storage systems or materials to the building. This changes the thermophysical behavior of the building to that of a high thermal mass building, which also means that the benefit of a short pre-heating period is lost. Thus, to make use of the thermophysical benefits of low and high thermal mass buildings, buildings should be able to adapt (on demand) to the most optimal thermal mass. In the past, various studies investigated how to design and use thermal mass for thermal energy storage in buildings, e.g. [7,8]. However, in these studies the thermal mass is not made (fully) adaptable as meant above. This novel adaptable approach is the main topic of this research. Building concepts that use this approach are referred to as *adaptable thermal energy storage* concepts. The term *hybrid* is added to indicate the possibility of combining two or more of these concepts in one (hybrid) building concept. Therefore, the term *hybrid adaptable thermal storage* (HATS) concept is used in this work.

1.3. Lightweight building constructions

This research focuses on HATS concepts that can be used in combination with lightweight constructions. Lightweight constructions are not commonly used for residential buildings in the Netherlands; heavyweight concrete and brick building constructions are traditionally the dominant construction method. However, according to various recent studies, lightweight constructions are an interesting alternative. In these studies, the environmental impact of lightweight and heavyweight structural materials for the whole building lifecycle is investigated using life cycle analysis (LCA). Cole [9] finds that wood and steel frame buildings use less energy and produce less CO_2 emissions during construction compared to concrete buildings. Xing et al. [10] compare steel frame buildings to concrete buildings and confirm Cole's findings for steel frame buildings. Other researchers suggest that the use of wood as construction material has the potential to reduce global CO_2 emissions [11,12]. Goverse et al. [13] argue that using wood as construction material for Dutch houses could reduce CO_2 emissions by almost 50% compared to traditional constructions. Vefago and Avellaneda [14] argue that the recyclability of wood and steel frame buildings is higher than concrete structures, which increases the sustainability of these building designs. In general, the findings of these LCA studies should be handled with care, since the results may be influenced by the building location and available resources. However, these studies clearly indicate that lightweight constructions should not be overlooked in the design process (certainly with the CO_2 emission goals in mind). This is also true for specific retrofitting cases, e.g. top-up extensions. Lightweight constructions can be used for these extensions without the need to change the building's foundations. In the Netherlands these sort of retrofitting methods are interesting due to high prices for building estates. Other specific buildings cases that are well suited for lightweight constructions are for example temporary and floating buildings.

1.4. Objectives and paper structure

The main objective of the work presented in this paper is to identify if the HATS approach shows potential to reduce the energy demand of new lightweight residential buildings in the Netherlands (with the 2020-goal in mind) and maintain or improve thermal comfort. The latter is important, since it is assumed that building occupants will not accept solutions that compromise thermal comfort. It is hypothesized that the HATS approach is able to reduce the energy demand and increase thermal comfort in lightweight Dutch residential buildings. The performance of the HATS approach is investigated using *computational building performance simulation*, i.e. using 'virtual buildings', and it should determine if the HATS approach shows enough potential to justify further study, e.g. by measurements in a mock-up.

This paper is structured as follows. Section 2 briefly introduces the results of a preliminary potential study of the HATS approach. Section 3 describes several HATS concepts and identifies which concepts are promising for Dutch residential buildings. Section 4 introduces a performance assessment methodology and the case studies used in this paper. Section 5 discusses the predicted performance of the three promising concepts compared to conventional lightweight and heavyweight buildings. Section 6 concludes this paper with a discussion of the results.

2. Preliminary potential study

A preliminary indication of the potential of the HATS approach is presented in two papers [15,16]. In the first paper a simplified adaptable thermal energy storage model is used. The model represents a fictitious, idealized adaptable thermal energy storage concept. The model switches between two extreme building cases (lightweight and heavyweight) and chooses the building variant with the lowest discomfort (primary criterium) and lowest