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Improving thermal response of lightweight timber building envelopes during cooling season in three European locations

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ABSTRACT

In recent years the use of wood based products in building industry has expanded. Although lightweight timber constructions essentially decrease environmental impact of a building, their consequential low thermal mass can lead to overheating during summer. Therefore, the purpose of this paper was to investigate various examples of enhanced lightweight constructions from the thermal response point of view. Several improvements were investigated (e.g. clay boards, wood wool thermal insulation, Phase Change Materials, etc.) and compared with the performance of a conventional thermally insulated high mass wall. Finite element model was created and dynamic thermal performance of enhanced lightweight external walls was analysed in three different European locations: Helsinki (Finland), Vienna (Austria) and Madrid (Spain). Certain enhancements resulted in lower internal surface temperature of constructions up to 1 °C, depending on location. In addition, it was shown that in order to further improve thermal performance, application of high intensity ventilation is necessary, which additionally lowered the internal surface temperature up to 8 °C. It was shown that enhanced and naturally cooled lightweight constructions are more suitable for locations with milder summer temperatures (Northern, Central Europe), rather than for hot climates (Mediterranean). It was concluded that the application of lightweight constructions should be thoughtful in order to achieve adequate thermal response of buildings. However, in lightweight buildings the integration of materials characterised by high thermal mass, high thermal effusivity and low environmental impact should be encouraged.

1. Introduction

Providing thermal comfort in buildings during cooling season (i.e. summer) demands great attention, since environmental temperature is one of the most critical factors determining human comfort (Pohl, 2011) and perception of “healthy homes” among Europeans (VELUX Group, 2016). This is very important in situations, when buildings are during cooling season left in “free-run” mode, i.e. are not mechanically cooled, which is a common case for residential buildings in EU. According to an Intelligent Energy Europe project (RESCUE, 2014) only 7% of the total floor area of the EU residential building stock is equipped with an active cooling system, while this share in tertiary sector is roughly 40%. In most parts of Europe the overheating of buildings is often regarded as non-problematic by the general public as well as the designers, while statistical data show that large amount of residential buildings are not comfortably cool during summer period, even in Finland or Latvia (Eurostat, 2012). Nevertheless, a majority of Western European countries (e.g. Ireland, UK, Atlantic coast of France, and Benelux) rarely confront overheating of buildings due to their oceanic climate and relatively mild air temperatures in summer. However, in countries with milder climate the overheating usually occurs in buildings that lack thermal mass (e.g. timber construction) (Adekunle and Nikolopoulou, 2016). Furthermore, the problem of summer time overheating of buildings is additionally escalated in highly urbanised environments (i.e. cities) by the occurrence of urban heat island (Paolini et al., 2016). Little is known how lightweight constructions (LWCs), used in building envelopes, respond to summer time climate conditions in distinct parts of Europe, where different thermal transmittances are prescribed by the local government legislation. Accordingly, differences in thermal insulation thickness are a common case. While legislation and simulations of thermal response of buildings are primarily focused on the winter time performance and the

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reduction of heating energy demand, the summer time overheating of buildings is often overlooked by legislators as well as designers (Košir et al., 2016a). This is particularly true for central and northern parts of Europe where buildings are traditionally regarded as being heating driven. In this respect, bioclimatic potential analysis as presented by Pajek and Košir (2017) can be used to analytically evaluate the climatic characteristics of a location, emphasising the relation between heating and cooling design strategies. Additionally, buildings that lack thermal mass are especially susceptible to the occurrence of overheating (Zhu et al., 2009; Adekunle and Nikolopoulou, 2016). Tonelli and Grimaudo (2014) emphasized the importance of increasing thermal inertia of lightweight constructions when speaking of prefabricated timber buildings in Mediterranean climate. Generally, the usage of materials with high thermal mass is omitted in case of LWCs (Gregory et al., 2008; Němeček and Kalousek, 2015). This is mostly practiced because of the typical construction types suggested by manufacturers, to improve structural properties and to lower the total quantity of used materials and thus to decrease the environmental impact (Kutnar and Muthu, 2016) by using lower total weight of constructional materials. These properties are frequently achieved by wood, which is a recyclable, reusable and naturally renewable material, has excellent strength-to-weight ratios and a good seismic performance (Asdrubali et al., 2017). However, the indoor environment parameters (e.g. indoor temperature) are highly dependent of the thermal response of materials used in building envelope, beside the other parameters, such as ventilation rate. Thus, Hudobivnik et al. (2016) suggest further research in dynamic thermal response of LWCs and research in their potential enhancements, especially due to the growing trend in popularity of such constructions.

Several materials, which could improve the thermal response of LWCs, by means of added thermal mass and the corresponding impact on indoor temperature fluctuations, have been introduced so far. Conventional high thermal mass materials like concrete, brick, stone and similar materials are impractical for applications in LWCs and are therefore principally avoided. Consequently, alternative materials should be used and their application studied. For instance, Jeanjean et al. (2013) presented a new ceramic material made of vitrified asbestos waste, which performed well as a thermal storage material, although its form and thickness could present an obstacle during installation. Mounir et al. (2014, 2015a, 2015b) investigated the thermal inertia of clay composite materials, where different combinations of clay, wool, cork, cement, etc., were analysed. The clay-wool composites as well as clay itself proved to have good thermal characteristics resulting in lower diurnal temperature fluctuations and heat flow through the wall. Similar enhancements (e.g. massive inner linings combined with natural or hybrid ventilation) and their impact on summer thermal behaviour were investigated by Stazi et al. (2017) in the case of super-insulated (e.g. U value of walls 0.12 W/m^{2}K) wooden residential building in Mediterranean climate. Although this research with its findings greatly contributes to the professional knowledge, it was a case study; therefore, it is hard to draw general conclusions. In addition, it was not shown whether the thermal performance of the building envelope could be further improved or not.

Another way to enhance the performance of LWCs is application of materials with high latent heat, used for storing large amount of energy per specific weight or volume. These materials are commonly known as Phase Change Materials (PCMs). The usage of PCMs in buildings has become prominent and is widely studied (Akeiber et al., 2016). Studies mostly include variations and effect of different PCM types (Khudhair and Farid, 2004; Evers et al., 2010), PCM layer's in-wall positions (Jin et al., 2017), wall orientations (Zhang et al., 2005) and locations (Ascione et al., 2014) on thermal performance of building envelope. In particular, Ascione et al. (2014) investigated the building envelope response in relation to the phase change temperature, the thickness of the PCM wallboard and the location of the PCM layer during cooling season in Mediterranean area. The results pointed out that at fixed phase change enthalpy the phase change temperature was the most important parameter, with appropriate summer time melting temperature values of 25–30 °C, although the optimization of the PCM properties is strictly connected to climatic location and building use. Mandilaras et al. (2013) calculated the average monthly decrement factor and time lag values at the surface of the gypsum plasterboard panels with incorporated PCM. PCM implementation resulted in increment of delay in peak temperature time and decrease in decrement factor during late spring, early summer and autumn. Similarly, Sharifi et al. (2017) showed that the use of gypsum boards with PCMs results in a reduction of the indoor peak temperature, thus improving thermal comfort and decreasing energy consumption of buildings. In the case of LWC walls, Zhang et al. (2005) and Evers et al. (2010) studied the addition of PCMs into in-wall cellulose thermal insulation and highlighted the effectiveness of different PCM materials, for example paraffin PCM, which performed much better than hydrated salt PCM. However, Kenisarin and Mahkamov (2016) pointed out the inapplicability of such solution, since it is practically impossible to provide effective reversible melting and freezing of the PCM due to its internal position, without deploying an intensive ventilation system. Charging and discharging stage of PCM can be managed by either active (e.g. HVAC system) or passive (e.g. high intensity natural ventilation) cooling principle. By the fact that high intensity passive cooling is much more energy efficient and has significantly lower impact on environment (i.e., no or very low electricity demand) than alternative active solutions for PCMs phase change, its usage is much more appropriate. Further on, as described by Akeiber et al. (2016), the usage of PCMs in building envelope can help providing thermal comfort for longer periods without depending on HVAC system. Kenisarin and Mahkamov (2016) suggest further research of PCM performance in building envelope, focused on the development of accurate mathematical models for thermal performance prediction of buildings in relation with various types of climate and daily and seasonal fluctuations of outdoor conditions. However, few studies have been conducted to investigate the influence of PCM integration in LWC external walls on the effectiveness of high intensity ventilation and vice versa. Hudobivnik et al. (2016) emphasized the importance of ventilation regime consideration and its impact on thermal response of building envelope. Their results showed that differences in heavy and lightweight constructions cannot be neglected and should be considered, while LWC thermal performance enhancements are highly appreciated.

Accordingly, greater attention of construction industry is needed to more precisely understand the behaviour of LWC buildings. Kitek Kuzman et al. (2013) and Tonelli and Grimaudo (2014) showed that the usage of LWCs, especially timber based LWCs, is considerably growing, despite the still present negative prejudice about timber buildings reported by Gold and Rubik (2009). In this context, it is of great importance to find possible solutions or enhancements of such constructions in order to improve their thermal performance. This should be of priority especially during cooling season, because the cooling energy share in the total energy consumption of buildings in EU is projected to substantially increase by 2050 (STRATEGO cofounded by Intelligent Europe Programme, Project number IEE/13/650., 2015). Therefore, the main purpose of the study was to perform a dynamic thermal response analysis of various enhanced LWC building envelope systems (e.g. timber-framed). The analysis was carried out with the help of finite element model simulations. Three different typical