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Computational analysis of thermal performance of a passive family house built of hollow clay bricks

Václav Kočí, Zdeňka Bažantová, Robert Černý*

Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, Prague 6 166 29, Czech Republic

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ABSTRACT

The architectural, constructional, and material solution of a brick-built passive family house is presented, together with a computational analysis of the overall thermal performance. The obtained results show that the thickness of the thermal insulation layer can be reduced several times if the up-to-date hollow bricks with lightened brick body and sophisticated systems of internal cavities are used, instead of traditional bricks or the old-fashioned hollow bricks with only several large cavities. The designed brick-built passive house is thus almost equalized with the timber-based houses from a point of view of building envelope thickness. In addition, it preserves some very important advantages characteristic for common brick structures, such as the fast water vapor transport through the wall, good thermal accumulation properties and fire resistance, or a low risk of biological degradation. Therefore, an up-to-date hollow brick block can be considered a suitable construction material for the passive-house design. This solution is particularly suitable for the Central European countries where using ceramic brick, in general, in building structures is a well established tradition; it was the most frequently used building material for many centuries.

1. Introduction

Nowadays, the building industry is influenced by quite a few factors and trends reflecting the current situation and development on the social [1], economical [2], technical, or scientific field [3,4]. One of these trends is an effort to minimize the energy demand [5–8], because the average share of buildings' energy consumption is almost 40% [9,10] and its rise is expected in the future. According to [11], 69% of energy used in buildings is consumed on heating in the European Union, thus significant reduction in energy demands can be achieved by promoting buildings with better thermal insulating capabilities of their envelopes. Comparing the old and new thermal standards, this phenomenon becomes evident. For example, in UK the requested *U*-value for external walls was reduced from 1.70 W/m^{2}K in 1965 [12] to the current 0.30 W/m^{2}K [13]. It means that while in the not very distant past brick masonry with a thickness of 0.45 m was considered sufficient from a thermal point of view, according to the current thermal standards this wall should be over two meters thick. In the building practice, the increasing demands of thermal standards during the last few decades were, of course, not met by increasing the wall thickness but using thermal insulation layers in the composition of building envelopes, or better constructional solutions. The designers went even beyond the standards, introducing so called "passive houses".

The term "passive house" is used for an internationally established building standard with very low energy consumption. The first passive house was built in Germany in 1992 and its goal was to meet a heat load below 15 kWh/m^2 per year [14] by using standard construction materials and technologies. Independently of climate and functionality, the passive house concept was defined in [15]. The criteria for residential passive house are among others: space heating demand has to be lower than 15 kWh/(m^{2}a) and specific primary energy demand for heating, cooling, hot water, auxiliary electricity, domestic and common area electricity has to be lower than 120 kWh/(m^{2}a). They can be achieved by a substantial improvement of the construction details for each relevant component. It is necessary to use very good thermal insulation of the building envelope, windows with very low heat losses and very high heat gains, ventilation system with highly efficient heat recovery, etc.

The passive standard does not define a maximal *U*-value for external walls but some recommendations are available for guidance. In the scientific community, a generally accepted *U*-value is around 0.15 W/m^{2}K [16–18]. Some national thermal standards

* Corresponding author. Tel.: +420 224355044.
E-mail address: cernyr@fsv.cvut.cz (R. Černý).

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recommend or prescribe maximum admissible U-value for external walls of passive houses as well; the Czech standard [19] recommends 0.12–0.18 W/m^{2}K, the German standard [20] prescribes 0.15 W/m^{2}K. Most of other standards, however, do not offer yet any such specification; for example the Irish standard [21] prescribes U-value for external walls only generally (0.27 W/m^{2}K), as well as the English thermal standard (0.30 W/m^{2}K) [13]. In any case, the number of passive houses rises very fast at the present time. Furthermore, regarding the commitment to implement the European directive EPBD II [22] into national thermal standards, their share on the overall building market will grow even more within the next few years.

Although the material type is not a crucial factor to meet the passive standard, most passive houses were built on the timber basis, until now [23–28]. The biggest advantage of timber buildings is their stud system with boarding, which allows the thermal insulation to be implemented into the wooden frame between the studs. This reduces the thickness of building envelope. Other advantages of timber houses are very quick assembling thanks to the dry process or minimal thermal bridging.

Passive houses on the brick basis [29–31] appeared much less frequently in the past. According to the analysis presented in [32], only 15% of passive houses in EU were built of bricks, until now. The main reasons were probably the higher overall thickness of the wall due to the necessary application of relatively thick exterior thermal insulation layers and the more labor intensive construction. The traditional use of timber as construction material in some European countries could be another argument for its preference.

However, the passive brick-based buildings certainly have a potential to increase their share on the market of passive buildings, at least in some geographical regions of Europe. In the Central European countries the first argument can be the tradition; ceramic brick was a building material most frequently used here for many centuries.

The second important factor is that brick-based buildings have some important advantages from a building-physics point of view. They have lesser problems with moisture condensation because most bricks are characterized by fast water vapor transport. The relatively low value of water vapor diffusion resistance factor of bricks in a comparison with wood allows faster transport of water vapor through a construction. This is very important, because it leads to prevention of water vapor accumulation and its subsequent possible condensation. The problems of water vapor condensation during the winter period are well known in general and, of course, water vapor condensation can occur also in this case, but the high vapor permeability of bricks helps to increase the evaporation so that the overall condensation/evaporation balance is better than in the case of less permeable materials.

The bricks also have a good thermal accumulation function which cannot be achieved for timber-based buildings. In addition, contrary to the timber structures, which may face problems with a poor fire resistance [33,34] or a possibility of biological degradation [35,36], the brick-based houses, by their nature, resist well to high temperatures. They are also rarely affected by microorganism attacks.

The current developments in the brick industry aimed at the improvement of thermal insulation properties can provide further arguments in favor of constructing passive buildings on the brick basis. The thermal insulation properties of the brick body itself were subject of continual improvements within the last decade or two [37–40]. While the traditional bricks used in the past century had the thermal conductivity, λ, ~0.50 W/mK [41,42], for recent bricks the common λ values are within a range of 0.20–0.30 W/mK [43,44]. The production technology of hollow bricks was greatly improved as well, which resulted in new designs of sophisticated layouts of internal cavities minimizing the thermal bridges inside a brick block. The effective thermal conductivity of the hollow brick blocks was thus reduced from ~0.35 to 0.40 W/mK, typical for the older designs with only several cavities [45], to the recent ~0.10 0.15 W/mK [41,44,46]. Therefore, also the current argument of a too high wall thickness of brick-based passive houses may lose its convincingness in the near future.

In this paper, we present a family house built using an up-to-date hollow brick technology which meets the passive standard for residential buildings, including the architectural design, the constructional and material solution of the building envelope, and the computational analysis of the overall thermal performance.

2. Simulation tools for passive houses

The simulation tools suitable for design of passive houses and their parts or to verify their correct function are widely available. The dynamic simulation software used by Thiers and Peuportier [47], the computer-aided design tool for passive solar systems applied by Yakubu [48], the simulation software for zero energy building design used by Wang et al. [49], the methodology of design of low energy buildings introduced by Chlela et al.[50], the optimization tools BEopt (Building Energy Optimization) [51] and EGUSA (Energy Gauge USA) [52] can be quoted as characteristic examples.

There are also several non-dynamic software tools for calculation of building energy performance. One of the most advanced and detailed models with an accuracy of ±0.5 kWh is PHPP (Passive House Planning Package) [53], which was created by W. Feist at Passivhaus Institut in Germany. It is based on European standards related to thermal protection of buildings, passive house design or energy performance calculations, converting them to more convenient and user friendly form. Therefore, it is one of the most frequently used design tool for passive houses. For scientific purposes it was used e.g. by Ridley et al. [16] or Stephan et al. [30].

3. Description of the building

3.1. Architectural solution and technical equipment

The designed family house has a rectangular shape with the dimensions of 11 m × 8.25 m. The main entrance is from the north side, with a light translucent roofing made from polycarbonate. Behind the door, there is a small hall for clothes and shoes to be taken off and this hall continues by the corridor connecting the main living space with the kitchen and dining room. On the 1st floor, there is also workroom with enough space for rest, where a bed can be placed. The plan view of the 1st floor is presented in Fig. 1.

The parents' bedroom is located in the 2nd floor above the main living space in the 1st floor. It is lit from the south through a glass wall with an entrance to the balcony. There are also two smaller bedrooms for children oriented to the west and to the south. While in the 1st floor there is only small bathroom with toilet and shower, in the second floor there is also large bathroom with bathtub and two sinks. The plan view of the 2nd floor is shown in Fig. 2. The list of rooms including their floor-space areas is given in Tables 1 and 2.

It is supposed, that the house will be occupied by a family of four members. It will be occupied permanently except the workdays, when it will be empty from 8:00 until 18:00. This occupancy schedule will be used for calculation of internal heat gains, which are important for estimation of energy performance.

Similarly to other passive houses, also in this case standard heating system is not installed. Space heating is ensured by ground source heat pump (GSHP) with the coefficient of performance (COP) 3.5 (it usually lies between 3 and 5 [54]). The cooling set point