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Computational assessment of thermal performance of contemporary ceramic blocks with complex internal geometry in building envelopes

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ABSTRACT

Contemporary ceramic blocks with the cavities filled by thermal insulation materials appeared in some European countries as a reaction of the brick industry to the increasing requirements on the energy efficiency of buildings. Their dual load-bearing and thermal insulating function, together with the good building-physical qualities and technological advantages makes them competitive on the building materials market. The assessment of their thermal properties is, however, a demanding task which often involves using large-scale experimental facilities for considerable time periods. In this paper, an alternative to the commonly used methods for determination of thermal performance of ceramic blocks with complex internal geometry is presented. The proposed approach is based on the computational modeling of heat transfer in the block, using the thermal properties of involved materials measured in a laboratory experiment as input parameters. The calculated temperature fields and heat fluxes are used for the determination of the effective thermal conductivity, thermal resistance and thermal transmittance. A practical applicability of the method is demonstrated for three ceramic blocks with different thermal insulation materials in the cavities. An uncertainty analysis of the calculated thermal parameters is performed and the results are compared with the data obtained by two different experimental approaches.

1. Introduction

During the last several decades, the process of industrialization and urbanization resulted in the construction of millions of new residential houses annually worldwide. The International Energy Agency and Organization for Economic Cooperation and Development predicted in their common study [1] that the energy demand in the housing sector will increase by 60% between 2010 and 2050, which is more than in the transport or industrial sector. Apparently, a reasonable solution to such enormous projected increase of energy demand cannot lie in cutting the construction activities but rather in decreasing the energy consumption and improving the energy efficiency of building structures.

In the European Union (EU), the residential sector is responsible for around 40% of the total energy consumption [2] which is considered too high. Therefore, the Energy Performance of Building Directive [3] and its recast [4] came into force that require all EU members to enhance their building regulations including, e.g., introduction of nearly zero energy buildings by 2020 or application of cost-optimal methodology for setting minimum requirements for both envelope and mechanical systems. The new energy requirements on the building sector were reflected in quite a few research studies, ranging from the design of energy efficient wall systems [5] and optimization of the alternative energy production systems [6] to the methodology for benchmarking the building energy consumption [7] and predicting the next-day peak power demand [8].

Some producers of building materials reacted to the current need for energy savings by the development of advanced types of thermal insulation materials, such as the vacuum insulation panels [9] or aerogels [10]. Other innovations were aimed at the materials of load-bearing structures. The production of new materials with better thermal insulating properties which made possible to avoid thermal insulation layers in building envelopes became one of the important trends in the building industry. A typical material of this kind was autoclaved aerated concrete (AAC); the innovations in composition and production technology led to the appearance of many advanced AAC products on the European market during the last decade [11].

In the brick industry, a great effort was devoted to the reduction of thermal conductivity of the brick body using, e.g., vegetable matter [12] or paper pulp [13]. In parallel, the producers tried to

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utilize the positive thermal properties of dry air by involving it into the brick. As a result of these improvements, the hollow clay bricks appeared on the European market [14]. The hollow bricks with the cavities filled by air became a subject of intensive studies, aimed at the optimization of the brick internal geometry [15], experimental assessment of thermal performance [16], or analysis of the effect of external conditions on the thermal insulation properties [17].

A specific target of the investigations on the hollow bricks was the complex heat transfer in the air cavities where the magnitude of the effects of convection and radiation on the thermal resistance of the brick blocks was one of the most important tasks to be solved. Alhazmy [18] presented a numerical steady-state study on the effect of natural convection in the cavities on the heat flux and proposed a method for its reduction. Antar [19] analyzed numerically the effect of radiation in the air cavities on the steady-state heat transfer across a multiple-cavity building block and found it very significant. Arendt et al. [20] investigated the influence of the cavity concentration in hollow bricks on several static and dynamic parameters, and also in this case the effect of radiation was remarkable. Filling the air cavities by thermal insulation materials thus appeared as a possible solution to suppressing the negative radiation and convection effects. This was confirmed in the experimental studies on the thermal insulation properties of ceramic blocks with the cavities filled by perlite [21], expanded polystyrene [22], mineral wool [23], or foam polyurethane [23].

The assessment of the thermal properties of contemporary ceramic blocks is not an easy task in general, no matter if the cavities are filled by air or thermal insulation materials. The heterogeneities with a typical dimension of at least several centimeters, which are inevitable for this type of blocks, do not make it possible to use common methods for determination of thermal conductivity of homogeneous solids. The application of robust large-scale experimental facilities with the high demands on time, labor, and financial means is thus the most straightforward way to obtain the necessary thermal parameters [24]. The other alternatives, such as the semi-scale experiments [23] or modifications to the standard laboratory methods [25], are less expensive but the time and labor requirements are not much lower. Therefore, there certainly exists a niche for reducing both the cost and labor requirements while keeping the accuracy of the acquired data on a similar level.

In this paper, we describe a fast computational approach for determination of the effective thermal conductivity, thermal resistance and thermal transmittance of contemporary ceramic blocks with the cavities filled by thermal insulation materials. The proposed method requires a knowledge of the thermal conductivities of materials involved in the block, which can either be adopted from the available literature or measured by some commonly used transient technique. The calculation of the thermal parameters is done using the finite-element based computational simulation of the steady-state temperature field in the ceramic block. The sensitivity analysis of the proposed method, which is based on the uncertainty analysis of the experimental input data, is performed afterwards, and the results are compared with the data obtained by two well established experimental techniques.

2. Materials and methods

2.1. Description of the analyzed ceramic blocks

Three contemporary ceramic blocks with the cavities filled by expanded polystyrene, mineral wool and foam polyurethane, which are produced in the Czech Republic, were analyzed. They were designed for the application in low-energy buildings as a part of load-bearing insulation masonry. The horizontal cross-section of the blocks with the dimensions of 500 mm × 247 mm together with the direction of the heat flux is presented in Fig. 1.

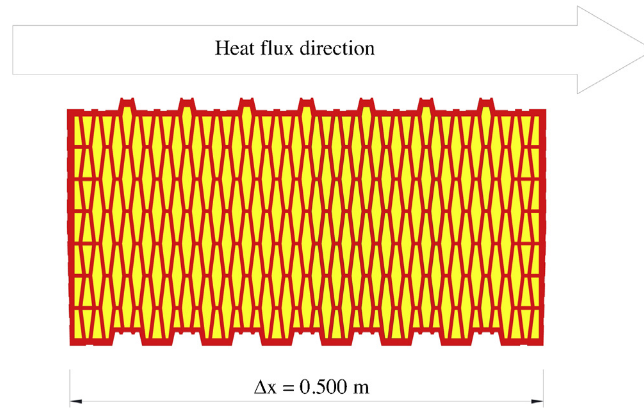

Fig. 1. The cross-section of the analyzed ceramic blocks.

2.2. Computational method for the assessment of thermal parameters

A steady-state heat conduction problem was solved on a two-dimensional space domain defined by the cross-section of the ceramic block. An ideal heat transfer across the internal interfaces between the brick body and thermal insulation cavity fillings was assumed. In accordance with the supposed application of the blocks in the building envelopes, Newton boundary conditions were set on the face sides while on the lateral sides zero-flux boundary conditions were postulated.

The computer implementation was performed using the general finite element package SIFEL (SImple Finite ELements) [26]. The ceramic block was meshed and the particular materials were assigned to the respective elements. In total, the mesh was formed by 78 687 nodes and 77 819 quadrilateral elements. A detail of the meshed cross-section of the ceramic block is given in Fig. 2.

The input parameters included the thermal conductivities of the brick body and thermal insulation materials used as cavity fillers in the dry state, and the heat transfer coefficients and air temperatures on the face sides of the block. All input parameters were assumed constant, in order to facilitate a comparison with the data obtained

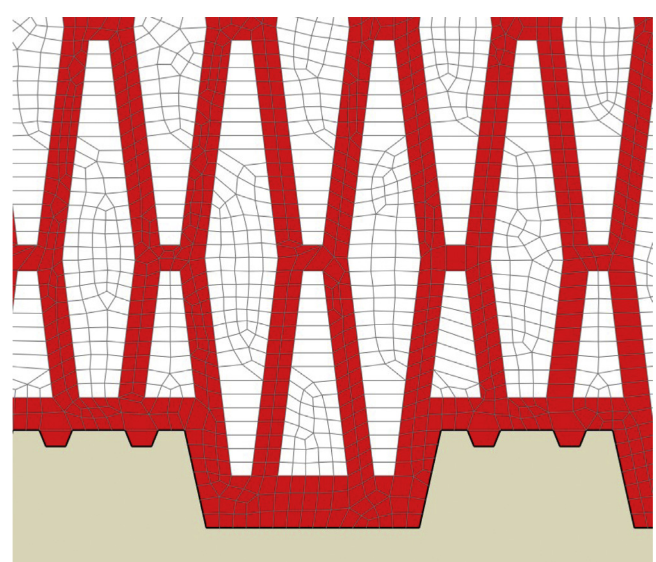

Fig. 2. Detail of the meshed cross-section of the ceramic block.