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# A fast computational approach for the determination of thermal properties of hollow bricks in energy-related calculations

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ABSTRACT

As successful products of the recent developments in the building industry aimed at increasing the energy efficiency of buildings, the hollow clay brick blocks with complex systems of internal cavities present a prospective alternative to the traditional solid bricks on the building ceramics market. Determination of their thermal properties, which are essential for any energy-related calculations, is though not an easy task. Contrary to the solid bricks, the application of sophisticated methods is a necessity. In this paper, a fast computational approach for the determination of equivalent thermal conductivity of hollow brick blocks with the cavities filled by air is presented, which can be used as an integral part of energy-related calculations. The thermal conductivity of the brick body is the main input parameter of the model, the convection and radiation in the cavities are taken into account in a simplified form. The error range of the designed method is identified using a thorough uncertainty analysis. A direct comparison of the calculated equivalent thermal conductivity with the results obtained by two different experimental techniques for the same hollow brick block shows a satisfactory agreement, making the designed computational approach a viable alternative to the currently used methods.


## 1. Introduction

It is a commonly known fact that buildings significantly contribute to the total energy consumption all over the world. According to the current studies [1–3], the building sector accounts for approximately 30–50% of total energy consumption globally. In Europe, the building sector represents 40% of the final primary energy consumed [4]. As the growing energy demands present big environmental issues, reducing energy consumption in the building sector has become an important policy target [5]. The forecast made by EIA suggests that energy use in the building environment will grow by 34% in the next 20 years [6]. The most of energy in buildings is consumed by HVAC systems (heat, ventilation and air-conditioning). The increasing interest in improving the energy efficiency of buildings has been reflected in many studies [7–9]. As there is a big potential for reducing the energy consumption in buildings, in 2002 the EU (European Union) introduced EPBD (Energy Performance of Building Directive) [10], which required all EU member states to enhance their building regulations and to introduce energy certification schemes for buildings. In 2010 there was introduced a new adoption of the recast EPBD [11], which toughened the regulations given by the original EPBD. The EU Members are facing new tough challenges, among them moving towards new and retrofitted nearly-zero energy buildings by 2020 (2018 in the case of public buildings) and the application of cost-optimal methodology for setting minimum requirements for both envelope and technical systems.

The increasing requirements to the energy efficiency of buildings have led the building material producers to the recent development of new materials that could find their use in low-energy and nearly-zero energy buildings. One of the results of this development was the appearance of hollow clay bricks on the European building market which almost completely replaced the traditional solid clay bricks. The thermal properties of the hollow bricks as the essential parameters for any energy-related calculations were, however, not so easy to acquire as the thermal conductivity of solid bricks which could be measured by any standard technique, such as the guarded hot-plate, hot-wire, or flash methods. The complex geometry of the hollow brick blocks, together with the convective and radiative heat transfer in the cavities, made the application of

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common methods not feasible. Therefore, alternative experimental or computational treatments were being sought.

An application of large-scale facilities was the most robust experimental solution to the problem of determination of equivalent thermal conductivity of hollow bricks [12,13]. However, the high demands on time, labor, and financial means necessary for this kind of experiment could present prohibitive factors for many laboratories. A utilization of a semi-scale experiment [14] could be considered as a compromise with respect to the cost of the experiment but the time and labor requirements were not much lower. The modifications to the standard laboratory methods [15,16] brought an increased accuracy and control of the experiment but still the time necessary for a single measurement could be as long as several weeks.

The simplest computational method presented until now consisted in using the nested homogenization techniques [17]. Its idea was simple and the calculation was rather fast but the need for a specific calibration using some of the experimental techniques mentioned above which was essential for its accuracy presented a serious obstacle. Another simple computational method was introduced by Antoniadis et al. [18] who investigated the equivalent thermal conductivity of Greek hollow clay bricks. Their method involved the determination of thermal conductivity of solid clay brick by the transient hot-wire technique completed by the calculation of the equivalent thermal conductivity using the finite element method. However, they assumed that heat transfer by radiation and convection could be neglected due to the relatively low width of the air holes, which was clearly an oversimplification.

The effect of convection and radiation in the cavities of the hollow bricks was analyzed in several specific studies. Alhazmy [19] presented a numerical steady-state study on the effect of natural convection in the cavities on the heat flux. Antar [20] analyzed numerically the effect of radiation in the air cavities on steady-state heat transfer across a multiple-cavity building block. Arendt et al. [21] investigated the influence of the cavity concentration in hollow bricks on several static and dynamic parameters. They took into account the radiative heat transfer but neglected the natural convection, arguing by a strong reduction of convective heat exchange due to a use of optimal cavity shape.

A detailed finite element solution of the heat transfer in hollow bricks including complex radiation and convection modeling in the cavities was presented by Del Coz Diaz et al. [22–24]. They performed extensive finite-element computational studies aimed at the determination of the equivalent thermal conductivity of various clay, concrete, and lightweight concrete hollow blocks including the optimization procedures, as for the geometry and organization of the holes. Three dimensional numerical simulations were done in order to determine the heat transmission coefficients of the studied bricks while three different modes of heat transfer were taken into account. The authors characterized the solution of the problem as very difficult starting from the mesh generation and ending with the numerical solution of the non-linear problem. Similar type of research was done by Li et al. [25]. They used finite volume method to determine the equivalent thermal conductivity of a multi-holed clay brick. As they included radiation, convection and conduction into their numerical simulations, they were facing the same problem of non-linear problem solving as Del Coz Diaz et al. in Refs. [22–24].

As it follows from the above survey, the computational techniques for determination of equivalent thermal conductivity of hollow bricks should be taken with care. Too simple models can neglect some important modes of heat transfer and the results can be devalued just by the improper definition of the model. The most sophisticated models involving the necessity of non-linear problem solving may require powerful and expensive computer machines and the solution of such complex problems may be very time-consuming. Therefore, some compromises in the choice of a particular model may have to be adopted.

Most computational approaches also suffer two important flaws. The first consists in their purely deterministic presentation, without any serious uncertainty and sensitivity analysis. The second lies in an absence of any direct validation of the applied models which is supposed to be done using the data obtained for the same experimental setup in a real measurement. Therefore, the computational modeling of equivalent thermal conductivity of hollow bricks is still an issue deserving a close attention.

In this paper, a new computational approach is applied for the determination of equivalent thermal conductivity of hollow brick blocks with the cavities filled by air. The thermal conductivity of the brick body is the main input parameter, the convection and radiation in the cavities are expressed using simplified approaches, making possible fast and effective calculation of the apparent thermal conductivity of the air. The error range of the designed method is identified using a combination of uncertainty and sensitivity analysis. Finally, a direct comparison of the calculated equivalent thermal conductivity with the results obtained by two different experimental techniques for the same hollow brick block is presented.

## 2. Physical model of heat transfer in hollow bricks

A hollow brick block consists of a brick body having a complex shape and a system of internal cavities filled by air. In the brick-body parts of the block the only mode of heat transfer is assumed to be conduction, with the thermal conductivity of the brick body, $\lambda_{bb}$, as the main heat transport parameter. The brick body itself is porous but the dimensions of the pores are so small that convection and radiation in the pore space can be neglected. In the cavities, on the other hand, complex heat transfer occurs including conduction, convection and radiation at the same time. Its solution generally involves an application of momentum transport equation in the cavities, and convection and radiation boundary conditions on the interface between the brick body and the air in the cavities. Implementation of the radiation boundary conditions is particularly difficult because its coupling with the system of transport equations brings strong nonlinearities into the computational solution (see, e.g., Ref. [23]). Therefore, in this paper we adopted a concept of apparent thermal conductivity, $\lambda_{app}$, of the air in the cavities,

$$\lambda_{app} = \lambda_{cond} + \lambda_{conv} + \lambda_{rad}, \tag{1}$$

where $\lambda_{cond}$ [W m$^{-1}$ K$^{-1}$] is the thermal conductivity of air by conduction, $\lambda_{conv}$ [W m$^{-1}$ K$^{-1}$] the thermal conductivity of air by convection, and $\lambda_{rad}$ [W m$^{-1}$ K$^{-1}$] the thermal conductivity of air by radiation.

The simplified physical model based on the application of Eq. (1) assumes an ideal heat transfer on the internal interfaces of the hollow brick block which makes it possible to treat the whole hollow brick as a nonhomogeneous system of two materials with different thermal conductivities, thus to apply the common Fourier heat conduction equation. For a steady-state heat transfer problem, there are only four input parameters of the model, namely $\lambda_{bb}$, $\lambda_{cond}$, $\lambda_{conv}$ and $\lambda_{rad}$. While $\lambda_{bb}$ can be measured by standard laboratory methods and $\lambda_{cond}$ of the air is well known, $\lambda_{conv}$ and $\lambda_{rad}$ have to be determined in a dependence on the specific cavity size and shape.

In the calculation of $\lambda_{rad}$ in the cavities, the theory of non-participating media which is valid for vacuum, monoatomic and most diatomic gases including air at low to moderate temperatures [26] was used. A simplified geometrical scheme was adopted