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COMPUTATIONAL APPROACH FOR ESTIMATING HYGRIC PROPERTIES OF HETEROGENEOUS MATERIALS IN LONG-TERM ASSESSMENT OF MOISTURE-INDUCED DAMAGE

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Long-term assessment of degradation processes is a very useful tool for an analysis of building materials performance. Since computational techniques are mostly used for this purpose, hygric properties of involved materials are required as substantial input data. Unfortunately, some construction details or heterogeneous materials have to be solved by means of multi-dimensional modelling which is demanding on computing power and thus the calculations may take a lot of time. The presented paper aims at determination of effective hygric properties of heterogeneous materials which would allow one-dimensional transformation. The parameter identification process is carried out on the basis of results of multi-dimensional modeling, using genetic algorithms. The main objective is to find such effective global moisture transport and accumulation functions that provide in one-dimensional modeling as similar results to multi-dimensional modeling as possible. The obtained functions give a very good agreement; the investigated relative humidity profiles differ only by 1.48 percentage points in average. The correctness of obtained results is also verified using the Lichtenecker's mixing rule as homogenization technique. The transformation of the original multi-dimensional problem into one-dimensional is found to substantially contribute to minimization of computational time, which is reduced from weeks to minutes.

Keywords: Moisture transport, Hygric performance, Parallel computing, Computer simulations, Genetic algorithms, One-dimensional transformation.

1 INTRODUCTION

During the past years, computational modelling of hygric performance became a favorable tool for assessment of building materials, as reported, e.g., by Medjelekh *et al*. (2016) or Brischke and Thelandersson (2014) in their reviews. Since this approach is time-saving and cost effective at the same time, it is predisposed to be used even more in the nearest future. Accurate mathematical and physical models that require tight sets of input parameters only contribute to this trend. The possibility of predicting hygric behavior of building materials enables a broad range of practical applications as moisture transport is involved in most processes or damage mechanisms (Abbasion *et al.* 2015, Bishara *et al.* 2014, Goto *et al.* 2012, Koudelka *et al.* 2015).

Computational investigation of homogeneous materials is relatively simple because the solved problems can be easily transformed to lower the necessary space dimensions. However, complications may occur when heterogeneous materials are considered. In these cases, the problem must be solved as multi-dimensional in order to accommodate the non-uniform structure. Highly perforated bricks can be stated as an example in that respect (Kočí *et al.* 2014), requiring at least a two-dimensional perspective. Unfortunately, multi-dimensional modelling is often time-consuming and requires large computing power. Sometimes even a parallelization of the problem is unavoidable (Kruis *et al.* 2016), being beyond possibilities of many research groups. Several other techniques have been therefore proposed, overcoming the demands of parallel or high-performance computing. Probably the easiest way is an application of homogenization techniques which estimate the effective (homogenized) parameters of heterogeneous systems. Such methods were described e.g. by Fiala and Černý (2015) who applied the Lichtenecker's mixing formula for determination of thermal conductivity of aerated concrete at different levels of saturation. However, since these techniques are sometimes based on estimation of several input parameters such as constants in Lichtenecker's model, the accuracy of the outputs might be questionable, especially when the results are not validated by means of experimental measurements.

Another method for determination of effective hygric properties of highly perforated bricks is therefore presented in this paper. It is based on an evaluation of results of high-performance parallel computing that can reliably describe hygric behavior of bricks when exposed to climatic conditions. Transferring the problem to one-dimensional, the results of parallel computing are fitted using the effective hygric parameters. The identified parameters can be subsequently used for any calculations, a long-term assessment of moisture-induced damage of the bricks or whole constructions can be mentioned as a typical example. Being performed as one-dimensional, these calculations are less time demanding and require less computing power, which is the biggest advantage making the obtained parameters widely applicable.

2 DESCRIPTION OF THE SOLVED PROBLEM

The hygric performance of external wall made of highly perforated bricks filled with expanded polystyrene which will be solved in this paper was described by Maděra *et al.* (2016). Provided with exterior and interior plaster, the wall with an overall thickness of 520 mm (10+500+10) was exposed to climatic conditions of Prague. Since the discretization of the detail led to more than 134 million of stored matrix entries, due to the complicated internal structure of the brick, the problem was decomposed into 16 subdomains that were solved as parallel (see Figure 1). Even though the parallel modeling was applied, the computations took couple of weeks in order to obtain the long-term performance of the envelope.

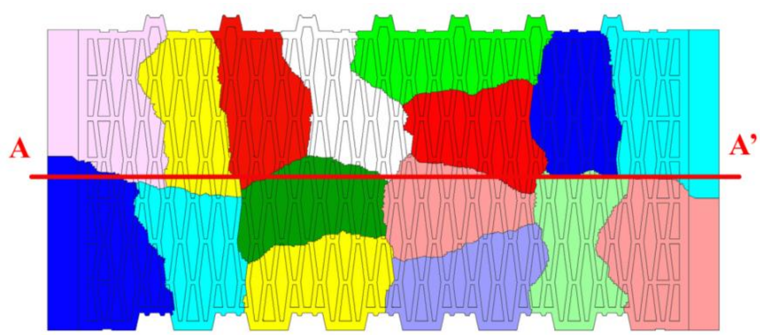

Figure 1. Problem parallelization: modelling of hygric performance of highly perforated brick.

For the purpose of a transformation to a one-dimensional problem, three relative humidity profiles, corresponding to the cross-section AA', in randomly selected time of the reference year were recorded. These profiles, depicted in Figure 2, were subsequently fitted as one-dimensional using the effective hygric parameters of the brick. In Figure 2, 0.00 m on the horizontal axis corresponds to the interior side of the envelope.

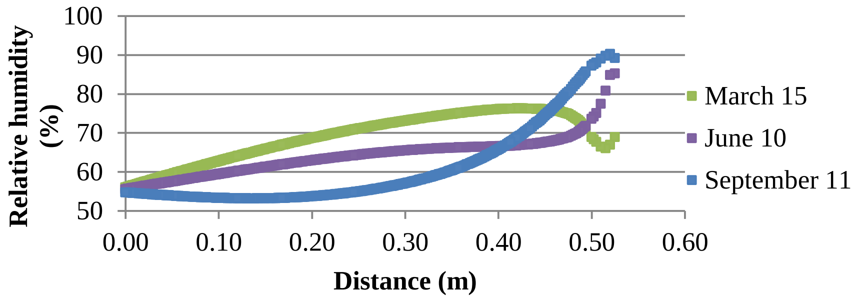

Figure 2. Selected moisture profiles obtained using parallel two-dimensional computations.

3 MATHEMATICAL MODEL AND FITTING PROCEDURE

All calculations in this paper were performed using a diffusion type of mathematical model for description of coupled heat and moisture transport in porous building materials. Regarding to the topic of this research, only results related to hygric performance are presented. The model was derived from Künzel's, however after certain modifications presented by Maděra *et al*. (2016) it is more precise as it more accurately distinguishes between the moisture phases due to an implementation of a transition function. Furthermore, partial pressure of water vapor is used as the primary variable instead of relative humidity, providing a numerical stability while the overall time of computations is reduced.

Based on the above mentioned modifications, all moisture transport and accumulation parameters have to be consolidated into global transport and global accumulation function, respectively. The global transport functions, constructed on the basis of water vapor diffusion resistance factor and moisture diffusivity, and the global accumulation functions, formed by sorption isotherm and retention curve, are shown in Figure 3. The remaining material properties entering the model are summarized in Table 1 (the data were taken from Ďurana *et al*. 2013, Korecký *et al*. 2013).

Table 1. Material properties of involved materials.

	Brick body	**Expanded polystyrene**		**Brick body**	**Expanded polystyrene**
ρ (kg m^{-3})	1389.0	18.2	c (J kg^{-1}K^{-1})	1020 – 1711	1898
ψ (%)	50.1	10.3	μ (-)	8.10 – 13.38	12.66
λ (W m^{-1}K^{-1})	0.299 – 1.210	0.037 – 0.066	κ_{app} (m^{2}s^{-1})	$2.91 \cdot 10^{-7}$	$5.55 \cdot 10^{-12}$

The main objective of the presented research is to find effective moisture transport and accumulation functions of complete brick, involving both the brick body and EPS filling, that enables the transformation to one-dimensional problem. To avoid a method of "trial and error", advanced fitting techniques based on genetic algorithms are employed. Using genetic operators, such as mutation, selection or cross-over, the best solution can be effectively found. Detailed description including a practical application of genetic algorithms was given by Kočí *et al*.

(2016). The best solution in this case means finding such global moisture transport and accumulation functions that provide the best match of all moisture profiles with those obtained by two-dimensional modelling (see Figure 2). The evaluation of the match is done on the basis of the least square method. It means the differences of relative humidity values of six selected points on the profiles are quantified and used for the least square calculations.

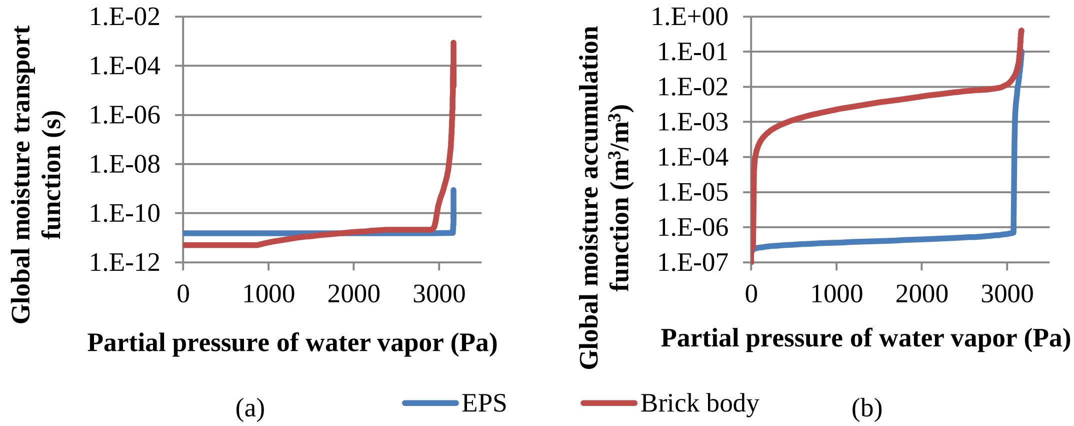

Figure 3. Global moisture transport (a) and accumulation (b) functions.

4 RESULTS AND DISCUSSION

From the computations, effective values of moisture transport and accumulation functions were obtained (Figure 4). For ease of comprehension, the functions were compared with those of brick body and EPS that are presented in Figure 3. Additionally, the results obtained using the Lichtenecker's mixing rule are presented to emphasize the diversity of particular techniques.

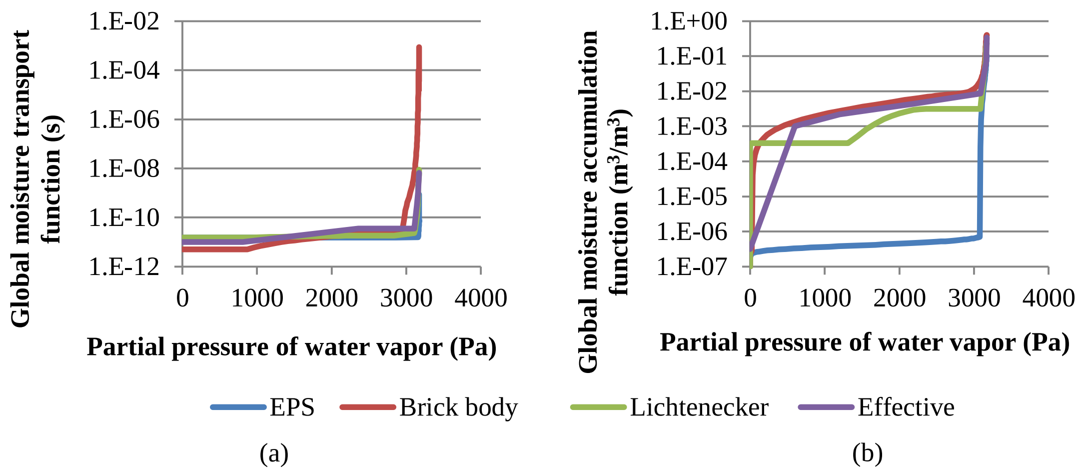

Figure 4. Effective and Lichtenecker's global moisture transport (a) and accumulation (b) functions.

One can notice that global accumulation functions, both the effective and the Lichtenecker's, tend to correlate with that of brick body but the effective is more similar. Anyway, it indicates that the moisture accumulation processes in the brick are rather governed by the body than by the cavity filling, EPS in this case. Regardless the used technique, the global transport functions are very similar, ranging between EPS- and brick body-curves.

Using the obtained effective hygric parameters, the relative humidity profiles in specific days of the reference year were calculated and compared with those presented in Figure 2 that were determined by means of two-dimensional modelling. Evincing a very good match, the results of the comparison are presented in Figure 5. The accuracy of profiles obtained using the presented computations with effective parameters is much better than of those obtained using the Lichtenecker's mixing rule. Expressed by numbers, the average difference in six evaluated points is 1.45 % of RH, while the Lichtenecker's mixing rule gives 2.69 % of RH.

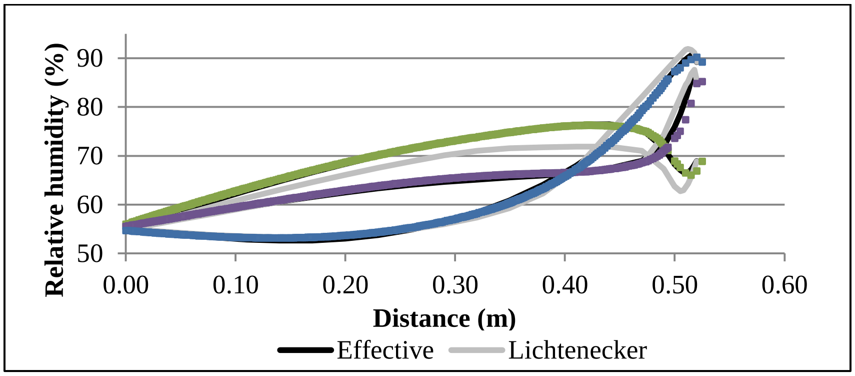

Figure 5. Comparison of relative humidity profiles obtained using one-dimensional and multi-dimensional parallel modelling.

The results of computations could have been even more accurate when the match in more profile points had been evaluated or when finer transport and accumulation functions had been defined. On the other hand, especially the latter would slow down the genetic algorithms and thus extend the seeking procedure. However, the one-dimensional calculations of hygric performance take only few minutes which is disproportionally less than the couple of weeks required by multi-dimensional parallel modelling. The overall time of computations will therefore be still shorter. Computational determination of effective hygric parameters based on results of multi-dimensional parallel modelling represents then another alternative for the transformation of a problem to one-dimensional, being less demanding on time and computing power as well. This can be highly advantageous especially in case of long-term computational assessment of performance of building materials or constructions. The assessment of moisture induced damage may be stated as a typical example.

5 CONCLUSIONS

A new approach for estimation of effective hygric parameters of heterogeneous materials was presented in the paper. The effective parameters were determined on the basis of a long-term assessment of hygric behavior that had been achieved using multi-dimensional parallel computing. Since the high performance computing is very time consuming and requires large computing power being usually out of possibilities of many research groups, the estimation of effective parameters enables solving multi-dimensional problems as one-dimensional, eliminating the mentioned disadvantages.

Having calculated several relative humidity profiles by means of multi-dimensional modelling, the effective hygric parameters were determined in order to reach the highest agreement for one-dimensional results. Genetic algorithms were used for this purpose, achieving a better accuracy (1.45 % of RH) than the Lichtenecker's mixing rule used as homogenization technique (2.69 % of RH). The biggest advantage of the presented approach may be seen in time savings after utilization of obtained effective parameters as the one-dimensional calculations took only couple of minutes, while the multi-dimensional needed couple of weeks.

Acknowledgments

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