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Critical assessment of the moisture distribution in existing building walls

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ABSTRACT Current environmental issues focus on the energy performance of existing buildings. Thus, the problem of the moisture content within a wall is of capital importance. However, its assessment in existing buildings is difficult to obtain. Therefore, the inverse problem approach is proposed. In this article the moisture distribution within the existing building wall is presented through the spatial variation. Then, the coefficients of polynomial representation are estimated using the temperature measurements. The case study of the existing building wall is considered. The obtained results and issues raised by this approach are discussed.

INTRODUCTION

The problem of the moisture content in walls in existing buildings is present across the globe. Before starting the retrofitting works of such objects, the moisture content should be determined. If the moisture content in walls exceeds the reference value, a special treatment should be applied. The moisture spatial distribution cannot be determined with accuracy through on-site experimental measurement for thick walls [Hola et al., 2017]. Destructive design are also not an option. Thus, an inverse problem can be defined by acquiring on-site observation and minimizing a cost function to estimate the moisture spatial distribution. Local moisture content measurement can be achieved using time domain reflectometry sensors drilled into the wall. However, their accuracy is only satisfactory for high moisture content. Inversely, relative humidity sensors can be employed but their accuracy is acceptable only for low moisture content. In other words, there is no accurate measurement related to the moisture content that could be used to estimate the spatial distribution. It is necessary to obtain an observation of other fields.

In building walls, the heat and mass transfer are strongly coupled driven by the climatic conditions. Particularly, the thermal conductivity of the layers composing the walls are linearly dependent with the moisture content. Furthermore, the temperature measurement inside a wall can be obtained by drilling the wall and setting up sensors. It is easy, accurate and has already proven its efficiency to estimate the thermal conductivity of several layers [Jumabekova et al., 2020]. Therefore, the idea is to use temperature observations to determine the spatial distribution of the thermal conductivity [Krapez, 2000]. Knowing the empirical relation between the thermal conductivity and the moisture content of the material, the moisture distribution in the wall could then be estimated.

The objective of this article is to explore the aforementioned methodology. A polynomial approximation is proposed, moreover, the variation range of the coefficients is suggested. Investigations are carried out on an existing building wall, which is composed of bricks. The moisture content distribution is estimated using the temperature observations within the wall. Additionally, the sensitivity coefficients of the temperature according to the moisture content are computed. The article is organized in the following way. At first, the physical model is defined, a relation between material thermal properties and the moisture content variation is established. Then, the spatial representation of the moisture content using the shifted LEGENDRE polynomials is introduced. Finally, the case study of an existing building wall is described, and the approximation of the moisture content variation is found.

METHODOLOGY

Physical model. First, a mathematical formulation of heat transfer through a building wall is presented. The

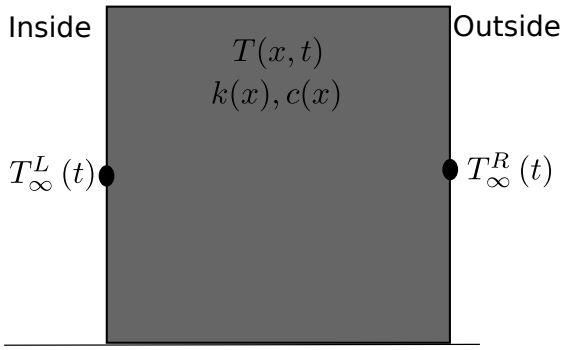


Figure 1. *Illustration of a wall domain.*

physical problem considers one–dimensional heat conduction transfer through a building wall. The temperature $T\,[\,\mathsf{K}\,]$ in the wall is defined on the domains $\Omega_x = \{\,x\,|\,x \in [\,0\,,L\,]\,\}$ and $\Omega_t = \{\,t\,|\,t \in [\,0\,,\tau_{\max}\,]\,\}$, where $L\,[\,\mathsf{m}\,]$ is the length of the wall and $\tau_{\max}\,[\,\mathsf{s}\,]$ is the duration of the experiment:

$$T : [\,0\,,L\,] \times [\,0\,,\tau_{\max}\,] \longrightarrow \mathbb{R}\,.$$

The mathematical formulation of the heat transfer process is given below [Incropera et al., 2006]:

$$c\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right), \tag{1}$$

where $c\,[\,\mathsf{J}\cdot\mathsf{K}^{-1}\cdot\mathsf{m}^{-3}\,]$ is the volumetric heat capacity, or $c = \rho\cdot c_p$, corresponding to the product between the material density $\rho\,[\,\mathsf{kg}\cdot\mathsf{m}^{-3}\,]$ and the specific heat $c_p\,[\,\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}\,]$, and $k\,[\,\mathsf{W}\cdot\mathsf{m}^{-1}\cdot\mathsf{K}^{-1}\,]$ is the thermal conductivity. Material thermal properties depend on the moisture content $\omega\,[\,\mathsf{kg}\cdot\mathsf{m}^{-3}\,]$, which is assumed to depend on space, but not on time, thus, equation (1) becomes [Mendes and Philippi, 2005]:

$$c\,(\,\omega\,)\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\,(\,\omega\,)\,\frac{\partial T}{\partial x}\right). \tag{2}$$

The following DIRICHLET boundary conditions are defined, using the obtained inside and outside surface temperatures of the wall:

$$T = T_\infty^L\,(\,t\,)\,, \qquad x = 0\,, \tag{3}$$
$$T = T_\infty^R\,(\,t\,)\,, \qquad x = L\,. \tag{4}$$

At the initial state the temperature is given as:

$$T\,(\,x\,,t = 0\,) = T_0\,(\,x\,) \tag{5}$$

Material properties. The thermal conductivity $k\,[\,\mathsf{W}\cdot\mathsf{m}^{-1}\cdot\mathsf{K}^{-1}\,]$ depends on the water content [Berger et al., 2021]:

$$k\,(\,\omega\,) = k_0 + k_1\cdot\omega\,,$$

where k_0 is the thermal conductivity at the dry state, $k_1\,[\,\mathsf{W}\cdot\mathsf{m}^2/(\mathsf{kg}\cdot\mathsf{K})\,]$ is the dependency coefficient related to the moisture content $\omega\,[\,\mathsf{kg}\cdot\mathsf{m}^{-3}\,]$. The heat capacity coefficient $c\,[\,\mathsf{J}\cdot\mathsf{K}^{-1}\cdot\mathsf{m}^{-3}\,]$ is defined as follows:

$$c\,(\,\omega\,) = c_0\cdot\rho_0 + c_1\cdot\omega\,,$$

where $\rho_0\,[\,\mathsf{kg}\cdot\mathsf{m}^{-3}\,]$ is the dry density, $c_0\,[\,\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}\,]$ is the specific heat of the material, and $c_1\,[\,\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}\,]$ is the specific heat of liquid water.
Additionally, it should be noted that the moisture content is within the following constraints:

$$0 \le \omega \le \omega_{\text{sat}}\,, \tag{6}$$

where ω_{sat} is the saturation moisture content.

Dimensionless formulation. In order to minimize the round–off numerical errors and to analyze the model behaviour regardless the used units for variables, it is essential to obtain a dimensionless formulation of the problem [Trabelsi et al., 2018; Berger et al., 2020]. To convert equation (1) let us introduce the following dimensionless variables:

$$x^\star \;=\; \frac{x}{L}\,, \qquad\qquad u \;=\; \frac{T \;-\; T_{\mathrm{ref}}}{\Delta T_{\mathrm{ref}}}\,, \qquad\qquad t^\star \;=\; \frac{t}{t_{\mathrm{ref}}}\,,$$

as well as dimensionless thermal properties functions by:

$$k^\star \stackrel{\mathrm{def}}{:=} \frac{k}{k_{\mathrm{ref}}}\,, \qquad\qquad c^\star \stackrel{\mathrm{def}}{:=} \frac{c}{c_{\mathrm{ref}}}\,.$$

where subscripts **ref** relate for a characteristic reference value, and superscript $\star$ for dimensionless parameters. Additionally, the moisture content is expressed as:

$$\omega \;=\; \omega_{\mathrm{sat}}\,\omega^\star\,,$$

where

$$0 \;\le\; \omega^\star \;\le\; 1\,. \tag{7}$$

Thus, equation (1) transforms to:

$$c^\star(\omega^\star)\,\frac{\partial u}{\partial t^\star} \;=\; \mathrm{Fo}\,\frac{\partial}{\partial x}\left(k^\star(\omega^\star)\,\frac{\partial u}{\partial x^\star}\right), \tag{8}$$

where $\mathrm{Fo} \;=\; \dfrac{t_{\mathrm{ref}}\,k_{\mathrm{ref}}}{L^2\,c_{\mathrm{ref}}}$ is Fourier number, and

$$c^\star(\omega^\star) \;=\; c_0^\star \;+\; c_1^\star\omega^\star\,, \qquad k^\star(\omega^\star) \;=\; k_0^\star \;+\; k_1^\star\omega^\star\,.$$

The Dirichlet–type boundary conditions are converted to:

$$u \;= u_{\mathrm{L}}(t^\star)\,, \qquad x^\star \;=\; 0\,, \qquad \text{where} \qquad u_{\mathrm{L}} \;=\; \frac{T_\infty^L \;-\; T_{\mathrm{ref}}}{\Delta T_{\mathrm{ref}}}\,, \tag{9}$$

$$u \;= u_{\mathrm{R}}(t^\star)\,, \qquad x^\star \;=\; 1\,, \qquad \text{where} \qquad u_{\mathrm{R}} \;=\; \frac{T_\infty^R \;-\; T_{\mathrm{ref}}}{\Delta T_{\mathrm{ref}}}\,. \tag{10}$$

Furthermore, the initial condition is transformed to:

$$u \;=\; u_0(x^\star)\,, \qquad \text{where} \qquad u_0 \;=\; \frac{T_0 \;-\; T_{\mathrm{ref}}}{\Delta T_{\mathrm{ref}}}\,. \tag{11}$$

Further in the article, for the sake of the clarity the superscript $\star$ is omitted, and all results are presented in dimensionless form unless stated otherwise.

Moisture content parameterization. The material moisture content value depends on the position inside the wall, thus, it can be characterized as a polynomial approximation of the spatial variable. Due to the dimensionless representation, one may use shifted Legendre polynomials [Abramowitz and Stegun, 1965] to represent the moisture content variation. Therefore, the following expression holds:

$$\omega(x) \;=\; \sum_{r=0}^{M} a_r\,Q_r(x)\,,$$

where $Q_r(x)$ - is the shifted Legendre polynomials, and $x \;\in\; [0\,,1]$. The first four shifted Legendre polynomials are as follows:

$$\begin{aligned}
Q_0(x) \;&= 1\,,\\
Q_1(x) \;&= 2x \;-\; 1\,,\\
Q_2(x) \;&= 6x^2 \;-\; 6x \;+\; 1\,,\\
Q_3(x) \;&= 20x^3 \;-\; 30x^2 \;+\; 12x \;-\; 1\,.
\end{aligned}$$

Additionally, one may express the thermophysical properties as:

$$c(x) = c(\omega(x)) = c_0 + c_1\omega(x), \qquad k(x) = k(\omega(x)) = k_0 + k_1\omega(x).$$

To find the range of variation of the coefficients a_r the following property of orthogonal polynomials is used:

$$a_r = \frac{1}{b_r}\int_0^1 \omega(x)\,Q_r(x)\,\mathrm{d}x,$$

where $b_r = \int_0^1 Q_r^2(x)\,\mathrm{d}x$. One may apply Cauchy–Schwarz to determine upper and lower bounds of the coefficients a_r as:

$$\left|a_r\right| \le \left(\frac{1}{b_r^2}\int_0^1 \omega^2(x)\,\mathrm{d}x\right)^{\frac{1}{2}}\left(\int_0^1 Q_r^2(x)\,\mathrm{d}x\right)^{\frac{1}{2}}.$$

By taking into account the inequality (7), one may assume that:

$$\left|a_r\right| \le \frac{1}{b_r}\left(\int_0^1 Q_r^2(x)\,\mathrm{d}x\right)^{\frac{1}{2}}, \quad \text{or}$$
$$\left|a_r\right| \le \frac{1}{\sqrt{b_r}}.$$

Sensitivity equations. In this section, sensitivity coefficients are introduced. They quantify the model output sensitivity to the parameter a_r:

$$X_{a_r} \stackrel{\text{def}}{:=} \frac{\partial u}{\partial a_r}.$$

The sensitivity coefficients are obtained as a solution of a differential equation or sensitivity equation, which is a result of partial differentiation of the model equation Eq. (8). One may obtain the following sensitivity equation for coefficient a_r:

$$c(x)\frac{\partial X_{a_r}}{\partial t} = \frac{\partial}{\partial x}\left(k(x)\frac{\partial X_{a_r}}{\partial x}\right) + S(u, x, t, a_r),$$

where $S(u, x, t, a_r) = \frac{\partial}{\partial x}\left(\frac{\partial\omega(x)}{\partial a_r}\frac{\partial u}{\partial x}\right) - \frac{\partial\omega(x)}{\partial a_r}\frac{\partial u}{\partial t}$, and $\frac{\partial\omega(x)}{\partial a_r} = Q_r$.
The sensitivity equations together with the governing equation are solved using the function `ode23s` from the `Matlab` environment [MATLAB, 2018], which is based on a modified Rosenbrock formula of order 2 [Shampine and Reichelt, 1997].

Cost function minimization. Next, the parameter estimation problem is solved by minimizing the following cost function by the optimization method:

$$\mathrm{J}(\boldsymbol{p}) = \sum_{i=1}^{N_s}\frac{1}{\sigma_i^2}\left\|u^{\mathrm{num}}(x = \chi_i, \boldsymbol{p}) - u_i^{\mathrm{obs}}\right\|_2. \tag{12}$$

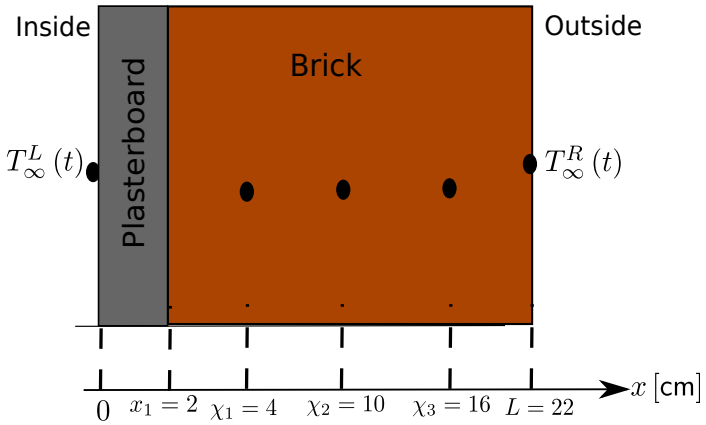
The value of u^{num} results from the solution of the direct problem (8) for given parameters values $\boldsymbol{p} = (a_0, a_1, a_2)$. The values of u_i^{obs} are given by the measurements at the points $x = \chi_i$ respectively, N_s is the total number of sensors. It is assumed that measurement errors are additive with zero mean, constant variance, uncorrelated and normal distribution. A value σ_i is a standard deviation of the measurement u_i^{obs} of the $i-$th sensor [Ozisik and Orlande, 2000]. The norm is calculated according to:

$$\left\|y\right\|_2 = \int_0^{t_{\max}}\left(y(t)\right)^2\mathrm{d}t \tag{13}$$

The optimization of cost function is performed using the function `particleswarm` from the `Matlab` environment. This method is based on the algorithm described in [Kennedy and Eberhart, 1995], using modifications suggested in [Mezura-Montes and Coello, 2011; Pedersen, 2010].

CASE STUDY

In this article a wall of an existing building is considered. The building is situated in Paris, France, and was built in 1918 [Cantin et al., 2010]. Figure 2b displays an image of the building. The wall is composed of two layers, the first layer (from inside) is a 2 cm plasterboard, the second one - a brick.The length of the wall is equal to 22 cm, moreover, three temperature sensors are installed within the wall. The wall composition is illustrated in Figure 2a, where sensors locations are $\{4, 10, 16\}$ cm. The wall surface and inside temperatures are monitored during 7 days. The *a priori* thermophysical properties of wall materials are described below [RT, 2012; Berger et al., 2021], they correspond to dry state. Using the *a priori* parameter values, one may compute the temperature variation without taking into account the relation between material properties and the moisture content. These values are compared to the measurements. Figure 3 displays results for three sensor positions respectively. Moreover, the inside and outside wall surface temperatures are presented in Figure 3a and Figure 3c respectively. To decrease a gap between the model predictions and the observations, one may estimate the moisture content variation. Therefore, the hypothesis of the moisture content influence is taken into account for the second layer. The *a priori* material properties and no moisture content are considered within the plasterboard layer.



(a)



(b)

Figure 2. (a) *Illustration of the wall domain and installed sensors,* (b) *illustration of the building.*

Brick:

$$\rho_0 = 2000\,[\mathsf{kg}\cdot\mathsf{m}^{-3}], \qquad \omega_{\text{sat}} = 225.8\,[\mathsf{kg}\cdot\mathsf{m}^{-3}],$$
$$k_0 = 1.0\,[\mathsf{W}\cdot\mathsf{m}^{-1}\cdot\mathsf{K}^{-1}], \qquad k_1 = 0.0032\,[\mathsf{W}\cdot\mathsf{m}^{2}/(\mathsf{kg}\cdot\mathsf{K})],$$
$$c_0 = 800\,[\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}], \qquad c_1 = 4180\,[\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}],$$

Plasterboard:

$$\rho_2 = 1000\,[\mathsf{kg}\cdot\mathsf{m}^{-3}], \qquad k_2 = 0.4\,[\mathsf{W}\cdot\mathsf{m}^{-1}\cdot\mathsf{K}^{-1}], \qquad c_2 = 1000\,[\mathsf{J}\cdot\mathsf{kg}^{-1}\cdot\mathsf{K}^{-1}].$$

Parameter Estimation Results. This section deals with an estimation of the moisture content spatial representation, using the shifted LEGENDRE polynomials. In this case study three sensors are installed within the wall, so, the hypothesis that the order of polynomial does not exceed 2 is applied. Therefore, the moisture content is as follows:

$$\omega(x) = a_0 Q_0(x) + a_1 Q_1(x) + a_2 Q_2(x), \qquad 0 \le \omega(x) \le 1,$$
$$\left|a_0\right| \le 1, \quad \left|a_1\right| \le \frac{1}{\sqrt{3}}, \quad \left|a_2\right| \le \frac{1}{\sqrt{5}}.$$

Results of the optimisation process are presented in Figure 4. Figures 4a, 4b, 4c display the measured temperatures together with uncertainty bond, which includes a measurement uncertainty and the uncertainty of sensor position, and the calculated temperatures, using the estimated moisture content distribution. One may note that a satisfactory agreement between the observations and the calculated temperature values is demonstrated for second and third sensor locations. However, it can be remarked that the temperature observed with the first sensor is different from the computed values. This difference can be associated with different reasons, which are

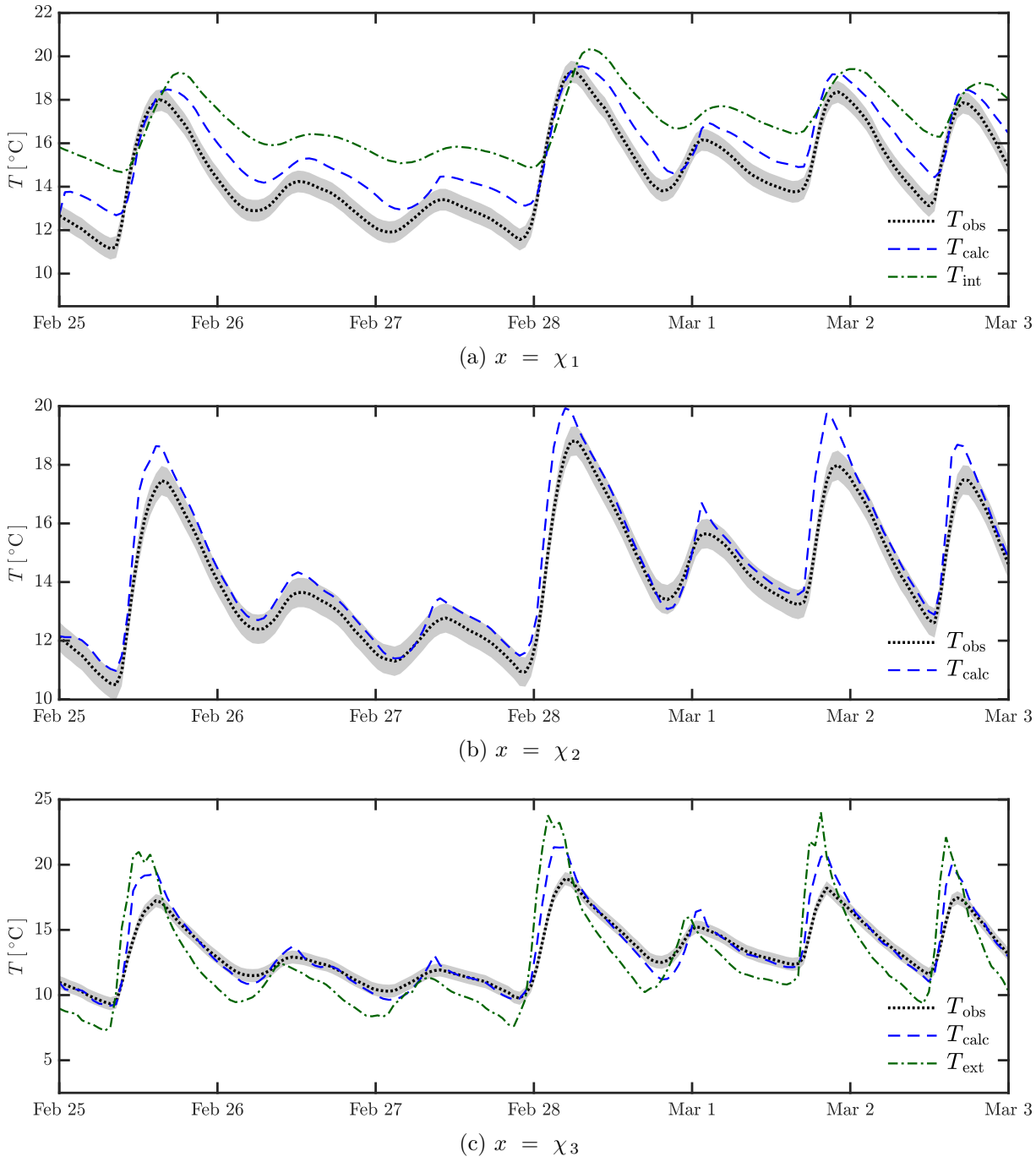


Figure 3. *Variation of the observations and computed temperature using* a priori *material properties, without effect of the moisture content, for* (a) *the first sensor and the interior wall surface;* (b) *the second sensor position;* (c) *the third sensor and the exterior wall surface.*

discussed below.

First, in this case study only three sensors are installed within the wall. Moreover, the polynomial approximation is assumed to be the second order. One may question whether the quadratic polynomial is sufficient to represent the moisture variation. Next, the objective of this study is to find a spatial representation of the moisture content variation. However, the moisture content can be dependent on the temperature variation as well as on the time. These dependencies are not considered in the methodology and should be further investigated. A gap can be seen in Figure 4c between the predictions and observations for some particular days, during daytime, probably, at midday. This is interpreted as the consequence of the moisture content temporal variation. There is a gap between the predictions and observations during day due to a drying process of the external wall surface. Moreover, only the heat transfer process through a wall is examined, while in practice, coupled heat and mass

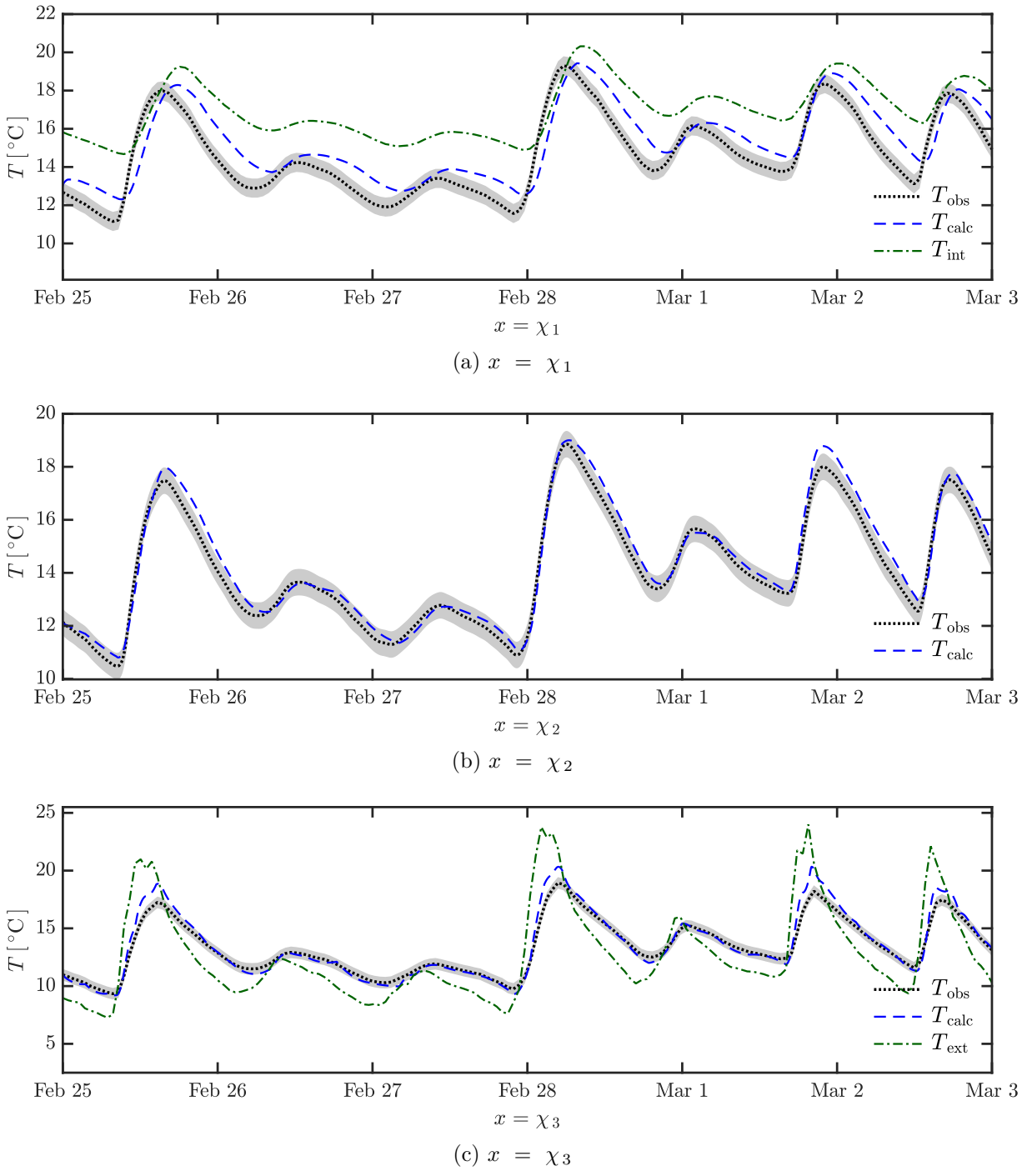


Figure 4. *Variation of the observations and computed temperature using the estimated moisture content distribution, for* (a) *the first sensor and the interior wall surface;* (b) *the second sensor position;* (c) *the third sensor and the exterior wall surface.*

transfer phenomena take place in porous building materials.

Additionally, the thermal conductivity and volumetric heat capacity spatial variations are computed using the estimated moisture content variation, where the related to the material properties coefficients are given by reference values. However, one may question the reliability of the *a priori* values. Due to building operation and degradation the material properties change, and the values, provided by references, may be different from the actual properties. According to experimental studies, the brick thermal properties significantly vary regarding the moisture content within the wall [Sassine et al., 2017; Rhee-Duverne and Baker, 2013]. Thus, it is important to investigate the estimation of the parameters c_0, k_0 or k_1. One may identify values of k_0 or k_1 using the optimization procedure, while decreasing the order of polynomials, which represents the moisture content variation. Therefore, two possible cases are considered. The first approach deals with the estimation the

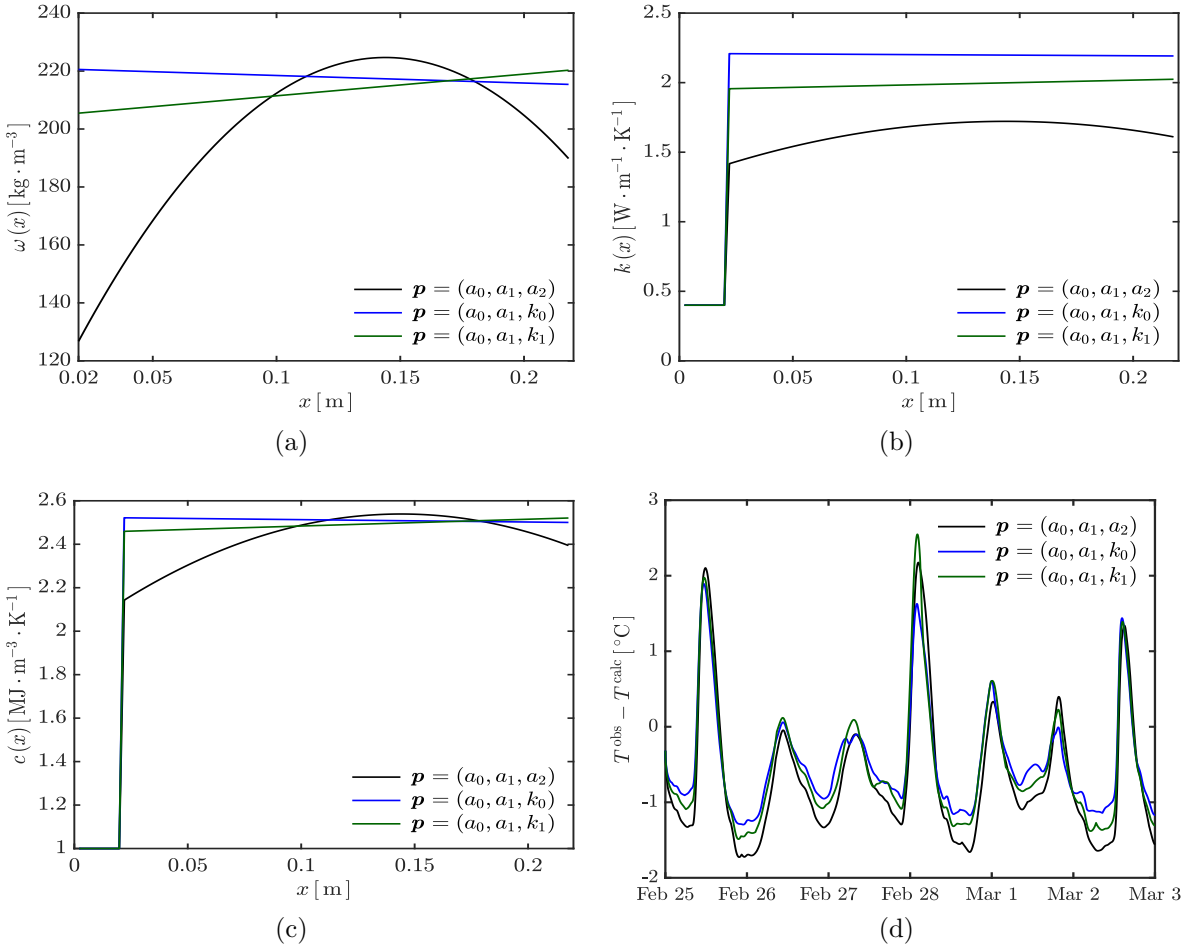


Figure 5. *Variation of the* (a) *the estimated moisture distribution representation in the brick layer,* (b) *estimated thermal conductivity and* (c) *volumetric heat capacity representations;* (d) *the difference between the observations and the calculated temperature values for different estimates at the first sensor location.*

following vector of parameters $\boldsymbol{p} = (a_0, a_1, k_0)$, second - $\boldsymbol{p} = (a_0, a_1, k_1)$. The estimated profiles of the moisture content variation are shown in Figure 5a. They differ according to the vector of parameters to be estimated. It can be noted the moisture content values are close to the saturation value on the external wall surface. Figures 5b, 5c display variation of the thermal conductivity and the volumetric heat capacity respectively. It can be noted that the values of material properties increase toward the external wall surface. However, these results do not improve much the model prediction values at the first sensor position. Figure 5d illustrate the difference between the observations and the calculated temperature values at the first sensor. One may note that the residuals are high for each approach, and reach $2\,^{\circ}\mathrm{C}$. It can be remarked a small advancement when the thermal conductivity value k_0 is identified together with the linear representation of the moisture content. However, the results still indicate that the mathematical model does not consider some physical phenomena. As an example, the moisture impact is considered only for the brick layer, however, the interior ambiance may influence the plasterboard as well. One may assume that moisture is homogeneous in the plasterboard layer due to its small thickness, thus, this value can be added to the set of parameters to be estimated. These relations can be also a key to close the gap between the model predictions and the observations.

Sensitivity Coefficients. The issue now is to investigate the practical identifiability of the estimated parameters. Three sensitivity functions of the coefficients a_0, a_1, a_2, of the polynomial approximation are computed, their variations are presented in Figure 6. One may note that the sensitivity function values are low, at order $\mathcal{O}(10^{-3})$. This fact indicates a small accuracy of the coefficients estimates. These results are in line with the gap between the model predictions and the observations, discussed earlier. Moreover, it can be seen in Figure 6c that the sensitivity coefficients of a_1 and a_2, are linearly dependent. Thus, it may impact on the accuracy of the estimates. Additionally, the residuals between the calculated temperature values and the measurements for three sensor positions are computed. The results are shown in Figure 6d. One may note that the first sensor values are high compared to the other two. Moreover, the mean is not equal to zero, highlighting the issue with

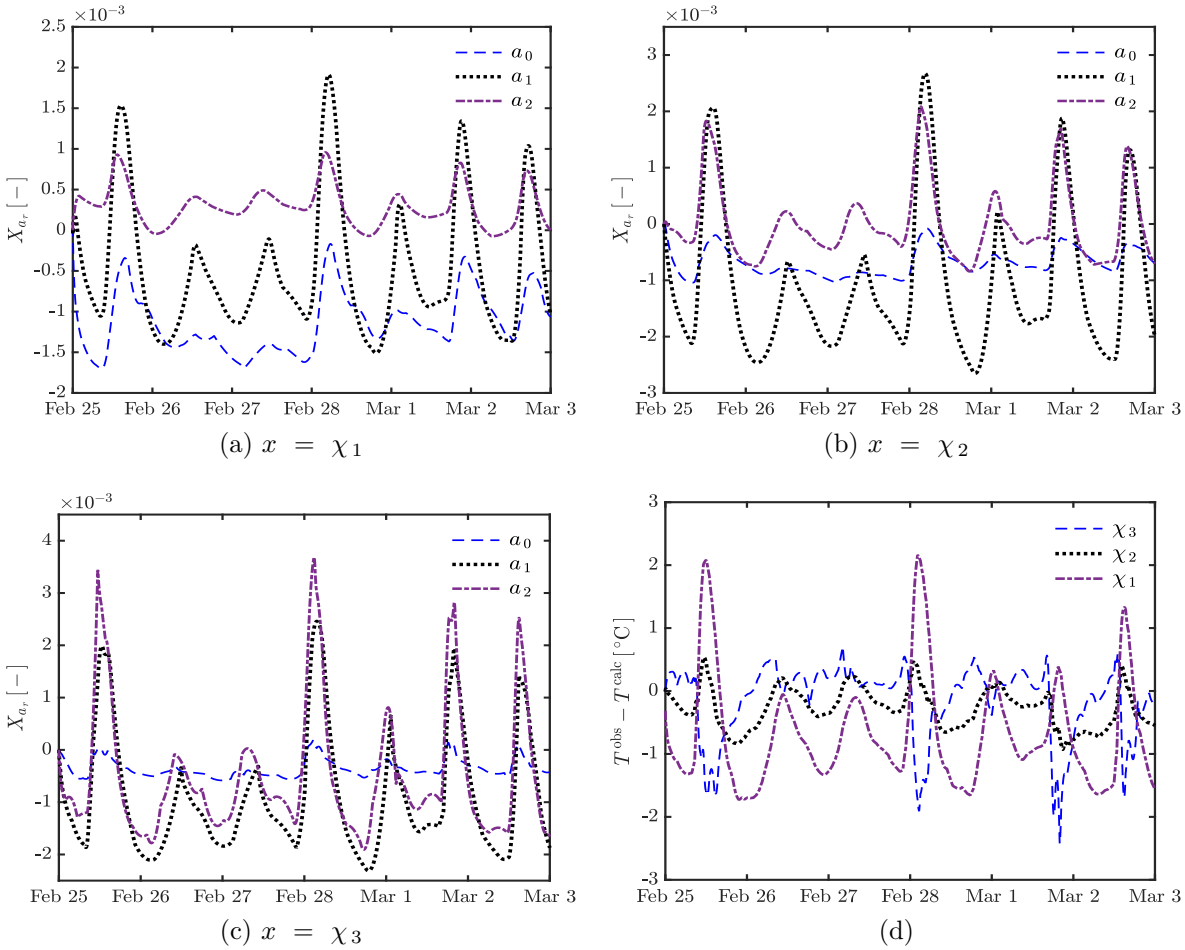


Figure 6. *Variation of the calculated sensitivity coefficients for* (a) *first,* (b) *second and* (c) *third sensor locations;* (d) *residuals between the calculated and the measurements.*

the mathematical model assumption.

CONCLUSION

The moisture distribution in existing building walls is of major importance. Its knowledge is required to accurately predict the building energy efficiency and the retrofitting actions. In this article several issues linked to determination of the moisture content variation within a wall are discussed. First, a spatial representation of the moisture content variation is presented using the shifted LEGENDRE polynomials. Moreover, a variation range of the approximation coefficients is discussed. Finally, a case study of an existing brick wall is investigated. Measurements of three sensors, installed within the wall, are used to solve the parameter estimation problem. Thus, the coefficients of the moisture content polynomial representations are estimated, the sensitivity functions are computed. However, results show a difference between computed temperature values and the measurements on the first sensor position. Several assumptions, used in the methodology, may produce this gap. Further investigations are required to determine a more accurate solution. These include a variation of the moisture content over the time and length of the wall, the heat and mass coupled phenomena, estimation of the thermal properties together with the moisture content distribution.

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