The Exploration of an Inverse Problem Technique to Obtain Material Properties of a Building Construction

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The exploration of an inverse problem technique to obtain material properties of a building construction

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ABSTRACT: The main goal of this work is to investigate whether material properties can be obtained using an inverse problem technique. The inverse problem technique used in this paper consists of three main parts: First, a set of input data (time series and parameters) and the objective data (time series) to be reproduced. Second, a model capable of simulating the requested data. Third, optimisation of the modeling parameters by fitting simulated data with the objective data. The suggested methodology of the inverse problem technique seems promising for estimating material properties but requires that: (1) All measurements errors must be known; (2) The (measured) signals itself should deliver enough input power into the system; (3) The simulated objective data should be sensitive enough for changes in material properties.

1 INTRODUCTION

Hunting Lodge St. Hubertus is one of the most prominent buildings from the beginning of the twentieth century and is noted in the top 100 list of Dutch monuments. The conservation of the building and its interior are of great importance.

Figure 1. Hunting Lodge St. Hubertus.

The Dutch Government Building Department, which takes care of the maintenance of the building, has expressed their concern about the observed damage due to high moisture levels by the rain that finds its way to the interior at places of inadequate detailing and therefore causes damage mainly near openings in the façade and on the inside of the façade below balconies.

The main problem is that the location and nature of the moisture leakages are not easily detectable. Often the relation between the observed inside surface moisture patterns and where the moisture enters the construction is unclear. Furthermore, there is also often a lack of information on material properties and boundary conditions. The latter has thoroughly been studied by Briggen et al. (2007 & 2009). Due to the monumental status of the building, it was not allowed to perform (destructive) measurements in order to get some information on the material properties of the façade.

The main goal of this work is to investigate whether material properties can be obtained using an inverse problem technique. A second goal is to evaluate this technique for heat and moisture engineering.

An inverse problem is the task that often occurs in many branches of science and mathematics where the values of some model parameter(s) must be obtained from the observed data (Wikipedia 2008).

The inverse problem technique used in this paper consists of three main parts:

* A set of input *data* (time series and parameters) and the objective data (time series) to be reproduced
* A *model* capable of simulating the requested data.
* Optimisation of the modeling parameters by fitting simulated data with the objective data..

The paper is organised according the above mentioned three parts. Section 2 provides specific information on the data set. Section 3 presents the modeling tool including verification data. Section 4 shows the simulation results using a preliminary model and the first steps of an optimisation study. Finally, Section 5 provides a discussion of the results.

2 DATA SET (MEASUREMENTS)

The data set is part of the measurement program at the Hunting Lodge St. Hubertus site, performed during 2006-2007 by Briggen (2007). Details of this project can be found in Briggen et al (2009). One of problems seemed to be high moisture contents at the inside surface of the façade of the tower. The construction of this façade is shown in figure 2.

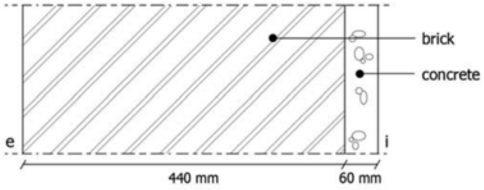

Figure 2. The building façade

The outside climate conditions were measured by a weather station within 50m from the building. The inside air temperature and relative humidity were measured using standard equipment (see figure 3). A representation of inside surface conditions were obtained by placing a small box (5cm x 5cm x 1cm) against the wall and measure the air temperature and relative humidity inside. The estimation of the measurement error of this method is left over for future research.

Figure 3. Measurement of the surface temperature and relative humidity using a box

The *input* data consists of the measured time series of the indoor and outdoor climate as presented in figures 4 and 5.

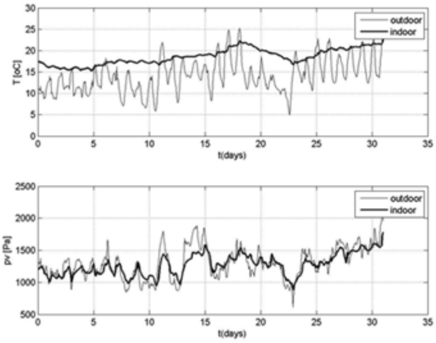

Figure 4. The measured air temperatures (top) and calculated vapour pressures (bottom, from measured T/RH)

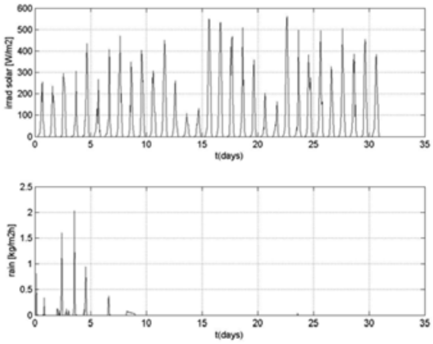

Figure 5. The measured solar irradiance (top) and rain intensity (bottom)

The *objective* data consists of the measured time series of the surface conditions at the indoor surface as shown in figure 6.

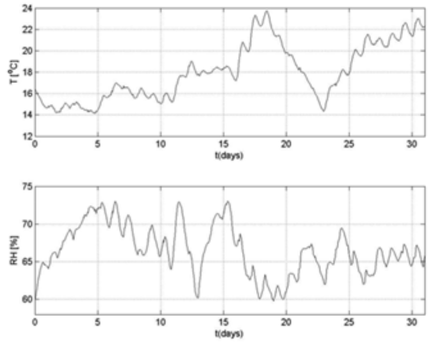

Figure 6. The objective data to be simulated: Air temperatures (top) and relative humidity (bottom) near the indoor wall surface.

3 MODELING

As mentioned in Section 1, a model capable of simulating the requested data is required. Amongst other possibilities, the multiphysics modeling approach of van Schijndel (2007) is selected. A guideline on how to implement up to 3D heat air and moisture (HAM) transport models using COMSOL (2008) is already provided (van Schijndel 2006). There are two major extensions to this work, described in the following sections: First, the implementation of LPc as moisture potential for including both vapour and liquid transport and second, the implementation of material and boundary functions for calculating the PDE coefficients from the material properties. The implementation of the two new extensions is verified using the HAMStad benmark 1 (Hagentoft et al 2002). This is shown Section 3.3.

3.1 *Extension 1: Implementation of LPc potential*

The heat and moisture transport can be described by the following PDEs:

$$C_T \frac{\partial T}{\partial t} = \nabla \cdot (K_{11} \nabla T + K_{12} \nabla LPc)$$
$$C_{LPc} \frac{\partial LPc}{\partial t} = \nabla \cdot (K_{21} \nabla T + K_{22} \nabla LPc) \qquad (1)$$

With

$$LPc = {}^{10}\log(Pc)$$
$$C_T = \rho \cdot c$$
$$K_{11} = \lambda$$
$$K_{12} = -l_{lv} \cdot \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT},$$
$$C_{LPc} = \frac{\partial w}{\partial Pc} \cdot \frac{\partial Pc}{\partial LPc} \qquad (2)$$
$$K_{22} = -K \cdot \frac{\partial Pc}{\partial LPc} - \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT},$$

$$K_{21} = \delta_p \cdot \phi \cdot \frac{\partial Psat}{\partial T},$$

Where t is time [s]; T is temperature [^{o}C]; P_c is capillary pressure [Pa]; ρ is material density [kg/m^3]; c is specific heat capacity [J/kgK]; λ is thermal conductivity [W/mK]; l_{lv} is specific latent heat of evaporation [J/kg]; δ_p vapour permeability [s]; φ is relative humidity [-]; Psat is saturation pressure [Pa]; M_w = 0.018 [kg/mol]; R = 8.314 [J/molK]; ρ_a is air density [kg/m^3]; w is moisture content [kg/m^3];K is liquid water permeability [s].

3.2 *Extension 2: Implementation of advanced material and boundary functions*

The second extension is the implementation of advanced material and boundary functions using Matlab. These functions are used to convert measurable material properties such as K, φ, δ_p and λ which are depent on the moisture content into PDE coefficients which are dependent on the LPc and T. This is schematically shown in figure 7.

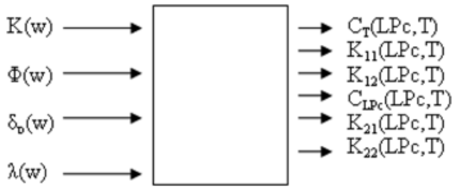

Figure 7. The conversion from measurable material properties into PDE coefficients

The results for two materials (based on HAMstad benchmark 1) are presented in figure 9.
For each material and at each point the vapour pressure can be calculated using a similar corresponding function.

3.3 *Verification using HAMSTad benchmark 1*

Benchmarks are important tools to verify computational models. In the research area of building physics, the so-called HAMSTAD (Heat, Air and Moisture STAnDardization) project is a very well known reference for the testing of simulation tools. This Section summarizes the results for the HAMSTAD benchmark no.1: 'Insulated roof'. The roof structure is analyzed in 1D regarding dynamic heat and moisture transport. The thermal insulation is facing the interior and a there is moisture barrier facing the exterior. The structure is perfectly airtight. Figure 8 shows the structure:

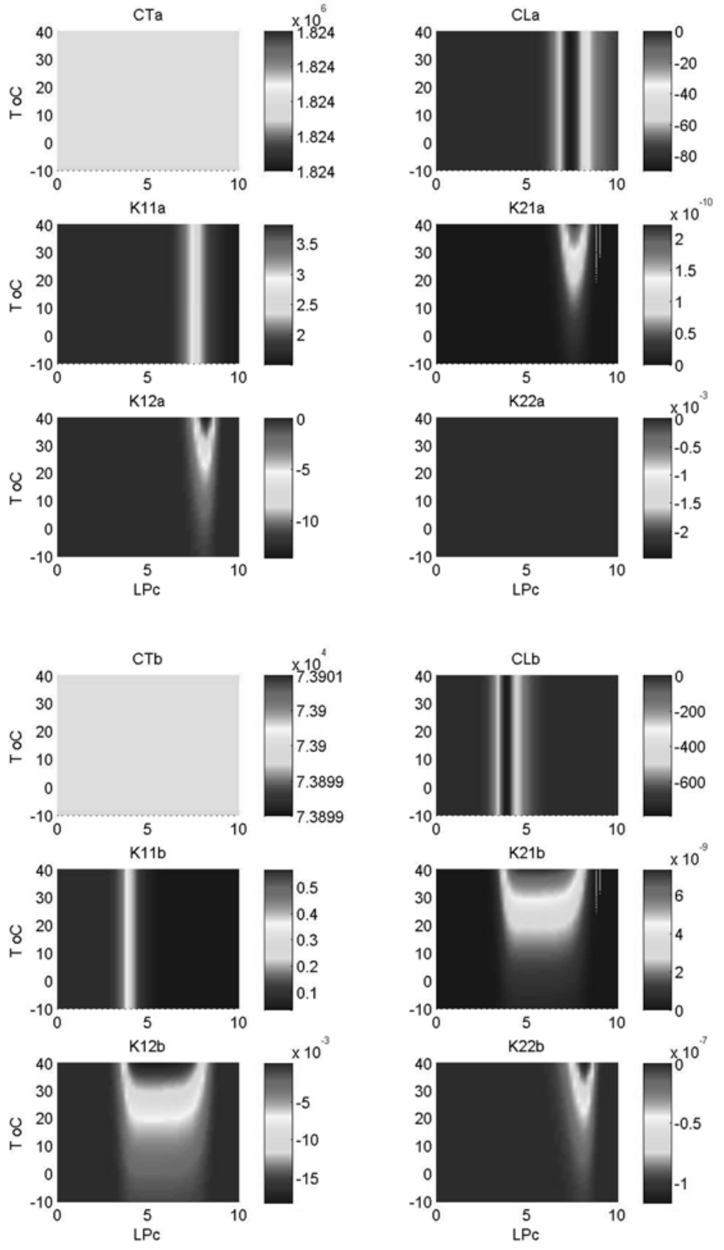

Figure 9. PDE coefficients C_T,C_{LPc},K_{ij} as functions of LPc and T calculated from the provided HAMSTAD benchmark no.1 material properties for the load bearing (a) and insulation (b) material (please note that this figure relies on colour, see digital version)

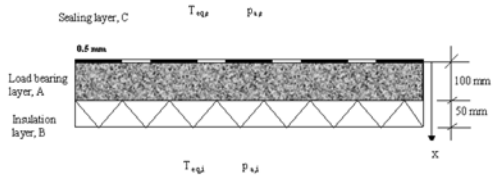

Figure 8. A schematic of the structure of the benchmark

The governing PDE equations are given by (1). Figure 9 provides the PDE coefficients for load bearing material a and insulation material b. The boundary conditions are at the (i)nternal (connected with material a):

$$\begin{aligned} q &= h_i \cdot (T_i - T) + l_{lv} \cdot \beta \cdot (p_i - p) \\ g &= \beta \cdot (p_i - p) \end{aligned} \tag{3}$$

and (e)xternal (connected with material b):

$$\begin{aligned} q &= h_e \cdot (T_e - T) \\ g &= 0 \end{aligned} \tag{4}$$

Where q is heat flux [W/m^2]; h is convective heat transfer coefficient [W/m^{2}K]; β is vapour transfer coefficient [kg/Pam^{2}s]; p is vapour pressure [Pa]; g is moisture flux [kg/m^{2}s]; The boundary conditions are hourly based values provided by benchmark.. The results are shown in figures 10 and 11.

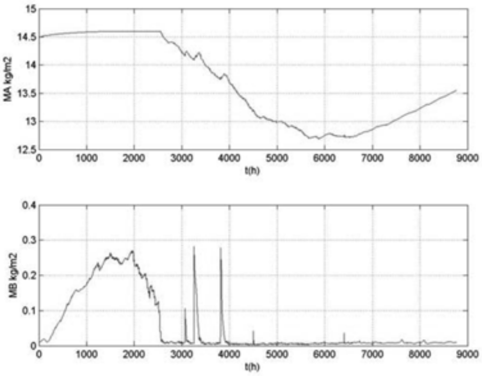

Figure 10 The simulated total mass in the load bearing material (top) and insulation material (bottom) during the first year

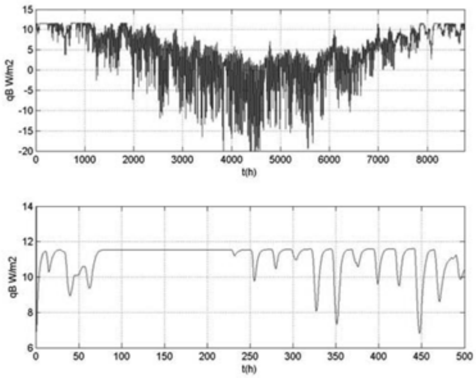

Figure 11 The simulated heat flows interior (bottom) and exterior (top) to the wall during the first year

Confronting these results with the benchmark, it is concluded that the results are within the provided bandwidths. Other benchmarks will be evaluated in near future. Moreover, the ‘benchmark 1’ model using COMSOL (2008) and companying report are published at the HAMLab (2008) research and education website.

At this point it is concluded that the model is promising in simulating the requested objective data (see figure 6).

4 THE INVERSE PROBLEM

4.1 *Signal analysis*

First of all, the sampling and Nyquist frequency Brigham (2004) of the signal are analyzed. The reader should notice that, when sampling a signal, the sampling frequency must be greater than twice the bandwidth of the input signal in order to be able to reconstruct the original perfectly from the sampled version (Nyquist-Shannon theorem Brigham (2004)). Mathematically, the theorem is formulated as a statement about the Fourier transformation. If a function s(x) has a Fourier transform $F[s(x)] = S(f) = 0$ for $|f| \geq W$ then it is completely determined by giving the value of the function at a series of points spaced 1/(2W) apart. The values sn = s(n/(2W)) are called the samples of s(x). The minimum sample frequency that allows reconstruction of the original signal, that is 2W samples per unit distance, is known as the Nyquist frequency. With respect to the Nyquist-Shannon theorem, an inverse problem model is able to capture information regarding building dynamics perfectly for all frequencies with a smaller frequency than the frequency of the data used for identification (Sample frequency). For higher frequencies the inverse model may cause deviations. In this case it is expected that the latter is no problem because the time scale of interest is one hour and the sample time is 10 minutes.

Second, the input signal (u(t)) should deliver as much input power into the system as possible. The amount of input power, present in the input signal, is defined as the Crest factor $C_{f,}$ Equation (5) (Girod et al. (2001); wiki (2008)). The Crest Factor, originating from electrical engineering, is a quick and useful calculation that gives the analyst an idea of how much impacting is occurring in a time waveform. This is useful information that is lost if one is only viewing a spectrum as the Fast Fourier Transform cannot differentiate between impacting and random noise. The smaller the Crest factor, the better the signal excitation resulting in larger total energy delivery and enhanced signal-to-noise ratio. The theoretical lower bound for the Crest factor is 1.

$$C_f = \frac{\max(u(t))}{\sqrt{\langle u^2 \rangle}} \tag{5}$$

In table I the Crest factor for each signal of figures 4 through 6 is presented.

Table I The Crest factors for each signal

Signal	Crest factor
T_i	7.0
T_e	12.7
pv_i	7.9
pv_e	10.2
$Irrad_{sol}$	4.6
Rain	17.8
T_{oppi}	9.1
RH_{oppi}	23.8

From table I it is observed that the rain intensity has a relative high Crest factor. This could be expected because there are less than 10 rain events in one month. Moreover, the measured inside surface relative humidity has the highest Crest factor. This could indicate a small signal excitation. Due to the mentioned high Crest factors present at some of the crucial time signals, it is doubtful whether these signals are usable for inverse problem modeling. Perhaps longer measurement periods are necessary the provide better Crest factors. On the other hand, the Crest factor which is an important measure from the electrical engineering point of view, could be less important in this case study. Nevertheless, more research on the applicability of the Crest factor is needed.

4.2 *The results of a first guess*

The material database of DELPHIN (2008) is used to provide material properties for the first guess. For brick, the Brick material properties of DELPHIN are used with constant ρ= 1700; c = 840; λ = 0.85 and variable moisture properties using the tables. For concrete, the Lime plaster properties of DELPHIN (ρ= 1800; c = 840; λ = 1.05) are used in the same way. From these data, the PDE coefficients were determined similar to figure 9 and together with the boundary conditions implemented using the COMSOL model of Section 3. Figure 12 and 13 show the results.

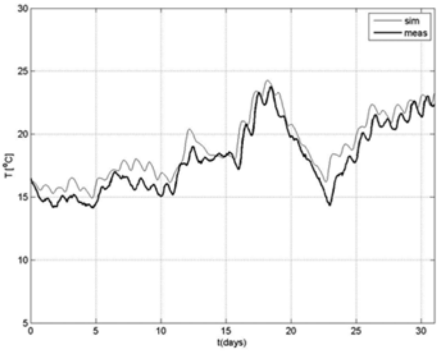

Figure 12. The measured and simulated inside surface temperature.

Figure 12 shows that the simulated inside surface temperature is already quite close to the measured one. At this point it is very important to consider possible errors (due to measurement methodology) of the objective data. The main questions are: First, what is uncertainty band of the measured inside temperature? Second, is it possible simulated the inside temperature inside the uncertainty band by manipulating PDE and boundary coefficients?

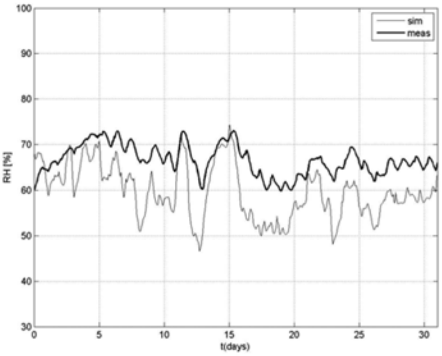

Figure 13. The measured and simulated relative humidity at the surface.

The simulated relative humidity at the inside surface of figure 13 seems to be less close to the measured one compared to the previous figure. This gives also rise to the just mentioned questions

4.3 *Optimisation*

As a first step towards a full model parameter optimisation, the dependency of simulated indoor surfaced temperature to the PDE coefficients (including the boundaries) was investigated. The outcome was that it the simulated indoor surface conditions seem to be quite insensitive for the PDE coefficients and surface coefficients as exemplary shown in figures 14 and 15.

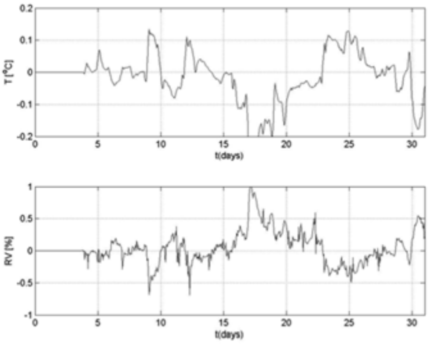

Figure 14. The difference in simulated surface temperature (top) and relative humidity (bottom) using 0.5 λ and 2 λ.

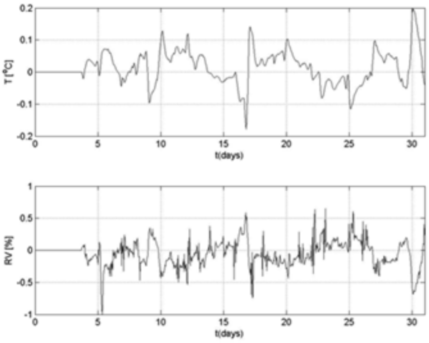

Figure 15. The difference in simulated surface temperature (top) and relative humidity (bottom) using $h_i = 2.5$ versus $h_i = 25$.

Both figures show low sensitivities (temperature ~ 0.2 °C and relative humidity ~ 1%) close to the expected (stochastic) measurement error. This could mean that the methodology is not applicable for this type of building construction.

5 DISCUSSION AND CONCLUSIONS

It is quite clear that there are still major problems to be solved before the suggested methodology of the inverse problem technique will be useful for estimating material properties. Before going into the drawbacks of the approach, the reader should notice that the major benefit, in case of a successful method, could be that material properties are very easy obtained in situ and without damaging the construction by quite simple measurements. However, this is clearly not the case yet due to the following limitations:

(1) All measurements errors must be known. For example, in this case sensors are placed in a small box attached to the inside wall (see figure 3). This means that there is also a systematic error in measuring the inside surface conditions.

(2) The (measured) signals itself should deliver enough input power into the system. For example in this research, the rain intensity has a relative high Crest factor due to the less than 10 rain events in one month.

(3) The simulated objective data (in this case inside surface conditions) should be sensitive enough for changes in material properties. For example in this case the heat conduction coefficients of both materials were simultaneously doubled or halved and the results were compared (see figure 14). The result was only a minor effect. The effect seems to be too low for obtaining reliable material properties.

It is recommended, in case of applying inverse problem techniques, to simulate the sensitivity of the objective data on the material properties before starting measurements. Furthermore, if this simulated sensitivity is promising, the measurement error should be an order lower than the sensitivity.

ACKNOWLEDGEMENT

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