3. GENERATION OF THE DATA

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ABSTRACT

This chapter is concerned with the generation of data for the System Identification Competition. A simulation model based on the physical properties of a wall has been developed in order to simulate a wall in practical situations. Various data series were generated to simulate internal and external surface temperatures of the concerning wall which are the inputs for the simulation model. The generation of these temperatures as well as the heat flow is described in detail. Furthermore different existing identification are applied on the generated data series in order to check the quality of the data.

3.1. INTRODUCTION

A variety of new techniques is being applied to the analysis problems involved with estimation of thermal characteristic parameters of building components in order to describe and predict the thermal behaviour of whole buildings. Similar problems arise in most observational disciplines, including physics, biology, and economics. New commercially available software tools, promise to provide results that are unobtainable just a decade ago.

Because the realisation and evaluation of this promise has been hampered by the difficulty of making rigorous comparisons between competing techniques, particularly ones that come from different disciplines, the Joint Research Centre has set up a competition in order to make a comparison between different techniques. This competition consists of five cases with different identification problems which are to be identified by the participant.

These five cases represent an one or more layer slab that can be compared with a wall. In order to provide reliable data an accurate simulation of the physical process has to be made for these walls, which is described in section 3.2. In this chapter the whole process of simulation and generation of the data series is described as well as the different temperature series and noise series that were used.

Three different identification techniques have been applied on the generated data to verify the quality of the data, these are briefly presented in section 3.6.

3.2. SIMULATION MODEL

The only possible way to develop a realistic simulation model for the density of heat flow rate in a wall is to base this model on the physical theory of heat transfer in a layer. In this simulation model the assumption has been made that the heat transfer in a wall is only a result of conductivity in that wall. Although in real situations the heat flows in three dimensions this model describes the flow in one dimension because the assumption has been made that the

surface temperatures were constant. The thermal properties of each layer are also supposed to be independent of time and temperature.

3.2.1 Theory of simulation model

Conductive heat transfer is governed by the time and space dependent Kirchhoff-Fourier equation which for one dimension x takes form;

$$\frac{\delta\,\theta(t,x)}{\delta\,t} = a_t \frac{\delta^2\theta(t,x)}{\delta\,x^2}$$

(3.1)

where :

t	: time [sec]
x	: position [m]
$\theta(t,x)$	: temperature distribution in the wall as a function of time t [°C]
$a_t = \dfrac{\lambda}{\rho\,c_p}$	: thermal diffusely $\left[\dfrac{m^2}{s}\right]$
ρ	: density $\left[\dfrac{kg}{m^3}\right]$
λ	: thermal conductivity $\left[\dfrac{W}{°Cm}\right]$
c_p	: specific heat capacity $\left[\dfrac{Wh}{°Ckg}\right]$

The solution of equation (3.1) requires one initial and two boundary conditions :

$$\theta(t,x)\big|_{t=0} = 0 \ for \ 0 \ £ \ x \ £ \ d$$

This assumption does not mean any restrictive on the solution since it may be proven, that a non-zero condition always can be reduced to a zero condition.

$$\boldsymbol{q}(t,x)\big|_{x=0} = \boldsymbol{q}_i(t)$$

$$\boldsymbol{q}(t,x)\big|_{x=d} = \boldsymbol{q}_e(t)$$

Now the heat conduction problem of the single layer is completely defined and the solution can easily be obtained by applying the Laplace transform to both sides of equation (3.1) yields:

$$\frac{\delta\,\theta(s,x)}{\delta\,x^2} - q^2\theta(s,x) = 0$$

(3.2)

where: s is the Laplace variable associated with time t, and
$\theta(s,x)$ is the Laplace transform of $\theta(t,x)$

Equation (3.2) is an ordinary differential equation with the general solution in the s-domain:

$$\theta(s,x) = C_1(s)\sinh(qx) + C_2(s)\cosh(qx) \qquad (3.3)$$

The heat flow satisfies the equality:

$$J(x,t) = -\lambda \frac{\delta\theta\ (x,t)}{\delta\ x} \qquad (3.4)$$

Applying the Laplace transform to equation (3.4):

$$J(s,t) = -\lambda \frac{\delta\theta\ (s,t)}{\delta\ s} \qquad (3.5)$$

With equation (3.3) equation (3.5) denotes:

$$J(s,t) = -\lambda\ q\left[C_1(s)\cosh(qx) + C_2(s)\sinh(qx)\right] \qquad (3.6)$$

The constants C_1 and C_2 can be expressed as follows:

$$C_1 = -\frac{1}{\lambda\ q}J(s,0) = -\frac{1}{\lambda\ q}J_0 \qquad (3.7)$$

$$C_2 = \theta(s,0) = \theta_0 \qquad (3.8)$$

Substitution from equations (3.7) and (3.8) into equations (3.3) and (3.5) yields :

$$\theta(s,x) = \cosh(qx) \times \theta_0 - \frac{1}{\lambda\ q}\sinh(qx) \times J_0 \qquad (3.9)$$

$$J(s,x) = -\lambda\ q\sinh(qx) \times \theta_0 + \cosh(qx) \times J_0 \qquad (3.10)$$

Equations (4.9) and (4.10) can be written in a more general matrix relationship :

$$\begin{pmatrix} q(s,x) \\ J(s,x) \end{pmatrix} = \begin{bmatrix} \cosh(qx) & \dfrac{-\sinh(qx)}{lq} \\ -lq\sinh(qx) & \cosh(qx) \end{bmatrix} \begin{pmatrix} q_0(s) \\ J_0(s) \end{pmatrix} \qquad (3.11)$$

With :

$$\lambda\ q = \sqrt{\rho\ c_p\lambda\ s} \qquad (3.12)$$

$$qx = \sqrt{\frac{\rho\ cx^2 s}{\lambda}} \qquad (3.13)$$

Defining the heat resistance R and the heat capacity per unit area C as follows:

$$R = \frac{d}{l}\quad \left[\frac{{}^{\circ}C\cdot m^2}{W}\right] \qquad\qquad C = rc_p d\quad \left[\frac{Wh}{{}^{\circ}C\cdot m^2}\right]$$

and :

$\boldsymbol{q}_i$: internal surface temperature

$\boldsymbol{q}_e$: external surface temperature

q_i : internal density of heat flow rate

q_e : external density of heat flow rate

a matrix relationship can be written in the Fourier domain for a one-layer wall:

$$\begin{pmatrix} \boldsymbol{q}_i(\boldsymbol{w}) \\ q_i(\boldsymbol{w}) \end{pmatrix} = \begin{bmatrix} \cosh(\sqrt{i\boldsymbol{w}RC}) & \dfrac{R \cdot \sinh(\sqrt{i\boldsymbol{w}RC})}{\sqrt{i\boldsymbol{w}RC}} \\ \dfrac{\sqrt{i\boldsymbol{w}RC} \cdot \sinh(\sqrt{i\boldsymbol{w}RC})}{R} & \cosh(\sqrt{i\boldsymbol{w}RC}) \end{bmatrix} \begin{pmatrix} \boldsymbol{q}_e(\boldsymbol{w}) \\ q_e(\boldsymbol{w}) \end{pmatrix} \tag{3.14}$$

This matrix formulation is especially useful in multi-layer models because these models can be expressed as a matrix multiplication of the individual matrices of the different layers. For a n-layer wall the matrix relationship takes the form :

$$\begin{pmatrix} \boldsymbol{q}_i(\boldsymbol{w}) \\ q_i(\boldsymbol{w}) \end{pmatrix} = M_{total} \begin{pmatrix} \boldsymbol{q}_e(\boldsymbol{w}) \\ q_e(\boldsymbol{w}) \end{pmatrix} \tag{3.15}$$

With :

$$M_{total} = \overset{x=n}{\underset{x=1}{\mathbf{O}}} M_{layer\,x} \tag{3.16}$$

and

$$M_{layer\,x} = \begin{bmatrix} \cosh(\sqrt{i\boldsymbol{w}R_x C_x}) & \dfrac{R_x \cdot \sinh(\sqrt{i\boldsymbol{w}R_x C_x})}{\sqrt{i\boldsymbol{w}R_x C_x}} \\ \dfrac{\sqrt{i\boldsymbol{w}R_x C_x} \cdot \sinh(\sqrt{i\boldsymbol{w}R_x C_x})}{R_x} & \cosh(\sqrt{i\boldsymbol{w}R_x C_x}) \end{bmatrix} \tag{3.17}$$

An expression for the density of heat flow rate is needed, therefore it is of interest to find an equation that expresses the relation between q_i, $\boldsymbol{q}_i$ and $\boldsymbol{q}_e$. The equation for the density of heat flow rate can be expressed as follows :

$$q_i(\boldsymbol{w}) = \frac{M_{total}(2,2)}{M_{total}(1,2)} \cdot \boldsymbol{q}_i(\boldsymbol{w}) - \frac{1}{M_{total}(1,2)} \cdot \boldsymbol{q}_e(\boldsymbol{w}) \tag{3.18}$$

where: w is the cycle frequency in cycles/hour.

Equation (3.18) makes it possible to simulate the internal heat flow for different walls by using both surface temperatures.

3.2.2 Application of simulation

To simulate the density of heat flow rate properly, the simulation model was based on the above derived theoretical differential equations. Equation (3.18) can only be solved in the frequency domain, a Fourier transform is applied on the input signals. This results in a density of heat flow rate expressed in the frequency domain that can be transformed to the time domain by using an inverse Fourier transform.


Internal side   External side

$\theta_i(t)$ **R, C** $\theta_e(t)$

$q_i(t)$ $q_e(t)$
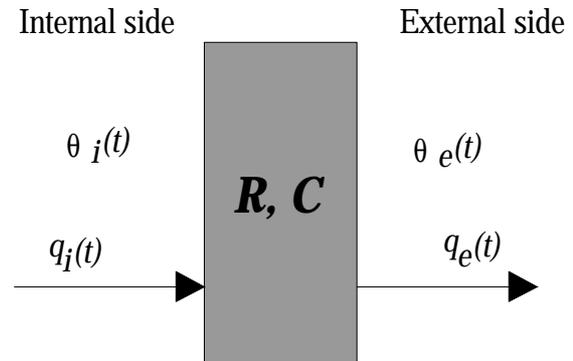
Figure 3.1 : Picture of a wall

The simulation model is based on a wall with known thermo-physical properties and surface temperatures, so the input variables of the model are :

- number of layers
- R_x, thermal resistance of layer x [°C m^2/W]
- C_x, thermal capacity per unit area of layer x [Wh/(°C m^2)]
- $q_i(t)$, internal surface temperature at time t [°C]
- $q_e(t)$, external surface temperature at time t [°C]

A schematic picture of an one layer wall is shown in figure 3.1.

The output variable is :

- $q_i(t)$, density of heat flow rate on the inside layer at time t

The program, *simuwall.m*, that is based on this model was written in the MATLAB 4.0 environment and consists of the following steps:

- input of surface temperatures
- input of wall type and wall properties
- calculation of model in frequency domain
- calculation of heat flow in frequency domain by term by term multiplication of temperatures and model
- application of inverse Fourier transform on this heat flow

MATLAB 4.0 computes in eight decimals, therefore the heat flow is calculated in eight decimals accuracy. However data will be delivered in maximum 4 decimals.

3.3 GENERATION IN GENERAL

The aim of the competition has been to make a comparison possible between identification techniques that are used to analyse building energy data as well as to understand similarities

and differences among these techniques. For this reason four of the five cases are comparable with practical experiments in order to see the characteristics of the different techniques. Two of these four cases are related to the identification of the thermal resistance and the thermal capacity of a wall, the other two are defined to test the ability of a technique to predict the heat flow on the inside layer of a wall.

In the previous section it was demonstrated that with the surface temperatures of the wall a density of heat flow can be simulated for different kinds of walls. In this section it will be explained what input signals has been used to simulate the heat flow.

3.3.1 Procedure

In figure 3.2 the applied procedure is shown how the final data series that simulate the outcome of an experience were obtained. The first step is the production of surface temperatures out of TRY data series which are used as inputs for the heat flow simulation program and have to be comparable with practical surface temperatures. After the simulation of a noise-free density of heat flow rate noise is added to this heat flow as well as to the surface temperatures to simulate the outcome of a measurement.
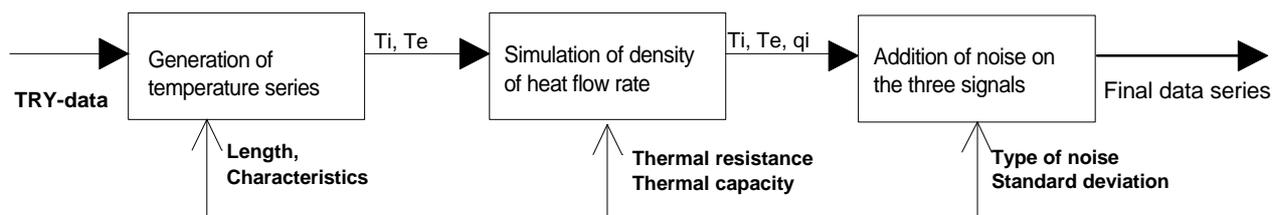

Figure 3.2: Scheme of generation

3.3.2 Temperatures

The data that has been used to generate the surface temperatures is TRY-data. 'Test Reference Year' (TRY) is the common used for climatic data for simulating the performance of solar energy systems, building energy consumption and for indoor climate calculations. A TRY data series consists of hourly values for a period of one year for a number of weather parameters, which are important for the above-mentioned purposes.

Real measured data has been used in the TRY's in order to obtain ;
- true frequencies and a natural distribution of higher and lower values for single days
- true sequences

TRY data series are available for several sites in Europe and are provided in one decimal accuracy. The minimum difference between two non identical values (the discretisation level) is 0.1°C, however the noise that will be put on the signals after the simulation makes this difference very small.

For the external surface temperatures several TRY-data series were used.

Internal surface temperatures usually have other characteristics than external temperatures as a result of the absence of wind, rain, solar radiation and big temperature fluctuations. In order to adjust the TRY series to internal surface temperatures the following alterations were made ;

- attenuation of the magnitude of the fluctuations by multiplication of the TRY data with a attenuation factor in the time domain.
- filtering the very high frequencies by a low pass filter with a high cut-off frequency

The second step also avoids an aliasing effect on the heat flow that could appear if the T_i contains high frequencies that are amplified by the heat flow simulator. A second order ideal Butterworth filter was applied on the internal temperatures to attenuate the frequencies with period of less than three hours. The cut-off frequency corresponding to this filter is 2/3 (number of data points/(maximum frequency * 3 hour)). The transfer function of this filter is plotted in figure 3.3.

Of course these changes in the temperatures have no effect or the resistance of capacitance of the wall, because the density of heat flow rate was simulated using these "changed" temperatures.
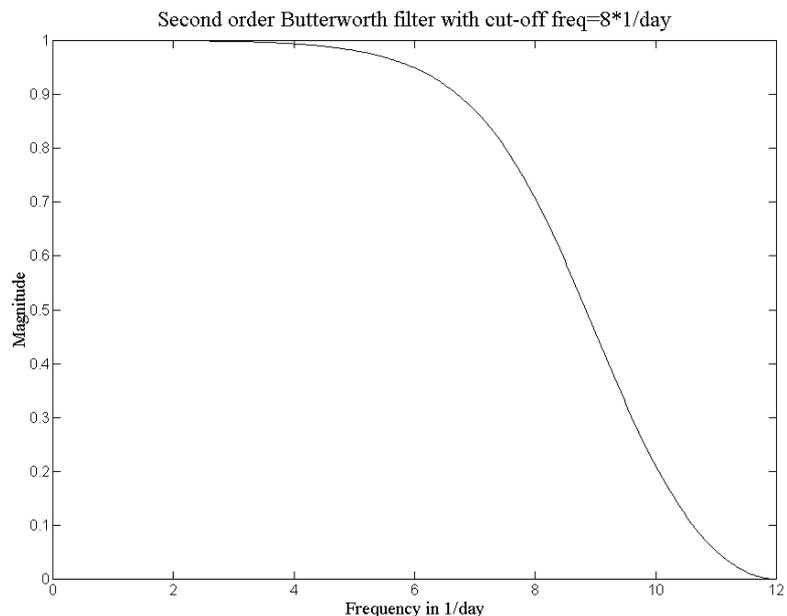

Figure 3.3 : Transfer function of filter

3.3.3 Heat flow

The generation of the density of heat flow rate on the internal layer is made with the heat flow simulator that is described in section 3.2. This simulator is capable to simulate one layer walls as well as multi-layer walls. For each case a longer period than necessary was generated to avoid start and end effects.

3.3.4 Noise

After the simulation to the time domain, noise was added to all three variables in order to simulate the output of a sensor. The noise that has been added to the signals is white noise. It has an uniform distribution and has been produced by the white noise generator, a procedure that is written in FORTRAN. This is a noise generator using the *drand48* generator with coefficients : a = 25214903917, b = 11, c = 2^48 and initial seed = 0d0. The Fortran procedure computes in double precision. It is desired not to add a same noise sequence to the different data series. Thus for each case the initial seed has been changed to obtain another realisation of the 'same' kind of white noise. The Fortran procedure that generates the noise is

taken from "Stochastic Simulation" by Brian D. Ripley. The standard deviations were selected different for each case and each data series, comparable to realistic situations.

3.4 CASES

3.4.1 Case 1

Case 1 is a simulation of a homogeneous wall with high thermal mass and high thermal resistance. The goal of Case 1 is to make estimates of R and C. The density of heat flow rate is assumed to be the average of four heat flow sensors. To approximate a practical measurement real data series were used and noise was added to the temperatures as well as to the density of heat flow rate.

This case consists of two files, *Data11.txt* and *Data12.txt*, that are consecutive. The first data set has a length of eight weeks, the second is two weeks longer and reflects a sensor breakdown started in the beginning of the last two weeks. The change as a result of this breakdown lasts for the rest of the measurement period.

In order to avoid initial effects of the heat flow simulation a longer period than necessary are produced, the simulation will start two weeks before and will end two weeks after the ten weeks, see figure 3.4. The sensor breakdown was simulated by subtracting one fourth of the value from the point of breakdown before the noise was added ;

$$T(t) = \frac{3}{4} * T(t) \ for \ t \geq t_{breakdown} \ \text{and} \ T_{final}(t) = T(t) + noise$$

the temperatures are supposed to be the averages of four sensors.
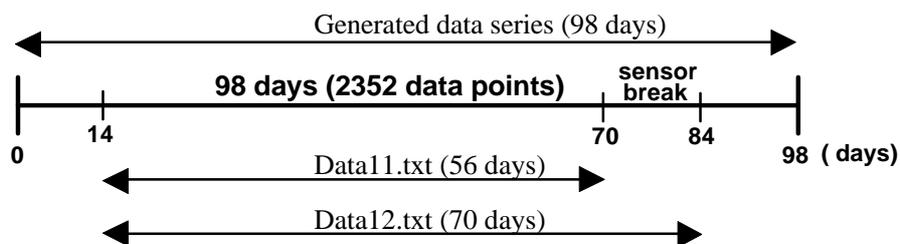
Figure 3.4 : Generation of case 1

The characteristics of the data series are:

File name data file   : *Data11.txt, Data12.txt*
File name statistic file   : *Datastat.txt*
Total generated period   : 98 days, (hourly sampled), 2352 points
Length *Data11.txt*   : 56 days, (hourly sampled), 1344 points
Length *Data12.txt*   : 70 days, (hourly sampled), 1680 points
Number of layers   : 1
The thermal resistance of the wall   : R = 8.651 Km^2/W

The thermal capacitance of the wall	: $C = 53.472$ Wh/Km^2

Initial seed of *noise.for*	: 0d0
Length noise series	: 1680 points (70 days)
Standard deviation noise on Te	: 0.5 °C (*n11.dat*)
Standard deviation noise on Ti	: 0.2 °C (*n12.dat*)
Standard deviation noise on q	: 0.1 W/m^2 (*n13.dat*)

TRY data used for external temp.	: *milano.txt* from point 4489 till 6840
TRY data used for internal temp.	: *debilt.txt* from point 3985 till 6336
Correction on Te	: milano (4489:6840)/10-5
Correction on Ti	: debilt (3985:6336)/20+15
Final data series *Data12.txt*	: final=generated (337:2016)
Sensor breakdown Data12.txt	: Te from data point 1440

3.4.2 Case 2

Case 2 is a simulation of a three-layer wall with two brick layers with an insulation layer in between. This case is especially meant to evaluate the capability of a method to calculate the standard error of the estimated parameters. For this reason one data series is produced and twenty different noise series are added, which results in twenty data files: *Data201.txt - Data220.txt*. So the twenty data series only differ in the noise that was added to the data, however the standard deviations of the noise series are equal.

The result of the identification by the participant consist of twenty estimates of the thermal resistance, capacity and their standard errors (total 80 estimates).

For Case 2 a period of 39 days was generated, while 25 days were used for the final data series. With the noise generator a noise series of 20 * 25 days was generated and added to the data sets.
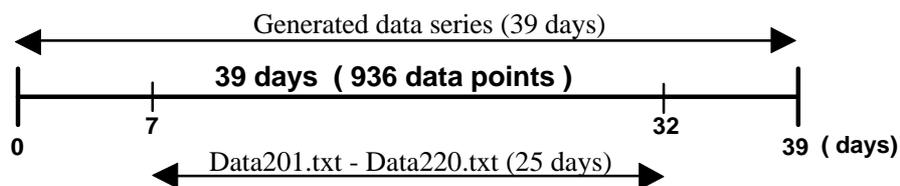
Figure 3.5 : Generation of case 2

The characteristics of the data series are :

File name data file	: *Data201.txt - Data220.txt*
File name statistic file	: *Datastat.txt*
Total generated period	: 39 days, (hourly sampled), 936 points
Length *Data201.txt - Data220.txt*	: 25 days, (hourly sampled), 600 points
Number of layers	: 3
The thermal properties of the wall	: $R_1 = 0.1143$ Km^2/W $C_1 = 40.00$ Wh/Km^2

	: $R_2 = 3.0000$ Km^2/W $C_2 = 1.00$ Wh/Km^2
	: $R_3 = 0.1143$ Km^2/W $C3 = 40.00$ Wh/Km^2
Total thermal properties	: $R_{total} = 3.2286$ Km^2/W $C_{total} = 81.00$ Wh/Km^2

Initial seed of *noise.for*   : 4d0
Length noise series   : 12000 points (20 * 25 days)
Standard deviation noise on Te   : 0.4 °C   (*n21.dat*)
Standard deviation noise on Ti   : 0.2 °C   (*n22.dat*)
Standard deviation noise on qi   : 0.1 W/m^2 (*n23.dat*)

TRY data used for external temp.   : *copenh.txt*   from point 3793 till 4728
TRY data used for internal temp.   : *venezia.txt*   from point 3385 till 4320
Correction on Te   : copenh (3793:4728)/10-5
Correction on Ti   : venezia (3385:4320)/15+8
Final data series *Data201-220.txt*   : final=generated (169:768)

3.4.3 Case 3

In case 3 the data are generated from a second order linear thermal network. The objective is to reveal the capabilities of a numerical method to estimate parameters and uncertainties for lumped parameter systems. Twenty data sets are provided corrupted by white noise. The thermal network is configured with 3 conductances and 2 capacitances as given in figure 3.6.

For the generation of temperatures TRY data was also used for this case, however the generation of the density of heat flow rate was prepared using the thermal network.
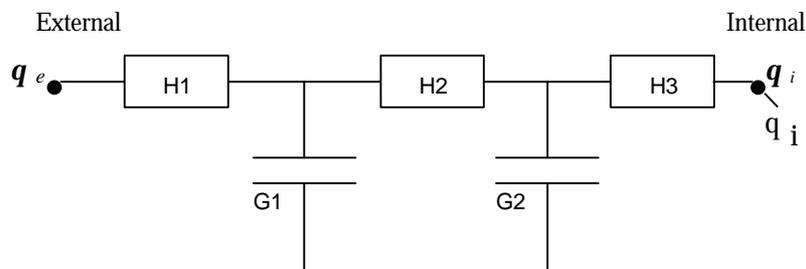
Figure 3.6 : Thermal model for case 3

H1 = 1.0 W/ Km^2, H2 = 10.0 W/ Km^2, H3 = 0.1 W/ Km^2,
G1 = 100.0 Km^2/Wh and G2 = 50.0 Km^2/Wh

The characteristics of temperature series are :

Length of temperature series   : 40 days (hourly sampled), 960 points
File name data file   : *Data301.txt - Data320.txt*
File name statistic file   : *Datastat.txt*

Initial seed of *noise.for*   : 12d0
Length noise series   : generated continuous for (20 * 40 days)

Standard deviation noise on Text	: 3.0 °C (*n31.dat*)
Standard deviation noise on Tint	: 0.0 °C
Standard deviation noise on q	: 0.001 W/m^2 (*n33.dat*)

TRY data used for external temp.	: *uccle.txt* from point 4489 till 6840
TRY data used for internal temp.	: *bolzano.txt* from point 3985 till 6336
Correction on Te	: uccle (4920:5879)/10-5;
Correction on Ti	: bolzano (4920:5879)/20+15

3.4.4 Case 4

Case 4 is a simulation of a two-layer wall with on the inside an insulation layer and on the outside a brick layer. The goal of this case is to test the capability of an identification technique to make a prediction of an output signal for a certain period given the input signals for that period and all the signals for a preceding period.

Data41.txt is the estimation data set that contains both temperatures and heat flow for a period of ten weeks (70 days), Data42.txt is the succeeding period that only contains the surface temperatures. The participant is supposed to predict the density of heat flow rate for this period. The weather conditions are supposed to be similar in both periods. The participants are encouraged to try their estimation method for the thermal properties on this wall as well.

In order to avoid initial effects of the heat flow simulation a longer period than necessary are produced, the simulation will start two weeks before and will end two weeks after the ten weeks as shown in figure 3.7. The original TRY-temperatures were changed to obtain the same weather condition in both the estimation and the prediction set. In the statistics file *Datastat.txt* can be seen that the maximum, minimum and average values are quite similar for both periods.
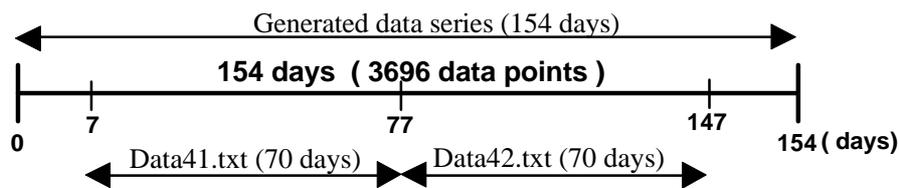
Figure 3.7 : Generation of case 4

File name data file	: *Data41.txt, Data42.txt*
File name statistic file	: *Datastat.txt*
Total generated period	: 154 days, (hourly sampled), 3696 points
Length *Data41.txt*	: 70 days, (hourly sampled), 1680 points
Length *Data42.txt*	: 70 days, (hourly sampled), 1680 points
Number of layers	: 2
The thermal properties of the wall	: $R_1 = 2.5280$ Km^2/W $C_1 = 0.6667$ Wh/Km^2
	: $R_2 = 0.6120$ Km^2/W $C_2 = 26.1111$ Wh/Km^2
Total thermal properties	: $R_{total} = 3.1400$ Km^2/W $C_{total} = 26.7778$ Wh/Km^2

Initial seed of *noise.for*	:	12d0
Length noise series	:	3360 points (140 days)
Standard deviation noise on Text	:	0.3 °C (*n41.dat*)
Standard deviation noise on Tint	:	0.15 °C (*n42.dat*)
Standard deviation noise on q	:	0.1 W/m^2 (*n43.dat*)

TRY data used for external temp.	:	*cagliari.txt* from point 2352 till 6047
TRY data used for internal temp.	:	*trapani.txt* from point 2352 till 6047
Correction on Te	:	cagliari (2352:6047)/10+3 - (1:3696)'/369.6 , Te(2344:2348)=[25.13 25.38 25.54 25.19 24.66]
Correction on Ti	:	trapani (2352:6047)/20+13 - 0.3*(1:3696)'/369.6
Final series *Data41.txt + Data42.txt*	:	final=generated (169:3528)

3.4.5 Case 5

Case 5 is a simulation of a homogeneous wall with other properties than the wall in Case 1. The goal of this case is to test the capability of an identification technique to make a prediction of an output signal for a certain period given the input signals for that period and all the signals for a preceding period. In contrary to Case 4, the weather conditions for the periods in Case 5 are not the same.

Data51.txt is the estimation data set that contains both temperatures and heat flow for a period of eighth weeks (56 days), Data52.txt is the succeeding period that only contains the surface temperatures. The participant is supposed to predict the density of heat flow rate for this period. The participants are encouraged to try their estimation method for the thermal properties on this wall as well.

In order to avoid initial effects of the heat flow simulation a longer period than necessary are produced, the simulation will start one week before and will end one week after the eight weeks.

Figure 3.8 : Generation of case 5

The characteristics of the data series are :

File name data file	:	*Data51.txt, Data52.txt*
File name statistic file	:	*Datastat.txt*
Total generated period	:	70 days, (hourly sampled), 1680 points
Length *Data51.txt*	:	28 days, (hourly sampled), 672 points
Length *Data52.txt*	:	28 days, (hourly sampled), 672 points
Number of layers	:	1

The thermal properties of the wall   : $R = 2.2683$ K m^2/W $C = 22.000$ Wh/Km^2

Initial seed of *noise.for*   : 8d0
Length noise series   : 1344 points (56 days)
Standard deviation noise on Text   : 0.3 °C   (*n51.dat*)
Standard deviation noise on Tint   : 0.15 °C   (*n52.dat*)
Standard deviation noise on q   : 0.15 W/m^2 (*n53.dat*)

Data used for external temperature : Generated from different Ispra data series
TRY data used for internal temp.   : *roma.txt* from point 5401 till 7080
Correction on Ti   : roma (5401:7080)/20+12
Final series *Data51.txt* + *Data52.txt* : final=generated (169:1512)

3.5 REPRESENTATION OF THE DATASERIES

The data is represented in data files called *'Data**.txt'* which contain the data series for each case. The series in these files are in the following order :

Column 1	Column 2	Column 3
Internal surface temperature	External surface temperature	Density of heat flow rate

The file, *Datastat.txt* gives the statistics of the previous data files, and have been summarised in the following order, for each file :

```
Statistics of   <'filename'>

        Te        Ti       qi

Max

Average

Min

Var

Length
```

The result after the addition of noise is three data series in eight decimals. These eight decimals are rounded off towards the nearest two decimals in case of the temperatures and towards the nearest three decimals in case of the density of heat flow rate. The statistic values of the temperatures are rounded towards the nearest three decimals and those of heat flow are rounded towards the nearest four decimals. See also Chapter 2.3.

3.6 TESTS ON THE DATA

Different tests were applied on the data. The main goal of these tests is to guarantee the capability of some standard methods to identify the thermal parameters from the data series. The application of the average method is described in Chapter 6. The state space and the prediction error methods were applied on the total period of each series and the best model

was selected by assessing the fit and the calculated standard deviation. It is obvious that better results might be achieved using further processing or different, more sophisticated methods.

3.6.1 Prediction Error method

The general prediction error method covers all types of single-output, multi-input systems. The equation for these systems can in discrete time be written as :

$$A(q) \cdot y(t) = \frac{B_1(q)}{F_1(q)} u_1(t - nk_1) + \ldots + \frac{B_{nu}(q)}{F_{nu}(q)} u_{nu}(t - nk_{nu}) + \frac{C(q)}{D(q)} e(t) \qquad (3.19)$$

where :

$y(t)$	output signal
$u_1(t) .. u_{nu}(t)$	input signal(s), nu is number of input signals
$e(t)$	disturbance term
$nk_1 .. nk_u$	time lags for different input signals
$A(q) \ldots F(q)$	are polynomials in the lag operator q, defined by $q^{-1} \cdot y(t) = y(t-1)$ These polynomials also take into account the previous values of y(t).

These polynomials are defined as follows :

$$A(q) = 1 + a_1 q^{-1} + \ldots a_{na} q^{-na} \quad (3.20)$$
$$B(q) = b_1 + b_2 q^{-1} + \ldots b_{nb} q^{-nb+1} \quad (3.21) \text{ (for each of the } nu \text{ input signals)}$$
$$C(q) = 1 + c_1 q^{-1} + \ldots c_{nc} q^{-nc} \quad (3.22)$$
$$D(q) = 1 + d_1 q^{-1} + \ldots d_{nd} q^{-nd} \quad (3.23)$$
$$F(q) = 1 + f_1 q^{-1} + \ldots f_{nf} q^{-nf} \quad (3.24) \text{ (for each of the } nu \text{ input signals)}$$

All these different can be easily implemented in MATLAB by using the PEM routine in the ystem Identification Toolbox. Within the structure of equation (3.19), virtually all of the usual linear black-box model structures are obtained as special cases. These special cases and their restrictions in equations (3.20) - (3.24) are :

ARMAX   : Auto Regressive Moving Average with eXogenous input
                restriction : nd = nf = 0

ARX   : Auto Regressive with eXogenous input model
                restriction : nc = nd = nf = 0

BJ   : Box-Jenkins model
                restriction : na = 0

OE   : Output Error model
                restriction : na = nc = nd = 0

The purpose of the identification model is to determine the physical properties from the given data series. The goal is to obtain the static thermal resistance R and the thermal capacity C.

The input parameters are the temperatures $T_{in}(t)$ and $T_{out}(t)$ and the output parameter is the heat flux $Q(t)$. So nu=2, $u_1(t)=T_{in}(t)$, $u_2(t)=T_{out}(t)$ and $y(t)=Q(t)$. From the model two estimates of the R-value can be obtained as follows:

$$R_{in} = A(1)\frac{F_1(1)}{B_1(1)} \qquad R_{out} = -A(1)\frac{F_2(1)}{B_2(1)} \tag{3.25}$$

By the assumption that in a static situation the lag operator equals one and the estimation of R_{in} equals the estimation of R_{out}. From two values an adjusted estimator can be obtained by using Lagrange's method, which weights the estimations for R_{in} and R_{out} and makes a final estimation for the thermal resistance. The easiest way to estimate the thermal capacity is to simulate with the estimated coefficients a step function (using the MATLAB-command *idsim*) and to calculate the time constant.

3.6.2 State Space

The following description of the state space model can be found in: Norlén, 1994. The heat flow density at the internal surface of a homogeneous building element may be written as:

$$q_i(t) = \frac{1}{R}\left[q_i(t) - q_e(t)\right] + \frac{1}{R}\sum_{m=1}^{\infty} x_m(t) \tag{3.26}$$

where *t* denotes time, and where the x-variables are defined by the differential equations

$$\overset{\bullet}{x}_m(t) = -m^2 a\, x_m(t) + 2\left[\overset{\bullet}{q}_i(t) - (-1)^m \overset{\bullet}{q}_e(t)\right] \tag{3.27}$$

where $\quad a = \dfrac{p^2}{RC}$ \hfill (3.28)

and where R is the thermal resistance and C is the thermal capacity of the element.

The relationship between the temperature variables (inputs) and the heat flow density variable (output) is thus expressed *via* the x-variables. These variables are called state variables. Equation system (3.26) is generally referred to as the measurement equation. The differential equations (3.27) are referred to as the state equations. This model is derived from the heat conduction equation.

From (3.26) it follows that the heat flow density can be divided in two terms. The first term may be called the 'static' part. The second term may be called the 'dynamic' part. It vanishes if the temperature derivatives are equal to zero, *i.e.*, if there are no temperature variations.

For discrete time the measurement and state equations for a model with M state variables become:

$$q_i(nT) = \frac{1}{R}\left[q_i(nT) - q_e(nT)\right] + \frac{1}{R}\sum_{m=1}^{M} x_m(nT) \tag{3.29}$$

$$x_m(nT+T) = a_m x_m(nT) + b_m \left[\dot{q}_i(nT) - (-1)^m \dot{q}_e(nT) \right] \qquad (3.30)$$

where:

$$a_m = e^{-m^2 a} \quad \text{and} \quad b_m = 2\frac{1 - e^{-m^2 a}}{m^2 a} \qquad (3.31)$$

A routine in MATLAB can be written now, to make an estimation of the thermal properties of an one layer wall.

3.7 RESULTS FROM THE TESTS

3.7.1 Case 1

PEM method. We found two PEM models that fit well and had the smallest standard deviation. The configuration of these models is :
        (0 (2 3) 0 0 (0 1) (0 2))
        (0 (3 5) 0 0 (0 3) (0 2))
The average thermal resistance estimated by these models equals : R = 8.6195 ± 0.332 °C/W.

State-Space method. In order to skip the high-frequencies a low-pass filter with a cut-off frequency of $\omega_{\text{cut-off}}$ = 0.021 was applied on the data. The best fitting model turned out to be one with the order of 20.
This resulted in the following estimates for R and C :

    R = 8.611 ± 0.009 °C/W, C = 55.577 ± 0.140 Wh/ °Cm²

3.7.2 Case 2

PEM method. The best model that was found for "data201.txt" had the following configuration :
        (0 (3 4) 0 0 (0 2) (0 1))
The thermal resistance estimated by this models equals : R = 3.107 ± 0.161 °C/W.

State space method. This model is not actually meant to use for multi-layer walls, since it was originally developed for a single-layer wall. Especially the estimate for the thermal capacity will show significant deviation with the real value. However, we ran a test on this model and found the following results :

    R = 2.963 ± 0.025 °C/W, C = 60.459 ± 3.590 Wh/ °C m²

with a model of order 20 and with $\omega_{\text{cut-off}}$ = 0.021.

3.7.3 Case 3

The methods have not been applied to Case 3. The result from the application of the average method can be found in Chapter 6.

3.7.4 Case 4

PEM method. For this case the following PEM model was used :
      (0 (3 5) 0 0 (0 3) (0 2))
The thermal resistance estimated by this model equals : R = 3.183 ± 0.010 °C/W.

State space method. Although this case does not represent a homogeneous wall, a state space model was found that estimated the thermal fairly well. This model had the order 20 and to preprocess the data a low-pass filter was used with : $\omega_{cut-off}$ = 0.010. The final estimates for R and C were :

R = 3.069 ± 0.004 °C/W, C = 4.629 ± 0.250 Wh/ °C m^2

3.7.5 Case 5

PEM method. The following PEM-model turned out to be the best fit :
      (0 (3 5) 0 0 (0 3) (0 2))
The estimate for the thermal resistance made by this model was : R = 2.275 ± 0.014 °C/W

State space method. Case 5 is an example of a homogeneous wall. The state space model that was specially developed for a single layer wall perfromed best when we used a 20 order model with a $\omega_{cut-off}$ = 0.021. The obtained results were :

R= 2.260 ± 0.002 °C/W, C = 21.224 ± 0.385 Wh/ °C m^2

3.8 REFERENCES
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