

DEFINING THE PERFORMANCE OF THE DOUBLE SKIN FAÇADE WITH THE USE OF THE SIMULATION MODEL

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ABSTRACT

The objective of this paper is to model the double skin façade in order to determine the thermal and flow performance and to find out how the façade should be combined with the HVAC system inside of the building. In order to analyze these aspects a simulation model of the double skin façade was built and validated with the use of the test facilities and a real office building. Models of different configurations were tested and validated. In future it will be used to analyze the design of the double skin façade, its dimensions and integration with the HVAC system

This paper is mainly focussed on the model of the double skin façade and the experimental validation

INTRODUCTION

A simulation model was developed to define the properties of the double skin façade. After validating the simulations with the measurements the performance of the double skin façade may be analysed in a reliable way for many different configurations of the façade constructions and external conditions.

The mathematical model consists of three main parts:

- Airflow model
- Thermal model of the double skin façade
- Thermal model of the building

These three models are simultaneously interacting. The models are simulated with the computer codes MATLAB™ and SIMULINK™.

AIRFLOW MODEL

The air flow in the double skin façade is caused by two main driving forces:

- Buoyancy effect caused by the temperature difference between the air inside and outside the cavity of the double skin façade.
- Wind effect that creates the pressure difference between the inlet and outlet of the façade.

A detailed description of buoyancy and wind effect is given below. These two effects create the flow through the façade and through the building if windows in the internal façade are open. It is possible to measure the quantity of the flow in the laboratory test facility what makes the buoyancy effect well validated. In case of the wind effect the task is more complicated. Equations proposed in literature for predicting the wind pressure around the building are used and tested comparing the resulting overall temperatures of the model with the measurement. With the total pressure difference in the cavity the airflow can be calculated (formula 1)

$$\Delta P_{tot} = \Delta P_{stack} + \Delta P_{wind} \quad (1)$$

Total pressure difference is considered to be the difference in pressure between the inlet and outlet of the cavity. That means that the detailed flow exchange between the different points inside of the cavity is not described. Instead a simplified model is proposed that results in a flow pattern close to the observed one. Figure 1 shows the diagram of the considered flow exchange.

$$q_{in} = C_{tot} \sqrt{\Delta p_{tot}}, \quad (2)$$

$$C_{tot} = \frac{1}{\frac{1}{C_{inlet}} + \frac{1}{C_{valve}} + \frac{1}{C_{cavity}} + \frac{1}{C_{outlet}}}, \quad (3)$$

$$C_{i,v,c,o} = \sqrt{\frac{2 \cdot A_{i,v,c,o}^2}{\rho \cdot \xi_{i,v,c,o}}}, \quad (4)$$

$$\xi_{v,c} = \xi_{v,c_min} + X_{v,b} (\xi_{v,c_max} - \xi_{v,c_min}) \quad (5)$$

The values of the resistance coefficients were selected based on the literature (Koch, 2001; Recknagel et al., 1994)

Table 1. The values of the resistance coefficients

Coefficient	Value
ξ_{inlet}	2,01
ξ_{valve_max}	0,78
ξ_{valve_min}	100
ξ_{cavity_max}	1,60
ξ_{cavity_min}	1,90
ξ_{outlet}	1,45

It is assumed that there are two flows which can be superimposed. These are the main flow (q_{in}) and the flow q_{turb} entering and leaving the cavity through the junctions openings due to the turbulence of the wind.

The airflow entering the façade is calculated with formula 2. It summarizes the resistance of the façade, so it represents the total flow through the cavity, in case windows and openings between the panels of the inside surface are closed.

The outlet airflow of the cavity is the difference of the flow inside the cavity and the ventilation flow through the window.

$$q_{out} = q_{in} - q_{vent} \quad (6)$$

Where flow through the window is calculated based on the Paassen and Gröninger (1998)

$$q_{vent} = A_{eff} \sqrt{\frac{2}{10^{-3.333y+2.198} \rho}} \sqrt{\Delta p_{window}} \quad (7)$$

$$A_{eff} = \sqrt{\frac{1}{\frac{1}{(h_w \cdot b_w)^2} + \frac{1}{(2 \cdot h_w \cdot b_w \cdot \sin(0.5\phi) + h_w^2 \cdot \sin(\phi))^2}}} \quad (8)$$

The room pressure is created by the pressure around the building and by the mechanical ventilation system. Here it is supposed that pressure inside depends only on the ventilation system.

The turbulence flow entering and leaving the cavity through the openings between the junctions of the glass panels is calculated with the formulas 9 and 10 (van Paassen & van Galen, 1995). Formula 9 calculates the flow for the weather side and formula 10 for the lee side of the building. These formulas are based on experiments done in a confined test cell at various windows openings and wind speed and directions. Although the junction's openings are not completely the same as windows openings it is supposed that the equations can be used for describing the ventilation through the turbulence of the wind. There is a simplification made in estimating the effect of this flow. It is assumed that the air is flowing alternating in and out the cavity.

That means that the q_{turb} influence only the temperature inside of the cavity, no airflow.

$$q_{turb} = 0.05 A_{junction} + 0.035 v_{wind} A_{junction}^{0.39} \quad (9)$$

$$q_{turb} = 0.05 A_{junction} + 0.009 v_{wind} A_{junction}^{0.16} \quad (10)$$

Buoyancy effect

The buoyancy effect is caused by a difference in temperature between the air in the cavity and the outside air. To determine the quantity of the stack effect the laboratory test facility was used.

The test facility is situated inside the laboratory. It consists of a cavity formed by a front surface of glass and a well insulated back wall. In between an electric heating mat is mounted. During the measurements it was protected from the air movements inside of the laboratory. This allows for the assumption that the only driving force of the flow inside of the cavity of the test facility is the buoyancy effect.

The pressure difference in the model was calculated with the formula (11):

$$\Delta p_{stack} = \left[\frac{\theta_c - \theta_o}{273 + \frac{\theta_c + \theta_o}{2}} \right] \cdot g \cdot h \cdot \rho \quad (11)$$

The airflow is defined with the Bernoulli formula:

$$\Delta p_{stack} = \sum_1^n \xi_{i,v,c,o} \cdot \frac{1}{2} \cdot \rho \cdot v^2 \quad (12)$$

$$\Delta p_{stack} = \sum_1^n \xi_{i,v,c,o} \cdot \frac{1}{2} \cdot \rho \cdot \omega^2 =$$

$$\sum_1^n \xi_{i,v,c,o} \cdot \frac{1}{2} \cdot \rho \cdot \left(\frac{q}{A_i} \right)^2 = \frac{1}{2} \cdot \rho \cdot q^2 \cdot \sum_1^n \left(\xi_{i,v,c,o} \cdot \frac{1}{A_i^2} \right) \quad (13)$$

Because A_i is the same for every part of the model ($A_i = 0.1m^2$ for every part of the model) then final shape is following:

$$\Delta p_{stack} = 0.5 \cdot \rho \cdot \frac{1}{A_i^2} \cdot q^2 \cdot \sum_1^n \xi_{i,v,c,o} \quad (14)$$

$$q = A_i \left[\frac{\Delta p_{stack} \cdot 2}{\rho \cdot \sum_1^n \xi_{i,v,c,o}} \right]^{0.5} \quad (15)$$

The validation was carried out as follows. With the mentioned formulas the airflow was calculated with the measured temperatures and the resulting calculated value was compared with the measured one (figure 2). The average difference between the calculated flows is 0.001 l/m³/s. This means a fault of

4.17%. This fault is not caused by the calculation method only. The accuracy of the airflow measurement instrument itself is of the order of 5%. Moreover we should assume that there are some leakages in the system. Taking this into account it can be concluded that the model predicts the air flow in the cavity in an acceptable way.

Wind effect

The wind acting on the building creates the differences of pressure around the building that stimulate the airflow through the building. Values of pressure differences on the façade of the building depend on the direction of the wind, shape and height of the building. General formula to calculate the pressure difference caused by the wind is given by equation 16.

$$\Delta p_{wind} = 0.5 \cdot (c_{p_inlet} - c_{p_outlet}) \cdot \rho \cdot v_{wind}^2 \quad (16)$$

Value of the wind pressure coefficient depends first of all from the direction of wind and for different building construction different formulas are given.

Here the formula of Swami Chandra (88) for the high rise buildings is selected.

THERMAL MODEL OF THE DOUBLE SKIN FAÇADE

The thermal model is represented by the heat exchange between each layer of the façade. To simulate the double skin façade several assumptions were made:

- The model is divided into segments. In this paper it is an one storey high façade. The heat balance of each layer is represented by one node.
- The model is one dimensional. The direction of heat exchange is perpendicular to each layer of the façade.

The encountered heat exchanges inside the façade are (figure 3):

- Conduction heat transfer
- Convection heat transfer (Knutsen & Katz, 1958)
- Radiation heat transfer
- Transportation heat transfer, caused by the airflow predicted by the flow model.

The detailed thermal model was analyzed with the use of the laboratory test facility. Under fully controlled steady state conditions each way of heat transfer could be determined and verified. More detailed description of the modelling the thermal behaviour can be found in Stec 2002.

THERMAL MODEL OF THE BUILDING

Thermal model of the building was built based on the previous works of Gröninger 1999 and Di Maio 2001. The model consists of the following main elements:

- Models of the enclosing walls
- Model of the room air
- Model of the auxiliary energy supply (heating, cooling, lightening, ventilation)

Diagram of the heat exchange is shown on the figure 4 (More details in Stec 2002).

VALIDATION

With the formulas mentioned above the thermal performance of the double skin façade was simulated and the output temperatures were compared with the measurements in a laboratory facility. The graph shown in figure 5 represents temperatures (measured and simulated) in every layer.

Standard deviations between the temperatures (calculated and measured) in every layer of the model are in range of 0.18 – 0.38 K. Correlation coefficients are in range of 0.918 – 0.982.

More tests were done with the use of the test cell situated outside under real weather conditions (Stec 2002). The simulation model is tested for different sort of the glass, different sizes of the openings, different positions of the blinds, valves and windows. The results from the simulations agree quite well with the measurements. The comparison of the temperatures in the cavity is shown in figures 6 and 7. During the night the simulated temperature is actually equal to the measured one. The differences appear when the solar radiation influences the performance of the system. The calculation formulas of the solar heat gains in the double skin façade should be improved to make the distribution of the solar radiation in the façade more accurate. The simulations and measurements proofed that even a small change of the solar radiation may have a significant influence on the temperature in the cavity. The temperature inside of the test cell is shown in figure 8. In general the main reason for inaccuracy between the measurements and simulations is the modelling of the solar radiation. It is expected that these difficulties will increase when ventilation through open window are considered. This will be investigated in the future.

Finally the temperature of the room in the real office building is shown in the figure 9. Here additionally HVAC system was simulated. The extra difficulty with the real office building is simulating the occupancy of the room (in quantity and quality). Despite of this handicap the presented comparison is very satisfactory.

CONCLUSIONS

In general the results of the simulations reflect the measurements with a satisfactory accuracy. Based on the existing model a sensitivity analysis is carried to establish the influence of different construction aspects on the overall performance of the double skin façade and building behind (Stec, 2002).

In the meantime the improvement of the existing model will proceed. The main reason for the inaccuracy in the simulation model is the distribution of the solar radiation and the modelling of the airflow in a double skin façade under real weather conditions.

The topic of the solar radiation was already analyzed by the number of the researches and this problem may be solved based on the solutions found in literature.

The airflow modelling in the double skin façade and especially through the building is a more complicated task. Here the simplified solution shows to give acceptable results. Nevertheless more research is needed. This concerns especially the following topics:

- The induction of the flow in the double skin façade due to the wind pressure and buoyancy effect under real weather conditions.
- The airflow between the cavity and the interior of the building through the window openings in case a overpressure or under pressure is induced by a mechanical ventilation system.
- The influence of the construction details of the double skin façade on the airflow inside.

The airflow problems related with the double skin facade are currently the main scope of interest for the research group of double skin facades inside of the indoor climate technology at TU Delft.

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NOMENCLATURE

ΔP_{tot}	Total pressure difference between inlet and outlet of the cavity.
ΔP_{stack}	Pressure difference caused by Buoyancy (stack) effect.
ΔP_{wind}	Pressure difference caused by wind pressure
Δp_{window}	Difference in pressure between the cavity and the room

$A_{i,v,c,o}$	Area of the cross section of the inlet, valve, cavity or outlet
$\xi_{i,v,c,o}$	Flow resistance of the inlet, valve, cavity or outlet.
ξ_{v,c_max}	Flow resistance through the valve when closed or through the cavity when the blinds are down
ξ_{v,c_min}	Flow resistance through the valve when open or through the cavity when blinds are up.
$X_{v,b}$	Position of the valve or blinds (0 open-1 closed)
A_{eff}	Area of the effective opening of the window,
h_w	Height of the window,
b_w	Width of the window,
φ	Opening angle of the window,
$A_{junction}$	Area of the openings between the panels of the second skin.
$g = 9.81$	Acceleration due to gravity $[m/s^2]$
h	Height of the wall $[m]$
ρ	Air density for a temperature of the air that enters the cavity $[kg/m^3]$,
θ_o	Temperature outside the model (in the middle of the height) $[^\circ C]$,
θ_c	Temperature in the cavities $[^\circ C]$
$v = \frac{q}{A_i}$	Velocity of the air in the duct $[m/s]$
q	Airflow in the cavity, $[m^3/s]$
A_i	Area of the cross section of the duct, $[m^2]$
c_{p_inlet}	Wind pressure coefficient for the inlet of the air.
c_{p_outlet}	Wind pressure coefficient for the outlet of the air.
v_{wind}	Wind velocity (m/s),

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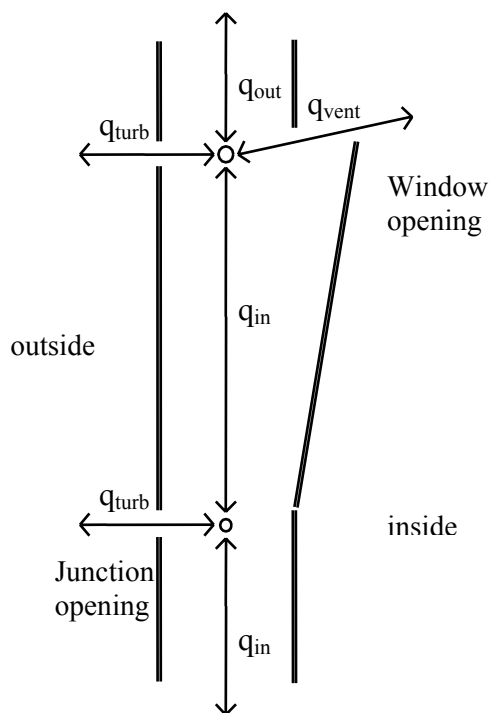


Figure 1. Diagram of flow exchange In the model of the double skin facade

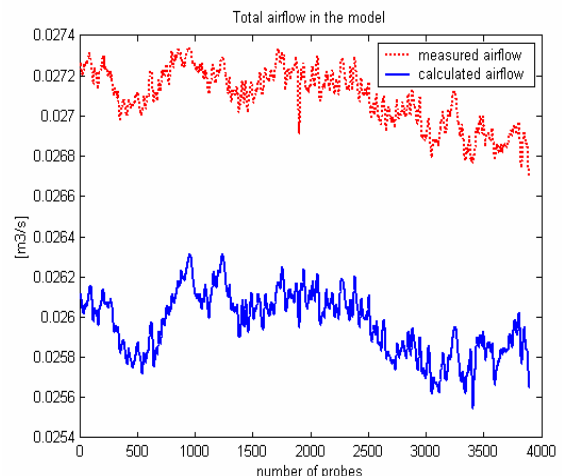


Figure 2. Total airflow through the model of the double skin façade

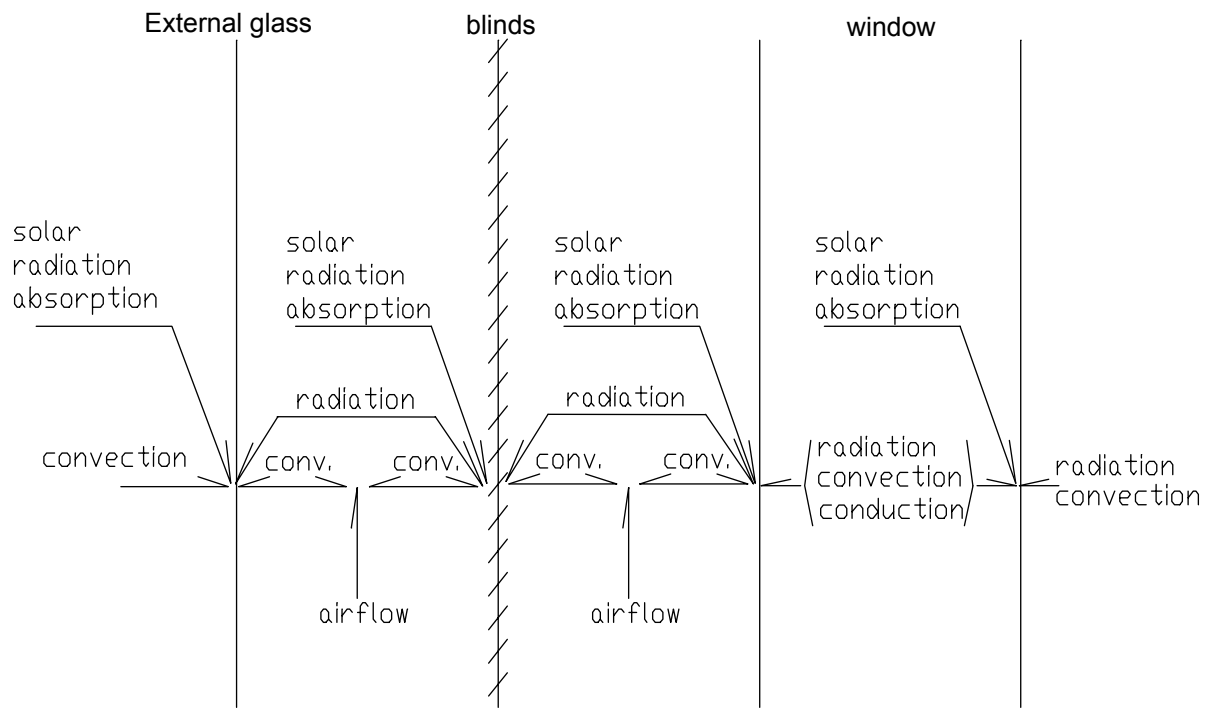


Figure 3 . Network of heat exchange In the structure of the double skin facade

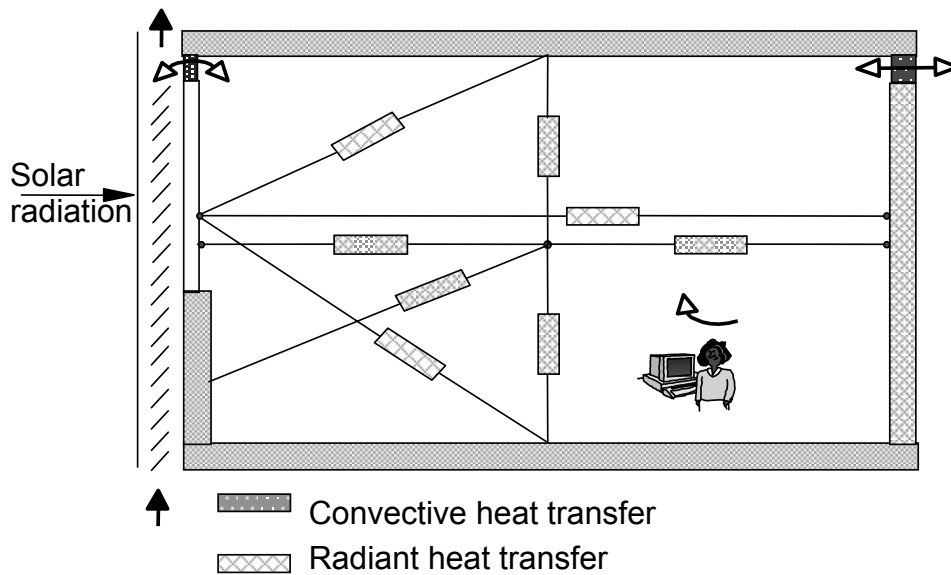


Figure 4. Diagram of the heat exchange between the air and the walls

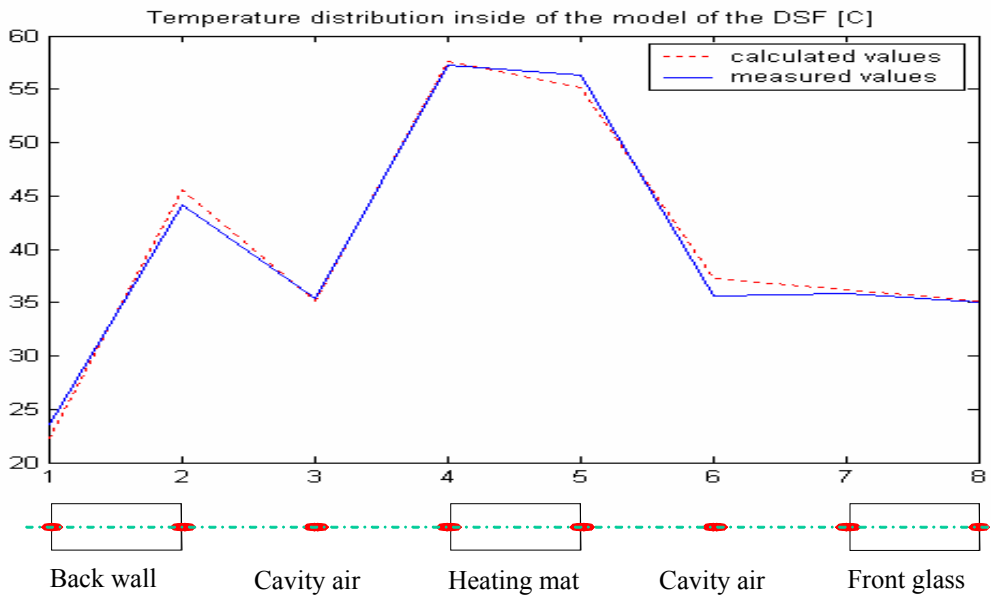


Figure 5. Distribution of the temperature (measured and simulated) in the model of the double skin façade

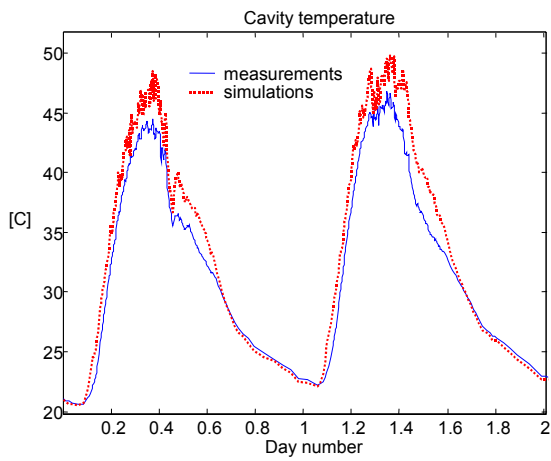


Figure 6. Temperature of the cavity for the open blinds (real weather conditions)

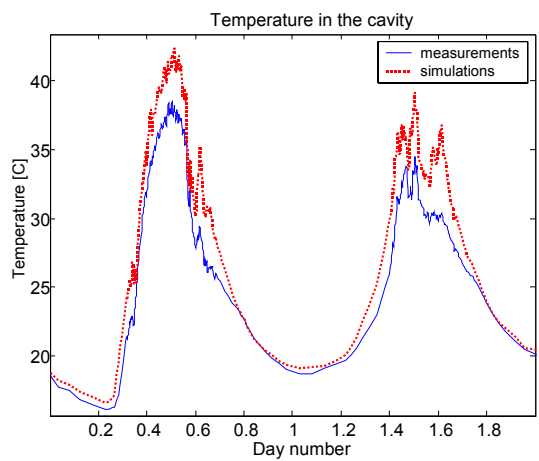


Figure 7. Temperature of the cavity for the closed blinds (real weather conditions)

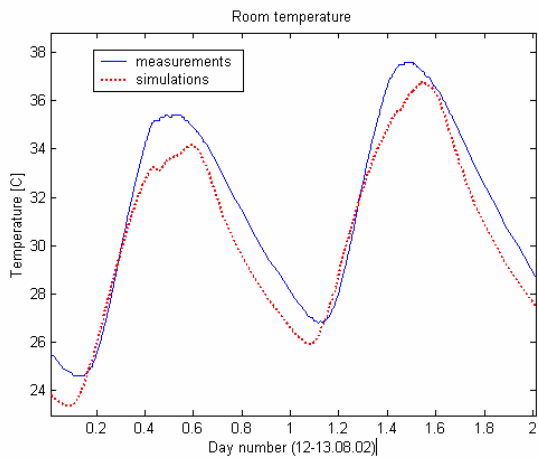


Figure 8. Temperature inside of the test cell

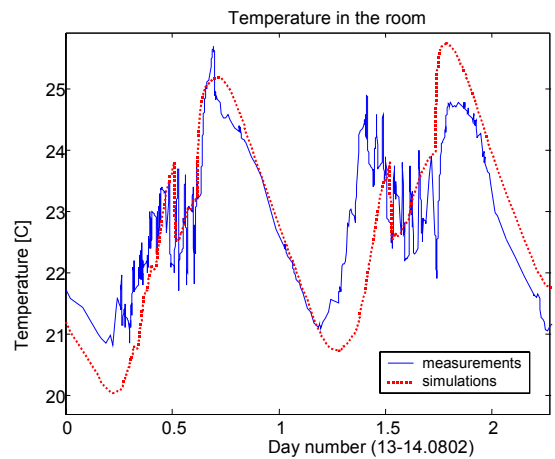


Figure 9. Temperature in the room in the Unica office building

