F: Physical responses & physiology
F.2. Health assessment (incl. Thermal comfort)

# A coupled BES-zonal model to predict stratification in a large building

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## SUMMARY

In the past in a church no heating was foreseen. The thick stone walls alleviated the fluctuations of the ambient air temperature and relative humidity. Consequently, the indoor climate in the church was quite stable. After the Second World War the living standard of the people increased and the increased prosperity lead to higher comfort demands, not only in residential dwellings, but also in churches. As a consequence many heating systems were introduced that heated the whole indoor air volume of the church. Often these systems were rugged air inlets, designed to quickly heat a space without taking the effect of the fluctuating temperature and relative humidity on the artworks into account. Consequently, the many artworks in the church like the organ, the pulpit and the panel paintings are also exposed to this changing climate, which leaded to faster deterioration or even to damage.

## INTRODUCTION

In the past in a church no heating was foreseen. The thick stone walls alleviated the fluctuations of the ambient air temperature and relative humidity. Consequently, the indoor climate in the church was quite stable. After the Second World War the living standard of the people increased and the increased prosperity lead to higher comfort demands, not only in residential dwellings, but also in churches. As a consequence many heating systems were introduced that heated the whole indoor air volume of the church. Often these systems were rugged air inlets, designed to quickly heat a space. The whole church is heated to become thermal comfortable for the churchgoers.
Churches preserve many valuable artworks, like panel paintings, an organ and textiles. Often there is only heated to provide thermal comfort without taking the effect of the fluctuating temperature and relative humidity on the artworks into account. Consequently, the many artworks in the church like the organ, the pulpit and the panel paintings are also exposed to this changing climate, which leaded to faster deterioration or even to damage. The temperature and temperature variation is less important, than the related relative humidity variations. Variations in relative humidity are associated with swelling and shrinking of the materials, resulting in stress, which

can lead to deformation or damage. An example of how the climate in a church that is heated intermittently helps to indicate the problem. Figure 1 shows the peak in temperature and the drop in relative humidity while heating during a service.

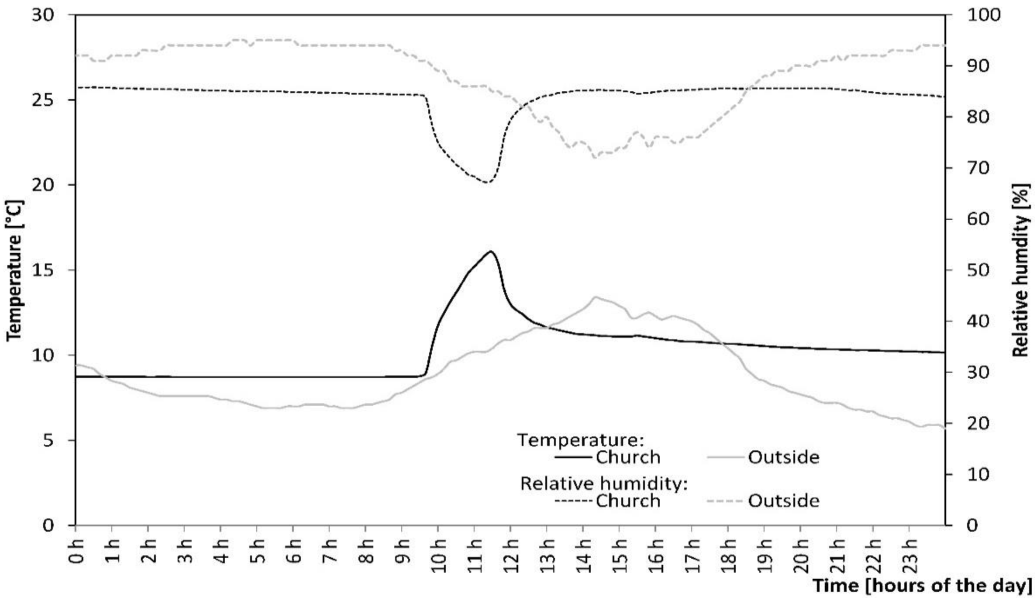


Figure 1. Measured climate in a church building (Watervliet) where there is only heated during services: temperature [°C] and relative humidity [%].

The attention to this problem is not new. In literature (Bratasz et al., 2007;Pitschet al., 2010; Troi and Hausladen, 2006) several cases are described in which adapting the climate to the comfort requirements had drastic effects on the artworks. Likewise the Flemish Monumental Building Guard stated that from observations more damage was observed the last 30 years, due to uncontrolled installations of hot air systems, than in a period of the preceding 150 years (Vlaamse Gemeenschap, 2011). Due to the many cases in Belgium where damage occurred at the interior objects in churches, advises for heating parameters were also given in the circular ML/11 (Vlaamse Gemeenschap, 2011), written in 2011 by the department of Urban Planning of the Flemish government. These are summarized below.

- When heating during the service, the temperature must be limited to 15°C, and this limitation holds not only at the place where visitors are located, but also at the organ.
- The heating of the space may not be more than 2°C at one hour.
- The minimum temperature in the church must be between 10 to 12°C, involving permanent heating in colder periods. Better would be to keep the temperature all the time at 13-14°C, without heating during services.
- The outlet temperature must be between 40°C to 45°C.
- The relative humidity in the church must be kept, if possible, between 55% and 70%.

To evaluate these criteria, reliable simulation tools are needed to predict the course of the surface and the indoor conditions of temperature and relative humidity. Moisture engineering of historic buildings can only be performed by studying simultaneously the hygrothermal behaviour of the building envelope, the moisture balance of the indoor environment and the interaction with the heating or HVAC-system.

To do so there is obtained in the paper to find a simulation strategy to analyse the indoor temperature and relative humidity, which can be related to thermal comfort and the preservation conditions for the artworks.

## METHODOLOGIES

The goal of the simulation study is to evaluate the effect of a common heating system on the thermal comfort and the preservation conditions in the church. Evaluating the conservation conditions for the artworks in a large space requires knowledge of the stratification in temperature and relative humidity inside a large volume that occurs while heating. The use of Computational Fluid Dynamics (CFD) is probably the most suitable method to predict the airflow pattern, but it is quite time consuming and requires a powerful computer. As an alternative, a zonal model is a suitable method to predict the airflow in a large space in a simplified way. These models can be linked to a BES- software in which each zone is assumed to be perfectly mixed. The use of a BES-software is interesting because a BES software is widespread used for the evaluation or comparison of different heating techniques to meet sizing and energy operating cost requirements (Bouia and Dalicieux, 1991). By this coupling, the influence of the airflow on the temperature distribution and vice versa can be calculated, in order to judge the thermal comfort and preservation conditions in one zone.

To calculate the stratification in a large space there was opted to use a temperature-zonal model. This kind of model can be easily integrated in a BES-software. Also no prior knowledge is needed of the type of cell, whereas in a pressure zonal model a normal cell must be differentiated from a specialised cell, in which the airflow is driven by a jet or a plume. For this purpose the thermal-zonal model of Togari (Togari et al.,1993), which was suggested in Annex 26 (Heiselberg et al., 1998) is coded in C++ and coupled to the commercial BES simulation environment TRNSYS v17 (De Backer, 2014). In this model Togari et al. (1993) assumed that the main components of the air movement in the large space are airflows along the vertical wall surfaces and supply airstreams. Further, they also assumed that the horizontal temperature is uniform, except for the regions affected by supply air jet ventilation. Based on these assumptions a method was proposed to calculate the occurring stratification.

Hereby the space is divided into a finite number of horizontal layers or blocks. Each layer consist of a core cell and so-called walls cells. The core cell represents one layer and when the layer is bounded by a wall, a wall cell is defined which accounts for the mass flows in the boundary layer at the wall. A wall cell has no volume or dimension. Between a “wall cell” and a “core cell” there is an exchange of mass and energy.

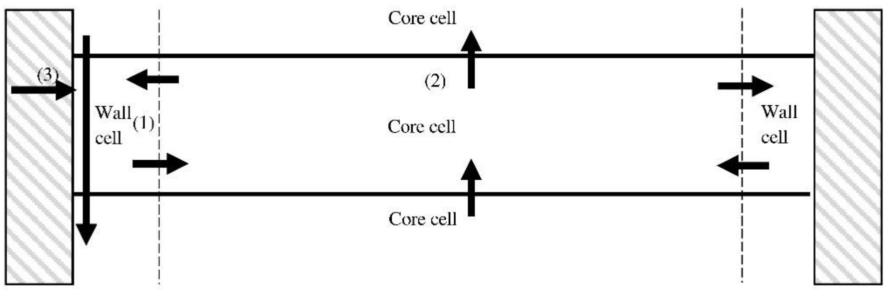

Figure 2. Schematic representation of the division of the space into layers, each layer consisting of a core cell and wall cells.

Because the typical conditions in monumental historic buildings have to be taken into account, among them the presence of moisture in heavy building walls , it is necessary to implement the moisture exchange with these walls. Therefore the moisture flux $m_{wall(I,K)}$coming or going to the wall is defined (Figure 3).

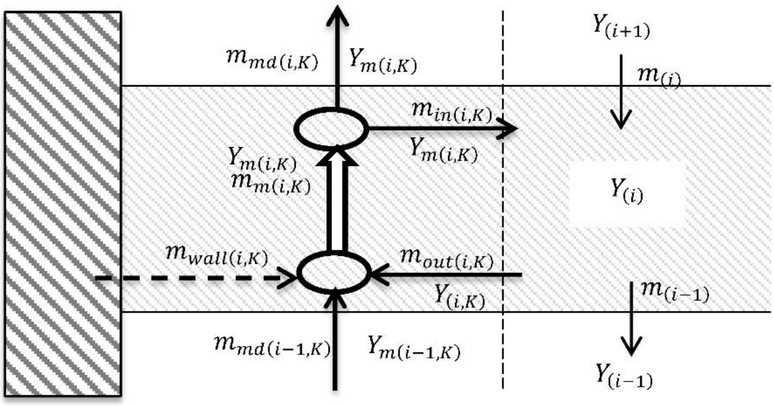


Figure 3. Schematic representation of the composition of the vapour flow balance.

To implement this moisture flux, the mass $m_{wall(I,K)}$ is added in the equation used to determine the humidity ratio of the wall current $Y_{m(i,K)}$, yielding:

$$\frac{{}_{(i,K)}{}^{p-1}m_{out(i,K)} + Y_{m(i-1,K)}{}^{p-1}\max(m_{md(i-1,K)}) + m_{wall(i,K)}}{m_{m(i,K)}} \qquad (1)$$

The amount of water vapour exchange ($m_{wall(I,K)}$) between room air and the wall (i,K) was modelled with a simplified algorithm. The chosen model was an effective moisture penetration depth (EMPD) model (Janssens et al., 2008). This approach assumes that the moisture transfer takes place between the zone air and a thin fictitious layer of a uniform moisture content with a thickness $d_{buf,}$ which is related to the variation of water vapour pressure at the material surface. The effective penetration depth $d_{buf}$ is calculated by equation 2, in which $t_p$ is the period of cyclic variation (s).

$$d_{buf} = \sqrt{\frac{\delta(\varphi)P_{v,sat}(T)t_p}{\rho\xi(\varphi)\pi}} \qquad (2)$$

Where $\delta(\varphi)$ is vapour permeability [s], $\rho\xi(\varphi)$ is the moisture capacity in terms of humidity derived from the material sorption isotherm [kg/m$^3$] and $P_{v,sat}(T)$ represents the saturation water vapour pressure at temperature T [Pa]. The following equation is then solved together with the moisture balance equation for indoor air within a space under the non-steady-state.

$$m_{wall} = \frac{A(P_{v,i} - P_{v,buf})}{\frac{1}{\beta_i} + Z_{buf}} = A\rho\xi(\varphi)d_{buf}\frac{\left(\frac{P_{v,buf}}{P_{v,sat}(T_{buf})}\right)^{t+\Delta t} - \left(\frac{P_{v,buf}}{P_{v,sat}(T_{buf})}\right)^{t}}{\Delta t} \qquad (3)$$

To illustrate the working of the model a simulation study has been carried out of a typical church building (Figure 4). In the TRNSYS model only the volume of the church is simulated. The attic is taken into account by defining it as a boundary condition.

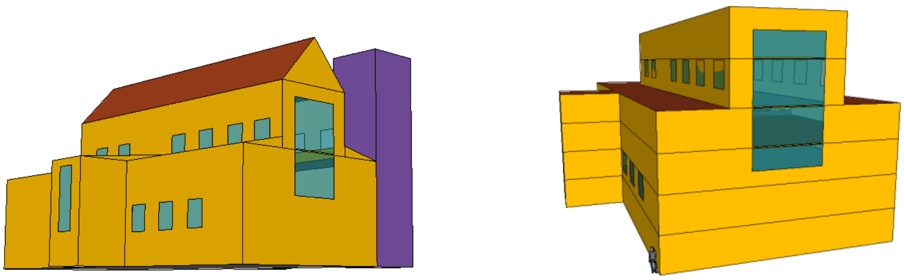

Figure 4. Illustration of the modelled church building. (a) The whole building. (b) The considered volume.

The main geometric characteristics of the church are the following:

- Length: 40m, depth 17m, height 10m and 16m
- The side aisles measure 5mx5mx10m
- Ground surface: 730m²
- Volume:8836m³

The outdoor walls of the church are made of masonry and have a mean thickness of 0.75m. At the inside the walls are covered with a plaster. The glazing in the outdoor walls are leaded windows. The ceiling of the church has a similar building-up and consist of masonry with a thickness of 0.2m covered with plaster. The building up of the floor was based on literature (Fawcett, 2001) and consist of a stone floor, laid on mortar and sand. The building-up of the floor was modelled using ISO EN 13370. The values used for the materials are presented in Table 1. To model the ambient conditions, the meteonorm-file for Uccle, Belgium was used.

Table 1: Material properties

| Building part | material | d [m] | lambda [W/mK] | density [kg/m³] | capacity [kJ/kgK] |
|---|---|---|---|---|---|
| outdoor wall | brick | 0.75 | 1.39 | 2100.00 | 1.00 |
| | plaster | 0.02 | 0.80 | 1900.00 | 0.84 |
| ceiling | brick | 0.2 | 1.39 | 2100.00 | 1.00 |
| | plaster | 0.02 | 0.80 | 1900.00 | 0.84 |
| floor | stone floor | 0.02 | 3.50 | 2550.00 | 0.84 |
| | mortar | 0.05 | 1.20 | 1600.00 | 1.00 |
| | sand | 0.5 | 2.00 | 1800.00 | 1.00 |
| | virtual layer | | 0.05 | 1000.00 | 1.00 |

| Building part | material | Resistance m²K/W |
|---|---|---|

| windows | leaded glass | 5.6 |
|---|---|---|

The volume of the church building is divided into 6 layers. The church is heated by a hot air system from 9h30 till 11h30. The hot air is brought into the church by a re-circulation system. The inlet consist of a single grille of 1m by 1m at about 3m above floor level. The outlet is a single grille of 1m by 1m at 1m above floor level. The temperature of the incoming air is 45°C and the mass flow of the jet is 20000m³/hr. Several configurations for these settings are simulated:

- In the first case there is a set point temperature of 5°C. During a service this set point is raised till 16°C. The moisture exchange with the walls is not included.
- In the second case the moisture exchange with the walls is taken into account. There is assumed that the walls in the lowest zone are saturated.
- In the third case the basic temperature in the church is 12°C. During a service there is heated till 16°C.

## RESULTS AND DISCUSSION

Simulation results for the first case are shown on Figure 5. Figure 5 illustrates the temperature progress and the relative humidity progress. The different coloured lines illustrates the temperature and relative humidity at the different heights.

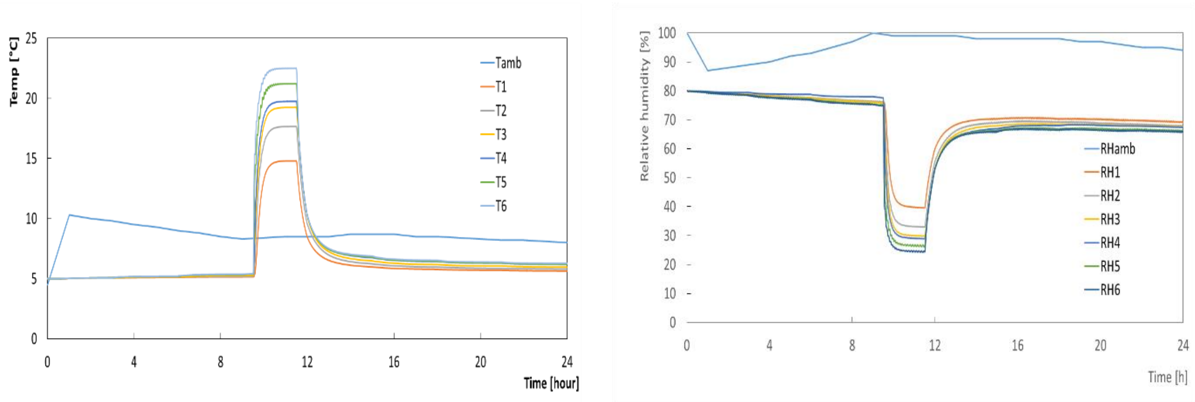


Figure 4. Temperature progress and relative humidity progress.

## CONCLUSIONS

Conclusions should be solid, new and concise, supported by the results presented earlier.

## ACKNOWLEDGEMENT

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## REFERENCES

Bouia H, Dalicieux P (1991) Simplified modeling of air movements inside dwelling room. In: Proceedings of the Biulding Simulation ’91 Conference, IBPSA (The International Building Performance Simulation Association), Nice, France, pp.106-110.

Bratasz L, Kozlowski R, Camuffo D et al (2007) Impact of indoor heating on painted wood - Monitoring the altarpiece in the Church of Santa Maria Maddalena in Rocca Pietore. Italy. Studies in Conservation*, 52*(3), pp.199-210.

De Backer L, De Paepe M, Janssens A (2014) On the coupling of a zonal model with a BES model for predicting vertical temperature distribution. In: Proceedingsof the 10$^{th}$ international conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Orlando, Florida, USA, 14-16 July 2014, pp. 2008-2013.

Fawcett J (2001). Historic floors: their history and conservation. Butterworth-Heinemann.

Heiselberg P, Murakami S, Rulet C-A (1998) Annex 26: Ventilation of large spaces in buildings. Part 3. Analysis and Prediction Techniques, IEA Annex 26 Report: Energy Efficient Ventilation of Large Enclosures, Denmark, Aalborg, Aalborg University, pp. 324.

Janssens A, Rode C, De Paepe M, Woloszyn M, & Sasic-Kalagasidis A (2008) From EMPD to CFD – overview of different approaches for Heat Air and Moisture modeling. In: Proceedings of the IEA ECBCS Annex 41 Closing Seminar, Copenhagen, Denmark, pp.9-20.

Pitsch S, Holmberg S, & Angster J (2010), Ventilation system design for a church pipe organ using numerical simulation and on-site measurement. Building and Environment*,* 45(12), pp.2629-2643.

Togari S, Arai Y, Milura K (1993) A Simplified Model for Predicting Vertical Temperature Distribution in a Large Space. ASHRAE Transaction, 99(part 1), pp.84-90.

Troi A, Hausladen G. (2006). Indoor Climate & Damage Risk Due To Heating Systems In South Tyrolean Churches. In proceedings of Conference And Brokerage Event The Construction Aspects Of Built Heritage Protection, Dubrovnik, Croatia, 14 – 17 October 2006.

Vlaamse Gemeenschap (19/11/2011) Omzendbrief ML/11 betreffende de kerkverwarmingen van beschermde monumenten*.* Ruimtelijke Ordening, Woonbeleid en Onroerend erfgoed, Brussel.