Optimal setpoint operation to reduce peak drying of a church organ

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ABSTRACT

The paper presents the characteristics of the Walloon Church in Delft (Netherlands) and a description of constraints for the indoor climate, giving criteria for the indoor air temperature and relative humidity with the focus on the preservation of the monumental church organ. The set point operation of the Heating Venting and Air Conditioning (HVAC) system is evaluated by simulation. The next main model components are presented and combined in a single integrated model: 1) a whole building response model for simulating the indoor temperature and relative humidity, 2) a Partial Differential Equation (PDE) based model for simulating detailed dynamic moisture transport in the monumental wood (church organ) and 3) a SimuLink controller model. The building model is validated with measurements. The main advantage of the integrated model is that it directly simulates the impact of HVAC control set point strategies on the indoor climate and the church organ. Two types of control strategies are discussed. The first type is a limited indoor air temperature-changing rate. The second type is a limited indoor air relative humidity changing rate. Recommendations from international literature suggest that 1) a changing rate of 2 K/h will preserve the interior of churches and 2) a limited drying rate is important for the conservation of monumental wood. This preliminary study shows that a limitation of indoor air temperature changing rate of 2 K/h can reduce the peak drying rates by a factor 20 and a limitation of the relative humidity changing rate of 2%/h can reduce the peak drying rates by a factor 50. The second strategy has the disadvantage that the heating time is not constant.

1. INTRODUCTION

In the Walloon Church in Delft a monumental church organ is present which has been restored in the spring of 2000. To prevent damage to the church organ again, the indoor climate has to meet certain requirements. Schellen [1] presented a study on the indoor climate performance related with the preservation of this monumental church organ. The Walloon Church is not only used for services, but also for several other activities e.g. church organ recitals. Since people are sitting in the church without wearing their overcoat, a temperature of 18 to 20°C is desirable. The result of this rather high temperature for monumental churches is that the Relative

Humidity (RH) of the indoor air becomes very low (30%). Since such a low RH can cause damage to the church organ, the heating system is restricted. As soon as the RH of the indoor air threatens to drop below 40%, the heating system is shut down. As a result of this restriction it is not possible to reach an indoor temperature of 18°C in winter when it is freezing outside. Humidifying of the indoor air was seen as a possible solution. Due to this measure, the RH of the indoor air remains high enough for preserving the church organ and at the same time the indoor air can be heated to the required comfort temperature of 18°C. As a consequence of humidifying during winter conditions there is a risk that condensation and fungal growth develops on cold surfaces. For that reason a request for further research by simulations was received from the church council. With the help of these simulations an assessment can be made of the potential risks. The main task is to protect the wooden monumental church organ from drying induced stresses. In this context, Kowalski [2,3], concludes that: 'increase of drying rate causes a non uniform distribution of the moisture content in dried material and this involves the drying induced stress', and 'fracture is more likely if the dried body is thick and/or the drying rate is high' These studies show that the peak drying rate has to be minimized in order to minimize the risk of drying induced stress and fracture. In this paper simulation is used as a tool to minimize the risk of drying induced stress and fracture. Moreover, simulation of peak drying rates is a challenging problem because: (1) small times scales (order seconds) are important; (2) Heat, Air & Moisture (HAM) transport in wood must be modeled with enough spatial resolution; (3) the continuous dynamic interaction between indoor climate, wood and Heating Venting and Air Conditioning (HVAC) systems; (4) the dependency of the HVAC control strategy.

The objectives of this paper are: (1) Development of a single model for simulating the indoor climate, the detailed moisture distributions of wood and the HVAC system. (2) Evaluation of the current set point operation strategy of the HVAC system of the Walloon church. (3) Development and evaluation of new strategies including RH control.

The outline of the paper is as follows: Section 2 presents the results of the development of an integrated model in SimuLink. The main model includes sub-models for the indoor climate of the church, moisture transport in wood, the HVAC system and controller. Section 3 provides simulation and validation results of the sub-models using measurements. Section 4 shows the results of two operation strategies for minimizing the peak drying rates, based on limitation of the air temperature and relative humidity changing rates. Section 5 presents a discussion of the results and revisits the above provided objectives.

2. MODELING IN SIMULINK

The simulation environment Matlab/SimuLink/COMSOL is capable of solving a large range of HAM problems [4]. The main reasons for implementing our models into SimuLink were: (1) it seemed promising in solving simulation problems caused by the interaction of components with different time constants i.e. HVAC system and church responses; (2) we expected a relative easy integration of a distributed parameter model (moisture transport in wood) in our lumped model by using the FEM capabilities of COMSOL; (3) if necessary, we would be able to model quite complex controllers and setpoint operations in SimuLink; (4) we had a state-of-art indoor climate model at our disposal (see next Section).

2.1. THE CHURCH INDOOR CLIMATE

The indoor climate is simulated using the Heat Air and Moisture Building and systems engineering tool (HAMBase, de Wit [5]). The main objective of HAMBase is the simulation of the thermal and hygric indoor climate and the energy consumption. Details of how the inside climate of a church can be simulated, including effects of ventilation on the church climate and how to account for a spatial distribution of temperature and RH were studied by Schellen [1].

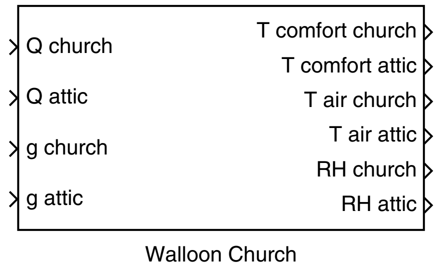

Figure 1 The church model in SimuLink. With Q = heating power [W], g = humidifying [kg/s], T comfort = comfort temperature [°C], T air = air temperature [°C], RH air = air relative humidity [-].

In SimuLink, the HAMBase model is visualized by a single block with input and output connections. The interface variables are: (1) the input signal of the HAMBase SimuLink model. This is vector contains for each zone the heating/cooling power and moisture sources/sinks to the air nodes. (2) The output signal containing for each zone the mean comfort temperature, the mean air temperature and RH. In figure 1 the input/output structure for the church model (containing 2 zones: church and attic) is shown.

2.2. THE MOISTURE TRANSPORT IN WOOD

COMSOL [6] is used to model the moisture transport in wood. In this case we are mainly interested in the moisture interaction of indoor climate and wood, dominated by vapor transport. Therefore a 1D moisture diffusion transport model (1) is sufficient.

$$\frac{\partial w}{\partial t} = \nabla \cdot (D_w(w)\nabla w) \tag{1}$$

where w = moisture content [kg/m^3], D_w = moisture diffusivity [m^2/s],

The model is implemented using the so-called *coefficient form* (2abc) specified by COMSOL [6] (see also van Schijndel [4]):

$$d_a \frac{\partial u}{\partial t} - \nabla \cdot (c\nabla u + \alpha u - \gamma) + \beta \nabla u + a u = f \tag{2a}$$

$$\underline{n} \cdot (c\nabla u + \alpha u - \gamma) + q u = g - \lambda \tag{2b}$$

$$h u = r \tag{2c}$$

This means for the PDE coefficients of (2a – 2c):

$$u = w \tag{3a}$$

$$d_a = 1 \tag{3b}$$

$$c = D_w \tag{3c}$$

$$g = \beta_{RH} \cdot (RH_{air} - RH_{surface}(w)) \tag{3d}$$

$$\alpha = \beta = \gamma = a = f = q = h = r = 0 \tag{3e}$$

where RH_{air} = indoor air relative humidity, $RH_{surface}(w)$ = relative humidity at surface calculated from the hygroscopic curve (temperature effect is neglected).

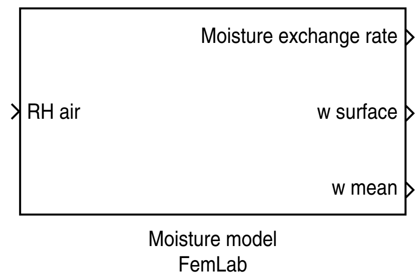

Figure 2 The moisture transport model in SimuLink. The moisture exchange rate in [kg/m^{2}s], w surface = moisture content near the wood surface [kg/m^3] and w mean = mean moisture content of the wood [kg/m^3].

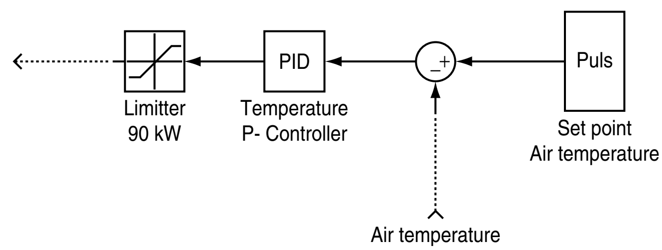

Figure 3 The HVAC system and controller model in SimuLink.

Furthermore it is assumed that the diffusion coefficient is constant and the moisture retention curve is linear in the range of 20% < RH < 90%. The thickness of the wood is 1cm. The COMSOL model is exported to SimuLink by the standard facility provided by COMSOL. In figure 2 the SimuLink model and its input/output structure are shown.

2.3. THE HVAC SYSTEM AND CONTROLLER

The HVAC system and controller are modeled using the standard library of SimuLink. In figure 3 the model is shown. The set point of the air temperature is generated by a pulse block with properties: Period: 1 week, start time 04.00 o′clock Sunday, duration: 12 hours, lower value: 10°C higher value 20°C. The input of the PID controller consists of the set point minus the actual air temperature. The settings of the PID controller are: $P = 10^7$, I=D=0, so in this case it acts like a proportional controller. The output of the controller is limited between 0 en 90 kW.

2.4. THE MAIN MODEL

The main model consists of the models of the church, wood and controller. In figure 4 this model is shown. There are two closed circuits: (1) An output of the church, the air temperature, is connected to input of the controller and the output of the controller, heating power, is connected to an input (heating/cooling) of the church; (2) another output of the church, relative humidity, is connected to the input of the wood and an output of the wood, moisture exchange rate is connected to an input (humidifying) of the church.

3. RESULTS

3.1. VALIDATION OF THE INDOOR CLIMATE MODEL

The HAMBase model has been subjected to a validation study by Schellen [1]. The measured and simulated air temperature and relative humidity of one month (December 2000) are compared. In figure 5 the results are shown. It shows that simulation and measurement are in good agreement.

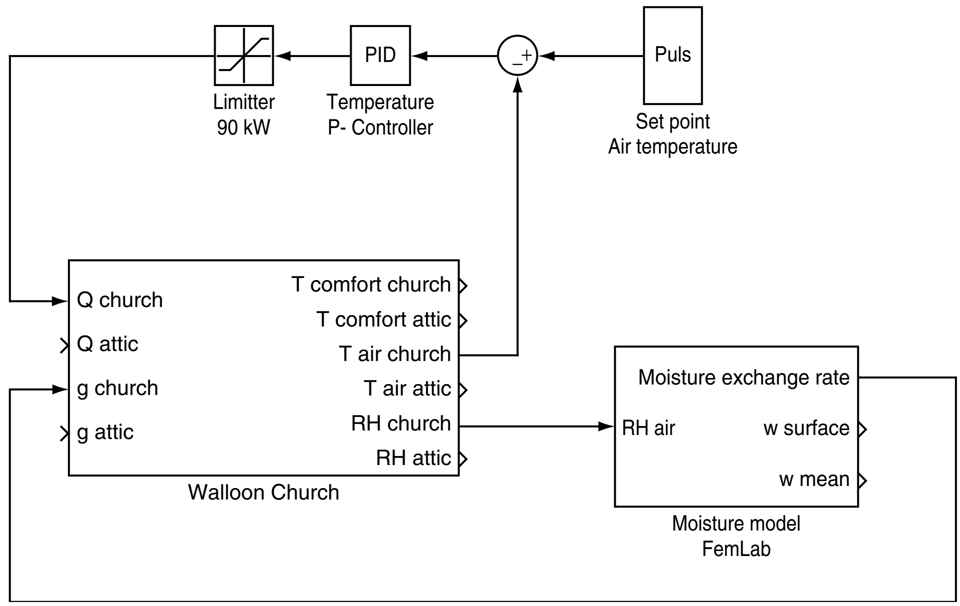

Figure 4 The main model in SimuLink.

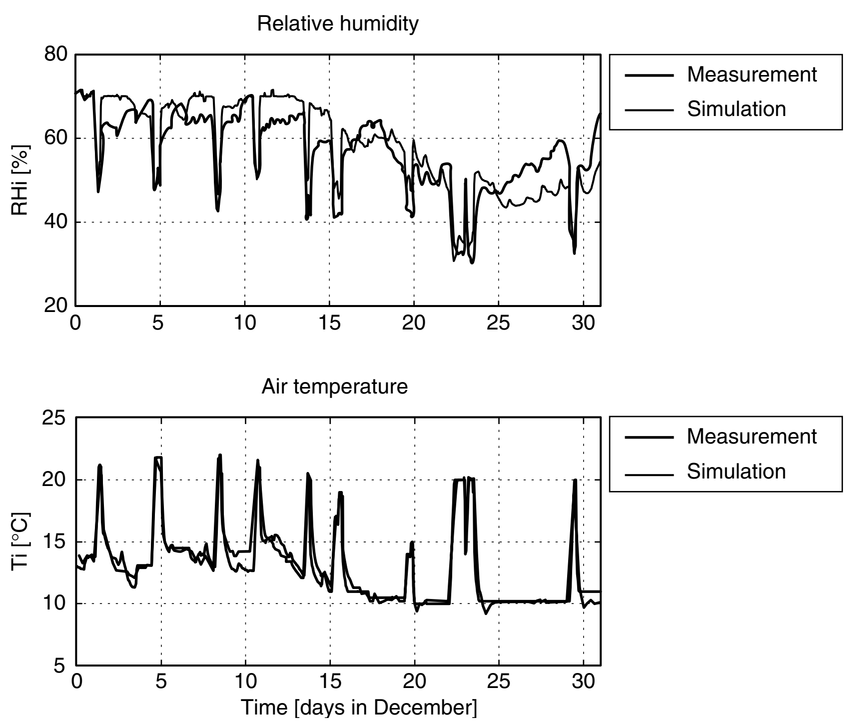

Figure 5 Validation of the HAMBase model. The measured and simulated air temperature and relative humidity of one month (December 2000) are compared by Schellen [1].

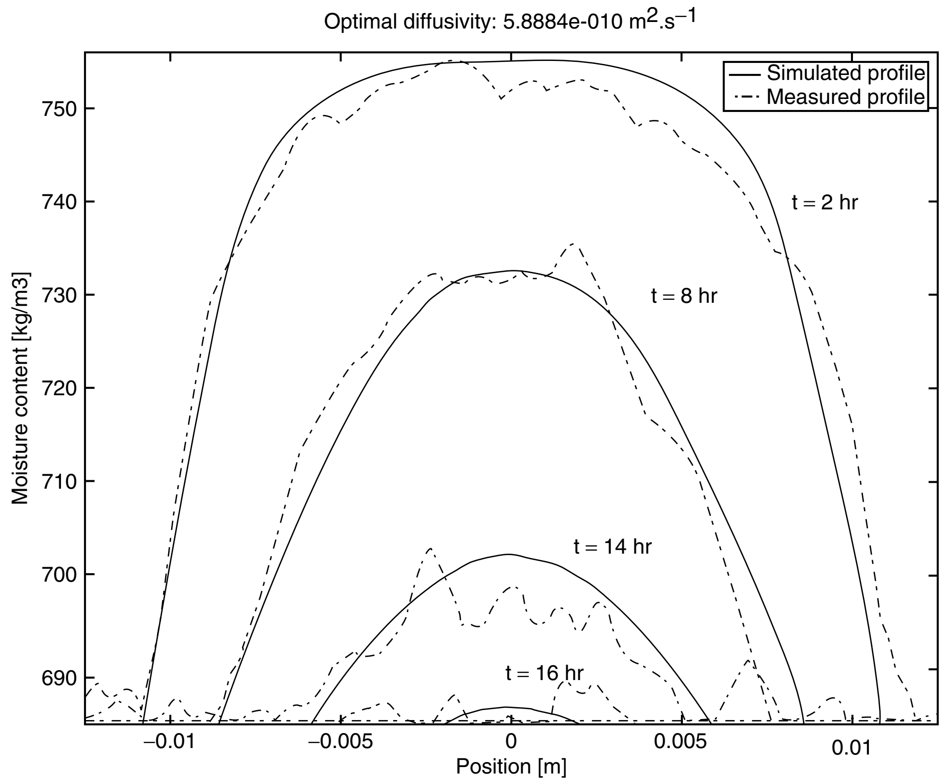

Figure 6 Simulation and measurement of moisture profiles in case of drying of a cylinder of wood (diameter 25 mm) by a step in relative humidity from 85% to 35% by Schellen [1].

3.2. VALIDATION OF THE MOISTURE TRANSPORT IN WOOD MODEL

In van Schijndel [4], a 1D-moisture transport model in COMSOL is validated and shows a good agreement between measurement and simulation. The same model is used, but with other material properties (wood) by Schellen [1]. Figure 6 presents a result of his thesis, where it is shown that simulation and measurement are in good agreement in case of drying and wetting of wood by a fluctuating air relative humidity (35% < RH < 85%).

3.3. DRYING RATES

The moisture content near the surface and the drying rate (= rate of change of moisture content near the surface) is studied, by using the model of figure 4, for two cases: (1) no heating and (2) full heating (max) capacity, i.e. no limitations in air temperature or relative humidity changing rate. The simulation period is again one month (December 2000). For all following case studies, the set point operation of figure 3 is used. This means that the church is heated 4 times a month. In figure 7, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface is shown for the two cases. In figure 8, the drying rate is shown during a period of 1 day (starting Saturday 0.00 o′clock), again for the two cases. A negative drying rate means that water is transported from the material to the surroundings i.e. drying. In figure 9, the peak-drying rate defined as the absolute value of the drying rate for that same period is shown on a log scale. From figure 9 the

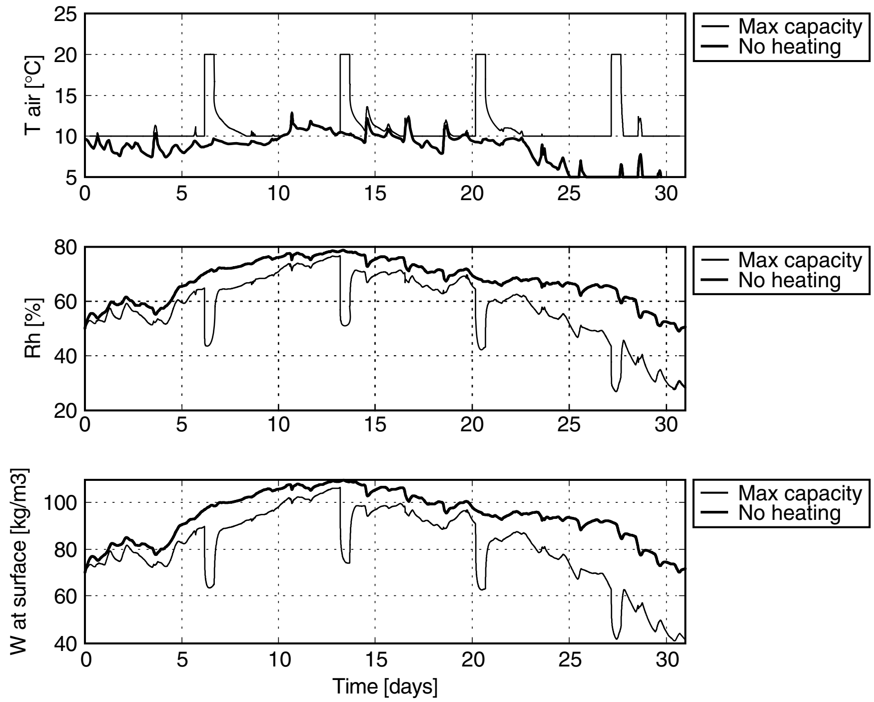

Figure 7 The simulated indoor air temperature, the relative humidity and the moisture content of the wood near the surface. The simulation period is December 2000.

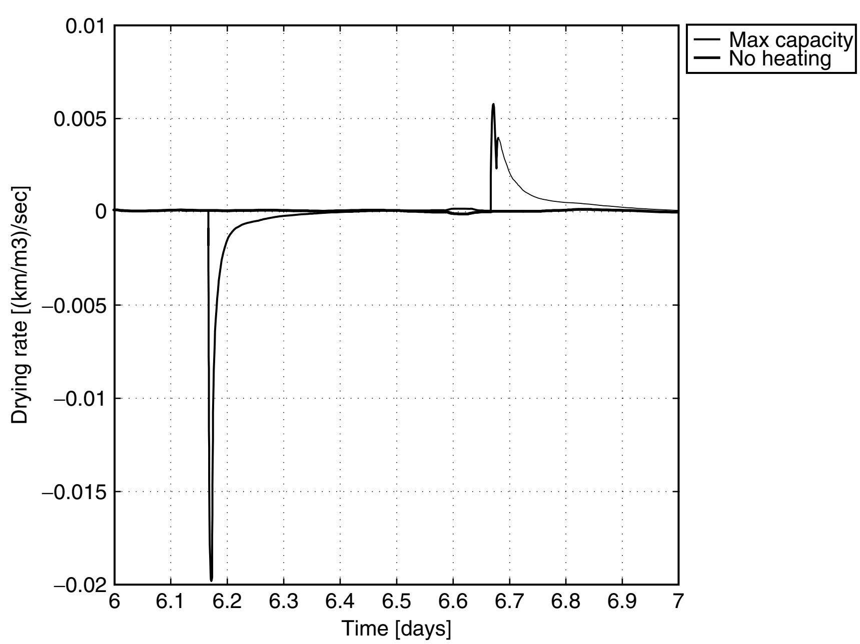

Figure 8 The simulated drying rate during a period of 1 day (starting Saturday 0.00 o'clock).

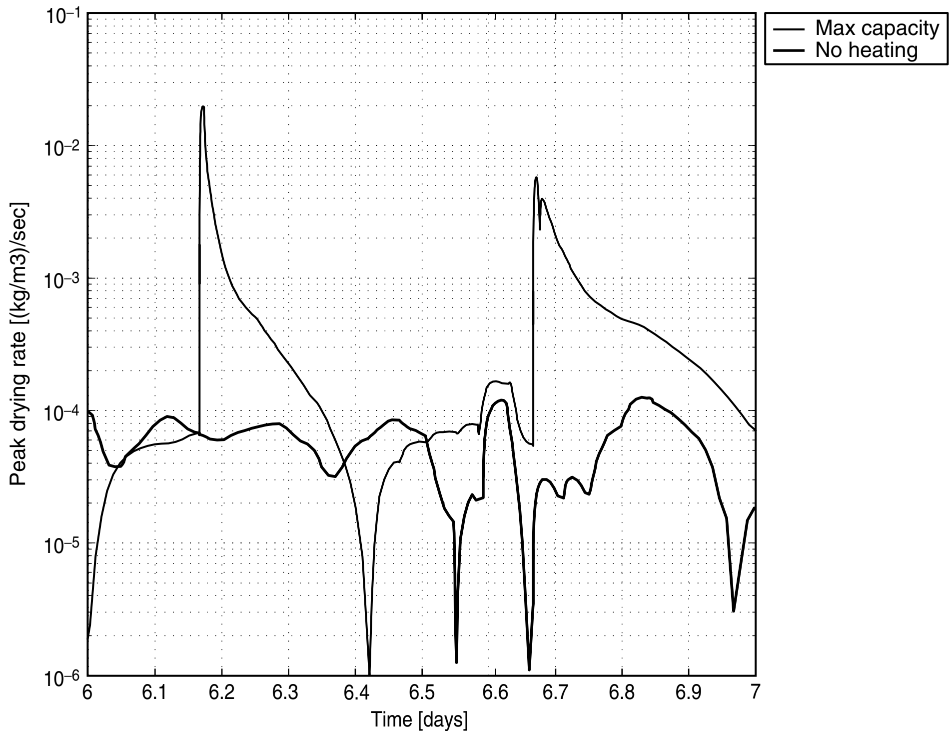

Figure 9 The simulated peak drying rate on a logarithmic scale during a period of 1 day (starting Saturday 0.00 o'clock).

difference in peak drying rate for the case of no heating and the case of full heating capacity is very clear: The peak drying rate, in the case of full heating, is of order ~100 times bigger than in case of no heating. These peaks can cause drying induced stresses (Kowalski [2,3]) and have to be minimized to prevent possible damaging of the (monumental) wood. In the next Section, alternative set point operations will be presented and discussed.

4. SET POINT OPERATION STRATEGY STUDY

In previous Section, the results of two extreme control strategies 'No heating' and 'full heating capacity' are already presented. The latter strategy was formerly used in the Walloon Church and lead to irreparable damage to the monumental church organ. In this Section two alternative set point operation simulations are shown.

4.1. LIMITATION OF THE AIR TEMPERATURE-CHANGING RATE (STRATEGY 1)

Recommendations from Schellen [1] suggest that a limitation to the air temperature-changing rate of 2 K/h will preserve the interior of churches. A 'Rate Limiter' block in SimuLink can model such a limitation of the air temperature-changing rate. The complete model including the set point temperature Rate Limiter is shown in figure 10. The output of the air temperature set point is connected to a 'Rate Limiter' block of SimuLink. This block has two parameters: the Rising slew rate (R) and the falling slew rate (F). This block is modeled by:

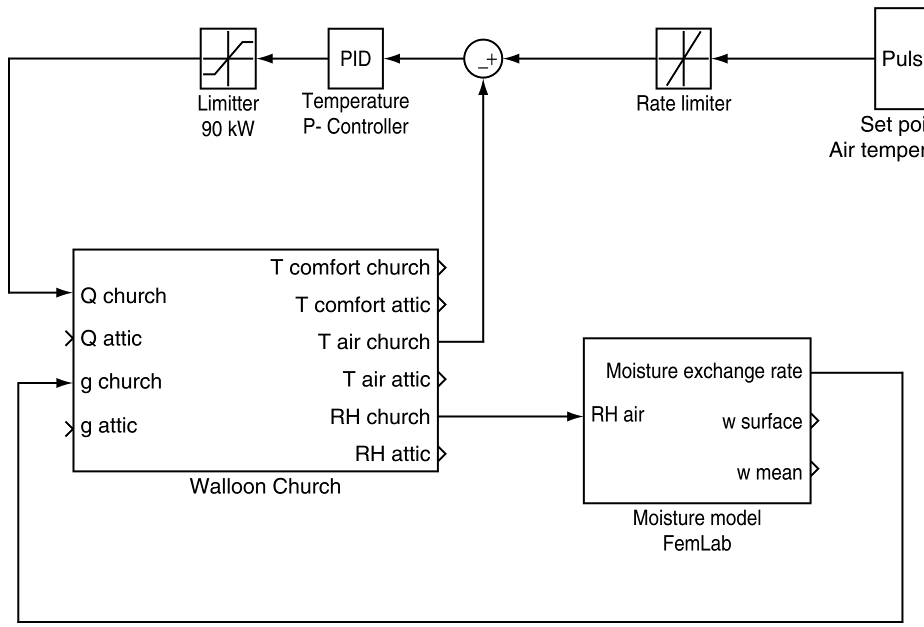

Figure 10 The complete model including a 'Rate Limiter' block for the limitation of the air temperature changing rate.

$$rate = \frac{u(i) - y(i-1)}{t(i) - t(i-1)}, \tag{4a}$$

$$if\ \ rate > R : y(i) = \Delta t \cdot R + y(i-1) \tag{4b}$$

$$if\ \ rate < F : y(i) = \Delta t \cdot F + y(i-1) \tag{4c}$$

$$else : y(i) = u(i) \tag{4d}$$

where u = input of the block, y = output of the block, t = time, Δt = t(i) – t(i – 1), (i) = actual time step, (i – 1) = previous time step.

In figure 11, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o′clock) is shown, for different cases including limitation of the air temperature heating change rate of 1.5 K/h and 2.5 K/h. (This means for the parameters of the rate limiter that the rising slew rate R equals 1.5/3600 resp. 2.5/3600 and the falling slew rate F equals -∞ in both cases). In figure 12 the peak drying rate is shown for these cases. From figure 12 it follows that a limitation of the temperature changing rate of 2 K/h reduces the peak drying rates by an order of ~10 compared with no limited temperature heating change. However, the peak factor is still an order of ~10 higher compared with no heating.

4.2. LIMITATION OF THE RELATIVE HUMIDITY CHANGING RATE (STRATEGY 2)

Perhaps a more challenging task is to model the heating of the church with a limitation of the relative humidity. In figure 13 the complete model including the relative humidity changing

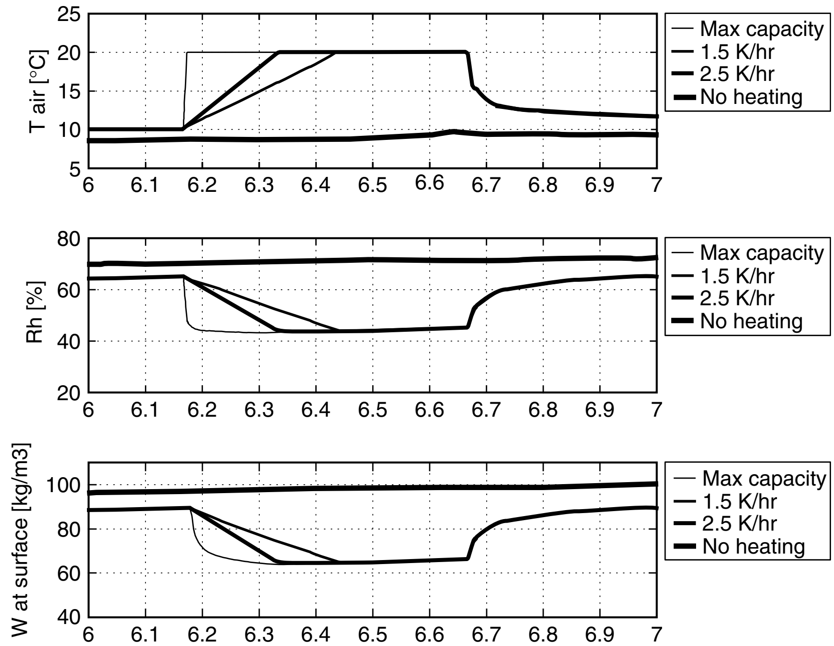

Figure 11 Simulation of indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock) in case of Strategy 1.

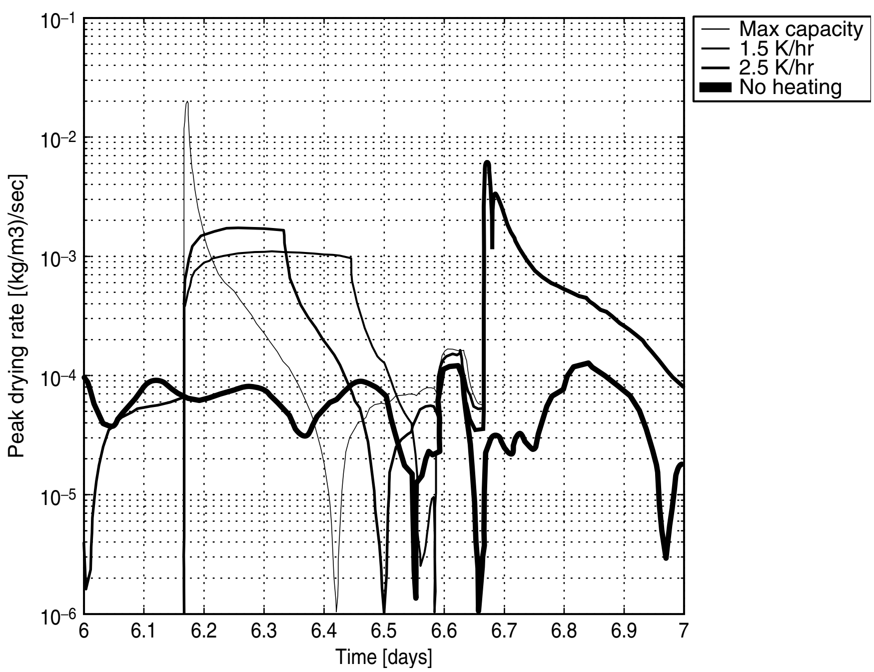

Figure 12 Simulation of the peak drying rate during a period of 1 day (starting Saturday 0.00 o'clock) in case of Strategy 1.

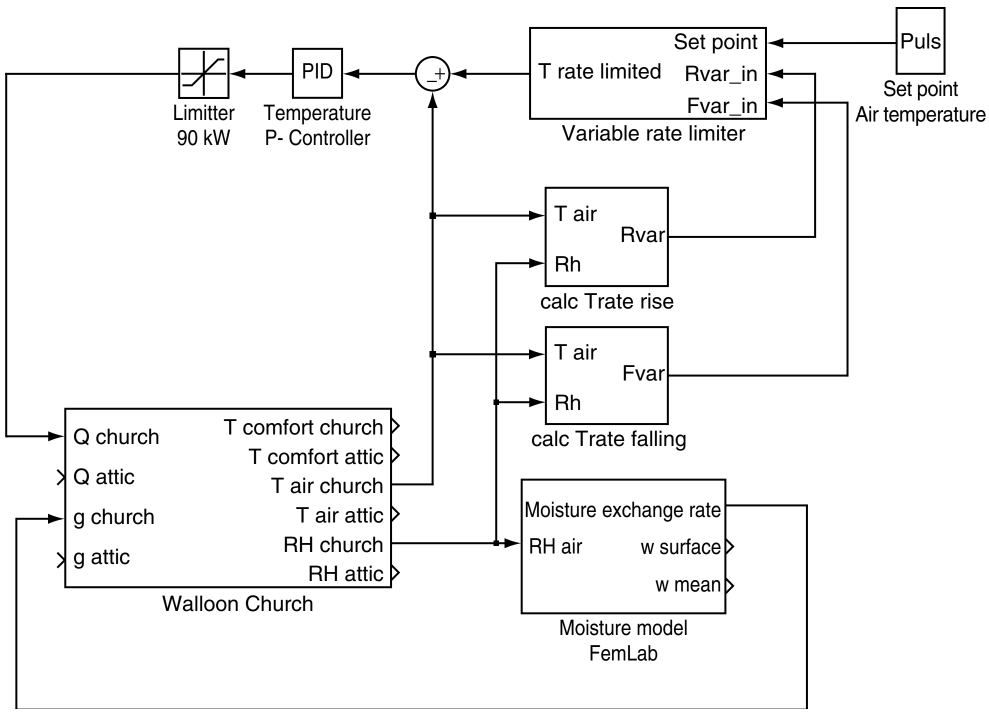

Figure 13 The complete model including the relative humidity changing limiter.

limiter is shown. The output of the air temperature set point block is connected to a new developed ‘Variable Rate Limiter’ block. This block has 3 inputs: the air temperature set point, the (variable) rising slew rate (Rvar) and the (variable) falling slew rate (Fvar). The output of this block is analog to the ‘Rate Limiter’. It can now also handle variable rising and falling slew rates. The slew rates Rvar and Fvar are calculated by the block ‘calcTrate’. The inputs of this block are the air temperature and the relative humidity. The output consists of the slew rate of the air temperature. The output is calculated from standard psychometrics functions, already programmed in MatLab and the only parameter of this block, dRh, the relative humidity changing rate in %/h:

$$T_{rate} = \left| T_{air} - t_{dew}\left(\frac{RH \cdot p_{sat}(T_{air})}{RH - dRH}\right)\right| \Big/ 3600 \qquad (5)$$

where T_{rate} = computed temperature changing rate [°C/sec], T_{air} = air temperature [°C], t_{dew} = dew-point function [°C], RH = relative humidity [%], p_{sat} = saturation pressure function [Pa], dRH = maximum relative humidity changing rate [%/h].

In figure 14, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o′clock), is shown for different cases including limitation of the relative humidity changing rate of 2%/h and 5%/h. In figure 15 the peak-drying rate is shown for these cases. From figure 15 it follows that a limitation of the relative humidity changing rate of 2% /h reduces the peak drying rates

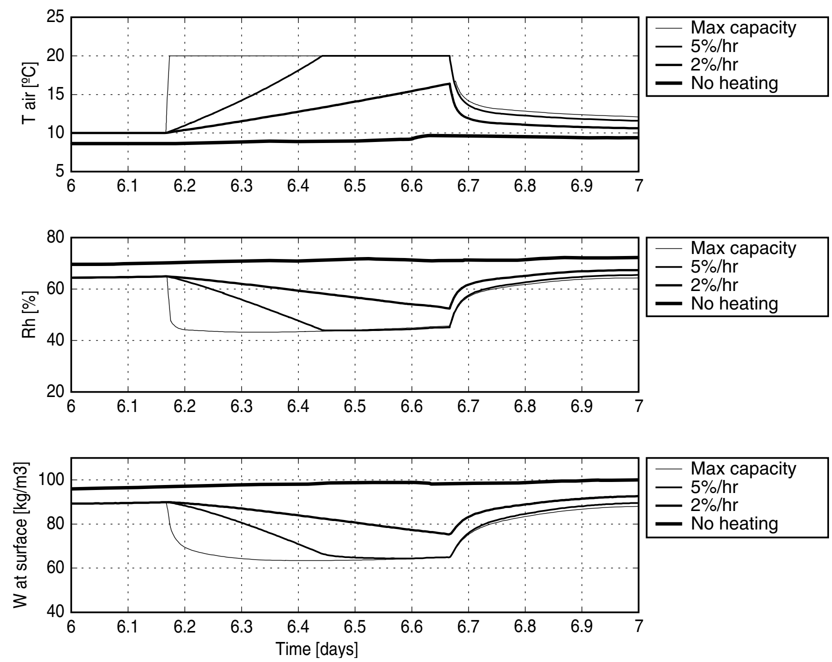

Figure 14 Simulation of indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock) in case of Strategy 2.

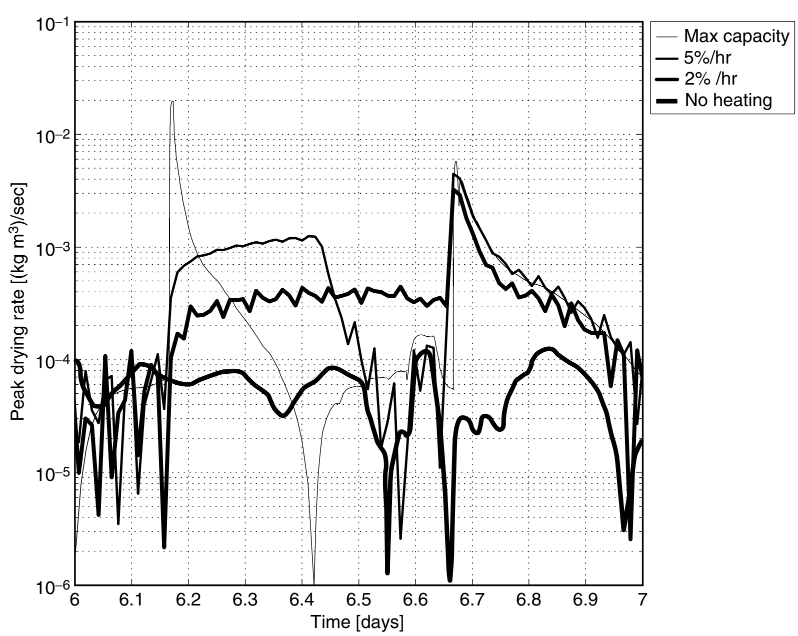

Figure 15 Simulation of the peak drying rate during a period of 1 day (starting Saturday 0.00 o'clock) in case of Strategy 2.

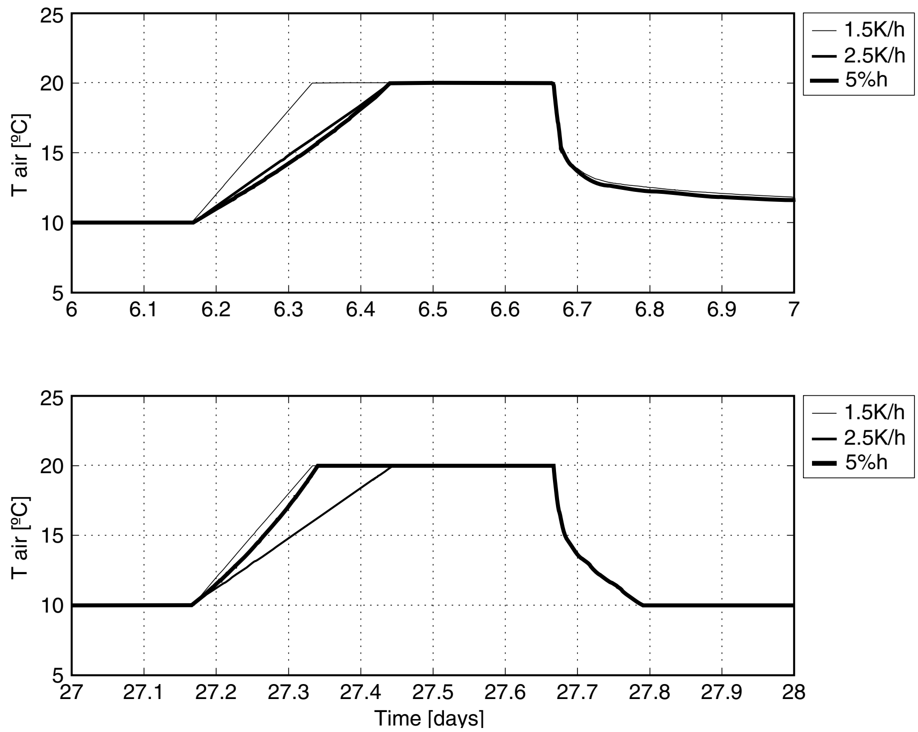

Figure 16 The air temperature for the controlling strategies. The upper part shows the air temperature at 6 December, the lower part shows the air temperature at 27 December.

by an order of ~50 compared with no limited temperature heating change. However, the peak factor is still an order of ~5 higher compared with no heating. Notice that in this case, the maximum occurring indoor air temperature is 16°C. This is far below the set point temperature of 20°C.

5. DISCUSSION

5.1. THE DIFFERENCE BETWEEN STRATEGY 1 AND 2

The control strategies of limiting the temperature or relative humidity changing rates look rather familiar for the peak drying rates (see figure 12 and 15). However, they are not the same. The difference in the controlling strategy is shown in figure 16. In this figure the air temperatures of figures 11 and 14 are combined and shown for 2 different days. From figure 16 it follows that the 5%/h relative humidity rate limitation approaches the 2.5 K/h temperature rate at 6 December, but it approaches the 1.5 K/h temperature rate at 27 December. Also from figure 16 it can be seen that the time needed for heating the church to 20°C in case of the 5%/h relative humidity rate limitation varies from 0.25 days (= 6 hours) on 6 December to 0.15 days (=3.6 hours) on 27 December. These differences show that the 2 strategies, temperature and relative humidity change rate limitation are quite different. This is also shown in figure 17, where the air temperature (variable) Rising slew rate (Rvar) is plotted against time for the relative humidity change rate limitations. From figure 17 it

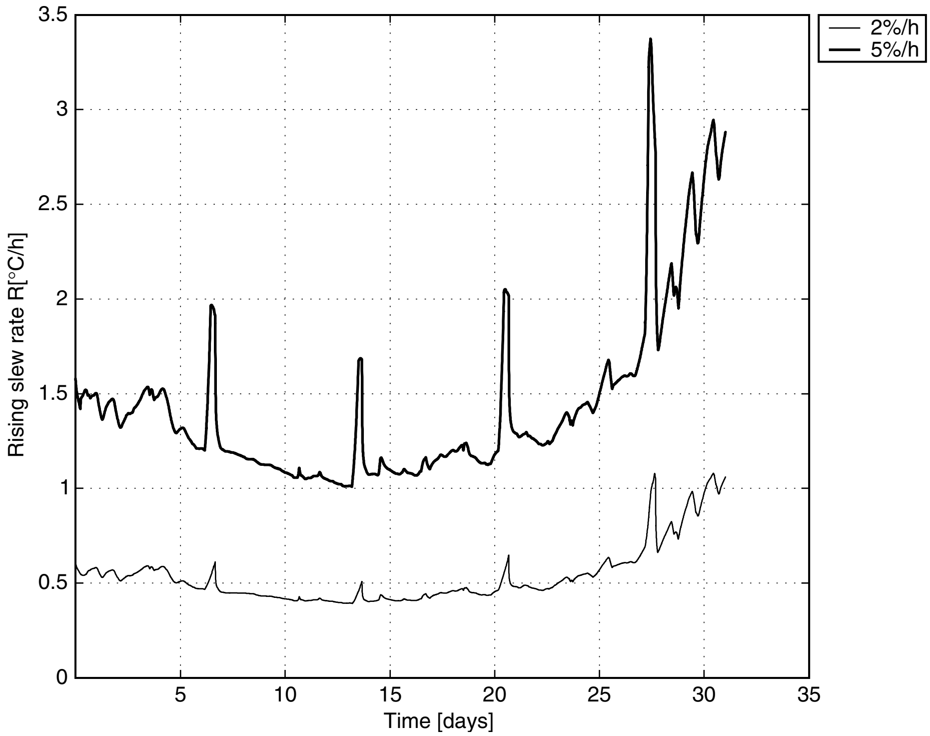

Figure 17 The (variable) Rising slew rate (Rvar) versus time for the relative humidity change rate limitations. The time period is December 2000.

follows that the air temperature Rising slew rate (Rvar) can change by a factor ~3 during the time period in case of relative humidity change rate limitation.

5.2. EVALUATION OF ALL STRATEGIES

The best solution to prevent high peak drying rates is no heating. Due to thermal discomfort, this is not an acceptable solution. The worst solution to prevent high peak drying rates is full heating capacity. From figure 9 it follows that the peak drying rate is of order ~100 times bigger than in case of no heating. This is seen as the main cause of the damaging of the previous church organ of the Walloon church (Schellen [1]) and is therefore not acceptable. Two possibilities to limit the peak drying rates are studied: Limitation of the changing rate of the air temperature and the relative humidity. Both are rather familiar in case of the limitation of the peak drying rates. The disadvantages of a limitation of the relative humidity changing rate compared to a limitation of the air temperature changing rate are (1) The time to heat the church is not constant, so it is more difficult to predict the time to heat the church and switching on the controller at the appropriate time; (2) A more complex controller is needed (compare figure 10 with 13). Therefore a limitation of the air temperature-changing rate is preferred.

5.3. PRACTICAL APPLICATION OF THE RESULTS OF THIS STUDY

As a result of this research several adjustments have been made to the heating system. Afterwards measurements showed that the indoor climate did meet the requirements for preservation of the church organ.

6. CONCLUSIONS

The set point operation of the HVAC system is evaluated by simulation using MatLab, COMSOL and SimuLink models. The next main model components are presented and combined in a single integrated SimuLink model: 1) a HAMBase SimuLink building model for simulating the indoor temperature and relative humidity, 2) a COMSOL PDE model for simulating detailed dynamic moisture transport in the monumental wood (church organ) and 3) a SimuLink controller model. The main advantage of the integrated model is that it directly simulates the impact of HVAC control set point strategies on the indoor climate and the church organ in terms of peak drying rates.

Two types of control strategies are discussed. The first type is a limited indoor air temperature-changing rate. The second type is a limited indoor air relative humidity changing rate. A limitation of the air temperature-changing rate of 1.5 to 2.5 K/h is preferred.

Future research include the implementation of a more accurate model for the moisture transport and moisture induced stresses.

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