Humidity change rate control in intermittently heated historic buildings

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Abstract. Many massive historic buildings such as stone churches are intermittently heated. The predominant heating strategy is to heat the building with as high heating power as possible to achieve a fast and energy efficient heat-up process. However, the fast change rate of temperature induces a high change rate of relative humidity, which can be dangerous for interiors and objects in churches. It has been suggested that the change rate of relative humidity should be limited with respect to conservation. Desorption from the walls has a significant effect on the change rate of relative humidity. Typically, the absolute humidity can increase by 50% when the church is heated. Based on a hygrothermal model that allows for a prediction of both temperature and absolute humidity as function of time, this paper presents a model-based feed-forward control algorithm that calculates the maximum hourly heating power increase allowed for limit the change rate in relative humidity to a pre-defined value. The control algorithm is validated using simulations.

1 Introduction

Traditionally many historic building have been heated intermittently with open fireplaces or stoves [1]. Even with more modern heating sources, intermittent heating is still common in historic buildings as it provides a reasonable comfort in combination with relatively low energy use [2]. Typically, the building is heated rapidly before use and in between, the building is kept cold or with background heating.

The thermal models for intermittent heating were established already in the 19th century [3]. More recent research have shown how these models can be practically used in order to predict heat up time and to determine the proper heating power when installing a new heating system [4, 5].

Art objects and furniture made from hygroscopic materials are sensible to changes in relative humidity (RH) as this may cause cracking and loss of paint [6]. Thus, for a given temperature increase, with respect to thermal comfort, we must consider how much the RH would change and how quickly it changes. However, the relation between T and RH is not trivial as moisture is added to the air through desorption from wall as result of heating.

The objective of the present paper is to present a simplified hygrothermal model that allows for control of RH with respect to conservation during intermittent heating. In the first part, hygrothermal model is presented. The second part presents a model-based control strategy for step-wise increasing the heating power in order to avoid too fast changes in RH during the heat up process. Finally, the practical use of this control strategy is discussed.

This paper, based on a PhD thesis [5], aims to highlight the aspect of controlling RH rate of change and its practical implementation.

2 Theory

In this section, an approximate model for air temperature and humidity mixing ratio (MR) in response to a constant heat input in a massive historic building is described. Based on this model a RH change rate control method is presented.

2.1 Thermal model

A simplified thermal model for the temperature increase at a heat-up event in intermittently heated heavy buildings was developed in [7] and further in [8].

$$T_1 \frac{d\Delta\vartheta_a(t)}{dt} + \Delta\vartheta_a(t) = a_1 P_s \sqrt{t} + b_1 P_s. \qquad (1)$$

where a_1, $b_1$and T_1 are parameters. Parameter a_1 depends on the properties of the building envelope i.e. heat conduction, density, specific heat capacity and effective wall surface area. Parameter b_1 depends on the heat transfer coefficient between air and wall and the effective wall surface area. T_1 is the time constant of the model.

However, because it is complicated to determine the construction and the materials of historic masonry walls, it is difficult to determine their thermal parameters. The heat transfer coefficient between the wall and the air depends on the air flow close to the wall surface, which also is difficult to determine. However, these parameters can be estimated from measurements of the temperature during a step response test (i.e., a heat-up event) [8]. The task is thus to find parameters T_1, a_1 and b_1 which then determine the model (1).

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After the impact of the time constant T_1, the increase in air temperature is very close to a linear function of the square root of time ($\sqrt{t}$). Parameters a_1 and b_1 can then be determined by linear regression of air temperature measurements at a step response test. The regression must be conducted on the latter part of the data, where the influence of time constant accumulation has none or very little impact.

2.2 Hygric model

Analogously to the thermal model a simplified hygric model was developed which is briefly described in the following [8]. The hygric model describes how air humidity in a massive building with hygroscopic walls changes in response to a heat input step. During a heat-up event, the indoor air MR increases with the increase in air temperature as moisture evaporates from the indoor walls and interiors.

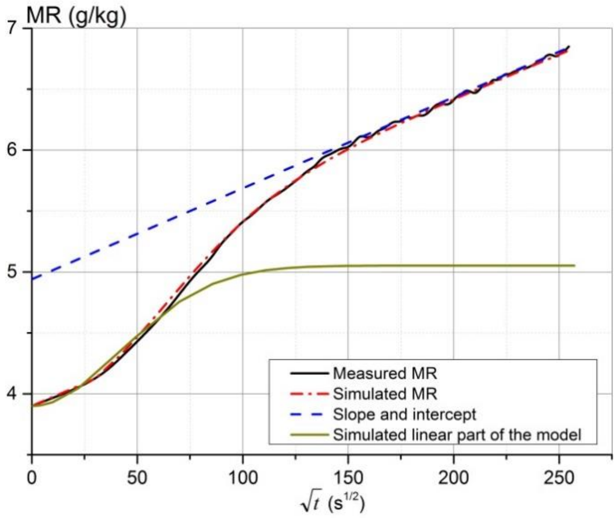

Fig. 1. Indoor air MR response at the heat-up event in Fide Church – measured versus simulated responses by the model.

The model for air MR $\Delta x_a(t)$ is given by

$$T_2 \frac{d\Delta x_a(t)}{dt} + \Delta x_a(t) = P_s\left(a_2\sqrt{t} + b_2\right) \qquad (2)$$

where $a_2, b_2$and T_2 are constant parameters. The hygric parameters a_2, b_2, T_2, can be determined, like the thermal parameters, using measured data from a step response to a heat input step by performing a linear regression on the measured data from the time when the impact of the time constant T_2 has subsided to the end of the heat-up event [8]. In Figure 1, the linear regression is performed on the measured data from150 to 250. Observe that the scale is in $s^{1/2}$. As can be seen in Figure 1, the conformity with measured data is very good.

The combined thermal and hygric models will be used for controlling the heat-up procedure.

2.3 RH change rate control

To control the increase of temperature and thereby the relative humidity (RH) change rate, a step-wise adjustment of heating power in time intervals $i\Delta t, i = 0,1,2$ ... is determined to satisfy a given maximum change rate of RH per Δt. The method is developed in [8] and is working like this

First determine the largest allowable RH change rate per time unit. $\Delta\varphi_{a,s}$ In our example -2%RH per hour has been used but any change rate and any time interval is possible.

Then the method temperature and humidity increase can be expressed in the following form:

$$\Delta\vartheta_a(t) = K_\vartheta(t)\Delta P_s, \qquad (3)$$

$$\Delta x_a(t) = K_x(t)\Delta P_s, \qquad (4)$$

where $K_\vartheta(t)$ and $K_x(t)$ are the step responses for the temperature- and humidity models respectively for a heat input step.

For a fixed t, $K_\vartheta(t)$ and $K_x(t)$ are constant gains. Considering this, the design task at $t = 0$ is to determine maximal ΔP_s for which

$$\Delta\varphi_a(\Delta t) \leq \Delta\varphi_{a,s}. \qquad (5)$$

Using the simplified Magnus formula [9], changes in $\Delta\vartheta_a$ and Δx_a can be transformed to change in $\Delta\varphi_a$.

$$\varphi_a = f_\varphi(x_a, \vartheta_a). \qquad (6)$$

Assuming that the variations in $\Delta\vartheta_a$ and Δx_a from the equilibrium initial values $\vartheta_{a,0}, x_{a,0}$ (determining $\varphi_{a,0}$) within Δt are small, equation (6) can be transformed to a linear incremental form

$$\Delta\varphi_a = C_x\left(\vartheta_{a,0}, x_{a,0}\right)\Delta x_a + C_\vartheta\left(\vartheta_{a,0}, x_{a,0}\right)\Delta\vartheta_a, \quad (7)$$

where

$$C_x\left(\vartheta_{a,0}, x_{a,0}\right) = \left.\frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial x_a}\right|_0 \qquad (8)$$

and

$$C_\vartheta\left(\vartheta_{a,0}, x_{a,0}\right) = \left.\frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial \vartheta_a}\right|_0 \qquad (9)$$

Substituting equations (3) and (4) in equation (7) and considering $t = \Delta t$, we obtain

$$\Delta\varphi_a = C_x\left(\vartheta_{a,0}, x_{a,0}\right)K_x(\Delta t)\Delta P_{s,0} +$$

$$+C_\vartheta\left(\vartheta_{a,0}, x_{a,0}\right)K_\vartheta(\Delta t)\Delta P_{s,0}. \qquad (10)$$

The heating-power step at $t = 0$ to achieve maximum allowable RH drop $\Delta\varphi_{a,s}$ over period Δt can be then determined by rearrange equation (10)

$$\Delta P_{s,0} = \frac{1}{C_x(\vartheta_{a,0},x_{a,0})K_x(\Delta t)+C_\vartheta(\vartheta_{a,0},x_{a,0})K_\vartheta(\Delta t)}\Delta\varphi_{a,s}. \quad (11)$$

The subscript in $\Delta P_{s,0}$ indicates the heating-power step at $t = 0$. In the unlikely case $\Delta P_{s,0} \geq P_{s,m}$, where $P_{s,m}$ indicates the maximum available heating power, $\Delta P_{s,0} = P_{s,m}$. If the inequality is not satisfied, we proceed as described below.

Based on the determined heating-power step $\Delta P_{s,0}$, the values of $x_a(t)$ and $\vartheta_a(t)$ at $t = \Delta t$ can be expressed as

$$\vartheta_{a,1} = \vartheta_{a,0} + K_\vartheta(\Delta t)\Delta P_{s,0}, \quad (12)$$

$$x_{a,1} = x_{a,0} + K_x(\Delta t)\Delta P_{s,0}. \quad (13)$$

Consequently, the RH change is given by equation (6)

$$\varphi_{a,1} = f_\varphi\left(x_{a,1}, \vartheta_{a,1}\right). \quad (14)$$

Next, the subsequent heating-power steps $\Delta P_{s,i}$ to be added at $t = i\Delta t$, $i = 1,2, \ldots$ are determined.

Under the linearity assumption, the overall response to a stepwise heating-power distribution consists of a superposition of single heating-power steps $\Delta P_{s,i}$ at $t = i\Delta t$, $i = 0,1,2$. The overall response is then the result of a superposition of the partial responses to the heating-power steps $\Delta P_{s,i}$, taken at $t = i\Delta t, i = 0,1,2$. Simulation-based validation was performed on higher-order model derived in [8], which models the heat distribution in the wall more precisely.

To determine the power increment at $t = 2\Delta t$, the superposition of the first and second steps needs to be considered. For this purpose, values of $\bar{x}_a(t)$ and $\bar{\vartheta}_a(t)$ at $t = 2\,\Delta t$ as a consequence of $\Delta P_{s,0}$ are expressed as

$$\bar{\vartheta}_{a,2} = \vartheta_{a,0} + K_\vartheta(2\Delta t)\Delta P_{s,0}, \quad (15)$$

$$\bar{x}_{a,2} = x_{a,0} + K_x(2\Delta t)\Delta P_{s,0}, \quad (16)$$

which leads to $\bar{\varphi}_{a,2} = f_\varphi\left(\bar{x}_{a,2}, \bar{\vartheta}_{a,2}\right)$ by equation (6). Then, the maximum allowed RH decrement due to $\Delta P_{s,1}$ is given by

$$\Delta\varphi_{a,r_1} = \Delta\varphi_{a,s} + \left(\varphi_{a,1} - \bar{\varphi}_{a,2}\right), \quad (17)$$

i.e. the maximum allowed RH decrease $\Delta\varphi_{a,s}$ is reduced by the decrease caused already by $\Delta P_{s,0}$. The power increment then can be determined as

$$\Delta P_{s,1} = \frac{1}{C_x(\vartheta_{a,1}, x_{a,1})K_x(\Delta t) + C_\vartheta(\vartheta_{a,1}, x_{a,1})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_1} \quad (18)$$

If $\Delta P_{s,0} + \Delta P_{s,1} < P_{s,m}$, the above procedure is repeated. Otherwise $\Delta P_{s,1} = P_{s,m} - \Delta P_{s,0}$ and the procedure stops.

This procedure is formalised to an algorithm

Algorithm 1. Determining the power increment $\Delta P_{s,i}$ at $i - th$ step

1. Values $x_a(t)$ and $\vartheta_a(t)$ at $t = i\,\Delta t$ are determined as

$$\vartheta_{a,i} = \vartheta_{a,0} + \textstyle\sum_{k=0}^{i-1} K_\vartheta\left((i-k)\Delta t\right)\Delta P_{s,k}, \quad (19)$$

$$x_{a,i} = x_{a,0} + \textstyle\sum_{k=0}^{i-1} K_x\left((i-k)\Delta t\right)\Delta P_{s,k}, \quad (20)$$

leading to the RH value $\varphi_{a,i}(t) = f_\varphi\left(x_{a,i}, \vartheta_{a,i}\right)$ calculated using the simplified Magnus formula [9]

2. Auxiliary values $\bar{x}_a(t)$ and $\bar{\vartheta}_a(t)$ are determined at $t = (i+1)\,\Delta t$

$$\bar{\vartheta}_{a,i+1} = \vartheta_{a,0} + \textstyle\sum_{k=0}^{i-1} K_\vartheta((i-k+1)\Delta t)\Delta P_{s,k}, \quad (21)$$

$$\bar{x}_{a,i+1} = x_{a,0} + \textstyle\sum_{k=0}^{i-1} K_x((i-k+1)\Delta t)\Delta P_{s,k}, \quad (22)$$

leading to the RH value $\bar{\varphi}_{a,i+1}(t) = f_\varphi\left(\bar{x}_{a,i+1}, \bar{\vartheta}_{a,i+1}\right)$ by equation (6).

3. The RH decrement is given as

$$\Delta\varphi_{a,r_i} = \Delta\varphi_{a,s} + (\varphi_{a,i} - \bar{\varphi}_{a,i+1}). \quad (23)$$

4. The heating-power step at $t = i\,\Delta t$ is finally estimated as

$$\Delta P_{s,i} = \frac{1}{C_x(\vartheta_{a,i}, x_{a,i})K_x(\Delta t) + C_\vartheta(\vartheta_{a,i}, x_{a,i})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_i}. \quad (24)$$

5. If the following inequality is satisfied

$$\textstyle\sum_{k=0}^{i} \Delta P_{s,k} \geq P_{s,m}, \quad (25)$$

$\Delta P_{s,i}$ is reduced to $\Delta P_{s,i} = P_{s,m} - \sum_{k=0}^{i-1} \Delta P_{s,k}$ and the procedure ends. Otherwise $i = i + 1$ and the procedure is repeated from step 1.

3 Case studies

The hygrothermal model with its parameters was validated with data measured in three different medieval churches in Sweden [5]. The conformity between model and measured data was the same as in Figure 1, even though the model parameters differed somewhat. In Figure 2, the churches interior, exterior and floor plans are showed. All three churches have pew heating system supplemented with radiators. In Fide church, the walls and floor are made of sandstone. The wall and vault are rendered both inside and outside with lime mortar. The roof is constructed with two cross vaults without a central pillar. The indoor volume of the open space is approximately 1000 m3. The installed power of the heating system is 32 kW.

The walls and vault of Hangvar church are constructed of lime stone which is rendered with lime mortar both inside and outside. The roof has four cross vaults and a central pillar in the middle of the hall. It has a wooden floor. The church has three building parts, hall, chancel and tower connected together to form a large open space. The indoor volume is approximately 1000 m3. The installed heating power in the church is 27 kW.

The walls and vault of Tingstäde church are constructed of limestone. It is rendered with lime mortar on the inside only. The roof consists of four cross vaults and a central pillar in the middle of the hall. It has a wooden floor. The interior volume is approximately 1200 m3. The installed heating power is 50 kW.

Temperature and RH were measured hourly with data loggers placed approximately 2.5 m above the floor in the centre of the church. See Figure 2.

4 Results

The control procedure for shaping the heating power by Algorithm 1 was simulated with models of the three churches. The simulation results are shown in Figures 3-5. The target temperature for comfort was selected to $\vartheta_{af} = 20°\mathrm{C}$ for all the three churches. Initial values of temperature and RH was taken from measured data in respective church. Fide church $\vartheta_{a,0} = 6°\mathrm{C}, \varphi_{a,0} = 69.5\%$, Hangvar church $\vartheta_{a,0} = 1.3°\mathrm{C}, \varphi_{a,0} = 74.7\%$ and Tingstäde church $\vartheta_{a,0} = 8°\mathrm{C}, \varphi_{a,0} = 85\%$. The responses of temperature and RH to a normal heating event at full power are shown in the left parts of the figures. The RH graphs show, a high change rate of RH at the beginning of all three heating events, which could be risky for wooden objects.

When the stepwise control procedure was applied. the RH change rate is kept below 2 % for all three churches, se fig 3, 4 and 5 right side.

For validation and comparison of model (1), a more accurate temperature model of the outer walls was discretised by use of the Finite Difference Method (FDM) [8] [10]. Coupling the FDM model of the wall with a single accumulation model, a good fit of the simulated and measured data was obtained for the three churches (Figures 3-5). Some parameters were then slightly tuned (within 15% range) for a better fit with the measured data. As seen in Figures 3–5, both models practically provide the same results as a good match can be observed.

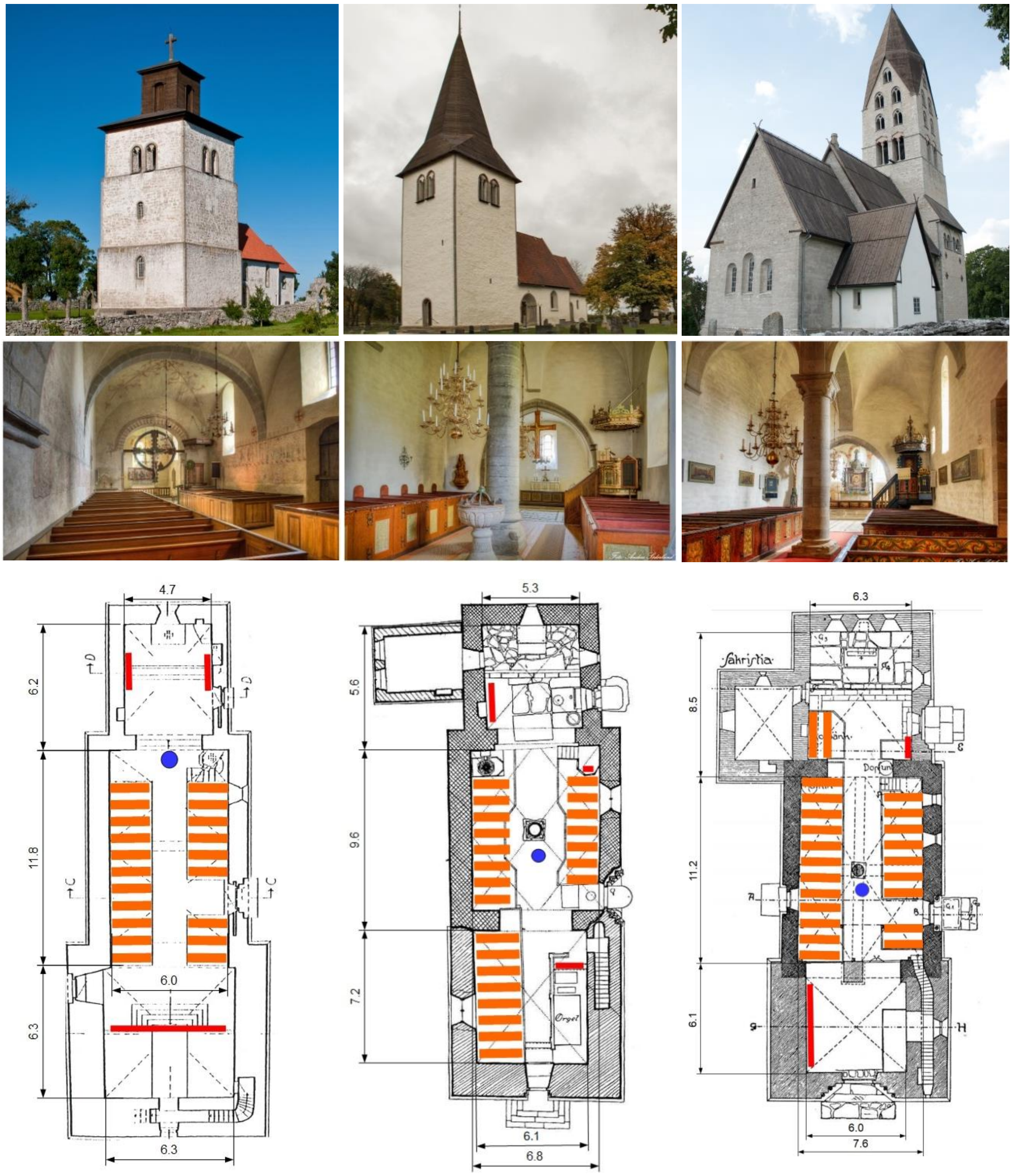

Fig. 2. Exterior and interior from the three case study churches Fide church, Hangvar church and Tingstäde church. The orange and red rectangles shows the location of the pew heating and radiators respectively.

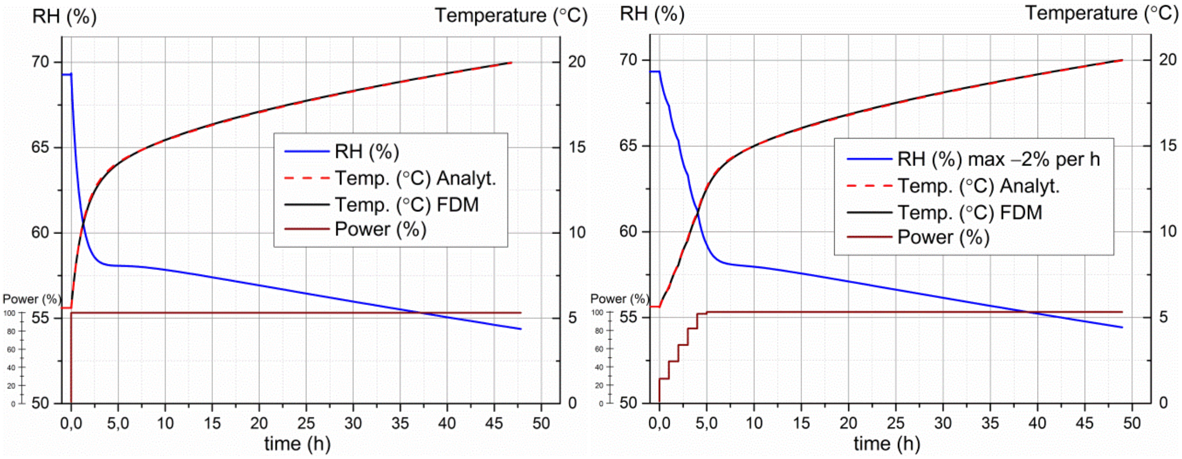

Fig. 3. Fide church: Simulation of a heating event by a single heating-power step (left), and a stepped heating-power distribution determined by Algorithm 1 (right). Note that the temperature simulations which is carried out with both analytical method and FDM method show the same result (black curve and red dashed curve).

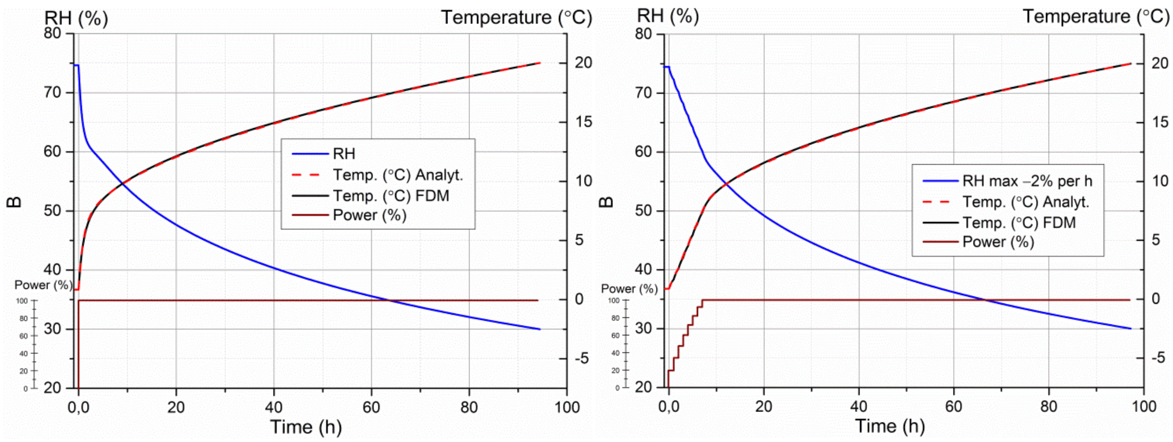

Fig. 4. Hangvar church: Simulation of a heating event by a single heating-power step (left), and a stepped heating-power distribution determined by Algorithm 1 (right). Note that the temperature simulations which is carried out with both analytical method and FDM method show the same result (black curve and red dashed curve).

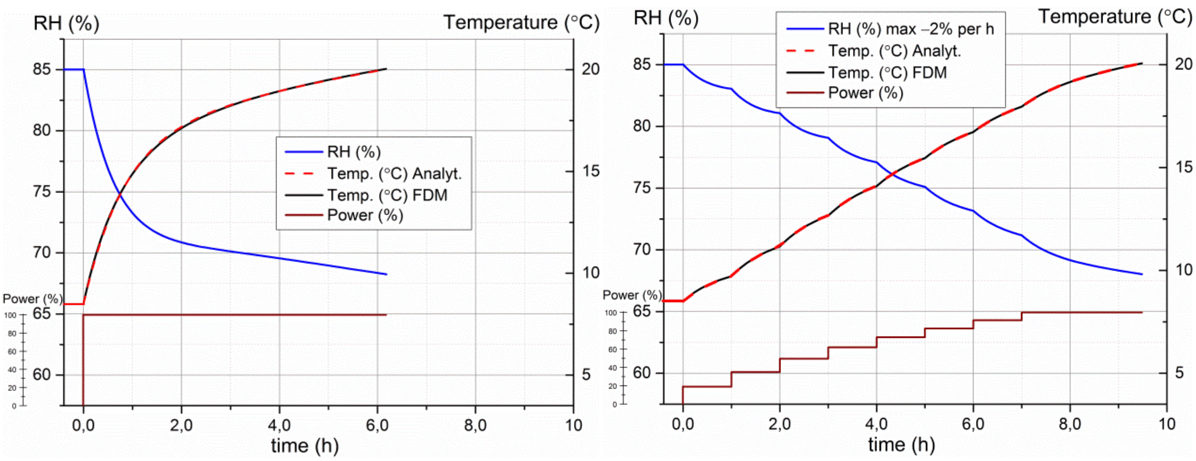

Fig. 5. Tingstäde church: Simulation of a heating event by a single heating-power step (left), and a stepped heating-power distribution determined by Algorithm 1 (right). Note that the temperature simulations which is carried out with both analytical method and FDM method show the same result (black curve and red dashed curve).

5 Conclusions

We have presented a practically useful method of shaping the heating power for intermittent heating in historic buildings with heavy masonry walls where the primary objective is to keep the RH change rate within a safe range. The method is based on simplified thermal and hygric analytical models with easy-to-apply parameter identification procedures based on in-situ measurements.

The control method has been applied and successfully validated on the models of the three churches. It needs to be stressed that the approximative models were developed for massive historic buildings with heavy masonry walls and small window areas and assume a relatively small and constant infiltration rate as well as relatively small effects of solar radiation during the heat-up event. Typical representatives of such buildings are historic stone churches such as the ones considered here.

The proposed control method has limitations. The method does not compensate for external disturbances, such as substantial changes of infiltration rate, effect of solar radiation and impact of visitors. However, these disturbances will not influence the indoor climate of the churches during a short intermittent heat-up event.

5.1 Practical use

The RH (hourly) change rate can be controlled by the proposed sub-step procedure. As shown from the comparison with the single-heating power step response, the increase of heating time for the start-up step-wise power increase is relatively small. In addition, the heating power can be controlled manually at given times (e.g., every hour) where a person turns on the heat based on tabularised values. Alternatively, the whole algorithm can be automated and implemented in a building automation system but also a low-cost controller could be used (e.g., Raspberry-Pi).

We propose the following practical approach:

1. In situ measurements of air temperature and RH during at least two heating events using full power.
2. Parameter identification from measurements for the thermal and hygric models using eq (1) and (2).
3. Determine acceptable RH change rate with respect to conservation
4. Determine the step function for the increase of heating power as presented in 2.2
5. The control algorithm, when applied, can be continuously calibrated using feedback from monitoring each heating event.

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