Design and analysis of energy efficient indoor climate control methods for historic buildings

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Introduction

Establishing a proper indoor climate in historic buildings with respect to both comfort and conservation in a non-invasive, sustainable, and energy efficient way pose both practical and scientific challenges.

In a conservation perspective, the indoor climate in a historic building is mainly determined by temperature and relative humidity (RH). Common climate related problems in occasionally used historic buildings are high values of RH causing biodegradation and large variations in temperature and RH, often related to heating, causing mechanical damage.

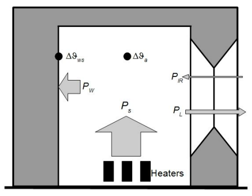
Three areas of research was identified from the state of the art:

- Intermittent heating
- Adaptive ventilation
- Evaluation of Mould growth prevention with RH reducing measures

Intermittent heating in massive historic buildings

Objective 1 - Propose and validate a methodology for shaping the heating power for intermittent heating in massive historic buildings with regard to heat up time and change rate of RH.

Intermittent heating systems in historic buildings are often manually controlled. The fast increase of temperature during a heating event induces a fast decrease in relative humidity that can be harmful for the building and its interior. A hygrothermal model for intermittent heating and a control method for limiting large fluctuations in RH at the beginning of the heating event is developed. By controlling the starting time as well as the heating power of a heat-up event, the temperature change rate can be controlled and thereby also the RH change rate.



Major heat flux and temperatures during intermittent heating.

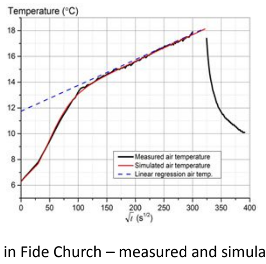
In the figure, the main heat fluxes are shown. The supplied heat, $P_s\ (W)$, is divided in two main fluxes. The main flux $P_W(W)$, heats the walls and interiors via the air. The air temperature, $\Delta\vartheta_a\ (°C)$, can be modelled by

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

Which has the following solution for a step input in P_s.

$$\Delta\vartheta_a = P_s\left(a_1\left(\sqrt{t} - \sqrt{T_1}\cdot\frac{\sqrt{\pi}}{2}\operatorname{erfi}\left(\sqrt{t/T_1}\right)e^{-t/T_1}\right) + b_1\left(1 - e^{-t/T_1}\right)\right) = P_s K_\vartheta(t)$$

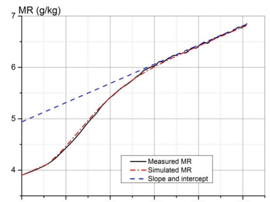
Parameters a_1 and b_1 can be determined by linear regression of air temperature measurements where the temperature is plotted against the square root of time ($\sqrt{t}$). See figure below. The regression must be conducted on the latter part of the data, when $t \gg T_1$. The time constant T_1, can then be found by signal integration of the model.



Heat-up event in Fide Church – measured and simulated response

Similar to the thermal model, an approximate hygric model for air humidity in response to the heat input step is developed. During a heat-up event the indoor air mixing ratio (MR) i.e. the mass of water vapour in the air to the mass of dry air, increases as moisture desorbs from the indoor walls.

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



Heat-up event in Fide Church – measured and simulated humidity response

The primary objective of deriving hygrothermal models is to involve them in the optimisation of the heat-up procedure. The control strategy should have the following requirements:

RH change. The heating power should be shaped so that the magnitude of RH change rate associated with temperature increase does not exceed a specified value.

Energy consumption. To keep the energy consumption low, the heater should be turned on just in time before using the building and with as much power as possible considering the safety constraints on the RH change rate requirement.

Comfort temperature: The predefined comfort temperature must be achieved at a specific time.

A feed-forward controller based on the hygrothermal model and linearization of the Magnus formula was designed

$$\varphi_a = f_\varphi(x_a, \vartheta_a) = \frac{1}{3.795}\cdot 10^5 \cdot x_a \cdot 10^{-\frac{a\vartheta_a}{b+\vartheta_a}}$$

where

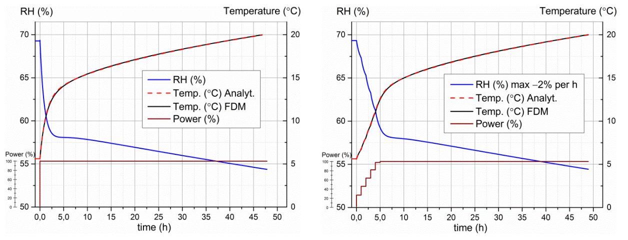
$$\Delta\vartheta_a(t) = K_\vartheta(t)\Delta P_s$$
$$\Delta x_a(t) = K_x(t)\Delta P_s$$

By local linearization of the Magnus formula

$$\Delta\varphi_{a,i} = C_x(\vartheta_{a,i}, x_{a,i})K_x(\Delta t)\Delta P_{s,i} + C_\vartheta(\vartheta_{a,i}, x_{a,i})K_\vartheta(\Delta t)\Delta P_{s,i}$$

A Feed-forward controller for safe heating power step can be designed.

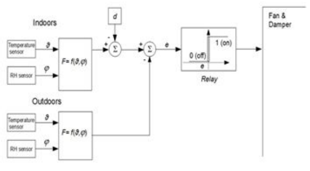
$$\Delta P_{s,i} = \frac{1}{C_x(\vartheta_{a,i}, x_{a,i})K_x(\Delta t) + C_\vartheta(\vartheta_{a,i}, x_{a,i})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_i}$$



Simulation of heating event. Left – a single heating power step; Right – a stepped heating power distribution determined by the proposed controller

Adaptive ventilation

Objective 2 - Perform validation and analysis of adaptive ventilation method for relative humidity control in historic buildings.



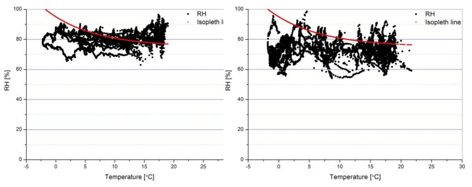
Ádaptive ventilation system

An AV systems lowers the MR in the inside air by taking advantage of the natural diurnal and seasonal variations in the outside humidity. The outside air is ventilated into a building only when MR is lower than indoor air. The best drying effect is achieved if the building is air tight as the building should also be closed when it is more humid outdoors than indoors.

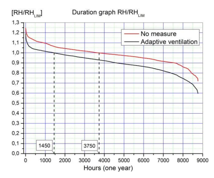
Left Klints farmhouse, Right. Hangvar church

AV was evaluated in two case studies. The first was carried out in an 18th century farm building. The study showed that AV has a significant effect. During one year some 1600 kg of water were removed from the building. However, in a typical diurnal cycle the temperature was lower outside when the fan was running. The ventilation system had a cooling effect that would tend to increase RH even though moisture was removed simultaneously.

The second case study was carried out in a Swedish 13th century stone church. To mitigate the cold air problem described above the inlet air was slightly heated a few degrees with energy produced by solar panels. Some 1100 kg of water was transported out and the mould risk hours where reduced with 2300 hours.



Left before installation of AV, Right. After installation of AV



Black graph, 3750 hours of risky climate before installation of AV. Red graph 1450 hours of risky climate. A reduction of 2300 hours

Positive aspects:

- substantial reduction of mould risk
- low-cost and low energy demand
- non-invasive technical installations
- improved indoor air quality as perceived by people
- reduction of indoor temperature during hot periods

Negative aspects:

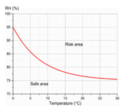
- increase of RH short-time fluctuations
- function is highly dependent on outdoor conditions
- decrease of indoor temperature in winter months
- needs auxiliary measures (i.e. heating or dehumidification) to fully prevent mould risk

Very important with tight building

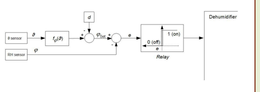
Mould control

Objective 3 - Propose and validate improvements of indoor climate control methods in historic interiors with the focus at the mould growth prevention

Conservation heating, dehumidification and adaptive ventilation can be used to reduce RH in order to reduce mould growth. As energy costs may be excessive there is a need to compare these three methods in terms of energy efficiency and mould prevention effectiveness. Traditionally, for these measures the RH set-point is set to 75% which will cause higher energy consumption than necessary. By using LIM I (Lowest Isopleth for Mould), a set-point strategy can be developed for mould growth climate control.

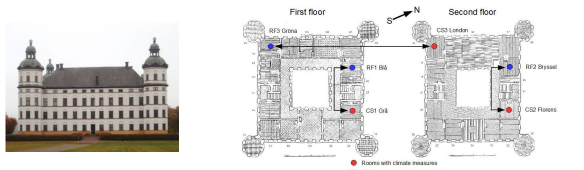


$$\varphi(\vartheta) = f_\varphi(\vartheta) = 75 + 20\mathrm{e}^{-0{,}1241\vartheta}$$



Set-point strategy for mould growth control

In a three year study in Skokloster Castle the three RH reducing methods conservation heating, dehumidification, and adaptive ventilation, controlled to minimise the long-term risk for mould growth and energy use was compared. The main results is showed below but one important result was that dehumidification consumed less energy and provided the most stable indoor climate .



Left. Skokloster Castle. Right the case study rooms in the castle

Total *operating time* , *energy* and *mould risk* per measure for all three years:

Dehumidification	381 hours	534 kWh	1 hour
Conservation heating	1196 hours	957 kWh	58 hours
Adaptive ventilation	6746 hours	741 kWh	67 hours

Total *energy* and *hours of mould risk* per room:

Case study room 1	512 kWh	1 h
Case study room 2	585 kWh	0 h
Case study room 3	1135 kWh	125 h

Conclusions

Objective 1 *- Propose a methodology for non-invasive temperature and humidity control of intermittent heating of massive construction historic buildings*

- Simplified thermal and hygric models of massive buildings proposed, together with parameters identification procedure.
- Models validated on measured data at three churches
- An algorithm for stepped shaping of the heating proposed to avoid risk of high change rate of RH.
- A procedure to determine the overall heating time proposed.

Objective 2 *- Perform validation and analysis of adaptive ventilation method for relative humidity control in historic buildings*

- A control system for adaptive ventilation developed and evaluated on two case studies.
- The performed research shows that adaptive ventilation essentially lowers the number of hours of risk for mould growth on a yearly basis, but there is still an increased risk at some short periods when adaptive ventilation is not a sufficient measure.
- It is recommended to combine AV with either conservation heating or direct dehumidification

Objective 3 *- Propose and validate adjustments of indoor climate control methods in historic interiors with the focus on the mould growth prevention*

- The damage function (LIM I) for mould growth used to generate the set-point for RH based on measured temperature.
- This approach, saves energy compared to constant set-point.
- A three-year case study in Skokloster Castle carried out to compare three methods of RH control to prevent mould growth.
- Direct dehumidification by sorption dehumidifier showed the best result regarding both indoor climate quality in terms of mould risk and stability and energy consumption.
- The drought proofing of the rooms prior to the case study was an important factor in lowering the mould growth risk.

Key publications

- Wessberg M, Broström T, Vyhlidal T. A method to determine heating power and heat up time for intermittent heating of churches. Energy Procedia, vol. 132, Elsevier B.V.; 2017, p. 915–920.
- **M. Wessberg, T. Vyhlídal, T. Broström, A model-based method to control temperature and humidity in intermittently heated massive historic buildings, Build. Environ. 2019,.**
- Broström T, Hagentoft C-E, Wessberg M. Humidity Control in Historic Buildings through Adaptive Ventilation : a Case Study. NSB 2011 9th Nord. Symp. Build. Phys., 2011, p. 1–8.
- Wessberg M, Larsen PK, Broström T. Solar energy augmented adaptive ventilation in historic buildings. NSB Nord. Symp. Build. Physic 2014, 2014, p. 648–655.
- **Napp M, Wessberg M, Kalamees T, Broström T. Adaptive ventilation for climate control in a medieval church in cold climate. Int J Vent 2016;15:1–14. doi:10.1080/14733315.2016.1173289.**
- Wessberg M, Leijonhufvud G, Broström T. An evaluation of three different methods for energy efficient indoor climate control in Skokloster Castle. In: de Bouw M, Dubois S, Dekeyser L, Vanhellemont Y, editors. Second Int. Conf. Energy Effic. Comf. Hist. Build., Flanders Heritage Agency; 2016, p. 144–150.