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

Technical cybernetics

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Declaration

I declare that the information provided in this document are true. The text that is related to the already published material is properly commented including the reference to the original source. All the materials used in this text are related to work achieved by the author as the main contributor to the resources or co-author of included appendix.

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Contents

Abstract

Indoor climate in historic buildings pose both a practical and a scientific challenge. There are two fundamental challenges that must be addressed. First, the setting of proper indoor climate is to be done with respect to both human comfort and, above all, conservation of the building itself and its interiors: artworks, furniture etc. The second aspect is achieving the desired indoor climate in a non-invasive, sustainable and energy efficient way. With the focus on preservation, relative humidity is the most important parameter. Not only the level but also the change rate of relative humidity is of importance. Even though the methods and technical equipment for humidity control in historic buildings have been widely investigated, still, number of problems remains open – towards the efficiency and safety, in particular.

This thesis aims to further explore the link between technical implementation and target ranges for indoor climate, i.e. control strategies and algorithms, taking into account cost effectiveness, energy efficiency and sustainability. The first addressed method is intermittent heating of massive historic buildings. In order to control the change rate of relative humidity at a heat-up event, a simplified model for heat and moisture transfer at the heat-up period in such buildings is presented. A method to derive the hygrothermal parameters and the time constant of the building from measurements measured at a step response test is presented and validated. Finally a feedforward control algorithm which uses the model for predicting and controlling the change rate of relative humidity during the heat-up procedure is presented. The method has been validated on measurements and models of three churches on the island of Gotland, Sweden.

Unheated historic buildings often face problem with high humidity levels which can lead to increased risk of mould growth. One of the energy efficient methods that can decrease the mould growth risk is the adaptive ventilation. It has been designed as potentially low-energy and low impact option, but still it needs to be validated and further developed. The main questions are if the measure is sufficient to limit the risk for mould growth, how it influences the stability in relative humidity and if it is an energy efficient measure. These aspects are widely addressed in the thesis. A great deal of attention is paid to installation aspects at case study objects and subsequent thorough data analysis. The performed research shows that adaptive ventilation essentially lowers the number of hours with 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. The performed study also indicated that the adaptive ventilation measure is likely to increase risk of mechanical damage of objects, due to increased variability of relative humidity fluctuations. Finally, in a three year study in a baroque Skokloster castle, three climate control measures - i) dehumidification, ii) conservation heating, and iii) adaptive ventilation - are compared regarding the efficiency to prevent risk for mould growth, indoor climate stability and energy efficiency. The study showed that dehumidifying had the best result regarding all three criteria, for the given building rooms located in the upper floors, which are typical by lack of internal moisture sources. However, rather than a method to eliminate the risky levels of relative humidity, the air-tightness of the interiors was revealed as the prime mitigation measure for the given interior class.

Abstrakt

Z výzkumného a implementačního hlediska je monitorování kvality a efektivní řízení vnitřního prostředí v historických objektech zajímavým problémem, s netriviálním řešením. Při stanovení charakteristik prostředí je nutné jednak zajistit akceptovatelný komfort pro návštěvníky a zejména pak zajistit jeho vhodnost z pohledu ochrany interiéru budovy a vystavených objektů památkové péče. Následným problémem je technická implementace systému úpravy vnitřního prostředí s ohledem na jeho neinvazivnost a šetrnost vůči interiéru historické budovy. Důležitým faktorem je též častý požadavek na nízké pořizovací náklady a nízkou energetickou náročnost. Z pohledu památkové péče, je klíčovým sledovaným parametrem relativní vlhkost vzduchu v interiéru. Kromě monitorování a řízení dosažených extremálních hodnot, je nutné sledovat též variabilitu relativní vlhkosti v krátkodobém časovém měřítku. I přes zvýšenou pozornost věnovanou návrhu metod řízení relativní vlhkosti v historických budovách a jejich technické implementaci, lze stále najít řadu otevřených problémů, a to zejména právě vzhledem k šetrnosti a energetické náročnosti daných řešení.

Tato práce je zaměřena na analýzu vybraných metod řízení prostředí v historických budovách, a to jak z pohledu stanovené metodiky, tak i z pohledu technické implementace. První analyzovanou metodou je krátkodobé vytápění historických objektů, typicky aplikované u příležitostně využívaných kostelů před církevními obřady. Nejprve je navržen aproximativní hygro-termální model dané třídy objektů, kde typickým faktorem je masivní konstrukce budovy s vysokou tepelnou kapacitou. V dalším kroku je stanoven postup parametrizace modelu na základě neměřených průběhů teploty a relativní vlhkosti v odezvě na skokovou změnu tepelného výkonu otopného systému. Hlavním výsledkem je poté návrh algoritmu pro postupné zvyšování tepelného výkonu tak, aby byl eliminován nebezpečně rychlý pokles relativní vlhkosti. Daná metodika je validována na měřených datech a simulačních modelech třech kostelů nacházejících se na ostrově Gotland, ve Švédsku.

U nevytápěných historických objektů lze často pozorovat zvýšené hodnoty relativní vlhkosti, které mohou vést k nežádoucímu růstu plísní v jejich interiérech. Jednou z energeticky šetrných metod, kterou lze dané riziko snížit, je tzv. adaptivní ventilace. Tato metoda byla zejména v posledních letech analyzována jak z pohledu algoritmizace, tak i technické implementace. Závěry provedených studií jsou ale nejednoznačné, v některých případech i protichůdné. Důkladná analýza této metody formuje druhý řešený problém disertační práce. Kromě teoretických aspektů, spočívajících zejména v aplikaci pokročilého zpracování dat pomocí kritérií mapujících riziko růstu plísní a riziko mechanického poškození vystavených objektů hygroskopického charakteru, jsou analyzovány implementační aspekty této metody a to včetně validace na historických budovách. Z provedené analýzy vyplývá efektivnost adaptivní ventilace ve významném snížení rizika vzniku plísní. Bohužel, při dlouhodobém provozu je možné indikovat nezanedbatelné časové intervaly, kdy vlivem nevhodných podmínek venkovního prostředí není možné kvalitu vnitřního prostředí řízenou ventilací zlepšit. V těchto intervalech je vhodné využít alternativních metod redukce relativní vlhkosti, např. pomocí sorpčních odvlhčovačů. Z analýzy naměřených dat též vyplývá, že adaptivní ventilace vede ke zvýšení variability relativní vlhkosti, čímž se zvyšuje riziko poškození vystavených objektů hygroskopické povahy následkem zvýšení sorpčně-pevnostních gradientů. Následně je v práci provedeno vyhodnocení tříletého experimentu na barokním zámku Skokloster ve Švédsku, s cílem porovnat tři různé metody úpravy vnitřního prostředí, jmenovitě – i) sorpční odvlhčování, ii) vlhkostně řízené vytápění, a iii) adaptivní ventilaci – a to vzhledem k schopnosti zamezení vzniku plísní, udržení stability prostředí a energetické efektivnosti. Z výsledků analýzy vyplývá, že pro daný typ interiérů nacházejících se ve vrchních patrech objektu, s absencí vnitřních zdrojů vlhkosti, je nejvhodnější aplikovat odvlhčování pomocí sorpčních odvlhčovačů. Analýza též poukazuje na důležitost zajištění vzduchotěsnosti jako primárního opatření pro zachování bezpečného prostředí dané třídy historických interiérů.

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1 Introduction

Indoor climate in historic buildings such as museums, castles and churches pose both a practical and a scientific challenge. There are two fundamental challenges that must be addressed [52]:

1. What is the proper indoor climate with respect to human comfort and with respect to conservation of the building itself and its interiors: artworks, furniture etc.
2. How do we achieve the desired indoor climate in a sustainable way.

In conservation science, much attention has been paid to defining climate induced risks and, as a consequence, safe ranges for temperature and relative humidity. Technical equipment for heating as humidity control in historic buildings is also well researched. This thesis aims to further explore the link between technical equipment and target ranges for indoor climate, i.e. control strategies and algorithms based on the hypothesis that smarter and more effective control of the indoor climate, based on an understanding of the specific characteristics of the building in question can be a cost effective way to achieve a sustainable indoor climate.

Heating practices in historic buildings have varied throughout the centuries. Monumental buildings such as churches, castles and manor houses were kept cold during the periods when they were not in use. If used during wintertime, only part of the building was heated. Stoves and open fireplaces were the main heat sources. More recently, central heating system such as electric radiators or hydronic systems were installed, which has made it possible to control the climate both for comfort and for conservation [24]. However still today, for economic reasons, many historic buildings are intermittently heated and kept cold when not in use. As a complement to intermittent heating, some buildings have simple climate control measures such as dehumidification or back ground heating at low temperatures.

Insufficient climate control will not only result in unfavourable indoor climate for both the building and the historical artefacts but also in unnecessarily high energy use. The energy cost associated with climate control is a major problem as they may prevent owners of historic buildings from using proper climate control thus leaving the building to disrepair.

According to the Intergovernmental Panel on Climate Change, IPCC, it is undisputable that the climate has warmed since the 1950s and most probably it will be warmer in the future [76]. With a warmer climate, the humidity and precipitation will most likely increase. Future warmer and more humid climate will lead to higher risk of damage to historic buildings as well as artefacts and objects. To manage the cultural heritage in a sustainable way, it is important to predict how the future climate will influence the indoor climate so necessary proactive activities can be performed.

The European project Climate for Culture (CfC)[1] [77, 86, 87] aimed to develop effective and efficient strategies for indoor climate control in order to preserve our cultural heritage. In the project, high resolution models for the future climate scenario in Europa are combined with building simulation software used to predict the future indoor climate. By studying the outcome of these simulations, damage risks for different regions in Europa can be identified. The project goes further and develops damage/risk assessments tools based on damage functions. For a definition of damage function see section 1.2.1. In connection to the future challenges of climate change, the project also had a focus on energy efficient climate control. The present thesis originates in the Climate for Culture for project, aiming to further develop model based control for historic buildings.

1.1 Climate requirements for conservation

In a conservation perspective, the indoor climate in a historic building is mainly determined by the air temperature and humidity. Common climate related problems in occasionally used historic buildings are high values of relative humidity causing corrosion and biodegradation, large variations in temperature and relative humidity due to the heating periods which can cause mechanical damage to the building and objects and also salt efflorescence on masonry walls. Below, major risk factors and climate target ranges are highlighted.

1.1.1 Damage functions

Generally, a damage function interprets some sort of input data to a quantified damage risk. In [88] a damage function is defined as "*A quantitative expression of cause and effect relationships between environmental factors and material change*". In the area of climate control for conservation, the damage functions are often used and defined for assessing the risk for microclimate conditions, often temperature and relative humidity, for various materials of cultural heritage objects and the output is for example quantified damage risk for mechanical degradation, chemical degradation or biological degradation [91]. The damage function is preferably in a form of formula or a dose-response relationship but can also be in the form of a graph or a table, etc. [88].

1.1.2 Moisture content

Moisture content in hygroscopic materials is determined by the relative humidity and temperature of the ambient air. The equilibrium moisture content (EMC), i.e. the moisture content when the material neither absorbs nor releases moisture, in relation to relative humidity is described by sorption isotherms empirically derived for different materials at a given temperature [94]. See figure 1.1. The sorption isotherms depend on the material and how the material is structured but common to all is that the EMC depends predominantly on relative humidity but also on temperature. See figure 1.1. From the preservation point of view, as it will be discussed later on in the text, it is recommended to keep the moisture content constant, or at least within the limited range [12]. It is motivated by the association of the EMC variation with mechanical damage [13]. Control methods concerning the EMC ramifications will be elaborated in the following text.

[1] https://www.climateforculture.eu/

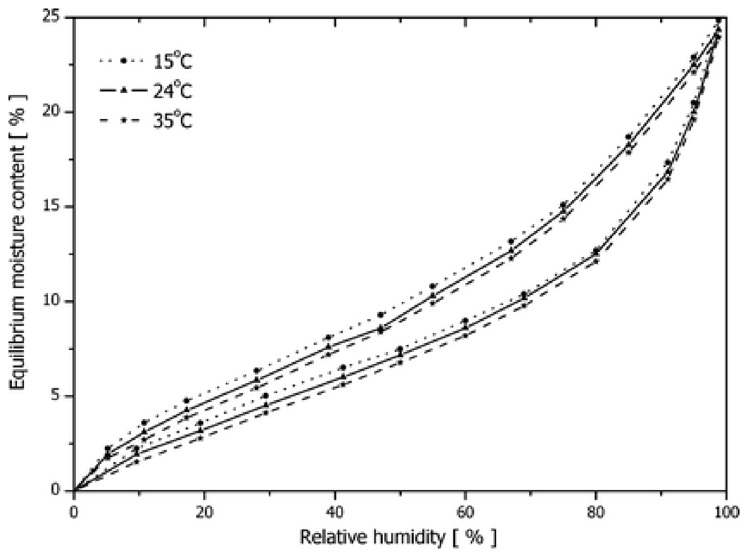

Figure 1.1 Sorption isotherms of lime wood for several temperatures. The lower for adsorption, the upper for desorption [14].

1.1.3 Mechanical degradation of wood

Due to absorption and desorption of moisture, hygroscopic objects will swell and shrink as the EMC changes due to change in relative humidity of the ambient air [15]. Dimensional change is also due to temperature change but humidity movements are generally orders of magnitude larger than thermal movement [14]. A restrained object exposed to fluctuating temperature or fluctuating relative humidity cannot swell or shrink, but rather experience stress [12, 16].

Fast changing relative humidity causes gradients in moisture content as the parts close to the surface respond faster to humidity changes than deeper parts. These moisture gradients lead to increased stress levels that in turn can result in cracks in the outer wood. The outer part will be strained by tension while the inner part will be strained by compression. These increased stress levels in combination with the week strength in the tangential direction can result in cracks in the radial direction [16, 17].

Slow changes in relative humidity are considered less harmful to wood as the moisture gradients are smaller. Rapid and slow changes are relative concepts, it depend on the object´s material, composition and size [14].

In a study of RH variations on a wooden cylinder with a diameter of 13 cm it was found that it is not only is the amplitude of the variation that is important but also the initial level. A RH variation of 10% is regarded safe only if the variation´s initial value was between 30% and 70%. Outside this range the object will experience irreversible strain levels. RH variations of 40% could cause direct failure if the initial value is above 90%. In these simulations the variation of RH was performed over a few seconds which mainly not is the case in a monumental building. However in simulations where the RH change over a time period of 24 hours the risk for irreversible strain is lower and the safe range of variations increase to approximately 20%. This result is in good agreement with the old conservator’s wisdom that a large change in RH can be harmless if only the time for the object to adapt to the new level is long enough [14].

One of the most sensitive type of objects are those including painted wood which is composed of several layers of materials with different hygroscopic properties which moves differently when the layers take up or release moisture [18, 19, 20]. In monumental buildings and especially churches there are a number of objects of this type for example the altarpiece, the pulpit, painted pews, parts of the organ etc. [21].

A case study of how real objects respond to variations in climate was conducted by Bratasz and Kozlowski on the altar piece in the church of Santa Maria Maddalena in Rocca Pietore, Italy where they used triangulation laser displacement sensors to examine the relation between the indoor climate and movements of wooden details on the altar piece [22]. They noticed a strong connection between the large fluctuations in relative humidity to change of size of wooden objects when the church was heated intermittently. At an intermittent heat-up event one small wooden part of the altarpiece was exposed to stress levels above the allowable limit which increase the risk for cracks.

The European standard EN 15757, Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials [23], does not specify the indoor climate in numbers but rather a method to determine allowable variations based on the recent climate. The method is based on the hypothesis that an object with hygroscopic materials that has been in a specific climate for "significant periods of time" has been acclimatised to this past climate. Possible damages to the object such as cracks and straining has already occurred which make the object more allowable to flexible indoor climate in the future compared to the climate that generally are accepted as good for preservation. The standard also states that these more flexible specifications can lead to the use of simpler climate control equipment which in turn leads to reduced costs for both investments and energy.

To determine the target range for the relative humidity, the standard proposes that climate monitoring should be performed during a period of at least one year or a multiple of a full year. Additionally to this another 15+15 days of measurements are necessary when calculating the 30 days running average during a full year. Then 30 days central running average over the full year is calculated by

$$\bar{\varphi}_{30}(t) = \frac{1}{T}\int_{-T/2}^{T/2} \varphi(t)\, dt. \qquad (1)$$

where T is 30 days. The 30 days running average can be seen as a running monthly average. Short term fluctuations are calculated as the standard deviation of the difference between a RH sample and the 30 day running average at the same time i.e.

$$SD30 = \sqrt{\frac{1}{T_s}\int_{0}^{T_s}\left(\varphi(t) - \bar{\varphi}_{30}(t)\right)^2 dt} \qquad (2)$$

where T_s is the whole time period investigated. The target range for the future climate is then between the 7th and the 93rd percentile of the fluctuations which corresponds 1.5 SD30 if the fluctuations can be considered to be Gaussian distributed. That means that 14% of the biggest fluctuations are removed. If the 7th and the 93rd are less than 10 % RH from the running average level, the target range is ± 10 % RH instead. In Figure 2.2, there is an example of this from a historic farmhouse. The fluctuations are rather small and the target range according to 7th to 93rd percentile is ± 3.3% RH from the running average, which according to the standard is regarded unnecessary small. The target range for future climate in this building is therefore set to ± 10 % RH.

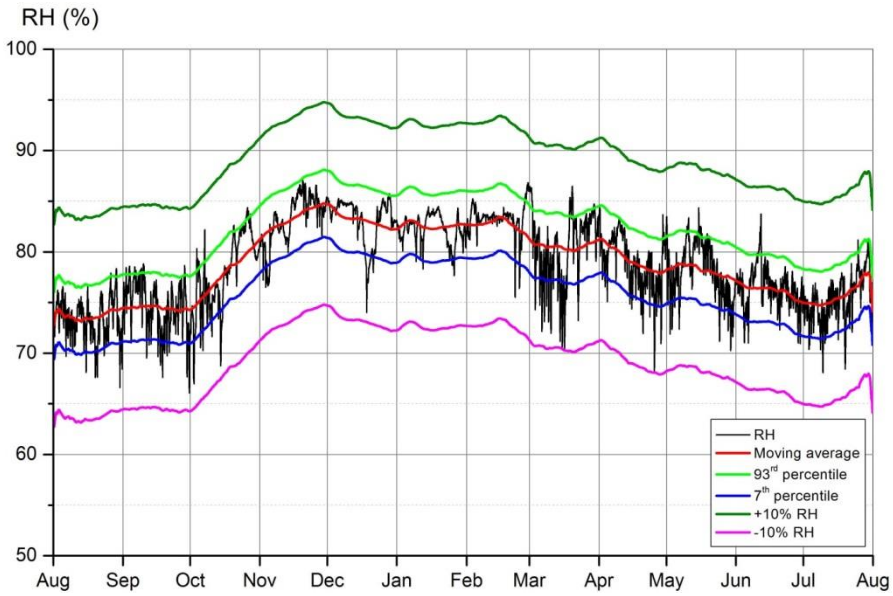

Figure 1.2 One year of climate data from a farm house.

1.1.4 Mould risk

A common problem in historic buildings is mould growth. Mould spores are always present in buildings [25, 26] germination and growth rate depends on three components; temperature, humidity and nutrition [27].

Mold fungi go through four life stages. See Figure 2.2 (left). From spores to germination further through hyphal growth and finally the reproduction stage which create new spores [27]. Mould fungi degrade biological materials to some extent for example by infesting and discoloring surfaces of objects but the primary danger with mould growth in buildings is the production of pathogens i.e. mycotoxins or other microbial volatile organic agents that can cause illness or odors [26, 28].

The surface humidity is quantified in water activity, a_w, which is defined as the ratio of the partial pressure of the water vapour on the surface and the partial pressure of pure water both given at the same temperature. The water activity is expressed in a fraction ranging from 0 to 1. If the surface is in equilibrium with the ambient air the water activity is the same as relative humidity divided by 100 [29] which is the case in a historic building.

Several mould growth predictions models have been presented e.g. the VVT model on wood [30], time of wetness [25], Mould growth indices [31].

A commonly used model to predict mould growth is the isopleth systems, an isoline in a RH - temperature diagram showing the combination of temperature and RH that represent climatic conditions for the same rate of mould growth [32, 33]. The lowest isopleth for mould, LIM, is an isoline that represents the lowest RH level at different temperatures required for mould growth on a specified substrate [28]. That is, the area above the LIM represents the climate favourable for mould growth and obviously the area below the LIM is non-favourable climate. Figure 2.3 (right) shows the LIM for substrate category I, building materials produced from biological raw material like gypsum board and wall paper [34]. The LIM I isopleth is used as damage function for evaluation of indoor climate for mould risk in the work that follows.

Traditionally climate control aiming to eliminate mould growth has been based on a safe range for RH only. As can be seen from fig 2.3, this is either a risky approach or requires a large safety margin which often is costly.

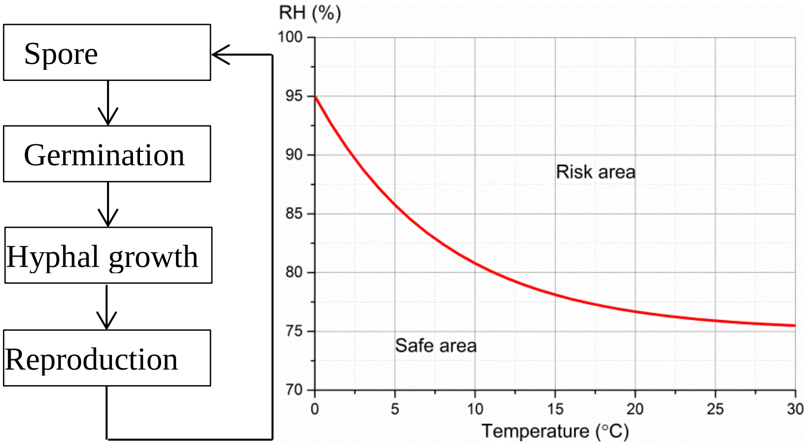

Figure 1.3 Left, mould growth stages. Right, Lowest Isopleth for Mould, LIM I, According to Sedlbauer [28]

1.2 Climate control for comfort

Thermal comfort for people depends mainly on temperature and air movements and to a lesser extent on relative humidity. Physical activity, clothing and duration of stay will determine comfort ranges for each person [35].

This section describes low energy climate control methods often used in rarely used historic buildings to achieve thermic comfort.

1.2.1 Intermittent heating of a massive building

Traditionally historic buildings have been heated intermittently with open fireplaces or stoves [36]. Even with new heating sources intermittent heating is still very common in historic buildings [37]. The principle is to heat rapidly some time before use. In between periods of use, the building is kept cold or with background heating. Rapid heating requires larger installed heating power as compared with installations for continuous heating [37]. Rapid intermittent heating is energy efficient but the fast changes in temperature and relative humidity may be harmful to some objects and materials.

In monumental buildings with massive walls, thermal inertia is the dominant factor in heat balance of the building. Most of the supplied energy is used to heat up the wall, the ceiling and the floor and therefore steady state models are not applicable for intermittent heating [38]. As a result the indoor air temperature is therefore largely influenced by the wall surface temperature.

Studies of intermittent heating in massive monumental buildings have been ongoing since the end of the 19th century when heating systems started to be installed in such buildings. Already In 1922 the Swedish state-owned energy company *Vattenfall* began to be interested in electrical heating in churches and therefore let engineer Frits Jacobsson do theoretical and practical studies for the design of heating systems [39]. In 1930 Krischer presented a model that was similar to the one that Jacobson had proposed. In 1936, Henning [40] made an extension of Jacobsson's work including heat losses from transmission and infiltration and in 1957 Krisher and Kast [41] also generalized the solution to include heat losses from transmission and infiltration. However the extended solutions were difficult to use practically and a simplification led back to the initial solutions of Jacobsson and Krischer. Pfeil [42] gives an overview of church heating models from Fisher in 1890 to Krischer and Kast in 1957. In [38] Broström use the equations from Jacobsson to develop a method to determine hygrothermal properties of a stone church. The main outcome of the church formulas states that when supplied with constant heat flux the increase in temperature during a heat-up event is proportional to the square root of time.

The fundamental theory for intermittent heating of massive buildings is thus well known and has been used e.g. in [39] when calculating the required installed power for intermittent heating systems. However the existing theories and models have not been used in control practice. Thus a model that can be used in massive historic buildings to control the heat up procedure is missing.

1.2.2 Local radiative heating

Local radiative heating is used in intermittently heated buildings to provide comfort in a limited part of the building without heating the whole building. Besides from saving energy, use of local heating will also save objects from unnecessary heating and drying. The convective air movements that often are a problem in intermittent heated churches will be reduced [43]. The heating is often performed with low-temperature radiant sources such as electric panels, integrated heating foils, electric heating glass, water pipes or water radiators and under floor heating, but also infrared emitters and electric radiators are used [44]. Local heating has been evaluated in churches where the churchgoers sit in pews for example in a study in the church of Santa Maria Maddalena in Rocca Pietore, Italy [45] and Lau church on Gotland [46]. In these studies the test participants in both churches experienced some slightly discomfort.

1.3 Climate control for conservation

This section describes low energy and low invasive climate control methods for rarely used historic buildings in order to maintain a proper climate i.e. lower relative humidity mostly to prevent mould growth.

1.3.1 Conservation heating

Conservation heating is a technique for climate control where heaters are controlled by humidistats rather than by thermostats. The temperature varies to adjust the relative humidity to the set value. This technique is also referred to as humidistatic heating control [47]. The term conservation heating was introduced by the National Trust, UK, in the 1990s but the technique was used earlier for example by the Canadian Conservation Institute [48].

If there are no major moisture supplements to the building, power requirement for conservation heating is relatively small. For example in Scandinavia, heating the building to a temperature 5-7 degrees above the outdoor temperature will keep RH at approximately 60% [49]. The required heating power can be five times lower compared with permanent heating [50]. The energy consumption depends of course on the building infiltration rate and U-value but in comparative studies conservation heating consumes more energy than dehumidification if the heat is supplied by direct electric heating but less if the heat is supplied by heat pumps [51][3].

Conservation heating is simple and cheap to implement if there is already a heating system installed in the building. If not, it can on the contrary cause damages when installed in a historic building. It gives a stabile indoor climate if the building is reasonable air tight and it is reliable. One drawback is that conservation heating may result in uncomfortably high temperatures during the summer. If there are people in the building one has to either accept poor thermal comfort or turn of the heat and accept a temporarily higher mould risk.

Another potential problem is that indoor air mixing ratio will increase due to evaporation from floors or walls which counteract the effect [50]. Especially if there is any sources of humidity in the building like rising damp in walls or if a large part of the room volume is filled with hygroscopic material such as wood [53]. According to life time calculations, chemical degradation will increase with higher temperature which is harmful for e.g. paper [54].

To summarise, conservation heating has some advantages and some disadvantages. Even though the method has been used and has been investigated, there are still discussions how the method stands against others in terms of energy consumption. A systematic investigation of the performance in situ in a massive historic building with high temperature inertia and buffered moisture is needed to see how it performs when controlled to minimize the risk for mould growth in relation to other climate control methods.

1.3.2 Dehumidification

In practise there are two techniques used to dehumidify air in historic buildings, sorption dehumidifying and condensing dehumidifying [47, 48].

The basic idea behind sorption dehumidifying is to pass the air over a desiccant that adsorbs or absorbs the water vapour in the air. This type of dehumidifiers operates in two stages. In the first stage, humid air streams through the desiccant which adsorbs water vapour from the air. In the second stage the desiccant is regenerated i.e. dried, often by a hot air stream that heats the desiccant so that the water evaporates and evacuate the moisture from the desiccant. This drying process is often implemented in a turning wheel where the desiccant is placed and in which the desiccant is rotating through the two air flows and alternatingly taking up moister from the air and regenerating i.e. giving away moister to the regenerating air stream.

Condensing dehumidification uses a cooling element that cools the air below the dew point and therefore water will condense on the cooled element. The condensed water is ether collected in a tank or drained through a tube. Some dehumidifiers have a built-in pump that empties the water tank at a certain level. The cooling element is cooled by either a thermoelectric element [49] but more often a heat pump. Some dehumidifiers take advantage of the heat from the heat pump condenser or if it is a thermoelectric element the warm side of the thermoelectric unit to reheat the air after it has been cooled down and dehumidified. This principle makes the condensing dehumidifier very energy efficient. Condensing dehumidifiers do not work efficiently under approximately 8°C [45] because of the frosting on the cooling element. More advanced condensing dehumidifiers use the heat from the heat pump to defrost the cooling element periodically which then can operate down to 0 °C but with lower efficiency [47].

The two techniques work completely different. The sorption dehumidifier works adiabatic i.e. there is almost no difference in enthalpy between inlets and exhaust air. This means that the temperature actually increases during the drying process as latent heat is taken out from the air. Energy is instead consumed when heat is used to evaporate and evacuate the moisture and the moist air respectively in the regenerating process. In a condensing dehumidifier the air stream temperature is instead lowered to a level under the dew point and water starts to condensate on the cooling coil. However, the indoor environment will gain heat from the condensing dehumidifying apparatus which is larger than the cooling effect and often is welcomed in occasionally used historic buildings [44]. The condensing dehumidifier has a container for the condensed water that periodically needs to be emptied manually or by an automatic pump. That fact makes the condensing dehumidifier unsuitable in buildings where the temperature goes down below 0°C. The sorption dehumidifier works at any temperature but requires an outlet pipe for the moist air somewhere through the climate envelope.

Dehumidification is a well established and reliable method to reduce relative humidity. In order to minimise the energy use and ensure the right capacity a study of the performance when controlled to minimize the risk for mould growth under realistic conditions in massive historic buildings over long periods is needed.

1.3.3 Equal sorption humidity control

Equal-Sorption humidity control is a climate control method developed for use in exhibitions and other locations where sensitive artefacts are kept The control method focuses on controlling the moisture content in the object rather than the conventional control method of keeping constant relative humidity or temperature in the ambient air [55].

The common approach is to control relative humidity and temperature but because of the large thermal inertia in heavy stone walls in historic buildings it is relatively expensive to control temperature compared to control humidity and therefore dehumidifiers and humidifiers are the actuator in such system. Instead by focusing on the important part, the EMC in the material, the temperature can be allowed to fluctuate a little while the EMC will be compensated by adjusting the relative humidity.

As it is not practically possible to measure the moisture content in the historic objects materials directly, the equal-sorption humidity control method is based on a mathematical model that predicts the EMC in the material from the relative humidity and temperature in the ambient air.

Zitek and Vyhlidal use the logarithmic Henderson three parameter model [56, 94], for the equal sorption control method [55]

$$u = \left[\frac{-\ln\left(1-\frac{\varphi}{100}\right)}{A(\vartheta-B)}\right]^{C} = \Psi(\varphi,\vartheta) \quad (3)$$

where $\varphi \epsilon [0, 100]$ the relative humidity of the surrounding air, ϑ is the temperature of the surrounding air in centigrades and *u is the EMC* expressed as the ratio of the mass of water to the mass of dry material. *A*, *B* (*B*<273,16 K) and $C \in [0, 1[$ are material specific parameters.

If relative humidity is the controlling parameter it can be expressed as

$$\varphi_D = 100\left(1-\left(1-\frac{\varphi_0}{100}\right)^{\frac{(273,16+\vartheta-B)}{(273,16+\vartheta_0-B)}}\right) \quad (4)$$

Where ϑ_0, φ_0 is the reference state and ϑ is the actual temperature. φ_D is the set point value to an air handling device controlling the relative humidity in the room.

Equal sorption humidity control has been tested in two sites with good results. In the Chapel of Holy Cross at Karlštejn Castle, some 30 km southwest of Prague, Czech Republic, a full air handling system is controlled by the equal sorption humidity control. Even though the chapel is visited by a large number of people that will add a lot of moisture to the air the system manage to keep an even EMC level in the chapels artefacts [55]. In the Historical Collection in State Archives in Třeboň Castle, Czech Republic previous studies showed that a dehumidifier was the only needed air handling device. Measurements showed that the EMC level in the archives was very stable during the period tested [57].

A new revision of the Equal-sorption humidity control has been developed in the European project Climate for culture [77] called *Quasi equal-sorption humidity control*. In the new approach the system is designed to avoid unrecoverable plastic deformation caused by anisotropic swelling or shrinking due to variations in moisture content in hygroscopic materials. Therefore the allowed variations are larger than in the original version [58].

Equal sorption humidity control is an innovative and energy efficient method to control moisture content in historic objects and wooden buildings but its main purpose to maintain the moisture content stable in order to prevent mechanical degradation. Not to prevent mould growth. This method will thus not be further evaluated in this thesis.

1.3.4 Adaptive ventilation

The traditionally method to reduce humidity, bad smell or pollutants is to ventilate. Either by manually control by opening windows and doors to let fresh air into the building or uncontrolled by natural infiltration. However in occasionally used unheated or intermittently heated historic buildings the humidity level indoors can be alternately higher or lower than outdoors and to ventilate when it is very humid outside will instead add moister to the indoor air and cause high humidity levels indoors with mould growth and other damage as result. The highest risk for this is at spring and the beginning of the summer when warm and humid air will be cooled down in an often cold monumental building.

An adaptive ventilation system has sensors for relative humidity and temperature both indoors and outdoors allowing the system to calculate the absolute humidity and compare the humidity levels and decide when to ventilate. The system ventilates only when the humidity is lower outside compared with indoors. An adaptive ventilation system is thus a type of natural dehumidifier that uses the difference in humidity between outdoor and indoor air. When the humidity is lower outdoors compared with indoors a fan is started and a drying effect indoors is achieved.

In the church in Zillis in Schwitzerland, adaptive ventilation was used to stabilize the climate for the painted wooden ceiling [59]. The system had embedded limits for relative humidity and temperature in the way that if they were lower than the limits the system stopped which led to that the system was not running during the winter. The results showed that the system had a positive effect on the relative humidity when running but the air leakage was probably big as the humidity levels went back as soon as the fans shut off. During the two years the system was in use it ran approximately half the time and removed approximately 3400 liters of water.

In the Antikentempel in Potsdam-Sanssouci Park an adaptive ventilation system was used to avert mould growth on the walls and ceiling [60]. The system controlled a fan in the ceiling and was in operation from May to September 2005. The study showed a positive result as the absolute humidity was 1-2 g/m^3 lower indoors compared with outdoors during the whole test period. Measurements without the adaptive ventilation system in operation were made in May to September 2007 which showed that the absolute humidity instead was 1-2 g/m^3 higher indoors compared with outdoors.

Case studies with adaptive ventilation were also made in Torhalle in Lorsch in Germany where the goal was to prevent condensation on the wall paintings in the building [61]. The system, that controlled the fan, had sensors for temperature and relative humidity both indoors and outdoors and the system´s task was to keep the dew point of the indoor air below the surface temperature of the wall. The system was used only for a short time as it was shut down by a sceptical conservator [62].

Hagentoft, Sasic Kalagasidis, Nilsson and Thorin tested and made simulations for adaptive ventilation on cold attics in dwellings to prevent mould growth [63]. Their system ran if the partial pressure of the water vapour in the outdoor air is lower than in the indoor air on the attic. The study showed that the mould risk substantially decreased after the adaptive ventilation system was installed.

Hagentoft and Sasic made a field measurement campaign in eight different cold attics in Sweden which showed that the adaptive ventilation gave lower and more stable RH during the winter period compared with traditional ventilation. The risk of mould growth was reduced significantly as the humidity levels became lower [64]. In both studies Hagentoft et al pointed out the importance of air tight attics but they also concluded that normal air tightness measures are enough to get a positive effect of the adaptive ventilation system.

Anretter, Kosmann, Kilian, Holm, Ritter and Wehleet made hygrothermal simulations with WUFI®-Plus in two historic buildings with different ventilation strategies including adaptive ventilation [62]. They conclude that it is possible to lower the absolute humidity during some periods of the year with adaptive ventilation but it is more effective if it is running in a building where there are some internal moisture loads such as rising damp etc. Anretter et al notes that the fluctuations in temperature and relative humidity increases with the use of ventilation and point out the relationship between fluctuating indoor climate and salt damage which often can be a problem in the historic stone buildings with plaster on the internal walls as every phase change of the salt increases the risk for flaking damage on plastered walls and wall paintings.

A study of heat supported adaptive ventilation was carried out in [65]. The building had high numbers of visitors and one major purpose of the system was to lower the CO_2 level in the visitor's zone. The supportive heaters were set on only when the RH level was higher than maximal allowed RH indoors combined by the MR outdoors was higher than indoors. Otherwise it was working as other adaptive ventilation systems. At the same time the indoor temperature set point during the winter season was decreased from 19,5°C to 14,5°C. The result showed on less low RH values during the winter period due to the lowered temperature set point but also lower RH levels during the whole year.

Adaptive ventilation is potentially a very cost effective way to reduce relative humidity and could be an alternative for preventing mould growth in historic buildings. However the results from the previously performed studies show deviating results for the stability of relative humidity. Also the control methods deviate. In earlier studies the absolute humidity is used to control the system but latter use mixing ratio and some also incorporates relative humidity and temperature. Thus the method needs to be further validated and closely analysed in situ in massive historic buildings in order to refine control algorithms and to define the need for auxiliary moisture control.

1.4 Modelling and control

To control the indoor climate in a building in efficient way hygrothermal models and the building as well as of objects can lead to a better climate control for both comfort and conservation and improve the energy efficiency.

Generally building models can be categorized in three groups, black box, white box and gray box models [66]. Black box models are, as the name implies, developed on empirical methods which mean that the parameters in a black box model do not have any physical significance but reflect the behavior of the modeled system when tested with input data [67]. The disadvantage of the black box models is that they require a large amount of data to identify the parameters and the model is not very exact outside the area of its training data. Also as the parameters are not physical they are not suitable for optimization of a real building [66]. Neural networks are example of black box models. The white box model, on the contrary, is based on physical laws. However it is cumbersome to develop a complete white box model for all possible parameters in a building, especially for a monumental building where it is impossible to know the exact hygrothermal properties of the building structure [68]. Lumped capacitance models are the dominating type of white box models. A gray box model can be a combination of black box and white box models. For example a white box building model combined with a black box model for a subsystem in the building [66]. Linear parametric models are in many cases considered gray box models. The linear model is a black box model but the parameters can be derived with physical data [69].

In [68], Kramer et al have developed a method to estimate a building model that includes both thermal and hygroscopic properties of a building. The use lumped capacitance models for both thermal and hygroscopic model. Yearly data processed in an optimization algorithm in Matlab gives the parameters for the model. Full building models are complex and require a lot of time and for controlling the indoor climate the trend is to use simplified mathematical models [68, 70, 71].

In modern houses and offices that are intermittently heated on a diurnal schedule, first order or second order building models have been applied in e.g. [72] and [73]. Model Predictive Control was used to control intermittent heating in [74] and [75] also using a low order model. However low order models will not work in a massive historic building. As the heat-up procedure in a massive historic building does not follow any linear patterns and a model for controlling this procedure must mirror the behaviour of the temperature increase. Therefore a new nonlinear model must be developed and used for this case. Building models for temperature and humidity in massive historic buildings that are intermittently heated has not been found except for the church formulas mentioned in section 1.3.1.

2 Problem statement

Climate control of historic buildings is a complex task where the climate must meet a number of requirements, some of them contradictory, as stated in previous sections. Too high humidity increases the risk for mould growth, too low humidity increases the risk for mechanical damages. Too high temperature increases the energy consumption and too large fluctuations in temperature and relative humidity increase risk for mechanical damage. An optimal situation is when temperature and relative humidity are stable at levels that entails no or low damage risk. The overall challenge is to achieve this without intrusive installations and large energy consumption.

Today, intermittent heating systems in historic buildings are often controlled by on-off control and are turned on manually. At the heat up event, a person set on the system some arbitrary time before use and, as a rule, the maximum heating power is used in order to minimise the heat-up time and thereby also the energy use. Poor timing will lead to either insufficient heating or excessively high energy use. Furthermore, sensitive object may require a limited RH as well as a limited change rate of RH. In order to provide an acceptable comfort, and to minimise energy use and detrimental effects on valuable objects, the timing and heating-power of intermittent heating is thus crucial. Due to the temperature dependency, RH tends to decrease as the temperature rises. In massive buildings with masonry walls the large change rate of RH is to some extent counteracted by moisture buffering in the walls. As the indoor RH decreases, moisture is released from the walls. This is a complex interaction, specific for each building and can also change over the year [38]. Therefore a control system for intermittent heating is needed where three factors must be balanced:
i) Comfort for visitors,
ii) Conservation of the building and its interiors, and
iii) Energy use.

By controlling the switch-on time as well as the heating power at a heat-up event, the temperature change rate can be controlled and thereby also the RH change rate. The downside is that the heat-up time will be prolonged and energy use may increase. By using hygrothermal dynamical models an improved climate control system can be achieved which saves energy and makes better indoor climate. This leads to the first objective defined in the next section. Let us note that analogous, model based techniques were applied by Zitek and Vyhlidal to derive the equilibrium moisture content (EMC) control method [55], described briefly in Section 1.3.3 above. It should be stressed, however, that the purpose of EMC control method is different. It was designed to vary the relative humidity set-point for a dehumidifier based on temperate variation (4) with the objective to keep the equilibrium moisture content constant in long term operation, utilizing the static Henderson model (3). No dynamical models of the indoor climate response were involved in the design. For intermittent heating, however, no direct relative humidity control by dehumidification is considered. The well-known dependence of RH on temperature coupled with simple structure indoor climate models are to be used to keep the conditions safe in this unsolved optimised intermittent heating task.

In between use of a building there is a need for an energy efficient control of RH, mainly to prevent mould growth. **Adaptive ventilation** has been shown to be a cost efficient option but there are still questions about the method as such and if it really is an effective measure to prevent mould growth. Thus, adaptive ventilation needs to be further validated, analysed and compared to other low energy and low invasive climate control measures. This leads to the second objective of the Thesis.

As stated in the state of the art there are mainly two measures, conservation heating and dehumidification, which are used for RH reduction in order to reduce mould growth. In addition to this, adaptive ventilation is a candidate for mould prediction. The case study comparison of these three different RH reducing technologies in order to **prevent mould growth** controlled in a way to minimize energy use in a practical long-term use in a massive historic building, has not been carried out before [51]. This forms the third objective of the thesis form next.

3 Thesis objectives

Based on the identified research gaps in the non-invasive control methods of indoor climate in historic buildings, the objectives of the thesis are defined as follows:

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.

The objective is to propose and validate a low-cost and energy efficient methodology for the heat-up procedure of intermittently heated massive historic buildings (typically churches) with regard to the safe indoor climate for deposited valuable historic objects. In the first stage, an approximate hygrothermal model of air temperature and relative humidity during a heat up procedure in such building is to be developed, together with a method for finding the model parameters based on measured data. The subsequent and main task is to design a model-based control strategy for shaping the heating power so that the requirements on the indoor climate safety and low energy consumption are reached. Next to achieving the desired indoor temperature in the predefined time, the objective is to avoid fast changes of relative humidity in the beginning of the heating procedure - as the fast changes of relative humidity were identified in literature as very risky for the upper layers of historic objects of hygroscopic nature (wood, canvas, paper, etc.).

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

The objective is to perform case study based analysis of indoor climate control of historic buildings by adaptive ventilation. The particular task is to contribute to answering the question whether the adaptive ventilation is an efficient alternative to other climate control measures for lowering relative humidity, in order to prevent mould growth in particular. Therefore, adaptive ventilation systems are to be designed, tested and be validate in real case studies in situ to find the practical and theoretical obstacles. The control methods are to be evaluated and refined based on the analysis of measured data.

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

The objective is to propose adjustments of interior relative humidity control in historic buildings, taking into account recently quantified mould growth characteristics. Subsequent task is to evaluate selected climate control measures for lowering relative humidity in order to prevent mould growth in massive historic buildings, in terms of energy efficiency, mould prevention effectivity and stability in relative humidity. This is to be done in a selected case study historic building, under comparable parameters of the controlled interior. The analysis is to be performed taking into account recent developments in the indoor climate analysis.

3.1 Thesis outline

The Objective 1 is solved in the subsequent Chapter 4. A thermal and hygric model is developed based on the heat conduction equation. The model is validated against measured data from three different churches. A method for how to derive parameters to the models from a step response test is studied and further developed. The Objective 2 is solved in Chapter 5. A system for adaptive ventilation is designed and two case studies are performed and evaluated. Objective 3 is solved in Chapter 6. A three year comparative study on climate control to prevent mould prediction is carried out in Skokloster castle. In the study, adaptive ventilation is compared with conservation heating and dehumidification.

4 Intermittent heating of massive structure historic buildings

Intermittent heating, introduced in detail in Section 1.2.1, is a common heat up strategy in many historic buildings. The systems are often on off controlled and the heat-up procedure is not controlled at all. The lack of control proves it self when buildings does not reach comfort temperature during winter period or on the contrary that the building is heated unnecessarily long time (days) before use which is a waste of energy. 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 interiors. This section will solve the problem stated in Objective 1 by developing a hygrothermal model for intermittent heating and designing a control method for limiting large changes in relative humidity at the beginning of the heating event. This section is an extension of published paper [1], and submitted paper [2], where the doctoral candidate is the leading author.

4.1 Model for intermittent heating of massive buildings

The main objective of this section is to develop an approximate model for air temperature in a building of massive construction in response to a constant heat input. First, we present known equations based on heat balance in a building and the wall heat transfer equation. Then, as the main result of this section, we develop the approximate model under specified assumptions.

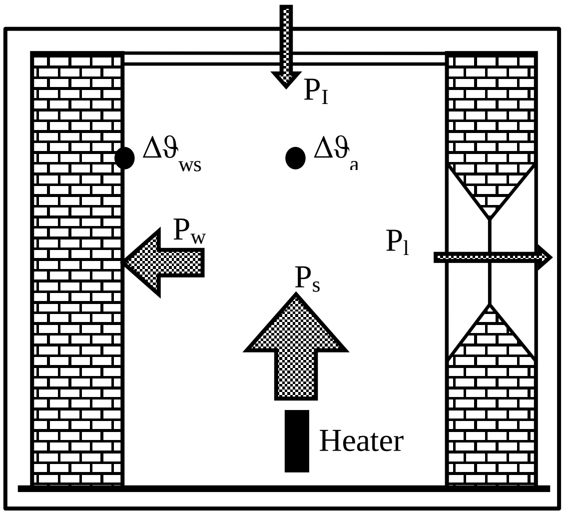

Figure 4.1 Major heat flux and temperatures during intermittent heating according to the simplified model.

In Figure 4.1 the main heat fluxes at a heat-up event are shown schematically. The supplied heat from the heater P_s (W), is mainly divided in two main fluxes. The large part $P_w(W)$ will heat up the walls and interiors via the air. The smaller part $P_l(W)$ represent losses due to infiltration and conductive losses. Irradiation $P_{I(W)}$ will also contribute to the temperature in the building. The heat balance can then be described as follows.

$$V_a \rho_a c_{pa} \frac{d\vartheta_a}{dt} = Ah\big(\vartheta_w(0,t) - \vartheta_a(t)\big) + P_s - P_l + P_I, \tag{5}$$

where V_a (m^3) is the indoor volume, $\rho_a (kg\, m^{-3})$ is the density of the indoor air, c_{pa} $(J\, K^{-1} kg^{-1})$ is the heat capacity of indoor air at constant pressure, A (m^2) is the effective indoor wall surface area, and h $(W\, m^{-2} K^{-1})$ is the heat transfer coefficient. Further on, $\vartheta_{ws}(0,t)$ (°C) is the wall surface temperature and $\vartheta_a(t)$ (°C) is indoor air temperature.

In a medieval building, the overall area of windows and doors is small compared to the wall area and thus the infiltration rate is small as a rule. Even though the heat losses are dependent on the difference in indoor-outdoor temperature, P_l is assumed to be a small fraction of the supplied heat compared to the heat flowing into the wall. Due to the small window area, the irradiation does not have a substantial impact on a single heat-up event. Of course, it has an influence on the long-term conditions but during a heat-up event which often lasts for less than 24 hours the impact is assumed to be negligible. Further, the need for heating is mostly during the winter months, where the contribution from irradiation is very low. Thus, the effective power used for heating is $P_e = F_1 P_s$ where F_1 is a constant loss factor ($F_1 \leq 1$), which accounts for all losses in the building (assuming $P_l > P_I$). The heat balance at a heat-up event can then be simplified to

$$\frac{V_a \rho_a c_{pa}}{Ah} \frac{d\vartheta_a}{dt} = (\vartheta_w(0,t) - \vartheta_a) + \frac{1}{Ah} F_1 P_s. \tag{6}$$

As the buildings volume and effective wall area as well as the heat transfer coefficient between air and wall is difficult to determine by real physical parameters the equation is simplified to

$$T_1 \frac{d\Delta\vartheta_a}{dt} + \Delta\vartheta_a = \Delta\vartheta_w(0,t) + b_1 P_s, \tag{7}$$

where $\Delta\vartheta_a$ and $\Delta\vartheta_w$ denote the increments of the temperatures from the equilibrium,

$$T_1 = \frac{V_a \rho_a c_{pa}}{Ah} \tag{8}$$

denotes the time constant and

$$b_1 = \frac{F_1}{Ah} \tag{9}$$

is the static gain. To simplify the notation, the wall surface temperature is denoted by $\Delta\vartheta_{ws} = \Delta\vartheta_w(0,t)$ in further text. The two parameters T_1 and b_1 of the model (7) will then be determined experimentally based on input-output data in the sense of the grey-box modelling approach.

4.1.1 Model for massive wall surface temperature

The temperature increase at the wall surface $\Delta\vartheta_{ws}$, can be calculated with the heat equation

$$\frac{\partial^2 \vartheta_w}{\partial x^2} = \frac{c_w \rho_w}{\lambda_w} \cdot \frac{\partial \vartheta_w}{\partial t}, \tag{10}$$

See section 4.1.7 for its derivation, where ϑ_w $(°C)$ is the wall temperature, λ_w $(\mathrm{Wm^{-1}K^{-1}})$ is the heat conductivity of the wall, c_w $(\mathrm{J\,kg^{-1}K^{-1}})$ is the specific heat of the wall, $\rho_w(kg\ m^{-3})$ is the density of the wall, t (s) time and x (m) is the distance into the wall from the wall surface. Equation (10) can be solved both analytically and numerically in one dimension, for example by using the numerical Finite Difference Method (FDM), see e.g. [78]. In [12], the FDM method was applied to a structurally analogous problem of moisture sorption in a wooden desk. The method is adapted to the problem at hand (10) in section 2.1.7 and used for the cross-comparison of the further derived results.

An analytical solution of equation (10) is solved for the case of a constant heat flux into a semi-infinite slab, see e.g. [79] with initial conditions typical for initial and warming up massive buildings intermittently:

- In the beginning of the heat-up event, i.e. $t = 0$ the temperature distribution in the wall is constant and equal to the indoor and outdoor air temperature. $\vartheta_w(x) = \vartheta_{a0}$.
- The heat flux P_w into the wall is considered constant during the heat-up event i.e.

  $$\frac{\partial \vartheta_w}{\partial x} = \frac{P_w}{A\lambda_w},\ x = 0. \tag{11}$$

- The heat-up event is short enough that only a part of the wall is practically affected by the heat wave. Thus, the problem can be reformulated to the case of infinitely thick wall, for which

  $$\frac{\partial \vartheta_w}{\partial t} = 0,\ x \to \infty.$$

Under the above assumptions, according to e.g. [79] the wall inner surface $(x = 0)$ temperature can be expressed as

$$\vartheta_{ws} - \vartheta_{ws0} = \frac{P_w}{A} \cdot \frac{2}{\sqrt{\pi}} \cdot \frac{1}{\sqrt{\lambda_w c_w \rho_w}} \cdot \sqrt{t}, \tag{12}$$

where ϑ_{ws0} $(°C)$ is the wall surface temperature at the beginning of the heat-up event. To simplify equation (12) a parameter

$$a_1 = \frac{F_2}{A\sqrt{\pi}} \cdot \frac{2}{\sqrt{\lambda_w c_w \rho_w}}\ , \tag{13}$$

is introduced, considering $P_w = F_2 P_s$ where F_2 is a constant loss factor ($F_2 \leq 1$). As equation (12) expresses the rise in temperature as a function of elapsed time at a heat-up event from an initial temperature, a more proper designation is therefore the incremental form

$$\Delta\vartheta_{ws} = a_1 P_s \sqrt{t}. \tag{14}$$

4.1.2 Approximate model for air temperature.

If equation (7) is coupled with equation (14) we obtain

$$T_1 \frac{d\Delta\vartheta_a(t)}{dt} + \Delta\vartheta_a(t) = a_1 P_s \sqrt{t} + b_1 P_s. \quad (15)$$

Equation (15) has the following solution for a step input P_s

$$\Delta\vartheta_a = P_s \left(a_1 \left(\sqrt{t} - \sqrt{T_1} \cdot \frac{\sqrt{\pi}}{2} \operatorname{erfi}\left(\sqrt{t/T_1} \right) e^{-t/T_1} \right) + b_1 \left(1 - e^{-t/T_1} \right) \right), \quad (16)$$

where $\operatorname{erfi}(z)$ is the imaginary error function and $\frac{\sqrt{\pi}}{2} \cdot \operatorname{erfi}\left(\sqrt{t/T_1}\right) \cdot e^{-t/T_1}$ is known as Dawson's integral [80].

4.1.3 Model parameter identification from measured data

Because of the difficulty to determine the construction and the materials of a historic masonry wall it is equally difficult to determine the material parameters of the wall. The heat transfer coefficient between the wall and the air is dependent on the air flow close to the wall surface which also is difficult to determine. Instead these parameters can be estimated from measurements of temperature during a step response test, i.e. a heat-up event [38]. The task is to find parameters T_1, a_1 and b_1 which then determine the dynamic equation (15) or its solution (16).

As the increase of temperature in the air after the impact of the time constant, according to equation (16) is very close to a linear function of the square root of time, a_1 and b_1 can be determined by linear regression of the air temperature measurements at a step response test, as it will be demonstrated in the following case study example. The regression must be carried out on the later part of the data where the influence of the time constant accumulation has none or very little impact. From the equation of the regressed line parameters a_1 and b_1 can be derived by the following equations

$$a_1 = \frac{K_1}{P_s}, \quad (17)$$

$$b_1 = \frac{(\vartheta_{ar0} - \vartheta_{a0})}{P_s}, \quad (18)$$

where K_1 is the slope of the regressed temperature line when plotted against the square root of time, ϑ_{ar0} is the intercept of the regressed temperature line, ϑ_{a0} is the air temperature at the start of the heat-up event.

The time constant T_1, for the indoor air and interiors can then be found by integration of equation (15), analogously as proposed e.g. in [81],

$$\int_0^{t_m} \left(T_1 \frac{d\Delta\vartheta_a(t)}{dt} + \Delta\vartheta_a(t) \right) dt = \int_0^{t_m} \left(a_1 P_s \sqrt{t} + b_1 P_s \right) dt, \quad (19)$$

and solving for T_1

$$T_1 = \frac{\frac{2}{3} a_1 P_s t_m^{3/2} + b_1 P_s t_m - \int_0^{t_m} \Delta\vartheta_a(t) dt}{\Delta\vartheta_a(t_m)}, \quad (20)$$

where $\Delta\vartheta_a(t_m)$ are measurements of the air temperature increment from the equilibrium state and t_m is duration of step response. As equation (20) depends on the single value from the measurements, $\Delta\vartheta_a(t_m)$, T_1 is likely to be very sensitive to noise in the measurements. To reduce the undesirable influence of noise on the measured value, equation (15) is integrated two times which provides

$$T_1 = \frac{\frac{4a_1 P_s t_m^{5/2}}{15} + \frac{b_1 P_s t_m^2}{2} - \iint_0^{t_m} \Delta\vartheta_a dt dt}{\int_0^{t_m} \Delta\vartheta_a dt}. \quad (21)$$

4.1.4 Case study analysis and discussion

The proposed model identification procedure was tested on data measured at three different 13th century churches, see Figure 4.2. All the three churches have walls and vaults of limestone as the main building material. Both inside and outside surfaces are rendered with lime mortar. Hangvar church has an indoor volume of approximately 1000 m^3 and is heated by electrical pew heaters with installed heating power of 27 kW. Tingstäde church, has an indoor volume of approximately 1200 m^3 and its heating system has installed power of 50 kW. Fide church has an indoor volume of approximately 1120 $m^3$and is heated with electric pew heaters of 32 kW. Hangvar and Tingstäde churches have wooden floors while Fide church has a stone floor.

Figure 4.2 Left, Fide church, middle, Hangvar church, right, Tingstäde church. Photo Anders Söderlund.

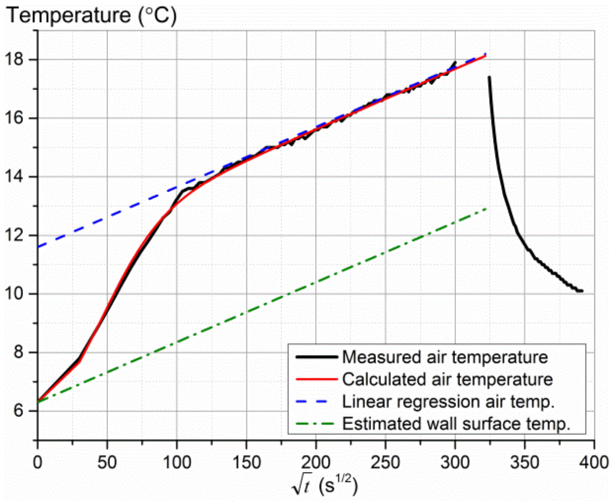

Figure 4.3 Heat-up event in Fide church – measured versus simulated responses by the model (15) with identified parameters in Table 4.1.

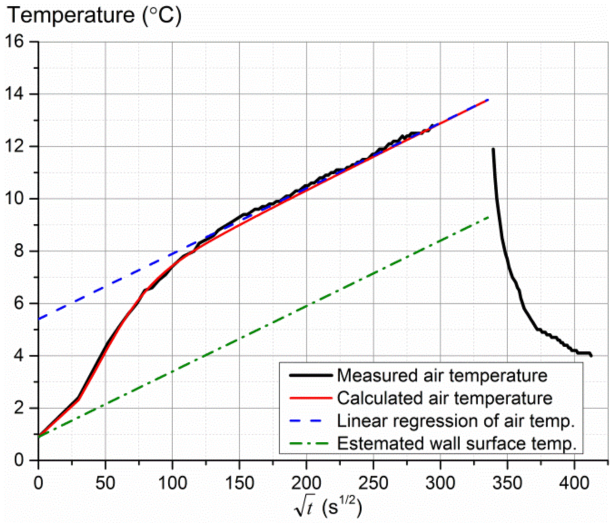

Figure 4.4 Heat-up event for Hangvar church – measured versus simulated responses by the model (15) with identified parameters in Table 4.1.

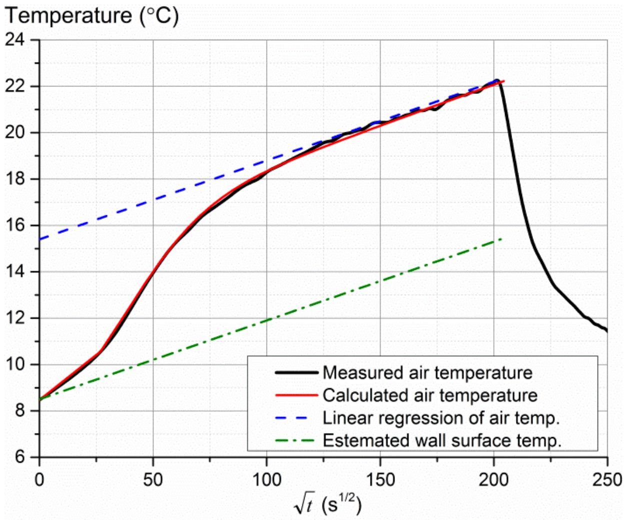

Figure 4.5 Heat-up event in Tingstäde church – measured versus simulated responses by the model (15) with identified parameters in Table 4.1.

Table 4.1 Thermal parameters from a step response test. See figure 2.3, 2.4 and 2.5.

	ϑ_{a0} (°C)	ϑ_{ar0} (°C)	K_1 (°C/s^{1/2})	P_s (kW)	a_1 (°C/kW/s^{1/2})	b_1 (°C/kW)	T_1 (s)
Fide church	6.3	11.8	0.020	32	$5.7 \cdot 10^{-4}$	$1.7 \cdot 10^{-1}$	3400
Hangvar church	0.9	5.4	0.025	27	$9.3 \cdot 10^{-4}$	$1.7 \cdot 10^{-1}$	2800
Tingstäde church	8.4	15.4	0.034	50	$6.6 \cdot 10^{-4}$	$1.4 \cdot 10^{-1}$	2250

4.1.5 Model parameter identification

The step responses measured at the churches can be seen in Figures 4.3-4.5. The upper blue dashed line corresponds to the linear regressed air temperature. The linear regression is performed only on the latter part of the step response, where the dynamics with time constant T_1 has none or very little impact. From the linear regression line, the slope K_1 and the intercept ϑ_{ar0} are determined. Parameters a_1 and b_1 are calculated by (17) and (18), respectively. The time constant is determined by (21) implemented in Matlab software, where the integrals $\iint_0^{t_m} \Delta\vartheta_a \, dtdt$ and $\int_0^{t_m} \Delta\vartheta_a dt$ is performed numerically on the measured data. The integration limit t_m is set to the time where the linear part of the data in the root-square time scale starts. The parameters a_1, $b_1$and T_1 derived from the step responses as described in the identification procedure above are presented in in Table 4.1 and the model (15) simulated results are shown in Figures 4.3-4.5 in comparison with the measured data. As can be seen, very good match between the measured and simulated data have been achieved for all the three churches.

Even though there are only three parameters in this simplified model parametrized at a single step response test, very good conformity between the model and the measurements has been achieved. The parameter a_1 is a material specific constant, see equation (13), but can change during the year depending on the of moisture content of the wall. The static gain b_1 includes the heat transfer coefficient and is thereby temperature dependent, see equation (9). However step response tests, which were carried out under different seasons in different churches, showed that the variations in all these above mentioned parameters are relatively small and it is not much influenced by seasonal changes [38].

4.1.6 Alternative model with discretized PDE of heat transfer in the wall

For the comparison purposes, FDM model of the wall (10) described in section 4.1.7 has also been parametrized for the data measured on the three churches. Coupling the discretized model of the wall in the state space form (40) with the single accumulation model (7), a well fit of the simulated and measured data was obtained for the three churches, as can be seen in Figures 4.7 - 4.9. The model parameters have been tuned to obtain this good match. As the starting point, parameters from Table 4.1 were considered together with the wall parameters: thickness $L = 1$ m, number of slices (i.e. order) $N = 100$ (slice thickness $\Delta L = 0.01$ m), material parameter of limestone $\lambda_w = 1.9\,(\mathrm{Wm^{-1}K^{-1}})$, $\rho = 2750(\mathrm{kg\,m^{-3}})$, $c_w = 840\,(\mathrm{J\,kg^{-1}K^{-1}})$, $h = 10{,}0\,(\mathrm{Wm^{-2}K^{-1}})$. Note that some of the parameters needed to be slightly tuned (within 15% range) to obtain good fit of the measured data, in particular b_1 and h. The purpose of parametrizing the coupled and discretised high order model (7)-(10) is to justify the simplifying assumptions which will be applied to model (15) in the indoor climate control design presented in Section 4.3. The control procedure synthetized for model (7) will be validated on this higher order model. Next to the simulated air temperature, which fits very well the measured data, also simulated wall temperature is visualized in the node points in the left parts of Figures 6-8. In the right parts of Figures 4.7-4.9 comparisons of the two considered models are visualised. Also in this case, the very good match can be seen for all the three simulation sets.

4.1.7 Discrete approximation

One dimension discrete approximation of the heat conduction equation perpendicular to a masonry wall surface is derived following the discretization scheme applied in [12]. Consider a masonry wall in a massive building of thickness denoted by L (m) divided by equidistant parallel planes into N slices of equal thickness $\Delta x = L \,/\, N$. These planes determine $N+1$ nodes of of the discrete representation of the thickness variable x. At the beginning i.e. $t=0$ the building is unheated so the temperature in the building as well as the wall and outside is considered equal, i.e. $\vartheta_w(0,x)=\vartheta_0$, $\vartheta_a=\vartheta_0$ and $\vartheta_{out}=\vartheta_0$. During a heat-up event, the wall model described by PDE (s) is theoretically considered semi-infinite which means that the heat wave from inside will not reach the outside of the wall. For the numerical implementation of the model, the width of the wall is fixed to L, which however needs to be large enough so that heat wave would not influence the outside side of the wall substantially.

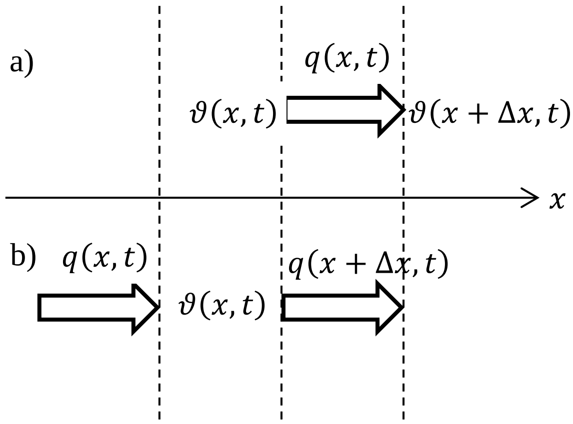

Figure 4.6 a) Heat flux through a plane, b) conservation of energy.

Consider the heat flux scheme in Figure 2.6 a). The heat flux through a small plane of a masonry wall is given by

$$q(x,t) = -\lambda_w \cdot \frac{\vartheta_w(x+\Delta x,t)-\vartheta_w(x,t)}{\Delta x}, \qquad (22)$$

which turns to

$$q(x,t) = -\lambda_w \cdot \frac{\partial \vartheta_w(x,t)}{\partial x} \qquad (23)$$

for $\Delta x \to 0$, where ϑ_w $(°C)$ is the temperature, λ_w $(W/m\,°C)$ heat conductivity of the wall, t time (s) and x (m) is the distance into the wall from the wall surface. The change of heat flux with respect to x through the wall is given by

$$\frac{\partial q(x,t)}{\partial x} = \frac{\partial}{\partial x}\left(-\lambda_w \cdot \frac{\partial \vartheta_w(x,t)}{\partial x}\right) = -\lambda_w \cdot \frac{\partial^2 \vartheta_w(x,t)}{\partial x^2}. \tag{24}$$

By conservation of energy we get that the change of energy level in a small slice Δx, during a short time Δt, depends on the difference of the heat in the slice, as sketched in Figure 2.6b,

$$\frac{\Delta \vartheta_w(x,t)}{\Delta t} = -\frac{1}{c_w \rho_w} \cdot \left(\frac{q(x+\Delta x,t) - q(x,t)}{\Delta x}\right), \tag{25}$$

which turns to

$$\frac{\partial \vartheta_w(x,t)}{\partial t} = -\frac{1}{c_w \rho_w} \cdot \frac{\partial q(x,t)}{\partial x} \tag{26}$$

for $\Delta x \to 0$. Now equation (24) can be substituted in to equation (26) and the result becomes

$$\frac{\partial \vartheta_w(x,t)}{\partial t} = \frac{\lambda_w}{c_w \rho_w} \cdot \frac{\partial^2 \vartheta_w(x,t)}{\partial x^2}, \tag{27}$$

where $c_w(J\ kg^{-1}\ °C^{-1})$ is the specific heat of the wall, $\rho_w(kg\ m^{-3})$ is the density of the wall. Equation (27) is a Partial Differential Equation well-known as the heat equation.

To numerically simulate the temperature in the wall and the wall surface a discretisation of the heat equation must be carried out. At the boundaries the heat flow is described by

$$\lambda_w \left.\frac{\partial \vartheta_w(x,t)}{\partial x}\right|_{x=0} = h_{in}\big(\vartheta_a(t) - \vartheta_w(0,t)\big) = -q(0,t), \tag{28}$$

$$\lambda_w \left.\frac{\partial \vartheta_w(x,t)}{\partial x}\right|_{x=L} = h_{out}\big(\vartheta_w(L,t) - \vartheta_{out}(t)\big) = -q(L,t), \tag{29}$$

where h_{in} and h_{out} is the inside and outside heat transfer coefficient $(W\ m^{-2}K^{-1})$ and ϑ_a and ϑ_{out} is the indoor and outdoor temperature. For the discrete approximation of the second order derivatives with respect to x the three-node method can be applied [78], [12]

$$\left.\frac{\partial^2 \vartheta(x,t)}{\partial x^2}\right|_{x=i} \cong \frac{1}{\Delta x^2}[\vartheta(i-1,t) - 2\vartheta(i,t) - \vartheta(i+1,t)] \tag{30}$$

Everywhere where it is feasible the symmetrical formulae are preferred. Only in the boundary nodes $x = 0$ and $x = L$ an asymmetrical version must be used. At the boundaries, the asymmetrical Lagrangian three-point formula for the heat flow is to be applied

$$\left.\frac{\partial q(x,t)}{\partial x}\right|_{x=0} \cong \frac{1}{2\Delta x}\big(-3q(0,t) + 4q(1,t) - q(2,t)\big). \tag{31}$$

The heat flux at the first ($x = 1$) and the second ($x = 2$) slice is described by

$$q(1,t) = -\frac{\lambda_w}{2\Delta x} \cdot \big(\vartheta(2,t) - \vartheta(0,t)\big), \tag{32}$$

$$q(2,t) = -\frac{\lambda_w}{2\Delta x} \cdot \big(\vartheta(3,t) - \vartheta(1,t)\big). \tag{33}$$

By substituting equation (28) and (29) for the respectively boundary and equation (32) and (33) for $x = 1$ and $x = 2$ respectively into equation (31) we get

$$\left.\frac{\partial q(x,t)}{\partial x}\right|_{x=0} \cong \frac{3h_{in}}{2\Delta x}\left(\vartheta_a(t) - \vartheta_w(0,t)\right) + \frac{\lambda_w}{4\Delta x^2}\left(4\vartheta(0,t) - \vartheta(1,t) - 4\vartheta(2,t) + \vartheta(3,t)\right). \quad (34)$$

Finally, by using equation (26) we get

$$\left.\frac{\partial \vartheta(x,t)}{\partial t}\right|_{x=0} = a\left(\vartheta_a(t) - \vartheta_w(0,t)\right) + \frac{K}{4}\left[-\vartheta(3,t) + 4\vartheta(2,t) + \vartheta(1,t) - 4\vartheta(0,t)\right], \quad (35)$$

and

$$\left.\frac{\partial \vartheta(x,t)}{\partial t}\right|_{x=L} = b\left(\vartheta_{out}(t) - \vartheta_w(L,t)\right) +$$
$$+\frac{K}{4}\left[-\vartheta(L-3,t) + 4\vartheta(L-2,t) + \vartheta(L-1,t) - 4\vartheta(L,t)\right], \quad (36)$$

at the boundaries, where

$$a = \frac{3h_{in}}{2c_w\rho_w\Delta x}, \quad (37)$$

$$b = \frac{3h_{out}}{2c_w\rho_w\Delta x}, \quad (38)$$

$$K = \frac{\lambda_w}{c_w\rho_w\Delta x^2}. \quad (39)$$

Then, the following state space model of order $N + 1$ can be obtained

$$\frac{d\boldsymbol{x}(t)}{dt} = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) \quad (40)$$

$$y(x) = \boldsymbol{C}\boldsymbol{x}(t) \quad (41)$$

with the state vector $\boldsymbol{x}(t) = [\vartheta_w(0,t), \vartheta_w(1,t), \dots, \vartheta_w(N,t)]^T$, input vector $\boldsymbol{u}(t) = [\vartheta_A(t), \vartheta_B(t)]^T$ and the output $y(t) = \vartheta_w(0,t)$ and with the following matrices

$$\boldsymbol{A} = \begin{bmatrix} -a-K, & K/4, & K, & -K/4, & \dots & 0, & 0, & 0, \\ K, & -2K & K, & 0, & \dots & 0, & 0, & 0, \\ 0, & K & -2K & K & \dots & 0, & 0, & 0, \\ --- & --- & --- & --- & --- & --- & --- & --- \\ 0, & 0, & 0, & \dots & K, & -2K, & K, & 0, \\ 0, & 0, & 0, & \dots & 0, & K, & -2K, & K, \\ 0, & 0, & 0, & \dots & -K/4, & K, & K/4, & -b-K \end{bmatrix},$$

$$\boldsymbol{B} = \begin{bmatrix} a, & 0 & 0, & 0 & \dots & 0, & 0, & 0, \\ 0, & 0 & 0, & 0, & \dots & 0, & 0, & b \end{bmatrix}^T,$$
$$\boldsymbol{C} = [1, \quad 0, \quad 0, \quad 0, \quad \dots \quad 0, \quad 0, \quad 0].$$

This model has been implemented in Matlab Simulink.

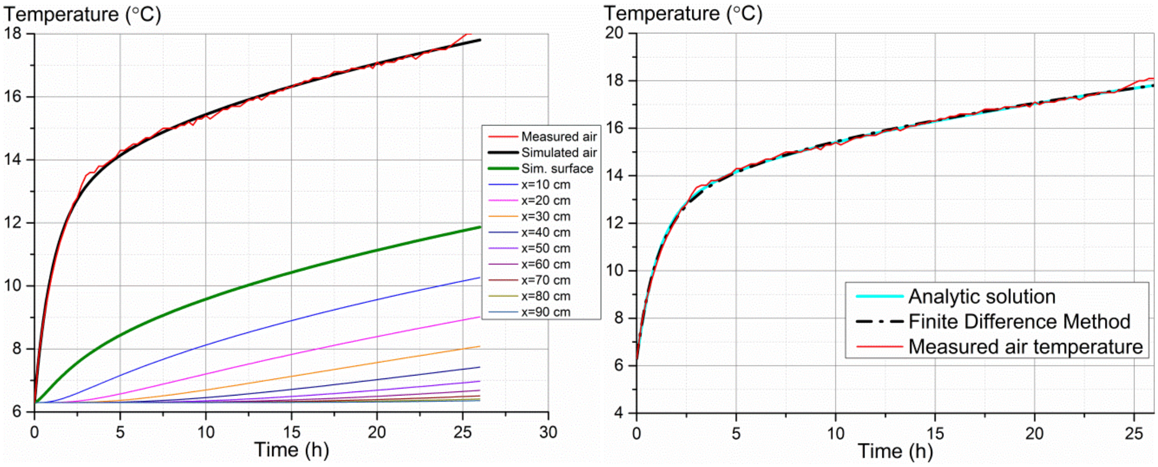

Figure 4.7 Fide church: Left - measured versus simulated data by model (7) coupled with heat equation (10) approximated by FDM. Right - comparison of air temperature simulated by model (16) and (7)-(10) approximated by FDM.

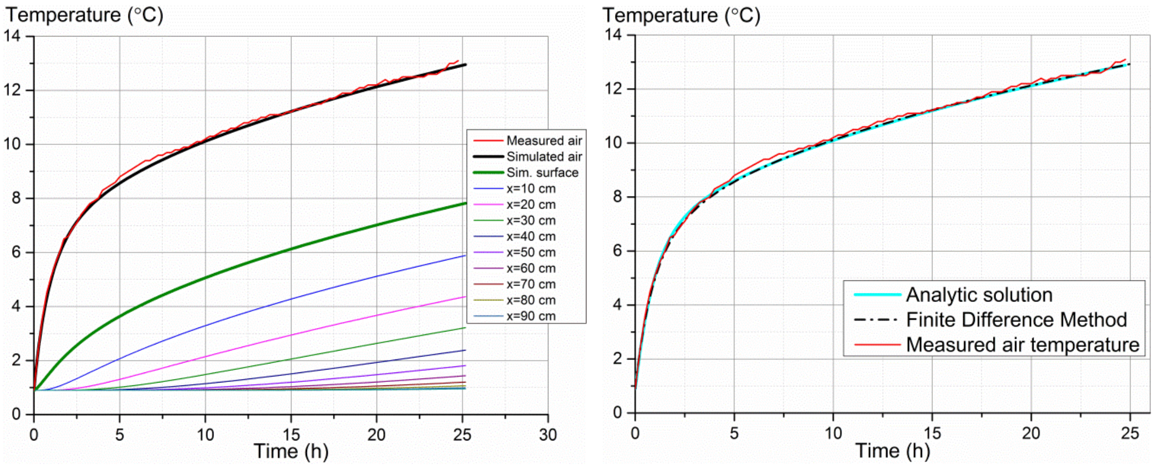

Figure 4.8 Hangvar church: Left - measured versus simulated data by model (7) coupled with heat equation (10) approximated by FDM. Right - comparison of air temperature simulated by model (16) and (7)-(10) approximated by FDM.

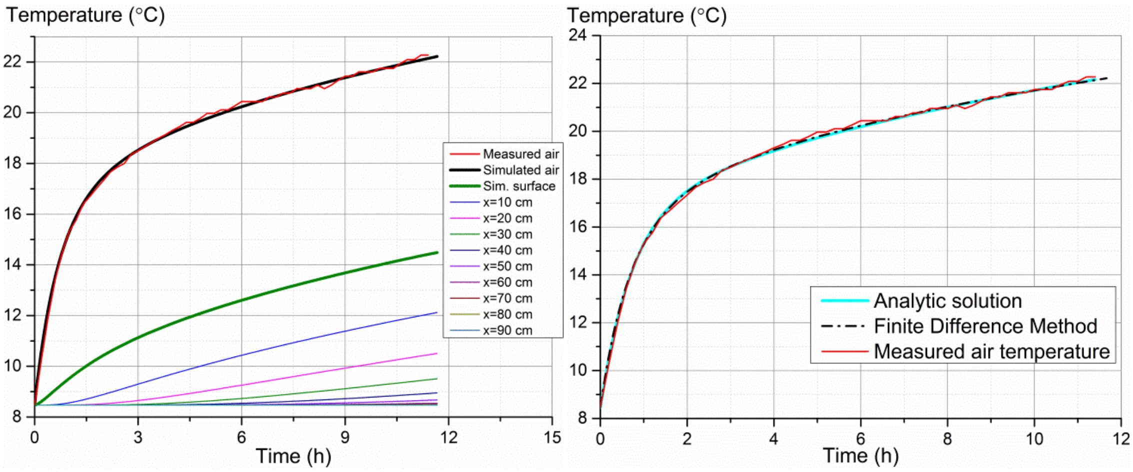

Figure 4.9 Tingstäde church: Left - measured versus simulated data by model (7) coupled with heat equation (10) approximated by FDM. Right - comparison of air temperature simulated by model (16) and (7)-(10) approximated by FDM.

4.1.8 Simplified model to determine heat-up time with no constrains on RH change rate

The air temperature at the end of a heat-up event as a function of elapsed time is relevant for practical calculations. The time constant has large impact only at the first part of the heat-up event but on the final temperature the impact of the time constant is only some tenths of a centigrade. If the heat-up time is larger than five time constants i.e. $5T_1$ and constants a_1 and b_1 is known thorough calculations from a step response test the final temperature can be approximated with a simplified equation where the impact from the time constant can be approximated to zero.

$$\vartheta_{af} - \vartheta_{a0} = P_s\left(a_1\sqrt{t_f} + b_1\right), \quad (42)$$

where ϑ_{af} is the final temperature at the at the end of heat-up period t_f. Equation (37) can in turn be rearranged to calculate the heat-up time

$$t_f = \left(\frac{\vartheta_{af} - \vartheta_{a0} - P_s b_1}{P_s \cdot a_1}\right)^2, \quad (43)$$

which is very useful for people working in the building to know when to set on the heating. Equation (38) can also be rearranged to determine required power

$$P_r = \frac{\vartheta_{af} - \vartheta_{a0}}{a_1\sqrt{t_f} + b_1}, \quad (44)$$

to reach the required final temperature as a function of time t_f. This simplified model was proposed and analysed in [1], presenting preliminary results to this paper.

It should however be stressed that this single step procedure is likely to be risky for the interior due to uncontrolled change rate of RH, which is visualised in Left parts of Figures 4.13-4.15. In order to control the change rate of RH, an approximate hygric model is developed together with parametrization procedure, analogously to the temperature model proposed above.

4.2 Simplified hygric model for intermittent heating of massive buildings

Performing analogous steps as for the thermal balance model, the objective of this part is to develop an approximate hygric model for air humidity in a building of massive construction in response to step in heat input. Both the coupled thermal and hygric models will then serve for planning the safe heat up procedure. At a heat-up event the indoor air mixing ratio (MR) increases as moisture evaporates from the saturated indoor walls and interiors when the temperature increases. According to [38], the mass balance during such heat-up event can be expressed by

$$K_a A\left(x_w(t) - x_a(t)\right) = \rho_a V_a \frac{dx_a}{dt} + n\rho_a V_a\left(x_a(t) - x_{out}(t)\right), \quad (45)$$

where K_a $(kg\ m^{-2}s^{-1})$ is a evaporating constant, A (m^2) is the effective evaporating wall area, x_w $(g\ kg^{-1})$ the saturated MR at the wall surface, x_a $(g\ kg^{-1})$, the MR in the indoor air, $\rho_a (kg\ m^{-3})$ the density of the air, n (s^{-1}) the air exchange rate, V_a (m^3) the volume of the indoor air (the building) and x_{out} $(g\,kg^{-1})$ MR of the outdoor air. Large variations in MR in the outdoor air will influence the humidity inside if the infiltration rate is large. However during a single heat-up event the variation is usually not large enough to affect the indoor air in any large scale. During the heat-up event, x_{out} can therefore be regarded as a constant [38].

Equation (45) can therefore be simplified to

$$T_2 \frac{d\Delta x_a(t)}{dt} + \Delta x_a(t) = C_1 \Delta x_w(t), \tag{46}$$

where

$$T_2 = \frac{\rho_a V_a}{K_a A + n\rho_a V_a}, \tag{47}$$

and

$$C_1 = \frac{1}{1+n\frac{\rho_a V_a}{K_a A}} \quad . \tag{48}$$

To proceed further, it is assumed that the wall surface is saturated with moisture (RH=100%). MR at the wall surface is therefore dependent on the wall surface temperature only [38]. As the wall surface temperature at intermittent heat-up event is a function of square root of time, analogously to (15), the right hand side of equation (46) can be approximated as

$$C_1 \Delta x_w(t) = P_s\left(a_2\sqrt{t} + b_2\right), \tag{49}$$

where a_2 and b_2 are constants. The expression for air MR then becomes

$$T_2 \frac{d\Delta x_a(t)}{dt} + \Delta x_a(t) = P_s\left(a_2\sqrt{t} + b_2\right), \tag{50}$$

which has the same type of solution for a step in heating power as for temperature

$$\Delta x_a = P_s\left(a_2\left(\sqrt{t} - \sqrt{T_2}\cdot\frac{\sqrt{\pi}}{2}\operatorname{erfi}\left(\sqrt{t/T_2}\right)e^{-t/T_2}\right) + b_2\left(1 - e^{-t/T_2}\right)\right). \tag{51}$$

To find the parameters a_2, b_2 and T_2 the same approach as with air temperature can be applied and can thus be derived from measured data from a step response test. A linear regression is performed from the time when the impact of the time constant has subsided to the end of the heat-up time. From the regressed line slope K_2, intercept x_{ar0} and air mixing ratio at the beginning x_{a0} parameters a_2 and b_2 are derived as follows

$$a_2 = \frac{K_2}{P_s}, \tag{52}$$

$$b_2 = \frac{(x_{ar0} - x_{a0})}{P_s}. \tag{53}$$

The time constant T_2, can be found by integration of equation (50) two times

$$\iint_0^{t_m} \left(T_2 \frac{d\Delta x_a(t)}{dt} + \Delta x_a(t) \right) dtdt = \iint_0^{t_m} \left(a_2 P_s \sqrt{t} + b_2 P_s \right) dtdt, \tag{54}$$

and solved for T_2 as

$$T_2 = \frac{\frac{4a_2 P_s t_m^{5/2}}{15} + \frac{b_2 P_s t_m^2}{2} - \iint_0^{t_m} \Delta x_a dtdt}{\int_0^{t_m} \Delta x_a dt}. \tag{55}$$

4.2.1 Experimental verification

The identification procedure has been tested on data measured at the three churches considered in the case study Section 4.1.4. The measured data and determination of the slope K_2 and intercept x_{ar0} is shown in Figures 4.10-4.12. The resulting parameters are given in Table 4.2. As can be seen from the simulation results, the model (51) fits the data very well for all the churches. Note that as the moisture conditions of the wall are likely to change over the seasons, the hygrothermal parameters of the model must be adjusted to the current conditions of the wall.

Table 4.2 Humidity parameters from step response tests

	x_{a0} (g/kg)	x_{ai} (g/kg)	P_s (kW)	K_2 $(g/kg\ /s^{1/2})$	a_2 $(g\ /kg/kW/s^{1/2})$	b_2 $(g/kg/kW)$	T_2 (s)
Fide church	3.8	4.96	32	0.0072	$230 \cdot 10^{-6}$	$36 \cdot 10^{-3}$	3600
Hangvar church	3	3.99	27	0.00071	$27 \cdot 10^{-6}$	$36 \cdot 10^{-3}$	5900
Tingstäde church	5.86	8.2	50	0.0135	$270 \cdot 10^{-6}$	$47 \cdot 10^{-3}$	3500

4.3 RH Control at a heat-up event

The primary objective of deriving the approximate hygrothermal models above is the optimization of the heating period. A controller for intermittent heating of a heavy masonry building should have the following requirements.

- **RH change**: the controller should adjust the heating power so a specified RH change rate is not exceeded.
- **Energy consumption**: in order to keep the energy consumption low, the heat should be turned on as short time as possible before the use of the building and with as much power as possible without constraining the RH change requirement.
- **Comfort temperature:** The predefined comfort temperature needs to be achieved at specific time.

In order to follow safety measures for RH variation in historic interior [23] the RH change rate at the beginning of the heating period is to be kept in the limited range. In this aspect, the hourly RH change rate limit $\Delta\varphi_{a,s} = 2\%$ suggested in [82] is to be considered (the observed period is thus $\Delta t = 1$ hour). However, the user can define different values of both the change rate limit and period. In what follows, the step-wise adjustment of the heating power in the time intervals Δt is to be determined in order to satisfy the given maximum RH change rate per Δt.

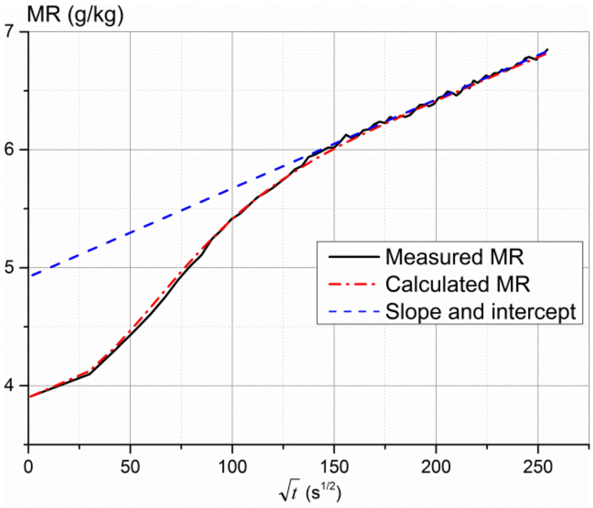

Figure 4.10 Indoor air mixing ratio response at the heat-up event in Fide church - measured versus simulated responses by the model (51) with identified parameters in Table 4.2.

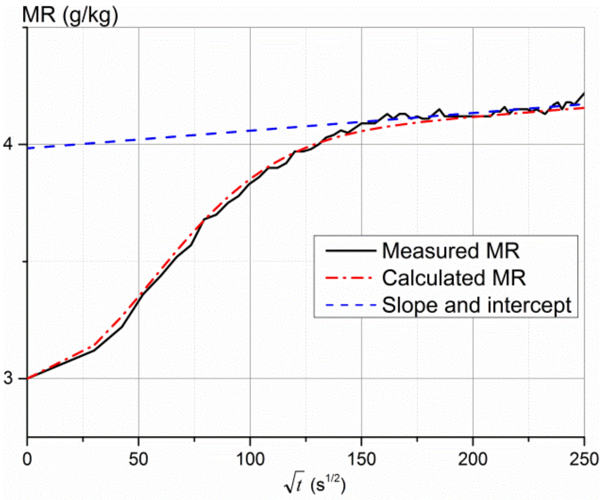

Figure 4.11 Indoor air mixing ratio response at the heat-up event in Hangvar church - measured versus simulated responses by the model (51) with identified parameters in Table 4.2.

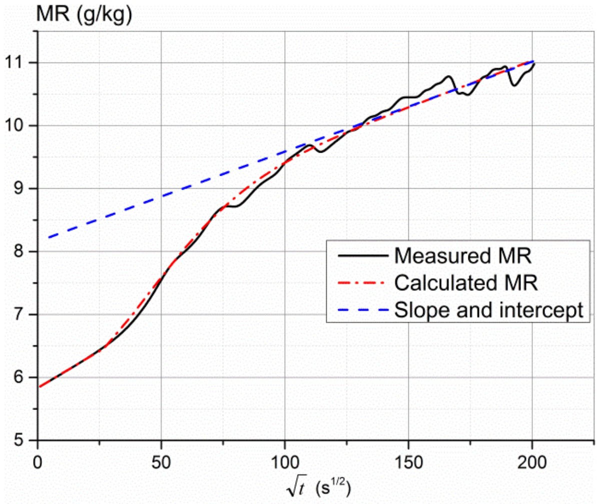

Figure 4.12 Indoor air mixing ratio response at the heat-up event in Tingstäde church - measured versus simulated responses by the model (51) with identified parameters in Table 4.2.

As a preliminary step, we express the equations (16) and (51) in the form

$$\Delta\vartheta_a(t) = K_\vartheta(t)\Delta P_s, \tag{56}$$

$$\Delta x_a(t) = K_x(t)\Delta P_s, \tag{57}$$

where

$$K_\vartheta(t) = a_1\left(\sqrt{t} - \sqrt{T_1}\cdot\frac{\sqrt{\pi}}{2}\mathrm{erfi}\left(\sqrt{t/T_1}\right)e^{-t/T_1}\right) + b_1\left(1 - e^{-t/T_1}\right), \tag{58}$$

$$K_x(t) = a_2\left(\sqrt{t} - \sqrt{T_2}\cdot\frac{\sqrt{\pi}}{2}\mathrm{erfi}\left(\sqrt{t/T_2}\right)e^{-t/T_2}\right) + b_2\left(1 - e^{-t/T_2}\right). \tag{59}$$

Notice that for the fixed t, $K_\vartheta(t)$ and $K_x(t)$ are constants. Taking this into account, the design task is to determine ΔP_s for which

$$\Delta\varphi_a(\Delta t) \le \Delta\varphi_{a,s}. \tag{60}$$

Considering the well - known Magnus formula [83], the changes of $\Delta\vartheta_a$ and Δx_a can be transformed to the change of $\Delta\varphi_a$. For this transformation, we apply the simplified version of the formula [18]

$$x_a = 3.795 \times 10^{-5}\varphi_a 10^{\frac{a\vartheta_a}{b+\vartheta_a}}, \tag{61}$$

where $a = 7.65$ and $b = 243.12°C$ [83]. From (61), the RH value can easily be determined as

$$\varphi_a = f_\varphi(x_a, \vartheta_a) = \frac{1}{3.795} \times 10^5 x_a 10^{-\frac{a\vartheta_a}{b+\vartheta_a}}. \tag{62}$$

Assuming the variations of $\Delta\vartheta_a$ and Δx_a from the equilibrium initial values $\vartheta_{a,0}, x_{a,0}$ (determining $\varphi_{a,0}$) within Δt are small, (62) can be turned to a linear incremental form

$$\Delta\varphi_a = C_x(\vartheta_{a,0}, x_{a,0})\Delta x_a + C_\vartheta(\vartheta_{a,0}, x_{a,0})\Delta\vartheta_a, \tag{63}$$

where

$$C_x(\vartheta_{a,0}, x_{a,0}) = \frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial x_a}\bigg|_0 = \frac{1}{3.795} \times 10^5 \times 10^{-\frac{a\vartheta_{a,0}}{b+\vartheta_{a,0}}} , \tag{64}$$

$$C_\vartheta(\vartheta_{a,0}, x_{a,0}) = \frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial \vartheta_a}\bigg|_0 = -\frac{1}{3.795} \times 10^5 x_{a,0} 10^{-\frac{a\vartheta_{a,0}}{b+\vartheta_{a,0}}} \times \frac{ab}{(b+\vartheta_{a,0})^2} \ln(10) . \tag{65}$$

Substituting (56) and (57) to (63) and considering $t = \Delta t$, we obtain

$$\Delta\varphi_a = C_x(\vartheta_{a,0}, x_{a,0}) K_x(\Delta t) \Delta P_{s,1} + C_\vartheta(\vartheta_{a,0}, x_{a,0}) K_\vartheta(\Delta t) \Delta P_{s,1}. \tag{66}$$

The heating power step at $t = 0$ to achieve maximal allowable RH change rate $\Delta\varphi_{a,s}$ over the period Δt can be then determined as

$$\Delta P_{s,0} = \frac{1}{C_x(\vartheta_{a,0},x_{a,0})K_x(\Delta t) + C_\vartheta(\vartheta_{a,0},x_{a,0})K_\vartheta(\Delta t)} \Delta\varphi_{a,s}. \tag{67}$$

Note that the subscript in $\Delta P_{s,0}$ indicates that it is the size of the step in the heating power to be set at $t = 0$. In the unlikely case $\Delta P_{s,0} \geq P_{s,m}$, where $P_{s,m}$ indicates the maximal available heating power, the guidelines proposed in part 4.1.8 are to be followed. If the inequality is not satisfied, we proceed as described below.

As a consequence to the determined heating power step $\Delta P_{s,0}$, we can express values of $x_a(t)$ and $\vartheta_a(t)$ at $t = \Delta t$ as

$$\vartheta_{a,1} = \vartheta_{a,0} + K_\vartheta(\Delta t) \Delta P_{s,0}, \tag{68}$$

$$x_{a,1} = x_{a,0} + K_x(\Delta t) \Delta P_{s,0}. \tag{69}$$

Consequently, the RH change is given by

$$\varphi_{a,1} = f_\varphi(x_{a,1}, \vartheta_{a,1}) . \tag{70}$$

Another step in the procedure is to determine the second power step $\Delta P_{s,1}$ to be added at $t = \Delta t$. Here, however, a key simplifying assumption is to be stated. Note that the equations (16) and (51) were derived and identified considering the equilibrium distribution of temperature in the wall. This is not valid any more after applying the first (and possibly subsequent) heating power step(s). However, due to high thermal inertia of the wall, the non-homogeneity of the temperature distribution by the initial steps at the beginning of the heating period is likely to be small. Therefore, it is neglected in the next steps of the procedure. Under linearity assumption [84], the equations (16) and (51) will be used to assess the responses of the subsequent heating power steps. The overall response then will be derived as a superposition of the partial responses to the heating power steps $\Delta P_{s,i}$, taken in $t = i\Delta t, i = 0,1,2,\ldots$

To determine the power increment at $t = \Delta t$, the superposition of the first and the second step needs to be taken into account. In this, the decrease of RH caused by $\Delta P_{s,0}$ needs to be taken into account. For this purpose, values of $\bar{x}_a(t)$ and $\bar{\vartheta}_a(t)$ at $t = 2\Delta t$ as a consequence of $\Delta P_{s,0}$ needs to be expressed as

$$\bar{\vartheta}_{a,2} = \vartheta_{a,0} + K_\vartheta(2\Delta t)\Delta P_{s,0}, \quad (71)$$

$$\bar{x}_{a,2} = x_{a,0} + K_x(2\Delta t)\Delta P_{s,0}. \quad (72)$$

which leads to $\bar{\varphi}_{a,2} = f_\varphi(\bar{x}_{a,2}, \bar{\vartheta}_{a,2})$ by (70). Then, the maximal possible RH decrement due to $\Delta P_{s,1}$ is given by

$$\Delta\varphi_{a,r_1} = \Delta\varphi_{a,s} + (\varphi_{a,1} - \bar{\varphi}_{a,2}). \quad (73)$$

Note that $\Delta\varphi_{a,s}$ is negative. The power increment then can be determined as

$$\Delta P_{s,1} = \frac{1}{C_x(\vartheta_{a,1}, x_{a,1})K_x(\Delta t) + C_\vartheta(\vartheta_{a,1}, x_{a,1})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_1} \quad (74)$$

Notice that $C_x(\vartheta_{a,1}, x_{a,1})$ and $C_\vartheta(\vartheta_{a,1}, x_{a,1})$ are evaluated for $\vartheta_{a,1}$ and $x_{a,1}$ in this case. So these coefficients will slightly differ from those applied to determine the first step. If $\Delta P_{s,0} + \Delta P_{s,1} < P_{s,m}$, the above procedure is to be repeated. Otherwise $\Delta P_{s,1} = P_{s,m} - \Delta P_{s,0}$ and the procedure stops.

The procedure can be generalized for the $i - th$ step, taking into account the above mentioned superposition concept. First, the values of $x_a(t)$ and $\varphi_a(t)$ at $t = i\Delta t$ are to be determined as

$$\vartheta_{a,i} = \vartheta_{a,0} + \sum_{k=0}^{i-1} K_\vartheta((i-k)\Delta t)\Delta P_{s,k}, \quad (75)$$

$$x_{a,i} = x_{a,0} + \sum_{k=0}^{i-1} K_x((i-k)\Delta t)\Delta P_{s,k}, \quad (76).$$

leading to the new RH value $\varphi_{a,i}(t) = f_\varphi(x_{a,i}, \vartheta_{a,i})$. Analogously to the above case, these quantities are to be determined at $t = (i+1)\Delta t$

$$\bar{\vartheta}_{a,i+1} = \vartheta_{a,0} + \sum_{k=0}^{i-1} K_\vartheta((i-k+1)\Delta t)\Delta P_{s,k}, \quad (77)$$

$$\bar{x}_{a,i+1} = x_{a,0} + \sum_{k=0}^{i-1} K_x((i-k+1)\Delta t)\Delta P_{s,k}, \quad (78).$$

leading to the RH value $\bar{\varphi}_{a,i+1}(t) = f_\varphi(\bar{x}_{a,i+1}, \bar{\vartheta}_{a,i+1})$ by (57). Then, the reduced RH decrement is given as

$$\Delta\varphi_{a,r_i} = \Delta\varphi_{a,s} + (\varphi_{a,i} - \bar{\varphi}_{a,i+1}). \quad (79)$$

The heating power step at $t = i\Delta t$ is finally estimated as

$$\Delta P_{s,i} = \frac{1}{C_x(\vartheta_{a,i}, x_{a,i})K_x(\Delta t) + C_\vartheta(\vartheta_{a,i}, x_{a,i})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_i}. \quad (80)$$

If

$$\sum_{k=0}^{i} \Delta P_{s,k} \geq P_{s,m}, \quad (81)$$

$\Delta P_{s,i}$ is reduced to $\Delta P_{s,i} = P_{s,m} - \sum_{k=0}^{i-1} \Delta P_{s,k}$ and the procedure stops. Otherwise $i = i + 1$ and the procedure is repeated from equation (75). After shaping the heating power distribution at the beginning of the heating period, the last task is to estimate the overall heating time t_f to reach the temperature $\vartheta_{a,f}$. Following the above considered superposition rule, the time can be determined as a solution of the following nonlinear equation

$$\vartheta_{a,f} = \vartheta_{a,0} + \sum_{k=0}^{i} K_\vartheta\left(t_f - k\Delta t\right)\Delta P_{s,k}, \tag{82}$$

considering $t_f > i\Delta t$. The equation can be solved by an established numerical method, e.g. Newton's method [85], or simply by sweeping time t_f starting from $t_{f,0} = i_{max}\Delta t$. Analogously to the Section 4.1.8, equation (43), considering the assumption that the heat-up time of each of the steps is larger than five time constants i.e. $5T_1$, the equation (82) can be considerably simplified to the form

$$\vartheta_{af} = \vartheta_{a,0} + \sum_{k=0}^{i}\left(a_1\sqrt{t_f - k\Delta t} + b_1\right)\Delta P_{s,k}. \tag{83}$$

Equation (83) is still nonlinear and numerical solution is needed to determine t_f.

4.3.1 Simulation based validation of the proposed indoor-climate control

Results by simulations validating the above derived control procedure in the three churches are shown in Figures 4.13-4.15. The target temperature was selected as $\vartheta_{af} = 20^\circ C$ for all the three churches. Next to the validation of the proposed control method, responses of the temperature and RH to a single heating power step discussed in Section 4.1 are shown in the left parts of the figures. The heating time to achieve $\vartheta_{af} = 20^\circ C$ was determined by (43) as $t_f = 47$ hours for Fide, $t_f = 94$ hours for Hangvar and t_f =6.2 hours for Tingstäde. As can be seen in the figures, a considerably fast change rate of RH can be observed at the beginning of all the heating events, which would certainly bring risks to the building interior, heritage wooden objects in particular.

As can be seen in the right parts of the figures, the predefined RH change rate 2% per hour has been achieved for all the three churches when the above defined control procedure was applied. For Fide church, the heating power increase has been divided into five full and one shortened sub-steps determined by the procedure (75)-(81), i.e. with $i_{max} = 5$. For both the Hangvar and Tingstäde, the number of steps results as $i_{max} = 7$. Notice that according to (79)-(80), the magnitude of the power sub-steps tend to decrease as i increases. As regards determination of the heating time, solving (83) via sweeping the time over predefined dense grid, it results as $t_f = 48.5$ hours for Fide, $t_f = 97$ hours for Hangvar and t_f =9.4 hours for Tingstäde. When compared to the heating time for single step alternative, only relatively small heating time increment can be observed for all the three churches.

Note that next to validating the method by temperature simulations using simplified model (16), more accurate model arising from coupling (7) and PDE (10) discretized by FDM and parametrized in Section 4.4.2 was used. The staircase power signal generated by applying the above derived control design procedure is considered as the input of the model (7) coupled with FDM wall model. On the other hand, the results by (15) are composed as sum of the partial responses to $\Delta P_{s,i}$ taken in time instants $i\Delta t$, $i = 0,1,..i_{max}$. As can be seen in Figures 4.13-4.15, both the model types give almost the same results - a perfect match can be observed. This agreement justifies the assumption on neglecting the temperature non-homogeneity in the wall when determining the heat power steps $\Delta P_{s,i}$. Note also that for obtaining the RH change rate estimation, superposition of step responses simulated by (51) to get $\Delta x_{a,i}$ was applied, which was then turned to RH by (62) utilizing also the responses of the temperature.

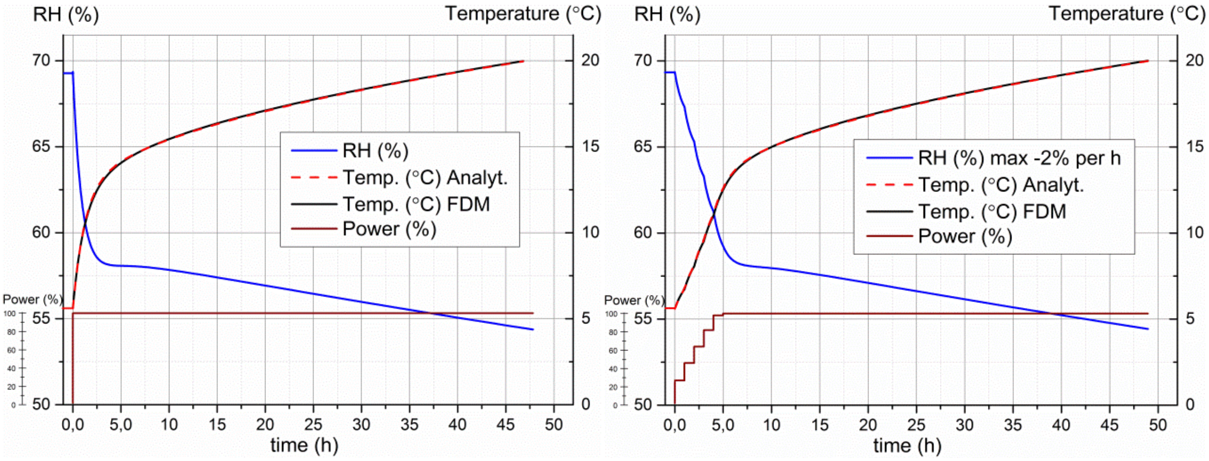

Figure 4.13 Fide church: Simulation of heating event by: Left - a single heating power step; Right – a staircase heating power distribution determined by the proposed control method (75)-(81), with $\boldsymbol{i} = \mathbf{0}, .., \mathbf{5}$. (Temperature simulation performed with both FDM and analytical method).

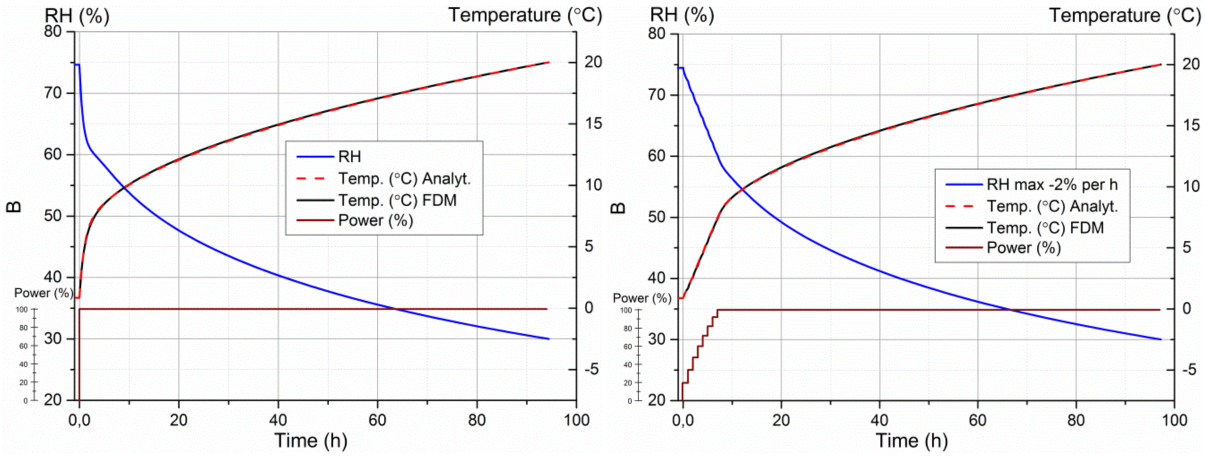

Figure 4.14 Hangvar church: Simulation of heating event by: Left - a single heating power step; Right – a staircase heating power distribution determined by the proposed control method (75)-(81), with $\boldsymbol{i} = \mathbf{0}, .., \mathbf{7}$. (Temperature simulation performed with both FDM and analytical method).

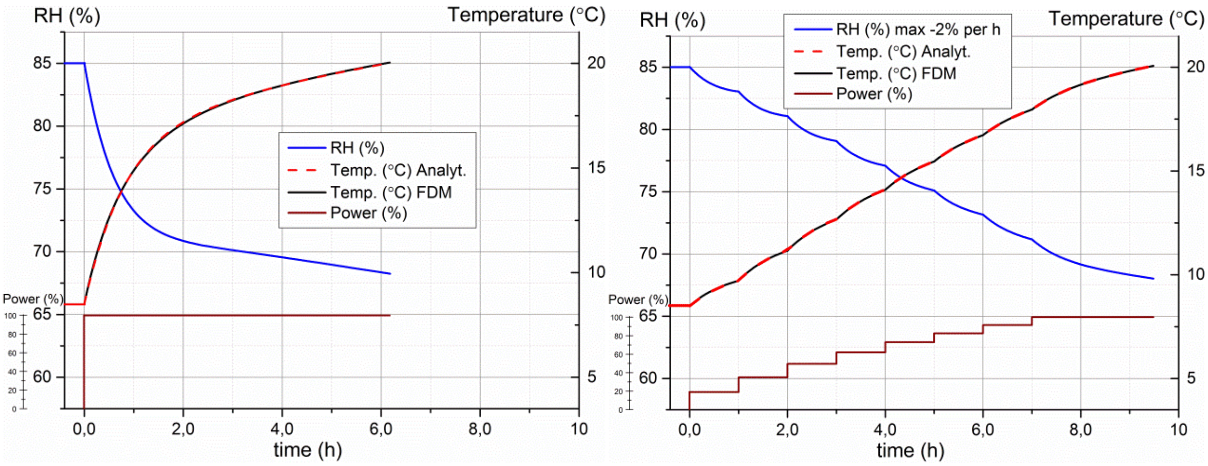

Figure 4.15 Tingstäde church: Simulation of heating event by: Left - a single heating power step; Right – a staircase heating power distribution determined by the proposed control method (75)-(81), with $\boldsymbol{i} = \mathbf{0}, .., \mathbf{7}$. (Temperature simulation performed with both FDM and analytical method).

4.4 Conclusions

A conceptual design of shaping the heating power increase at the beginning of the intermittent heating event at massive historic building with heavy masonry walls was proposed. The primary objective was to keep the RH change rate at the beginning of the heating event within safe range, as a fast change rate of RH was identified in literature as risky for heritage objects deposited in the historic interior. The method is based on a simplified thermal and hygric analytical models, both derived in a form of accumulation-type first order nonlinear differential equations. For both the models, the parameter identification procedures are proposed. They are performed in two steps. First, the static (sensitivity) parameters are obtained directly from the linear parts of the responses, when visualised with root square scaling of the time. The accumulation time constants are then obtained by applying the method of signal integration. The proposed models and identification procedure were successfully validated on measured data at three churches in Sweden (Fide, Hangvar and Tingstäde churches). These models are in turn used to calculate the decrease of relative humidity during the heat-up event. The indoor air relative humidity change rate is predictable, e.g. by the well-known Magnus law, as it is determined by the air temperature and the air mixing ratio.

The parameterised models are then used in the synthesis of control design procedure. The key idea is to divide the available heating power to (hourly) sub-steps in order to limit the defined (hourly) RH change rate. An iterative procedure is based on sensitivity analysis considering simplifying assumptions under which the whole response is composed of superposition of the responses to the heating power sub-steps distributed in time. In order to validate the assumption, a higher order dynamical model was also proposed and parametrized, where the heat dynamics in the wall was modelled by the heat second order partial differential equation solved by the finite difference method. Next to determining the magnitude of the heating power sub-steps, a method to determine the heating time to achieve the target temperature was proposed.

The control method is then applied and successfully validated on the models of the three churches. It is shown that the RH (hourly) change rate can be well 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 staircase power increase is relatively small. Concerning the practical implementation, the heating power can be controlled manually when the operating personnel increases the power at given time instants (e.g. every hour) based on tabularized values. Alternatively, the whole algorithm can be well automated and implemented using a smart switch or a low-cost controller (e.g. Raspberry-Pi).

Concerning the future research step, the validation of the control procedure in one of the test churches is planned. From the practical point of view, the procedure could also be simplified by determining the unified magnitude of the safe heating power sub-step, which could then be used in the cost of slightly longer heat-up time. An alternative to the step-wise signal could also be a ramp or other continuous signal, suitable if the heating start-up is automated. Besides, note that the presented model is only valid for the heat-up period of an event but not the cooling part. A next step would be to find a complete dynamic model that uses the parameters from the step response test. Another research direction is in design and analysis of feedback control approach, e.g. by applying model predictive control. In this case however, considerably more powerful (and more expensive) control unit would need to be used for the control method implementation.

5 Validation and analysis of adaptive ventilation method

The primary objective of this chapter is to conclude if adaptive ventilation (AV) is an efficient alternative to other climate control measures for lowering relative humidity in order to prevent mould growth. For this analysis an adaptive ventilation system is to be designed and tested on real case studies in situ to find the practical and theoretical obstacles of the approach. The control methods must be evaluated and refined. Note that this section is an extension of systematic work presented in [3], [4], [5] and [6] where the doctoral candidate is either main author or a key co-author. The chapter is organized as follows. Section 5.1-5.2 describes the development of a system for adaptive ventilation and section 5.3 addresses a first case study in an old farm house and 5.4 a case study in Hangvar church. Section 5.5 contains discussion and conclusions.

5.1 Introduction

Many historic buildings that are unheated or unheated between usages have problems with high humidity levels which lead to increased risk for mould growth. Climate control in between the heating events to lower the relative humidity is necessary to preserve the building as well as the interiors. Adaptive ventilation is a potentially low-energy and low impact option but needs to be validated and developed. The main questions are if it actually work to limit the risk for mould growth, and how the stability in relative humidity is affected, if the control methods are optimized for its purpose.

In some congregations the tradition has been to "let the spring in to the church" i.e. to open the doors wide open to get warmness into the winter cold building. Sometimes it worked but sometimes the church got wet due to condensation of warm and humid air on the still cold masonry walls. Ventilation by opening doors and windows is the traditional way of controlling the intake of outside air, but as the example above shows, it is difficult for a person to decide when the climatic conditions are favourable for improving the indoor climate and when it will have the opposite effect. Therefore humidity controlled mechanical ventilation is required either to inject outside air into the building or exhaust air from the building [4].

The idea with adaptive ventilation is to lower the level of moisture content in the inside air using the outside air by taking advantage of the natural diurnal and seasonal variations in the outside humidity. The outdoor air is taken in only when the moisture content is lower than indoors [4]. The best drying effect is achieved if the building is air tight because as important it is to ventilate when it is dryer outdoors than indoors it is to close the building when it is more humid outdoors than indoors. In a leaky building the drying effect will be counteracted if humid air entering the house by natural air infiltration [3].

As air moisture content not is measurable, the adaptive ventilation control system must calculate air moisture content both indoors and outdoors from the measurable quantities temperature and relative humidity. As can be seen in Figure 5.1, the fan is then controlled by a relay (on/off control) based on the value of control error

$$e = F_a - F_{out} - d \quad (84)$$

Where F_a and F_{out} is any of the quantities; absolute humidity AH, mixing ratio x or water vapour partial pressure p_w calculated from temperature and relative humidity. d is a bias for safety margin. Psychrometrics formulas in Appendix 1.

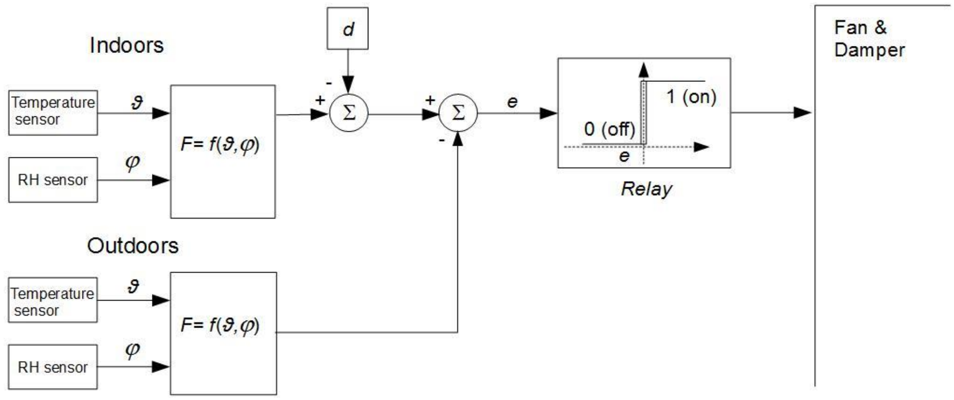

Figure 5.1 Principle of adaptive ventilation

5.2 Instrumentation

An adaptive ventilation control system can be designed on different levels. A low cost system can be designed with a small single-board computer like Rasberry Pi[2] or Arduino[3], equipped with an IO-module connected to a relay for control of the fan. Sensors to such system are preferably a system on chip solution i.e. pre-calibrated integrated relative humidity and temperature sensors on one chip. These sensor types have instrumentation amplifiers and A/D conversion embedded in the chip and the data is transmitted via I2C[4] bus interface to the single board computer. This type of sensors have become more and more used in this type of applications as they don’t require instrumentation amplifiers nor expensive calibration after manufacturing and assembly. For the outdoor sensor it is important to use a filter cap to prevent the senor from salt and other airborne pollutions. In addition to the hardware also housing for the single-board computer and sensors is required, together with power modules to the hardware and finally some cabling between computer and sensors. The hardware of the whole system can be purchased for approximately 100-150 Euros, but it requires some skills

[2] www.raspberrypi.org

[3] www.arduino.cc

[4] www.i2c-bus.org

in electronics and software development before it will run. Manufacturing such system in large series would of course result in decreased prices.

A perhaps more professional alternative is to integrate the adaptive ventilation system in a commercial of-the-shelf building automation system. The sensors must then be adapted for industrial interface which means that the sensors have embedded instrument amplifiers with industry standard 0-10 V or 4-20 mA analogue interfaces to connect to the automation system. There are combined sensor units with temperature and relative humidity as well as pure temperature and relative humidity units. The building automation system choice is of course more reliable and sensors and installation material can be purchased classified for outdoor use. Further, a building automation system has often possibilities to store data and is also more user friendly to program. The cost is on the other hand much higher. Up to 10 times higher compared with the first solution, but then the number of hours of engineering work becomes lesser. Still it is a low cost measure compared to the other common climate control measures.

In order to better understand how the adaptive ventilation is working practically and how it should be designed within a control system, the latter high end type was developed. The AV controller was developed in LabVIEW on a PC with an NI Compact DAQ I/O chassis with modules for 0-10 V analogue automation signals, PT100 sensors, digital input with edge detection and relay output. The Compact DAQ was connected via USB to the PC. The Compact DAQ was mounted in a cabinet together with two power supplies, one for measurements and one for control in order to minimize the effect of disturbances. The outdoor sensor was a Vaisala Humicap for temperature and relative humidity connected to a HMT100 Transmitter. Between the transmitter and the LabVIEW CDAQ unit, two 0-10V analogue signal wires were connected. Indoors temperature and relative unit was measured with a Testo 6621 A01C01 with display. Also this unit was connected to the LabVIEW CDAQ unit with two 0-10V analogue signal wires. Four PT100 temperature sensors adapted for surface mounting were also connected to the LabWIEW CDAQ unit, only for the surface temperature measurements. The LabVIEW software saved data on the laptop hard drive with 10 minute sampling.

For control of the fan a relay was connected to the NI Compact NAQ relay output modules. See Figure 5.3.

Figure 5.2 The cabinet with control equipment.

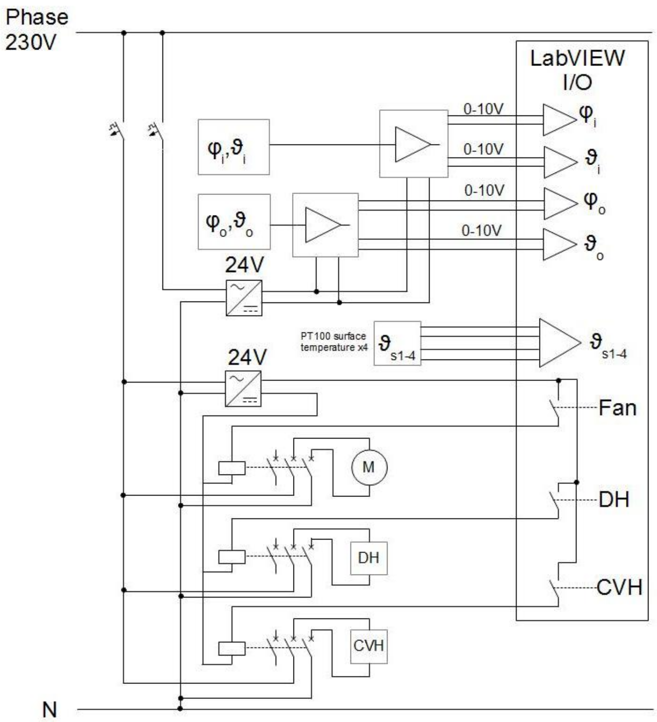

Figure 5.3 Scheme of the electrical peripheral components required to the control system.

The controller software was developed in the graphical environment from LabVIEV. See figure 5.4. The software compared indoor AH with outdoor AH which was calculated from the respective temperature and relative humidity sensors. A hysteresis of 0.1 g/m^3 was also implemented within the relay based controller. Additionally to the adaptive ventilation, optional controller functions were implemented that started a heater if the indoor temperature was below 5°C and switched on a dehumidifier, if the indoor relative humidity increased to values over 75% RH. After development and programming, the control system was tested in situ in a small building to validate that the control system worked. To validate the adaptive ventilation controller, humidity tests were carried out by buckets of water were poured on the floor in the building at the same time as the system was running and comparative measurements were carried out. The result showed that the adaptive ventilation control was running according to the requirements. Other things that had to be tested were how the system worked at power break-down and also test of the remote control i.e. the ability to operate the PC on remote. The remote control possibilities were solved by using the software LogMeIn. Internet was established by a radio router connected to the PC. The conclusion for the design was that the control system worked as required and was ready to be tested in real case studies.

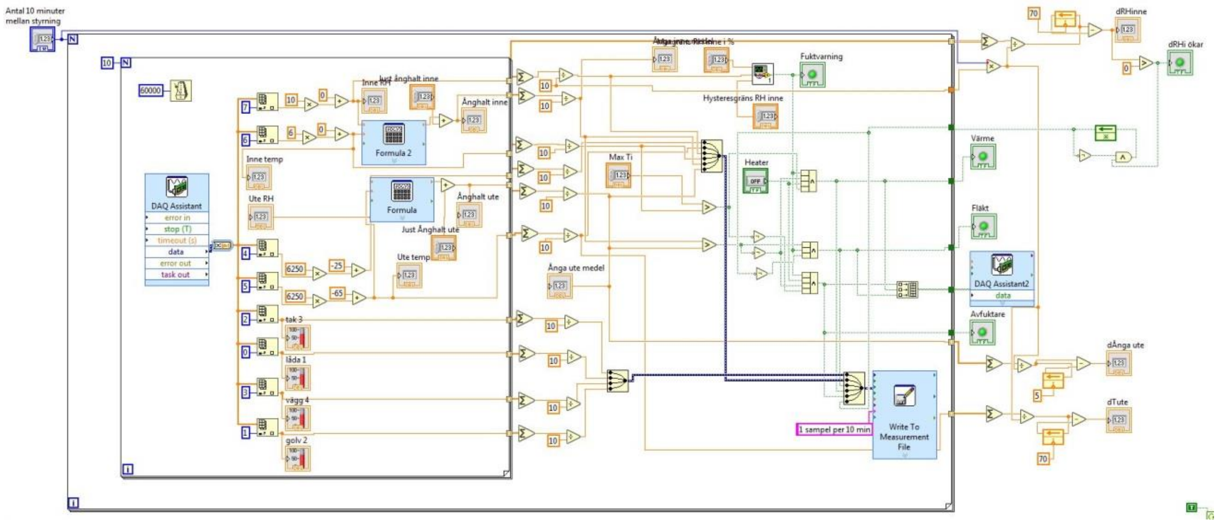

Figure 5.4 The LabVIEV software scheme for the control system

5.3 Case study I - Klints old farm house

A case study in the first floor of an old split level farmhouse was carried out to evaluate the assembled adaptive ventilation control unit. As the split level house is partly located under ground level, the building is very humid. In order to validate only adaptive ventilation, this case study had no auxiliary climate control measures installed. The building used in the case study is located on the northern part of Gotland, Sweden. The house was built in the early part of the 18th century. It is of a lime stone construction with at least 60 cm thick walls. The walls are covered with lime plaster both inside and outside, with the exception of the western façade, which has no plaster on the outside. The windows are single glazed. The building was naturally ventilated, mainly through fireplaces. Note that the building went through an extensive restoration in the 1990's after having been neglected for decades. After the restoration, the building was left unused and without any climate control. In the bottom floor of the southern part of the building, see Figure 5.5 right, severe moisture problems were noticed only years after the restoration. Furniture and wooden floors show signs of wood worms and there are algae growing on the walls.

In the case study, an exhaust fan was placed in one of the fireplaces in the building, se Fig 5.5 left. Inlet air was mainly through leakage as the flue pipes of other fireplaces were sealed. See figure 5.7. Except for the one-way damper on the fan, no controlled dampers were used. The indoor sensors where located in the same room as the extraction fan and the outdoor sensors where located in a solar radiation shield just outside the building's wall. See figure 5.6.

Figure 5.5 Left - the exhaust fan mounted in a wooden board used for sealing. Rigth - the investigation was carried out in the bottom floor of the left (southern) lower part of the split-levelled building.

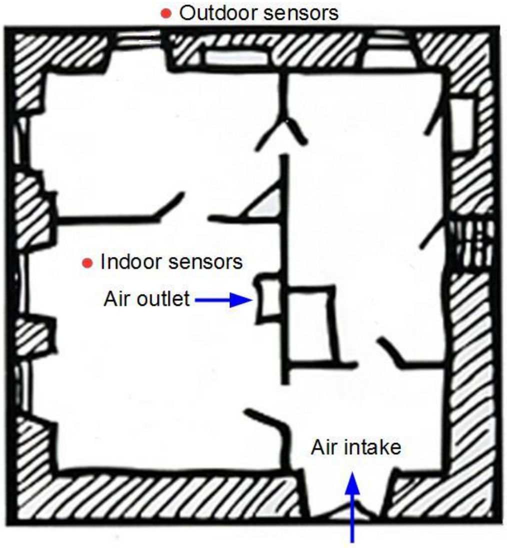

Figure 5.6 Plan over the farmhouse with indication of sensor and actuators positioning

5.3.1 Results and data analysis

The temperature and RH were monitored with 30 min sampling time during a whole year. Figure 5.7 shows the measured values of temperature and RH both inside the building and in the outdoor air. A statistical summary is given in Table 5.1. The energy consumption of the fan during the test year was less than 200 kWh. Air exchange was measured using a passive tracer gas technique according to NORDTEST Standard VVS118. Four measurements at different seasons gave a range of 2.3 to 3.1 air exchanges per hour.

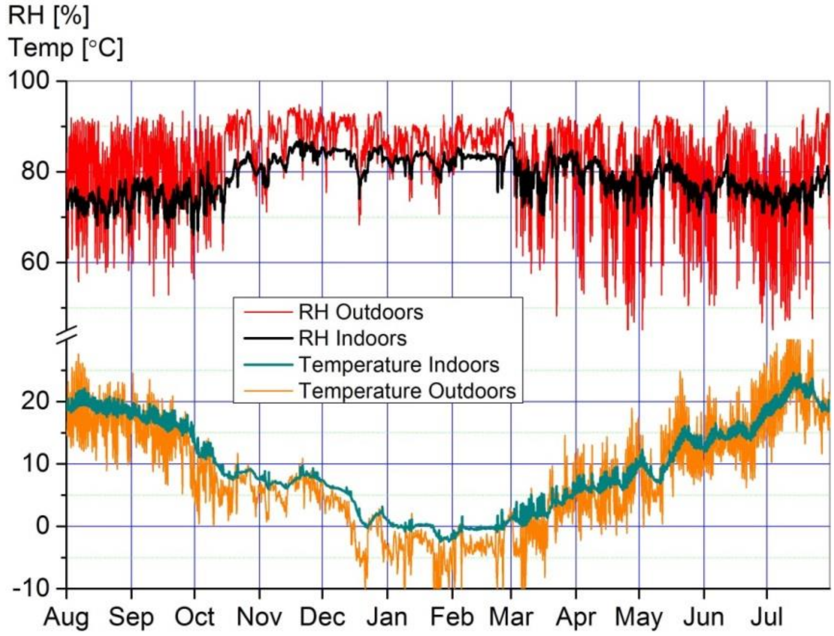

Figure 5.7 Temperature and RH in the outdoor air and in the ventilated space.

Table 5.1 A statistical summary of the indoor and outdoor climate for one year based on 30 min sampling.

	Average	**Std dev**	**Max**	**Min**
RH indoors (%)	79	4.2	87	66
RH outdoors(%)	82	9.1	95	40
T indoors (°C)	9.5	7.2	25	-2.5
T outdoors (°C)	7.5	8.6	33	-16
AH indoors (g/m^3)	7.7	3.2	17	3.1
AH outdoors (g/m^3)	7.2	3.6	20	1.0

The driving force of adaptive ventilation is the difference in indoor and outdoor AH. In order to show the long term variations, a moving 30 day average was calculated for the difference in AH, shown in Figure 5.8. The measurements range from -0.5 to 1.1(gm^{-3}) , with an average of 0.4 1(gm^{-3}). This clearly indicates that there is an inside moisture source in the building. Most likely this is due to water evaporating from the building foundations and from the walls that are in contact with the foundations or are wetted by rain. Even though the long term differences are quite small, a closer look at the diurnal variations shown in Figure 5.8 gives a different picture. By taking the advantage of the diurnal variation in AH, a drying effect can be achieved even during periods when the outside climate on an average is more humid. Continuous ventilation would, in average, reduce the AH during most of the year. However, results in Figure 5.8 clearly show the greater drying potential of AV active measure.

Figure 5.9 - Left shows a duration graph of the difference between the indoor and outdoor AH. Around 30% of the time, ventilation would actually increase the amount of moisture in the room instead of drying it. The adaptive ventilation switches off the ventilation system during these periods. The average of the positive component is 0.99 and for the negative component -0.85.

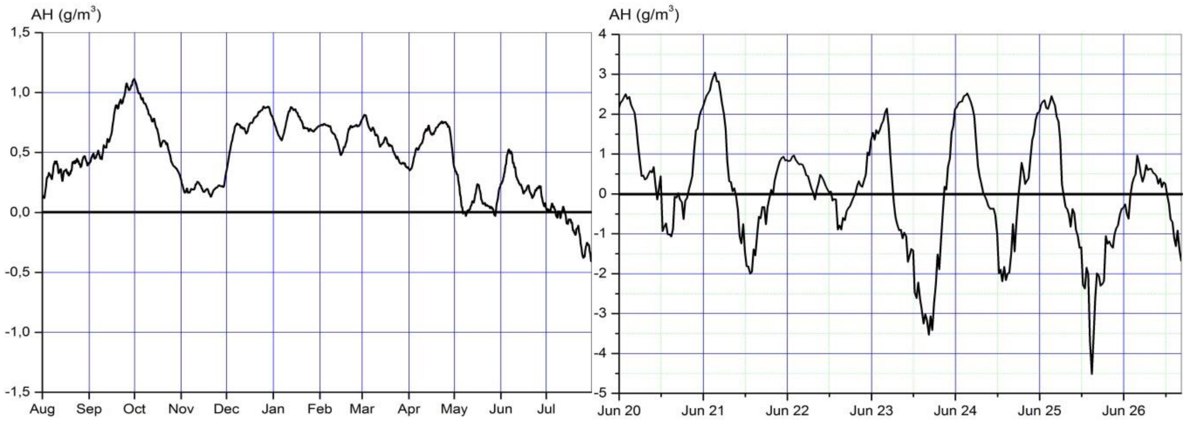

Figure 5.8 Measured difference between indoor and outdoor humidity by volume. Left - Moving 30 days average of AH indoors –AH outdoors. Right - AH indoors – AH outdoors one week in June.

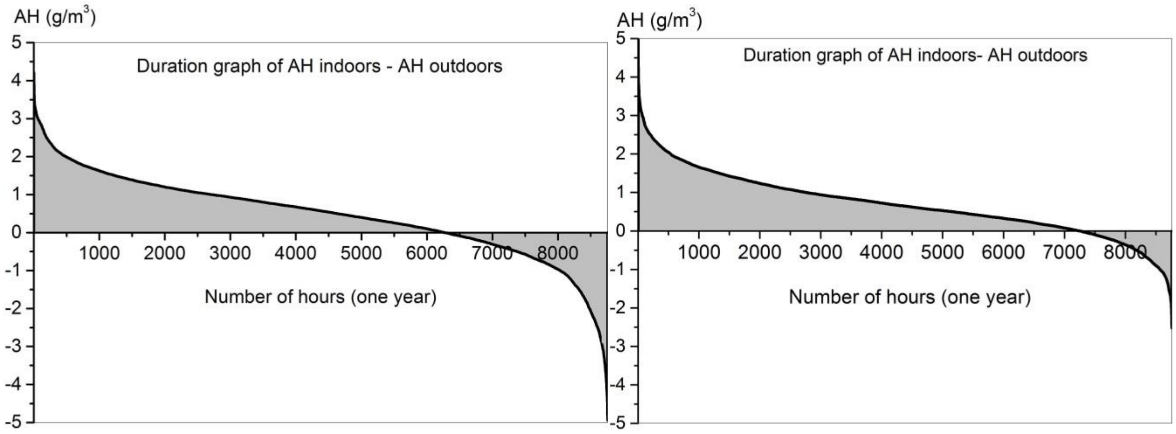

Figure 5.9 Duration graph for the difference in AH based on measurements. Left – with adaptive ventilation. Right – with conservation heating. Sampling time 30 minutes.

Figure 5.9, right, shows a duration graph for the same building in 2008 - 2009 when conservation heating and natural ventilation was used. In this case, the average difference in AH is more than two times higher than with AV.

Based on the ventilation air flow and the actual difference in mixing ratio an approximation of the amount of removed water from the building can be calculated by

$$RW = \int_0^{T_p} \Big(\big(x_a(t) - x_{out}(t) \big) Q_a(t) \rho_a \Big) \, dt, \qquad (85)$$

where $Q_a(t)$ is the air flow of the fan when it's running and ρ_a is the average density of the indoor air. During the year of the case study some 1600 kg of water was removed from the building. The duration graph, Figure 5.9 - left, shows that performance can be improved by enhancing ventilation for the positive part and improving air tightness to reduce the effect of the negative part of the curve. Even for an unheated building, ventilation has a dominant effect on the heat balance. In a typical diurnal cycle the temperature will be lower outside when the AH is higher inside and the fan is running, see Figure 5.10. This means that the ventilation has a cooling effect that would tend to increase RH, even though moisture at the same time is removed from the building.

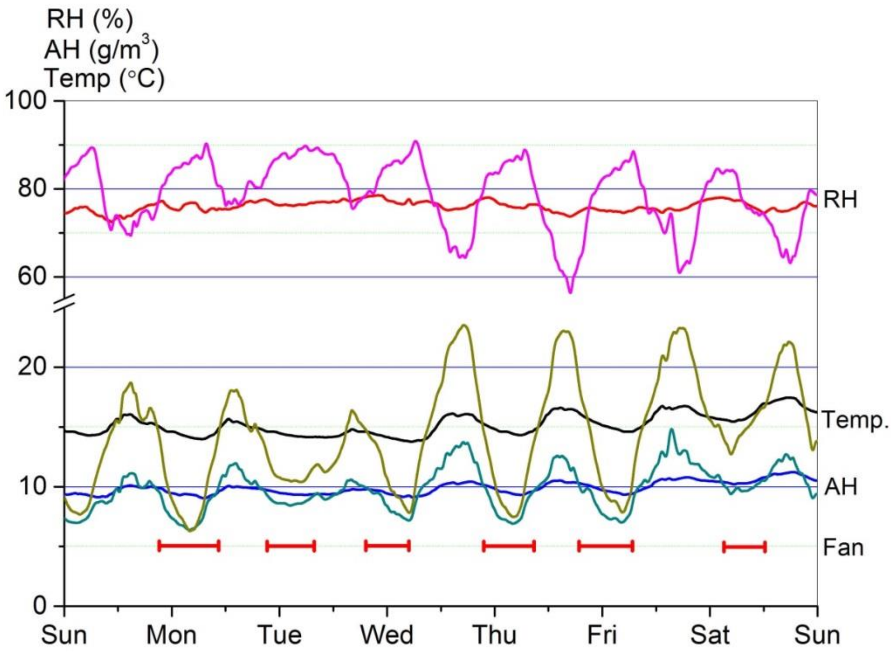

Figure 5.10 RH, AH and temperature indoors and outdoors for one week in June. Indoor variations are small in relation to outdoors. The lowest line indicates when the fan was in operation

With increased ventilation indoor RH would approach the outdoor value. This is a complex phenomenon, involving the thermal inertia of the building in relation to diurnal variations of temperature as well as the long term effects on the moisture balance and RH inside. Further investigations will aim to investigate if and how control can be improved with respect to this effect. The RH in the building shows no obvious long term trend after ventilation was introduced, see Fig 5.10. Looking closer at the daily cycles, there is no distinct pattern that shows a short term effect on RH indoors. Gathering from experience with an adaptive ventilation in attics, [64] and other historic buildings, one would expect a relatively small, but significant, change in RH. Thus long term effects on the moisture balance of the building may have to be evaluated over several years.

Consequently, the influence of RH on mould risk is assessed based on a method used by Broström, Hagentoft & Wessberg in [3]. As a measure of the mould risk, a mould risk potential has been defined, which is RH divided by the critical RH i.e. the LIM I, Lowest isopleth for mould growth to start according to Sedlebauer at the actual temperature [34]. Theoretically, mould growth is possible only when $RH/RH_{LIM\,I} > 1$, but as also time is important for mould to start to growth, the mould risk potential must be larger than one for some consecutive time (days) before mould starts to grow. However, number of hours when $RH/RH_{LIM\,I} > 1$ allows us to evaluate risk for mould growth and mould control measures. The mould risk potential for the case study is shown in figure 5.11 - Left. The mould growth potential stays below one for most of the year except for short periods. Here heating or dehumidification would be needed to further reduce mould risk. In order to keep $RH/RH_{LIM\,I}$ below 1, auxiliary climate control would be needed for duration of around 1400

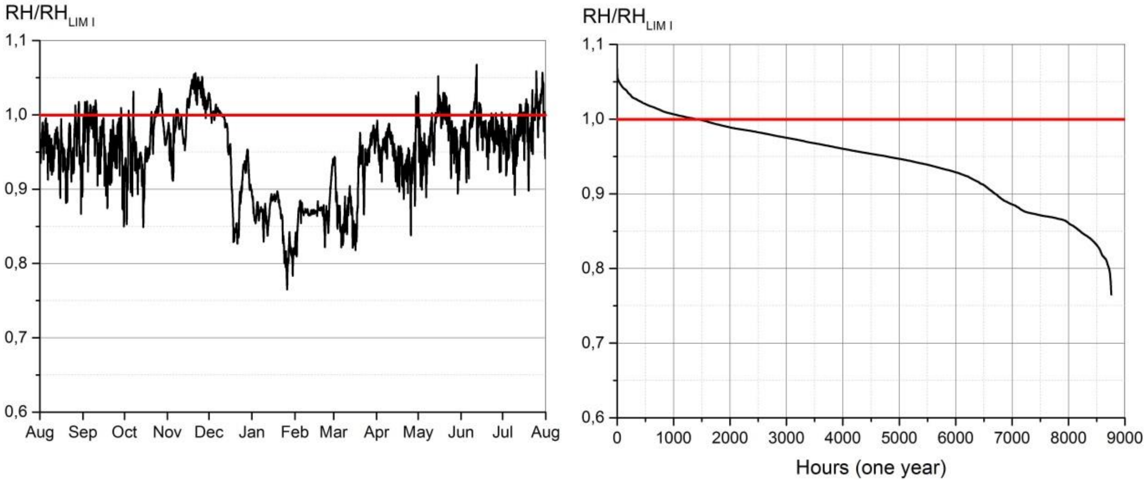

Figure 5.11 Left - mould risk during the test period. Right - mould risk represented as a duration graph

hours, see figure 5.11 - Right. As single periods shorter than 24 hours with mould potential larger than one still are considered safe, a deeper analysis shows that it was only nine occasions where the duration of the risky event ($RH/RH_{LIM\ I} > 1$) was longer than 24 hours. If an auxiliary climate control would run only those nine occasions the number of hours was reduced to 907. The longest period of dangerous mould risk potential was 328 hours which is too long to be accepted.

In Section 1.1.3, the European standard EN15757 [23] was presented. The standard specifies allowable fluctuations in RH based on historic climateand gives a method to examine, quantify and compare RH fluctuations during a given time period with another time period. A fluctuation from the seasonal cycle is considered outside the safe range when the magnitude is more than 1,5 of standard deviation. Deviations of less than ±10% RH are considered safe. By definition, adaptive ventilation should enhance short term variations in the indoor climate. In this case, both short term and long term variations are moderate or even small in relation to comparable buildings. Even though the building is actively ventilated during most of the year, the indoor climate is still much more stable than the outdoor climate both in the short and long term, see Fig 5.7 and Table 5.1. The calculated range is ±3,3% RH, which is much less than the minimum level of ±10% RH suggested in the standard [23]. Thus according to the EN15757 standard, the variations in RH are acceptable. If necessary, one could easily add a secondary control condition in order to reduce short term variations in relation to the seasonal cycle. A control method based on the standard EN 1575 is presented in [9].

5.4 Case study II - Hangvar church

From the previous case study in Klints farmhouse it was apparent that when the outdoor air is dryer then the indoor air it´s also cooler than the indoor air. Cool air is counterproductive when it comes to lowering the relative humidity and thus the effect on relative humidity inside a building is limited. In the short term, this means that the ventilation has a cooling effect, which would tend to increase RH, even though moisture at the same time is removed from the building. This situation occurs when the climate conditions $x_{out} < x_a$ and $\varphi_{out} > \varphi_a$ are fulfilled. The obvious mitigation measure is to heat the inlet air a few degrees up which will decrease RH and the mould risk will fall down. But heating the inlet air is energy consuming so the new concept applied in the Hangvar case study was to let the inlet air be slightly heated with energy produced by solar panels placed just outside the churchyard's wall.

The concept operates as follows:

1. In the day time, solar energy is collected and stored.
2. At night, when the outside air generally is drier but also cooler, the inlet air is preheated using the stored energy.

The system can either be electric (photovoltaic) or thermal depending on costs and practical aspects. In this study, considering the installations and other practical aspects, an electric system was used. Solar energy was seen as a sustainable solution both in terms of resource use and economy, also by the parish. But of course preheating can also be achieved by conventional means.

Hangvar church is a 13th century stone church situated on the North West part on the island of Gotland, Sweden. The construction is typical for Gotland churches with outer walls and vaults made of lime stone in lime mortar and a roof construction of wood with tiles. The volume of the nave and chancel in total is 1000 m^3. The church is used only approximately 10 times per year, mostly for funerals and weddings. The church is intermittently heated for services and unheated in between. The church has been very humid. During springtime there was condensation on the walls and floors. In the winter, the indoor temperature can go below zero degrees centigrade and in July it can go up to 20 degrees, but often it doesn't go higher than 18 degrees. The members of the parish have complained about bad smell and there had been visual growth of algae and mould in corners and on the northern wall. Many tourists visit the church during summer and the church door has often been left open in the day time.

In order to improve the indoorclimate conditions, the adaptive ventilation system was installed in the church. A vent pipe was installed from an opening in the tower staircase to the fan and then through a new temporary tower door with built-in exhaust. See figure 5.12. and 5.13. The leaving air went out through leaks in the building envelope and the doors.

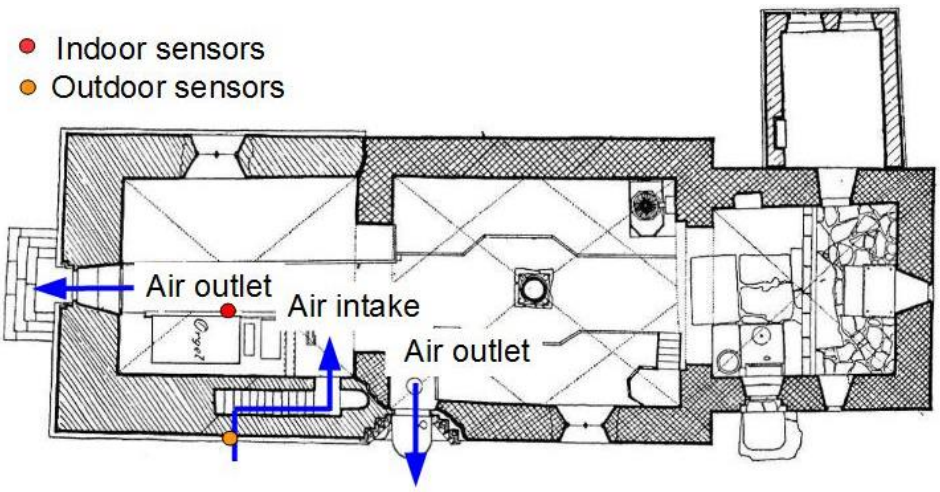

Figure 5.12 Floor plan over Hangvar church with indication of sensor and actuator position

5.4.1 System

The fan had a capacity of 500 m^3 per hour. The indoor sensors for relative humidity and temperature where located in the rear part of the church. The outdoor sensor was located close to the air intake, in an opening in the church wall. The control unit was improved and programmed to compare indoor and outdoor water vapour partial pressure and with a ratio instead of a difference. The fan was thus running if the ratio between indoor water vapour partial pressure were larger than 1.05. A hysteresis of 0.05 was also implemented.

$$F_{p_w}\left(\frac{p_{wa}}{p_{wout}}\right) = \begin{cases} 1, \text{if } \frac{p_{wa}}{p_{wout}} > 1.05 \\ 0, \text{if } \frac{p_{wa}}{p_{wout}} < 1.05 \end{cases} \tag{86}$$

The control system had no other limits for the inside RH, but there was a lower limit of -10 ˚C for the outside air temperature i.e. if the outdoor temperature was lower than -10 ˚C the fan stopped. In the inlet air duct there were two electric heaters with a total power of 1800 W. At the given air flow when the two heaters were on it gave a temperature increase $\Delta\vartheta$ of the inlet air of 11 ˚C.

Figure 5.13 Left - the air intake and outdoor sensor. Middle - the fan and the flexible air duct. Right - the new temporary tower door.

The case study was designed for 25 m^2 of photovoltaic elements but due to costs and the fact that this set up was experimental, only 5 m^2 were installed. Therefore the amount of produced energy was multiplied by 5 in the control system. The photovoltaic elements were placed outside the church yard in order to avoid a discussion on the visual impact of roof placement, see figure 5.15. In this case, the electric grid was used to store the energy, rather than a local storage. A commercial off the shelf DC to AC converter was connected between the photovoltaic panels and the grid via an energy meter which in turn was connected to the control system. See Figure 5.14.

The heaters were controlled by a control system developed in the LabVIEW environment on a PC with an NI Compact DAQ I/O chassis with modules for PT100 temperature sensors, digital input with edge detection and relay output. The Compact DAQ chassis was connected via USB to the PC. The energy meter that measures the produced solar energy sends 1000 pulses per kWh and the edge sensing LabVIEW module detected and countered pulses from the energy meter (a 50 m long cable was dug down at the church yard about a decimetre into the ground for that purpose). The system software could thus keep records of both produced energy by the voltaic panels as well as the energy consumed when the heaters was set on by the system. Consumed energy was not measured but calculated by in real-time by the system. The total amount of stored energy produced by the photovoltaic elements could therefore be compared with the total amount of consumed energy by the heaters.

A signal, *AV running*, indicating when the fan was running was connected to a digital input on the control system shown in Figure 5.14. The heater was set on only if this signal indicated and the energy difference between produced energy and consumed energy was larger than zero. That way the heaters were only consuming stored energy produced from the voltaic panels. A problem which occurred was in the frequent power cuts of the grid as LabVIEW lost its memory when the PC went down. The solution was that the LabVIEW software stored all data on the PC's secondary memory i.e. the HD every 10^{th} minutes and before new calculation, the software read back the last saved data.

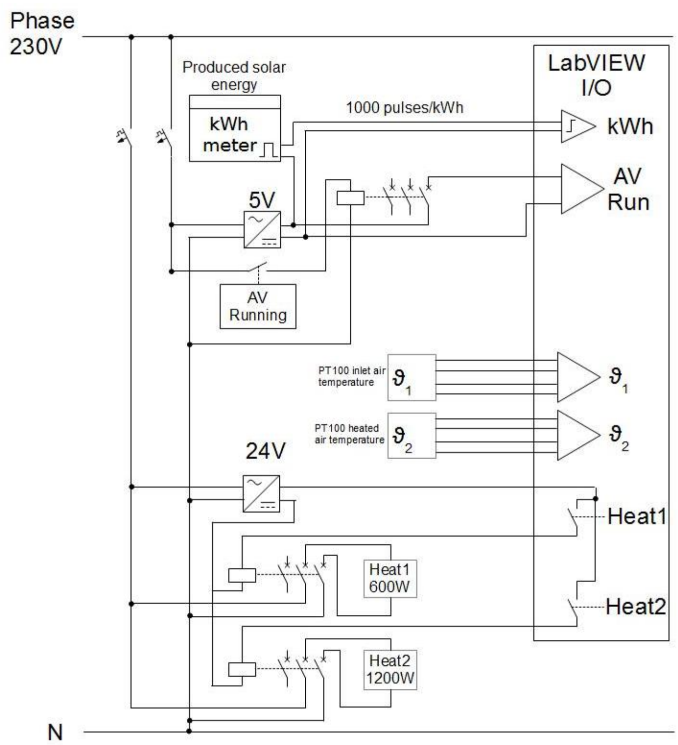

Figure 5.14 Electrical Schematics over the peripherals circuits for the heating system.

Figure 5.15 Hangvar church with the photo voltaic elements place outside the church fence.

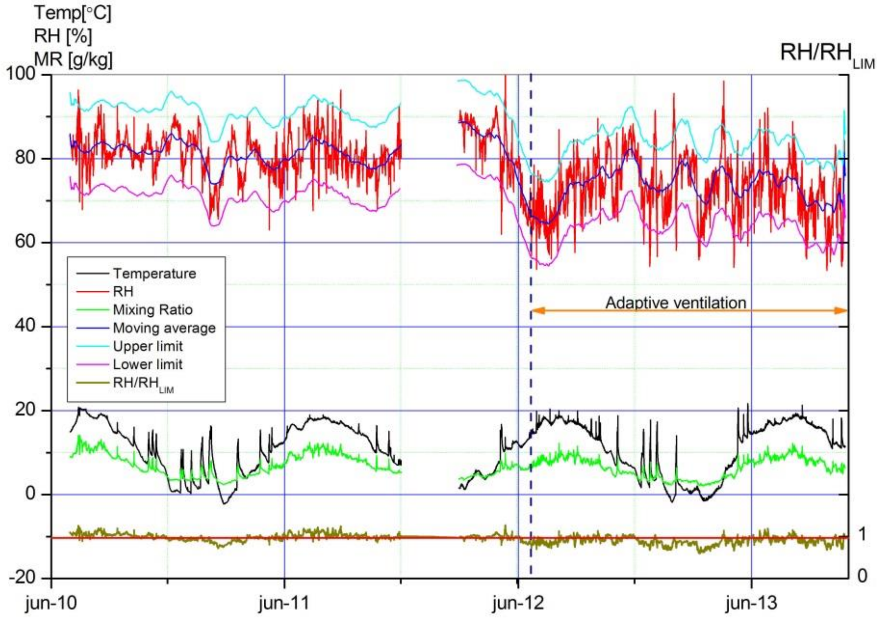

Figure 5.16 Indoor climate in Hangvar church. The graph shows that during the period with adaptive ventilation the relative humidity in average has decreased but the variations have increased

Table 5.2 Statistics for the two periods

Period	Average Temperature	Average RH	Average MR	Standard deviation of short term fluctuations SD30
Without climate control	9,6	81	6,5	**3,5**
Adaptive ventilation	**9,3**	**75**	**5,9**	**5,2**

5.4.2 Results and analysis

From July 2010 to June 2012 there was no climate control in the church except for the intermittent heating periods for services. Solar augmented adaptive ventilation was installed in July 2012. There was no climate monitoring between December 2011 and March 2012. Figure 5.16 shows indoor climate over three years. It can be seen that the average relative humidity has decreased after the introduction of adaptive ventilation but the short term variations have increased.

Table 5.2 shows a statistical comparison between the time period without any climate control, September 2010 to August 2011 and the time period with adaptive ventilation September 2012 to August 2013. The comparison shows that average relative humidity has decreased from 81 to 76 %. The average temperature is approximately the same in the two periods, only 0.2 degrees of difference. The short term variations in RH are important from a conservation point of view. Deviations of less than ±10% RH are considered safe. Figure 5.16 shows that when using adaptive ventilation there are more short term excursions outside the target range, which can be considered as negative feature increasing risk of mechanical damage of wooden objects. The standard deviation, in relation to the moving average increased from 3.5% to 5.2%.

Measurements of the church air tightness were carried out in August 2013. Two different methods were used. The blower door test [89] showed a result of Q_{50} = 0.89 L/s/m^2 and the pressure pulse method [90] showed on a resulting equivalent leakage area at 4 Pa of 0.051 m^2. Both methods showed a result of Q_4 = 138 L/s which is on the same order of magnitude as adaptive ventilation. However this result is regarded as a relatively air tight church.

In the next step of the analysis, mould risk was assessed in relation to the isopleth curve LIM I for biologically recyclable building materials [34]. Figure 5.18 - Left shows the period without climate control and Figure 5.18 - Right the period with adaptive ventilation. It is clear that the risk for mould has decreased during the year with adaptive ventilation. The year without climate control, 44% of the overall time, the indoor climate was above the LIM. When the adaptive ventilation system was running only, 16.7% of the time the indoor climate was above the LIM. Thus, the adaptive ventilation improved the indoorclimate in this aspect.

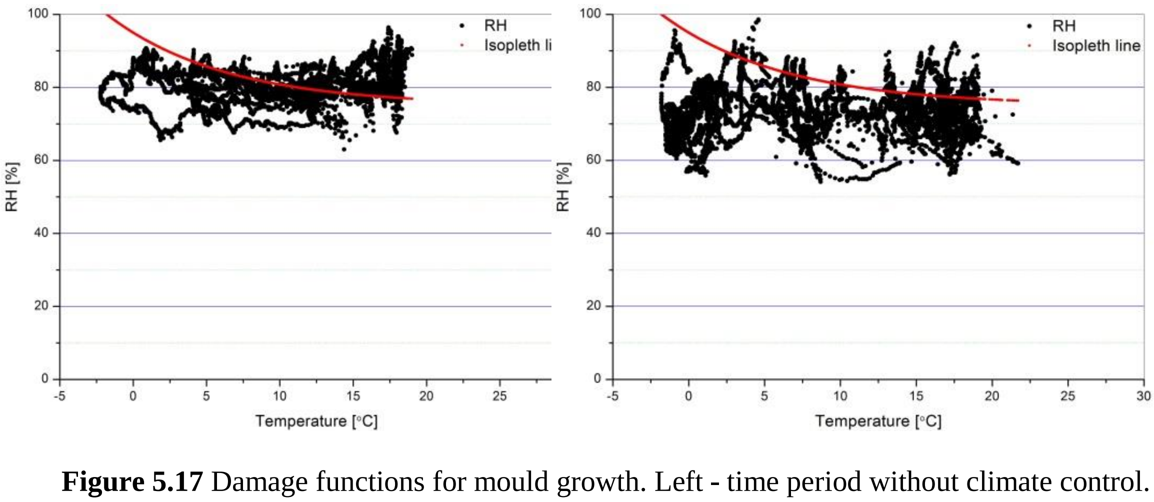

Figure 5.17 Damage functions for mould growth. Left - time period without climate control. Right - time period with adaptive ventilation.

Figure 5.18 then shows RH/RH_{LIM} where RH_{LIM} represents the RH values corresponding to lowest isopleth for mould that can be seen e.g. in Figure 5.17. If the value is above 1, the climate is beneficial for mould growth. The duration in the area above LIM is critical for mould growth. According to [34] RH/RH_{LIM} has to be above 1 for longer periods (days) for mould to grow. In the year without climate control the average duration length above LIM was 72 hours and the longest period was 826 hours. In the year with adaptive ventilation, the average was 32 hours and longest period 134 hours. In the latter case the extended periods were in the summer. Consequently, the overall duration graph in Figure 5.19 shows that even small changes in the RH levels have a significant impact on climate control requirements. The figure shows the duration graph for RH/RH_{LIM} for the year with adaptive ventilation (black) and the year without (red). If the requirement is decided to $RH/RH_{LIM} < 1$ the time of operation for a dehumidifier was 1450 hours in combination with adaptive ventilation while it was 3750 hours the year without climate control. The number of hours with mould risk where thus reduced with 2300 hours.

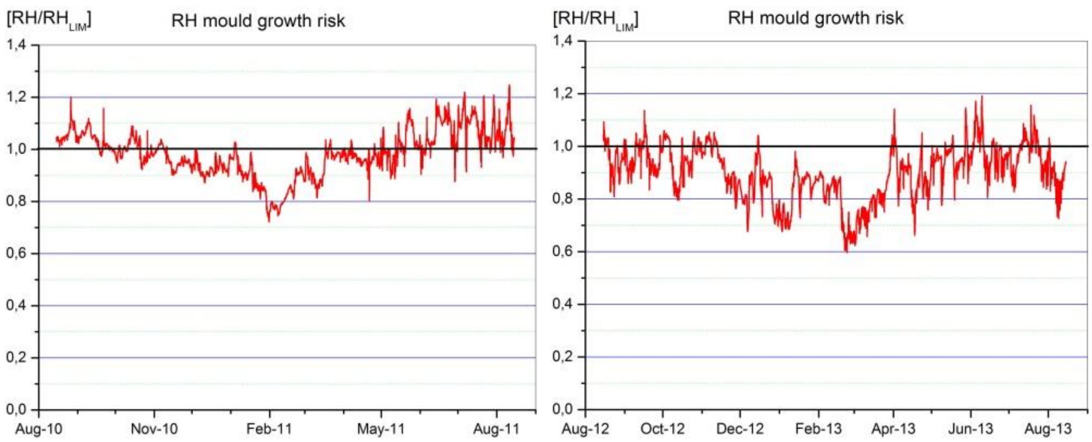

Figure 5.18 RH/RH_{LIM}. Left - time period without climate control. Right - time period with adaptive ventilation

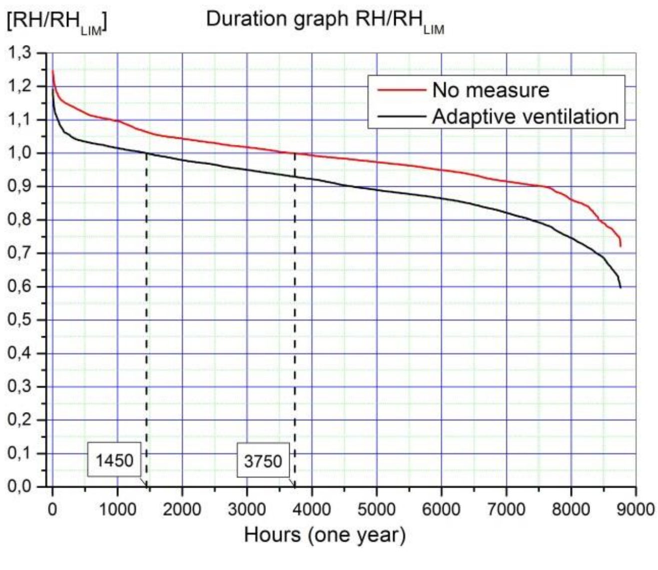

Figure 5.19 Duration graph of RH/RH_{LIM}

Based on the difference between mixing ratio indoors and outdoors every hour and the air flow, the total moisture transport during the test period is calculated with equation (85). From September 2012 to August 2013, 1100 kg of water was transported out of the church. The ventilator has consumed 250 kWh of electrical energy during the same period. This gives a drying efficiency of 4.4 kg water per kWh.

The inlet air heaters were used only when stored solar energy was available and the ventilator was running. In October, November, December and half of January the 25m^2 'nominal' photovoltaic panels did not produce enough energy for preheating the whole time when the ventilation was in operation. In the rest of the year the produced energy was larger than the amount of consumed energy. See Figure 5.20.

From September 2012 to August 2013, the 5m^2 photo voltaic panels have produced 645 kWh, thus the 'nominal' panels of 25m^2 would produce 5 × 645kWh = 3 225 kWh. The amount of energy used for the inlet air heaters was 2 066 kWh. When the fan was running at full speed the heaters gave a temperature difference of 11°C. When solar energy has been available, this has generally been sufficient to counteract or mitigate the cooling effect without causing any harmful temperature variations. In January 2013 there was no solar energy available. During one week, the adaptive ventilation ran without preheating and the indoor temperature decreased by 6 °C. At the same time the MR decreased, but RH was still around 65%.

Concerning the user perspective, the church has perceived an improvement in indoor air quality after installation of AV. 'Bad smell' is no longer a problem. The negative aspect is that the fan is too noisy to operate during services; it has been turned off manually at these occasions. Overall, the parish is positive towards this solution and wants to make it permanent.

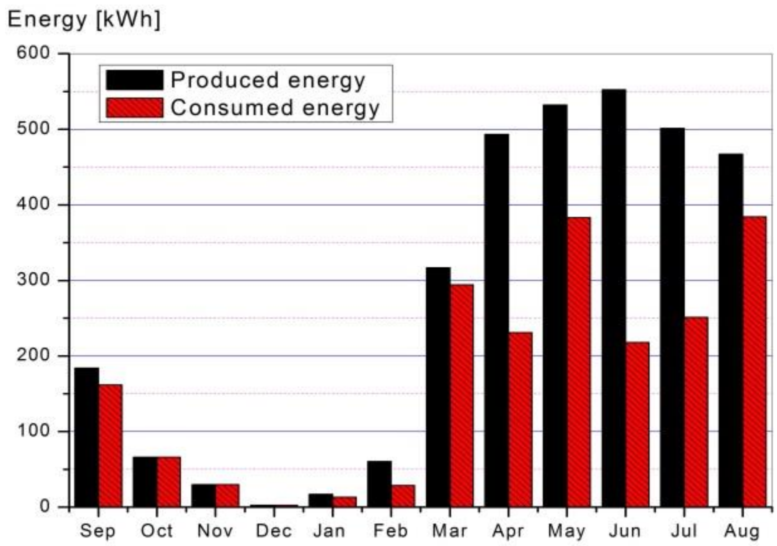

Figure 5.20 Monthly produced and consumed solar energy.

5.5 Conclusions on Adaptive Ventilation

In the two case studies, adaptive ventilation has had a significant drying effect removing some 1600 kg of water in Klints farmhouse and 1100 kg in Hangvar church in one year. The mould risk is kept at an acceptable level with exception of some periods. Concerning the RH fluctuations, AV considerably increased a number of events when the fluctuation peaks get above the $\pm 10\%$ RH with respect to the moving average proposed as save in the standard EN 15757. This can be considered as negative aspect, which however can easily be removed by adjusting the control algorithms.

The members of Hangvar parish have felt that the indoor air quality has improved, mainly in the elimination of bad smell. However, in these two case studies, adaptive ventilation is not sufficient to eliminate mould risk throughout the year; however it does significantly reduce the operational time and energy demand for auxiliary measures such as dehumidification or additional heating. The results presented in this paper are from one year of operation, over a longer time period the massive structure are expected to slowly become dryer thus reducing indoor RH levels.

Adaptive ventilation is a low-cost and low-energy option as compared to conventional humidity control. The annual energy consumption for the operation of the fan in Hangvar church was only 250 kWh. This gives an efficiency of 0.22 kWh/kg of exhausted water, which is about a tenth of energy per kg compared to conventional dehumidifiers. The preheating of the inlet air in Hangvar church has counteracted the cooling effect that was reported in the Klints study and other previous studies. However during one year, the contribution from the solar panels was 2000 kWh which is not economically viable unless the solar panels are subsidised. During the winter, the amount of energy produced by the solar panels wasn´t enough to heat the inlet air and then again on the summer the system use a fraction of the energy the solar panels produced.

Both case studies confirmed that adaptive ventilation is particularly useful when there are internal moisture sources in the building resulting in absolute humidity levels higher than outside. This situation is quite common in historic buildings due to evaporation of moisture from the floor or through the walls.

Generally, adaptive ventilation is best suited for unheated or occasionally heated buildings. For buildings with constant comfort or conservation heating, more elaborate control strategies are needed. A general problem with adaptive ventilation in historic buildings is achieving sufficient air tightness. The air tightness measurements in Hangvar church indicate that the air leakage maybe of the same order of magnitude as the fan air flow. In Klints farmhouse it was even larger. The effect of the ventilation can be improved by increased fan capacity and improving air tightness to reduce leakage when the fan is not in operation.

Given the complex interaction between the thermal inertia and the RH and T of the incoming air, control by water vapour partial pressure, rather than RH, has proven to be a robust method. Further research will investigate the effect of the hygrothermal inertia of the building, long term effects on the moisture balance, the potential for improving performance and the further integration of heating or dehumidification.

To sum up, based on the two case study experiments and the careful analysis, the pros and cons of the adaptive ventilation can be summarised as follows:

Positive aspects:

- low-cost and energy efficient method
- relatively non-invasive humidity mitigation measure
- improved indoor air quality
- reduction of indoor temperature in the hot periods, because it runs mainly during nights
- substantially reduction of mould risk in a sustainable way.

Negative aspects:

- increase of RH short time fluctuations which increases risk of mechanical damage
- operation is highly dependent on outdoor conditions
- decrease of indoor temperature in winter months
- alone it is not a sufficient measure to fully prevent mould risk

5.5.1 Overall recommendation on AV implementation and its enhancement

Adaptive ventilation is a useful measure to lower RH in unheated historic buildings and occasionally heated buildings, especially when there are internal moisture sources in the building as rising damp or humid walls due to precipitation. In the prevention of mould growth it will decrease the number of hours with mould risk but at some occasions per year the measure will not probably be sufficient. As it is mentioned in Section 5.5 the dehumidification capacity is depending of appropriate outdoor climate. To improve the technique, (and the indoor climate) the following actions can be considered.

During the cold period the outdoor air is mostly dry (in absolute terms) but there are often some occasions in October to December where the risk for mould growth increases i.e. $x_{out} < x_a$ but $\varphi_{out} > \varphi_a$ is fulfilled. That means the amount of water in the indoor air will decrease but the relative humidity will still increase. At those occasions the best measure is to combine adaptive ventilation with conservation heating i.e. to heat the in inlet air a few degrees to mitigate the decreased temperature that increase relative humidity. According to [49] it requires only a temperature increase of about 2-6 °C to mitigate the increased RH. As it was shown in Section 5.4.3 the energy consumption is low for that measure.

In the summer period the outdoor air contains more humidity and in May to September there are also some occasions when the outdoor climate is disadvantageous for adaptive ventilation. In that period a portable condensing dehumidifier with embedded water tank controlled by mould growth control is recommend. In that case the auxiliary dehumidifier will run only when the adaptive ventilation is unable to keep down the risk for mould growth.

A larger ventilating system will increase the dehumidification capacity but it will also increase the fluctuations in relative humidity. A larger system must thus be combined with a more advanced control system that not only on-off controls the fan on the difference in indoor outdoor air moister content but also on RH level and RH change rate. A speed control of the fan can be used. Also in this case conservation heating is useful to cut the fluctuations.

Finally it is very important to airtight the building. The positive effect of adaptive ventilation will effectively be counteracted by a leaky envelope.

6 Comparison of control methods with the emphasis on mould growth

One significant climatic related problem in massive historic buildings is high levels of relative humidity which in turn may cause mould growth. To mitigate these high humidity levels, conservation heating and dehumidification have been used with good results on the indoor climate. Additionally to these two, adaptive ventilation, which is analysed in the previous chapter, has emerged as an energy-efficient measure that could be a candidate for mould growth prevention. Studies on adaptive ventilation and dehumidification have been carried out before as outlined in the state of the art section. A new aspect of the presented analysis is cross-comparison of the methods with respect to mould prevention. The applied measures will be controlled in a way to mitigate mould growth while keeping the energy demands as low as possible. The objective of this section is thus to evaluate these three climate control measures for lowering RH in order to prevent mould growth in massive historic buildings, in terms of energy efficiency, mould prevention effectivity and stability. This requires a case study in a real massive historic building where the three climate control measures can fairly be compared and evaluated. This section is an extension of published paper [7] where the PhD candidate is the main author. This section includes also results presented in 'Deliverables' of the FP7 European project Climate for culture [111], [8] which were contributed by the PhD candidate .

The section is organized as follows. In section 6.1 - 6.4 mould growth control is presented. In section 6.2 and 6.3 simulations of mould growth control and traditionally humidity control is compared in terms of energy efficiency. Section 6.4 describes a case study in Fide church where mould growth control was implemented and tested. In section 6.5 a comparative study of three different climate control measures in Skokloster castle is described and discussed.

6.1 Mould growth climate control using isopleths

Traditionally when a climate control measure is installed to mitigate mould growth, the RH set-point is often set to a constant level 5-10% below 75%. This approach is however unnecessarily restrictive and will cause higher energy consumption than needed. By using a predictive criteria for mould growth a set-point strategy can be developed for climate control.

To assess the climate induced risk for mould growth in a building, Sedlebauer et al., has developed a predictive model [34] that describes mould fungus activity dependence of hygrothermal conditions allowing for the prediction of mould growth based on surface temperature and RH. The growth conditions for mould are nutrients, warmness and relative humidity, which must exist simultaneously for a certain period of time. The growth conditions are described in the so-called isopleth diagrams, as outlined in the state of the art section. These diagrams describe the germination times or growth rates, see Figure 6.1. Recall that the resulting lowest boundary line of possible fungus activity is called LIM (Lowest Isopleth for Mould). LIM I, which according to Sedlebauer is the lowest isopleth for mould on biological recyclable building materials, is shown in Figure 6.1 [34].

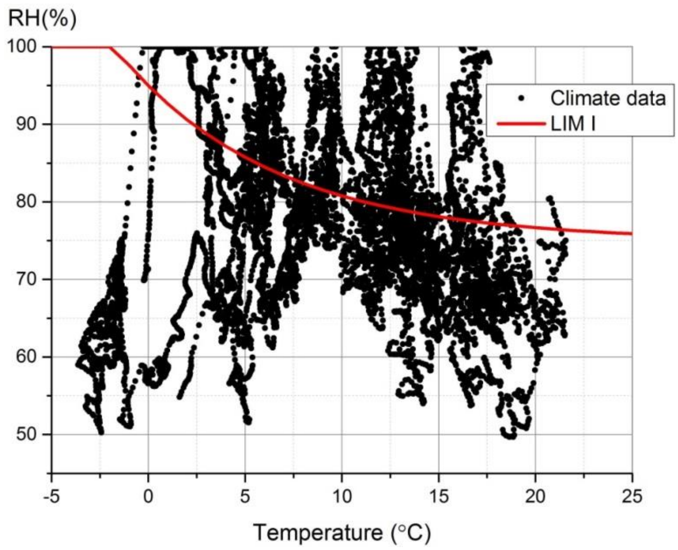

Figure 6.2 The red curve shows the Lowest Isopleth for Mould, LIM 1. Data from simulation of Hangvar church.

The LIM I curve in Figure 6.1 can be approximated by the following exponential function

$$\varphi(\vartheta) = f_{\varphi}(\vartheta) = 75 + 20\mathrm{e}^{-0.1241\vartheta}. \quad (87)$$

All the temperature and RH $[\vartheta, \varphi]$ combinations in Figure. 4.1 positioned below the LIM boundary red line, are considered safe with regard to the mould growth. However, the isopleth is based on empirical research and the damage risk cannot be determined exactly in absolute numbers. Further, when working with microclimate in historic buildings, microclimate can vary within a room. For example, if the climate is measured in the middle of a room the temperature can be a few degrees higher or lower on the walls, ceiling and floors which affect the relative humidity in those spots. If the LIM I isopleth is used as set point for climate control, it requires a safety margin to be sure to avoid damage within the whole interior.

One possible mitigation measure against mould growth is dehumidification. The control objective is to keep the microclimate conditions in the safe region of Fig. 6.1. This can be achieved by adjusting the set-point value of the dehumidifier φ_{set} based on the current (measured) temperature ϑ_m as follows

$$\varphi_{set}(\vartheta_m) = f_{\varphi}(\vartheta_m) = 75 + 20\mathrm{e}^{-0.1241\vartheta_m} - d, \quad (88)$$

where d is a bias, $d > 0$, which should guarantee that the humidity stays safely below the line given in Fig. 6.1. The overall control scheme implementing the given control objective is shown in Fig. 6.2. As can be seen, the dehumidifier is controlled by a relay (on/off control) based on the current value of control error

$$e = \varphi_{set}(\vartheta_m) - \varphi_m, \quad (89)$$

where $\varphi_{set}(\vartheta_m)$ is given by (83) and φ_m is actual value of the measured relative humidity. In assessing the parameter d one needs to consider the hysteresis of the relay h (usually 1-5%

RH), such that $d \geq h$. The temperature measurement readings could be filtered by a low pass-filter (e.g. Butterworth 2nd order filter with cut-off frequency $\omega \in [0.2,1]\ \mathrm{h}^{-1}$) with the objective to decrease the effect of projecting the short time fluctuations of temperature to the generated RH set-point value. However, in many historic buildings the short time temperature fluctuations are limited due to the heavy building construction.

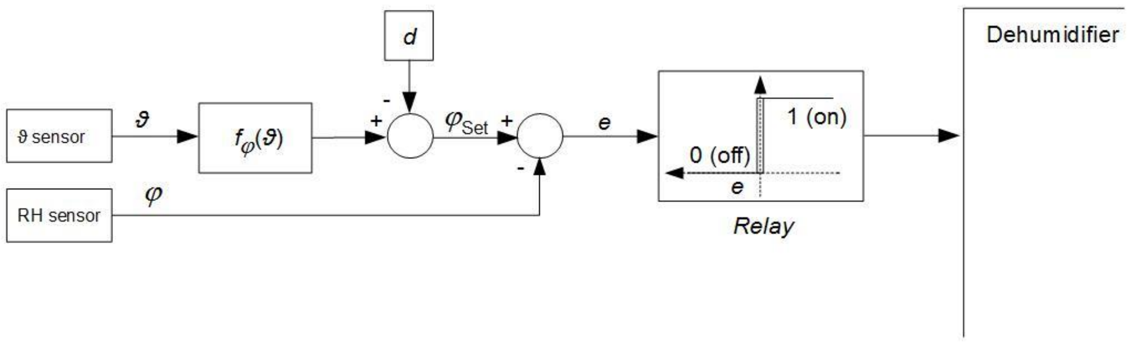

Figure 6.3 Control scheme to keep the microclimate in a safe region against mould growth using dehumidification

6.1.1 Simulation analysis on Hangvar church model

The designed microclimate control method is demonstrated by simulation tests with the hygrothermal model of the Hangvar Church on Gotland, Sweden, which was implemented in Hambase tool [92] and parametrized base on the measured data. The model and its parameters is described in Appendix 2.

In Figure 6.3, simulated (ϑ, φ) indoor data points of one year are shown in the subject to the given mould growth damage function. As can be seen, a large number of data points are found above the LIM I transformed to the figure scale by (83). Thus, according to the model and given climate conditions, the risk of mould growth in the church is very high. Implementing the control algorithm (84)-(85) and Figure 6.2, with hysteresis $h = 2\%$ and bias $d = 2\%$ controlling a model of a sorption dehumidifier (described in the Appendix 2) used together with the model of the church, the microclimate simulation data shown in Figure 6.4 are obtained. In Figure 6.4 (right), the estimated running hours by dehumidification are shown. The number of hours for one year is 915h. As can be seen in Figure 6.4, almost all the data points are now located below the boundary of the risky region. The couple of points located above is due to very fast indoorclimate changes which the dehumidifier could not handle. Thus, implementing the humidity control specified above, the microclimate would be protected against mould growth.

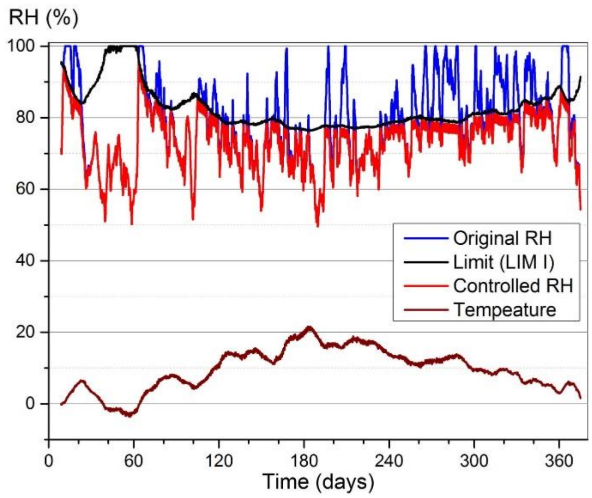

Figure 6.4 Results of RH control according to scheme in Fig. 2 with $\boldsymbol{h} = \pm\mathbf{2}\%, \boldsymbol{b} = \mathbf{2}\%$

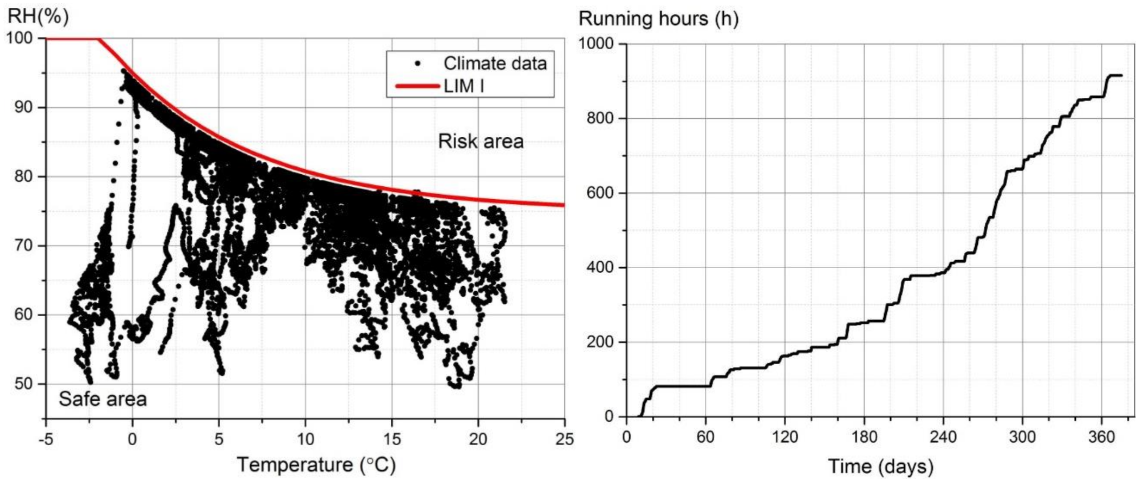

Figure 6.5 Left, simulated $[\boldsymbol{\vartheta}, \boldsymbol{\varphi}]$ data points of one year time period in the subject to mould growth damage function under the humidity control according to Figure 6.3. Right, running hours for dehumidification

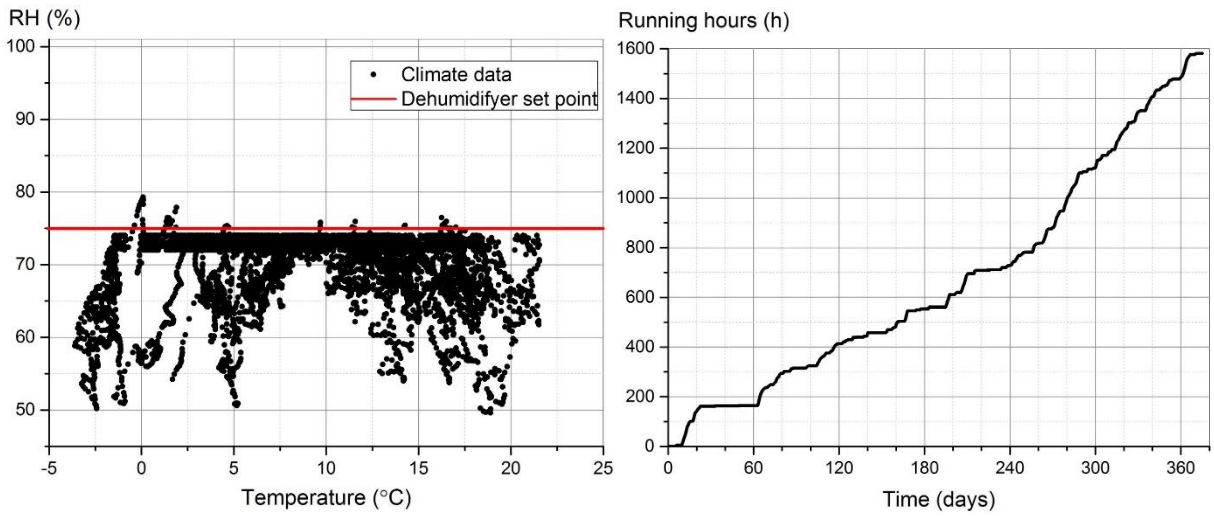

Figure 6.6. Left, simulation of traditional dehumidification with fixed set-point of 75%RH. Right, the number of running hours with traditional dehumidification. Set point 75% RH

To compare the result of mould growth control with the traditional way of using dehumidifiers a new simulation with a fixed RH set point to 75 % with the same model of a sorption dehumidifier was carried out. Figure 6.5 (left) shows the result of dehumidification and Figure 6.5 (right) shows the number of running hours. The runtime for this setup was 1581h, which is by 72% more compared with the mould growth control. To conclude this example, the adjustment of the RH control proposed in the previous section can bring substantial energy savings, compared to the traditional dehumidification to a fixed RH value.

6.2 Case study in Fide church

A case study on mould growth control was carried out in Fide church during one year from March 11 to March 11 the following year. A dehumidifier DR-010B with nominal capacity of 0.5 (kg/h), was installed on the organ loft and the dehumidifier was controlled with the Culturebee system [93], a wireless measurement and control system based on ZigBee-technology , which was evaluated and tested by the PhD candidate. Mould growth climate control was implemented on the system according to equation (70) and the set point for the dehumidifier was implemented according to equation (71). The bias was at first set to $d = 0\%$ and the hysteresis $h = 1\%$. It was found out that the capacity of the dehumidifier was too small and therefore a larger dehumidifier, DR-020 with nominal capacity of 0.8 (kg/h), was installed in mid-September. To achieve a larger safety margin the bias was adjusted to $d = 7\%$ and the hysteresis was set to $h = 2\%$. Figure 6.6 shows the *temperature – relative humidity* diagram for the case study. The black curve is from the period from March to September when the dehumidifying capacity was too small. The green curve is from September to March when the larger dehumidifier was installed. In connection with services, the church was heated and the dehumidifier was turned off to avoid noise. As a consequence, RH increased at one occasion to risky levels. The total running time of the dehumidifiers was 4340 hours during the year. It would have been less if a dehumidifier with higher capacity had been installed from the beginning.

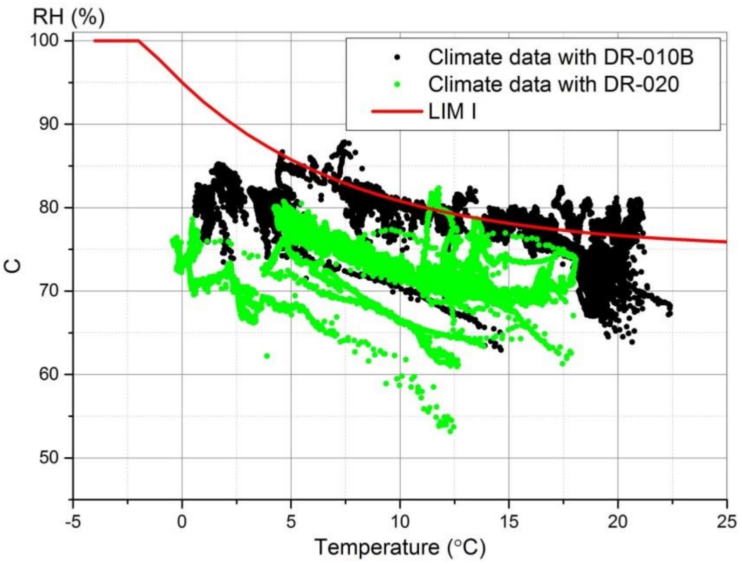

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Figure 6.7 Black, climate data from March to mid-September. Green, climate data from mid-September to March.

6.3 Comparative study in Skokloster Castle

The comparative case study in Skokloster castle had its preliminary purpose to compare three different RH reducing technologies in practical long-term use controlled in a way to minimize the risk for mould growth with minimum energy use, which had not been carried out before [51]. Hence, the objective of this study is to evaluate and compare, in situ, the relative performance in terms of mould prevention, energy consumption and indoor climate stability of conservation heating (CH), dehumidification (DH) and adaptive ventilation (AV) in a historic building.

The study was carried out at Skokloster castle, a unique Baroque palace museum. See Figure 6.7. The major part of the collection, which is dominated by objects from the 17th century, is still on display in their original historic setting. A series of detailed inventories beginning in 1716 reveal the status of individual objects. The castle has been a state operating museum since 1967. It is mainly open during summer, but there are occasional guided tours also in winter

The indoor climate due to the heavy and relatively leaky building envelope is characterized by high thermal inertia and a high and unstable RH [10]. The upper floors of the castle have been unheated for centuries. A few rooms on the ground floor are permanently heated to provide thermal comfort for staff and visitors. An increase of problems with mould growth, especially in rooms facing north, has called for preventive indoor climate control. In the 1990s it was decided that to reduce the risk for mould growth it would be beneficial to increase the air exchange rate. The chimneys, packed with centuries of old bird's nests, were cleared out in order to increase the infiltration of outdoor air. The doors in rooms with mould problems were kept open to provide more ventilation.

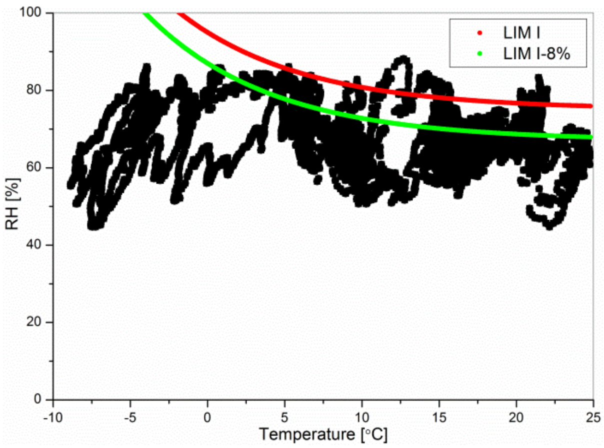

Figure 6.8 Left, Skokloster Castle. Right, T and RH in "Grå rummet" (Grey Room) during the reference year. The red line shows the isopleth LIM I, values above which indicate a risk for mould growth. The green line shows LIM I-8% which gives a conservative safety margin.

In 2008-2010 an extensive measuring campaign was performed to determine the impact of the building envelope on the indoor climate and to assess indoor climate-related risks [95]. There were two main results. On an average absolute humidity indoor and outdoor was about the same, which implies that there were no sources of moisture except from infiltration. Among the rooms there were considerable differences regarding the stability of RH. A conclusion was that draught-proofing the rooms would decrease the amplitude of RH fluctuations without increasing the average RH level. This measure would decrease the risk for mechanical damage of the objects without increasing the risk for bio-deterioration. It was also suggested that relying only on passive climate control would not be sufficient to eliminate the risk for future mould growth, as evident in Figure 6.7.

6.3.1 Methods

Three rooms known to have problems with bio-deterioration due to the indoor climate were chosen as case study rooms. The active measures were rotated annually according to Table 6.1. Three similar rooms with no active climate control were used for reference. Case study rooms CS1, CS2 and reference rooms RF1 and RF2 are facing north-northeast and case study room CS3 and reference room RF3 are facing south-southwest. See figure 6.8. Temperature and RH were monitored in all six rooms for whole three years and energy use was monitored in the case study rooms. Prior to the first year of the study it was decided that all rooms had to be draught proofed in order to make the active climate control more efficient. The windows were renovated, the doors were sealed and dampers were closed and sealed.

Table 6.1 Case study and reference rooms and associated rotation of climate control measures.

Reference rooms		Case study rooms		Measure		
Number	**Room**	**Number**	**Room**	**Year 1**	**Year 2**	**Year 3**
RF1	Blå rummet	CS1	Grå rummet	DH	AV	CH
RF2	Bryssel	CS2	Florens	AV	CH	DH
RF3	Gröna sängkammaren	CS3	London	CH	DH	AV

Installations in a building that have remained untouched for hundreds of years required great caution. All measures must be resettable and be characterized by the precautionary principle. To minimize the risk for overheating and fire, conservation heating was installed with four low temperature fire classified direct electric heaters with a total power of 800 W. In the choice between sorption and condensing dehumidifier a sorption dehumidifier was selected. The sorption dehumidifier can run in low temperatures, even below zero, and as the dehumidified water is transported with the moist regeneration air to the outside in an air duct it requires no manual service to handle water containers, which can be impractical and even risky. The selected dehumidifier, *Fuktkontroll DA-250*, had a maximum power of 1400 W and dehumidifying capacity of 1.1 kg/h (@ 20 °C, 60% RH). The dry air from the dehumidifier and the adaptive ventilation system was supplied through vertically directed nozzles making sure that no historic objects were directly exposed to the dry airstream, see Figure 4.8. The heaters and the dehumidifier were controlled with programmable hygrostats, with the set points for relative humidity approximately according to mould growth control strategy i.e. equation (71). A safety margin of d = 3% RH was used during the first year. In the second and third years a larger safety margin of d = 8% RH was used. The adaptive ventilation system consisted of a 110 W fan with a capacity of 300 m^3 per hour for the incoming air. The outgoing air was led through a valve mounted in the draught proofed chimney. The outdoor sensors where located just beside the air intake duct and the indoor sensor were located in the middle of the room on a stand. The fan was controlled by the ratio between indoor and outdoor water vapour partial pressure earlier described in Chapter 5. In this setup, the fan was running when the ratio was larger than 1.1. i.e.

$$F_{p_w}\left(\frac{p_{wa}}{p_{wout}}\right) = \begin{cases} 1, & \text{for } \frac{p_{wa}}{p_{wout}} > 1.1 \\ 0, & \text{for } \frac{p_{wa}}{p_{wout}} < 1.1 \end{cases} \tag{90}$$

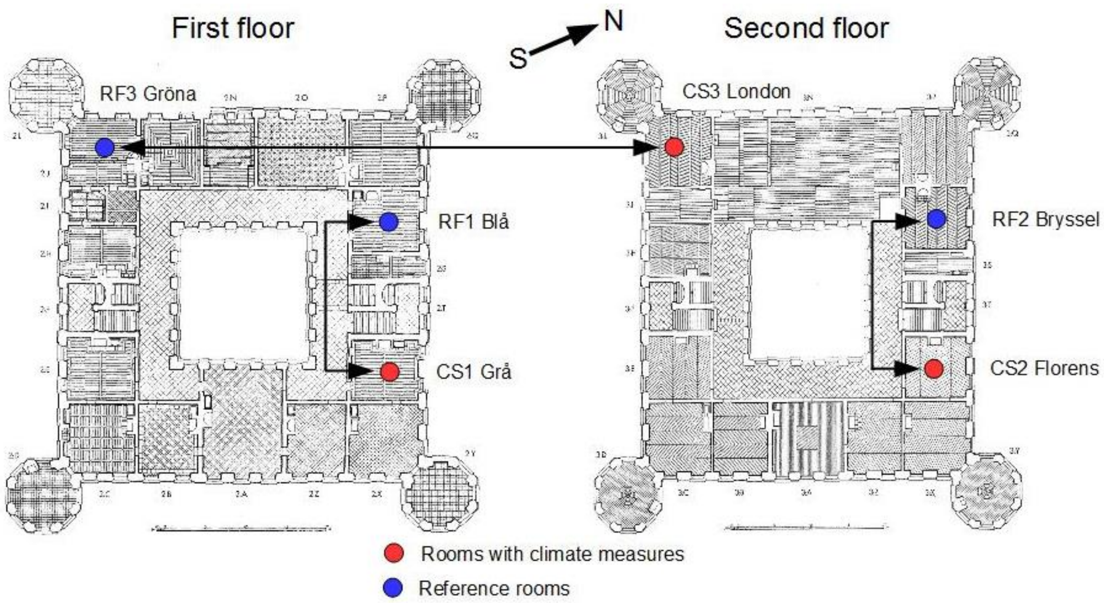

Figure 6.9 Rooms with measures and reference rooms in the study.

Figure 6.10 Left, dehumidifier in the room “Grå rummet”. Middle, adaptive ventilation in the room “Blå rummet”. Right, conservation heating in the room “London”.

6.4 Results and analysis

Table 6.2 shows that the need for active control has been so low during all three years that there are only small differences between the rooms, both between the case study rooms and between case study and reference rooms. The combination of a low demand for active control, existing differences in hygrothermal behaviour between the case study rooms and variations in outdoor climate between the years makes it difficult to compare the different methods. Still some observations can be made.

After the first year, it was evident that the indoor climate in CS1 had improved significantly even though the dehumidifier had not run for more than a few hours, most likely due to the draught proofing. It was decided to lower the control level by an additional 5 % RH, which means that for year two and three a safety margin of 8 % RH below LIM I was used (shown in the table in row $\text{Mould}_{\text{LIM I-8}}$). The draught proofing of the rooms has had a positive effect on the case study rooms in terms of more stable RH, as indicated by the standard deviation calculated from the 30-day moving average of RH (SD30). On the reference rooms the effect is less clear but these rooms were also more stable before draught proofing as can be seen in the statistics from the monitoring campaign in 2009-2010 referred as the reference year in table 6.2.

The energy use for all three control methods has been low. Dehumidification has used the lowest amount of energy, in total 534 kWh for all three years. Conservation heating has used 957 kWh and adaptive ventilation 742 kWh. The load for adaptive ventilation has been more or less constant regardless of room and year which is what one can expect as the systems controls by the difference in indoor outdoor climate and not mould growth risk. The load for conservation heating and Dehumidification has been highest in CS3, which also is the leakiest room. Dehumidification and Conservation heating has successfully kept temperature and RH below the mould growth limit LIM I, except in one occasion during year one when the CH in room CS3 was unable to lower RH during a rapid weather change with warm and humid air. Adaptive ventilation has lowered the mixing ratio (MR), i.e. mass of water vapour to mass of dry air, in comparison to the reference rooms and also to the other case study rooms but the mould risk has not been significantly lowered in comparison to the reference rooms; however the mould risk has been low in all rooms anyway. The SD30 fluctuations are significantly higher (25-30%) in the rooms where adaptive ventilation was installed.

Energy measurements showed that the Conservation heating and dehumidification were active mainly during the summer period. This period with increased mould risk was studied more closely in order to assess the impact of the active control. Table 6.3 shows the data for three summer months, July to September, for all three years. It is evident from Table 6.3 that year one had a beneficial outdoor climate during the three month period, resulting in a low mould growth risk in all rooms and an extremely low energy use in the case study rooms. There is a small mould risk in the reference rooms during year two, except in RF3 which always has a low mould risk due to heat gain, either from sunlight or the heated rooms below. Dehumidification and conservation heating effectively reduces the mould risk during this period. Adaptive ventilation consistently gives the lowest MR but increases RH fluctuations compared to the other methods. The difference in MR between Conservation heating and dehumidification is insignificant which is consistent with the low energy use for dehumidification, only 116 kWh in total for the summer months. Adaptive ventilation used 182 kWh and conservation heating 342 kWh.

An important result of this case study is the effect of draught proofing. The two rooms, CS1 and CS2 where well draught proof while CS3 was adjacent to a tower room on one side and the castle's most leaky room on the other side was hard to draught proof. Comparing energy consumption per room for the whole three years study shows that the two better draught proofed rooms CS1 and CS2 consumed in total 512 kWh and 585 kWh respectively while the leakier room CS3 consumed the double amount of energy 1135 kWh for the three years. This result points out importance of draught proofing when installing climate control measures in a historic building.

6.5 Discussion and Conclusions

A concept for using isopleths for mould growth analysis for determining the safe set-points for microclimate control has been introduced. Mould growth control was tested in Hangvar church simulations and in situ in a one-year Fide church case study. Both simulations and in situ testing showed that using mould growth control for determining the safe set points for mould growth control of a dehumidifier is working. In the simulated year, the energy saved compared to using fixed set point control was 57 %. The in situ test showed the importance of the use of a safety margin to be able to mitigate fast changes in indoor climate.Mould growth control was used and cross-compared in the three-year study in Skokloster Castle where conservation heating and dehumidification was controlled by the introduced set point strategy. Comparing the three climate control measures in terms of energy efficiency and mould risk prevention, dehumidification has consumed least energy and meanwhile was the most effective in reducing mould growth risk. Conservation heating is almost as good in reducing mould growth, but needed almost twice the amount of energy. Adaptive ventilation has had a positive impact on mould risk and managed to achieve safe climate in the rooms. However, there were occasionally some periods per every second or third year where this measure was not sufficient. The energy consumption was low, in between dehumidifying and conservation heating.

In the case of stability there is no significant difference between dehumidification and conservation heating. Both measure showed very low fluctuations. Adaptive ventilation has on the other hand increased short term variations of RH which are important in regard to mechanical damage. Looking at data from the three summer months it is obvious that dehumidification is both most effective to prevent mould growth and is most energy efficient during the warm period. The total amount of energy consumed during all three years is so low that the difference hardly can be important for decision-making in the case study building. Draught proofing had a positive impact on energy efficiency and it also has had a beneficial effect on RH stability and mould risk. However the indoor climate in Skokloster castle is only just below the risk zone and active control is necessary to reach an acceptable risk level and to mitigate bad indoor climate when humid weather conditions occur.

Table 6.2 One year data from all rooms and all three years. Two different thresholds are used to make a fine grained assessment of the risk for mould growth. The reference year is from a monitoring campaign in 2009-2010.

	Case study rooms															
	Reference year				**Year 1**				**Year 2**				**Year 3**			
Room	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out
Measure					DH	AV	CH		AV	CH	DH		CH	DH	AV	
Avg RH [%]	71	68	68	80	65	64	64	77	66	67	65	79	65	67	65	79.5
Avg T [°C]	8.0	8.5	8.6	6.8	10.5	10.0	11.3	8.0	10.0	10.3	11.0	8.1	10.2	9.6	10	7.2
Avg MR [g/kg]	5.4	5.2	5.2	5.5	5.6	5.3	5.6	5.4	5.4	5.6	5.7	5.6	5.4	5.5	5.3	5.3
SD	7.7	11.4	10.7	16.7	5.0	7.8	12.0	17.5	6.7	6.5	10.4	17.6	4.0	4.8	9.7	16.9
SD30	6.0	6.1	5.9	12.3	3.6	4.8	5.4	15.1	4.8	3.8	4.9	14.9	2.9	2.8	5.6	14.6
Runtime [h]					23	2264	539		2100	346	316		311	42	2382	
Energy [kWh]					32	249	431		231	277	443		249	59	262	
Mould $_{LIM\ I}$ [%]	3	3	3		0	0	1		0	0	0		0	0	1	
Mould $_{LIM\ I\text{-}8}$ [%]	32	11	14		4	2	20		9	2	1		0	0	10	
	Reference rooms															
Room	RF1	RF2	RF3		RF1	RF2	RF3		RF1	RF2	RF3		RF1	RF2	RF3	
Avg RH [%]	68	70	63		66	69	60		68	70	61		68	69	60	
Avg T [°C]	8.2	7.8	9.7		10.2	9.8	12.1		10.1	9.7	12.0		9.4	9.0	11.4	
Avg MR [g/kg]	5.3	5.2	5.3		5.5	5.5	5.6		5.6	5.7	5.7		5.4	5.4	5.4	
SD	5.5	8.8	7.0		5.3	10.0	9.3		5.3	9.7	8.9		3.8	8.0	7.3	
SD30	4.2	5.2	5.2		3.5	4.2	5.2		3.4	4.6	5.3		2.7	4.0	5.2	
Mould$_{LIM\ I}$ [%]	0	0	0		0	0	0		0	1	0		0	0	0	
Mould$_{LIM\ I\text{-}8}$ [%]	11	13	5		5	22	3		6	18	4		13	12	2	

Table 6.3 Three months data, July-September, from all rooms all three years.

	Case study rooms															
	Reference year				**Year 1**				**Year 2**				**Year 3**			
	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out	CS1	CS2	CS3	Out
Measure					DH	AV	CH		AV	CH	DH	-	CH	DH	AV	
Avg RH [%]	68	60	61	76	61	57	53	72	65	63	57	76	65	65	59	77
Avg T [°C]	18.6	20.1	20.0	15.5	18.9	19.1	20.7	15.7	18.5	19.8	21.0	16.7	18.7	18.8	19.6	15.6
Avg MR [g/kg]	9.2	8.8	8.9	8.2	8.4	7.9	8.1	7.8	8.8	9.2	9.1	8.9	8.8	8.8	8.4	8.4
SD30	4.5	4.0	4.7	16.8	3.7	4.2	4.4	18.2	3.7	2.0	3.5	16.9	2.1	2.1	4.2	15.9
Runtime [h]					2.2	636	3.8		454	140	51		283	30	563	
Energy [kWh]					3	70	3		50	112	71		227	42	62	
$Mould_{LIM\ I}$ [%]	1	0	0		0	0	0		0	0	0		0	0	0	
$Mould_{LIM\ I\text{-}8}$ [%]	51	2	5		1	0	0		18	0	0		0	0	6	
	Reference rooms															
	RF1	RF2	RF3		RF1	RF2	RF3		RF1	RF2	RF3		RF1	RF2	RF3	
Avg RH [%]	66	63	61		61	57	52		66	62	56		69	64	57	
Avg T [°C]	18.9	19.4	20.2		18.8	19.6	21.1		18.8	19.9	21.4		17.7	18.8	20.4	
Avg MR [g/kg]	9.1	8.9	9.1		8.4	8.2	8.2		9.1	9.2	9.0		8.7	8.7	8.9	
SD30	3.4	3.6	4.4		3.4	3.8	4.1		2.3	3.0	3.6		2.5	3.2	3.9	
$Mould_{LIM\ I}$ [%]	0	0	0		0	0	0		0	0	0		0	0	0	
$Mould_{LIM\ I\text{-}8}$ [%]	23	6	5		0	0	0		19	2	0		50	12	2	

7 Conclusions

This thesis studies and contributes to questions connected to climate control in historic massive buildings with the focus on problems related to temperature and humidity control by various methods. The research in this area is motivated by the fact that vast amount of European cultural heritage objects, such as paintings, frescoes, sculptures, altars, organs, etc., are located or deposited in historic buildings with none or limited care of the indoor climate. Next to the castles, museums and monasteries, historic churches are typical representatives of such buildings, which form a major case study class considered in this thesis. Lack of funding in the cultural heritage sector, or cleric institutions in case of the churches, together with interior protection rules that often limit possibility to install regular HVAC systems used in modern buildings, motivates the research efforts in development of non-invasive, low-cost and energy efficient solutions. In the thesis, in particular, three such methods have been targeted i) intermittent heating, ii) adaptive ventilation, and iii) humidity control.

First, the method of intermittent heating widely applied in churches have been analysed in Chapter 4, applying model based techniques. From the system theory, this part presents the major contribution of the thesis. An interesting point is that relatively simple structure model of the indoor climate was proposed with ability to almost perfectly fit the measurements at three different churches on the island of Gotland, Sweden. This model was then utilized for synthesis of shaping the starting stage of the heating event to limit the change rate of relative humidity. This is done in order to minimize the risk of mechanical damage to heritage objects of hygroscopic nature (e.g. made of wood, paper and canvas) due to associated climate induced moisture content gradient. At this stage, the control design method was validated on simulations. The experimental validation is then naturally a further step, which is left for the near-future research.

The subsequent part of the thesis presents results in rather applied directions. Existing indoor climate control methods: i) adaptive ventilation, and ii) humidity control, were analysed on selected case study historic buildings, with the objective to fill in the gaps in the state of the art by applying extensive analysis on the gained data. The aim was also to propose adjustments for the methods towards indoor climate safety and energy efficiency. Note that a significant contribution is also at the implementation side, as it was necessary to design, install and programme all the instrumentation, measurement and control systems for the case study tests.

Based on the measured data and gained experience, the adaptive ventilation, analysed mainly in Chapter 5, and partly in Chapter 6, was confirmed as a proper mitigation measure for buildings with internal source of moisture. In particular, its applicability is mainly in the direction of mould growth reduction. On the other hand, this mitigation measure can increase the risk of mechanical damage, due to enhanced fluctuations brought by the method. Elimination of these fluctuations is then the main proposed adjustment of the method, discussed in more detail in the conclusion section of Chapter 5. From the comparison of three different methods performed in Chapter 6 in Skokloster Castle, it results that as soon as the historic building does not have considerable internal source of moisture, the effect of adaptive ventilation method is low.

The last major direction studied in Chapter 6 of the thesis is in analysis of mould growth in interiors of historic buildings. The first contribution of this chapter, confirmed by both simulations and experiments, is that if the mould growth dependence on combination of relative humidity and temperature is taken into account when determining the relative humidity set-point, considerable energy savings can be achieved, compared to the common relative humidity control to a fixed set-point value. The second contribution of the chapter is case-study based cross-comparison of three different control strategies in Skokloster Castle, namely i) adaptive ventilation, ii) conservation heating, and iii) direct dehumidification by sorption dehumidifier. Under the given conditions, drought-proofed interiors and no substantial internal source of moisture, the dehumidification by sorption dehumidifiers is the most effective method.

To conclude, various methods and approaches were studied in the thesis. It covered the indoor climate concept development by applying approaches of model based control, designing and implementing novel control systems, including both instrumentation and software implementation aspects, and analysis of the methods by applying recently proposed criteria and damage functions. The specific contributions to both fundamental and applied research are outlined in more detail below, separately for each of the objective stated in Chapter 3.

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

This first objective is analysed and solved in Chapter 4 of the thesis. The main contribution is in performing the conceptual design of shaping the heating power increase at the beginning of the intermittent heating event at a massive historic building with heavy masonry walls. The motivation for this research is to avoid the indoor climate risk for heritage objects of hygroscopic nature induced by fast RH change rate at the beginning of the heat-up event, if the full heating power was set at its beginning. Following the emerging direction of applying model based methods in the given cultural heritage field, simplified thermal and hygric analytical models of massive buildings were proposed. When forming the model structure, the linearity of the temperature responses with respect to root-square of time, caused by heat transfer within thick walls and associated with solution of the heat equation, had to be respected. Next to that, the accumulation nature of the interior air volume needed to be covered by the model. First, balancing these phenomena under neglecting the minor factors, the first order nonlinear model was proposed to simulate air temperature response to the heating power step. The consequently proposed balance hygric model for simulating the air mixing ratio is of the same structure, due to a direct dependence of moisture evaporation from the walls on the temperature, under the assumption that the walls are saturated with moisture. For both the models, the two step parameter identification procedures are proposed. First, the static (sensitivity) parameters are obtained directly from the linear parts of the responses, when visualised with root square scaling of the time. The accumulation time constants are then obtained by applying the method of signal integration. The proposed models and identification procedure were successfully validated on measured data at three churches in Sweden (Fide, Hangvar and Tingstäde churches on island of Gotland). The models are well able to approximate the initial part of the response determined predominantly by indoor air accumulation, as well as subsequent root square of time dependence governed by the heat transfer to the massive wall. Note that the limitation of these models is in that they can be applied to simulate step responses only.

The main contribution of Chapter 4 is then in proposing an algorithm for step-wise shaping of the heating power at the starting stage of the heating event so that the relative humidity hourly (or any other interval) change rate due to the heating is kept within a predefined range. This is done by applying the Magnus law to determine the relative humidity from the temperature and the mixing ratio of the air. Based on sensitivity analysis and simplified assumptions on temperature homogeneity in the wall during the starting stage of the heating event, the magnitudes of maximal heating power steps at hourly (or other) intervals are determined to respect the constraint on the RH change rate. Besides, a procedure to determine the overall heating time is proposed. The designed control procedure is then applied and validated on the models of all the three case study churches. For validation of the method, higher order dynamical models were proposed and parametrized from the available data, involving discretized heat equation. An almost ideal match with the results by the simplified models used to derive the control strategy shows that the stated simplifying assumptions were meaningful. Finally, implementation aspects of the proposed method are discussed. Note that preliminary results presented in Chapter 4 were published in [1], and the final results are in the paper [2], currently in review. Summing up the above discussed results, it can be stated that the Objective 1 of the thesis was fulfilled.

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

The Objective 2, which focuses on analysis and design adjustments of adaptive ventilation, has been solved in Chapter 5, and partly also in the Chapter 6. The motivation for the given research lies in the fact that even though the adaptive ventilation has been implemented as a mitigation measure in a number of test historic buildings, it has not been investigated sufficiently, from the mould growth prevention, relative humidity variability, algorithm and technical implementation erudition points of view, in particular. All these aspects are widely analysed and solved in the thesis. The main contribution is an analysis and validation of the measure regarding humidity control, energy performance and stability of the indoor climate. However, the study contributes via enhancing the know-how in the implementation aspects gained during a number of case study tests. In particular, a case study with adaptive ventilation as the only climate control measure is carried out in a historic farm building from where data analysis is performed to study the reduction of relative humidity, mould risk reduction, indoor climate fluctuations and energy performance.

After the first study, it was apparent that when the outdoor air is dryer than the indoor air, it is very likely that it is also colder. Hence, ventilating the interior by cold air is counterproductive. Such ventilation has cooling effect, which is likely to increase RH, even though moisture at the same time is removed from the building. A new solar energy augmented system which slightly heats the inlet air is developed and tested in a subsequent, second case study - a medieval church building. The sustainable strategy is to heat the inlet air only when there is accumulated solar energy available. The solution in this study was to produce end export electrical energy to the grid during daytime and take it back from the grid when fan was running. If the system ran out of produced energy the heaters was set off. There is no doubt that adaptive ventilation lowers the humidity level. In the two case studies, the ventilation system transported out some 1600 kg and 1100 kg of water, respectively, during one year. The climate induced risk for mould growth was acceptable except for some periods. Energy performance was also very good. An important aspect that will need to be addressed in the subsequent analysis is the increased variability of relative humidity after application of adaptive ventilation. This can increase the risk of mechanical damage of heritage objects of hygroscopic nature via transferring the relative humidity variations to variation of moisture content and the associated gradients of stress within the material layers. The performed research shows that adaptive ventilation essentially lowers the number of hours with 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. For these time period, a backup strategy is to be applied, e.g. by using portable sorption dehumidifiers. To conclude, by the performed case study analysis which confirmed the adaptive ventilation as viable method, especially if the proposed adjustments are taken into account, the Objective 2 has been fulfilled. The results of performed research have been presented in [3], [4], [5] and [6] where the doctoral candidate is either the main author or a key co-author.

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

Even though the mould growth analysis of adaptive ventilation method was performed already in Chapter 5, its analysis forms the major scope of Chapter 6. The analysis of mould growth in interiors of historic buildings is performed, taking into account recently quantified mould growth intensity as a function of temperature, relative humidity and other factors. The quantified mould growth characteristic is then turned to a function for generating the relative humidity set-point based on measured temperature. By applying this approach, significant energy savings can be achieved compared to relative humidity to a constant set-point, which is often used in the cultural heritage sector as the primary indoor climate mitigation measure. This conclusion has been made based on both simulation and case study experiments. The simulation based validation was performed on a model of Hangvar Church on Gotland, Sweden, which was implemented in HAMbase tool in Matlab environment, and parametrized based on the measured data. Even when fixing the relative humidity set-point in rather high value of 75% of RH, the overall runtime of the dehumidifier was by 72% higher compared to dehumidification with following RH set-point with respect to the mould growth characteristic.

Applicability and benefits of the mould growth driven dehumidification were then confirmed also via yearly experiment in Fide church, Gotland, Sweden.

As a final contribution, a wide case analysis in Skokloster Castle is presented. From the three methods of mould growth targeted humidity control, namely i) adaptive ventilation, ii) conservation heating, and iii) direct dehumidification by sorption dehumidifier, the last proved as the best concerning the indoor climate quality and energy consumption. Note that this case study was specific by none internal source of moisture, as the test rooms were located in the first and second floor of the building. However, rather than a method, the drought-tightness of the rooms performed prior the first year of the study, showed as decisive factor in lowering the mould growth risk. Though, the supportive use by an active measure proved crucial in eliminating the residual risks in the tested rooms. A part of the results presented in this part of the thesis was published in [3] and in the deliverable report of the 7FP EU project Climate for Culture [9]. Based on the achieved results supported by thorough data analysis, also this Objective 3 can be considered as fulfilled.

8 Appendix

8.1 Psychrometrics

The relative humidity, φ, is specified as the ratio between the actual water vapour pressure and the saturated vapour pressure at the given temperature i.e.

$$\varphi = \frac{p_w}{p_{ws}} \cdot 100 \text{ (\%)} \tag{91}$$

where $p_w$is the water vapour pressure and p_{ws} is the saturated water vapour pressure at the given temperature [96].

The saturated water vapour partial pressure is a function of temperature and can be calculated with the Magnus and Tetens empirical formula [83]

$$p_{ws}(\vartheta) = p_{ws}(0) \cdot 10^{\frac{a\vartheta}{b+\vartheta}} \text{ (hPa)} \tag{92}$$

Where ϑ is temperature (°C), $p_{ws}(0) = 6.112$ (hPa) is the water vapour partial pressure at zero degrees centigrade, $a = 7.65$ and $b = 243.12$ are empirical developed constants [83].

In calculations of air condition for example in building physics and HVAC engineering, mixing ratio MR is useful and is specified as the mass of water vapour to the mass of dry air.

$$X_a = \frac{m_w}{m_{da}} \text{ (kg/kg)} \tag{93}$$

The SI-unit is kg per kg but often the more practical unit, grams of water vapour per kg dry air is often used. Mixing ratio is the vertical axis in a psychrometric chart and can be calculated from relative humidity and temperature either from a psychrometric chart or according to equation (94) [97].

$$X_a = 0.622 \frac{p_w}{p - p_w} \text{ (kg/kg)} \tag{94}$$

The constant 0.622 is the ratio between the molar mass of water vapour and dry air, p is the atmospheric pressure which often is approximated with 1013 hPa. $p_w$is the water vapor partial pressure which can be calculated by equation (91) rearranged

$$p_w = p_{ws} \cdot \frac{\varphi}{100} \text{ (hPa)} \tag{95}$$

As the difference between the atmospheric pressure and water vapour partial pressure $p - p_w$ is approximately 1000 hPa, equation (94) is often approximated with

$$X_a = 0.622 \frac{p_w}{1000} \tag{96}$$

If equation (96) is combined with equation (95) and equation (92) the result is

$$X_a = 3.802 \cdot 10^{-5} \cdot \varphi \cdot 10^{\frac{a\vartheta}{b+\vartheta}} \text{ (kg/kg)} \quad (97)$$

Absolute humidity, often denoted by the abbreviation AH, is the mass of water vapour in a certain volume of moist air V i.e. the density of the water vapour (kg/m^3).

$$AH_a = \frac{m_w}{V} \quad \text{(kg/m}^3\text{)} \quad (98)$$

And can according to [18] be calculated with.

$$AH_a = \frac{1.344 \cdot 10^{-2}}{273.3+\vartheta} \cdot \varphi \cdot 10^{\frac{a\vartheta}{b+\vartheta}} \quad \text{(kg/m}^3\text{)} \quad (99)$$

8.2 Simulation model of Hangvar church

For comparative studies of mould growth control, a model of Hangvar church, see Figure 4.2 (middle), has been developed and parametrised. The model was implemented in the Matlab - Simulink based software HAMbase [93] developed by TUE. See Figure 8.1.

The model consists of six zones with the following volumes:

Nave and chancel, 955 m^3
Sacristy 33 m^3
Attic above the nave 376 m^3
Attic in tower the part 353 m^3
Crawl space below the Nave 35 m^3
Crawl space below the Sacristy 2.5 m^3

A floor plan over Hangvar church can be seen in Figure 5.12.

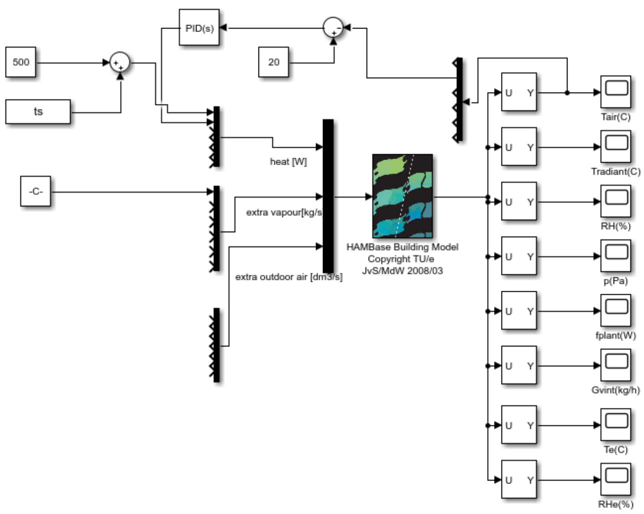

Figure 8.1, The HAMbase model in Simulink

In the model, properties of the construction components such as walls, windows, doors etc. are defined in an input file. The temperature in the sacristy was held constant to 20 °C as it is in the church. For simulation purpose, hourly energy data from the energy company was imported to the model in order to include the electrical heating and lighting at heat up events at service. Meteorological data measured at a weather station managed by the Swedish Meteorological and Hydrological institute (SMHI) located some 18 kilometres from the church ware used as outdoor data. The Irradiation data was measured at Visby Airport, 29 km from the church.

During the test year there are some differences between the simulations and measured data that most likely are caused by the distance between the church and the location of weather stations. See Figure 8.2 and 8.3. However the dynamics and the averaged levels are captured in the model.

The HAMBase building model has a feature for adding extra water vapour into the modelled building which can be used for simulations of dehumidification by adding negative vapour into the model. The capacity of a dehumidifier is however strongly temperature dependent and has to be modelled for that. In the simulations for mould growth control the capacity of a Munters ML 270 sorption dehumidifier was approximated by the model

$$C(\vartheta) = -(0.9 + 0.06\,\vartheta)/3600 \ \ (\mathrm{kg\ s^{-1}}), \qquad (100)$$

based on the product sheet from the supplier.

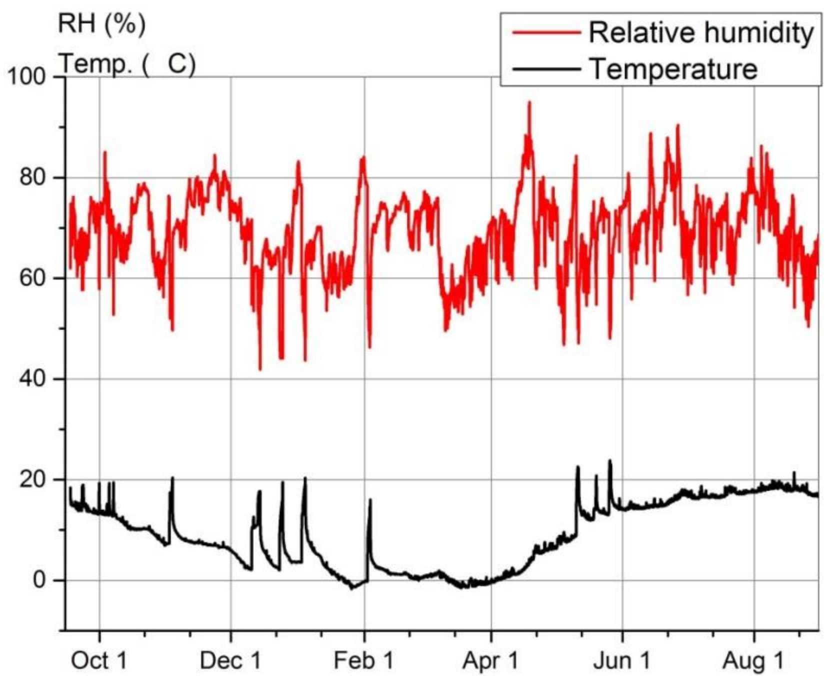

Figure 8.2. Meassured temperature and relative humidity in Hangvar church.

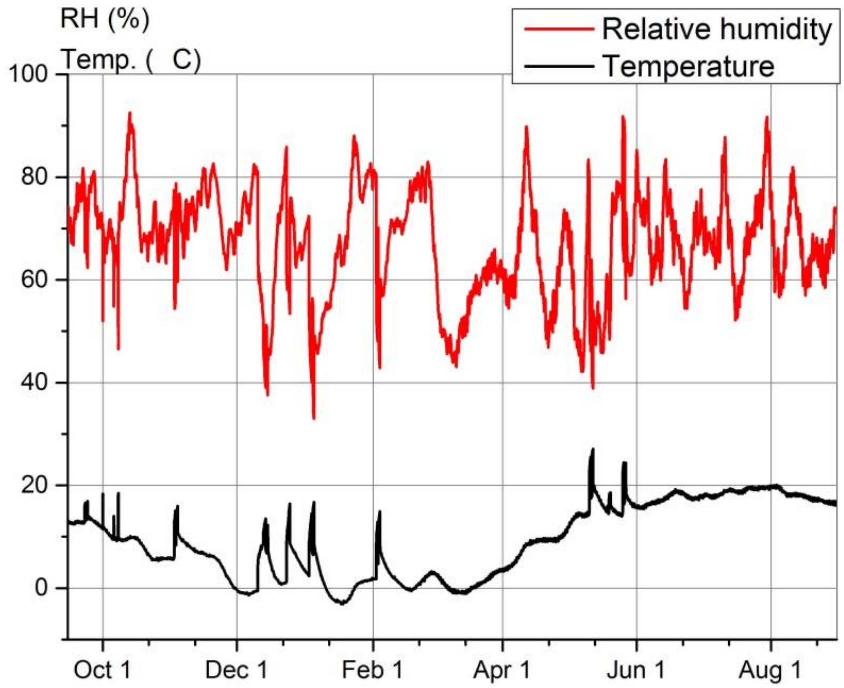

Figure 8.3. Simulated temperature and relative humidity in Hangvar church.

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