Measured and Modeled Influence of the Moisture Buffer Effect in a Historic Stone Church and its Influence on Possible HVAC Measures

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Abstract

Historic buildings often show a high thermal inertia, influencing the buildings thermal behavior. But not only thermal inertia, but also hygric inertia plays a significant role for the mean temperature and relative humidity and their fluctuations in those buildings. This paper presents measured values of temperature and humidity conditions in a historic massive stone church. The concept of moisture buffering is explained and discussed. To assess the influence of the hygric interaction of a building with its envelope in a simulation model, it is necessary to compute the coupled equations for energy and mass transfer in the building components. A hygrothermal whole building simulation software model of this church is presented and verified with the measured values to allow the assessment of the hygrothermal performance of this building. The verified model allows then to conclude on the effectiveness of different active and passive measures that might be implemented to ensure an indoor environment that fulfills preventive conservation requirements. Measurement results show a high influence of the hygric and thermal inertia on the indoor conditions. These indoor conditions were successfully modeled with a hygrothermal whole building model. It is shown, that it requires a thorough analysis to decide if passive measures can be preferred over active HVAC measures that demand more energy.

Keywords – hygrothermal building simulation; historic church; active and passive measures

1. Introduction

After a complete renovation of the chapel of ease St. Margaretha (see Figure 1) in September 2004, the churchwarden again noticed moisture damage on the walls. A subsequent climate measurement showed that the damage was a matter of condensation that occurs mainly in the transitional period during spring-time. At that time of the year the building is still cold because of the winter. If warm, humid air enters the building due to natural air flow or uncontrolled ventilation inside, it condenses on the cold wall surfaces. But even in the summer and fall warm humid weather conditions can cause problems due to condensation. Also new damages reoccurred on the completely restored altarpiece and other painted surfaces. Since 2004 these damages progress slowly and are monitored by a conservator. In 2011 restoration took place to secure detached parts of the paint from falling off. From December 2004 to August 2006 the temperature and relative humidity were measured inside and outside the church. To asses condensation events the wall surface temperature was also measured on the Western wall at the joint to the floor. During the period when measurements were taken the climate inside the church showed a high average humidity with values over 75 % RH for more than half of the time of the year. During winter time the church also freezes with temperatures below 0 °C for more than six weeks in a row [1]. Subsequently, the church starts with very low wall temperatures into spring time and the warm season.

Another problem that became evident was the uncontrolled opening of windows and doors over the warming period of spring that was supposed might reduce the moisture levels in the space by ventilating. In the summer 2005 “ventilation traffic lights” showing the times when the water content of the outdoor air was lower than indoors were used to give advice to the guardian of the church. This significantly increased the daily fluctuations of RH; in the spring and summer 2005 the fluctuations were above 15 % RH for more than 30 days. Daily changes above 15 % RH are thought to be critical to works of art [2], as the risk of structural damages due to swelling and shrinking of materials increases with the range of RH change per day. Also the newly restored altarpiece from the 19th century started showing additional damages at the gilding. Since 2011 new climate measurements are taking place inside the church that are used inside the European Large Scale Integrating Project “Climate for Culture” as one of several case studies for a common exercise on the possibilities and boundaries of hygrothermal whole building simulation of historic buildings.

2. Methodology

A detailed model of the chapel’s geometry was created in WUFI Plus [3] (Figure 1). The main building is about 12 m long and 9 m wide. The height from the ground to the top of the roof is about 6 m and to the top of the tower about 9 m. The simulation model is validated by comparison with measurements. Afterwards the validated model is used to estimate the influence of different strategies to reduce the humidity inside the church.

2.1 Simulation Model

The simulation is performed with the hygrothermal whole building simulation software WUFI® Plus. WUFI® Plus is a holistic model based on the hygrothermal envelope calculation model developed by Künzel [4]. The hygrothermal behavior of the building envelope affects the overall performance of a building. WUFI® Plus is a building performance simulation tool which computes the coupled heat and moisture transfer in the building envelope. It takes moisture sources and sinks inside a room, input from the envelope due to capillary action, diffusion and vapor ab- and desorption as a response to the exterior and interior climate conditions as well as the well-known thermal parameters into account. The coupled heat and mass transfer for vapor diffusion, liquid flow and heat transport in the building envelope is a strong feature of the model. The conductive heat flow and the enthalpy flow by vapour diffusion with phase changes in the energy equation are strongly dependent on the moisture fields. The vapour flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapour pressure with temperature. The model was validated by comparing its simulation results to the measured data of extensive field and laboratory experiments as well as other simulation software [5;6] Models like WUFI® Plus can help to improve energy simulations because latent heat loads and their temporal pattern can be calculated more accurately. At the same time the determination of indoor air and surface conditions in a building becomes more reliable.

For the simulation the main body is divided into five zones where the climate is modeled: the nave, sacristy and three attic zones. The infiltration ventilation air is taken from outside, with an infiltration air exchange rate for the nave of 0,2 1/h in winter and 0,5 1/h in summer. In the three attic zones high infiltration rates of 3 – 5 1/h are supposed caused by the leaky shingle roofs. The tower as well as the entrance area is treated as attached unheated zone with assumed exterior temperature and relative humidity. Although there are several events in the church during year no inner sources are assumed.

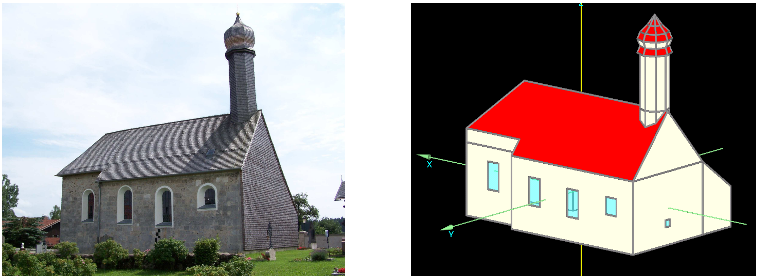


Fig 1 Picture and screenshot of the computer model of the exemplary church.

The outer walls of the chapel are built from tuffstone with a thickness of 0.52 to 0.77 m. At the inner surfaces there is a layer of lime plaster which is 2 cm thick. The base plate exists of a layer with loose material (0.15 m) which is mainly covered by natural stone plates with a thickness of 5 cm. Under the benches at the north and south side of the church there are panels of hard wood instead. The ceiling to the attic has an overall thickness of 0.3 m consisting of 2.5 cm softwood, a 15 cm thick air layer, 6 cm mineral wool and again 2.5 cm softwood. The chapel’s roof and its covering with a thickness of 3 cm is mainly built with softwood and shingles on the outside. The windows have a single glazing with an overall thermal transmission value of 3.7 W/m²K.

2.2 Measurements

Since December 2011 measurements of temperature, humidity and heat fluxes are carried out in the church. A gauging cylinder is measuring air temperature and surface moisture content of the south wall in different heights. On the outer side a radiation sensor is placed. Additionally heat flux and surface temperature of the wall and the floor are recorded. Similarly heat flux and surface temperature of the west wall are measured. As the west wall is covered with shingles temperatures and humidity of the air gap between stone and shingles are also gauged. Figure 2 shows photographs of some of the measurement devices.

Fig 2 Gauging cylinder placed on the south wall of the nave and west wall covered with shingles

On the north corner of the west wall a weather station is placed measuring temperature and humidity of the outer air. Temperature and humidity are also measured at the organ on the gallery. In the adjacent rooms (sacristy and attic) air temperature and humidity is recorded. In the other rooms (tower, attic of sacristy and attic of entrance area) temperature sensors were placed. In this manner the physical performance of the church was monitored and the measured data could be used to verify a simulation model. Since the only outer climate parameters which are measured at the church are temperature, relative humidity and radiation on the south wall it was necessary to get complete and consistent weather data of the period considered. Therefore data of the weather station at the Fraunhofer Institute for Building Physics (IBP) Holzkirchen was used which is around 5 km away. This weather data contains all parameters relevant for hygrothermal simulations with WUFI® Plus. Of course the data measured at the church could be compared with the weather used for the simulations.

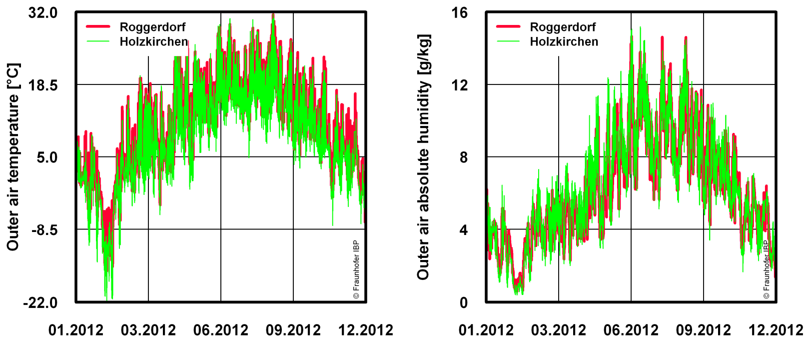


Fig 3 Air temperature [°C] and absolute humidity [g/kg] measured at the church (Roggersdorf) and at the IBP (Holzkirchen)

From Figure 3 it is apparent that temperatures in Holzkirchen are lightly colder especially in winter. In order to use a consistent climate data set the temperatures were not adapted. The graph with absolute humidity shows good correlation.

2.3 Variants

The simulation model as that described in the previous section is used as base case. The simulation results of this variant are compared to variants with any changes that might be implemented to ensure an indoor environment that fulfills preventive conservation requirements. That way the effectiveness of different active and passive measures is proven and evaluated. The analyzed variants are

- Surface coating: Therefore the sd-value of the walls in the cave was varied from 0 m to 100 m.
- Adaptive ventilation: A controlled ventilation system brings dryer air into the building whenever the outer humidity is lower
- Full HVAC: The energy for heating, cooling, humidification and dehumidification is simulated.

3. Measurements and Simulation Model Verification

Since this paper focuses on the hygrothermal behavior of the cave measurement and simulation is compared for some important parameters in the cave. In a first step mean temperature and mean absolute humidity of the indoor air is calculated by averaging the temperatures and humidity at the gauging cylinder and the temperature and humidity at the organ. This mean temperature and humidity is compared with simulation results (see Figure 4). Simulation results are produced first by only taking the moisture balance into account, but not modeling the hygrothermal interaction of the nave air volume with the building envelope (thermal). Second they are produced by accounting for moisture exchange and buffering with the envelope (hygrothermal).

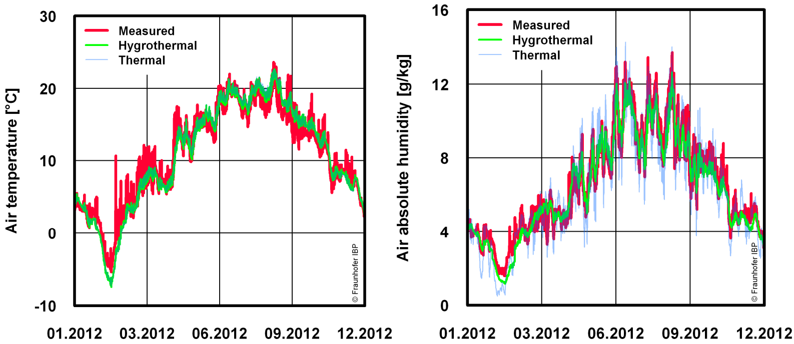
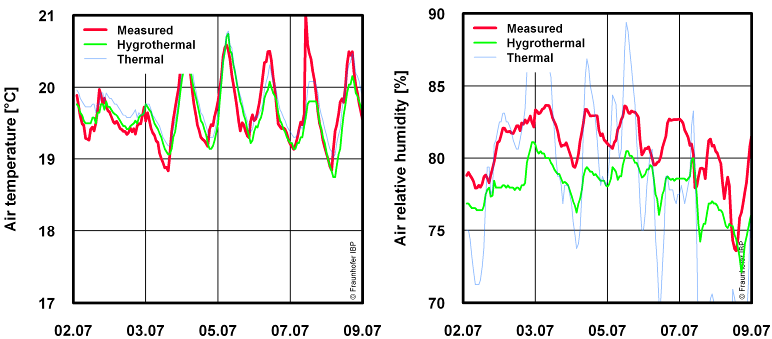


Fig 4 Simulated and measured air temperature and absolute humidity in the cave

The simulation results show a good agreement with the measured values. The simulated temperature does not change between thermal and hygrothermal simulation. The humidity in the space shows some deviation with an only thermal simulation and can only be reproduced by performing a real hygrothermal whole building simulation. Only in very cold periods of the year the simulation predicts lower temperature and absolute humidity inside the cave than the measurement results show. For a more detailed analysis of daily fluctuations temperature is plotted in Figure 5 for one week in July and December respectively. In these exemplary weeks, the difference in measured and modeled temperature is always below 0.5 °C and always less than 5 % relative humidity in case of hygrothermal simulation. If only a mass balance is used to determine the interior relative humidity, the modeled daily changes are way higher and do not represent realistic fluctuations. This allows concluding, that mean temperature and humidity conditions over a year as well as short time fluctuations are well represented by the simulation.



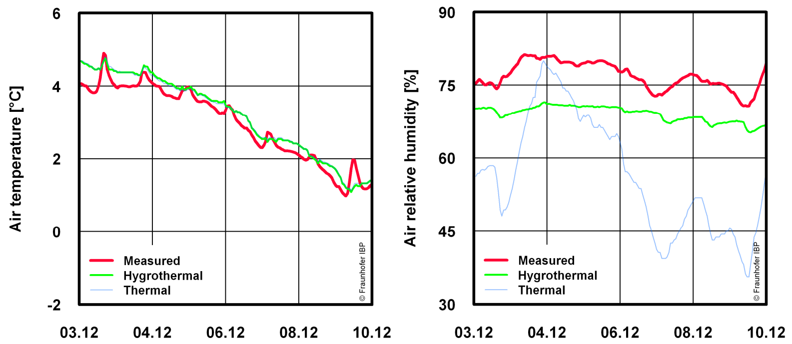


Fig 5 Simulated and measured air temperature and absolute humidity in the cave in Juli and December

4. Application of Active and Passive Measures

4.1 Surface Coating

Varying the sd-values of the walls in the cave is one of the analyzed variants. The idea is to analyze the effect of the inner wall covering, e.g. the selection of different paints. The influence of the surface coating is assessed by simulating the base case with inner wall sd-values of 0 m, 0,1 m, 1 m, 10 m and 100 m. The impact on the humidity on the wall surface and the humidity of the indoor air is shown in Figure 6.

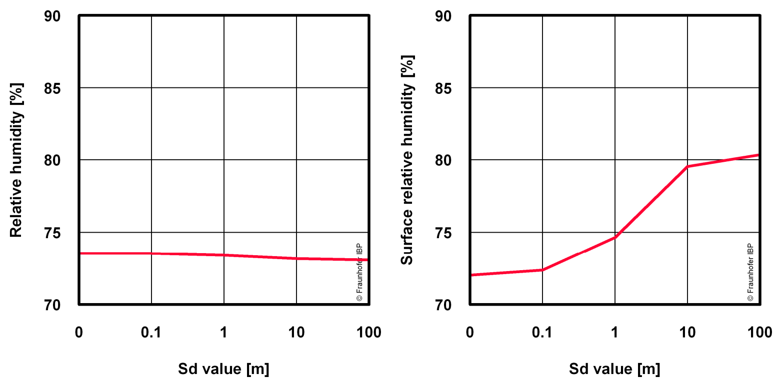


Fig 6 Impact of different sd values on the realtive humidity of the indoor air (left graph) and of the relative humidity on the surface of the south wall

It is noticeable that the sd-value of the wall has low influence on the indoor air humidity. This can be expected in the case under investigation, as no inner moisture loads are modeled. Covering the walls with an impermeable coating increases the moisture on the surface of the walls, though.

4.2 Adaptive Ventilation

A controlled ventilation system compares the absolute humidity inside and outside the building. Whenever the outer humidity is lower, a ventilator starts bringing dryer air into the building. Also, boundary conditions for the lower temperature can be given, as well as a maximum allowed range of RH change in the last 24 hours. That way the indoor humidity can be reduced. In this case an adaptive ventilation system is entered with an assumed air change rate of 3 ACH for ventilation during all periods with lower exterior absolute humidity than inside and while exterior temperatures are above 0°C.

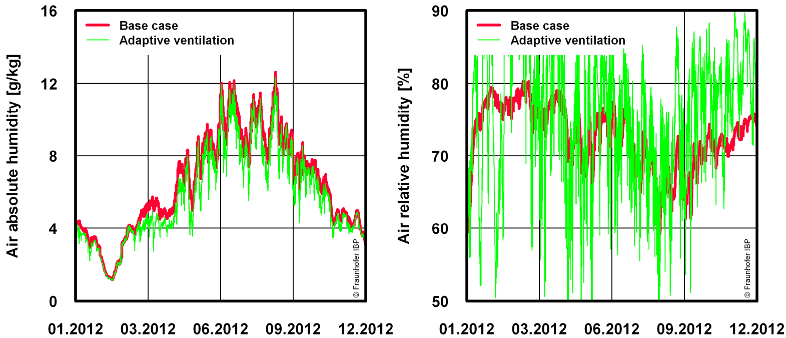


Fig 7 Absolute and relative humidity of the indoor air calculated with an adaptive ventilation system

Figure 7 shows that the absolute humidity inside the church can be reduced, especially in the transition periods. But by venting in dryer, but colder, air, the daily fluctuations of the relative humidity are much higher with adaptive ventilation. The relative humidity is even way more often above the relative humidity of the case without adaptive ventilation and therefore way above the critical limit for mould growth of 80 % RH. This is due to the lower interior temperature caused by the increased air exchange with colder exterior air.

4.3 Full HVAC

An ideal HVAC system is assumed which maintains the inner climate within defined limits. As design conditions temperatures above 0°C and relative humidity between 40 % and 60 % is chosen. The heating power for the period is nearly 1000 kWh which is required at the very cold period in February (see Figure 8). Dehumidification in contrast is required throughout the whole year. In sum 623 kg water are removed from the inner air to maintain the relative humidity below 60%.

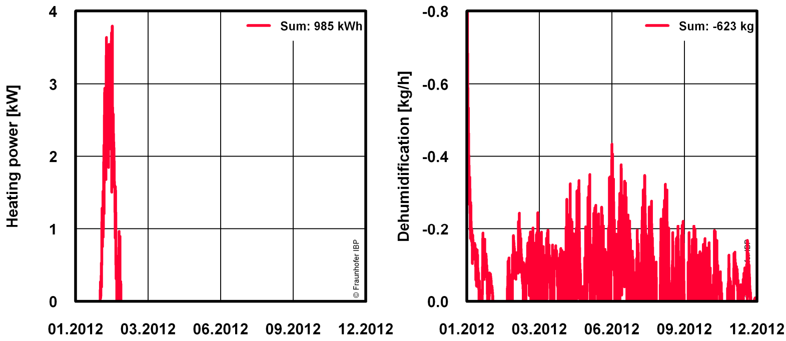


Fig 8 Heating power and dehumidification to maintain the designed conditions in the cave

Sometimes the higher temperatures are required to be maintained. Figure 9 compares the required heating and dehumidification for different set-point temperatures while keeping the relative humidity between 45 % and 55 %.

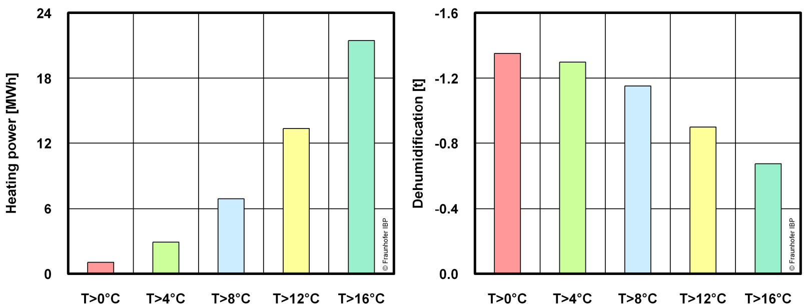


Fig 9 Heating power and dehumidification to maintain different inner minimum temperatures

The heating demand increases exponentially with rising set-point temperatures whereas the dehumidification demand decreases slowly. In a real environment it is to decide if the energy demand for heating and dehumidifying buildings like the example building is always justifiable or if other passive measures are as good for climate stabilization as a full HVAC.

5. Summary and Conclusions

A church in Roggersdorf, Germany, was equipped with comprehensive measurement devices to monitor the conditions in the different zones of the church and on and in building components. The measurement results were used to verify a building simulation model. The verification of the simulation showed, that it is possible to predict the temperature and humidity conditions in the church. Mean values as well as short time fluctuations were well reproduced. But for an accurate modeling of the interior relative humidity a hygrothermal simulation needs to be performed which accounts also for moisture exchange with the building envelope and moisture transport processes inside the building components.

After the successful verification of the building model some simple measures were applied to show their effect on the hygrothermal performance of the building. Adding an additional water vapor surface resistance to the inner surface, e.g. with an impermeable paint, was shown to be critical due to the resulting higher surface humidity's. Adaptive ventilation can also be critical. The simulation showed that the short term fluctuations of the inner relative humidity increases. The application of an ideal HVAC system to ensure that the conditions are kept within certain limits showed that the energy demand for heating and cooling can be quite high.

It can be concluded that the application of a hygrothermal whole building simulation software allows to realistically accounting for the hygric and thermal inertia of unheated historic buildings. Possible active and passive measures to be applied for these buildings can be assessed beforehand in the simulation and suitable solutions can be determined.

6. Acknowledgement

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