# ADAPTIVE VENTILATION FOR OCCASIONALLY USED CHURCHES

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## ABSTRACT

**Many churches in Denmark and Sweden are rarely used for services or other activities. A simple climate control strategy is essential to avoid mold growth and attack by insects. Ventilation is the traditional method to reduce the humidity but it sometimes has the opposite effect. The ventilation needs to be controlled only to take in outside air, when it is drier than inside, to provide acceptable conditions. Adaptive ventilation was applied in three churches in Denmark and Sweden, each with a different heating regime. Nødebo church had intermittent heating for services in winter with basic heating to a constant temperature in between. Adaptive ventilation was only applied in the summer. The air was drawn from the outside without preheating. The ventilation reduced the relative humidity, but increased the short term fluctuations. Tyvelse church had intermittent heating for services during the winter, but no heating in between services. The air was drawn from the attic in order to gain heat from solar radiation in summer. It was assumed that preheating would raise the inside temperature slightly, and thereby reduce the RH, but no effect was observed. In Hangvar church, the intake air was preheated by a solar powered heating element. The preheating had only little effect on the interior RH, probably because of the large thermal capacity of the building itself. This is the major restriction for adaptive ventilation to work in very heavy buildings. A positive side effect is that the air quality inside the churches was improved by the ventilation because bad smells were removed.**



## Keywords

Adaptive ventilation, climate control, rural church, mold growth


## 1. Introduction

Many medieval churches in Sweden and Denmark are rarely used, because the population is decreasing in the rural areas. These churches are only heated for services a few times during the winter, and remain cold for most of the time. In the absence of background heating, the interior climate is humid all year, with an average RH above 80 %. Appropriate climate control is essential to prevent mold growth and attack by insects.

Air exchange through infiltration or ventilation has an important effect on the indoor climate in general and relative humidity in particular. Infiltration is the random air leakage through cracks and openings in the building envelope. Ventilation is the deliberate intake of 'fresh' outside air and simultaneous outlet of 'used' air from the interior. It is mainly used to ensure human health and comfort by removing a surplus of moisture, pollutants or bad smells.

Ventilation can either be driven by natural pressure gradients or by mechanical means. Natural ventilation is free of energy use, except for the heat loss in the case of heating. Opening windows and doors is a simple way of controlling the intake of outside air. But it is difficult for a person to decide when the climatic conditions are favorable for adjusting the relative humidity, and when it will have the opposite effect. It is also impossible to know if the flow rate is large enough, because it relies entirely on the random air movements. Natural ventilation is therefore not recommended for humidity control. Mechanical ventilation is required either to inject outside air into the building or exhaust air from the building.

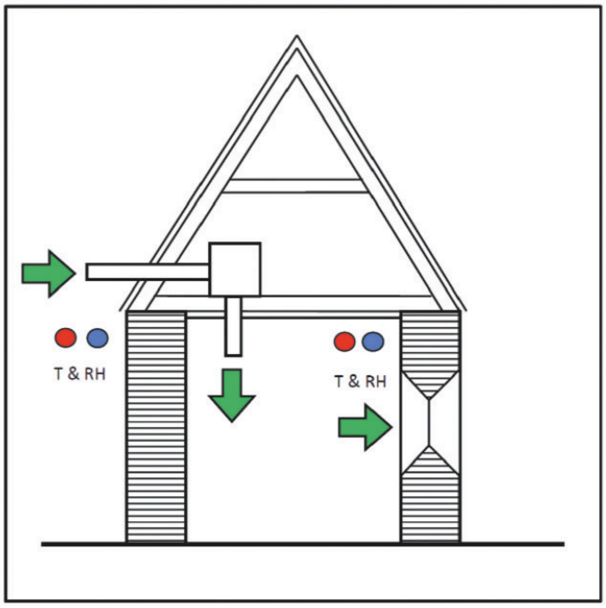


**Figure 1 Principle diagram of a system for adaptive ventilation. The operation of the fan is controlled by a small computer connected to the inside and outside sensors for temperature and relative humidity.**

Comfort ventilation is usually controlled only by the interior conditions, assuming the outside air is always a benefit. Contrary to this, adaptive ventilation also takes into consideration the outside conditions. This way adaptive ventilation is used to maintain a lower level of moisture content in the inside air than outside. This is done by taking advantage of the natural diurnal end seasonal variations in the outside absolute humidity. The outside air is taken in only when the moisture content is lower than inside. Equally important is not to ventilate when the outside air is more humid than inside.

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The concept was implemented in the Torhalle in Lorsch, Germany to avoid condensation on the wall paintings. Electric fans were controlled by indoor and outdoor climate sensors to keep the dew point of the inside air below the wall surface temperature [6]. However, the system was only in operation for a short time. In the church in Zillis, Schwitzerland, controlled ventilation was used to stabilize RH in favor of the painted wooden ceiling [3]. The effort was not very successful due to a large infiltration rate and the fact that ventilation was turned off in winter to reduce heat loss. A seasonal use was tested in the Antikentempel in Potsdam-Sanssouci Park to prevent mold growth on the walls and ceiling. From May to September there was adaptive ventilation by a fan mounted in the skylight [1].

In the above mentioned cases, the control system was custom designed for the individual purpose. But there are commercial solutions available which are intended for attics and crawl spaces under houses [4]. Such equipment was used in the basement of a historic building in Gotland [2]. This study 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 medieval churches due to evaporation of moisture from the floor or though the walls. In the present work a standard control system for adaptive ventilation was tested for use in churches in Denmark and Sweden.

## 2. Equipment

The system for adaptive ventilation has a control unit, two sensors for temperature and relative humidity, a ventilator, an exhaust valve and a hose for air intake (fig. 1). The ventilator has a capacity of 500 m$^3$ per hour, if there is no resistance to air movement. In practice the air flow will be less. The sensors are mounted inside and outside, and connected to the control unit. The control unit has a computer to calculate the water vapour pressure of the inside and outside air. When the inside water vapour pressure exceeds that outside by 10 %, the computer activates a switch to turn on the fan. There is no limit for the inside RH, but a lower limit of -10 ˚C for the outside temperature. The inside and outside temperature and humidity is recorded by separate data loggers to evaluate the effect of ventilation

## 3. Case studies

### 3.1. Nødebo Church

Nødebo Church is situated in a forest area on Zeeland, Denmark. It has a medieval nave and chancel with outer walls made of boulders laid in lime mortar, and vaults of fired bricks. The total volume of the space is 400 m$^3$ . Nødebo church has intermittent heating for services in winter with basic heating to a constant temperature of 8˚C in between. The climate record for three years is shown in fig. 3. The relative humidity inside the church is down to 60 %RH in winter due to the background heating. In summer the RH gets above 90 %RH if nothing is done to avoid it. This happened in the summer of 2011, where the data logger failed for some time due to condensation on the sensor. The main problem in summer is that the temperature is too low. It is a common problem for many churches that the solar gain is little, because there are only few and small south facing windows. Summer heating was implemented the year before in 2010 to overcome this problem. By heating the church a few degrees above the outside average to a maximum of 23 ˚C, it was possible to keep the RH below 80% most of the summer. Still the RH was above 80 % for a few weeks during September and October. Summer heating is a possible, but not very energy efficient solution to the problem of high relative humidity in the summer.

**Figure 2 Exterior view of Nødebo Church from the south east. Solar heating of the interior through the small windows is too little to heat up the interior in summer.**

Adaptive ventilation was applied in the summer 2012 by the reuse of an old exhaust ventilation system. The fan was located in the attic of the entrance porch and the air was drawn through a grate in the wall on the organ pulpit. The fan had been controlled manually to operate after the Sunday ceremony. A control unit for adaptive ventilation was installed, which would start the fan at any time, if the outside air was drier than inside. The air intake was though leaks in the windows. The ventilation was on from the end of May until the end of October. The climate record for 2012 is shown in fig. 3, and the period with adaptive ventilation is the blue shaded area. In this period the inside RH was 65 – 90 % and the temperature up to 19 ˚C in August, apart from a few occasions with comfort heating to 22 ˚C.

It seems that the short term fluctuations in RH were larger with adaptive ventilation than before. This is a known problem associated with ventilation in general, that the RH gets more unstable. The RH over the summer was clearly lower than the year before, but still too high to prevent biological activity. However the bad smell of fungi was entirely gone. A further benefit of the ventilation was a significant improvement of the air quality. The effect of ventilation on an annual range was evident when comparing the mixing ratio of the inside and outside air (fig 5). Over the summer the water vapour content inside was almost equal to that outside. During the winter the inside was always more humid than outside. This is because the winter heating promotes the evaporation of moisture from the floor or walls to the interior. This is an argument against heating for controlling the RH, and to use adaptive ventilation all year.

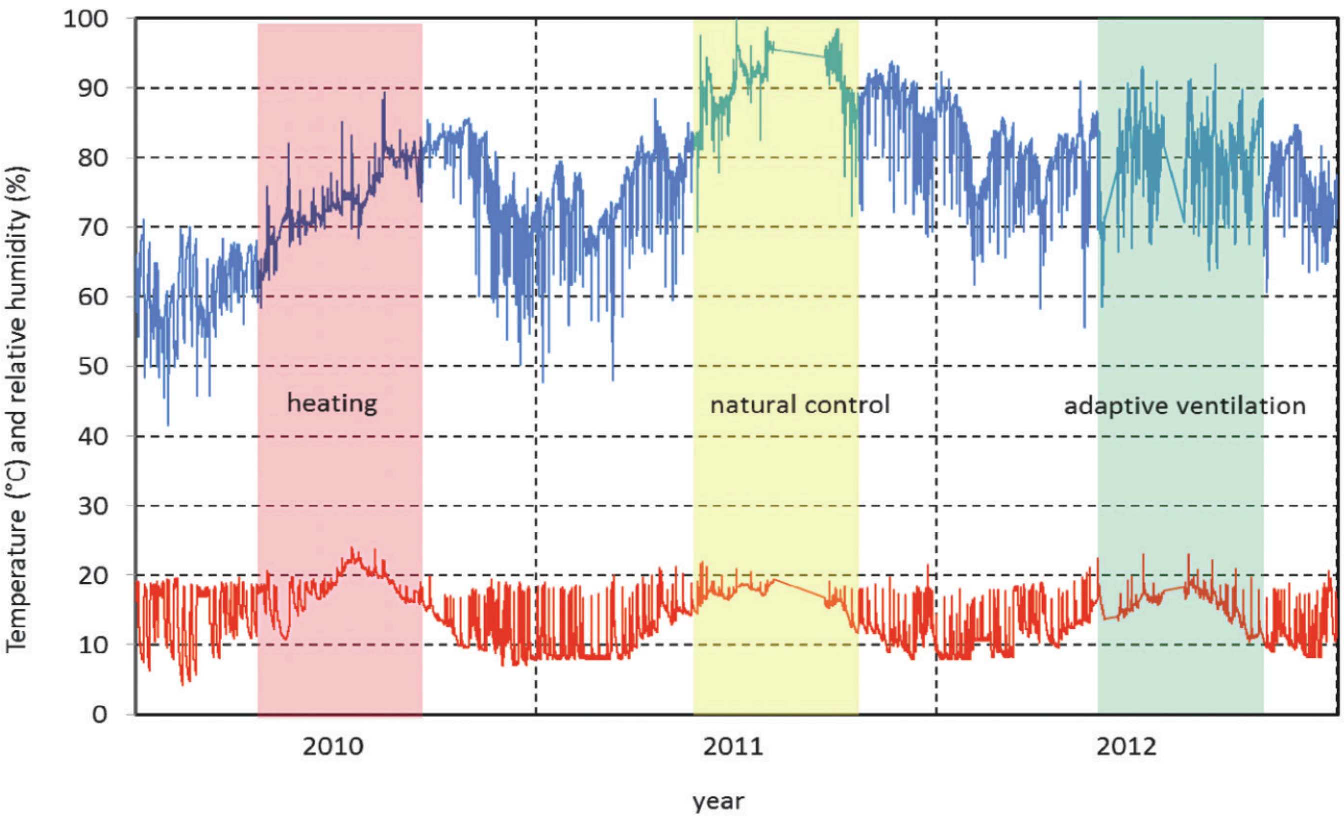



**Figure 3 Climate record from Nødebo Church over three years. The first summer had heating to keep the RH below 80%. The next summer had no control and the last summer had adaptive ventilation**

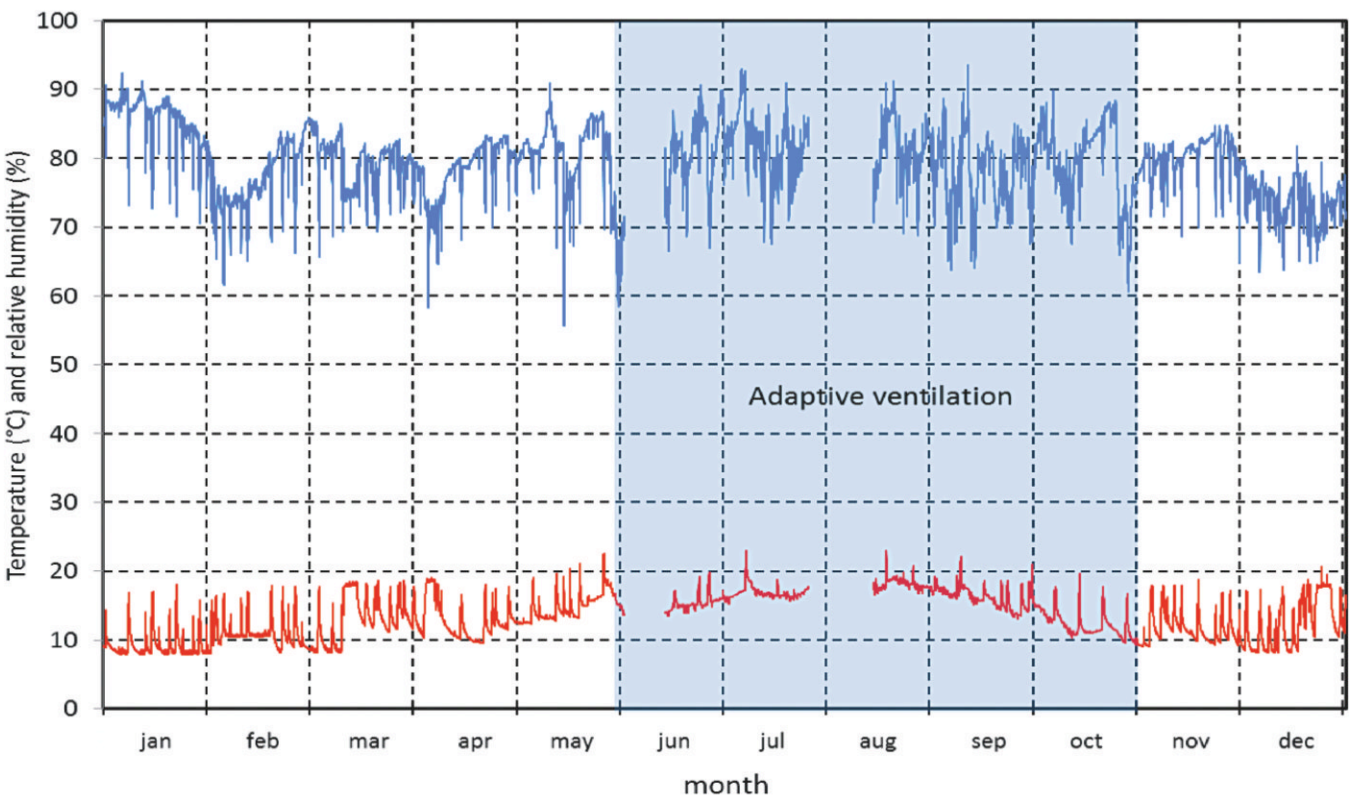



**Figure 4 Climate record from Nødebo Church in 2012. Adaptive ventilation was operated from the beginning of June until the end of October, when background heating was started. Figure 5 The mixing ratio of the inside air (green) and outside air (blue) in Nødebo Church shown as a moving average over 7 days. The inside MR is higher than outside in winter, but equal in summer due to the ventilation.**

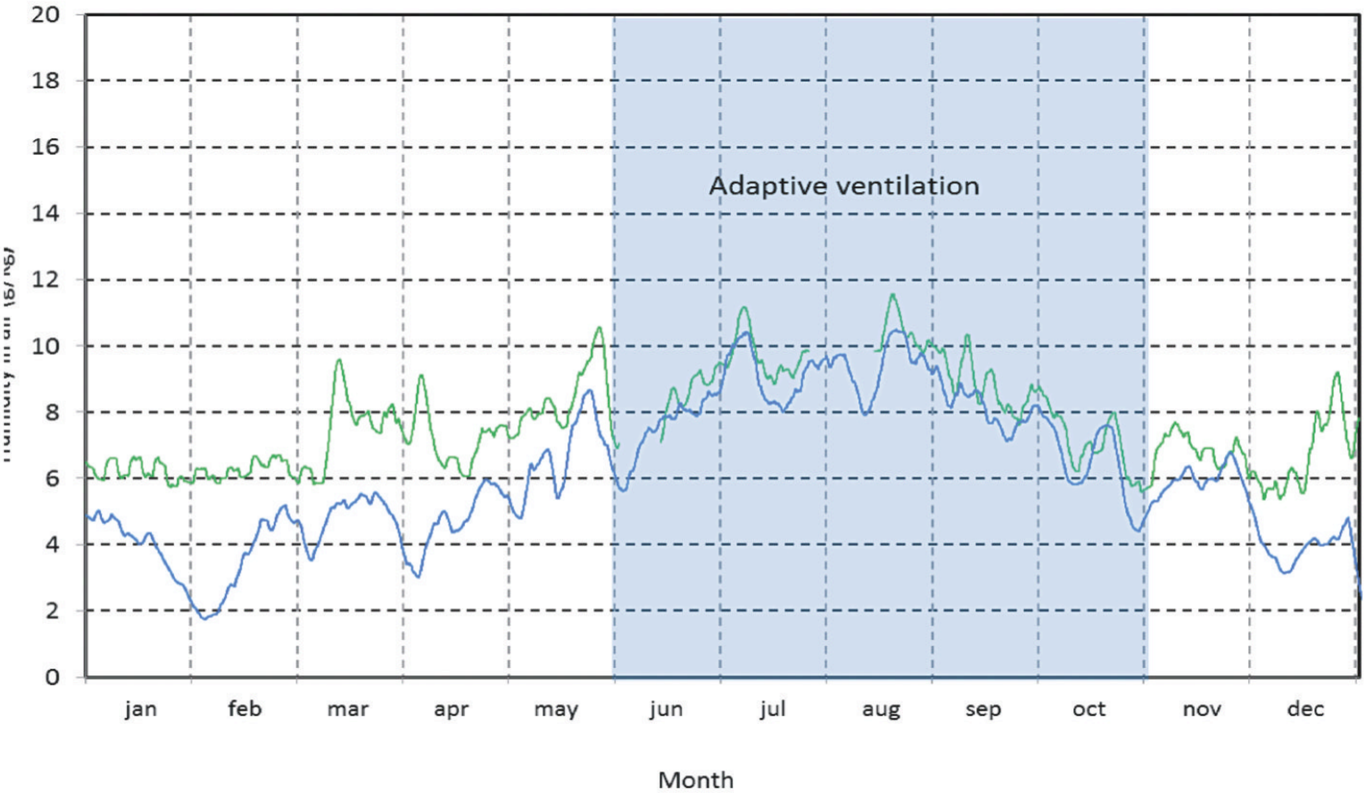



**Figure 5 The mixing ratio of the inside air (green) and outside air (blue) in Nødebo Church shown as a moving average over 7 days. The inside MR is higher than outside in winter, but equal in summer due to the ventilation.**

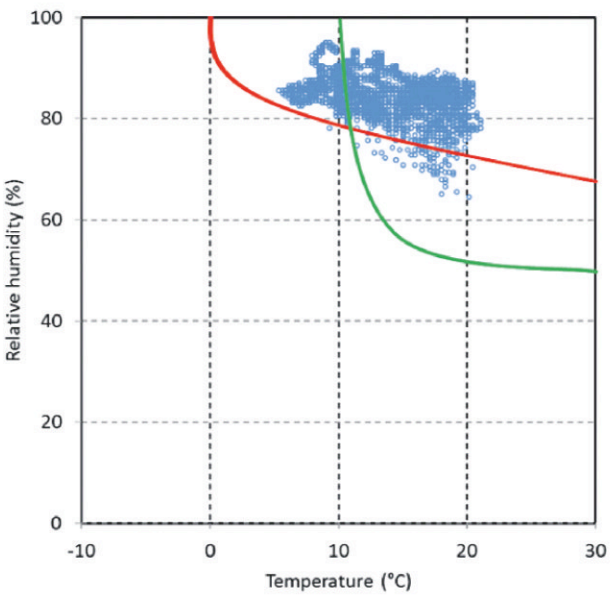
## 3.2. Tyvelse church

Tyvelse Church is situated in the countryside on Zeeland, Denmark. It has a medieval nave and chancel with outer walls made of boulders laid in lime mortar, and vaults of fired bricks. The interior volume is app. 400 $m^3$. The wall paintings in the chancel vault have a severe infestation of mold growth, related to the interior climate [5]. The church is rarely used, so the high RH is not due to human activity. The hourly data for temperature and relative humidity from 1 September 2006 to 31 August 2007 is shown in the upper diagram in fig. 7. The temperature ranged between 5 °C in winter and 22 °C in summer. Despite the basic heating in winter, the interior RH was between 80 % and 90 % most of the year with an annual average RH at 85 %. The red line indicates the limit for mold growth [7], whereas the green line is an approximation of the conditions needed for wood worms to develop [8]. It is evident that the climate was ideal for biological activitity.

An old ventilation system installed some years ago was reused for adaptive ventilation. An exhaust fan in a window had been controlled by a timer to operate at the same time each day. This was replaced by the control unit for adaptive ventilation, which would start the fan at any time, if the outside air was drier than inside. The fan had a damper which would be closed when the fan was not running. The air intake was through 12 small ducts in the lower part of the vaults. These openings remained open at all times. The advantage of taking the air from the attic was that there would be some preheating in the summer. On sunny days the temperature in the attic was higher than in the nave below due to the solar gain. It was assumed that warm air from the attic would raise the interior temperature in the nave slightly, and thereby lower the RH.

**Figure 6 Exterior view of Tyvelse Church from the northeast. The air supply to the nave and chancel was drawn from the attic to gain heat from the solar radiation to the tiled roof.**

The climate record of one year from 1 June to 31 May with adaptive ventilation is shown in the lower diagram in fig. 7. The basic heating in winter was abandoned, so the winter temperature was lower than before, below 0 °C. The summer temperature was no different than before, up to 22 °C. This indicates that the attempt to preheat the intake air through the attic was not very successful. The annual average relative humidity was 78 % which is lower than before, but there were still episodes with RH above 90 %. The annual climatic variation was larger than before, but the short time fluctuations did not increase. Apparently the attic served the purpose of ameliorating the outside air before it was drawn into the nave and chancel. It is difficult to determine if the reduction in RH had an effect on the risk of mold and wood worms in general. But it is evident that the lower temperature in winter is a good measure against biological activity. Perhaps the main benefit of adaptive ventilation is that it excludes basic heating in winter.



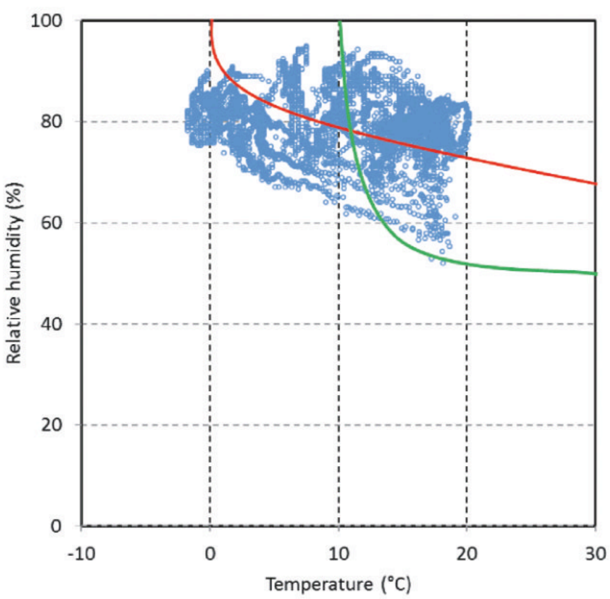




**Figure 7 Climate record in Tyvelse Church with basic heating in winter (above) and adaptive ventilation (below). Data periods are 1 September 2006 – 31 August 2007 and 1 June 2011 – 31. May 2012. Limits for mold growth (red line) and wood worms (green line)**

### 3.4. Hangvar Church

Hangvar church is situated on the north West part of the Swedish island Gotland in the Baltic Sea. The church was built in the 13th century and the outer walls and vaults are constructed in limestone and lime mortar. The total volume of the church is 750 m$^3$. Hangvar church is intermittently heated for services and unheated in between. The church was very humid and for the period 1 July 2010 to 30 June 2011 the average of the relative humidity was 81 % (fig 9, above). There have been recurring problems with mold growth. In the winter the indoor temperature can go below 0 °C and in July it can go up to 20 °C, but most of the time summer temperatures stay below 18 °C. The parish members have complained about a bad smell and the clerk has observed mold growth on the northern outer wall.

In August 2012 adaptive ventilation was installed. A ventilation duct was installed from an opening in the tower staircase to the ventilator and then through a temporary tower door with an inlet valve. The exhaust air goes out through leaks in the building envelope, mostly windows and doors. Previous experiences have shown that there is a codependency between mixing ratio and temperature. Often when the outdoor air is dryer than the indoor air it is also cooler than the indoor air. Cool air is counterproductive when it comes to lowering the relative humidity. To prevent this type of ventilated driven cooling of the church, the adaptive ventilation system was fitted with a preheater drawing energy from solar photovoltaic panels placed just outside the churchyard fence.

**Figure 8 . Exterior view of Hangvar Church from the south. The photovoltaic elements for preheating the inlet air is located outside the churchyard fence.**

Based on measurements for less than a year, a distinct improvement over the winter can be seen as compared to previous conditions (fig 9, b). The average relative humidity has decreased by approximately 10 %. The indoor climate has been below mold risk levels most of the time but not always. The church staff report that the air feels much better and there has been no visible mold growth. The temperature record for 7 months during winter and spring is shown in fig. 10. In winter the temperature inside is above that outside most of the time. There are few heating episodes for services, but the temperature rise is short lived. In spring the inside follow the outside average temperature, but sudden periods of warm outside weather does not penetrate to the inside. It seems the inside temperature is mainly controlled by the outside average with a substantial delay due to the thermal inertia of the floor and heavy walls. The benefit of preheating the intake air is difficult to identify, possibly because the solar panels mainly produce power in the summer period, which was not included in the data.

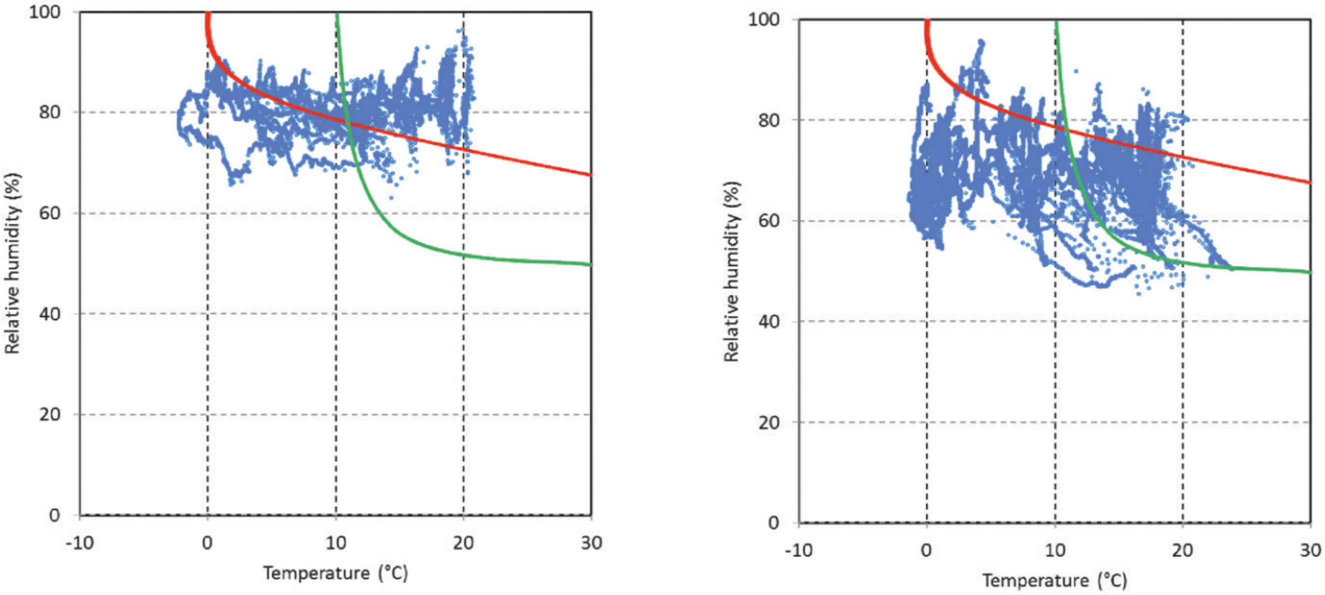



**Figure 9 Climate record in Hangvar Church without ventilation (above) and with adaptive ventilation (below). Data periods are 1 July 2010- 30 June 2011 and 10 July 2012 – 31 May 2013. Limits for mold growth (red line) and wood worms (green line)**

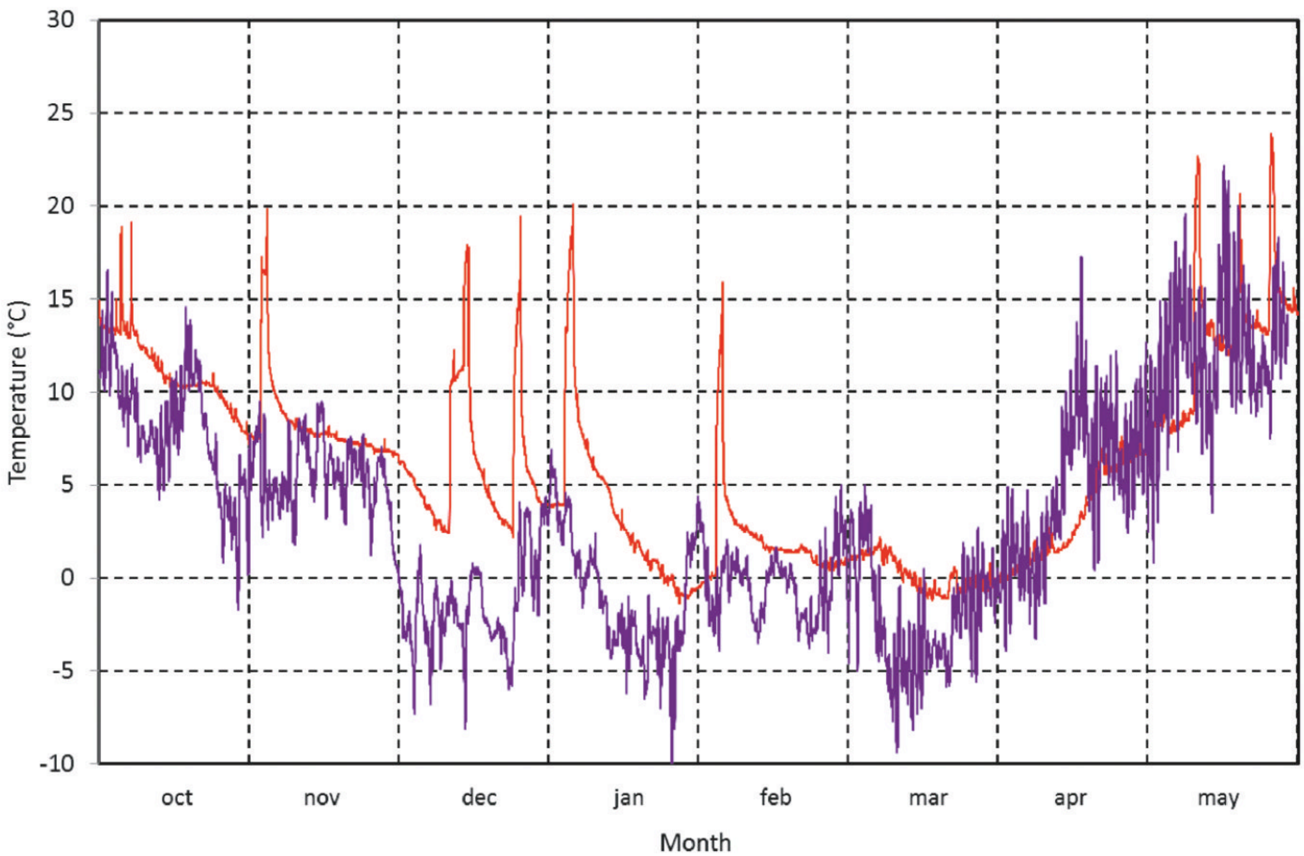



**Figure 10 . Inside temperature (red) and outside temperature (purple) in Hangvar Church 2012/2013.**


**Figure 11 . The mixing ratio inside (green) and outside (blue) in Hangvar Church 2012/2013**

The mixing ratio of the inside and outside air is shown in fig. 11. The inside humidity follows that outside most of the time, except for the heating episodes, where the inside air holds 2-3 g/kg more water vapour than the outside air. There is human activity only for a short while, so the increase in humidity is due to evaporation from the interior surfaces of the building and the furniture. The release of humidity is actually an advantage because it stabilizes the RH during the heating episodes. The drop in RH would be much larger if the interior of the church had less humidity buffer capacity. The surplus of moisture is soon removed by the ventilation, and the temperature gradually falls back to the starting point. These heating events illustrate the paradox of heat for humidity control, when the humidity buffer capacity of the building is large. The preheating of the intake air may have the same effect. Further studies will assess the effect of solar powered summer heating more in detail.

## 4. Conclusions

There is a need for a low energy climate control strategy for churches, which are used occasionally. The aim is to prevent biological degradation, so the average RH and the variation is the important parameter. Adaptive ventilation is an efficient method for churches with an internal source of humidity. It will reduce the inside mixing ratio towards the same level as outside. This is sufficient to prevent mold growth when the temperature is low enough. But in summer additional climate regulation is required in buildings with little solar gain. This is a very common situation for medieval churches, because the windows are few and small. Drawing the outside air through the attic will not give any supplementary heating, but it will reduce the short term fluctuations, which is otherwise induced by adaptive ventilation. Preheating of the intake air with an electric element will possibly raise the temperature slightly and thereby lower the RH. This solution is almost energy neutral if a solar panel is installed to supply the heating power. Adaptive ventilation is a robust and reliable climate control solution, which is important for rural churches, where resources for maintenance are limited. The challenge remains that the installations must not interfere with the use of the churches, and the visual and physical impact should be minimized.

## 5. Suppliers

Adaptive ventilation system: Corroventa AB, Mekanikervägen 3, 564 35 Bankeryd, Fax +4636-37 18 30, E-post: mail@corroventa.se

Climate monitoring: Gemini Data Loggers (UK) Ltd, Scientific House, Terminus Road, Chichester, West Sussex, PO19 8UJ, United Kingdom, Tel: +44 (0)1243 813000, Fax: +44 (0)1243 531948

Climate monitoring: Testo AG, Testo-Straße 1, 79853 Lenzkirch, Deutschland, Tel: 07653/681-0, Fax: 07653/681-1559, E-Mail: info@testo.de

## 6. Acknowledgements

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