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Energy use and indoor climate of conservation heating, dehumidification and adaptive ventilation for the climate control of a mediaeval church in a cold climate

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ABSTRACT

Mediaeval churches hold substantial historical and cultural values, organs, altars, paintings that need to be preserved. Many of these churches have no climate control systems installed. Thus the indoor climate is mainly determined by the outdoor climate. Focus in this study is on the possibilities to improve indoor climate in originally unheated churches to prevent and protect churches from mould growth and disintegration of wooden parts. A case study in the Church of the Holy Cross in Harju Risti, Estonia, was conducted to test two different indoor climate control systems: dehumidification and an air-to-air heat pump. The systems were controlled with relative humidity to prevent the indoor humidity from dropping low enough to start wood cracking and salt drying in the walls. Based on field measurements, simulation models were calibrated and used to test different climate control systems and their impact on churches' indoor climate and energy consumption. Our study showed that the adaptive ventilation performs well in high indoor humidity conditions, annual energy consumption of conservation heating with a heat pump is the lowest, and dehumidification is most effective during the cold period.

1. Introduction

Churches are an important part of cultural heritage and like museums, they contain a lot of artwork, the preservation of which is important for society and culture. If dampness and mould growth can be avoided, artistic wealth may survive for centuries in unheated churches [1]. Unfortunately, damage mainly caused by a damp environment is familiar for mediaeval churches [2,3].

Mediaeval churches were originally built and used unheated for centuries. Indoor climate in churches without any climate control is mainly determined by the outdoor climate and hygrothermal performance of the building envelope.

Low thermal resistance of the structures of a church causes freezing of the church in a cold climate. High thermal mass of structures keeps them cool during spring and summer. At higher moisture contents of the outdoor air, moisture enters through air leaks or by ventilation indoors and could condensate on the wall, floor, or ceiling surfaces. Availability of water or high relative humidity (RH) is the most important precondition for microbiological growth (mould, bacteria, and algae), decay, or soiling of surfaces, condensation on or within materials. Microorganisms on the surfaces can cause structural and aesthetic damage of paintings, stucco, wooden objects or even stone and stained-glass windows [4–8].

Freezing conditions in a church may reduce participation in services. The desire to provide more comfortable thermal conditions for congregations is a motivation to add heating systems in churches. Therefore, during the last century new heating systems have been installed in many European churches. However heating systems that are used for thermal comfort may present harm to the interior and the cultural heritage itself. Arnold and Zehnder [9] showed the nonrecurring deterioration of wall paintings in a monastery to be a result of the lowered relative humidity by a central heating system. Melina and Legnérb [10] showed a slight correlation between damage to the paint on the pulpits and energy released in the churches. Periodic heating for sermons, weddings and funerals in churches can cause high temperature and relative humidity fluctuation which causes extensive damage to a church interior. In many cases, the comfort requirements have had dramatic consequences on artwork [1] and organs [11] in churches. Varas-Muirel and Martinez-Garrido [12] analysed a parish church, where the forced hot-air system was found to induce wide fluctuations in indoor thermal–hygrometric (T/RH) conditions, in turn translating into the temporal and horizontal stratification of temperature and relative humidity.

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Providing suitable indoor climate conditions for mediaeval churches needs advanced climate control systems and appropriate usage. The preservation of culturally valuable structures and details is the prioritised purpose. It is important to ensure that objects of cultural value are preserved in the conditions which will not harm their properties or value. It is essential also from a user's point of view, as well as economy (cost of installation, use, and maintenance) and thermal comfort [13]. Different climate control solutions could be appropriate for different purposes. Broström and Leijonhufvud [14] studied conservation heating to control relative humidity in order to better preserve historic buildings and their interiors. They found that there is a huge potential for energy saving by using heat pumps and replacing thermostats with hygrostats. They concluded that further studies should take into account transient effects, dynamic indoor climate requirements, more representative data for the ambient climate, a wider geographical distribution. Simulations and detailed field studies are needed to better understand conservation heating. Also, Schellen and Neuhaus [15] point out in their conservation heating study in a historical building that future work is needed to identify in the climate conditions in which conservation heating is feasible.

With dehumidification, a suitable indoor climate for cultural heritage is achieved by lowering the indoor air moisture content. Janssen and Christensen [16] showed that auxiliary dehumidification is required to provide good conservation conditions for museum storage spaces. Larsen has also tested the performance of dehumidification in a Danish church. Larsen and Broström [17] showed that dehumidification could be more energy efficient than heating with a heat pump if the air exchange rate is lower than 1 per hour. Hagentoft and Kalagasidis [18] showed by field measurements that adaptive ventilation could provide more stable and lower relative humidity levels during winter than cold attics with a traditional ventilation design. In their study, Broström et al. [19] showed that adaptive ventilation, controlled with respect to absolute humidity inside and outside a building can be used to reduce RH below risk levels for biodeterioration.

There are many studies on the available methods to control the climate inside historic buildings. Nevertheless, a deficiency in studies prevails where different strategies are simultaneously measured, modelled and analysed. In this study indoor climate and energy performance of three different climate control solutions (conservation heating, dehumidification, and adaptive ventilation) are compared by field measurement and computer simulation to regulate indoor relative humidity in a small mediaeval rural church in a cold Estonian climate. The study shows the performance and efficiency of systems throughout a year in cold climate conditions.

2. Methods

2.1. Description of the church and local climate

The performance and efficiency of conservation heating, dehumidification, and adaptive ventilation to control the indoor climate was tested in a small mediaeval rural church: Church of the Holy Cross (Fig. 1). The church was established between the 13th and 14th centuries. It has massive walls typical of a mediaeval stronghold church, and a choir room and vaulted nave which radiates from its four pillars. A bulky pillar and a low triumphal arch add archaic charm to the church. The net floor area is 300 m^2 and the interior volume is 2330 m^2. There are regular services on every second Sunday and during holy days and irregular services for weddings, funeral, camps, etc.

The church has no active climate control. Indoor climate measurements [20] showed that RH has been high throughout the year, on the balcony 87% and near the altar 90%. This situation is similar to other unheated churches around the Baltic coast [3,21]; it is problematic due to considerable variation and too high RH, causing biodeterioration and damage to wooden objects. It is required to maintain a RH level that prevents the risk of mould growth, reduces fluctuations of air RH annually and avoids too high and too low humidity levels in the church during short term period that could cause flaking, peeling and cracking of wooden sculptures. The lowest measured temperature was −3 °C in February and the highest temperature 20 °C in July on the balcony. Monthly average indoor temperatures varied between −2 and 17 °C. Natural air infiltration varied between 0.3 h^{-1} (without airing through doors and windows) and 0.6 h^{-1} (with airing). The main air leakage sites were holes and gaps in arches, broken panes of windows and cracks around the doors. The air leakage rate at 50 Pascal was q_{50} = 8.3 m^3/(h·m^2) and the air change rate at 50 Pascal n_{50} = 4.2 h^{-1}.

The climate in Estonia can be described as a typical European continental influenced climate with warm, dry summers, humid autumns, and fairly cold winters. Monthly average temperature varies between −17 and +4 during the winter months and +11 and +20 during the summer months. The design temperature for heating capacity varies between −19 and −22 °C. The number of heating degree days at indoor temperature +17 °C is 4160 d °C [22].

2.2. Solutions for climate control

In constant absolute humidity conditions, the relative humidity decreases when the air temperature increases. By conservation heating (CH), the indoor RH is controlled by heating the room to the point where relative humidity is reduced to an acceptable value. In this study conservation heating was provided by two air-to-air heat pumps (AAHP) (Fuji Nordic: 5.6 kW, COP 4.12). The interior device was installed in the north wall of the church's hall, two metres above the floor level (Fig. 2). Air-to-air heat pump for conservation heating (AAHP-CH) was controlled by a humidistat with the setpoint 65–70% between: December 2012 to March 2013 and in May 2013. Between March and May 2013, the AAHP was used for heating purposes without RH control to provide suitable thermal conditions for conservation works.

With dehumidification (DEHUM) the suitable indoor climate for cultural heritage is achieved by lowering the indoor air moisture content. For dehumidification two Munters MCS300 (2 × 9.1 kW) rotary desiccant dehumidifiers were installed on the floor of the church's hall between September and June 2013. Rotary desiccant dehumidification was selected because it is more effective in colder conditions (2 × 0.4 kg/h @ −10 °C and 2 × 1.5 kg/h @ +20 °C) and needs no drainage of condensed water vapour. The setpoint for the RH was 75%. The dehumidifiers worked from September to December 2012 and from May to June 2013.

The third indoor climate control system studied was adaptive ventilation. The adaptive ventilation system only runs when the outdoor air has lower water vapour content than the indoor air and has a potential to dry out the church. With lower water vapour content outdoors, the ventilation starts and supplies dryer air to indoors and extract moist air to outdoors. The outdoor air was only supplied indoors when the water vapour content was lower than inside and the ventilation did not work when the outdoor air was more humid than inside. Adaptive ventilation was simulated with a different capacity of the preheater to heat up the injected air.

The performance of climate control systems was tested for several reasons. For example, the AAHP may use some of indoor heat to defrost an exterior unit. In a cold church the availability of indoor heat is limited. Therefore, some modifications may be needed. During dehumidification 2–3 units can be used in a church. Analysis was needed to determine how the location of a dehumidifier influences the achievement of indoor climate targets.