Design of indoor climate and energy efficiency of the medieval Episcopal Castle of Haapsalu museum

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Abstract – The design of indoor climate in museums in historic buildings is a complex, multidisciplinary problem. The ruins of the medieval Episcopal Castle of Haapsalu in Estonia, are taken into use as a museum. This article presents the results of the designing of indoor climate using energy efficient technologies and field measurements.

Field measurements before design and mould growth on paintings showed the need for improvement of indoor climate. The interaction of indoor air and moisture performance of the building envelope was taken into account in a combined heat, air, and moisture simulation model in IDA-ICE software. The simulation model was calibrated based on field measurements. Simulations analysed performance of different indoor climate control strategies and different outdoor climatic conditions (typical year, warm summer, cold winter, humid autumn).

Simulation results showed that it is difficult to provide strict required indoor climate conditions for museums throughout the year only with passive measures, and indoor climate is strongly dependent of the outdoor climate. In addition, large thermal and moisture capacity of massive limestone walls influenced the indoor climate. Without an indoor climate system there is extensive indoor temperature and relative humidity fluctuation throughout the year. The final design solution includes room heating, humidification during winter, and dehumidification during summer and autumn to ensure suitable indoor climate.

Based on the developed design solution, renovation works started in autumn 2017. The museum will be opened again in 2019, when the museum visitor centre for the Middle Ages exhibition is ready for year-round use.

Keywords – indoor climate; energy simulations; museums; monumental buildings, building physics

1. INTRODUCTION

The design of indoor climate in museums is a complicated and multidisciplinary problem. Integrated design is needed to guarantee the conservation of objects and architecture as well as to reach high performance in energy efficiency, indoor climate and moisture safety in building physics. The solution should fulfil the need for preservation of interior objects and the building itself, as well as providing appropriate climate conditions for human comfort. Indoor climate is strictly conditioned in modern museums [1].
It is popular to accommodate museums in historic monumental buildings that also have heritage value. Usually, these heritage buildings were not originally built for being museums. Therefore, in designing suitable indoor climate in historic buildings, it is necessary to pay extra attention to using the space for building service systems. The building’s massive walls with large thermal transmittance and large heat and moisture capacity need to be taken into account. Poor indoor climate design can cause damage to the artefacts in a museum [2]. The deterioration of wooden objects [3,4], mould growth [5], and indoor air pollution [6] can occur. There have been many case studies on museums in historic buildings classified as monuments. Schellen and Martens [7] conducted a case study in the Netherlands and investigated the indoor climate and HVAC systems in local museums housed in historic buildings. In their study, Kramer et al. [8] showed how different ASHRAE’s museum climate classes influence energy use and protect artefacts. Arumägi et al analysed the renovation possibilities of indoor climate in the Old Observatory in Tartu [9]. A RH-sensitive heating and ventilation system was developed to keep the RH and temperature at target level.

For the preservation of collections in a museum, complex and large climate systems are needed. There are many possibilities to provide indoor climate in medieval buildings with valuable interiors [10,11]. Due to conservation, architectural or economic reasons, it is difficult or sometimes impossible to install these systems into historic buildings.

In this study, indoor climate systems were designed based on measurements and simulations for the museum in the Episcopal Castle of Haapsalu.

2. METHODS

2.1 BUILDING AND MEASUREMENTS

The Episcopal Castle of Haapsalu was built in the 13th century and it is one of the oldest castles in Estonia (Figure 1). It has massive walls typical of a medieval stronghold castle. The castle is located in the city centre of Haapsalu and today, it accommodates a museum and the dome church.
Indoor climate measurements in the castle were carried out in autumn 2015 to obtain data for the calibration of the indoor climate simulation model. Temperature and relative humidity (RH) were measured with HOBO U-12 001 data loggers with the interval of 15 minutes in total 9 locations: 3 located in the dome church, 2 in the castle cellar, 2 on the first floor of the castle, and one on the third floor of the castle.

2.2 SIMULATION

Since the envelope of the dome church has a massive heat and moisture capacity, it is essential to use dynamic computer simulation to calculate the church's indoor climate and energy usage. IDA Indoor Climate and Energy software was used for indoor climate and energy simulations. This software is meticulously validated, allowing the modelling of a multi-zone building, internal and solar loads, outdoor climate, HVAC systems, dynamic simulation of heat transfer and air flows. The software has also been used in many energy performance and indoor climate applications [12–14]. The comparison of the simulation model was done with outdoor measurements from October to November 2015 with good agreement in temperature and satisfactory agreement between the measured and simulated moisture content. Four different climate conditions were used to test how different climate conditions affect the indoor climate: average year, warm summer, humid autumn, and cold winter, Table 1.

Table 1. Simulation cases. Targets for indoor climate were: $t_i > 10 \degree C$ and RH 40-70 %.

<table>
<thead>
<tr>
<th>Simulation case</th>
<th>Outdoor climate</th>
<th>Heating</th>
<th>Ventilation</th>
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<tbody>
<tr>
<td></td>
<td>Estonian TRY</td>
<td>Winter</td>
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<td>7</td>
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</tbody>
</table>

Winter period heating of +10 \degree C was taken as a base line (case 1). Conservation heating was added to prevent the relative humidity to rise above the desired set point (case 2). When room relative humidity exceeded the given set point of 70 % RH, the heater would start to work to decrease the RH level in the room. Two different ventilation airflow rates were used in the different cases of simulations: constant airflow rate of 1 l/(s•m$^2$) and variable airflow rates for day and night were used when 2.5 l/(s•m$^2$) was used from 10:00 to 18:00 and during night, airflow rate of 0.3 l/(s•m$^2$) was used. Different airflow rates were used to simulate more real conditions, where during day time, greater air change rate would be used.
during museum visiting hours. A water surface was used to simulate the massive heat and moisture capacity and moisture transfer between the room and the walls. Water surface of 25 m² was received with the model calibration (cases 1 and 2). A water surface of 4 m² was used in two simulations to see how indoor climate and the energy consumption of climate control systems would change after a longer period of time when the massive walls have dried out (cases 3 and 4). Humidification was added to keep the minimum RH of 40% in the room (cases 5-7). People were added to the simulation to see how their presence would change the indoor climate. Two groups of 20 people each were added to the simulations for two hours, from 11:00 to 13:00 and 14:00 to 16:00 (cases 6 and 7).

3. RESULTS AND DISCUSSION

3.1 INDOOR CLIMATE SIMULATIONS

The model was calibrated according to the field measurements that were carried out in the Castle of Haapsalu between the period from 24 October to 23 November 2015.

The calibration showed that there are few differences between the simulated and measured indoor temperature. Simulation temperature is slightly more affected by the change of outdoor temperature, but regardless of the fact that there is good agreement between the temperature of measured and calibrated model.

Table 2. Simulation results [15]

<table>
<thead>
<tr>
<th>Case</th>
<th>Purpose</th>
<th>The main result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>To determine the need of drying and humidifying systems</td>
<td>Highest room heating power was 60 W/m² to maintain the indoor temperature of +10 °C. The highest heating power applied to the supply air was also with the cold climate, 35 W/m². Relative humidity on the other hand, is very unstable and lies between 18...100%. Simulations show great moisture transfer fluctuation between the room and walls and mainly influenced by the outdoor climate. The highest energy consumption is with cold winter, 151 kWh/(m²•a).</td>
</tr>
<tr>
<td>2</td>
<td>Conservation heating</td>
<td>Annual average temperature increase is 1.3 °C and during the summer-autumn period when the RH is the highest, the average temperature increase is 2.2 °C. Indoor RH was controlled throughout the year to keep it RH 70% by heating the room. The energy consumption is the highest in cold climate, 190 kWh/(m²•a)</td>
</tr>
<tr>
<td>3–4</td>
<td>Cases 1–2 after drying out of the massive lime-stone walls</td>
<td>Indoor temperature difference was virtually unnoticeable. Annual average moisture transfer from the walls to the room was reduced by 0.77 g/m², from 0.83 g/m³ to 0.06 g/m³ and the annual RH was reduced by 7%. Total annual energy consumption with supply air heating, room heating, and CH was reduced from 186 to 172 kWh/(m²•a) (without drying or humidifying in air handling unit).</td>
</tr>
<tr>
<td>5</td>
<td>Variable air-flow: 2.5 l/(s•m²) at the day time and 0.3 l/(s•m²) at night</td>
<td>In summer, larger airflow rate during the day time increases the indoor temperature. The maximum indoor temperature is 28 °C in warm summer and above 24 °C, i.e. 25% of the time in July. RH in the summer time is 37% of time above 70% and in the autumn 41% of the time above 70%. Annual energy consumption compared to simulation case 1 has increased from 132 kWh/(m²•a) to 192 kWh/(m²•a).</td>
</tr>
<tr>
<td>6–7</td>
<td>The influence of heat and moisture production of the people</td>
<td>The room temperature reaches the maximum of 29.0 °C and in July, the temperature is 43% of the time above 24°C. This is 18% more than without people. High relative humidity levels with high enough temperature also make mould thrive. Therefore, in summer, cooling and dehumidification are needed.</td>
</tr>
</tbody>
</table>
Indoor climate simulations showed that it is not possible to provide desired indoor climate parameters (temperature >10 °C and relative humidity 40...70 %) in the exhibition rooms only with heating system without using additional mechanical air drying and humidification.

3.2 STRATEGY AND SOLUTION FOR BUILDING SERVICE SYSTEMS

The mechanical HVAC systems was designed due to the requirements of the heritage conservation. The best indoor climate of the exposition halls would have been ensured by a space-based air-conditioning device integrated with heater, humidification and drying, which would have allowed to keep and adjust indoor climate parameters precisely as required in each room. Central Air Handling Unit (AHU) is supplied with recirculation and heat recovery system.

The design of the HVAC system was complicated because the space for horizontal placement of HVAC pipelines was very limited. Placement of pipelines was also restricted because of the fact that openings (breaking existing walls) into existing walls were allowed only in places that did not have special historical value. There were very few such places in the building.

Considering aesthetic suitability of space-based equipment, high cost, very limited possibilities for connecting this equipment to pipelines and that not very precise indoor climate parameters in the exposition rooms were required, a space-based HVAC solution was abandoned and other alternatives were looked for.

It has to be emphasized once more, that not very high value exhibits are kept in the exposition rooms of the building. Demands on indoor climate are considerably milder than common known museum’s indoor climate requirements. For the client it is important, that the temperature would not drop below 10 °C and would not rise above 25 °C and that the relative humidity would be 40–70 %. If there are such milder requirements, it is possible to discard expensive space-based climate solutions and ensure indoor climate with central systems.

It was possible to deepen the basement floor by ca 0.5 m, which made it possible to install the main pipeline of the heating system under the floor. The heating of the premises was resolved as floor heating, which ensures air temperature of 10 °C during the cold period in the exposition rooms. The heat source of the building is district heating. There was not enough space for placing the ventilation ducts under the floor and under the arch.

The RH of the exposition rooms is kept by the Central AHU, Figure 2.

In winter, when moisture content of the outdoor air is low, the steam injector located in the AHU humidifies the supply air entering the exposition rooms to the extent that the relative humidity of the premises is guaranteed to be 40 %. During the summer period, when moisture content of the outdoor air is high, supply air is dried in the cooling coil, where the moisture condensates out. After the cooling battery, supply air is passed through a heating coil, in which the relative humidity of the air is reduced. The AHU has an integrated compressor-cooling unit that transfers the heat output of the condenser to the exhaust air in the AHU, so there is no need to install an external part of cooler to spoil the exterior of the building.
The cooling unit’s compressor integrated in the AHU is an inverter type and the unit operates on the variable refrigeration flow principle, which allows flexible adjusting of the cooling operation.

Another challenge in the design of indoor climate systems was to find a suitable location for horizontal air ducts heading from the ventilation chamber to the exposition rooms. According to the HVAC designer, the hinterland of the fortress would have been the most suitable location for the horizontal air ducts. Air ducts would have been located near the outer wall underneath the ground (see Figure 3). The underground solution would have caused excavation work in the

![Figure 2. The principle of the Central AHU.](image)

![Figure 3. The first option for ventilation ducts.](image)
court, very likely to have exposed objects of archaeological value in the ground. The client did not want to start archaeological excavations in that area, so other options had to be sought for the placement of air ducts – it would have demanded large scale destruction of heritage masonry. Holes for air ducts were possible only in limited places.

Considering other solutions, it was recognized that within the building it is not possible to find suitable location for horizontal air ducts. The roof over the exposition rooms is planned as a terrace for visitors. The external perimeter of the terrace must be encircled with security barriers for the safety of visitors. A solution was found in cooperation with the architect, namely to design

![Figure 4. Section of the northern wing (right).](image)

![Figure 5. Ventilation ducts and airflow on the rooms in ground floor.](image)
horizontal ventilation ducts inside the barrier (Figure 4 left). In order to avoid ventilation air to cool down and condensate, the protection barrier construction was insulated. Metal air ducts installed in the walls headed from the horizontal air ducts located in the barrier to the exposition rooms (Figure 4 right).

The original ventilation solution option provided that each exposition room had both a supply and an exhaust. Such solution would have ensured better indoor climate. Unfortunately, this solution would have required destruction of too many walls of high historical value and therefore the original principle of the air exchange of the premises had to be changed. The final solution provides supply air in every room. The spaces that are connected to each other with the doors will have extract air only from one of these spaces (Figure 5).

In addition to the aforementioned ventilation system, there are two more AHUs in the building, one serving the reception area of visitors and the second serving the cafe area.

4. CONCLUSIONS

The ruins of the medieval Episcopal Castle of Haapsalu in Estonia are taken into use as a museum. Field measurements before design and mould growth on paintings showed the need for improvement of indoor climate. Indoor climate systems were designed for the future museum using energy efficient technologies. The interaction of indoor air and moisture performance of the building envelope was taken into account in a combined heat, air, and moisture simulation model in IDA-ICE software using different indoor climate control strategies and different outdoor climatic conditions. Simulation results showed that it is difficult to provide strict required indoor climate conditions for museums throughout the year only with passive measures, and indoor climate is strongly dependent of the outdoor climate. The final design solution includes room heating, humidification during winter, and dehumidification during summer and autumn to ensure suitable indoor climate.

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6. REFERENCES


