Analysing indoor Climate in Building Heritage in Slovenia

Marjana ŠIJANEC ZAVRL[1]

ZRMK, Technological Building and Civil Enginering Institute, Ljubljana, Slovenia

Abstract:. *Considerable scientific effort and financial resources are involved in conserving historic buildings and creating appropriate indoor climate conditions and thermal comfort for users, visitors, exhibited objects and the building itself. In Slovenia the idea of establishment of central monitoring system of building heritage was at the first step realised through the co-operation in EU 1383 Eureka/Eurocare project Prevent. In order to improve the indoor conditions in historic buildings and to realise preventive restoration strategy the international co-operation had been established through the EU 1383 Prevent project that on the basis of permanent monitoring of indoor climate in some heritage buildings. The idea of using the "wall warming" method for energy-efficient improvement of microclimatic control in historic buildings was investigated in the further step. In the paper the monitoring campaigns in different types of heritage buildings (heated and unheated) in Slovenia are described and wall tempering system effects on indoor climate are presented more in detail, based on computer simulations and monitoring the performance of demo-installations. Further ideas for research in the field of improvement of indoor climate and consequently integrated preventive conservation are described.*

1. Introduction

Historic buildings represent a very sensitive part of built-up areas. Research into appropriate correct methods, long term monitoring and control of microclimate by the heritage friendly methods would provide necessary criteria for appropriate use of historic buildings under today's more complex indoor climate.

There are several important issues related to microclimatic and damp control in historic buildings to be solved. The first issue is preventing moisture in the buildings and in their elements, most often due to capillary rise resulting from the lack of damp barriers in basements of old structures. The further issues are related to preventing the inconvenient microclimatic conditions in historic buildings (indoor temperature, relative humidity, air velocity) for heritage building fabric and exhibited objects caused either by the installation of standard heating and air condition systems or by incorrect use and running the building.

The purpose of monitoring of indoor climate conditions in cultural monuments is to obtain data about the long term changing of indoor climate and their influence on the material fabrics that are of cultural value. The data are needed in process of mitigation of influence of moisture and temperature changing on the material fabrics of monument that should be preserved in good condition. That is especially the case when indoor surfaces are painted by fresco paintings or covered by other kinds of valuable coatings on wooden panels or textile curtains. The measuring campaigns provide data to be used as valuable source to support museum management concerning the future use of monument halls and protection of exhibited objects. They also help in decision making about the choice of the most suitable heating and ventilation systems in halls opened to public use. The recent years the efforts towards establishing the monitoring system to be used in Slovenian monuments are under way. The first systematic measuring is started in the huge Knight Hall of Brezice Castle.

---

[1] Dr., Civ. Eng., ZRMK, Technological Building and Civil Enginering Institute, Head of Department of Building Physics and Indoor Environment, Dimiceva 12, SI-1000 Ljubljana, Slovenia, e-mail: msijanec@gi-zrmk.si and Associate Researcher at University in Ljubljana, Faculty of Civil and Geodetic Engineering, Research in Materials and Structures

Following the experiences gained from the campaign the improved system is installed in Hrastovlje Church that is one of the most known Slovenian sacral monuments with indoor fresco wall paintings. Approach to monitoring and information gained from it is briefly described in the case of the above mentioned heritage buildings.

In order to improve the indoor conditions in historic buildings the international co-operation had been established through the EU 1383 Eureka/Eurocare project Prevent that generated the idea of using the “wall warming” (also: “wall heating”, “wall tempering”, “Temperierung,”, “Hypothermos”) method for energy-efficient improvement of microclimatic control in historical buildings. Wall heating is an alternative approach to preventive conservation of historic buildings, such as castles, churches, palaces and all other types of representative massive buildings built in cold climate. Wall heating in a very simple version, one or two levels of heating pipes just below the inner wall surface, offers many benefits: moderate heating of the building, good level of thermal comfort for occasional visitors, efficient use of energy, stabile indoor microclimate, warmer wall and prevention of damp raising in the walls, no decreasing of earthquake resistance of structure like in case of wall cutting, less restoration works due to less particles deposition on walls and exhibits. Camuffo [1] stressed the importance of heating walls instead of indoor air in order to exhibit cold wall condensation and damage. Grosseschmidt [2] elaborated the principles of wall heating and anticipated benefits were proven in many case studies [2],[3],[4].

To support wall heating installations in various historic buildings research projects were going on in order to describe more in detail the following areas: indoor climate in unheated and wall heated room, thermal comfort for visitors in wall tempered buildings, energy efficiency and energy use in wall heated historic buildings and drying process in the heated wall with capillary rise.

2. Brezice castle

2.1 Indoor climate management in museum in Brezice castle

The historic building management budgets are rarely sufficient to cover all needs concerning care for buildings, objects and running costs including energy consumption. Therefore maintenance of appropriate indoor climate conditions (thermal comfort) and rational use of energy is appearing to be an important contemporary and future issue in historic building management.

The energy consumption in museums is related to indoor climate conditions, which have requirements of users, visitors, objects and the building itself to meet. The rooms and halls with representative character do not require the same level of thermal comfort as living space, the need for installed power is expected to be lower. It is important that the space heating prolongs the period of holding events in the castle halls into the colder period of the year and that reduces the danger of cold wall effects especially in the case of fresco painted walls.

In Brezice Castle (16th cent., SE Slovenia) (Fig. 1) a microclimate monitoring system was installed [6,7] to analyse the indoor climate influence on progressive deterioration of fresco and covering layer of plaster noticed in last years in the main hall (Knight Hall) of the castle. Occasional surface condensation was assumed to be one of the most important reasons for the wall paintings deterioration and should have been therefore significantly reduced. In the past some controversial events were held in the castle main hall, like flowers and gardening exhibition with intensive moisture generation during a week period. There was a lot of interest to give concerts and short term exhibitions in the Knight Hall. Microclimatic measurements in the Knight Hall provided necessary data for evaluation of the cold wall condensation risk during events.

2.2 Monitoring of indoor climate conditions

The renaissance Brezice Castle (Figure 4) was erected in 1529 and rebuild in baroque manner in 1694. In the beginning of the 18th century the most important castle wall paintings were fresco painted on the walls and ceilings of the main castle hall named the Knight Hall, in the staircase and in the castle chapel. The wall paintings in the Knight Hall are the biggest secular opus in Slovenia. In the past the structure of the castle and paintings were partly damaged due to material deterioration and foundation settlements. The castle and the paintings are under permanent regard and restoration activities.

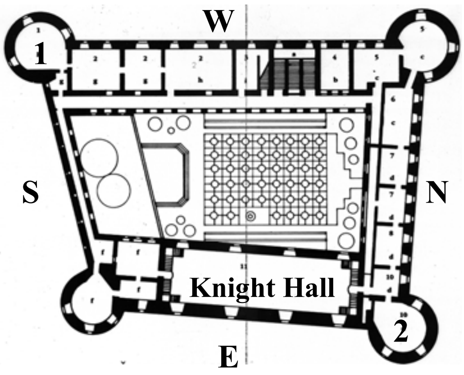


Figure 1. Layout of the Brezice castle, temperature and relative humidity monitoring in the wall heated room in tower 1, unheated exhibition room in tower 2, unheated fresco painted Knight Hall.

Figure 2. Knight Hall in Brezice castle.

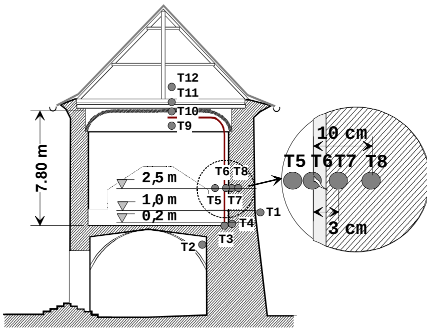


Figure 3. Position of temperature measuring points in the cross-section of the Knight Hall of Brezice Castle.

Figure 4. Brezice castle in Slovenia.

The large Knight Hall is 31.1 m long, 9.6 m wide and 7.8 m high (Figure 2). It stretches over the first and second floor of the eastern wing of the castle. The ground floor under the Knight Hall is used as a vine cellar. The castle walls are built of massive stone masonry. Their thickness is gradually lowering from ground floor up to roof. Outer walls are thicker than walls oriented to the courtyard. The roof construction and ceilings above the Knight Hall are made of timber. The timber beams of ceiling are plated with wooden boards thatched with reed that carry about 40-mm thick multi-layered plaster. To preserve the fresco painting quality, several preventive activities have been undertaken in the last decade. Since in the last years progressive fresco deterioration has been found in area of stairways the main idea was to assess the impact level of the outdoor air temperature and relative humidity and indoor climate changes because of the events. The main every years events in the Knight Hall are every second evening concerts in August with audience of about 300 persons.

Humidity fluctuations and water transport through walls are conditions for activation of other decay factors like frost, soluble salts, and corrosive gases from polluted air and biodegradation. Decay caused by these factors usually severely develops at the wall surface or beneath it. In the case of wall paintings, the paint layers suffer most of damages. In the case of paintings of the Brezice Castle, the most possible decaying factor is water. The paintings are sufficiently high above the ground level and therefore they are not affected by raising damp. The roof is regularly maintained so the leakage of rain over the walls is not the case. The only source of water that can harm the paintings is humidity caused by the wall surface condensation. In order to obtain data on decaying influences of moisture it was decided to measure the temperature changes and relative humidity changes in one cross-section of hall (Figure 3).

The steel mast provides the supporting construction for the instruments. Altogether twelve temperature measuring points and eight relative humidity measuring points are installed. Temperature sensors are thermocouples Cu-Con, Ni-NiCr. Relative humidity sensors are capacitating thin-film polymer sensors BMC Type GHTU. Their measuring range is 0 to 100% of relative humidity with linearity of 2% in recommended measuring range between 30% and 80% of relative humidity. Sensors are connected to the data acquisition system that constantly samples results in ten minutes intervals. They are placed in three levels inside the hall: 0,2 m above the floor, 2.5 m above the floor and beneath the ceiling. Instruments are also installed in the wine cellar beneath its floor and in the attic above the hall's floor. One pair of instruments is installed outside the building to measure temperature and relative humidity of outer air. The temperature and relative humidity is measured on the wall surface and few centimetres beneath the surface of wall. Temperature is also measured in the plaster of wall and in the plaster of ceiling. Additionally the longitudinal deformations of wooden structure of ceiling are measured by means of six dilatometers to obtain data on influence of wooden structure deformations on crack development in ceiling plaster.

2.3 Results of monitoring

The measuring campaign has started in the last week of April 1997 and is continuing with speed 6 readings per hour. In the figure 5 results of collecting data on selected points obtained in the first six months are presented. The diagram shows that increasing of wall temperature (T5) followed the increasing of outdoor temperature (T1) with the delay of about 10 days due to heat accumulation in masonry walls. The differences between indoor temperatures in the Knight Hall, in cellar and in attic have been observed as well as differences between temperatures measured on the wall surface and deeper inside the wall. The results of relative humidity measurements show the stable conditions in the only occasionally occupied Knight Hall.

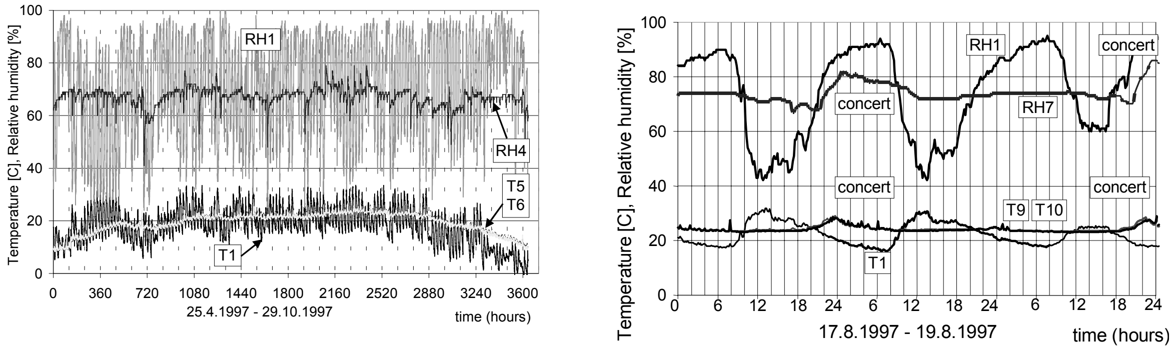


Figure 5. The results of half-year measuring of outdoor and indoor temperature and relative humidity and measuring during the period of concerts in Knight Hall

The microclimate conditions are changed in presence of large group of people or objects that excrete humidity, gasses or radiate heat. This fact was proved by results of temperature and relative humidity measurements. In August 1997, evening concerts were performed each second day with audience of about 300 persons. Each person radiates about 100W and excretes a significant quantity of humidity. Before the concert start, the air temperature in the mid-height of hall was about 24ºC and beneath the ceiling about 25ºC. The relative humidity of indoor air was in the same time about 75%. The mid-day outdoor temperature was 32ºC and outdoor relative humidity in the time of concerts was about 94%. Due to presence of audience the indoor air temperature rose up for about 2ºC at the mid-height of hall and for about 5ºC below the ceiling. The relative humidity in the mid-height of hall rose up for about 10% and beneath the ceiling for about 12%. Better insight in temperature and relative humidity changes during the events can be obtained from diagrams presented in figure 5. These data show how sensitive can be even a large indoor volume on the short time presence of large audience. The main concern related to preservation of fresco wall paintings was water condensation on plaster surface. It can lead to the capillary penetration of water solutions of agents beneath the surfaces of paint and cause deterioration and damaging of frescoes.

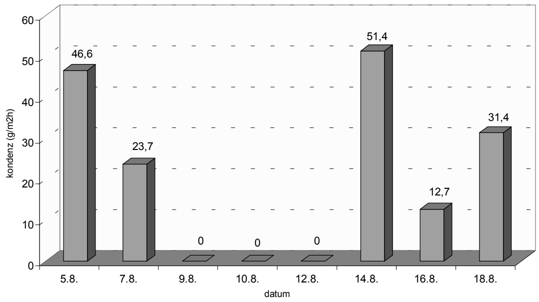


Figure 6. Amount of water condensed on the inner surfaces of the fresco painted wall during the series of concerts in 1997 in the Knight Hall of Brezice castle.

It can be concluded that also due to low ventilation rate microclimate in large hall responds slowly on the changing of external climatic conditions mainly because of massive masonry walls and relatively tight windows. Therefore, during the moderate occupancy of hall fresco wall paintings and exposed objects are not endangered. In the figure 6 the amount of water condensed on the inner surfaces of the fresco painted wall during the series of concerts in 1997 in the Knight Hall is presented. Analyses also showed [12] that in spring time period (April) a presence of aprox. 100 visitors for 1 hour creates critical conditions for surface condensation on cold walls. Therefore, the long term measuring results will enable better insight in this phenomenon and provide data for development of tools for analysis and prediction of deterioration processes.

The cracks propagation in painted plaster and in structural walls generated by permanent expansion and shrinkage of timber structure. The significant deformations are caused after long dry period when intensive humidity expands the floor timber structures and ceiling planks. Diagrams in figure 7 illustrate the case of rapid alternation of microclimatic conditions inside the attic of Brezice Castle due to summer showers that followed the long dry period. The increase of outdoor humidity and lowering of temperatures was followed by increase of humidity and lowering of temperature in attic. However, the microclimatic conditions did not changed significantly in hall below the attic due to better insulation from outdoor influence. The elevated humidity of attic caused the expansion of timber joists that are fixed atop of facade walls and consequently the widening of existing cracks in perpendicular walls. This influence can be diminished by rearrangement of joists' supports. The wooden planks expanded as well causing some influence on the ceiling painted plaster although the part of deformations can be compensated by reed. The data gained from future permanent several years measuring campaign are expected to provide information needed for assessment of influence of timber dilatation on decay of painted plaster.

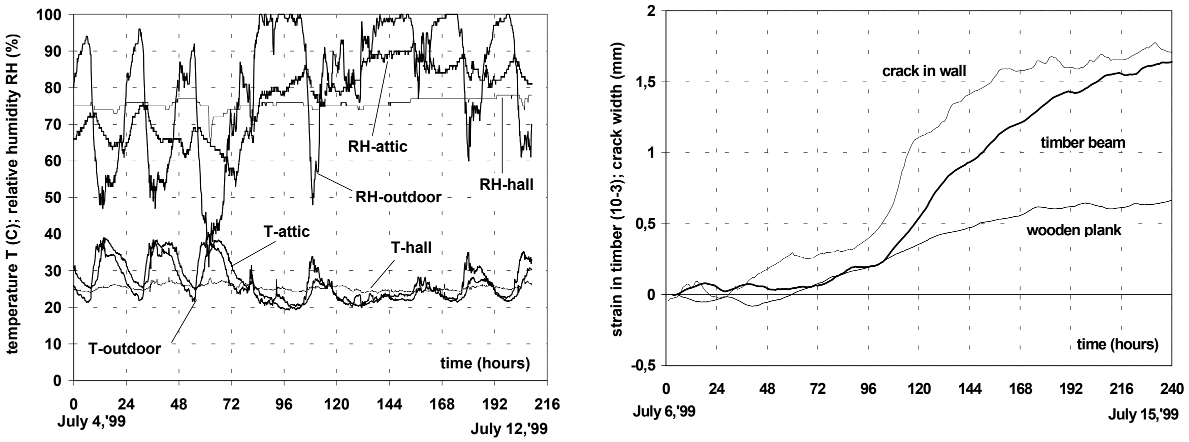


Figure 7. The results of measuring of outdoor and indoor temperature, relative humidity, of timber expansion and crack propagation in the attic of Knight hall

2.4 Wall tempering in Brezice castle

2.4.1 Design of wall tempering in auditorium

A low temperature wall heating system was found a promising solution to solve the cold wall surface condensation risk due to occasional events, to assure suitable thermal conditions in cold seasons for the visitors, as well as to establish stabile temperature and relative humidity conditions in exhibition rooms. The anticipated advantages of simple wall heating system are low investment cost, simple installation, low running costs due to energy efficiency and stable indoor climate conditions due to heat storage in massive castle wall. The performance of the wall tempering system was demonstrated in a tower room-auditorium of Brezice castle.

A wall tempering system was planned to be installed into a round room in the south-east tower (tower 1, Figure 1,8) in order to analyse expected benefits, possible side effects and to provide some basic design guidelines. The diameter of the round room is 8 m, the height is 3.7 m, the wall thickness is from 1.8 m up to 2.5 m, made of mixed stone brick wall. The tower room is located in the first floor above the unheated cellar and bellow the unheated exhibition rooms in the second floor. The floor and the ceiling of the round room are made of wooden structure containing pebble bed. There are three windows (1.2 m x 1.7 m) with double-glazing.

To determine the most appropriate heating pipes position in the wall the temperature distribution was simulated. The simulation was based on the two dimensional heat transfer in solid materials taking into consideration convection heat transfer in boundary layers. The boundary conditions were defined according to the winter temperature conditions: outer air temperature -5°C, cellar 0°C, target indoor air temperature 15°C. The temperature of the heating medium in the pipe was 60°C, following the heating curves for the already installed heating system for the offices in the castle. The cross-section of the lower part of the wall-floor joint is shown in the figure 3.

The surface temperature in the lower part of the surrounding walls for various pipes positions were compared (Figure 9). The case with two pipes in-built in the wall in two layers (see Figure 10) was selected. The target indoor air temperature 15°C with average temperature of bottom part of surrounding surface 19.7 °C was expected to results in the effective indoor temperature around 17 °C, convenient for exhibition areas. In case of occasional events in the room internal heat sources from occupants or additional heating device used only for a short time period can meet thermal comfort requirements. Simulation of the temperature field in the walls and of the indoor air temperature in rooms for the whole tower 1 showed good matching with the measured values.

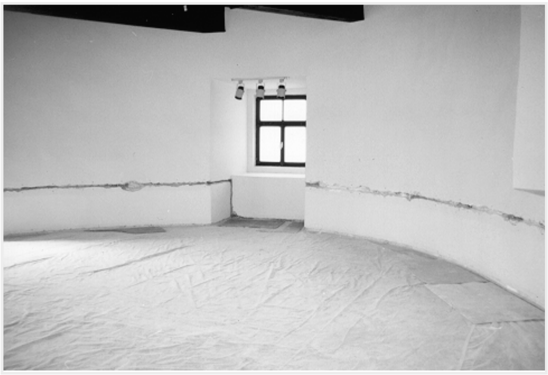


Figure 8. Installation of wall tempering in Audithorium in Brezice castle.

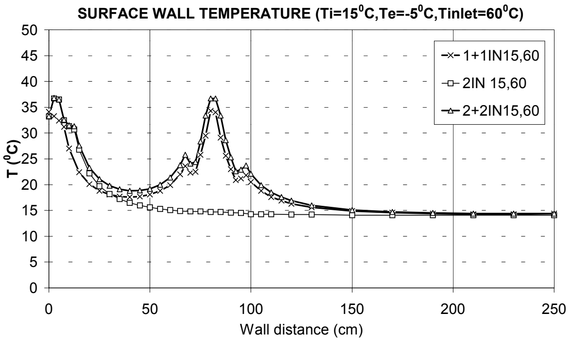


Figure 9. Comparison of wall surface temperature for different distribution of pipes.

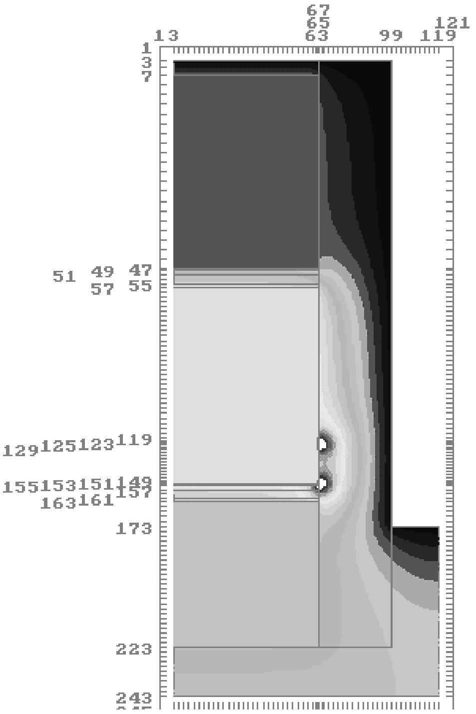


Figure 10. Simulation of temperature field in the tower 1, boundary conditions: T outdoor air 4.2°C, ground temperature 10°C in temperature of water in pipes 40°C, distance of pipes 80 cm, simulation by PHYSIBEL - RADCON [9].

2.4.2 Operation

In the test room – auditorium in the tower 1 of Brezice castle the wall tempering system was installed. Copper plastic covered pipes with diameter 18 mm were used in two loops of length 35 m each. The inlet pipe is on lower, corner, position, the outlet pipe at the height 80 cm above the floor. The pipes were in-build just below the surface and covered with wooden board only for aesthetic reasons. Heat flux from the pipe is 50 W/m at the temperature of the heating medium 60°C. For occasional use two radiators are installed and can be dismounted when the suitable thermal performance of the wall tempering system will be demonstrated. At this stage of the operation the heating loops are connected to the rest of the central heating system (90/70°C). Central regulation of the heating system dependent on constant indoor air temperature and outdoor temperature is implemented. The energy use is monitored as well as the inlet and outlet water temperature, heating medium flow.

Microclimatic parameters were monitored (Figure 11,12,13) to validate the wall tempering impact. The test run of the heating system in the round room (1) started in the middle of November 97 (Figure 11) and stopped on November 26 due to finishing works – restoration of wall plaster. The plaster drying process was finished on November 28. After that the room was heated only by the heat form the in-built pipes and stored in the wall, the radiators were closed. Outer air temperature in the first half of December was lower than in the second part. Therefore the inlet water temperature, controlled by the central regulation was higher (above 60°C) in the first part and lower (58°C) in the second part of December. As the outdoor temperature moderately raised the indoor air temperature was reduced form 20°C to 15°C. Corresponding drops and raises in relative humidity show the opportunity for establishing appropriate stabile microclimatic conditions for exhibition areas.

Microclimatic data for the reference room (Figure 12) showed to high level of relative humidity for the collection of arms (up to 80%) which is in correlation with seasonal temperature decrease of the unheated room with high heat storage capacity. The wall tempering system is to be considered as a convenient technology to improve the microclimatic conditions, without visible installation, using advantages of low temperature wall heating to reduce indoor air temperature and energy consumption.

Temperature flows of the rooms 1 and 2 were compared with the Knight hall (Figure 13). The temperature oscillation and in general lower temperature can be observed in the hall, due to relatively bigger windows, less compact form and less heat storage capacity of the hall.

In Brezice castle the wall tempering system is considered in the arms exhibition room to reduce relative humidity and in the Knight Hall to prevent surface condensation risk and its impact to fresco paintings deterioration. In both cases it enables use of the castle rooms in colder periods for exhibition purposes. Additional heat source can rapidly and with low additional energy meet the human thermal comfort requirements.

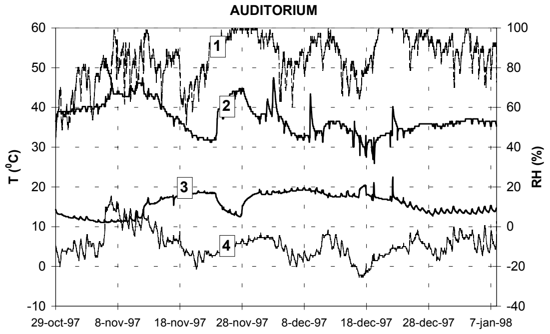


Figure 11. Temperature and relative humidity in the round room in the tower 1 – auditorium, heated by wall tempering system. Diagrams show outdoor (1) and indoor (2) relative humidity, outdoor (4) and indoor (3) temperature.

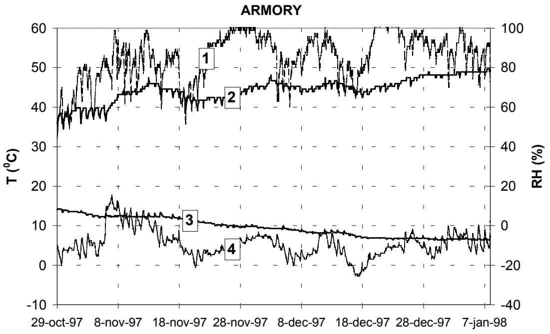


Figure 12. Temperature and relative humidity in the unheated reference room, armory exhibition room in the tower 2. Diagrams show outdoor (1) and indoor (2) relative humidity, outdoor (4) and indoor (3) temperature.

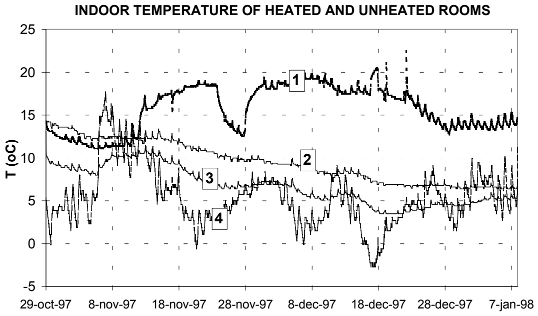


Figure 13. Temperature of the round room (1) heated by wall tempering, reference unheated room (2) and unheated Knight hall (3) compared to outer air temperature (4).

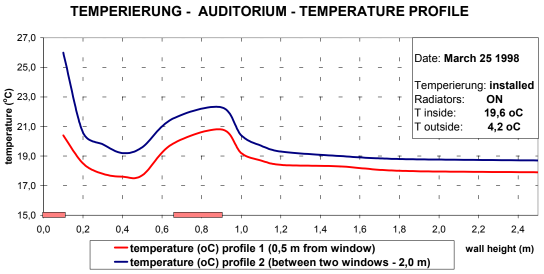


Figure 14. Vertical temperature profile – measured values, wall tempering (1+1 pipe) in Audithorium of Brezice castle, March 25, 1998.

3. Case studies in Slovenia

Based on the successful installation and good performance of wall tempering in Brezice castle, two churches in Teharje and Mokronog were wall tempered in 1999 [4]. Parish church St. Martin in Teharje (built in 1906/07) is 46 m long and 16 m wide. Heated volume of the church is 7700 m^3. The walls inside are painted with ornaments and paintings in fresco. The parish church St. Tilen in Mokronog (19th.century) originates from the years 1349 to 1364 and the existing building was constructed in 1824 (Figure 15). The interior walls are not painted and it was renovated in 1999. The plaster was removed up to the height of 3 m so that heat pipe installation wasn't causing any additional damage. The church is 27 m long and 13 m wide. Heated volume of the church is 3510 m^3

Both churches were wall tempered with three layers of pipes. Besides the basic heating of the church, indoor air temperature in the church above + 8°C at outdoor temperature – 15°C, the goal was also to reduce the capillary rise and humidity of the wall. The indoor air measurements showed stabile indoor temperature at around 10 °C. The relative air humidity in the cavity in the wall in the height approx. 50 cm is reduced from 88 to 82 % and in the ground level it is still 100 % after the first heating season of wall tempering operation. The energy consumption for Teharje church was reported 72 MWh (7.200 l of EL oil) between Oct. 18, 1999 and March 3, 2000.), in the period between Sept. 9, 1999 and March 3, 2000 8270 l of gas was used (equivalent to 60.400 kWh assuming 7.2 kWh/l of gas) [4].

Figure 15. Parish Church St. Tilen in Mokronog, position of temperature sensors.

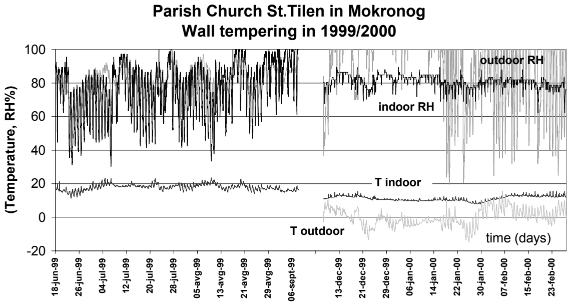


Figure 16. Temperature and RH in wall tempered church in Mokronog, 1999/2000.

Indoor air temperature and relative humidity was measured in both churches, in the figure 16 the seasonal measurements for Mokronog church are presented. Important additional effect of wall tempering is drying of the wet walls and reduction of capillary raise influence. The process of wall drying in case of all year round heating with the lower level of pipes was monitored and showed up to 15% reduction of equilibrium relative humidity measured in the sealed borehole in the wall 10 cm bellow the inner surface (Figure 17).

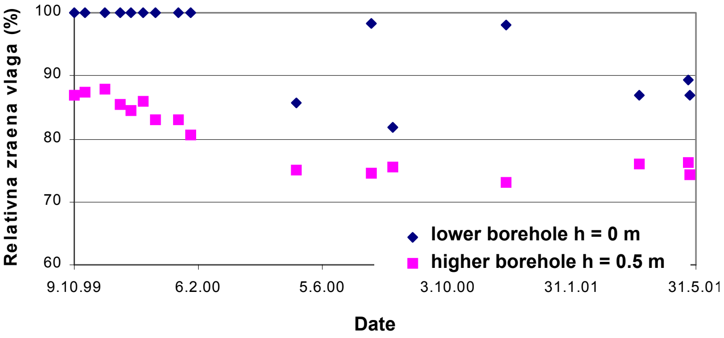


Figure 17. Equilibrium relative humidity of the air in a borehole 10 cm below the inner wall surface in case of drying of wet walls by wall tempering, Teharje church, [13].

4. Simulation of thermal performance of wall tempered building

Engineering design of wall tempering system in massive buildings is based on slightly modified methods for space heating. Basically, the goal of these methods is determination of energy demand and heating sources. However, when planning the wall tempering system our task is more specific and focused also on solving local heat transfer and building physics problems.

The first goal is determination/planning of inner surface temperature (mean radiant temperature) of the heated walls. It contributes to the thermal comfort level and together with indoor air temperature determines the effective temperature felt by the person standing in the space. For example, in large halls (churches, castles) the idea is to provide a thermal comfort for the users by a combination of moderate indoor temperature and a warm lower part of the walls along the height of a person.

The second goal that can be met by detailed analysis of the temperature field within the building element is the mitigation of the cold wall effect and surface condensation risk. This risk is much more serious where the massive building is occasionally used, intermittently heated and where the users produce additional moisture. This happens most usually in churches during the services.

Usually, there are two families of simulation tools available. One focuses heat transfer in the solid building elements in detail, the other focuses the thermal response of a building as a whole. The goal of the first tool is detailed two or three-dimensional analysis of the temperature filed in a part of the building fabric. The goal of the second, more general, tool is determination of the resulting indoor air temperature and/or energy use in the building. Advanced PHYSIBEL simulation tool [9] enables combined analysis of both problems: determination of temperatures in the building fabric due to heat source of the built-in pipes and determination of resulting indoor air temperature and energy demand.

4.1 Salsta castle

The joint research work of Swedish, Austrian, and Slovene partners on Salsta castle is a part of the EUREKA Eurocare Prevent EU 1383 project and the follow-up activities. The plans for the installation have been prepared by Techniches Buero Kaeferhaus, Austria [5], monitoring of the system performance is operated by Haftcourt Limited, Care of Cultural Property, Sweden [10] and the simulation of thermal performance has been done by the Civil Engineering Institute ZRMK, Slovenia [11].

The goal of our work, described in this paper, was to prove the suitability of the PHYSIBEL simulation software for determination of the thermal response of the wall-tempered building. In order to verify the simulation results we used the case study Salsta castle in Sweden [5,10]. The medieval Salsta caste (1675) (Figure 18) is situated in Sweden, close to Stockholm, composed of the main building and two equal pavilions. The two storey pavilions have a gross ground floor of 50 m^2. They are built of 55 cm thick brick walls, with unheated loft below the pitched roof and with 10 cm of mineral wool for loft insulation. The foundation soil is sand. The ground floor is high 3 m and the first floor 2.8 m. Useful net floor area per storey is 40 m^2. The windows are double glazed, equally distributed on all four facades. One of the pavilions is heated by radiator system, the other, which thermal response was simulated, was heated by wall tempering system.

In each floor, copper pipes of 18 mm were built in the walls just below the plaster, in two levels in 10 cm distance. The installed power of the electric boiler is 6 kW. The average inlet temperature of the heating media was 50°C, the average temperature of return 30°C. Air, pipe and wall temperature, RH and air exchange rate were monitored in the heating season 1998/99. The outdoor air temperature between the March 9 and March 13, 1999 was between -5°C and -4.5°C, the indoor air temperature in the upper floor was between 8.5°C and 10°C, the indoor air temperature in the basement was between 11.5°C and 13.5°C. The air exchange rate in the observing time period, measured by tracer gas method, was 0.9.

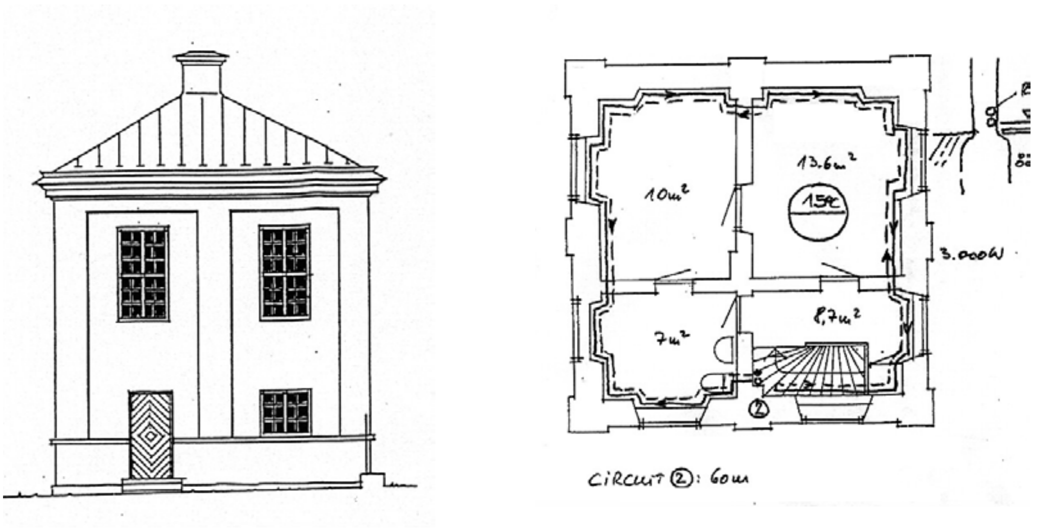


Figure 18. West Salsta pavilion, plan of wall tempering, [10].

4.2 Simulation results

When analysing the influence of wall tempering from the building physics perspective, the first step is modelling of the real building. Historic buildings architecture is often complicated and thus subject to many simplifications due to computational limitations. For more accurate results rather than a two- a three-dimensional model of the building was prepared. Steady state conditions are assumed: outdoors air temperature –5°C, earth temperature 10°C, lower pipe temperature 30°C, and upper pipe temperature 50°C. The indoor air temperature and the temperature in the unheated attics are simulated by PHYSIBEL software.

In the figure 21 the ground floor of the simulated building is presented where double symmetry is taken into account. Internal walls, windows and heat losses due to air exchange rate are taken into considerations. The inner air temperature and the temperature field in the building envelope was simulated by PHYSIBEL. In order to finally show the desired influence of the warm surrounding walls, the effective temperature in certain nodes of the wall was simulated. In the nodes of consideration, the black globe thermometer characteristics were modelled, so that the simulated temperatures in that nodes represent the effective temperature, resulting from the indoor air temperature and radiation due to the mean radiant temperature of the surrounding surfaces. The nodes were positioned on the diagonal of the ground floor and upper floor, at the height 0.85m and 1.8m.

Simulation results on 3D model (Table 1) showed good accuracy comparing to the measured temperatures in Salsta Castle (Figure 19,20). The difference of the calculated and measured temperature of the indoor air in ground floor was below 1°C; the difference in the upper floor was around 1°C. The results are validated to be optimal within the accuracy of the available data on the building geometry, material characteristics, thermal characteristics of the wall tempering system and the assumption of the steady state conditions.

The most important information is the effective temperature in the selected nodes that can be felt by a user of the room. The effective temperature is resulting form the indoor air temperature and the mean radiant temperature. The simulation showed that due to the warm walls the effective temperature is 1°C - 2°C above the indoor air temperature, which was calculated (and measured) to be between 10°C and 12°C.

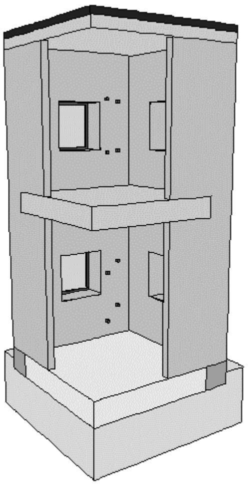


Figure 19. Salsta pavilion, 3D model with nodes for determination of effective temperature.

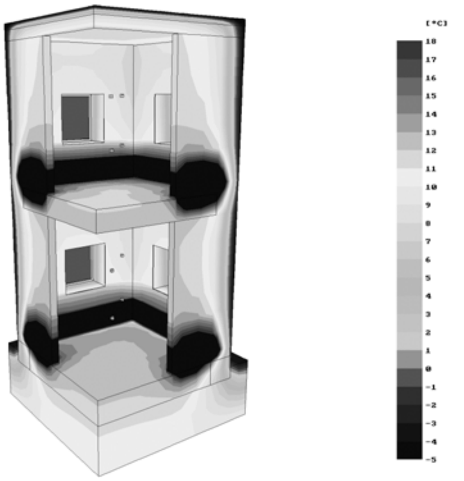


Figure 20. Simulation of thermal response of the Salsta pavilion, dark areas in the ground floor and upper floor represent warmer areas due to the wall tempering pipes at 50°C and/or 30 °C, air exchange rate 0.9.

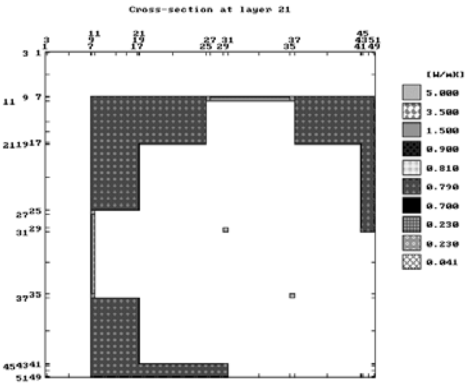


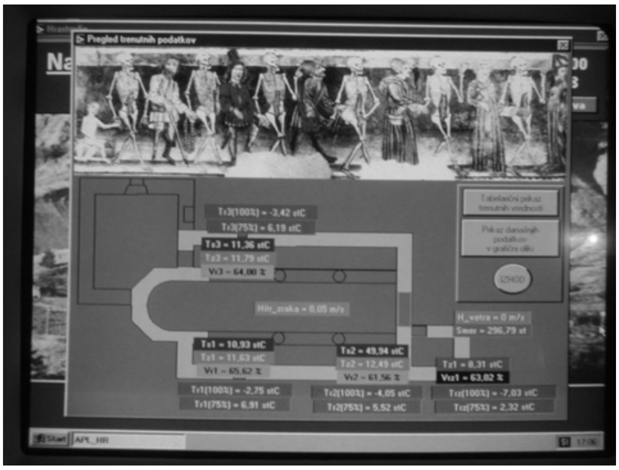
Figure 21. Salsta pavilion, 3D model, ground floor, double symmetry.

Table 1 PHYSIBEL simulation, 3D model of wall tempered Salsta Pavilion, air exchange rate 0.9.

Indoor air temperature, effective temperatures in selected nodes	(°C)
$T_{\text{air - ground floor}}$ – indoor air	10.0
$Tp_{1\text{ effective}}$- ground floor, at 80 cm, closer to corner	10.8
$Tp_{1A\text{ effective}}$- ground floor, at 80 cm, middle of the room	10.8
$Tp_{2\text{ effective}}$- ground floor, at 185 cm, closer to corner	9.9
$Tp_{2A\text{ effective}}$- ground floor, at 185 cm, middle of the room	10.4
$T_{\text{air-upper floor}}$ – indoor air	9.8
$Tn_{1\text{ effective}}$- upper floor, at 80 cm, closer to corner	10.9
$Tn_{1A\text{ effective}}$- upper floor, at 80 cm, middle of the room	10.7
$Tn_{2\text{ effective}}$- upper floor, at 185 cm, closer to corner	9.7
$Tn_{2A\text{ effective}}$- upper floor, at 185 cm, middle of the room	10.2

5. Microclimate monitoring system in Hrastovlje church

The system of permanent monitoring of microclimatic parameters was set in Holy Trinity church in Hrastovlje. The monument is well known on the fresco paintings by Janeza iz Kastva with origin from 15th century, with the most known motif of Danse macabre. The system was set in the framework of the initiative of the Restoration centre of Slovenia for establishment of central monitoring system of cultural monuments. The main goal of this programme is realisation of preventive conservation strategy.



```
Tr3(100%) = -3,42 stC
Tr3(75%) = 6,19 stC
Ts3 = 11,36 stC
Tz3 = 11,79 stC
Vr3 = 64,00 %
Hitr_zraka = 0,05 m/s
H_vetra = 0 m/s
Smer = 296,79 st
Ts1 = 10,93 stC
Tz1 = 11,63 stC
Vr1 = 65,62 %
Ts2 = 49,94 stC
Tz2 = 12,49 stC
Vr2 = 61,56 %
Tz1 = 8,31 stC
Vrz1 = 63,02 %
Tr1(100%) = -2,75 stC
Tr1(75%) = 6,91 stC
Tr2(100%) = -4,05 stC
Tr2(75%) = 5,52 stC
Trz(100%) = -7,03 stC
Trz(75%) = 2,32 stC
```

Figure 22. Monitoring indoor climate parametrs in Holy Trinity church in Hrastovlje, [14]

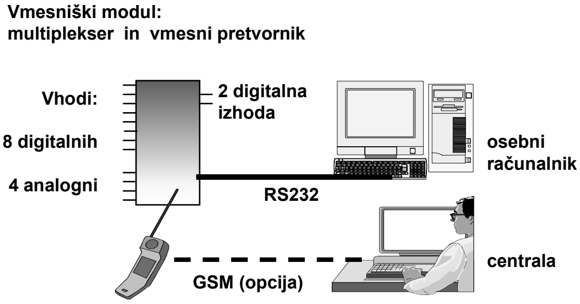


Figure 23. Scheme of authonomus microclimatic monitoring system in Hrastovlje, [14].

In spite of many efforts towards establishing the appropriate indoor climate in the church and eliminating other possible reasons for deterioration of fresco paintings, in spots biodegradation has occurred. Therfore permanent monitoring of indoor temperature, relative humidity, indoor air movement and dew point alarm has been started in 1998. The authonomus monithoring system is flexible for extensions. Currently the activities for its upgrade and integration in the central monitoring system of building heritage are going on.

6. Conclusions

Following the longer period of monitoring indoor climate parameters by ordinary analogue instruments and implementing a conservative methods and technologies for improvement of the microclimate in recent years more systematic approach was started in Slovenia. In recent years permanent indoor climate monitoring was set in reference heritage buildings, such as castle, unheated church monument, and some churches heated by alternative heating systems.

The measurement of indoor clime in these heritage buildings can provide valuable sources of data needed for optimal use and management of this type of cultural monuments. The major dilemma is how much can be cultural monument and its interior exposed to visitors. The knowledge about response of monument fabrics and objects on visitors' impact because of the influence on indoor climate conditions is the essential starting point for decision making.

One of the major problems is the condensation on the wall surfaces and on the exposed objects. This influence can be moderated in severity by appropriate organisation of planned events and by investment in systems that lower the condensation risk. One of the available long-term solutions that can enable using of castle halls for larger events is introduction of controlled low temperature heating system. It can regulate massive wall heat accumulation during the whole year to avoid surface conditions that can lead to condensation. The wall tempering system is considered to be promising technology for energy efficient retrofit of massive buildings, especially in the case of lower thermal requirements. Warmer walls, reduction of relative humidity and stabile indoor climate conditions are desired for exhibition areas. On the other hand low temperature radiation surfaces achieved by wall heating contribute to energy and cost savings in occupied rooms.

It was shown that the simulation of thermal performance can give us reliable results on temperature fields and on needed heat power, respectively. The possibility for simulation of effective temperatures, felt by the visitors in the tempered building due to radiative heat flows form the warm walls, allows the optimisation of positioning of the pipes and temperature levels during the planning process. Thus as a final goal the thermal comfort parameters can be analysed and consequently their influence on the human perception of thermal comfort and the efficient use of energy can be taken into account.

7. Further reserach

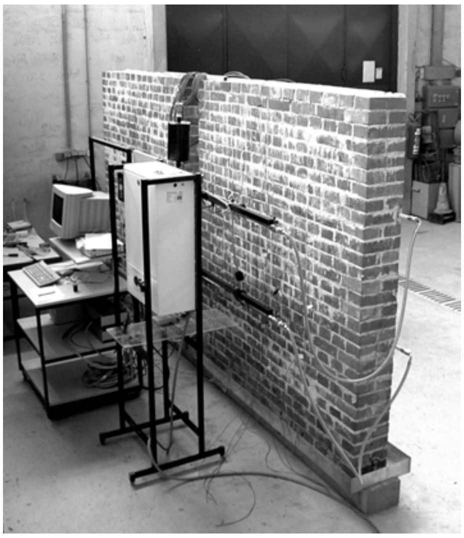


Figure 19. Laboratory testing of wall tempering performance.

To show the wall heating effects on prevention of damp raising in massive brick wall the laboratory experiment was prepared (Figure 19) where the drying process of the heated massive brick wall is monitored and compared with the energy used for drying the wall. Thus the potential for use of solar energy will be evaluated. To prove the energy saving potential also the consequent reduction of the U value shall be analysed. In addition the influence of the warming and drying process on contractions and cracks in different lime plasters, prepared according to the old recipes suitable for the buildings of cultural heritage, will be analysed. Future work will focus on laboratory testing of wall drying process accelerated by heating source from wall tempering. The potentials for use of wall tempering as a non-destructive technique for temporary mitigation of capillary rise in case of progressive deterioration on valuable fresco painting will be investigated in future.

Acknowledgements:

The work presented in this paper has been prepared in the framework of Eureka EU 1383 Prevent project and national research projects, financed by the Ministry of Science and Technology of Slovenia, by Civil Engineering Institute ZRMK internal research funds LARA and in co-operation with diploma works at the University in Ljubljana, Faculty of Civil Engineering and Geodesy.

8. References

[1] D.Camuffo, Microclimate for Cultural Heritage, Developments in Atmospheric Science 23, ISBN 0-444-82925-3, Elsevier, p.187, 1998

[2] EUREKA, EU 1383 PREVENT, 1995-97, partners from Austria, Sweden, Germany and Slovenia (CEI ZRMK), Set of reports.

[3] H.Grosseschmidt, Stabilisierung des Raumklimas als Grundlage sachgerechter Bewahrung oder: Das temperierte Haus, sanierte Architectur und Grossvitrine, Das Museumsdepot, Weltkunst Verlag Muenchen, pp. 49-79, ISBN 3-921669-27-8, Weltkunst Verlag GmbH, Muenchen, 1998

[4] M.Malovrh, M.Zupan, M.Praznik,, New Approach to Heating of Cultural Heritage Buildings, Proceedings of OPET Workshop Wall Tempering in Historic Public Buildings, Ljubljana, Dec. 7, 2000, Edts.: M.Sijanec Zavrl, K.Grepmeier, OPET Slovenia (CEI ZRMK), OPET Bavaria-Austria (ZREU), pp.7, 2000

[5] J.Kaeferhaus, Smart Building Services as a Way of Simplify Systems in Order to Improve Damage Prevention Especially in Historic Buildings, Proceedings of OPET Workshop Wall Tempering in Historic Public Buildings, Ljubljana, Dec. 7, 2000, Edts.: M.Sijanec Zavrl, K.Grepmeier, OPET Slovenia (CEI ZRMK), OPET Bavaria-Austria (ZREU), pp.12, 2000

[6] R.Zarnic, M.Sijanec-Zavrl, Performance Based Approach to Heritage Protection, Proc. Of. International Conference on Conservation, Krakow 2000, 12 pages, in press, 2001

[7] M.Šijanec Zavrl, R.Žarnić, I. Nemec, Monitoring Indoor Climate in Medieval Castle, PLEA 98, Edts.: E.Maldonado, S.Yannas. Environmentally friendly cities. London: James & James, pp. 307-310, 1998.

[8] M. Šijanec Zavrl, M.Malovrh, S.Jordan, Low Temperature Wall Heating System in a Room of Medieval Castle, PLEA 98, Edts.: E.Maldonado, S.Yannas. Environmentally friendly cities. London: James & James, pp. 311-314, 1998.

[9] PHYSIBEL, Users Manual, Maldegem, Belgium, 1999

[10] J.Holmberg, "Salsta Slott", EUROCARE EU 1383 PREVENT, Jamforelse av energisystem Statens Fastighetsverk, Uppsala Resultat av matningar 1998/1999

[11] M.Šijanec Zavrl, R.Žarnić, Analysis of Thermal Response of Wall Tempered Building, Case Study: Salsta Pavilion, Proceedings of OPET Workshop Wall Tempering in Historic Public Buildings, Ljubljana, Dec. 7, 2000, Edts.: M.Sijanec Zavrl, K.Grepmeier, OPET Slovenia (CEI ZRMK), OPET Bavaria-Austria (ZREU), pp.13, 2000

[12] S.Smid, Analysis of microclimatic parameter measurement in building heritage, Diploma work no. 1388, at University in Ljubljana, methors: R.Žarnič, M.Šijanec Zavrl, 1999

[13] OPET Slovenija, Information leaflet, Temepriranje v stavbah kulturne dediščine (Wall tempering in building heritage), 2001

[14] GI ZRMK, UL-FGG, AIP,d.o.o., ELTEH,d.o.o., (Monitoring indoor climate in Holy Trinity church in Hrastovlje) Spremljanje mikroklimatskih parametrov v cerkvi Sv.Trojice v Hrastovljah, RC Slovenije, 1998