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Technical problems in churches in different climatic conditions

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ABSTRACT

In buildings of cultural heritage, such as churches, it is quite difficult to ensure and to maintain the constant values of the indoor climate. Keeping a comfortable indoor environment throughout the year is a challenge due to special requirements for the preservation of the integrity of the interior decoration (frescoes, icons, stucco molding), strict canons to the exterior appearance, the presence of sharp peaks in the increase of hygrothermal parameters due to a peculiarly different number of visitors during church holidays compared to the rest of the year. Three churches described in this paper are situated in Russia and Latvia and despite different geographical position have similar problems: violation of the thermal insulation layer, problems with the provision of heat and humidity mode of condensation. The paper suggests possible ways of monitoring the state of the indoor climate of churches and possible solutions for its maintenance.

Content

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1. Introduction

Currently, energy efficiency is the main trend of the construction industry. Increasing thermal protection and provision of comfortable conditions of space microclimate are the most important parameters of the building during design, construction, operation and reconstruction. This problem is particularly relevant for the objects of cultural heritage of historical, architectural and artistic value.

Conservation-restoration of cultural heritage is the most important thing to preserve ancient value, history and sense of national identity. The newly constructed and renovated museums have all necessary HVAC systems components to ensure optimal indoor air parameters to preserve ancient values and to provide thermal comfort for the visitors and staff. While churches have unique usage profile and types of cultural heritage museums have a more constant visitors' flow as well as special exhibition stands for artifacts. Churches have unique architectural, historical and spiritual significance. The special temperature and moisture conditions inside the church must be ensured for long term preservation of internal painting, icons, manuscripts and at the same time must be comfortable for visitors.

Churches have an extremely high peak load only several days per year, mainly during holy days. Historically churches were constructed without any mechanical heating and ventilation systems. Architectural solutions ensure extremely large indoor volume, which allows to minimize negative effect of extra heat and moisture production during the holy days. For the last century cities were growing causing the significant increase of visitors for churches located in cities.

The authors of the study [1] found differences in water absorption of exhibition of San Juan Bautista Church (Madrid, Spain). These differences are caused by different design and orientation of the walls. It was established that wall thermal lag and decrement factor values contribute to indoor comfort in the church by transferring the heat absorbed during the day. Greater comfort is afforded by rubble stone than ashlar constructions.

Many mediaeval churches have no climate control systems and the indoor climate is mainly characterized by the outdoor. In study [2] the possibilities to improve indoor climate in originally unheated churches were investigated to prevent and protect churches from mould growth and disintegration of wooden parts. In this case the adaptive ventilation performs well in high indoor humidity conditions. By adding a heater to the adaptive ventilation, the indoor climate will improve, depending on the heating input power and air flow rate. The most effective tested solution was with a heating capacity of 20 W/m^{2}and an airflow rate of 1 l/(s·m^2).

In unheated churches, one of the most dominant problems is very high relative humidity throughout the year, creating a high risk for mold and algae growth [3]. In heated churches overheating causes a relative humidity (RH) below 50% during cold periods, so there is a height risk that the gesso may crack or delaminate.

It is found out by V. S. Hudisteanu, A. I. Baran and others that with under floor heating system and static heaters, the use of ventilation in towers generates two recirculation of air below them which creates a gradient of temperatures rising towards the sides of the church [4].

With only passive indoor climate measured the indoor climate is strongly dependent of the outdoor climate as well as the massive limestone walls with large thermal and moisture capacity. Without indoor climate systems there is extensive indoor temperature and relative humidity fluctuation throughout the year. To ensure suitable indoor climate, room heating, humidification during winter period, and dehumidification during summer and autumn periods is needed [5].

The study [6] produced in accordance with EN 15757:2010 introduced a novel method for risk assessment and preventive conservation of organic hygroscopic cultural heritage objects. The research method based on the analysis of the historic climate was applied to an inlaid wooden choir in the basilica of S. Giustina (Padua, Italy). Winter has been found to be the most critical season for the mechanical stress and wood yield. In spring and winter, RH fluctuations ranged from 35% to 65%; in summer from 35% to 75% especially because the doors were frequently kept open to enhance comfort by ventilation.

In the Basilica di Collemaggio case-study hydronic high-efficiency pew-based system was proposed and deeply analyzed. The work demonstrated that such solution could combine the advantages obtainable from electric benches with those of a hydronic heating system coupled with ground-source heat pumps, combining good local comfort levels to significant energy savings and low or no impact on the artworks and building structures [7].

The aim of this paper is to suggest possible ways of monitoring the state of the indoor climate of churches and to find possible solutions for such problems as its maintenance, violation of the thermal insulation layer, problems with the provision of heat and humidity mode of condensation.

In the course of the study the following tasks are carried out:

1. Visual and instrumental examination of the objects, detection of numerous common damages to churches;
2. Calculation of the thermal resistance value of the wall and the value of minimum temperature on internal surface of the wall using thermal analysis;
3. Calculation of interstitial condensation and monitoring indoor air quality parameters;
4. Thermographic analysis and temperature analysis.

2. Indoor air quality requirements

In Russia basic requirements for the thermal protection of enclosing structures and optimal air parameters of churches are defined by existing standards:

– Set of Rules SP 31-103-99 “The buildings, structures and complexes of orthodox temples”;

– АВОК Standart-2-2004 “Orthodox churches. Heating, ventilation and air conditioning”.

In Latvia according to data [8] the optimal climate conditions for heated churches would be a temperature less than 18°C and a relative humidity of 50±5%. Relative humidity under 30% has fatal impact on painted wooden elements and thick layers of distemper paint on wall surfaces. The requirement to human comfort can be assumed as data [9] presents.

The recommended air exchange rates and indoor air parameters mentioned in these standards are presented in Table 1 and Table 2.

Table 1. Air exchange rate in different church rooms [10]

Rooms	Air exchange or amount of supplied/exhausted air (m^3/h)
Church’s central part	According to the calculations of the assimilation of the harmful discharges produced by the system, not less than 20 m^3/h of outside air per person
Altar, vestry, chapel	According to the calculations of the assimilation of the harmful discharges produced by the system, not less than 20 m^3/h of outside air per person
Place for baptism	According to the calculations of the assimilation of the harmful discharges produced by the system, not less than 30 m^3/h of outside air per person

Table 2. Optimal air parameters of the main inner church room [10, 11]

Time of the year	Room	Air parameters		
		Temperature t_i, °C	Moisture φ_i, %	Speed ν_i, m/s
Cold and transition period	Church’s central part	14 – 16	40 – 55	0.2
	Altar	16 – 18	40 – 55	0.1
	Vestry, chapel	16 – 18	40 – 55	0.2
	Place for baptism	22 – 24	40 – 60	0.1
Non-heating period	All rooms	20 – 22	50 – 55	0.2

Set of Rules SP 50.13330.2012 determines measures for thermal protection of buildings in Russia is not subject to thermal protection of religious buildings [12].

Churches differ from each other with interior, maximal number of age, structural and architectural appearances, age, used building materials and special exploitation features.

The construction and reconstruction of religious buildings require an individual design approach involving highly qualified specialists.

Church can be operated during whole year or only during summer time [13]. The building envelope of summer churches doesn't have any heat insulation. This fact can cause significant problems as internal condensation and damage of mural in case than summer churches are used in winter. The huge number of churches in Russia and former USSR countries, which hadn't had heating before, were reconstructed and equipped with central or local heating system and ventilation system to ensure preservation of cultural heritage and to provide optimal indoor air parameters for parishioners and staff [14-16].

Existing studies showed importance of indoor air and relative humidity influence on preservation of heritage [17, 18]. The interior of old orthodox churches can be evaluated as museums. Orthodox churches have unique old things as cooper dishes, wooden icons with timber and gold and old murals. Study [19] on museums microclimate had shown high relative humidity values may cause mold growth and large relative humidity fluctuations may cause mechanical degradation of objects.

3. Material and Methods

3.1 The objects of research

The objects of research are Sergey Radonezhskiy temple in Volgograd, Russia (Figure 1a), All Saints Orthodox Church in Riga, Latvia (Figure 1b). and Church in Liepaja, Latvia (Figure 1c). Main damages to churches located in different climatic zones are described. Solutions of thermal protection of external walls, assessment of the degree of condensation in building component, recommendations for improvement of temperature and moisture conditions are mentioned in this article. Sergey Radonezhskiy temple was built in 1999. Reconstruction of the temple started in 2011. Reconstruction purpose is to increase total structural volume of the temple. Reconstruction objective is construction of the heated addition to western facade of temple for liturgical rooms. Riga All Saints Orthodox Church was constructed in period between 1812 and 1891. Church was used as summer church before 2010 and nowadays it used over the year. Church volume is 7708 m^3, dome height is 26 m. Optimal number of parishioners is 200 persons with maximal possible number 1000 persons. The church has water heating systems. Typically, indoor air temperature is kept at 12 ^{o}C to 14 ^{o}C and during the church services temperature increase till 18 ^{o}C – 20 ^{o}C to ensure priest optimal thermal comfort. Construction of Liepaja cathedral finished in December 1758. Cathedral built with brick masonry walls.

All analyzed objects are built using brick. The estimation [20] showed that the use a monolithic concrete with polystyrene aggregates as a thermal insulation increases thermal inertia of external wall approximately for 33.4 %.

a) Sergey Radonezhskiy, Volgogrado   b) All Saints Orthodox Church, Riga   c) Cathedral, Liepaja

Figure 1. Analyzed churches

The parameters of the external climate for these regions are shown in Table 3.

All three churches are placed in similar climatic conditions. However, there are some major difference in winter outdoor temperature peak loads and fluctuation of relative humidifies. City of Liepaja is located on Baltic Sea shore and buildings envelope by wind drive rain. City of Riga represents temperate climate. While City of Volgograd has an extreme summer and peak temperatures.

Table 3. Conditions of the outside air

	Volgograd, Russia	Riga, Latvia	Liepaja, Riga
Heating period			
Outside temperature (average value), °C	–1.29	4.8	5.6
Humidity (average value), %	81	82	83.6
Summer period			
Outside temperature (average value), °C	18.0	14.4	14.1
Humidity (average value), %	58	75.2	78.8

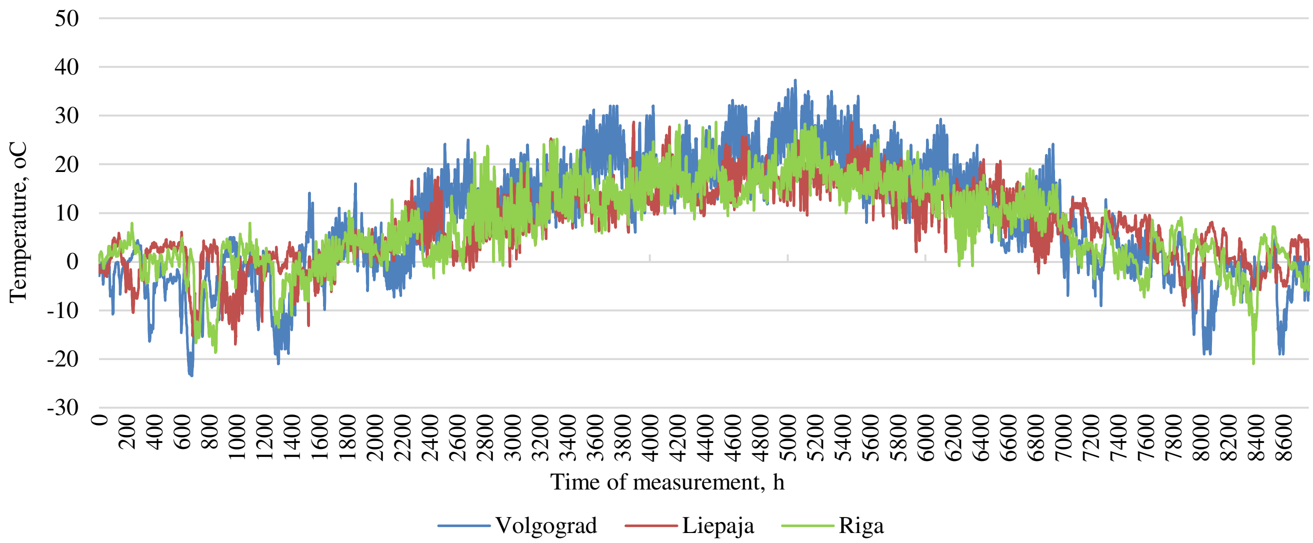

Figure 2. Temperature analyze of considered regions

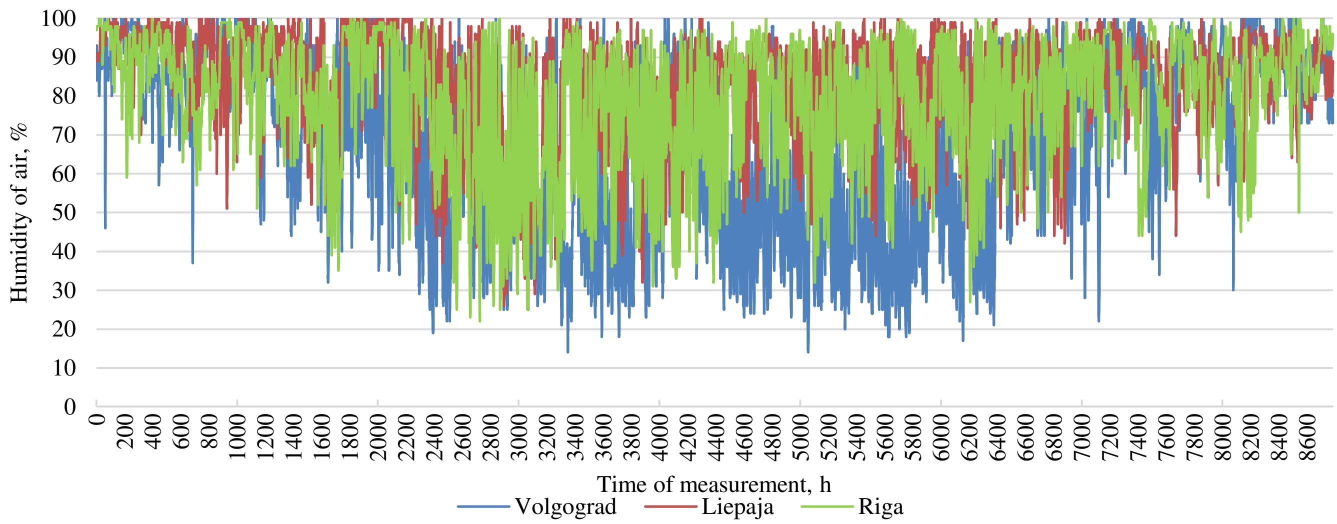

Figure 3. Humidity analyze of considered regions

All three churches have similar constructive solutions (Figure 4). Dome solutions main element church's central part

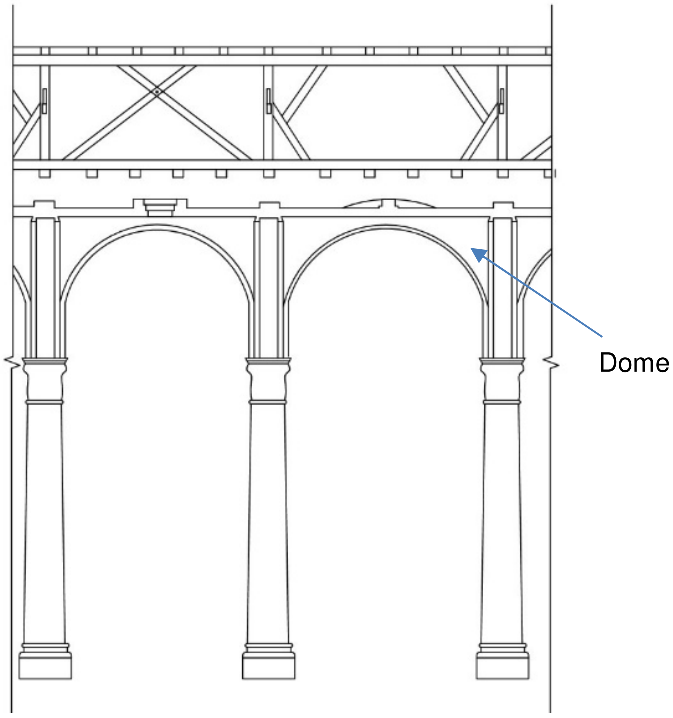

Figure 4. Constructive solution of analyzed churches

3.2 Visual and instrumental examination of the objects

Based on visual and instrumental examination numerous defects of external walls made in the construction process are revealed:

– Damages in mineral wool insulation (Figure 5, 6);
– The continuity of the thermal insulation of external walls in the plane of the façade is not provided;
  - The close contiguity of the insulation through heat-conducting inclusions in hollow masonry is not provided;
  - There is not fastening insulation in the cavities of masonry;
  - The continuity of the vapor barrier provided by the project is not provided;
  - There are numerous through heat-conducting inclusions in the form of vertical ribs of brick masonry and reinforced horizontal rows, which reduce the thermal uniformity of the exterior walls;
  - There are empty brickwork joints, which can lead to deterioration of operational qualities of the exterior walls due to air filtration;
– Dome inner surface damages (Figure 7);
– Mural damages (Figure 7);
– Condensate appearance on inner building surfaces (Figure 8);
– Visitors discomfort (human faints).

Figure 5. The fragment of the external wall in the area of insulation brick (Volgograd)

Figure 6. The fragment of the external wall in the area of the vertical fin (Volgograd)

Figure 7. Dome inner surface damages and mural damages (Riga)

Figure 8. Condensate on inner surface (Liepaja)

4. Results and discussion

4.1 Numerical thermal analysis

The analysis of the building envelope extension of Sergey Radonezhskiy temple, made according to concept [21] with the following composition of the enclosing walls: the three-layer brick wall, including thermal insulation layer from concrete with polystyrene aggregates.

Thermal analysis was carried out on the basis of mathematic modeling of the process using programming and computing software «Energy efficiency and heat protection of buildings (ENTEZA)» by S. Korniyenko [21]. Applicable two-dimensional heat-transfer analysis makes it possible to estimate impact of edge zones on heat protection properties of envelopes and outline ways to improve elements of buildings' covers according to computing of temperature fields.

The result of thermal analysis shows that 75 % of heat loss emerges through flat element and 25 % through thermal bridges. The bigger part of supplementary heat loss was found through horizontal linear element (17 %) and smaller part — through vertical linear element (8 %). Use of brick connectors in external walls reduces supplementary heat loss.

Calculated value of thermal resistance of the wall is R_o^{cal} = 1.35 $m^2 \cdot K/W$, using the data obtained above. Calculated R-value is more than required value determined in accordance with Set of Rules SP 50.13330.2011 and [21] R_h^{req} = 1,18 $m^2 \cdot K/W$.

Calculated value of minimum temperature on internal surface of the wall fragment is 12.1 °C. This value is higher than a dew point (Dew point at rated temperature of internal air t_{int}^{des} = 16 °C and a relative humidity φ_{int}^{des} = 50 % is equal to 5.6 °C [21]). Thus, the risk of moisture condensation on internal surface of the wall is practically excluded.

4.2 Hydrothermal analysis

Calculation of interstitial condensation in Sergey Radonezhskiy temple component is carried out according to simplified calculation method developed by the author [21] and harmonized with ISO 13788. Purpose of the method is one-dimensional moisture transfer on the mechanism of water hydrvapor diffusion under stationary boundary conditions.

Calculation of drying of building component procedure assumes that there is an excess moisture content concentrated at the center of a specified layer. And then moisture moves to the condensation interface and gradually evaporates from here. The condensation interface located between thermal insulation and outer brick layer in the coldest month (Figure 9).

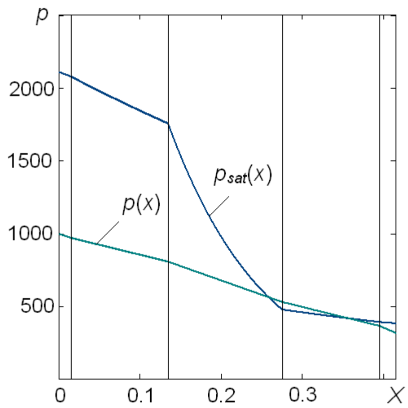

Figure 9. Schedules of p(x) and psat(x) in the cross section of external wall (key: x – coordinate; p – water vapor pressure; psat – saturated water vapor pressure) (Volgograd)

The moisture accumulation at condensation interface rises to a highest point in February (Figure 10). From March onwards, the rate of condensation becomes negative i.e. evaporation is occurring, and the accumulated moisture falls until it is close to zero in April.

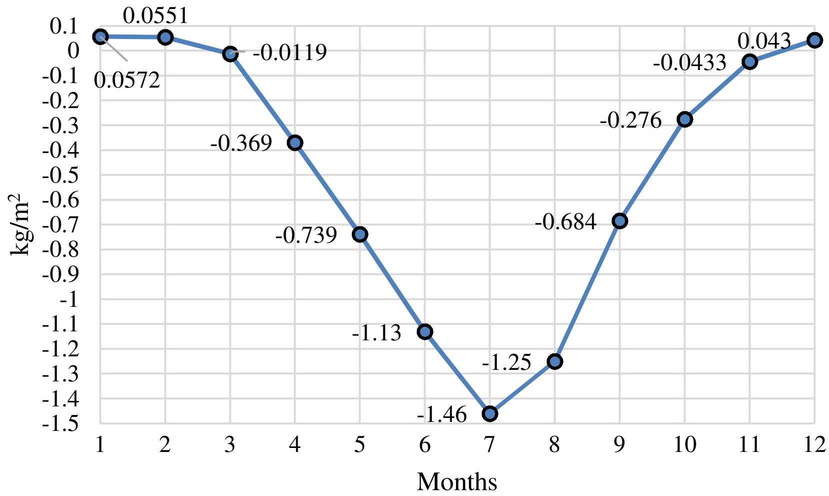

Figure 10. Moisture accumulation in external wall (Vertical axis – condensate, expressed in kg/m2) (Volgograd)

The condensation occurs at one interface during some months but there is no accumulation over the year as all the condensate is predicted to evaporate again. Thus, there is no systematic moisture accumulation at the building component within a year.

Analysis of the evaporation rates at the interface, with the procedure specified in ISO 13788, starting in July, shows (Figure 11) that mainly moisture evaporation from interface, until the amount of excess moisture reaches zero after 38 months. It is assumed that there is excess moisture content of 15 kg/m^2 as expected value at the moisture condensation interface and does not exceed admissible values.

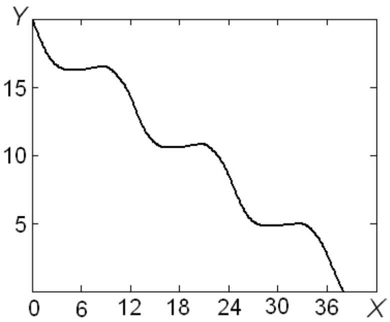

Figure 11. Drying of wetted layer in external wall (key: x – month; y – evaporated moisture, expressed in kg/m2; starting in July) (Volgograd)

4.3 Temperature and humidity monitoring methodology

For the evaluation of temperature and humidity parameters in Riga All Saints Orthodox Church following monitoring methodology was applied:

- Measurement of the inner air temperature, relative moisture and CO_2 with loggers;
- Church thermography with the aid of air permeability test
- Structure airtight check with the aid of fume generator and pressure difference forming tool.

Measurement of temperature and moisture with loggers gives opportunity to evaluate the compliance of these parameters with appropriate standards and identify temperature and moisture excitation values and their exposure times.

The research was conducted in two stages: summer and autumn-winter 2011/2012.

Summertime research includes the determination of the air exchange parameter and assessment of the compliance of those parameters with standards based on structure's thermovision survey and structure's faults determination using BlowerDoor pressure distance forming tool

Autumn/winter research includes the definition of the indoor air quality and thermal properties of building envelope.

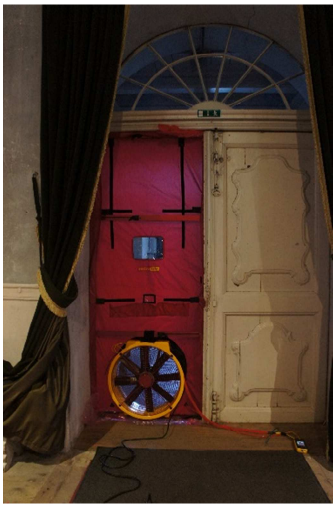

Figure 12. BlowerDoor pressure tool (Riga)

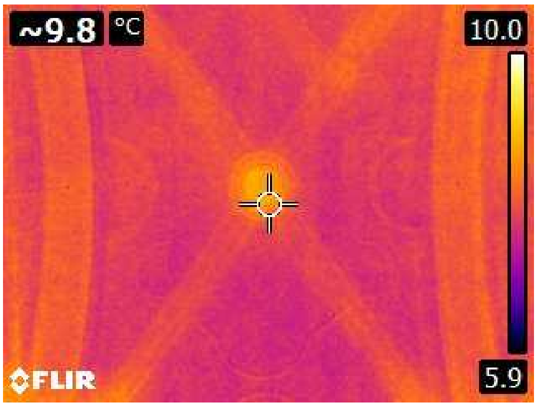

Figure 13. Thermovision picture of the arch (Riga)

4.3.1 Air exchange rate

The average value of the air flow at +/- 50 Pa during the summer season was 7000 m^3/h which allowed to calculate the air exchange to be 1.05 h^{-1}. This value does not correspond to a demand of air exchange 12000 m^3/h (for average value 600 people).

The reasons of the normal air exchange interruption might be shut ventilation openings (Figure 14) and other openings with low permeability.

A possible solution could be the use of existing ventilation system. Indoor air parameters in altar zone during the summer day under the moderate load are shown in Figure 15.

Figure 14. Ventilation channels (Riga)

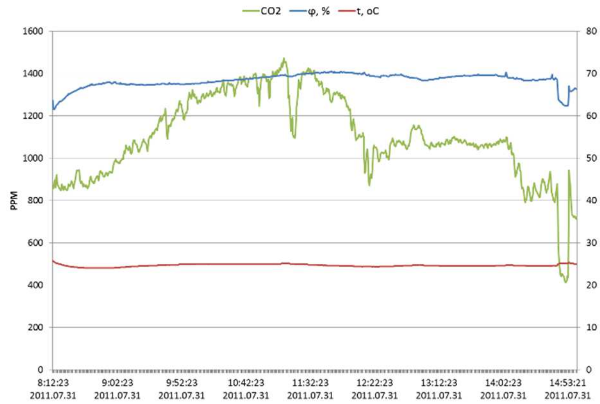

Figure 15. Indoor air parameters in altar zone (Riga)

The existing ventilation system is very efficient. However, it is not used during the church services. The main reason for that is noise level.

4.3.2 Air parameters

Accordance of the inner climate conditions to the SP 31-103-99 of the Riga Nativity Cathedral has been assessed in the days of the greatest worshipper number presence (04.12.2011 and 07.01.2012) with the aid of temperature, carbon dioxide concentration and relative humidity loggers.

The overrun of the relative humidity upper limit has been observed reaching 75% on 04.12.2011 as well as overrun of the carbon dioxide concentration upper limit reaching 3300 ppm on 07.01.2012.

CO_2 measurement results, which are illustrated on Figures 16 – 17 show the CO_2 concentration reduction efficiency of the mechanical ventilation during the public worship time.

Suggested solution to the problem is installation of mechanical ventilation system with low noise level.

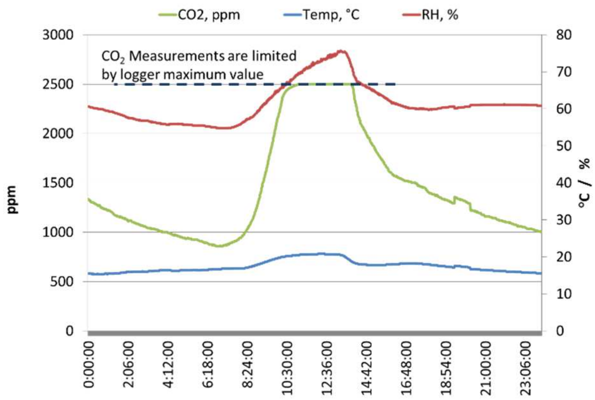

Figure 16. Indoor air quality parameters during maximal occupancy on December 4, 2011 (Riga)

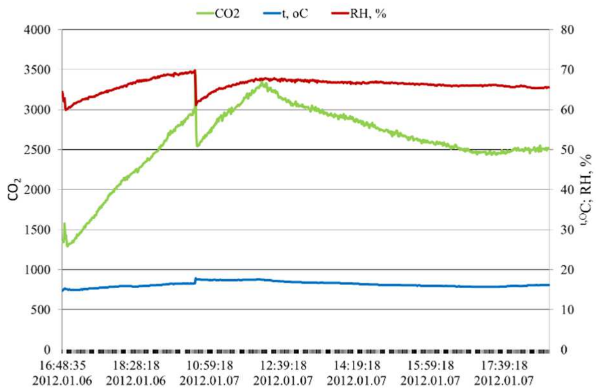

Figure 17. Indoor air quality parameters on January 6 - 7, 2012 (Riga)

4.3.3 Dome inner surface damages

In the summer the corrosion of the cupola inner surface appearance next to increased humidity, which is caused by insufficient air exchange, can also be due to the lack of thermal isolation, which causes condensate formation on the surface.

It is suggested that heat insulation is enhanced.

In the winter thermovision inspection of the cupola has been carried out after additional heat insulation manufactured after the summer examination. The results have shown minor thermal bridge in the places, where arch is connected to the ceiling (Figure 18). The reason behind the presence of the thermal bridges is insufficient isolation thickness across the ceiling and arch.

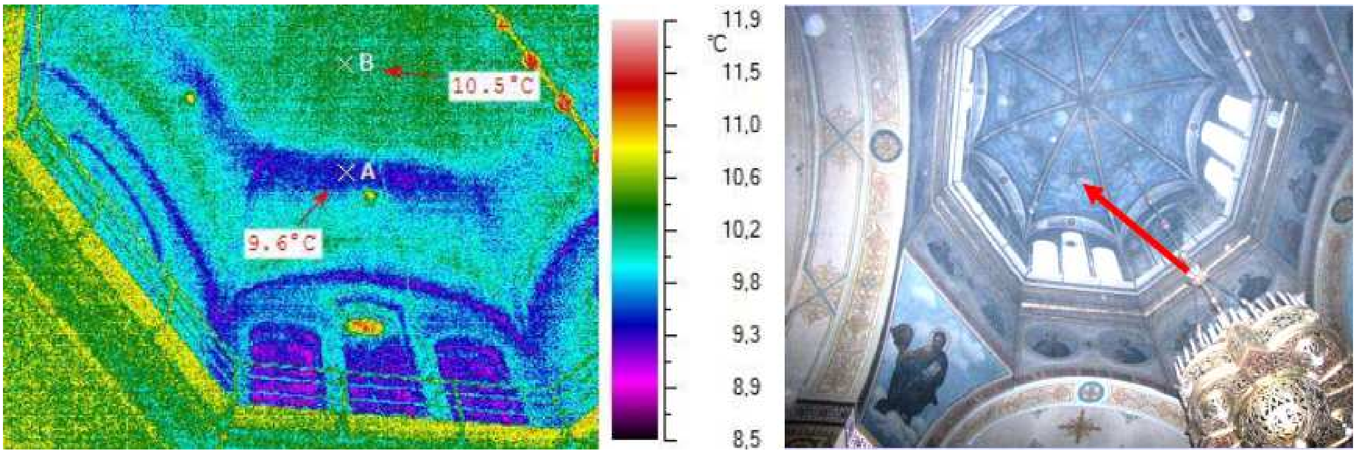

Figure 18. Thermovision inspection of the cupola after additional heat insulation (Riga)

4.3.4 CO concentration

The assessment during summer period has been done with the aid of fume generator at a forced pressure of +/-50 Pa between cathedral rooms and a room, where heating equipment is installed (Figure 19). The airproof level has been found out to be very low.

It has been determined during the cellar survey, that inputs into the heating system have been compacted with fitting foam, which is not airproof. That initiated unauthorized air exchange between cellar and main church rooms.

After improvements it is recommended to perform carbon monoxide measurements during the heating period.

During wintertime inspection ceiling and heating channel noncompactness places were eliminated.

CO concentration exceeds 2 ppm in the altar area and 3-4 ppm in the heating building, which is compliant with regulations.

Figure 19. Airproof assessment between cathedral rooms and a room where heating equipment is installed

4.3.5 Temperature analysis

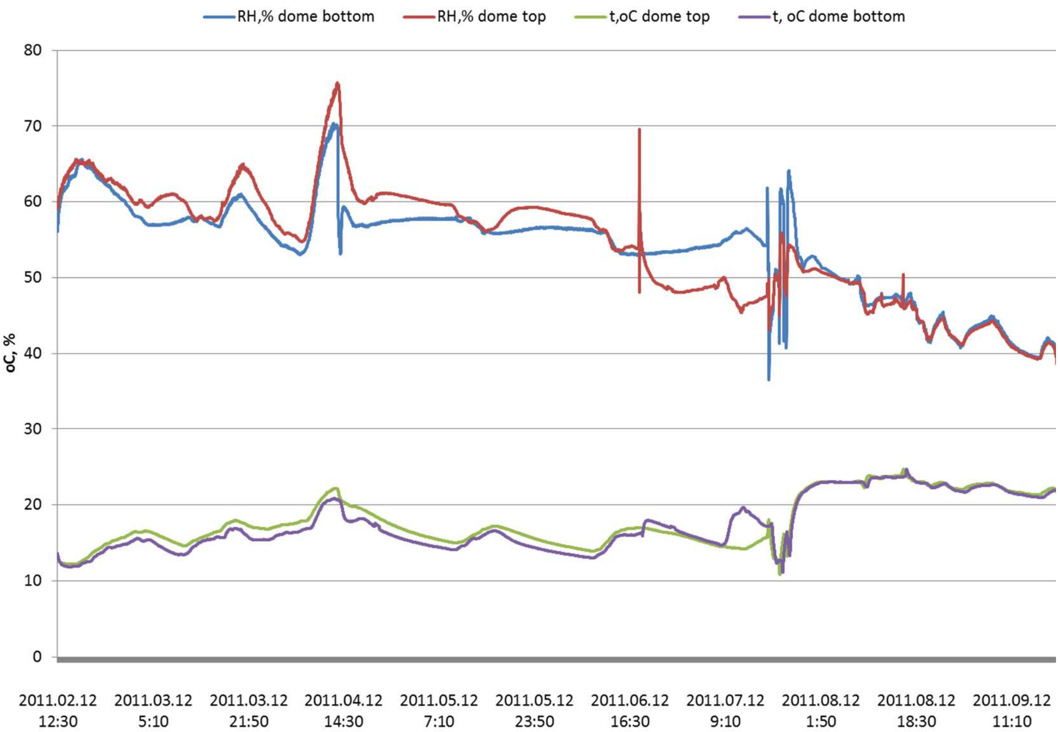

Figure 20. Fluctuation of temperature and relative humidity from December 2 till December 9 at top and bottom of dome

As can be seen from Figure 20 the temperature during the church operation varies due to periodic heating. The water heating system with old type coal boiler in combination with high thermal mass of building doesn't give possibilities for precise control of indoor air temperature. Also such system is not able to ensure temperature control in different zones.

The underfloor heating systems with several control zones could be a solution for improvement of temperature control.

4.3.6 Thermographic analysis

Repeated cathedral's inner part thermographic research confirmed the defects discovered during the summer research (Figure 21). These were caused by increased humidity levels in the ceiling and abnormal infiltration and exfiltration of the air through the window and door frames, as well as the points of contact of the walls with floor.

It is recommended to remove the air infiltration through the door and windows as well as conduct a study to determine the reasons of the temperature anomalies in the northern and southern walls of the cathedral as well as in altar arches and find out the moisture ingress ways into the structure.

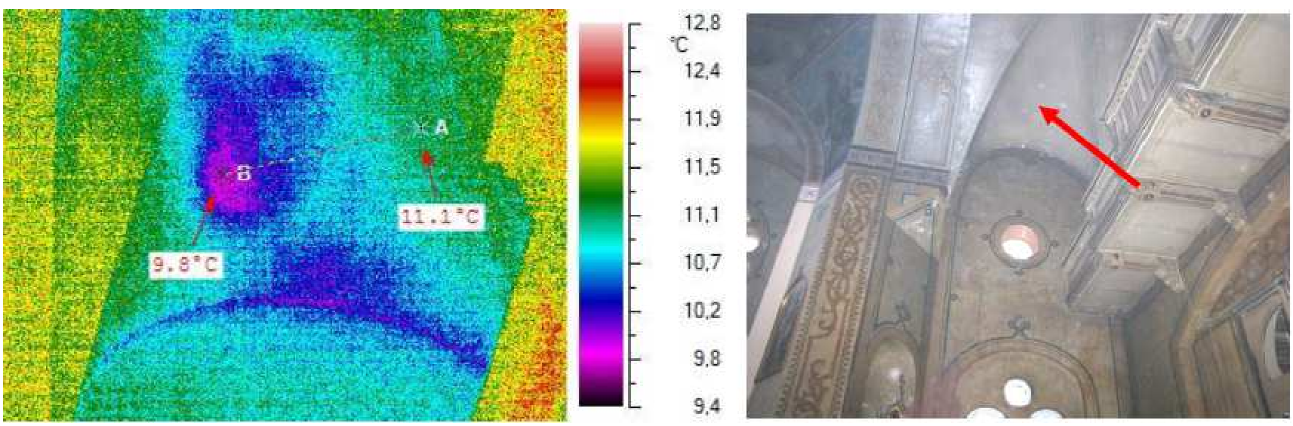

Figure 21. Spots of increased humidity levels

5. Conclusion

Ensuring and maintaining the constant values of the internal environment in buildings of cultural heritage, such as churches, is quite difficult. Keeping a comfortable indoor climate throughout the year is a challenge because of special requirements to maintain the integrity of internal decoration (frescoes, icons, stucco), strict canons to appearance, availability of sharp peaks of increasing heat and moisture parameters (because of different numbers of visitors during church holidays compared to the rest of the year).

Three churches described in this paper despite different geographical position have similar problems: violation of the thermal insulation layer, problems with the provision of heat and humidity mode of condensation.

The paper suggests possible ways of monitoring the state of the indoor climate of churches and possible solutions for its maintenance.

The bigger part of supplementary heat loss through enclosing structures was found via horizontal linear element (17%) and smaller part - through vertical linear element (8%). Use of brick connectors in external walls reduces supplementary heat loss.

During reconstruction work use of monolithic polystyrene insulation significantly increases the heat engineering uniformity of external walls.

In this case, the value of the temperature at the surface of the enclosing structures at critical design points does not exceed the value of the dew-point temperature.

Hygrothermal analysis proposed in [21] and corresponding to ISO 13788 allows to analyze the evaporation rates at the interface. In this variant excess of moisture content of 15 kg / m^2 is expected value at the moisture condensation interface and does not exceed admissible values.

Monitoring the temperature and humidity mode of churches according to the method described in the paper makes it possible to determine timely and accurately identify the reasons for the deterioration of the quality of the indoor climate and take measures to improve it.

The air permeability test allows to determine the air exchange parameters and to assess the compliance of this parameter with the requirements of normative acts. In the investigated churches ventilation 1.7 times less than critical

The registration of temperature and relative humidity with the help of loggers gives possibility to assess the compliance of these parameters with the requirements of regulatory enactments and to determine the peak values of temperature and humidity and their exposure time. Carbon dioxide concentration and carbon oxide loggers allows to estimate the concentration of harmful substances in different zones of the church. It was found out that the main problem was the high concentration of CO_2 which was equal to 3500 ppm, while the rated value was equal to 2500 ppm.

A possible solution to the problems described above would be the installation of duct ventilation system, but it is impossible because of the high noise produced. Another decision – to shut ventilation openings and other openings with low permeability.

Using thermography allows to determine the location of thermal bridges in the building envelopes, such as insufficient isolation thickness across the ceiling and arch.

The use of location thermography with a device creating a pressure difference makes it possible to determine the places of infiltration / air filtration and places of high humidity in structures. The underfloor heating systems with several control zones can be a solution for improvement of temperature control.

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Технические проблемы в церквях в различных климатических условиях

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ИНФОРМАЦИЯ О СТАТЬЕ	ИСТОРИЯ	КЛЮЧЕВЫЕ СЛОВА
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АННОТАЦИЯ

Обеспечение и сохранение неизменности показателей внутренней среды в зданиях культурного наследия, таких как церкви, достаточно сложно. Поддержание комфортной среды внутри помещения в течение всего года является непростой задачей вследствие особых требований к сохранности целостности внутреннего убранства (фрески, иконы, лепнина), строгих канонов к внешнему облику, наличия резких пиков повышения тепловлажностных параметров из-за заметно отличающегося количества посетителей во время церковных праздников, по сравнению с остальным годом. Рассмотренные в данной статье 3 церкви, расположенные в России и Латвии, несмотря на различное географическое положение имеют схожие проблемы: нарушение теплоизоляционного слоя, проблемы с обеспечением тепловлажностного режима, выпадение конденсата. В статье предложены возможные способы мониторинга состояния внутренней среды церквей и возможные решения по её поддержанию.

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