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Procedia Technology 22 (2016) 821 – 828

Procedia Technology

9th International Conference Interdisciplinarity in Engineering, INTER-ENG 2015, 8-9 October 2015, Tirgu-Mures, Romania

Churches Heating: The Optimum Balance Between Cost Management and Thermal Comfort

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Abstract

In this paper is presented a numerical and cost benefit approach of the indoor climate environment created inside of a historical Roman-Catholic church that will be subjected to restoration in the near future. The heating system used in present is with static heaters. The numerical model has as proposes to subject to comparison another heat system: floor heating and mechanical ventilation system in order to have a better understanding of the differences between them and the economical implication of this changes. Historical buildings and churches constitute a problem because they have enormous volumes and the envelope has a low efficiency. From the economical point of view, the solution must the feasible. The comparative results showed that the existing heating system is inefficient and has a lot of damage for the artworks and the painting inside the church.

Peer-review under responsibility of the "Petru Maior" University of Tirgu Mures, Faculty of Engineering

Keywords: heating system; energy efficiency; cost management; heating system modelling; indoor climate; conservation; underfloor heating; static heating system

Nomenclature

CFD	Computational Fluid Dynamics
EU	European Union
RH	Relative Humidity

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Peer-review under responsibility of the "Petru Maior" University of Tirgu Mures, Faculty of Engineering
doi:10.1016/j.protcy.2016.01.055

1. Introduction

Building energy performance represents one of the concerns in the EU politics. In Romania the energy consumption for buildings represents 45 % from the total energy consumption, fact that impose an energy efficiency plan for the existing buildings.

Buildings that have a heritage function, such as churches and monasteries have a lot of paintings, frescoes and order religious objects used for the liturgical services. Conservation of the paintings and objects inside the church is need in order to pass to future generation the history of our precursors and of the national identity. Some of this are part of the national and world heritage site. Because of this the conservation of such site must be in the politics of the country and a major concern of each EU government. Also the EU directive 31/2020 give the reason why each European country must have in its agenda heritage building conservation.

Cold churches have been used for centuries. Nowadays, the increases of demand of thermal comfort, give the reason to place them, but there are cases when it can cause damages. In temperate climate, as it is in Romania the heating system can generate a climatic condition different from the natural and unheated one, to which the artworks have become acclimatized during centuries. [1]

In general a heritage building is included in the touristic circuit. This fact put the building on the map of many tourists, such that their presence in a large number changes the interior climate. On the order hand when this building are rehabilitated and the thermal comfort in summer and winter is maintain the presence of people is higher.

Historical monument buildings that have a large number of operation hours must became energy efficient. Because of their historical value over their facades cannot be made any interventions. At the interior where the paintings and order heritage object are place, are affected by humidity, temperature fluctuations, dust etc. In order to place this objects in a safe environment, this inconvenience must be removed. This can be done by reevaluating the heating system and all the order service system to be closely chosen in order to create a proper air quality for heritage objects.

Comfort describes a subjective parameter that make people to find the interior climate acceptable. The temperature range for churches is between 12÷150C. The relative humidity has the comfort value between 30÷70%.

Conservation of materials requires an indoor climate that minimizes ageing and degradation of the materials that are preserved.

Cost is a key factor that must be take into account from the beginning. A solution to expensive can ruin the project.

This paper evaluate a particular case of a church that will be put in a rehabilitation process. It will be analyzed from the perspective of the heating system, ways to insulate the envelope and the financial analysis to see the budget implications. [2]

2. The Dormition of the Mother of God Church

The church is situated in Jassy, in the III climate and wind zone with the external temperature during winter of -18^{0}C. About 1782 the first stone of the church was laid. It is in Romano-Catholic church administration. In this time the church suffered multiple rehabilitation, after major earthquake and fires. Also the church was enlarged to the dimensions that is now (see Fig 1).

The monument with his historical value has the length of 40,61 meters and width of 15 meters. The height inside the church varies around 9,80 meters. The volume of air inside is 2710 m^3. The walls have the width of 85 centimeters to 1.1 meters and are made from sand limestone and masonry with the area of 711, 11 m^2.

The age of 233 year and the climate put their mark on the structure of the church. Exterior finishes have crack and in some area the cement plaster is missing (see Fig.2a). [3]

The roof made from wood, is uninsulated and is cover with steel sheet. The windows are made from 2 layer of glass on a steel framing having an area of 275.44 m^2(see Fig.2b). Also the flooring is made from marble with area of 266.01 m^2, and the ceiling is from masonry with a cement layer having the area of 305.9 m^2.

The interior is decorated with paintings and sculptures of different artist. The monumental organ from Jägerndorf, Austria, built in 1913, is famous for his marvellous sound. [4]

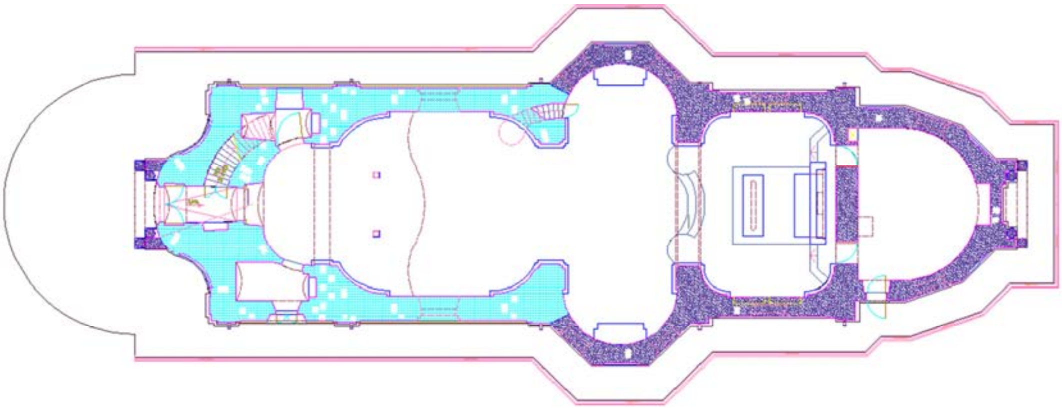
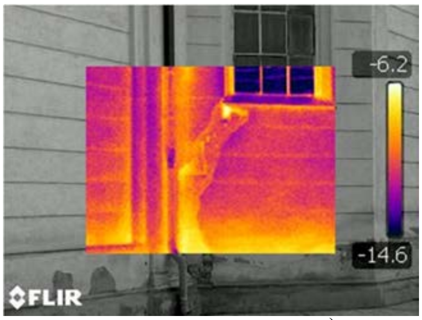


Fig. 1. Floor plan of the Church



a)

b)

Fig. 2. (a) Damage the exterior finishes taken with infrared camera; (b) Exterior view of the church

At present moment, the heating system inside de church is with static heaters, but they have some issues and heat is insufficient.

3. Measurements

In January 2015 a set of measurement has been started in the church. Temperature and relative humidity (RH) logger have been placed in the middle of the building at the level of anvon (see Fig.1). The global results are given in Fig. 3. For 5 days this parameter were followed. During this time the temperature variation was from 10,86^{0}C to 14, 21^{0}C with a mean value of 11,89^{0}C. The RH varies between 31,39 to 57,85 %. There is a time delay between the changes in the indoor and outside climate.

Measurements confirm that the church has a stable climate and the loss of heat by leakage is controlled. The temperature and humidity differences in the volume of the church are small. The actual heating system (static heaters) does not influence the indoor church climate, which is necessary for conservation of the artworks. The church can be approximately represented as a large, homogeneous volume, with a good moisture content. With a thermographical camera picture of the wall and ceiling were taken. There were found thermal bridges in several place, at the cracks from the wall also the windows provides a loss insulating characteristics and the ceiling has places with thermal bridges.

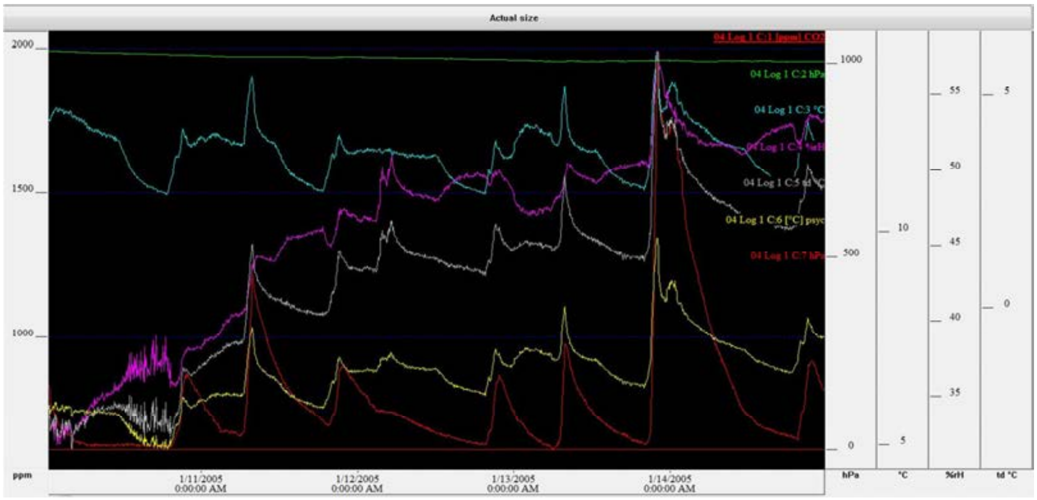


Fig. 3. Evolution of temperature, relative humidity (RH) inside the church of Dormition of the Mother of God

4. Modeling Temperature in Fluent

Fluent is **C**omputational **F**luid **D**ynamics (CFD) software that simulate fluid flow and heat transfer in different situation. It works by using finite-volume method to solve the mass, impulse and energy transfer equations. Also it can work with different kind of models such as incompressible or compressible, viscous or non-viscous, laminar, turbulent, k-ε models, etc. The geometry used in system was done in AutoCAD and exported in Fluent. [5]

4.1. Design models

The calculus was made in 2D models of the church. It has a simple and better understanding of the simulation made in Fluent and are representative for the church. [5]

4.2. Envelope Thermo technical design

The heat loss is model after the calculation of the global insulation coefficient (G) from C107-2005[6]. Knowing that the main reason of heat loss is caused by heat transportation through wall, is not easy to determine the model in Fluent. Therefore in order to approximately model to the real one the following choice where made:

- the wall temperature is dependent of the outside temperature.
- the estimated U-coefficient of the wall is 0,8 W/m^2K
- the U-coeficient for windows is 1,05 W/m^2K
- the U-coefficient for floor is 1,2 W/m^2K
- the U-coefficient for ceiling is 1 W/m^2K

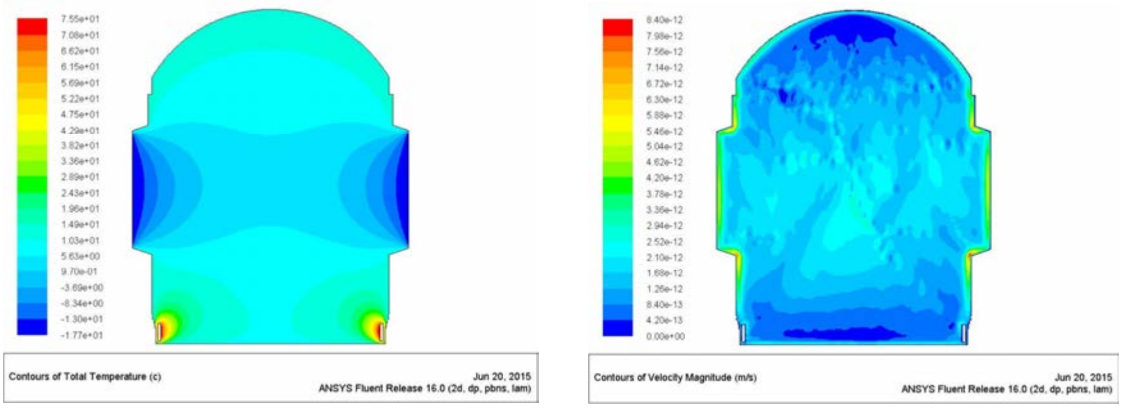
4.3. Static heaters

The static heaters is the system used now in the church. The hot water is distributed to the static heaters that are place under each windows. They are made from cast iron and the maxim power is for each of them is 5000 W. To simulate the effect of this system in Fluent, the static heater is defined as a wall with the temperature of the 80^0C.

The heat impute can be calculated using:

$$Q = m C_p \Delta T \ [W] \tag{1}$$

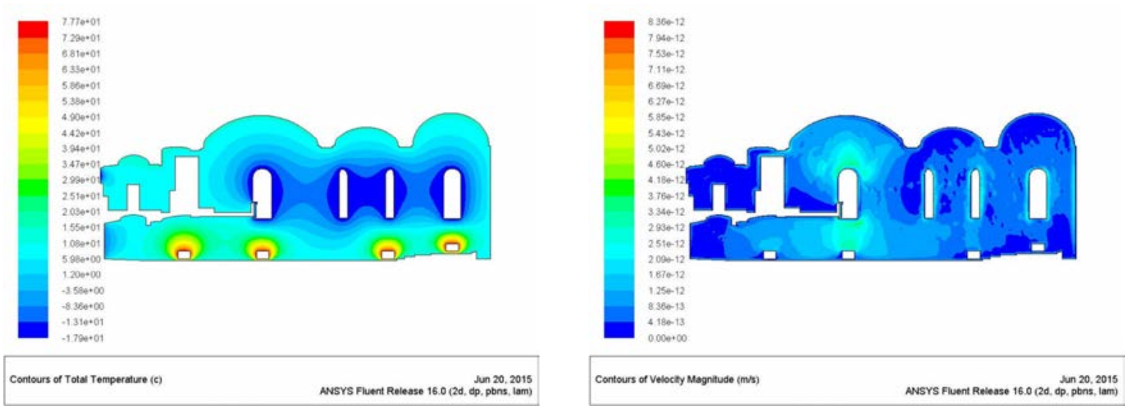
where: m - mass flow of the fluid; C_p - volumetric heat capacity of the fluid; ΔT temperature difference between incoming and outcoming fluid.



(a) (b)

Fig. 4. (a) Contours of Total Temperature; (b) Contours of Velocity Magnitude

In the figure 4a, 5a is presented the situation with 2 static heaters in transversal and longitudinal section. At the exterior temperature of -18^{0}C the temperature distribution in church is almost homogeneous of 10,3^{0}C. This temperature combined with the RH, give the reason to create local zones of humidity.



(a) (b)

Fig. 5. (a) Contours of Total Temperature; (b) Contours of Velocity Magnitude

In figure 4b, 5b is air velocity are presented. It can be observed that in the proximity of the walls the speed is higher, this aspect explains the paintings deterioration and the dust on them.

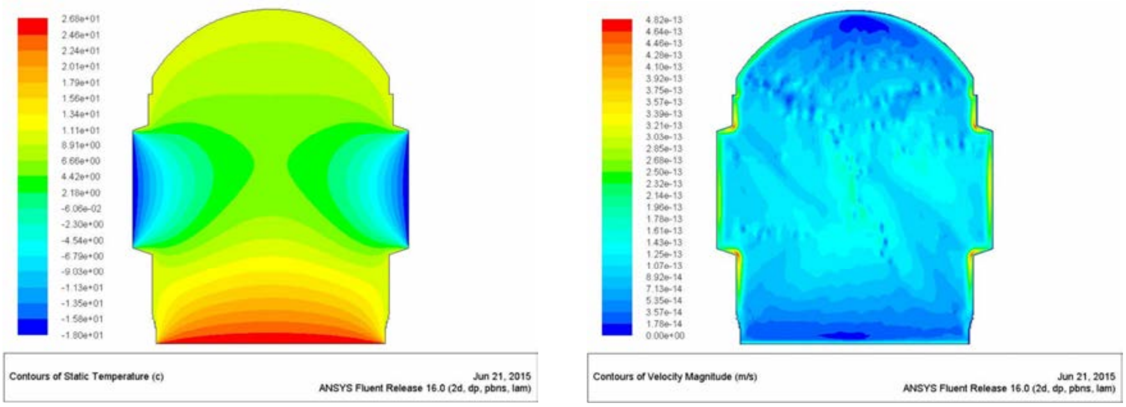
4.4. Underfloor heating

The model is analyzed in 2D. The boundary condition is put in such a way that the floor has a fixed temperature. Fluent solves the energy equation by searching an equilibrium of the incoming and outgoing heat flows. The heat flow through a wall is calculated by Fluent with the relation [7]:

$$Q = h_f (T_w - T_f) + q_{rad} \qquad [W] \tag{2}$$

with: h_f - fluid-side local heat transfer coefficient; T_w - wall surface temperature; T_f - wall surface temperature; q_{rad} - radiative heat flux

At the outdoor temperature of - 18^0C and a floor temperature of 20^0C, the temperature distribution is shown in the model fig. 6a, 7. The air speed and motion is shown in fig 6b with value that can be neglected and save for art



(a) (b)

Fig. 6. (a) Contours of Total Temperature; (b) Contours of Velocity Magnitude

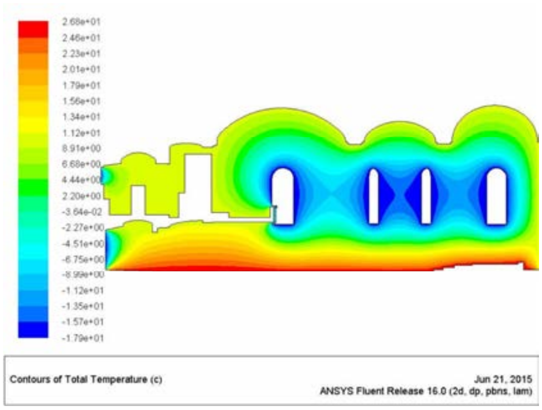


Fig. 7. Contours of Total Temperature in longitudinal section

The balance temperature in church is around 11^0C. The temperature is sufficiently without reaching an excessively high floor temperature to have a warm indoor climate. The detail simulation shows that the height of the church is suitable for underfloor heating.

5. Technical Solution from Energy Optimization

Using the NP-048-2000 and MC 001/2006 [8] is determined the energy consumption for the building:

- Energy Consumption for heating $Q_{heating}^{year} = 257{,}35 kW / m^2 year$
- Energy Consumption for domestic hot water $Q_{hotwater}^{year} = 30{,}15 kW / m^2 year$
- Energy Consumption for lighting $Q_{lighting}^{year} = 257{,}35 kW / m^2 year$

- Total Energy Consumption per year $Q_{TOTAL}^{year} = 316{,}26 kW/m^2 year$

This energy demands place the building in "D" class of consumption. So the demand of energy consumption reduction is argued.

Because of the category of the building any intervention on the facades is cancelled. The only places where we can increase thermal resistance are the roof, by insulating the outface of the ceiling and the floor. To increase the thermal resistance of the ceiling is used rock wool having the width of 15 cm and reaching a total resistance coefficient U=0.297 W/m^2K. To improve the thermal resistance at floor is used extruded polystyrene in a layer of 10 cm so that the thermal resistance is U=0.318 W/m^2K.

In order to increase the energy optimization a special attention is focused on the building service system, such as heating, lighting, domestic hot water systems optimization. The efficiency of the systems is increased by taken into account the following set of solutions:

- changing the static heaters with the ones more efficient and a better design of the total demand of heat Q need for the church.
- by using solution of optimization for the heating system, ex. thermostatic valves
- changing the classic lighting system with more esthetical and efficient ones ex. led or fluorescence light
- a better management of domestic and waste water by using thermostatic batteries, heat recovery system for the waste water

Considering the changes described a new energy classification is made. Using the same NP-048-2000 and MC 001/2006, the new result are:

- Energy Consumption for heating $Q_{heating}^{year} = 122.97 kW/m^2 year$
- Energy Consumption for domestic hot water $Q_{hotwater}^{year} = 7{,}26 kW/m^2 year$
- Energy Consumption for lighting $Q_{lighting}^{year} = 20{,}95 kW/m^2 year$
- Total Energy Consumption per year $Q_{TOTAL}^{year} = 151{,}19 kW/m^2 year$

This energy demands place the building in "B" class of consumption.

6. Economic Analysis for the Energy Efficiency Solution

Is a simple form of evaluation for cost investment and time returning of the investment. In the analysis is taking into consideration two situation as shown in table 1 and 2, one with the solution for rehabilitation of the envelop and one take consideration the rehabilitation of envelope and utility system(heating, domestic hot water and lighting system) The analysis is based on the following hypothesis [8] [9] [10]:

- thermal energy cost C_{the}=55,16 Euro/Gcal, C_{the}= 0,05 Euro/kWh
- electrical energy cost C_{ee}=0,1 Euro/kWh
- formula for the returning back period used is

$$N_R = \frac{C_{INV}}{\Delta E \cdot C_{et/ee}} \tag{3}$$

where: C_{INV} - total cost of investment [Euro]; ΔE - energy savings [Euro/year]; $C_{et/ee}$ - specific cost for thermal and electrical energy [Euro/kWh]; e - energy unit savings.

$$e = \frac{C_{INV}}{\Delta E \cdot N_S} \tag{4}$$

Where N_s - life span of the rehabilitation solutions

Table 1. Energy consumption for each solution type on each service system.

No.	Solution Type	Heat Consumption	Domestic Hot Water.	Lighting Energy Consumption	Total Energy Consumption
		[kWh/year]	[kWh/year]	[kWh/year]	[kWh/year]
1	Envelope Rehabilitation	70516	10598	10109	91223
2	Envelope and Service Utility Rehabilitation	43221	2552	7365	53138

Table 2. Comparison between the proposed solutions

No.	Solution Type	Energy Savings - ΔE	Life span- N_s	Investment Cost	Returning time of the investment - N_R	Enegy Cost Savings - E
		[kWh/year]	[Years]	[Euro]	[Years]	[Euro/kWh]
1	Envelope Rehabilitation	19933	30	40256	13.46	0.0673
2	Envelope and Service Utility Rehabilitation	58018	20	43623	9.40	0.0376

7. Conclusion and perspectives

It can be observed the difference in temperature distribution in the occupation zone. In case of classical solution with central heating and static heaters the whole volume of air is heat fig.4a, 5a. The warm air tends to rise to the upper part of church which contain the art works.

In case of the underfloor heating the heat is more uniformly distributed, having about the same value in the occupation zone fig. 6a, 7.

The air velocity of air is another important aspect. The system using static heats fig.4b, 5b, produce a high speed of air, that rises and in its move carry the dust, water vapor that has a strong destructive effect on paints and art works because is their condensing. Also the high speed of air causes a superficial drying of objects made from wood, painting of canvas, old book, etc. The movement of large mass of air has as result the movement of smoke from the candles that affect the paintings and fresco paintings.

Large space with big volume of air need time to heat to the comfort temperature. Doing this operation with static heaters takes a lot of time because the hot air will also stay up and the cold one down, also in case of static heaters the air has a strong stratification fig. 4a, 5a. Using underfloor heating fig. 6a, 6b, 7, the stratification of air is only in the occupation zone. Because the temperature of the supplying hot water for underfloor heating system is can stand in a standby mode, with a guard temperature and for a liturgical services will be start with 15 minute early.

As a final statement the optimal solution for church heating it can be underfloor heating, combined with a mechanical ventilation system with a heat exchanger to maintain the RH at the optimal level.

The aim of rehabilitation process and building modernization is to reduce energy consumption. Increasing energy efficiency has a strong benefit over the environment. The solution adopted for the rehabilitation shows that the energy efficiency can be achieved ever for heritage monument.

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