# A New Methodology Based On Infrared Thermography And Numerical Modelling For The Conservation Of Historical Buildings

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Abstract The indoor microclimate is very often the main hazard for the conservation of heritage buildings, including decorations such as wall and wood paintings. In many cases heating devices are requested inside the historical buildings, but it is difficult to forecast the long term effect of a conditioned microclimate on precious works of art. Generally, measures for safeguarding the historical buildings take into account information about indoor environmental conditions. These are usually collected through long term monitoring of the air temperature and relative humidity, coupled to visual inspection and photographic recording.

For more advanced surveys infrared thermography can be applied thanks to its contactless and non-invasive nature. The proposed approach is to couple infrared thermography monitoring with Computational Fluid Dynamics modelling. This methodology consists in two steps: at first a building survey using a Quantitative infrared thermography technique followed by a modelling of different Heating, Ventilating and Air Conditioning solutions. An additional step could be added after a retrofit intervention, in order to verify the efficiency of the selected solution. The main advantage of numerical simulations is the possibility to calculate the indoor parameters in a large number of internal points. The aim of this work is to set up an investigation method allowing the prediction of the best indoor conditions for the preservation of the frescos and the correct utilization of the air conditioning systems. This work presents the results of the proposed method applied to a small church (San Biagio di Baver, in the North-East of Italy) with a precious medieval fresco paintings. Thermographic survey was performed by the aIRview system that acquired simultaneously different microclimatic parameters (such as air temperature, wall temperature, relative humidity). The obtained data were used as a basis for the Computational Fluid Dynamics modelling. This leads to an accurate design and comparison of different retrofit interventions.

Keywords: Thermography, CFD, Frescos

### **1** Introduction

The aim of this study is to analyze the microclimate of an ancient church adorned with precious fresco paintings that date back to medieval times in order to assure their future conservation. The study exploits the possibility to simulate, by Computational Fluid Dynamics (CFD) technique, various environmental conditions and usage behavior. This provides reliable support data for the design of environmental control systems capable to maintain the optimal local microclimatic conditions for the works of art and to assure acceptable thermal comfort to people visiting the building during the religious events. In fact, the simulation allows to extend the results of the experimental investigations to different scenarios of environmental conditions and usage, which generally can not be detected on the field. Furthermore, the support of the experimental data to CFD simulations allows for the fine tuning of the model itself in order to improve the reliability of the computed outcomes.

Even if fresco is one of the oldest and most durable painting techniques, it is subject to deterioration due to several agents, such as biological or mechanical damages. These causes are often related and accelerated by factors as: bad air conditioning, wrong light systems and a massive flow of visitors.

Consequently, it is paramount to detect the presence of unsuitable microclimate conditions [1, 2], paying particular attention to the thermo-hygrometric status and its related air flows, as even the suspended pollutants propelled through the air by convective heat fluxes are considered amongst the main factors of risk. Finally, surface temperature data are extremely important to preserve frescoes against the risk of water vapor condensation, that may lead to detachments of the painted surfaces as effect of saline efflorescence phenomena [3]. Therefore, the evaluation of areas affected by abnormal cooling (e.g. thermal bridges) is mandatory indeed. To face these problems, a very detailed air temperature and velocity mapping both in

space and time is extremely helpful. In this context, infrared thermography (IRT) has a key role as this technique is capable to measure the temperature of wide surfaces instantly and without contact with the objects [4, 5]. The latter aspect is not negligible in the art conservation field, because invasive or destructive techniques are often limited or prohibited. Moreover, advanced applications of IRT have proven to be capable also to measure thermo-hygrometric parameters of air and walls [6, 7, 8]. Furthermore, the outcomes of a IRT building survey are also a reliable source of input data to be used to define the boundary conditions in CFD analysis.

A robotic IRT system developed by ITC CNR [9], has been applied in order to scan quickly and accurately the indoor surface temperatures of the church. Thermal data are integrated with local microclimatic information provided by the system itself thanks to a grid of special targets designed to work in the infrared range, which allows to automatically combine the thermographic data with a thermodynamic model developed for confined spaces, producing spatial maps of the parameters which determine the microclimate and the thermal comfort (e.g. air temperature, relative humidity and air velocity).

The final step of the procedure is the analysis of the acquired data and their integration with a thermal-fluid dynamics simulation software in order to predict the microclimate and the comfort conditions for arbitrary but realistic scenarios as seasonal conditions and for various options of thermal loads and occupational schedule.

### 2 Case study

San Biagio church is a small building (figure 1) located in Pianzano, a small hamlet near Treviso, in North-East of Italy. The building dates back to the XV century and it is remarkable from historical, artistic, and devotional standpoint.



Fig. 1 Plant of San Biagio in Baver Church

In particular, the fresco paintings that adorn the presbytery walls, shown in figure 2, are of significant artistic value and portray religious themes and episodes of the life of San Biagio.



Fig. 2 Frescos describing the story of Saint Biagio in the apse of the church

The main hall of the church has been built during the Renaissance and it is almost undecorated. This part of the building is intended to accommodate people during the religious services.

In 1993, the church was repaired to solve structural problems and to restore the fresco paintings badly damaged by atmospheric agents.

The present study is rather interesting because this little church, under certain conditions of overcrowding, suffers serious problems of surface condensation, especially in the presbytery wall facing East. In fact, during religious festivals in wintertime, there are lots of people in the hall of the church (i.e. exceptional source of water vapor and thermal load), and the surface moisture condensation is so evident that the colors of the paintings are altered by water. This phenomenon is causing a rapid deterioration of the frescoes of the apse, as shown in the next figure 3.



Fig. 3 Visual image of the South-East side of the apse (left) and West side of the apse (right). The area with decayed frescoes are marked in pink

### **3** Data collection

The presence of the fresco paintings in the presbytery, made this part of the church the main focus of the monitoring campaign, but the building has been investigated in its entirety nevertheless.

The IRT investigation was performed in December 2008 in passive mode, (i.e. without changing the environmental conditions and without imposing an external thermal stimulus), with the aim of detecting the natural thermal conditions of air and walls.

One important feature of this work is the application of an automated system called aIRview, a robotic system that can automatically acquire and process photographic and thermal images, scanning a surface at the pace of 30 square meters per minute. aIRview system is a complex apparatus whose core is made of a microbolometric infrared camera working in the range 7.5 to 13.0 µm with a Noise-Equivalent Temperature Difference (NETD) of 50 mK at 30°C. The detector size is 320x240 pixel. The IR camera is mounted on a pan-tilt device that allows to scan a wall by taking images of neighboring fields of view. The acquisition is automatically managed by custom Labview software [10] while the IR image processing is done in Matlab environment [11]. The images related to one scanning are automatically corrected for radiometric and geometric distortions [12, 13] and successively mosaicked to obtain a complete view of the surface of interest using a grid of special targets designed to work in the infrared range. The spatial resolution of the thermal mosaic is 1 pixel/centimeter and its size depends on the dimension of the investigated surface. The correct temperature of every pixel is automatically calculated taking into account the ambient radiation and considering the surfaces as Lambertian emitters with emissivity equal to 0.90 (evaluation done according to [14]).

The use of special infrared targets represents a distinguishing feature of aIRview system compared to the normal state of the art IRT building survey routine. These targets act as reference for the geometric reconstruction of the surfaces that leads to the ability to accurately locate any thermal anomalies or defects. But the most important aspect is the possibility of calculating, using thermal information gathered by the IRT camera thanks to the targets, local parameters such as relative humidity, reflected temperature, air temperature and air velocity. Every target consists of several parts: a small water tank containing distilled water, in which is immersed a piece of fabric, a scattering reflective material, and two thin layers of white and black plastic. These parts occupy one quarter of the surface of the target each, and they are arranged in a chessboard fashion. Every quadrant is built and placed according to a precise idea and a specific function. The white and black regions have high and known emissivity and known absorption coefficient. They easily reach thermal equilibrium with air acting as a reference for the air temperature. The wet fabric represents the wet bulb temperature, under natural air flow. The scattering reflector is made of multi faceted polished aluminum with very low emissivity, in order to collect ambient radiation randomly reflected from multiple directions. In the survey of San Biagio church, the targets were arranged in an almost regular pattern, with horizontal and vertical pace respectively of 1 m and 0.7 m. The number of infrared targets used is 31: they where mounted on a planar and arched structure that was placed at 10 cm of distance from the investigated wall. Furthermore, a cavity (black body), probed with a resistance temperature detector, was positioned near the targets: the temperature of the black body acted as an infrared camera calibrator. Finally, a wet fabric under imposed air flow with speed >5 m/s served as psicrometric wet bulb reference. The process of acquisition of the photographic and the thermal images was repeated as described in the previous section on each wall of the church. For the measurement of the remaining parts (i.e. floor and ceiling) only the average temperature values were acquired. Another key point in this kind of scan is the overall velocity of the data acquisition process, that must be compatible with the examined physical phenomena. A complete scan of the church surfaces, has been performed in less than 30 minutes, a time that is small enough to validate the otherwise awkward assumption of an instantaneous measurement.

### 4 Experimental data processing

The data processing were performed by the aIRview system automatically at the same time of the data acquisition. In addition to the average relative humidity value, for every wall of the church, four maps of different microclimatic parameters were obtained, with a data density of one value per square centimeter.

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These parameters are:

- surface temperature (direct measurement);
- air temperature at 10 cm from the surface (computation);
- air velocity at 10 cm from the surface (indirect measurement);
- reflected temperature at 10 cm from the surface(direct measurement).

The output maps and the visible images are registered and geometrically corrected as a ortho-image. Finally, the maps are overlapped to a three-dimensional model of the building for a much better interpretation of findings. In this way, a global and more effective idea about the situation, such as the evaluation of the microclimate inside the building, is achieved.

Figure 4 shows the temperature map of the North wall, where a cold area has been detected on the upper part. This strange thermal pattern is due to a side building, which is lower than the North-East wall and protect the church from the cold air. The cold area is evidenced with a pink line. Comparing with the visible band images on the right, where the deteriorated area on the fresco is evident, cold area and deteriorated area superimpose each other in a surprising way. The responsible of degradation could be the vapour condensation on cold surfaces during periods with high humidity concentration connected to huge people attendance or to specific climatic conditions (spring or autumn) when warm humid air come inside the church.

A second area of degradation is present on the lower right corner probably connected with capillary rising from ground. Also in this case a lower surface temperature is evidenced by the map of temperature.



Fig. 4 Surface temperature of the North-East wall (left) registered on the building model and visible band images (right) of the same wall. The areas of decayed fresco are evidenced with pink line

Furthermore, this representation of the results allows to evaluate the effects of the air leakage through doors and windows as air tightness is one of the main parameters involved in a microclimate, energy and thermal comfort survey. Observing the air temperature distribution, a cold air stream coming from outside is detected at the hall-presbytery intersection, near a not tightly closed wooden door (see figure 5).

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Fig. 5 Surface temperature of the North-West wall (S. Biagio, Baver, Italy) registered on the building model and the decayed fresco

An interesting feature of the new aIRview system is the possibility to map the air movement. It is important to stress the influence of the closed window on the East wall which affects the air circulation. Figure 6 represents the air velocity component parallel to the surface of the apse, expressed in m s<sup>-1</sup> and mapped every square centimeter. Analyzing the air temperature (10 cm far from the wall) shown in Figure 7 it is clear the role of the window of the South side, which push air during the day towards the East side. The air movement given by the new IRT technique is reported in Figure 8. It is clear that the warm air from the people during ceremonies may easily condensate on the cold surface of the East wall of the apse where the ventilation is very low (velocity<  $0.2 \text{ m s}^{-1}$ ).



Fig. 6 Air velocity at 10 cm from the North wall (left) and West wall (right) of the apse



Fig. 7 Air temperature 10 cm far from the surface of the apse, with a closed window on the East wall



Fig. 8 Component of the air velocity parallel to the surface of the apse at 10 cm from the surface with a closed window on the East (v. max 0.2 m/s)

### **5** Computational Fluid Dynamics Modelling

CFD is a precious tool to simulate the dynamic behavior of fluids and their relation with physical phenomenon. By means of mathematical models the evolution of the fluid is described through the dynamic parameters such as speed, pressure, temperature, and density.

Usually, Heating Ventilating and Air Conditioning (HVAC) experts make use of numerical simulation tools in the design phase for forecasting analysis, when the realization of a prototype is not possible. In this study, the CFD is used to predict the movement of the air inside the environment in order to support the analysis of the comfort of the occupants and of the conservation of the artworks. The analyzed parameters are: air speed, air temperature and its distribution.

Even the simplest application of CFD simulation requires a high number of variables for proper modelling. Therefore, a simplification, based on judicious assumptions, is often preferred. Nevertheless, reliable input data are required to avoid uncertain outcomes. As stated in the previous sections, the simulations are based on the real conditions, monitored by IRT.

A CFD modelling involves the description of the system considered in term of the three fundamental conservation equations: mass, energy and momentum. The following partial differential equations states:

Mass Conservation:  

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho u) = 0$$
(1)

Reynolds Momentum Conservation:

$$\frac{\partial \rho u}{\partial t} + \operatorname{div}(\rho u u) = -\frac{\partial p}{\partial x} + \operatorname{div}(\mu \operatorname{grad} u) + \left[\frac{-\partial \tau_{xx}}{\partial x} - \frac{\partial \tau_{xy}}{\partial y} - \frac{\partial \tau_{xz}}{\partial z}\right] + M_{\chi}$$
(2a)

$$\frac{\partial \rho v}{\partial t} + \operatorname{div}(\rho u u) = -\frac{\partial p}{\partial y} + \operatorname{div}(\mu \operatorname{grad} v) + \left[\frac{-\partial \tau_{yx}}{\partial x} - \frac{\partial \tau_{yy}}{\partial y} - \frac{\partial \tau_{yz}}{\partial z}\right] + M_y$$
(2b)

$$\frac{\partial \rho w}{\partial t} + \operatorname{div}(\rho u u) = -\frac{\partial p}{\partial y} + \operatorname{div}(\mu \operatorname{grad} w) + \left[\frac{-\partial \tau_{zx}}{\partial x} - \frac{\partial \tau_{zy}}{\partial y} - \frac{\partial \tau_{zz}}{\partial z}\right] + M_z$$
<sup>(2c)</sup>

Energy Equation:  $\frac{\partial \rho e}{\partial t} + \operatorname{div}(\rho e u) = -p \operatorname{div} u + \operatorname{div} \cdot (\lambda \operatorname{grad} T) + \Phi + H$ 

where: t (time),  $\rho$  (density), u (time-averaged velocity vector), u, v, w (time-averaged velocity components), p (time-averaged pressure),  $\mu$  (viscosity),  $\tau$  (Reynolds stress tensor),  $M_x$ ,  $M_y$ ,  $M_z$  (momentum productions), e (specific internal energy),  $\lambda$  (thermal conductivity of air),  $\Phi$  (viscous dissipation of energy for unit of volume), H (energy production per unit of volume).

In this work a commercial numerical model (PHOENICS-CHAM [15]) was applied to San Biagio church in order to obtain temperature and velocity fields which make viable the comparison among different scenarios including different boundary conditions and HVAC design solutions [16]. The solver procedure is based on the finite volumes method. The analyzed domain is divided in a large number of finite elements: the proposed partial differential equations are substituted with ordinary differential equations. The greatest advantage of this method is the intrinsic flexibility to treat complex flow situations and not regular geometry conditions. The continuum space domain is reduced to a discrete domain using a limited number of cells. The method adopted for the numerical solution allows to solve the equations of mass, energy and momentum. The main limitations of these codes are the computation of the radiation exchanges, and the restrictions in the maximum allowed number of cells that form the space domain. Both these limits can be overcome by using IRT measured temperatures as input data for surface temperature on the boundaries. The description of the boundary is in fact very detailed and radiative exchange is already been considered in the measured values.

The basic steps for the CFD simulation of the building have been as follows:

- Geometrical definition of a simplified three-dimensional model (the very same model has been used to present the outcomes of the experimental campaign as shown in the previous section) to facilitate the insertion within the calculation code;
- Definition of the size of the CFD calculation grid;
- Definition of the type of analysis to be performed, the type of regime and the computational domain;
- Inputting data related to surface temperatures, denser inside the presbytery and less refined in the hall;
- Definition of the boundary conditions and the elements within the simulated geometry (i.e. septa, stairs, altars, windows etc.);
- Analyzing the results and evaluations.

(3)

The three-dimensional model was created using a Computer-Aided Drafting software, based on the directly measured geometric features of the building. In this simplified 3D model many minor features are missing or pending, such as the seats (benches), but all internal septa, the openings, the stone altar, and the two doors are retained. Once the 3D model is built, the next operation is to define the optimal discretization grid in order to divide the internal space into a finite number of cells, which depends on the precision to be obtained in the calculation. A greater number of small cells produces more detailed output information, but an over discretization of the space domain may lead to data redundancy and to computing time wasting. Only after several tests on the degree of accuracy, resolution and efficiency of the mesh, it has been possible to set a grid of calculation equal to 500000 cells. The final grid pattern has been defined making the mesh denser close of the walls, for greater accuracy of calculation in the interface wall-fluid. A proper choice of the grid domain, combined with a correct number of iterative cycles that the software must perform (sweeps), is the basis for the achievement of the convergence, which is the tendency of the resultant to align to a final state with minimal changes to the progress of the iterations. The simulation is considered in steady state. Therefore, boundary conditions are assumed constant both in space and time. The flow-type has been considered "elliptical" within the domain, and this means that the physical phenomenon in every point is influenced by earlier and later situations in both time and space. It is assumed that the motion of the air within the domain is turbulent, hence, a model of interpretation that suit this phenomenon has been adopted. The air behavior within the environment has been considered comparable to an ideal gas, with density equal to the pressure divided by the universal gas constant and temperature. The calculation operations have been performed on both solids and gases, setting on the heat exchange by transmission and by convetion. The data provided by IRT analysis are geometrically placed in space corresponding to the positions of each targets. Particular attention was paid to the study of the geometric matching between the infrared data and rectangular tiles of the discretization grid to which to assign the information. The tiles that define the inner modeled surface of the walls have a size equal to 100x70 cm, as it corresponds at the pace used to place the targets during the experimental campaign. The boundary conditions are represented by all the physical elements contained within the domain (i.e. internal partitions, altar, steps, floor unevenness, doors and windows), the boundary walls, the temperature data by IRT analysis, the heat sources, the internal pressure, and the gravity force. More in details, the physical elements (i.e. baffles, altar, etc.) have been identified as physical bodies with a geometry and a constituent material (e.g stone, bricks, etc.) which is associated with a surface roughness (friction) parameter set by the software. The surface temperature of the walls resulting from IRT is identified through two solutions that the software offers: boundary walls and heat sources. The latter step is the most important because it is comprehensive of the comparative analysis between the experimental data and the CFD outcomes under the very same boundary conditions, in order to validate the model. In particular, the results of CFD are tested versus air temperature and air velocity, both measured by IRT.

### 6 Computational Fluid Dynamics results

The results given by the CFD numerical simulation forecast the air temperature values, that are in the range between 7 and 8 °C. A very high uniformity in the horizontal plane is evident. The gradient is confined near the walls and it is very limited, also in the vertical direction. This situation is not surprising, because it is frequent for historical buildings where a very high heat capacity of thick masonry exists. In addition, typical large rooms and the lack of thermal plants enhance this situation. The simplified shape of the analyzed domain adopted by the simulation can be justified because of the low velocity and temperature uniformity. Nevertheless, a comparison of the air temperatures detected by thermography, with the simulated values was found in a quite good agreement, confirming the validity of the proposed procedure. The second step evaluates the effects of the people inside the church in critical winter conditions. Fig. 9 shows the air temperature at 9 cm height from the floor, as simulated in case of only the hall being heated. Furthermore, a radiant heating floor hidden on the benches platforms and eventually on the altar platform has been simulated.



Fig. 9 Air temperature computed 9 cm from the floor

Figure 10 shows the air movement, as predicted on the church cross section set, in the middle of the heated bench platform. The warm air is pushed towards the apse and stopped abruptly by the East wall in a cascade effect, that makes the surface condensation possible. Adding the altar platform heating, this effect is significantly reduced.



Fig. 10 Computed air speed due to the heting of the church floor

Higher values of the air velocity are computed near the wall surface of coarse increasing with the height. Airflow is directed upward in correspondence of the two doors and downward along the surfaces of the walls. As a consequence of the asymmetric boundary conditions, also the circulation evidenced is non-symmetrical. The obtained limited air movements seem to limit the risk of dust dragging and particles' deposition by thermoforesis on walls surface. Also in this case the comparison of calculated values with the spot measurement on the same location is satisfying. The influences of the openings in the velocity pattern are clearly visible in this flow visualization, even if a limited mass exchange with adjacent rooms were evidenced. This confirms the low rate of natural ventilation, especially in presence of visitors, together with low surface temperatures detected during the measuring campaigns. On the other side, this set of concurrent

conditions is extremely critical for the risk of moisture condensation.

Fortunately, this situation could be easily evaluated at any specific point of the building envelope by means of thermographic temperature detection, coupled to the numerical simulation.

#### **6** Conclusions

The indoor air control is a main task for the historical building preservation. For the development of fluid dynamics analysis in building environment, the IR thermographic analysis is a valuable complementary tool of numerical codes. Not only a qualitative overview, but a global quantitative monitoring is possible using a combined approach. The knowledge of temperatures at the walls surface can be utilized directly, as boundary condition for the simulations and the mesh description can be more detailed. As a consequence, the solution proposed can be more accurate and less computationally heavy. In fact, the radiation exchanges can be resolved directly considering the temperature values and not by coupling of a radiation model to the fluid-dynamic one.

The simulated temperature for the baseline case have been compared with the experimental data showing good agreement. It has been also possible to study the effect of different control strategies of the heating floor.

The creation of a three-dimensional and georeferenced model of the building is usually required by CFD software but is also a powerful tool for the visualization of the results. The inclusion of the survey and simulation results in a synthetic view has proven to strongly enhance the understanding of the results, facilitating the interchange within the individuals involved in the project.

A future task is the moisture analysis, by measuring this parameter on site using aIRview and by numerical calculation of relative humidity in the boundary layer (near the painting film). This aspect should be very informative for the evaluation of the number and the time periods of the crystallization and for the dissolution of the soluble salts and for assessing the risk of alteration of painted surface. The successive stage is the implementation of the simulated energy saving actions. That could range from simple changes to the behavior of the occupants to the installation of a HVAC system coupled with the restoration of the building. The ultimate step of the procedure is the monitoring of the energy consumption and the experimental verification of the comfort conditions produced by the intervention, with the main objectives to optimize its operation, to verify the correctness of the implementation and possibly identify sources of errors in any of the previous stages.

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