# An integrated approach to the preventive conservation of cultural heritage: Computational Fluid Dynamics application

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## 1. Introduction

Today, the microclimate control of indoor environments has become essential for protecting cultural heritage. Air quality, temperature variations and humidity must be controlled in historic buildings in order to avoid hazards to cultural property as well as to operators and visitors. Optimal microclimatic conditions for objects are often not compatible with those recommended for people. Thus, research on conservation and prevention methods, together with long term monitoring campaigns and microclimate control, can suggest essential criteria for the appropriate use of historic buildings. They can provide useful data to help museum management concerning the use of rooms and the protection of exhibited objects, as well as useful information to help choosing the most suitable solution for heating, cooling, ventilating and dehumidifying/humidifying heritage buildings. The integrated approach we propose involves the biological monitoring of air and surfaces and the monitoring of microclimatic indoor conditions.

Microclimatic regulations and standards for historical buildings connected to their various uses, are still at present subject to controversy in the literature [ASHRAE,2001;ASHRAE,2003;MiBAC,2001;UNI 10829,1999;UNI EN 15757,2010]. Moisture induced damage is one of the most important causes of degradation processes and reduced thermo-physical performances of building components and the different materials of the collected and/or exhibited artefacts, especially rare books and manuscripts. At present, substantial published simulation programs and codes are available on moisture transfer in buildings, building materials and components, but also for prediction of the indoor thermal environment [Korjenic and Bednar, 2012; Langmans et alii., 2012]. There are also interesting, basic published models for the simulation of coupled heat and moisture transport providing a valuable method in which possible damage-related processes in building materials and components can be predicted [Schijndel, 2007a; Schijndel, 2007b]. The European standard [EN 15026,2007], that is based on the WTA (International Association for Science and Technology of Building Maintenance and Monument Preservation) Guideline 6-2, is usually issued for preservation, maintenance, conservation and restoration of heritage buildings, materials, works of art, ancient wood and paper artefacts [EN 15026,2007]. The emphasis on preventive conservation has given new directions to research; e.g. the discovery of the yellowing of paper inside the cut out of a passe-partout (mat) raised questions about the effects of a microclimate inside boxes and frames. The impact of the indoor environment in which organic objects are exposed has to be assessed by evaluating the risks posed by the overall environmental conditions on site. An official European (or international) standard that defines conditions and procedures does not exist. The ISO 11799 covers some aspects relating to exhibitions, such as exhibition room climate and security, but the specifications given are generally the same as those for repositories. The British Standard 5454:2000 covers many preservation-related requirements for exhibiting documents. After a general introduction on short-term and long-term exhibitions, it leads on to lighting, display cases as well as conditions for the display of seals, lead bulla, bound volumes and photographs. It also includes several recommendations on light exposure, such as the level of incident light for inks, dyes and light-sensitive pigments should not exceed 50 lux. It states that daylight should be excluded and ultraviolet light omitted from electric sources minimized by using filters. The American National Standard Institute standard ANSI/NISO Z39.79-2001 establishes criteria to minimize the effect of environmental factors on deterioration of library and archival materials on exhibition, the user is required to select specific limits for a particular exhibition situation. The Standard is intended as a guide for librarians, archivists, exhibition designers and others involved in preparing library and archival materials for exhibition. The most comprehensive document in the field is the 2002 French standard, “Preservation requirements for exhibiting graphic and photographic materials”. The chapter on exhibition conditions is very comprehensive and specifies conditions of rooms, placement, equipment, showcases and support materials for exhibited documents as well as principles of their installation, mounting and de-mounting. Our research concerns the study of indoor air ventilation and thermal-humidity assessment by transient simulation of coupled heat and moisture transfer, also taking into account occupant presence and movements. The Derossiana Room of the Palatina Library in Parma (Italy), that is one of the most important archives and reserved access consultation rooms, is the case study. The present study is based on a numerical model recently proposed [Balocco & alii, 2012; Balocco et alii, 2013] that provided the prediction of damage-related processes in materials, and also the knowledge of indoor air movement and air temperature and humidity distribution over time using Computational Fluid Dynamic (CFD) with multiphysic Finite Elements Method (FEM) approach.

## 2. The Derossiana Room

The Derossiana Room is one of the most important library room inside the Palatina Library in Parma (Italy). The room is 6.90 m wide, 12 m long with a total volume of 496.8 m3. It has two internal partition walls and two walls facing the external ambient. The smaller of these external walls, with an area of 48.28 m2, has a central window with an area of 3.5 m2 and is South-West oriented, the wider external wall is 42.20 m2 and South-East oriented. It has a cross-vaulted ceiling.

## 3. Experimental measurements

A short monitoring campaign, due to the opening hours and accessibility of the Library, was carried out for only one week, during July 2012. The experimental measurements concerned the microclimatic conditions of the Derossiana Room during those days. The external climate data on total horizontal solar irradiation, mean air temperature, mean air humidity, mean wind velocity, corresponding to the days of the experimental measurements campaign, were provided by the local climatic station located in the centre of the city near the Palatina Library. The climatic monitoring of the ambient was based on stratigraphic and altimetric measures concerning the air temperature and humidity, air velocity, mean air radiant temperature, differential pressure variations at specific and crucial zones and the surface temperature of different building materials, objects and components. The microclimatic measurements were acquired every 5 minutes and every 2 minutes, using the instruments shown in Table 1, connected to a radio master R-Log data logger capture system. Temperature and relative humidity monitoring were carried out for three different heights with respect to the internal floor: 1 m, 2.7 m and 4 m, 1m constantly spaced out from the internal wall. For monitoring the internal wood bookshelves and furniture were used at 2.7 and 4 m height as support.

| | Range | | Resolution | Accuracy |
|---|---|---|---|---|
| 2 Air Temperature sensors; 2 Air Humidity sensors | Temperature | - 20 ÷ 60 °C | ± 0.1°C | < ± 0.5°C per 5°C < T < 45°C<br>< ± 2% per 10% < RH < 90% |
| | Relative Humidity | 0 ÷ 100% | ± 0.1% | |
| 1 Globe Thermometer | Temperature | - 20 ÷ 60 °C | ± 0.1 °C | ± 0.2°C per 5°C < T < 45°C<br>± 0.4°C per 5°C < T and T > 45°C |
| 2 Hot Wire Anemometers | Air velocity | 0÷20 m/s | ± 0.01 m/s | 0÷0.5 m/s: ±5 cm/s<br>0.5÷1.5 m/s: ±10 cm/s<br>>1.5 m/s: ±4 % |
| 2 Differential Pressure sensors | Air pressure | 0 ÷ 2.54 hPa | ± 0.01 hPa | 2% (20°C) |
| 1 thermo-camera Flyr | Surface temperature | -20 °C ÷ +650 °C | 320x240 pixels | ± 2% or ± 2 °C of reading |

Table 1: Instruments data

The globe thermometer was set at 2m from the floor in the middle of the hall. Internal air velocity and differential air pressure, between monitored hall and the adjoining rooms, was evaluated in proximity to the internal door at 1m and 2m with respect to the floor. Thermo-camera monitoring was flanked at previous measurements for an accurate evaluation of the surface temperatures of the different elements of the hall, particularly incunabula and wooden bookshelves. The obtained results show how the internal temperature was almost constant despite the external climatic stress due to solar radiation and hourly modification of the external air temperature and relative humidity, during all the monitored days during winter and summer. It is important to note that all these experimental values are beyond the limits suggested by the present standards for paper material conservation and reported in Table 2. As a matter of fact, in the Figure 1 the trend of the measured indoor climatic data are shown for winter and summer period.

| | $\theta_0$ [°C] | $\Delta\ \theta_{max}$ [°C] | $u_0$ [%] | $\Delta u_{max}$ [%] |
|---|---|---|---|---|
| Mi.BAC 2001 | 18 – 22 | ± 1.5 | 40-55 | ± 6 |
| UNI 10829:1999 | 13 – 18 | - | 50-60% | - |
| ASHRAE protection class B | 21 – 22 | | 40 – 50 % | ± 6 |

Table 2 Air temperature and relative humidity bandwidth suggested by Standards

Particles counting was performed by a particle counter Climet CL 754 certified and validated in accordance with the requirements of UNI EN 13205:2002. The equipment used can sampling a volume of 75 L / min of air and gives the number of suspended particles, divided according to the diameter (≥0.3 - ≥0.5 -≥1.0 - ≥5.0 μm). The measurements were carried out in triplicate. For each sampling point it has been applied an activation delay of 2' and a delay of 10'' between each moment of aspiration of the triplicate sampling.
The sensor of particles used works on the principle of scattered light. The particle counter uses a diode laser of 50 mW as a light source and a collection system to elliptical mirror. The diffused light through the particles, is collected by the elliptical mirror, and focused on a photo-detector in the solid state, which converts light energy into electrical current.

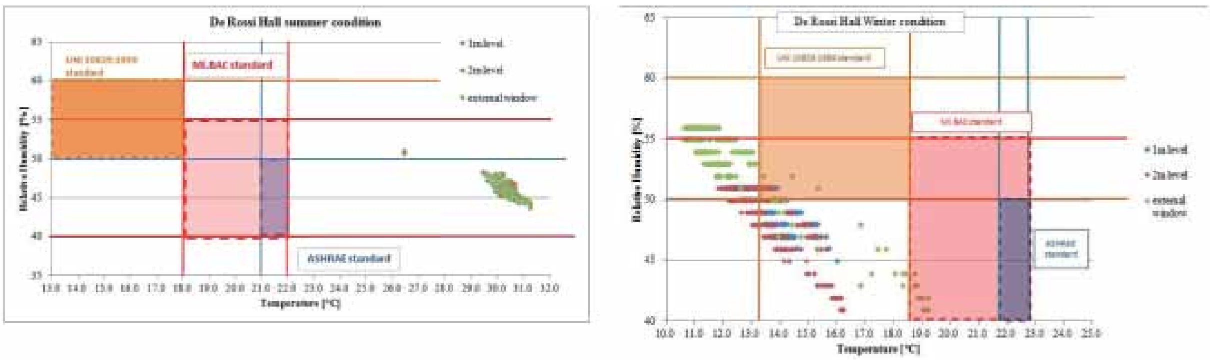



Fig.1 - Air temperature and Relative Humidity collected during summer (sx) andwinter (dx) campaing. Comparison with Standard limit values

## 4. CFD transient simulations

The geometry of the studied room was carried out by a solid modelling where all the different computational domains and the person standing considered in simulations were highlighted in blue (Figure 2).

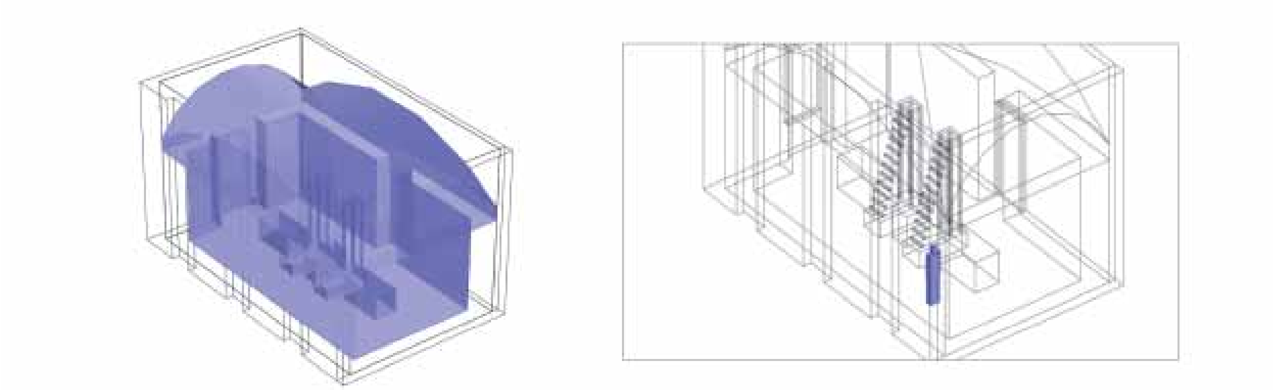
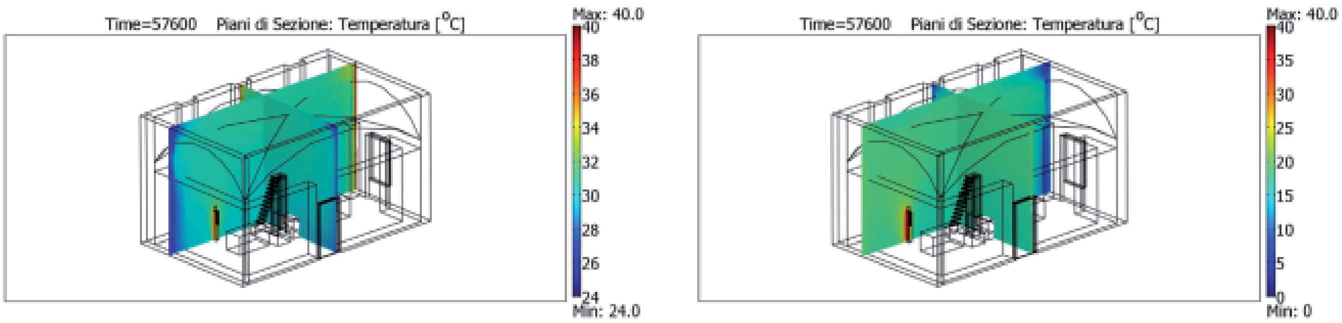


Fig.2 - 3d solid model of De Rossi room (sx) and inside standing people (dx)

Natural convection air flow inside the room was solved by the Reynolds Averaged Navier-Stokes and energy equations using a numerical model under the assumption of Newtonian fluid and uncompressible flow and combining a multi-physics approach with Finite Element Method (FEM). The validation and checking of the CFD transient simulation results and of the numerical model governing equations were presented in a recent paper [Balocco et alii, 2012; Balocco et alii, 2013]. In order to validate the applied numerical tool, results carried out by simulations were preliminary compared with available experimental data. Comparison concerns time histories of temperature and relative humidity evaluated at three different points inside the room, corresponding to locations where probes were arranged during the experimental campaign. Simulations were performed by imposing the same external environmental constraints occurring during acquisitions. Simulations were carried out for 3 conditions: the first one related to temperature fields inside the room and buoyancy driven air flow; the second concerns the relative humidity analysis inside the room and the third the effects on indoor air velocity field due to a person moving inside the room.

Fig.3 - Air temperature distribution during summer (sx) and winter (dx). h 16:00 Transient simulation result



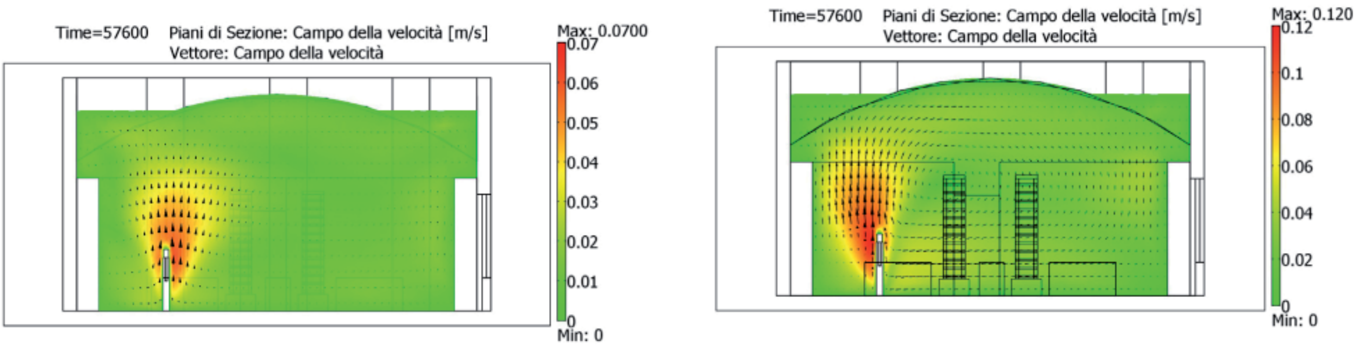




Fig.4 - Air velocity field and vector distribution during summer (sx) and winter (dx). h 16:00 Transient simulation result

From thermal analysis, both in summer and winter climatic conditions, the room appears to be well insulated with respect to external conditions, maintaining a constant temperature throughout the air domain. This finding agrees with experimental evidence. Otherwise, thermal transport is appreciably close to the simulated standing person inside the room, that represents the internal thermal source in the system. Isotherms appear locally shaped by the effect of the natural convection effect, determining a thermal plume above the simulated body. Fluid motion fields are due to local thermal gradient. Magnitude of air velocity reaches its maximum value close to the thermal source, determining a weak recirculation motion field also in the remaining portions of the room. Because of summer or winter conditions, the main fluid recirculation process presents opposite rolling directions: one way the hottest walls are the external ones, so that air moves upward close to them, otherwise they become the coldest ones, so that air tends to move downward in their proximity. This assumption explains why in winter conditions the motion field computed behind the person appears much more intense that in summer conditions. The bookcase and the paper/book material provide a vapour barrier from and towards the internal air volume of the room. The higher variations of humidity concentration are in the upper area of the wall in contact with the external environment. The latent heat power due to person presence standing near the bookcase does not notably modify the distribution of the vapour concentration in the inside air volume, even if the total vapour flux reaches its maximum values in the air volume around the person. Modification of flow patterns inside the room are evident due to person moving inside. This finding underlines the fact that, in the absence of imposed pressure gradient (forced indoor ventilation), the effect of person moving in the buoyancy-driven flow may have a considerable impact, especially with respect to powders and any small particle transport. To outline the integrated approach efficacy  the path-lines of small particles in fluid flow inside the room were computed using the biological measurements. CFD simulations based on a multi-physics approach was used to study the particles tracing and diffusion inside the room. Starting from the measured value on particles concentration measured at the defined different levels of the room, a particle tracing post-processing was carried-out once the air velocity fields were solved. The used procedure lies on the assumption that motion of the particles does not affect the flow field. In our study the Khan and Richardson formulation [Coulson and Richardson, 2009] is adopted. Figures 5 and 6 show with different slice planes the particles tracing and diffusion in the air volume of the room in summer conditions. The particle tracing is mostly influenced by the convective air flow.

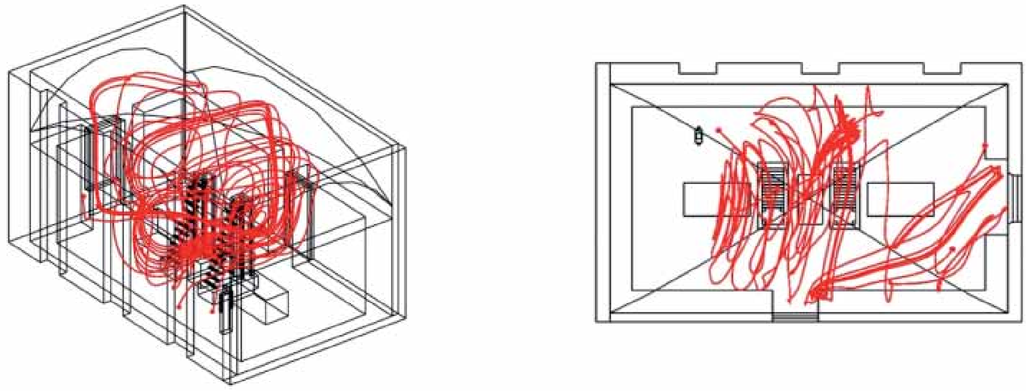
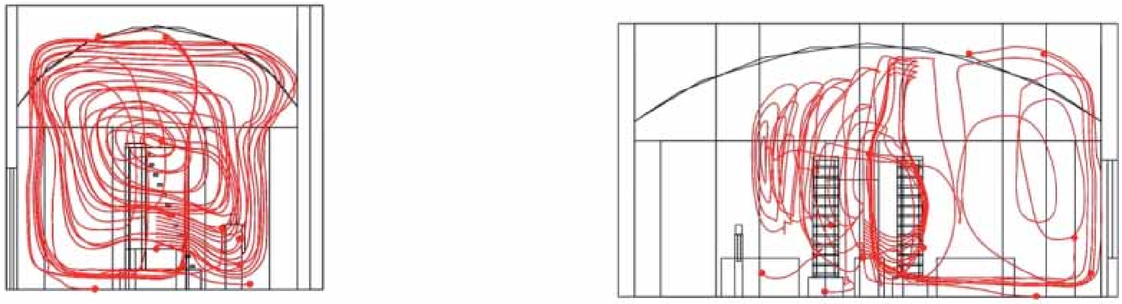


Fig.5 - Particle tracing and diffusion connected to the air flow. 3d view (sx) and overhead view (dx); Fig.6 - Particle tracing and diffusion connected to the air flow. Cross section (sx) and longitudinal section view (dx).



## 5. Conclusion

The question concerning an HVAC plant installation is mainly connected to the necessary ventilation and air change for the few occupants (archivists and librarians and few scholars) and contaminant removal (bacteria, spores, mildew and fungi species, furniture solvents and coats). The necessary air change for contaminant removal due to occupants, usually involves quite low air flow rates and in "demand" conditions. But the control and regulation system especially on humidification/dehumidification is very important, due to the problems connected to the chemical instability of paper stressed by impulsive and high hygrometric variations.

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**Abstract**
We present an integrated methodology comprising microclimate and particle monitoring, and Computational Fluid Dynamic (CFD) simulations that belongs to a wide research project that involves a multidisciplinary experts. A transient simulation model, for coupled heat and mass-moisture transfer, taking into account archivist and general public movements, combined with the related sensible and latent heat released to the ambient, is provided. Our method can be a useful tool for the evaluation of the indoor environment and air quality, with the aim of the best compromise between people working and visitor comfort. The evaluation of air temperature, relative humidity, presence of gases and particles tracing and distribution, recommended concentration levels for conservation and maintenance of works of art, conditioning and ventilation plant solutions can be evaluated. It can also suggest refurbishment actions for compliance with national and international regulations and standards for historical buildings protection and preventive conservation of works of art in them. Results from the transient simulation are in good agreement with the experimental data collected during our case study: a monitoring campaign of microclimatic conditions in the eighteenth-century Palatina library in Parma, Italy. The research was funded by the Cariparma Foundation.
Our work aims at contributing toward the definition of standardized methods for assessing the biological and microclimate quality of cultural heritage environments.