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THE USE OF INFRARED THERMOGRAPHY AND INTEGRATIVE TESTS FOR MEASURING RISING DAMP

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To my parents and brother,

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ABSTRACT

In Italy, moisture in cultural heritage, is a well-studied subject, as they have one of the largest number of historic buildings in the world and are always in the search for the standardization of the procedure to diagnose this problem. Moisture is one of the main damage problems in building degradation, and a common reason for the damages present in materials of ancient buildings. The diagnosis of its source and damage dimension, has to be perform without compromising the identity of the buildings. That is why the procedure of the methods applied was study, as well as, their applications, limitations and possible results. The comparison between several methods to assess moisture content is also a subject approached, regarding their feasibility, intrusiveness and principles.

The investigation realized in the matter of this thesis, aims to analyze the damages in the conference room of the Diocesan Museum of Mantua, diagnosing the source of the problem by combining non-destructive techniques as infrared thermography, with a destructive technique, the gravimetric test. The applicability of this methods, in addition with the microclimate monitoring, and the functioning of a device installed in the room to stop rising damp, are also objects of study in this paper.

By obtaining a moisture distribution map and assessing the changes in relative humidity and temperature in the conference room during several months, it was possible to reflect about the refurbishment work that had been done in the mentioned room, the conditions for the conservation of the materials and the possible solutions for the problem.

This case study was performed by the Experimental Laboratory ABC (Arquitecture, Built environment and Construction Engineering) and it is a continuation of a work requested by the Diocese of Mantua in 2013, as a part of an assessment program, involving several ancient buildings in the city, to study their state of decay and to find proper solutions to solve the problems found.

KEYWORDS: Rising Damp, Infrared Thermography, Diagnosis, Cultural Heritage, Non-destructive Techniques.

RESUMO

Em Itália, a humidade é um assunto recorrente, na medida em que se trata de um dos países com maior património cultural, assim como um dos mais influentes na procura pela padronização dos procedimentos de diagnostico deste problema.

O diagnóstico da origem e dimensão dos danos causados pela humidade deve ser executado sem comprometer a identidade dos edifícios, pelo que é fundamental estudar o procedimento dos métodos, bem como as suas aplicações, limitações e possíveis resultados. A comparação entre várias técnicas para avaliar o teor de humidade também é um assunto abordado nesta dissertação, em relação à sua viabilidade, destrutividade e princípios.

A investigação sobre a qual versa a presente dissertação tem como objetivo analisar os danos causados pela humidade na sala de conferências do Museu Diocesano de Mântua, diagnosticando a origem do problema através da combinação de técnicas não destrutivas, como a termografia de infravermelhos, com uma técnica destrutiva, o teste gravimétrico. A aplicabilidade destes métodos, a monitorização do microclima e a sua relação com os métodos referidos, assim como o funcionamento de um dispositivo de desumidificação instalado na sala, também são objetos de estudo neste trabalho.

Ao obter um mapa da distribuição de humidade e avaliar as variações de humidade relativa e temperatura na sala de conferências durante vários meses, foi possível refletir sobre a eficácia do trabalho de restauração que havia sido feito na sala, as condições apropriadas para a conservação dos materiais e as possíveis soluções para o problema.

O estudo de caso apresentado foi realizado pelo Laboratório Experimental ABC (Arquitecture, Built environment and Construction Engineering) e é uma continuação de um trabalho encomendado pela Diocese de Mântua, em 2013, como parte de um programa de diagnóstico, envolvendo vários edifícios antigos da cidade para estudar seu estado de decadência e encontrar soluções adequadas para resolver os problemas de degradação.

PALAVRAS-CHAVE: Humidade Ascensional, Termografia de Infravermelhos, Diagnóstico, Património Cultural, Ensaios Não Destrutivos.

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NOMENCLATURE

g' - flow density;

β - coefficient of surface moisture transfer;

C's - the water vapour concentration at the surface;

C'a - the concentration in the air.

σ - surface tension;

θ - contact angle,

r - capillary radius;

ρ - liquid density;

g – gravity;

h - water rise height by capillary.

N_{cam} - spectral radiant power incident on a surface per area unit or irradiance,

N_{sur} – radiance emitted from the surface, at a given temperature,

N_{env} - radiance emitted by the surrounding, considered as a blackbody,

ε - emissivity

θ – flux of radiant energy

ε - emissivity

T - temperature

σ - Stefan-Boltzmann constant

ps – pressure of water vapour;

pa – pressure of dry air;

Vs – volume of vapour;

Ra and Rs – gas constants;

Ta – dry air temperature;

Ts – vapour temperature.

μ - Relative humidity,

e – partial pressure of water vapour;

$esat(T_w)$ – saturation vapor pressure at the temperature;

A- psychrometer coefficient

p – atmospheric pressure

T – ambient temperature

Tw **– wet bulb temperature**

mv **– mass of water vapour**

ma **– mass of dry air**

s **– specific humidity**

MC **– moisture content**

m_H - wet mass

m_o - dry mass

mww **- wet mass obtained by volumetry**

mw **– wet mass corrected**

nv **-** number of molecules of water vapour

na **-**number of molecules of dry air

Mv – molecular mass of water

Ma **- molecular mass of dry air**

ABBREVIATIONS

SH – specific humidity (%)

RH – relative humidity (%)

EFD - evanescent-field dielectrometry

TDR - time-domain reflectometry

NMR - nuclear magnetic resonance

NIRS - near infrared spectroscopy

IRT - infrared thermography

1
INTRODUCTION

1.1. IMPORTANCE OF THE WORK

As economic and political pressure mounts for an energy-efficient Europe, finding a balance between heritage conservation and energy conservation in historic buildings becomes more urgent. A systematic approach is required that takes into account technological, environmental and economic factors and their impact on the heritage value of historical properties. [1]

Conservation and rehabilitation of ancient buildings is a current subject in our time, especially due to the growing importance of cultural heritage in developed countries. With the constant development of technology, but with the huge step back in the last few years in new constructions, due to the economic problems that affected Europe, it started to be given more attention to the already existent patrimony. Another factor that influenced, and still influences, this change is the growing tourism, which not only changes the microclimate inside an exhibition room, for example, but also creates an excuse to create plans of rehabilitation in order to be possible to take the most advantage of them.

Ancient buildings are under the action of meteorological agents for centuries, which lead to a visible degradation in the exterior and influence the climate conditions in the interior. Frescos, paintings and other pieces of art suffer, among other factors, from the incidence of the wind, relative humidity, temperature and mostly by the lack of maintenance and wrong application of restoring methods. Over the centuries these buildings go through a lot of changes, including in its use, refurbishments that are not adequate to their structure or materials and that, in the end, do not help in the preservation of their cultural value.

The recent concern in the restoration of cities historic centres, led to an increasing of the importance of the methods to diagnose the problems in structure and materials of these works of art. It is now known that having a complete background study, as well as a profound knowledge of the buildings function and interaction with the surrounding environment, results in a much better diagnosis of the existing problems, which leads to a perfect application of the rehabilitation interventions.

Italy, for example, is a well-known country for its ongoing efforts in preserving and managing its enormous cultural background. The continuous debates, not only in this country but also throughout Europe and abroad, between specialists in the matter, advantages the development of new and upgraded methods regarding the approaches in building diagnosis. [9]

The use of the innovative techniques for in-situ diagnostics is, therefore, a fundamental factor for keeping up to date records of the conservation work performed and to allow a continuous and correct maintenance respecting the building characteristics and to prevent all causes of damages.

1.2. Objectives of the work

The thesis here presented is part of a research started by the ABC department of the Polytechnic of Milan in 2013, on the Diocesan Museum of Mantua. The results presented include previous data collected since that date as well as new information processed from results collected since March, 2016.

The objective is first, to apply techniques as thermography, psychrometry, gravimetry and continuous monitoring of the microclimate in order to analyse their relation between each other, thus understanding the value that, the simultaneous application of these tests, have in the diagnostics of ancient buildings. Secondly, having the results obtained in mind and the background of the museum, the aim is to make the correct evaluation of degradation problems present, as well as their source. Finally, the last situation to be discussed is the influence of some non-destructive devices to stop rising damp.

Regarding the diagnosis techniques, in this thesis were studied, among many techniques for measuring water content, some standard and steady techniques referenced before in the previous paragraph that, applied together, allowed to obtain the results to the diagnostic of the museum.

1.3. Outline

Chapter 1 has a brief explanation of the work done for the purpose of this thesis as well as its importance and objectives.

Chapter 2 regards to the state of the art, where it was done a description of some base concepts concerning rising damp and conservation of historic buildings.

Chapter 3 consists in the explanation of each method used in the work, their basis, procedures and instrumentation

Chapter 4 presents the results obtained from the application of the innovative techniques in Diocesan Museum and the description of the information taken of each survey.

Chapter 5 explains the functioning of some devices regarding the stopping of rising damp in masonry.

To conclude, in chapter 6 are presented the conclusions taken from the experiment as well as developments for the future.

2
STATE OF THE ART

2.1. Moisture manifestation forms

2.1.1. Introduction

Moisture has several forms of manifestation and their knowledge is very important for a correct diagnosis of the problems. Although is rare that these manifestations appear isolated, it is possible to divide them in different groups: Hygroscopicity, superficial condensations, internal condensations, construction moisture, infiltrations, pipe leaks and rising damp. For the interest of this thesis, rising damp is the only one to be explained. [10]

2.1.2. Rising damp

The majority of construction materials have a porous structure that lead to a high capillary and consequent transport of water by capillary rising, as explained in 2.2.2.

There are two main sources of water: the ground water and the surface water. The height reached by the water due to this phenomenon depends on factors as the amount of water in contact with the element, evaporative conditions on the surface, thickness, orientation and presence of salts. [10] First of all, the environmental conditions in the surroundings have a strong influence in the drying process and in the height reached by moisture. High values of relative humidity result in a bigger difficulty of evaporation and consequently leads to an increase of the rising damp level. On the other hand, when the opposite happens and the values of RH are lower, the evaporation reaches higher levels, such that the height of damp decreases. [8]

This flow can be obtained by the expression 2.1:

$$g' = \beta . (C's - C'a) \qquad (2.1.)$$

Where:

g' - flow density;

β - coefficient of surface moisture transfer;

C's - the water vapour concentration at the surface;

C'a - the concentration in the air.

Secondly, insolation represents another phenomenon that influences rising damp, due to the fact that depending on the wall orientation, insolation and ventilation, the surface temperature has different values that affect the drying process. For example, the colour is an aspect that influence the temperature of the wall; as darker the colour the higher the temperature and consequently the lower the rising damp height.

In warm and dry climate, the pores of the materials in the walls are completely dry due to solar radiation and warmth of the environment. For the building to become wettable, i.e. to pass from hydrophobic to hydrophilic, the surface of the pores has to be covered by a monolayer of water in the solid state, just then is possible for the water to enter. [8]

The third factor that influences rising damp is the presence of salts, which is also one of the most important causes of decay. As the crystallization of the salts occur, their volume increase as the pressure in the pores, which can lead to the crack of their walls and consequent deterioration of the surface. [10]

Furthermore, some salts can change their crystalline form depending on the environmental conditions of the presence of contaminants. Deliquescent ones (i.e. that easily dissolve in water presence) are able to dissolve and recrystallize when relative humidity values drop below a certain limit, i.e. the lowest equilibrium of relative humidity at which the salt solution reaches saturation.

Salt migration is also an enormous problem originated by temperature and humidity cycles or variations of heating, that with different factors can grow, hydrate and expand creating disruptive cycles inside the pores. The result, as it was previously said, is usually fatigue and breakage of the internal material structure. [8]

Regarding to concentration of the salts present on the wall, a study was realized in 1991 by Arnold and Zehnandrr that concluded that they are mostly accumulated in a zone 0.5 to 3 meters above the ground level and can be distinguished in two areas. Most damages occur in the lower area, where it can be found crystallized carbonates and sulphates. The higher zone is characterized by the presence of chlorides and nitrates, because of their higher solubility that allows them to continue to rise and end by precipitating at the upper part of the wall. Whereas the low solubility salts become quickly saturated and precipitate in the lower area of the wall. The result of this vertical difference is a belt that can usually be seen in the top of the rising damp and is one of the most evident signs of the existence of the problem. [8]

Sea salts represents another complication regarding to the problems associated with the presence of salts in the rising damp phenomenon. When a stone is contaminated with sea spray, the NaCl can be in the crystalline form or in solution, if absorbs water vapour. If relative humidity values are lower than 75%, the salt is in dry state, otherwise it will absorb water and dissolve in it. The solubility of other salts is, in this way, affected by the presence of NaCl in the water, as it increases their solubility. [8]

The pores structure is the fourth factor influencing rising damp. Two types of porosity exist in the materials, the first is open porosity that is the most favourable for water rising by capillarity, as it has all the pores connected to each other. Regarding to the second type, close porosity, it can be said that constitutes a fantastic barrier to the water rise, as all the pores are independent.

Finally, the last factor is thickness and nature of the wall coating materials. A simulation study performed by Freitas and Guimarães, concludes that as thicker the element, the higher the damp level can reach. The phenomenon happens because, as the thickness increases it gets more difficult for the water to evaporate and to reach the equilibrium, i.e. when the flow through the absorbent area equals the total evaporation of the wall. In relation to the materials, as waterproofed the layer gets, it becomes more difficult for the evaporation to occur, and once again to reach the equilibrium; the damp need to rise until an upper zone to increase the evaporation surface. [10]

Sometimes it happens that dampness in the lower parts of building misleads to the interpretation that the problem is capillary rise. However, more often than expected, the reason is the absorbed or percolated rainwater that, under the influence of gravity force tends to do downwards and affect the basement of buildings. After taking corrective measures as inserting an impermeable layer, it becomes clear that the problem does not disappear. Instead the layer only prevents the water from descending through the foundations. In the area close to the layer, the only solution for the water can become by evaporating in the environment originating efflorescence in the wall. [8]

2.2. The concept of moisture

Moisture is one of the most important factors in building degradation, especially rising damp. There are three factors that are fundamental to the propagation of moisture:

2.2.1. Hygroscopicity

This parameter has different levels; a material that has a high water content fixated by adsorption is considered a hygroscopic material. On the other hand, we also have materials that are non-hygroscopic which means that their mass has an almost steady value whatever the relative humidity of the environment is.

The fixation of the water in the material happens when intermolecular forces act in the interface fluid-solid in the interior of the pores. In this case the process starts with the settling of water molecules in the pore's walls; as the layers of molecules increase the pores diameter decreases until the junction of the plurimolecules. [10]

2.2.2. Capillarity

This phenomenon occurs when a porous material is put in contact with liquid water, for example, while rainwater is flowing in a monuments surface, part of it may penetrate inside, depending, not only on the nature of the material, but also on microclimate factors. Between the fluid and the air in the pores a curve interface is formed (i.e. the meniscus of the water penetrating is concave), that creates a pressure difference that favours the water penetration. [8]

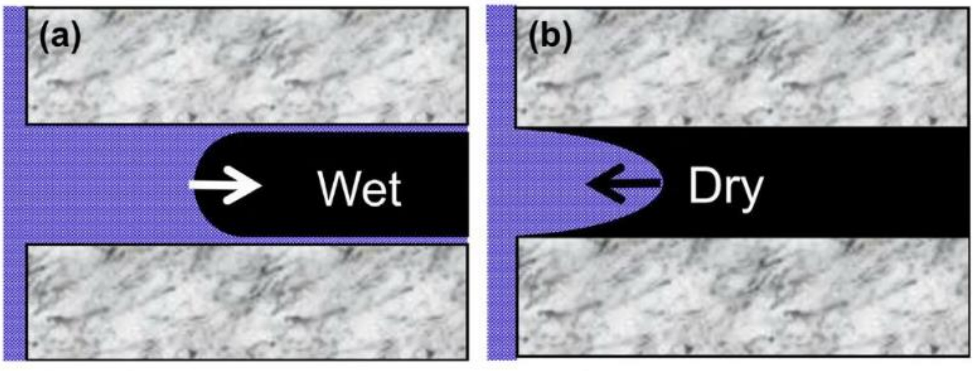

Fig 2.1 – Percolating of the water into a wet capillary when some water is percolating on the surface [8]

On the other hand, if the surface is dry, the meniscus acquires a convex form in the forward direction, which creates such a surface tension and high vapour pressure that the water does not have the capacity of enter in the pores, as it can be seen in figure 2.1. Capillary pressure is related with the interfacial tension, the curves ray and with the humidification angle. The suction is as lower as bigger the moisture content is and is zero when $W=W_{sat.}$. This phenomenon occurs in all directions, however, there only is a mathematical formula for the vertical orientation, as it is the most problematic and frequent situation.

$$h = \frac{2\sigma}{r\rho g} * \cos(\theta) \qquad (2.2.)$$

Where:

σ - surface tension;

θ - contact angle,

r - capillary radius;

ρ - liquid density;

g – gravity;

h - water rise height by capillary.

The previous equation, where σ is the surface tension, θ the contact angle, r the capillary radius, ρ is the liquid density and g is gravity, gives the water rise height by capillary. Therefore, the formula 2.2 states that h is bigger for thinner pores.

Despite that it was proved in laboratory that materials with pores smaller than 0.1 μm are unable to absorb water, it is real that materials with thin capillaries transport an enormous amount of water, such as they are currently misinterpreted as condensation on the surface of the walls. Basically, capillary suction is a much effective way to cause moisture indoors than condensation. [8]

2.2.3. Condensation

When the vapour pressure is equal to the saturation pressure, occurs condensation. Following Glaser's Method, when the saturation curve intercepts the installed pressures curve, the layer of the wall correspondent has liquid water.

A common error made when in the interpretation of the sources of moisture present in a wall, is the confusion between evaporation and condensation. Evaporation tends to lower the temperature of the interface between the air and the stone until the wet bulb temperature (explained in Chapter 3), but does not decrease the temperature indefinitely. Furthermore, the wet bulb temperature is higher than the dew point, which corresponds to the temperature at which condensation begins. In conclusion, none of them occur in cause of the other. [8]

The usual option of increasing the air temperature to decrease the relative humidity of the air can backfire and can increase the evaporation. Regarding to condensation, the only solution is to reduce directly the relative humidity or heat the surface of the wall.

The three mechanisms described are non-dissociable and may also join them the action of gravity and pressures generated by the wind. [10]

2.3. Moisture detection techniques

2.3.1. Diagnosis protocol

The diagnostic process should be based on an accurate survey, which should document the current state of the building. [4]

A diagnosis protocol as part of an integrated methodology for the conservation management of historic buildings, is a necessity already felt in previous studies. [3] In ancient buildings, the comparison of results with previous studies, is essential to comprehend the behaviour of the historic building materials, which only can be done if the same methodology is applied to the different cases. The steps for the diagnosis protocol are presented in figure 2.2.

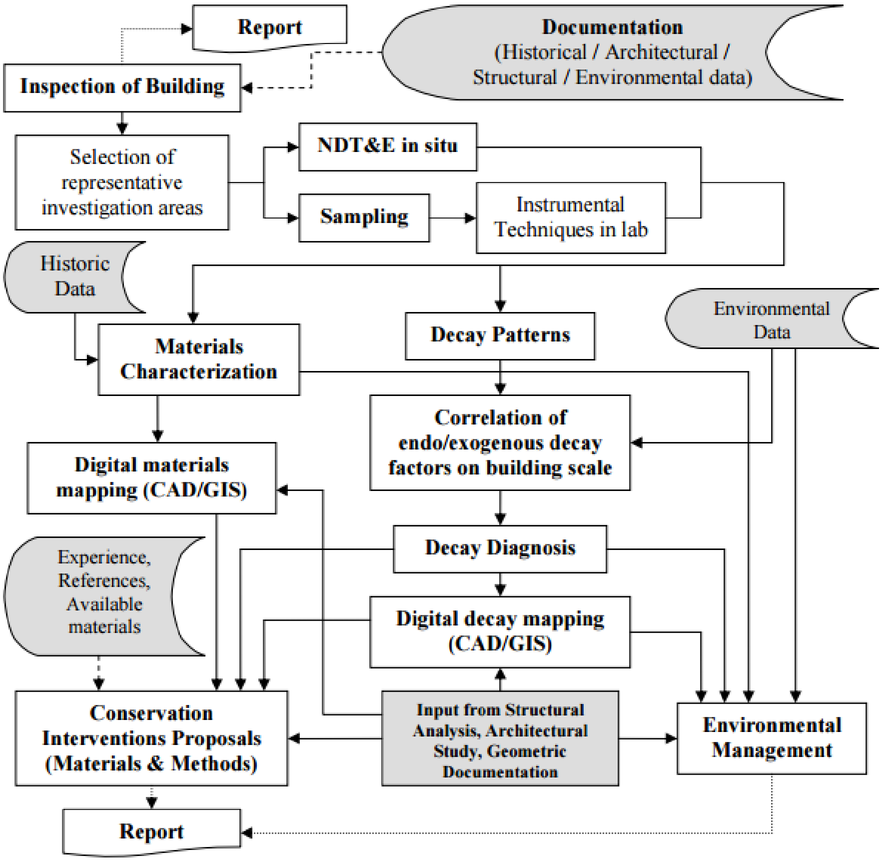

Fig. 2.2 – Proposed diagnosis protocol. [24]

The diagnosis process is constituted by, first, the preliminary inspection (i.e. the survey of existing defects) which is carried out by visual inspection and photographic registers. In this phase it is also important to collect information for the characterization of its structure, materials, changes in environmental conditions and history of interventions.

To a detailed assessment, it should be performed: in-situ tests, laboratory tests, field tests, assessment of the foundations and also field measurements. The tests can be non-destructive (or slightly intrusive), when they have a negligible influence on the building, or destructive (in any way), otherwise. Non-destructive tests ("NDT") are, obviously, the preferable ones for heritage buildings. If non-destructive tests will not be sufficient, destructive tests will be considered, but they will be carried out only after a cost-benefit analysis. [20]

The end of the diagnosis is a report that, not only includes the analysis of the problem, but also suggestions for correcting the situation and to restore the damaged materials.

2.3.2. Diagnosis techniques

Assessing the severity of the damage caused by the presence of water, is important for determining what is needed to start the damage repair and moisture removal. Furthermore, it is important to protect occupants from health problems and to protect the building, its materials, structure and its contents from physical or chemical damage.

Identifying the type of moisture damage and discovering its source, starts first by searching for common signs of visible as well as hidden moisture damage, such as: presence of standing water, mold, fungus, or mildew; wet stains, eroding surfaces, or efflorescence (salt deposits) on interior and exterior surfaces; flaking paint and plaster, peeling wallpaper, or moisture blisters on finished surfaces; dank, musty smells in areas of high humidity or poorly ventilated spaces; rust and corrosion stains on metal elements; damaged, cracked, or rotted wood; cracked masonry or eroded mortar joints; faulty roofs and gutters; condensation on window and wall surfaces. [33]

To diagnose and handle the cause of moisture it is required to, not only, assess the localized decay, but also to understand the performance of the entire building and site. For deficiencies, such as broken pipes, clogged gutters, or cracked walls that contribute to moisture damage, the obvious solution is to correct them properly. However, in the case of more complicated problems, such us hygroscopicity, superficial condensations, internal condensations, construction moisture, and rising damp, it may take several months of monitoring of the damage, as well as, of the variations in the surrounding environment (e.g. temperature, relative humidity, wind orientation, etc), in order to complete a full diagnosis.

The study of moisture, as cause of degradation of buildings, can be done focusing on different parameters that influence the decay process, such as: water content, dew, evaporation, drying index and dew temperature and mass and energy transfer. Each specialist addresses its study accordingly to their specific goal. [9]

In moisture content detection, there are different methods of approach, being in the case of ancient buildings the choice between NDT methods, the main concern. In order to decide which, have the best results, it must be done a comparison regarding their reliability, depth of measurement, surface condition, work procedures, viability and physical principles.

There are several procedures to measure the water content, first there are the absolute methods, based in the extraction of the water content, as gravimetry, KF titration [32], azeotropic distillation [50] and calcium carbide [6]. In addition, there also exist the relative methods that compare measurements in time or space. Relative methods have advantages over the absolutes ones, as they allow to perform with easiness the procedure in situ and in a short amount of time. In this category, it can be included the methods of electrical resistance, capacitance, equilibrium RH, microwave, evanescent-field dielectrometry (EFD), time-domain reflectometry (TDR), nuclear magnetic resonance (NMR), near infrared spectroscopy (NIRS), holographic method, ultrasound pulses and infrared thermography (IRT). Besides this, there are also methods that recur to X-rays, gamma rays and neutron scattering. [6]

All the methods are affected by a number of distributing factors that have, case-by-case, different relevance [6] . For the electrical resistance method, the distribution of water content is a factor that influences the measures, as well as, the presence of salts. The capacitance and microwave methods respond to a total amount of water molecules, but the output depends on other factors, as the proximity of the molecules to the sensor. In contradiction, the Karl Fischer titration and the gravimetric method, do not depend on the distribution, as they provide the total mass of water molecules in the sample regarding these circumstances.

The speed of the sound waves, in the ultrasound pulses method, varies with the moisture content, but varies also from material to material, and even within the same material, depending on the internal texture [e.g. fungal infestation, insect tunneling, wood grain angle]. Therefore, the Interpretation of the readings may be difficult in the case of moisture gradients. [6]

In the neutrons method, absolute moisture measurement is difficult due to large, unpredictable proportions of fast neutrons escaping into the atmosphere. Furthermore, the interpretation of results can be difficult because the actual volume that is evaluated by the detector is never precisely known. The gauged volume varies inversely with water content and water nearer the source has a greater effect on the shape of the volume. [6]

The relative humidity in equilibrium with the material based on sensors or proxies method, only offers results until water in the liquid form appears in the pores and his affected by the hygroscopic characteristic of the materials and by the presence of salts. [6]

The angle of the measures is another factor that varies between methods, for instance the EFD, NMR and holographic radar, require a flat surface to allow close and continuous contact between the probe and the surface. Whereas, for IRT it is preferable to maintain the recapture axis within a 60º angle of the measured surface in order to obtain reliable results. [42]

As for the environmental conditions, their influence is only deeply noticed in IRT method, as conditions of high relative humidity and low temperature prevent evaporative flux and the consequent cooling of the surface [42], which is what this method detects. However, despite being less affected, EFD, NMR, holographic radar, fixed points and weighing IRT are influenced by the environmental parameters, as it leads to a vapour exchange, thereby altering the physical sate of the material, to reach a humidity that is in balance with environmental conditions. [2]

A very important matter is also the reachable depth of each procedure, as it is valuable to adequate the chosen method to the thickness of the wall. While the holographic radar can detect moisture between 50 to 200mm, by a non-invasive procedure, the gravimetric and fixed points test can measure until 200mm or 300mm by collecting a sample of the material. [42] Regarding the X-ray, Gamma Rays and Neutrons methods, the penetration depth is through the entire body, by non-destructive procedures.[6] Methods as IRT, EFD and NMR obtain their data almost only from the surface.

Methods as X-ray, Gamma Rays and Neutrons, despite their advantages as the possibility to scan large structures at different depths or the possibility to process the measures in-situ or in the laboratory, they have the strong disadvantage of needing special safety measures regarding the protection against radiation. [6]

Representation of the data is different for each method. In IRT the results are maps of temperature that distinguish by means of colour the different temperatures detected in the surface. To obtain quantitative measures, the surface under consideration is segmented and the water content is expressed with each area using an index between 0 and 1, resulting in a segmentation map that allows the location of three main levels of water content: saturation, high and low. [42]

Data obtained by EFD are represented as a percentage of water content and with NMR, as a contour plot of moisture. [42] Regarding holographic radar, the results are maps of phase contrast and for gravimetric and fixed points, the result is a percentage of water of the dry sample weigh.

The number of techniques available for measuring water content within the masonry structure, decreases according to the depth. Several techniques are being developed and improved, but much remains to be accomplished.

At the present, CEN/TR 14748:2004[63], sets out basic principles and provides recommendations and general guidelines for carrying out qualification of non-destructive tests. However, techniques for measuring the moisture content are not standardized for materials in historic buildings, most of the techniques above referred are present in standards regarding other methods as, for instance, the gravimetric test. [60] The most recent standards, about the evaluation of moisture in ancient buildings, regard to test methods for determination of water absorption by capillarity [61], procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property [31] and specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials [62].

On January 2016 a new standard was proposed, and it is under approval at the present: Conservation of cultural heritage - Methods of measurement of moisture content, or water content, in materials constituting immovable cultural heritage; prEN 16682:2015 [6]. The identities responsible for the EN 16682 document, are NA 005-01-36 AA - Conservation of cultural heritage (national mirror committee for CEN/TC 346) and CEN/TC 346/WG 7 - Specifying and measuring Indoor/outdoor climate. This standard includes the appropriate methods for measure moisture content in wood and masonry in the case of built cultural heritage. The EN 16682 explains which methods are reliable to use, safety measures that should be carried out in the application of the procedures, as well as the explanation of each one of them.

3

DESCRIPTION OF THE METHODS

3.1. INFRARED THERMOGRAPHY

3.1.1. HISTORIC EVOLUTION

After the discovery of thermometers, starting with Galileo, in 1610, that invented the first device to measure temperature, passing through Gabriel Fahrenheit, that in 1715 used mercury to the same effect and Sir William Siemens that, in 1871, created a thermometer which uses a metallic conductor to measure the temperature values; the discover of the infrared radiation is one of the most important matters in the subject.

William Herschel, in 1800, discovered the infrared radiation when trying to discover which colour heated the objects, by making the sun light go through various filters of different colours. In order to measure the temperature of each colour contained in the sun light, Herschel directed it to a glass prism, which lead him to conclude that the temperature values increased from the violet until the red colour and the measure from light after the red, was even higher. This rays, invisible to the human eye, where defined as the reason for the heating of the objects and first named 'calorific rays' and posteriorly infrared rays. [12]

In 1843, Henry Becquerel applied the use of infrared in the discover of phosphorence, by applying this light to an object and observing is emission of light.

Forty years later, in 1880, the first bolometer was invented (i.e. a device capable of measure differences of temperature extremely small by heating the material with a temperature dependent electrical resistance). The increase of sensibility in infrared detection was majorly due to the development of this device.

The development in technology from 1870 to 1920 allowed the invention, in 1917, of the first quantic detector based in the direct interaction between the photons of the infrared radiation and the electrons of the material. With this instrument, the time test reduced and the precision increased, as the conversion from radiation to electric signs started to be direct. In 1929, Czerny made the first thermogram. [13]

The application of this technique increased specially in the mid 1940's, due to its military use in World war II. The objective was the detection of enemy tanks. As a response, the allies devised the FLIR - forward looking infrared – that detected the enemy and was used to create weapons with heat detectors. [13] As a result, a big number of detectors appeared, operated by opto-mechanical scanning systems and required cryogenic cooling. Their wavelength range depended on the materials used in their manufacture. [12]

From 1946 to 1954 the improvement in the subject was focused in the decrease of testing time and, in 1960, the first thermocamera was invented, that allowed to have a thermogram instantaneously. In 1975 it was invented a way to see both visual photographs and thermos ones facilitating its use in the discovery of anomalies.

In the 1980's and 1990's the real time image is strengthened, as well as the filters for data processing from the images. The cooling systems by liquid nitrogen, that were not easy to transport, were substituted by thermoelectric cooling systems. The improvement of computer programs and equipment, also lead to an association of them with the thermographic measures, making it easier to analyse all the data.

During the last decade of the 20th century, the expansion started to focus on the resolution of the camera and, in the beginning of the century it was already a possibility to video record and dynamic diagnose, using a thermocamera with 640x480 resolution.

Since 2000, the concern was the development of a multi-element detector array, which was replaced by a focal plane, the FPA – Focal plane array, with a growing number of pixels that provide high resolution at a video format speed.

At the moment, the main concern has stepped to be the actual application of the thermography method, trying to standardize the procedures and to understand which, and when, thermography can lead to the best results in addition to other tests, as gravimetric.

3.1.2. Concept

Infrared and thermal are interconnected concepts. [15] These testing techniques involve the measurement of heat flow and temperature to diagnose failure. In general, infrared thermography is a non-destructive, non-intrusive, non-contact method, in which, through the detection of the infrared radiation emitted by the surfaces, registers and detects different temperatures. The thermocamera, is equipped with infrared detectors that transform the radiation signal in a visual image where the various temperatures can be differenced, by a scale of colours.

The essential base of this procedure relies on the principle that heat flow, by both conduction and radiation, in a material, is altered by the presence of anomalies. These changes are translated in localized temperature differences, in the material surface. The intensity and frequency of the radiation can be correlated closely with the heat of the radiator. Thus, the temperature patterns are correspondent to radiation patterns in the surface of the material.

Heat flow is the key mechanism. [15] The density of heat flow rate is measured in watts per square meter ($W.m^{-2}$) and can occur by conduction, radiation, convection or by the combination of the three.

All bodies with temperatures above the absolute zero emit electromagnetic radiation thus, when a material is heated, the energy in the atomic particles increase and lead to a rise of temperature and emitted energy. This agitation of the atomic particles, results in an emission of infrared radiation. Most infrared non-destructive testing takes place in near infrared and slightly beyond it, up to ~15μm.[16]

The equation of infrared thermography is presented in equation 3.1. [16]

$$N_{cam} = \varepsilon .\ N_{sur} + (1-\varepsilon).\ N_{env} \quad (3.1.)$$

Where:

N_{cam} - spectral radiant power incident on a surface per area unit or irradiance, [W.m^{-2}].

N_{sur} – radiance emitted from the surface, at a given temperature, [W.m^{-2}].

N_{env} - radiance emitted by the surrounding, considered as a blackbody, [W.m^{-2}].

ε - emissivity

In this case, as in most non-destructive techniques, the temperature of the environment does not have any influence, so it is used N_{env}, [16]

The blackbody is a theoretical source of radiation, that produces the maximum radiation possible at a given temperature and that absorbs all incident radiation: it has an emissivity equal to 1.0. This unitless property of the material consists in the ratio between the total energy radiated by a surface and by a blackbody at the same temperature. In practice, real bodies have values of emissivity between 0 and 1.0, because of that, the Stefan-Boltzmann law that translates the flux of radiant energy [8] spontaneously emitted per unit of surface by unit time, by a body with temperature T by means of the IR emission is mathematically written by the equation 3.2. [8]

$$\emptyset = \varepsilon\sigma T^4 \qquad (3.2.)$$

Where:

$\emptyset$ – flux of radiant energy

ε - emissivity

T - temperature [K]

σ - Stefan-Boltzmann constant

As the object of infrared testing is to measure changes in surface temperature and the emissivity depends on the surface condition and composition, this phenomenon of the surface can induce false diagnosis. When the emissivity has a low value, in a localized region, the radiation intensity is also low, which can falsely indicate a localized reduction in temperature and vice-versa. [16]

3.1.3. Instrumentation

As it was previously said, the infrared method measures the temperatures of the surfaces by radiometers or infrared cameras. These devices consist in optics that collect and image, on a sensitive detector, the infrared radiation received. More specifically the collected data is transformed in an electrical signal that is processed by a microprocessor and presented, as a visual image, in the digital display (Figure 3.1).

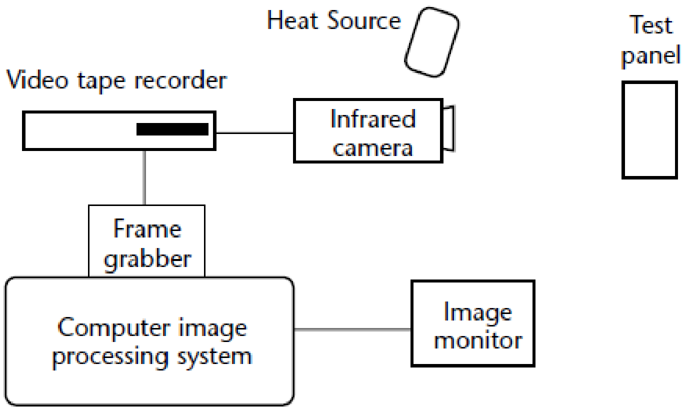

Fig 3.1 – Diagram of a typical infrared inspection system [15]

To perform a thermographic test there are several instruments that can be used according to different situations. [16]

i. Pyrometer: used to hot measurements, that give readings one point at a time.

ii. Video Radiometry: standard infrared video camera systems

iii. Scanning radiometry: the teste surface is optically scanned at high speed by mechanical deflection of mirrors and prisms. This action monitors an area with 0.75 to 3.2mm of diameter. By moving it along the surface, the scan covers the surface completely in a small fraction of second

iv. Real time radiometry: radiometers that feature real time image readout by incorporating an infrared sensitive vidicon tube.

v. Detector arrays: Each part of a detector array can detect the emissions from the object's surface during the entire video frame exposure.

3.1.4. Types of thermographic tests

Infrared testing has two types of procedures, active technique, which involves the cooling or heating of the sample, by external thermal excitation, to create the required heat flow and thermal gradients, and the passive technique where the material has already its internal source of heat.

Active methods are more often used in NDT of structures in comparison to passive methods. [40]

The choice to use one method or the other depends on whether the investigated target is in thermal equilibrium or not. For many years, passive thermography was applied as a standard quality control technique of historic structures acting as powerful tool for moisture detection and monitoring, while studies have further demonstrated its efficient use for structural integrity evaluations. On the other hand, the active configuration is deployed, for the evaluation of materials that are thermally static. The thermographic investigation during and after a heating process, has been proven to present much more potentiality than the conventional passive approach. For instance, in cases of structural multi-layered constructions where a thermally inhomogeneous regime is presented, active thermography can be applied to investigate quality problems due to the fact that can occur variations of the thermal properties of each layer. [41]

3.1.4.1. Passive Thermography

In passive thermography the goal is to find anomalies, however, if some thermal models are available, it is possible to relate the thermal discontinuities with specific behaviours.

Temperature is a fundamental parameter in order to assess proper operation. In this type of procedure, abnormal temperature profiles indicate a potential problem, thus is important to keep the temperature difference, or hot spot, under control.

The advantages of this method, comparing to the active method are, for instance, its applicability to a large surface, the direct connection between the evaporative flux and the damage, that lead to the possibility of an early diagnosis of zones with higher risk of degradation, identifiable due to the presence of high evaporative flux. [38]

The process of passive thermography must have in attention several factors as, for instance, in case of the source of the heating is natural, the orientation of the surface is fundamental to plan the scanning. The same surface could be radiated in different hours and for different time. Shadow due to other buildings or to projections may affect the thermal images. All these factors have to be recorded before scanning, in order to calculate the best time of the shot, which must be taken in emissive phase, after the end of the radiation. [11]

3.1.4.2. Active Thermography

Generally speaking, especially with regard the application to buildings, active thermography requires to apply a heating flow to the object under investigation, at controlled conditions, with the aim to stimulate a distribution of the surface temperatures that is meaningful to anomalies of defects located under the surface.

Considering the industrial field, active thermography can be divided in several techniques, as for example the pulsed thermography which consists in briefly heating the specimen and recording the temperature decay curve. Because of the radiation and convection losses and the quick diffusion of the thermal front under the surface, the temperature changes fast after the initial heating. When a discontinuity is found, the diffusion rate is modified and it can be observed in the thermogram as an area with different temperatures compared with the surrounding sound area. [16]

Step heating is another technique, the main difference compared with the one explained before is that the monitoring is done during the application of the step heating pulse. Lockin thermography is based on the use of thermal waves, periodically these waves are generated by deposing heat on the material, while the resulting oscillating temperature field in the stationary regime is remotely recorder through its thermal infrared emission (figure 3.2).

Finally, it also exists vibrothermography which is an active infrared technique where, by inducing mechanical vibrations to a structure (20-50Hz), it is possible to find discontinuities, due to the direct relation between mechanics and thermal energy. [16]

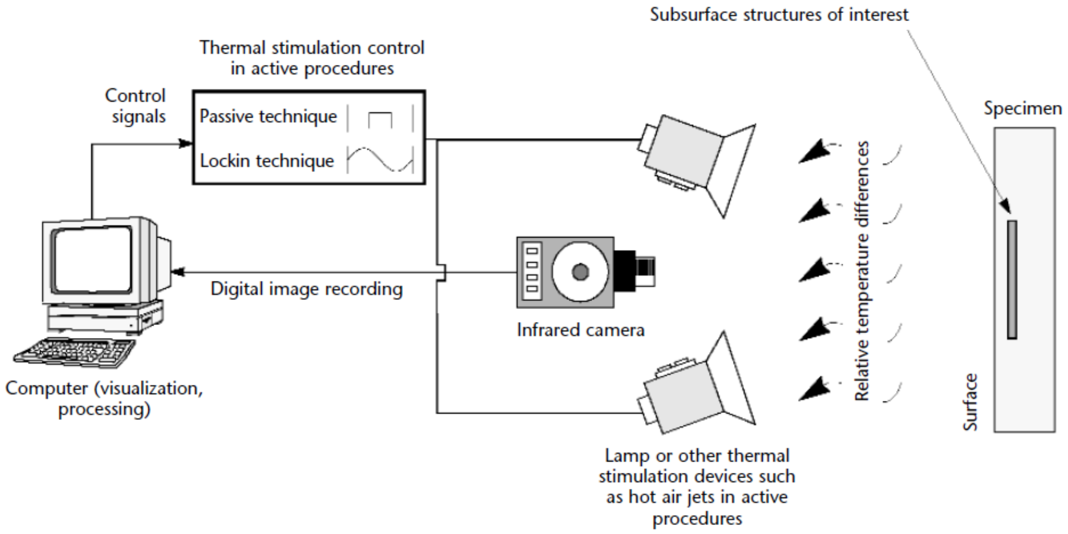

Fig 3.2– Diagram of the application of the active technique using optical excitation. [16]

3.1.5. Applications

Regarding to the applications, the infrared thermography is currently used for a wide range of situations. Leak testing is one of its uses in the field, this testing procedure involves three different techniques that can be summed as: infrared emission pattern, infrared absorption, infrared photoacoustic. [18]

The applications for infrared thermography, in the study of buildings, are for instance, to assess the floor covering comfort [49], detect insulation defects, thermal bridges and to inspect construction details. [5]

There are also other potentialities for it, as for example, to create theoretical models of leakage through walls with the objective of predict and maintain the safety of structures, the vibrothermography of earthquake resistant structures, a growing technique that is strongly connected with the resistance of materials under extreme actions. Inspection of thermal envelopes of new buildings is another area where this technique is currently used, as well for the conservation of fine art, where we can diagnose degradation problems. And, finally, for the purpose of this thesis, which is to use thermal testing for the conservation of historic buildings, to detect defects in façades and as inspection technique for frescoes assessment. [19]

3.1.6. Conservation of historic buildings

3.1.6.1. Introduction

Thermal scanning of buildings makes it possible to gather information regarding building technology and elements, their shape, their material characteristics and their state of decay. [19]

When talking about historic buildings, is important to have a profound knowledge of their structure, materials and components. However, it is usual that the plants and preliminary documents regarding the structure of the building are not available, as they sometimes have hundreds of years.

Thermography has a very important role in detecting the real state of the test surface and structure, giving the inspector the possibility to adequate the range of the scans, their location and to choose other suitable testing methods to validate the conclusions.

There are typical results that can be shown in a thermogram done to an ancient building and is due to the study of their pattern that we can identify them and do a correct diagnostic of the problem.

One of the usual discontinuities is detachments or lack of adhesion between the finishing and the substrate. This kind of problem appears as a warmer area when the heat flux enters the facade, especially in the first phase of heating. The warmth stays in the area, insulated by the air, instead of flowing through the structure. The duration of this warm signal depends on the depth and thickness of the discontinuity - the reason to adequate the time and frequency of the recording. The location of the detachments can be found by comparing the problematic area with the reference one and by doing the approach in transient conditions. This procedure consists in doing a homogeneous heating or scanning according the incidence of the sun, if in passive mode. [19]

Another situation that can occur is the crack of the plaster or even across the whole thickness of the masonry. [19] As the mass transfer flows through the cracking, it is possible to see its shape. The most adequate mode to study this problem is by creating a modulated thermal gradient between the two sides. In case the crack is just in the surface, the edges of the discontinuity are detected by being warmer because of their faster heating.

The identification of the structure of the building is one of the most important uses of thermography in ancient buildings and for that it is imperative to make a suitable choice of heating, time and boundary conditions. To have the needed design information for its restoration, the infrared thermography is the best method due to the different thermal properties of the materials. It can detect the lack of adhesion between the leaves of the bricks and the filling. The active approach is the better choice for the structure identification, as the best results are achieved when materials with different thermal characteristics are juxtaposed and because decreases the effects of the environmental conditions in the measurement. [19]

3.1.6.2. Limitations of thermography in historic buildings

It is usual that the walls of the historic buildings are larger due to their multilayer stone or brick structure. Which constitutes a problem, as some of the non-destructive techniques are not extremely effective in these conditions and, in this type of buildings, the use of destructive techniques is very strict and the temperature that can be reached is very limited. In addition, many misleading situations can be found in old surfaces, as, usually, they have a very heterogeneous constitution; various colours, materials and state of conservation. To solve this problem, it is effective to use software filters based on visual analysis to process the thermograms.

In ancient buildings the masonry is usually covered by an external layer, which frequently causes misinterpretation of the inner layers.

When a surface is coloured, its reflectance affects the solar radiation absorption in the visible and near infrared bands, which causes a major flux of heat into the zones where the reflectance is lower. In areas where the emissivity is higher, the surface cools down by irradiation quicker leading to a colder stain in the thermogram. This also happens when the external layer presents a certain state of decay. [19]

The use of a waterproof layer is also a situation that alters the reading of thermograms, as the product decreases the porosity of the material and changes the absorption of the radiation, resulting in an area with lower temperatures. [19]

To guarantee a correct diagnosis is important to compare the thermograms with the visual image, when is detected an alteration in the surface.

3.1.7. Detection of moisture and its source

3.1.7.1. Introduction

The presence of water in a structure and its changes of state are responsible for damage to the building, to the furniture and to the ones living inside them. Depending on the environmental conditions and water content, each material can have a different state of degradation. It is fundamental the study of the damage, to know the water amount, especially when the temperatures stay below zero during several months. [19] The water volume grows and generates strength within porous wall materials leading to cracks in the masonry. However, in moderate climates, the thermal inertia due to the thickness of the walls prevents the water from frosting, which only results in surface damages.

The thermal aspect related to the moisture present on a wall is a complicated phenomenon to mathematically model, because elementary fluxes are combined with each other. Besides that, the liquid and vapour phases are in equilibrium in the porous materials and the phases are constantly changing inside the walls and on their surfaces. This creates an increasing in moisture that leads to warmer and colder areas than normal, which depends on geometry and boundary conditions. [19]

3.1.7.2. Procedure

Different information, about water content, can be retained from a thermogram and only takes a very few measurements and the confirmation with other method to achieve them, as the thermogram is only a map of surface temperature and cannot give results on water content. Also, it is possible to take conclusions about the source of the moisture by looking to the location of the wet areas and their shapes, as well as their variation in size throughout the time. One of the most characteristic shapes of rising damp is the almost horizontal line at the bottom of the wall that usually separates the wet from the dry area. [19]

The investigation of rising damp is based on the comparison of the thermal behaviour between damp areas with dry ones, which can both appear in the same thermogram if the same conditions are considered. There are several problems that can cause false diagnosis and that can be anticipated. For the active approach, the following complications can happen.

i. The spot of high temperature zones, as hot pipelines or electric cables.

ii. The presence of delamination or coloured stains in the plaster.

iii. The heating during the winter can alter the detection of moisture.

iv. Thermal bridges (imperfect connection between walls, windows or doors)

In the case of the passive approach the most important influence is due to the environmental condition, as for example, a high relative humidity or a low temperature.

Thermography is able to detect moister because of the surface evaporation flux. Each gram of water evaporating absorbs 2500J and cools the surface very effectively, therefore, moist areas are colder then dry ones. [19]

Water content cannot be calculated only by measuring the cooling due to the evaporative flux, as the quantitative relation between evaporative flux and temperature in complex and variable. The evaporation most of all depends on RH of the air near the surface, on its temperature, on the water content in the material, on its chemical-physical characteristics and on soluble salts content. The influence of the temperature and RH on the evaporation speed, can be studied only keeping microclimatic conditions under control. [11]

During the application of the procedure, after doing a preliminary scanning from the wall to set the parameters, it is appropriate to do closer measurements to the surface in order to analyse small discontinuities. The procedure has to include the following steps:

i. Collect the description of the building, including its plans, materials and current state of degradation.

ii. Drawing of the interior and exterior of the building, to have a correct scale

iii. The temperature, relative humidity and solar radiation have to be recorder for at least 24h.

iv. The surface in study has to be kept out of the sun for 12h, so that the readings are not affected by the different absorption coefficients of the materials.

v. The environmental conditions have to be controlled - relative humidity has to be fewer than 80% and air temperature over 6ºC.

vi. The infrared camera should be set up to the maximum sensitivity.

vii. The view field has to have a double scale

viii. Compare the dry areas with the ones with moisture, to obtain the needed results.

ix. To have composite thermograms it is helpful to use removable marks to identify the position of each thermogram, record the pattern of the shots, position the camera perpendicularly to the surface and correct the perspective distortion. [19]

3.2. Psychrometry

3.2.1. Concept

Psychrometry is a field of engineering concerned with the determination of physical and thermodynamic properties of gas vapour mixtures. In the air mixture, the dry gases and associated water vapour, behave according to 'Danton's law of partial pressures'. [8] If two gases are combined in the same volume, the total pressure is the sum of the individual partial gas pressures. Which means they behave independently and the combined pressure is an overall 'atmospheric pressure'. Dalton also relies on the fact that the total enthalpy of the mixture will equal the sum of enthalpies of each component separately.

As we cannot confine the atmospheric gases out of the atmosphere, in psychometry, this combination is considered as an ideal or perfect gas, behaving as a single element called ‘dry air’. Besides this element, the air also contains different amounts of water vapour. Water can exist at the same time in the liquid and vapour phase, which is the reason why it is not considered as the other gases in the atmosphere, because its quantity varies constantly. It is known that the water vapour is not affected by the other gases, however, regarding to temperature, its amount has a limit for each temperature value. When this limit is reached it can be said that the air is fully saturated with water vapour. As heat is a force of internal energy, with the increase of temperature the partial pressure exerted by water molecules increase until a limit, in which the number of molecules evaporating from the liquid equals the number returning to it from the atmosphere, establishing a dynamic equilibrium between evaporation and condensation; it is reached the saturation point. It is important to keep in mind that being saturated is only a characteristic of the vapours and not of the gases, as a vapour is a substance in the gas phase at a temperature lower than its PVT point. Meaning that vapours can condensate by increasing their pressure without needing to reduce the temperature, but gases cannot.

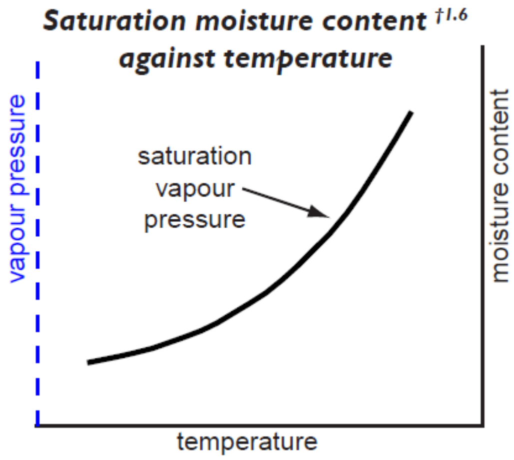

Fig 3.3 – Graph representative of the relation of moisture and temperature [14]

The relationship between saturated vapour pressure and temperature forms the basis for the psychrometric, which, despite deriving from this relationship, does not show vapour pressure, but rather shows moisture content against temperature (figure 3.3), as it is more convenient for the users. The temperature that appears on the chart corresponds to the dry-bulb temperature and the water content is one of the possible derivations from the measurement of the vapour pressure. One way of measuring this amount is by the mixing ratio of moist air, *w*, that represents the pondered mixture of these two gaseous substances and can be expressed as in equation 3.3:

$$w = \frac{mass\ of\ water\ vapour}{mass\ of\ dry\ air} = \frac{mv}{ma} = \frac{nv.Mv}{na.Ma} \quad (3.3.)$$

Knowing that nv and na represent the number of molecules of water vapour and dry air, respectively, and the molecular mass of water is $Mv = 18.016$ and the molecular mass of dry air is $Ma = 28.966$ the previous expression can be rewritten as in equation 3.4:

$$w = \frac{18.016}{28.966} * \frac{nv}{na} = 0.622 * \frac{nv}{na} \tag{3.4.}$$

Although in the psychrometric chart the scale represents the moisture content, the vapour pressure can be reached by relating the several proprieties explained before. As, for definition, the vapour pressure can be a specific value or a ratio between the mass of vapour, $ms,$ and the mass of dry air, $ma,$ it can be concluded, as in equation 3.5, that:

$$w = \frac{ms}{ma} \tag{3.5.}$$

Considering the perfect gas law, in equation 3.6, where

$$pV = nRT \tag{3.6.}$$

The moisture content can also be defined as in equation 3.7:

$$w = \frac{ps.Vs * Ra.Ta}{pa.Va * Rs.Ts} \tag{3.7.}$$

Where:

ps – pressure of water vapour;

pa – pressure of dry air;

Vs – volume of vapour;

$Ra \text{ and } Rs$ – gas constants;

Ta – dry air temperature;

Ts – vapour temperature.

.

Knowing the gas constants and that, for a mixture, the volumes and temperatures are the same a new expression can be written. Adding that the partial pressure of dry air, pa, is the difference between, e, partial pressure of water vapour and, p, the atmospheric pressure, the moisture content can be obtained by the pressure as in equation 3.8:

$$w = \frac{e}{p - e} * \frac{Rs}{Ra} = 0.622 * \frac{e}{(p - e)} \tag{3.8.}$$

Relative humidity, $\mu,$ is another property that is represented in the psychrometric chart and that characterizes the relative humidity of the water vapour or the degree of saturation of the vapour. It can be reached by doing the ratio between the vapour pressure of an air sample and the saturated vapour pressure $esat$, as in equation 3.9. [8]

$$\mu = \frac{partial\ pressure\ of\ water\ vapour\ sample\ (Pa)}{partial\ pressure\ of\ water\ vapour\ in\ saturated\ air\ (Pa)} = \frac{e}{esat(t)} \quad (3.9.)$$

Or, as in equation 3.10, as it is currently used:

$$RH = 100 * \mu \quad (3.10.)$$

Comparing the percentage saturation and the relative humidity, the equation 3.11 can be concluded:

$$\mu(\%) = \frac{w}{wsat} * 100 \quad (3.11.)$$

or, relating with the expressions seen before, the equation 3.12 can be reached:

$$\mu(\%) = \frac{e.(p - esat)}{esat.(p - e)} * 100 \quad (3.12.)$$

As well as the expression 3.13:

$$RH = \frac{e}{esat} * 100 \quad (3.13.)$$

The $RH \approx \mu(\%)$, because p is a much higher value than e and $esat$.

Both properties are very useful to the reading of the comfort in a room, however it is difficult to measure them directly, that is why it is used the wet-bulb method.

The wet-bulb temperature, T_w, or isobaric wet bulb temperature, is the temperature an air parcel would have if adiabatically cooled to saturation at constant pressure by evaporation of water into it, all latent heat being supplied by the parcel. Or from the thermodynamic point of view, is the temperature that an air parcel would have when some liquid water is supplied gradually, in very small quantities and at the same temperature as the environmental air, and then this water is evaporated unto the air adiabatically at constant pressure, until saturation point. [8] Measuring this parameter, with a psychrometer, consists in using a thermometer with a bulb covered by a cloth sleeve and kept moist with distilled water during the measurements. As the air flows in the bulb, the moisture evaporates from the muslin cloth and mixes with the surrounding air. More specifically, for the evaporation to happen, heat from the surrounding air has to be supplied, which results in a decrease of temperature in the air that must be equal to the heat lost and compensate the moisture gain. The wet-bulb temperature is also shown in the psychrometric chart and is important to remember that the saturated vapour pressure, e_{sat}, is taken in the wet-bulb temperature. [8]

The psychrometric equation relates the dry bulb and the wet bulb to their vapour and atmospheric pressures. From knowing that $e_{sat}(T_w)$ corresponds to the saturation vapour pressure in the surface of the muslin sleeve, in a way that the heat increase is proportional to the difference in saturation vapour pressure between the layer of air surrounding the cloth and the surrounding air, ($e_{sat}(T_w)$ - e). In the same way, the heat lost is proportional to the difference between the temperature of the wet-bulb and the ambient, represented by (T-T_w). [14; 8] As the previous processes are a consequence of each other the equation 3.14 can be translated by:

$$e = e_{sat}(T_w) - A * p * (T - T_w) \tag{3.14.}$$

Where:

e – partial pressure of water vapour; [Pa]

e_{sat}(T_w) – saturation vapor pressure at the temperature; [Pa]

A- psychrometer coefficient

p – atmospheric pressure [K^{-1}]

T – ambient temperature [K]

T_w – wet bulb temperature [K]

3.2.2. Instruments

Any instrument capable of measuring the psychrometric state of air is called a psychrometer. In order to measure the psychrometric state of air, it is required to measure the barometric pressure and air dry-bulb temperature.

There are several types of psychrometers, as Dunmore Electric Hygrometer, DPT meter and hygrometer, however, the most common types are the sling psychrometer and the aspirated psychrometer. Both of them consist in two thermometers, where one of them has the bulb covered by a moist wick. The two sensing bulbs are separated and shaded from each other so that the radiation heat transfer between them becomes negligible. Radiation shields may have to be used over the bulbs if the surrounding temperatures are considerably different from the air temperature. For instance, the surrounding structure of the device, constitutes a barrier for the influence of the operator's body temperature.

Regarding the sling psychrometer, this instrument is widely used for measurements where the air velocity inside the room is small. It consists in two thermometers mounted side by side and fitted in a frame with a handle for rotating the device through air. The required air circulation of approximately 3 to 5 m/s, over the sensing bulbs, is obtained by moving the psychrometer with ≈ 300 RPM. [34] The results are obtained when the readings are stable.

The aspirated psychrometer differs from the previous one, as the thermometers remain stationary, and the air across the thermometer bulbs is moved by a fan, blower or syringe. The function of the cloth on the wet-bulb thermometer is to provide a thin film of water on the sensing bulb. To prevent errors, there should be a continuous film of water on the cloth.

There are certain cares that must be taken with fabric wicks, for example, they should be replaced frequently, and only distilled water should be used for wetting it, the fabric should extend beyond the bulb by 1 or 2 cm to minimize the heat conduction effects along the stem. [34]

3.2.3. Procedure

The objective of psychrometry, in the field, is to identify possible micro-climatic causes that generate degradation of the materials. From the maps of relative humidity (RH%), specific humidity (q g/mc) and temperature (°C) it can be distinguished the anomalies present in the room.

In order to measure the water content in the air it is used the psychrometer, that consists in a device with a wet and a dry bulb thermometer. As the air in the measured points flows through both bulbs, the dry bulb registers the ordinary air temperature and the wet bulb, depending on its percentage of mixture between air and vapour, registers the depression/temperature. [8] Knowing that the wet bulb depression is a function of the percentage of the air/steam mixture, it can be used, in addition to the psychrometer readings, the psychrometric chart.

In recent times, the humidity is determined from the capacitance measurement of a thin film whose electrical properties are found to vary with water vapour content. There is also an automated instrument which has a cooling and heating element. The temperature of a mirror is adjusted until condensate is first detected; the measured mirror temperature at this condition is the dew point temperature. [20]

The measuring procedure starts with the creation of a grid where the points are separated from each other by 1 to 1,5 meters. The measures must be done in three occasions of the day, first in the morning, mid-day and the last on at the end of the afternoon. When the experience is done indoors, a measure to the relative humidity and temperature from the exterior, to confront both values.

The software used to download the values from the psychrometer allows to create a map for each property. First, the point grid must be transferred from the paper to the program so that the values collected in serpentine appear in the correct order. Secondly for each map it should be chosen an appropriated scale so that it can be easy to distinguish the pics and flotations of temperature, relative humidity and specific humidity [8]. This last property is not read by the device, but knowing that the specific humidity, s, is the ratio of the mass of water vapour, mv, to the mass of moist air, $ma + mv$, and represents the pondered dilution of the vapour in the atmosphere, it can be calculated by the equation 3.15:

$$s = \frac{mv}{mv + ma} \tag{3.15.}$$

Where:

mv – mass of water vapour [g]

ma – mass of dry air [g]

s – specific humidity

3.3. Gravimetric test

3.3.1. Concept

The gravimetric method has particular relevance because it can provide precise quantitative results.

The application of the gravimetric test on ancient buildings is the most accurate methodology to measure moisture content in materials. However, every norm created until now is for application in materials where all the physical properties are known, homogeneous and equal in all the samples of the wall. In historic buildings this factor is very hard to satisfy. First, because usually it is impossible to extract a big sample, secondly, the materials in a wall have different densities and finally, it is common not to know the exact state of degradation, or if the building suffered transformations or treatments that were not registered. [8]

Moisture content is that way determined resourcing to the following mathematical formula 3.16 and is expressed in percentage (%):

$$MC = 100 * \frac{m_H - m_o}{m_o} \quad (3.16.)$$

Where:

MC – moisture content [%]

m_H - wet mass; [g]

m_o - dry mass; [g]

m_H is the initial mass of the sample, whereas m_o corresponds to the mass after being dried and ventilated until the constant mass has been reached. With both the values we obtain m_w, which is the difference between the two masses, $m_w = m_H - m_o$.

It is also possible to determine MC by the volume instead of the mass, the difference is that the volume should be measured by volumetric determination. This method does not use the oven drying and resorts to mathematical formulas, as the reading has some differences compared with the first one. So, after obtaining the water content m_{ww} by volumetry, we can calculate m_w using the equation 3.17 and then substitute it in the first one 3.16.

$$m_w = 100 * \frac{m_{ww}}{100 - m_{ww}} \quad (3.17)$$

Where

m_{ww} - wet mass obtained by volumetry [g]

m_w – wet mass corrected [g]

3.3.2. Instruments

Currently, the procedure of the gravimetric test is simplified by the use of thermobalance (figure 3.4), that after collecting the sample and introducing it in the plate, measure all the masses and give directly the value of moisture content. The device is equipped with a lamp or electrical resistance (working as an oven), balance, sample holder and temperature sensor. Besides that, it also includes a temperature programmer, recording and control system of the atmosphere inside the device. The atmosphere control allows to work with static atmospheres, dynamic pressure or under reduced pressure.

The oven temperature and the sample are determined by means of a thermocouple or, more rarely through a resistance thermometer and they must be located as close as possible to the sample.

Regarding the balance, some operate continuously in equilibrium because any displacement of the indent is detected by a beam and the balance is restored by the force of a motor. Other systems use the type of spiral deflection scales or beams, whose displacements are accused by a transformer of linear voltage differential (LVDT), or other transducers. Usually the ovens are built to operate at temperatures of 100-1200ºC, being also available some that can reach 1600ºC to 2400ºC or more. The sample holder should be chosen according to the sample and the maximum temperature at which it should be heated. Platinum, tungsten, nickel, aluminum, quartz, alumina and graphite are the most common materials chosen to the purpose. [6]

According to the standard the analytical balance must have four digits, 0.1g of resolution and be able to read from 0.1% of the mass of the test sample. Sample containers should be inert, airtight and non-corrodible. The drying system has to a be an equipment as, for example, a ventilated oven or similar to the ones described in the last paragraph. [6]

Fig 3.4 – Thermobalance used in diocesan museum;

3.3.3. Procedure

To perform the gravimetric test, the first step is to collect the sample from the building materials, as explained in chapter 4, then the first mass must be weight in the analytical balance obtaining m_H. The third step is to oven dry the sample according to the standard procedure, until the sample reaches the constant mass (i.e. when being done consecutive readings at 4h interval the mass differs less than 0,5%). However, either EN 13183-1:2012 for wood [35] and EN 772-10:1999 for masonry [36], advise the heating at (103 ± 2) ºC [6]. For ancient buildings, to put their materials under this conditions, has the high risk of losing and deteriorating the sample. In that case, the material should be protected with varnish or impregnated with organic substances that volatilize when exposed to the oven heating. The limitation of this situation is that the weight lost does not correspond only to the water loss, but also to the volatile organic compound. [8]

To avoid misleading results there are three alternative techniques from which the desiccation can be done.

The first of this techniques supposes that besides the material does not resist to high temperatures, it resists to low ones, and it is called Vacuum drying. The procedure involves a vacuum pump that decreases the pressure inside the chamber to (4 ± 2) hPa. The equipment must be in an environment in which the temperature is above the water's freezing point.

The other two techniques, compressed-air drying and adsorption drying, are advise to be used in materials that, also, do not resist to low pressure. In the first one the sample is dried by a continuous flow of clean dry air obtained from compressed air, at a rate between 10,000 and 40,000 $cm^3.hr^{-1}$, inside the chamber. Some limitations are associated with this procedure, as the fact that in comparison with the previous ones, is the one that takes the longest time to conclude, that the drying rate depends on the type of material and that it is difficult to use in materials that are in powder. The second technique, resorts to a desiccator for general laboratory, where the sample is placed with a desiccant with high affinity for water. The test ends when the mass reaches a constant value and is in equilibrium with the RH inside the device. [6]

The thermos-gravimetric analysis (TGA) referred before is the most innovative method in this subject and consists in, after collecting the sample, placing it inside the device where the temperature gradually rises and the moisture is continuously removed from the sample. The temperature is monitored by a thermocouple and the weight changes are recorded by a microbalance. [6] The results presented are the weight percentage, temperature and the time that takes the procedure to occur. Regarding this process, it can be notice some advantages compared with the previous ones, such as the need of smaller samples, the fast measurements and the automatically record of the moisture percentage.

3.3.4. Limitations

Besides it was said that the moisture content could be determined by volumetry, this method has a problem regarding the study of ancient buildings as the materials collected usually suffer from degradation, as for example wood can be ruined by mould rotting, leading to internal cavities that change the internal volume and not the external one. In conclusion, the ration between the two masses it is not altered by this problem, however, the volumetric is. For that reason, in the conservation field the two measures cannot be compared. [8]

The main limitation of this method is that it is a destructive method, which makes impossible to do an ongoing record of moister content in the materials, especially in cultural heritage.

In addition, there are other problems as the inhomogeneity of the materials inside the masonry, that makes the water content vary also according to the materials, which, consequently, can become the comparison between different samples difficult. Another problematic situation is the temperature of the drill, that could dry the sample during the extraction; the pressure of the worker's hand during the drilling and the collection of powders from deep holes, for the reason that the crumble and powder could mix with the more exterior ones.

3.4. Microclimate

3.4.1. Concept

Microclimate, if described in the literally way, is the climate in a portion of the surrounding air. The prefix micro lead to believe that the size corresponds to the established scale for the appropriate size unit, for example 1 km, relates to mili=10^{-3}, micro=10^{-6}, nano=10^{-9}, pico=10^{-12}. Following this idea, microclimate would be a site sized only 10^{-6} Km= 1mm, which is an impossible standard. That is why microclimate is actually used, in conservation of buildings, for a small location as, for example, a corner of a street, a square, a room, a corner near to a painting, where a monument or an object is placed. This designation does not specify the size, but focus the importance in the specific artefact. Regarding to 'climate' it can be defined by Maunder as the «[…] statistical description of weather and atmospheric conditions in a given area.». Translating this description to the study area it can be concluded that microclimate is «the synthesis of the ambient physical conditions (e.g. time and space distributions, fluctuating values and trends, average and extreme values, space gradients and frequency of oscillations) due to either atmospheric variables (e.g.

temperature, humidity, sunshine, airspeed) or exchanges with other bodies (e.g. infrared emission, heating, lighting, ventilating) over a period of time representative of all the conditions determined by the natural and artificial forcing factors» [8]

3.4.2. Microclimate in conservation

In the conservation field, observations are made to study certain specific problems, so the equipment and the operative methodologies must be appropriate to the situation. In addition, it can be very useful to collect previous information from the local meteorological station to have a more complete understanding of the phenomenon, as they are tailored by international standards and the measurements made in the studied building are interconnected with them. More than in the meteorological field, in conservation of buildings, microclimate is a description of the complex interactions between air, constructions and objects from the surroundings. Locations in need of preservation measures appear not only outdoors, but also indoors and they have very distinct environments, which sometimes leads to different methods collecting the data. However, both have conditions that can be treated in a similar way, for example, the two go through a daily cycle of temperature and humidity, in one caused by the solar cycle and in the other by the heating and ventilating systems. Both are exposed to light, either from the sun, in open sky or through a window, or from the artificial lighting; both are effected by shortwave radiation. The wind or air currents affecting the exterior can enter through openings or turbulence generated by sources of momentum, being the two zones affected by advective air movements. Due to the existence of disconnections or to condensation in the window glass, walls or other cold surfaces, the rainfall and dew typical from the outdoors also influence the conditions indoors. The pollutants that enter through openings are transported from room to room and installed in the same way either outside and inside the building. In conclusion, the same problems can be found indoors and outdoors, the difference is the scale in which they occur. The main difference between them is the fact that in the interior the conditions can, ideally, be controlled and is important to know how to do it. [2]

Despite the constant study of this matter, the conditions indoors are not always perfect to the preservation of the cultural heritage, not only because usually the owners are misinformed, but also because in public places, as museums, is also important to create a pleasant environment for the visitors. [8] That said, is of the biggest importance to compromise and create the conditions that satisfy the two conflicting needs, most importantly having in mind that injuries caused to works of art are cumulative and irreversible. The current environmental guidelines are 45% RH +/- 8% RH and 70o F +/- 4o F for exhibitions and storage spaces [40] which in Celsius is approximately 21ºC.

Although Hippocrates, Pliny, Vitruvius and Palladium believed and shown, in the past, how to build prioritising the integration of the construction in its local conditions, taking the most advantage of the sun orientation, wind direction and precipitation conditions. Today, all of that, looks forgotten as it is believed that it can be created an internal environment resourcing only on modern technology, an artificial microclimate, where humidity and temperature are controlled by processors and microprocessors. In commercial buildings or museums maintaining the admission of air higher than the exhaustion leads to an indoor pressure higher than the exterior which, despite reducing the infiltrations of external air and pollutants, creates an artificial microclimate that does not agree with the conditions needed for the preservation of the elements of the building as walls, ceilings and floors, or even with the exhibits exposed inside them. [8] This problem results in a frequent need of mechanical equipment to balance the values of moist and temperature deregulated by the air leakage and exchanges of air between air and the surfaces.

There are several problems caused by the excessive use of HVAC systems. It was proved by Rosenhow in 1985 that 30% of the moisture supplied to a room is absorbed by its surfaces, which despite the positive mitigation of air dryness, also leads to the increase of moisture in the surfaces. Along the years, new equipment has been used to control the moisture inside a room, however, although the machines function correctly, their long-term application is not favourable to the exhibits. The result is the generation of clouds of moist/dry, cool/warm air and the direct blown of dry or moist air directly to, for example, paintings or wooden furniture. Consequently, objects and collections will suffer for repeated humidity and temperature fluctuations. The perfect situation for the development of new technology would be a device capable of creating an unchangeable uniform climate within all rooms, distributing homogeneously heat and vapour by capillary distribution of blowers and diffusers, located everywhere and at short distances from each other. [8]

In conclusion, microclimate monitoring as well as atmospheric thermodynamics are essential tools to the progress and development of solutions for the basic processes affecting cultural heritage, by discovering causes, effects and deterioration mechanisms.

4
CASE STUDY

4.1. BACKGROUND

4.1.1. INTRODUCTION

On behalf of the Diocese of Mantua, Polytechnic of Milan started the monitoring of the Diocesan Museum to obtain the map of the climate variations that occur inside the museum, especially in the conference room. The present thesis summarizes the results of the diagnostics up to 2016, performed by the experimental laboratory of ABC department, referring to the measurements of March, April, May and June. The author of this thesis collected and processed the data from March to June and analysed the data that had already been collected in the previous surveys.

In 2013, refurbishment operations were made in the building, including the renewal of the air conditioning system in the conference room, the introduction of new window frames at the first floor and the renovation of the plaster in some interior and exterior walls at the ground level, as can be seen in figure 4.1. However, after a few months some stains and detachments appeared on the walls of the conference room. To discover the origin of the problem, the focus of the study transferred more specifically to this room instead of the entire museum.

In addition, aiming to decrease the moisture content on the walls, the property manager of the museum installed in the conference room a dehumidification device, the SMERALDO[88], With the tests and measurements performed and the information given by the company, it is possible to conclude if the machine's functioning is reliable.


Fig 4.1 – Conference room at the present (left); Exterior wall of the conference room (right);

4.1.2. Historic background

The diocesan Museum of Mantua is headquartered in the grander cloister of the former Augustinian monastery of St. Agnes. In the fourteenth century, followers of the Blessed Giovanni Bono (1168-1249; founder of a religious order that was part of the Augustinian), founded in Mantua the monastery of St. Agnes, with a church, rich in works of art, the great cloister and outbuilding bodies. After the suppression in the eighteen century all the monasteries and convents were designated for civil use and Mantua was no exception. In addition, the church was demolished and, during the nineteenth century, the building had no maintenance measures, which lead to a gradual degradation. In the mid-twentieth century, after a restoration intervention, it started being used as a school, under the name of 'House of the Blessed Contardo Ferrini student'. In the end of the twentieth century, became the site of diocesan organizations and the first nucleus of the museum. Today, the museum occupies the entire building.

In 1974 an exhibition was held in the Ducal Palace entitled 'Art treasures in the land of Gonzaga', the success of the show led its founder Monsignor Luigi Bosio, to design a permanent exhibition this time in the Diocesan Museum, in 1983, called 'Diocesan Museum of Sacred Art'. The rapid growth of the exhibits resulted in the expansion of the exposition to the entire museum, become one of the largest and with a preciousness of treasures unparalleled in the world.

On June 7th, 2008, after being under the recovery of the neoclassical front, the building was inaugurated with a new production. In addition, since October 12, 2013 a new conference room opened in the museum. With the intention of promoting the cultural and associative activities of the city. The room has the capacity of 90 seats and is equipped with the appropriate technology.

4.2. Description

4.2.1. Mantua Soil

The City of Mantua is located in the center of the province, with the same name, and has an extension of approximately 64.01 square kilometers; It is between 45 ° 06'05 " and 45 ° 11'10 " North latitude, and between 10 ° 43'23 " and 10 ° 54'17 " east longitude with respect to the Greenwich meridian. [43]

It is characterized for being a flat region, whose highest points are situated near the northern administrative boundary (28,80 m a.s.l. at location Mounted Norsa). The slope Main, mostly oriented from North- West to South- East, is characterized by values in the order of 1¸3 ‰.

The most morphologically depressed areas are state within the Valley of the Mincio (14,20 m a.s.l. on the shore of Lago di Mezzo, south of the Cartiera Burgo) , in Valle Cauldron (14,00 m a.s.l. on the border with the town of Virgil , along the Valley of the Rats) and Southeastern end the municipality, in the area between Canal and White River Mincio (14,40 m a.s.l. in the neighborhood of C.te Beffa) .[43]

In terms of land uses, the area is characterized by massive production facilities, the largest of which is Petrochemical Ash - Borgo Virgiliana. Besides that, mainly concentrated in the outer areas, it remains present some agricultural use.

4.2.2. Regional geological framework

The Po Plane corresponds to a definitely affected area from early Oligocene subsidence (i.e. the third epoch of the Tertiary period, between the Eocene and Miocene epochs), connected to the lifting of the surrounding mountain ranges. The Pliocene and Pleistocene Inferior were characterized by the appearance of a wide bay, whose size and depth were regulated by imposing ingressive phases and regressive sea. The transition from the marine to the continental probably occurred to the end of the Lower Pleistocene; Lifting movements continued throughout the rest of Pleistocene, affecting both the erosion of the reliefs accumulation in subsidence areas. [43]

The distribution and characteristics of the plain land, were established in the course of the Pleistocene climatic variations, directly related to the succession of phases glacial and interglacial.

The northern sector of the Province of Mantua is located, immediately close to the 'Colline Moreniche', which means that the geological units on the Plain are characterized by predominantly gravelly-sandy soils, deposited by arresters fluvioglacial once fed from the front moraine of Lake Garda. On the other hand, further south, such deposits are constituted by finer materials, as sand, silt and clay, accumulated by the rivers of Media Plain. According lithostratigraphic data, in the surrounding area of Mantua, the alluvial blanket, reaches a thickness of more than 350 m and is formed mainly by thick sandy cylinder banks with interbedded clay and peat layers also with considerable power. This decrease in the particle size, that leads to a diminution of permeability, from the upper part to the lower. [43]

In this area there were waterlogging phases, particularly in extended interglacial periods, and the formation of a complex river network, that evolved until it became the current system Mincio River - Mantua Lakes. The transition to the High Media Plain is marked by a characteristic succession of natural or man-made fountains commonly called line of springs. The area located a few kilometers south of the provincial capital, it also enters the zone of influence of River Po, characterized by predominantly clay-silt sediment and identified as Low Plain.

In 2013, the area was extensively investigated, in all aspects concerning the geological component, namely: recognition of the depth of the water table in certain water wells, reconnaissance on the ground as part of the delineation of the water network in collaboration with the officials of the Directorate for Territorial Development and Environmental Protection of the municipality of Mantova, geotechnical surveys in the areas of possible transformation planning, seismic tests with refraction method.

4.2.3. Climate characterization

The meteorological characteristics of the investigated area are typical of across the Po Valley. The climate is typical continental with harsh winters, where the average temperature range is between 0 ° C and 2 ° C and by hot summers where it is above 22 ° C, in July (figure 4.2). Thus, the temperature range is quite high, above 18 ° C, setting the annual average temperature at values between 12 ° C and 13 ° C. Regarding the average annual rainfall, it has values around 650 mm, with more frequent rainfall in spring and autumn; the wettest months are April and May, while the least rainy is February (figure 4.3). Thunderstorms are more frequent in the summer, when this event can occur for approximately 45 days.

The values for relative humidity reach their highest in January, rounding 85%, and their lowest in July, with 55% (figure 4.4). The autumn and winter climate are characterized by a persistent fog, originated by the lowering of the temperatures. [45]

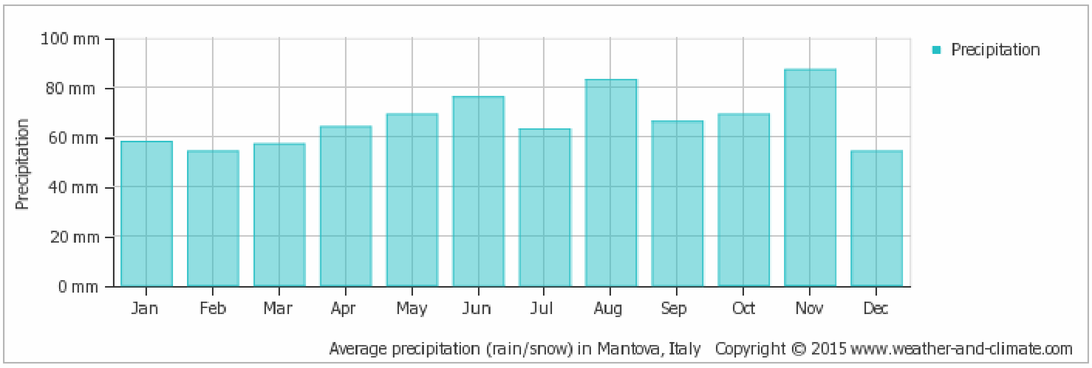

Fig 4.2 – Average of monthly precipitation over the year, in Mantua[37]

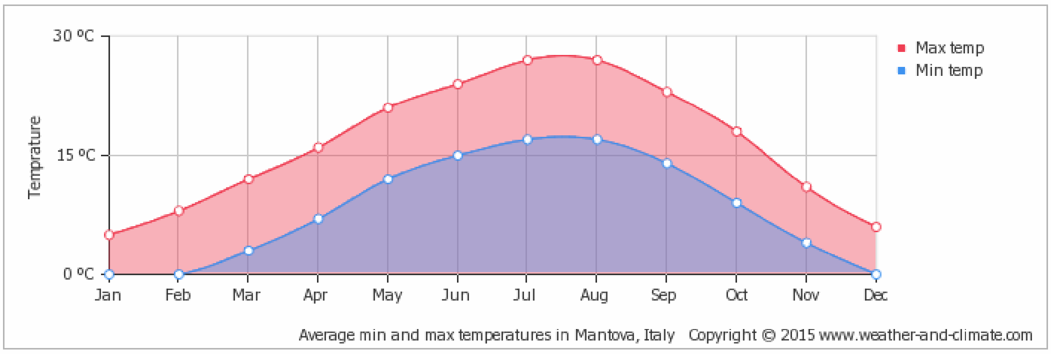

Fig 4.3 – Average of monthly minimum and maximum temperature over the year, in Mantua[37]

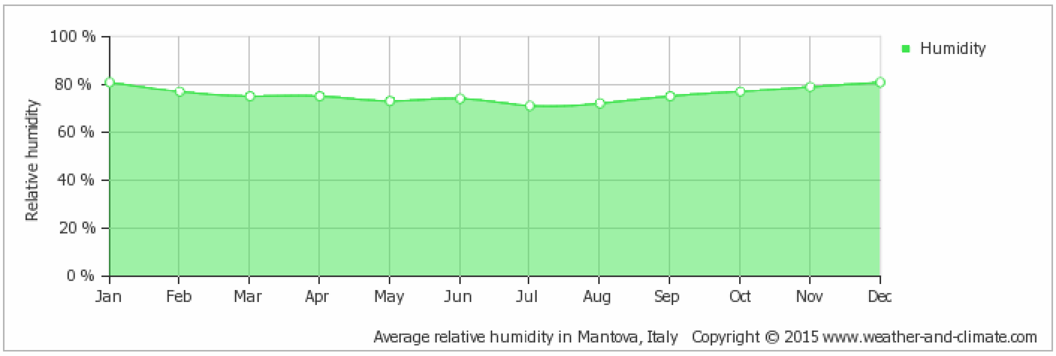

Fig 4.4 – Average of monthly humidity over the year, in Mantua[37]

4.2.4. Lithology

Based on the geological study carried out by Spagnolo, 2011, directly on the ground with grain size estimates collected on land, at a depth between 80 and 100 centimeters from the floor campaign and always below the first horizon affected by agricultural processing. The conclusion was that the area is characterized by floodplains (i.e. fluvioglacial deposits covered by younger sediments with flood origin); it also has rolling areas, described as fluvioglacial deposits, mainly fine and limestone. Another characteristic situation is the engraved riverbeds, which are oversized compared to current water courses, formed by recent alluvial deposits. And finally for the areas that occupy the bottom of the rivers between the embankments and artificial embankments, including areas reclaimed from marsh.

The deposits intercepted in the area include mainly fine matrix (silt, silt-clay and fine sands), sandy deposits that were detected at a depth of 20 m below ground level. At 5 m of profundity, the deposits appeared with a permeable layer of water proof material, clayey silts. The silty materials detected are mixed with clay fractions. [45]

4.2.5. Hydrogeology

Regarding the hydrogeological investigations, the study was made recurring to the bibliography available, data collected on stratigraphic columns and levels of wells next to the study area.

As evident from the analysis of literature sources and direct surveys carried out on site, it can be said that the first aquifer subdued over the medium-fine sands. The groundwater aquifer of the Province of Mantua confirm the presence of a first layer covered with silty-clay, whose average power reaches about ten meters and in certain cases, 15 m, concluding that this blanket is certainly capable of protecting the groundwater from potential pollution. A second layer appears under the first one, based on fine sand with medium/clear color. The thickness of this aquifer increases appreciably proceeding from north to south. The local water table structure of the first aquifer is marked by a sense of flow towards the southern sector. The flow field of aquifers present in the investigated areas is directed from north to South. [45]

4.3. The building

4.3.1. Visual inspection

The building is composed by two floors, with a cloister in the centre. The first floor holds the exhibit rooms and the ground floor has several unoccupied rooms, at the moment. During the characterization of the building structure, it was realized that the designs of the building did not include its foundations or the description of the masonry structure under the plaster. Therefore, as it was impossible to conduct a destructive survey to analyse the conditions above the ground level and the type of masonry, it was recurred to previous literature about the ancient buildings of the region.

Regarding the foundations, excavations inspections could not be done, it was supposed that, for a building without cellars, with a height of two floors and a thickness of the walls of approximately 50 cm, the foundations are only 60 to 80cm deep, as it was usual in buildings in the fourteenth century. [47]

The masonry contained in the Diocesan Museum is known to be solid bricks bound together with mortar of lime and sand (figure 4.5). This type of masonry is a very common material in the historic buildings of the region, as they are composed by a ceramic porous paste, that derivers from processing clayed soils, in which this area is rich. The walls in the building reach a thickness of 50 cm and the typical bricks used in the area are of variable size and that often present stretched courses. [45] Furthermore, their composition results from different materials having different porous and hygrometric characteristics.

Fig 4.5 – Exterior wall from Diocesan Museum (left); Downspouts in the cloister (right).

Concerning the coatings of the walls it can be noticed that the plaster has not only a decorative effect, but also the function of protecting the wall materials from any form of surface degradation agent as: the weather (specially rain), deposit of pollutants and usage. The plaster in diocesan museum concerns to a recent application, as it was substituted at the bottom, up to 2 m from the floor, and the existing one was covered in the upper part of the wall.

During the visual inspection to the entire museum it could be noticed that some of the rooms are not in good conditions, having some of them the appearance of abandonment. In addition, it can be noticed some plaster detachments in the lower part of the walls, as it is shown in figure 4.6.

Fig 4.6 – Plaster detachments on a wall from the ground floor (left); Lower part of wall from the conference room (right);

The conference room, placed on the ground level, is a rectangular room barrel vaulted, with five windows along the longest sides, facing Piazza Virgiliana and the cloister.

There are problematic areas at two meters from the floor, where it can be seen some darker stains compared to the rest of the plaster in the wall (figure 4.12 and figure 4.14) and also along the southwest wall, where the stains appear similarly at the bottom (figure 4.7). Besides that, on this room it was also noticed painting and plaster detachments in the lower part of some of the walls, as it can be seen in figure 4.6.

In addition, it was noticed that the downspouts draining the water from the roof enter the soil, with no drainage system for the municipal sewer collector. So it is believed that the rain water is draining directly to the soil. Similarly, in the sidewalks it could not be seen a draining system for rain waters.

4.3.2. LOCATION

In the urban context, it is placed a few meters from the Cathedral and the Ducal Palace. The frontage of the museum faces the Virgiliana square, created in the eighteenth century and surrounded by neoclassic buildings, which is also the style of the museum's facade, designed by Paolo Pozzo in 1795.

4.4. DIAGNOSTICS

4.4.1. THERMOGRAPHY TEST

4.4.1.1. Introduction

On September 9th, November 1st, 2015 and March 24th and June 16th, 2016, thermographic surveys were carried out on the conference room of Diocesan Museum. Beside other diagnostic tests, as gravimetric tests and microclimate monitoring, the thermal pictures have the objective of obtaining a map of moisture distribution in the walls, the causes of the stains seen in the visual photos and the variations caused by the installation of a dehumidification device.

During the mapping of the surface temperature, were identified some areas in which it can be assumed the presence of moisture, in particular on the southwest and northeastern walls of the room, toward the wall of Piazza Virgiliana.

The following thermograms show the most significant temperature differences that may indicate the presence of moisture.

4.4.1.2. Applied procedure

The thermographic pictures were taken in the passive mode in order to identify areas that have lower temperatures due to the presence of water evaporation on the surface, in the absence of thermal stress. The procedure consists in scanning the entire surface by only recurring to natural heating.

The analysis of the thermograms consists in the observations of darker areas, in this case, the detection of dark blue areas. Comparing the visual photos with the thermal ones and registering the environmental conditions, at the time of the test, it is possible to evaluate and predict which areas have a higher probability of having damages due to the content of water.

On the base of the analysis of the thermograms, the laboratory of the ABC department set after a long time of experiments and publications [55;56;57;58;59], that it should be performed a gravimetric test with the purpose of confirming the presence of moisture.

4.4.1.3. Equipment used

To collect the thermograms it was used a thermocamera with the following characteristics: 2D FDA infrared thermal imaging system uncooled (micro bolometer), FLIR P640. The IR resolution is 640x480 pixels, the spectral range is 7.5 13 Hm and the emissivity programed for plaster surfaces was 0.92.

4.4.1.4. Environmental conditions

The average temperature and relative humidity, regarding the interior and exterior of the conference room, at the time of each survey are presented in table 4.1.

Table 4.1 – Averages of relative humidity and temperature in the interior and exterior of the conference room

	2015				2016			
	9 September		11 November		24 March		16 June	
	int	ext	int	ext	int	ext	int	ext
Relative Humidity (%)	55	57,5	70	69,5	71	84,5	80	73,6
Temperature (ºC)	21,5	20	13	10,5	19,5	10,5	22	20,5

4.4.1.5. Obtained results

The following figures concern to the thermograms and visual pictures collected during the several surveys to the conference room.

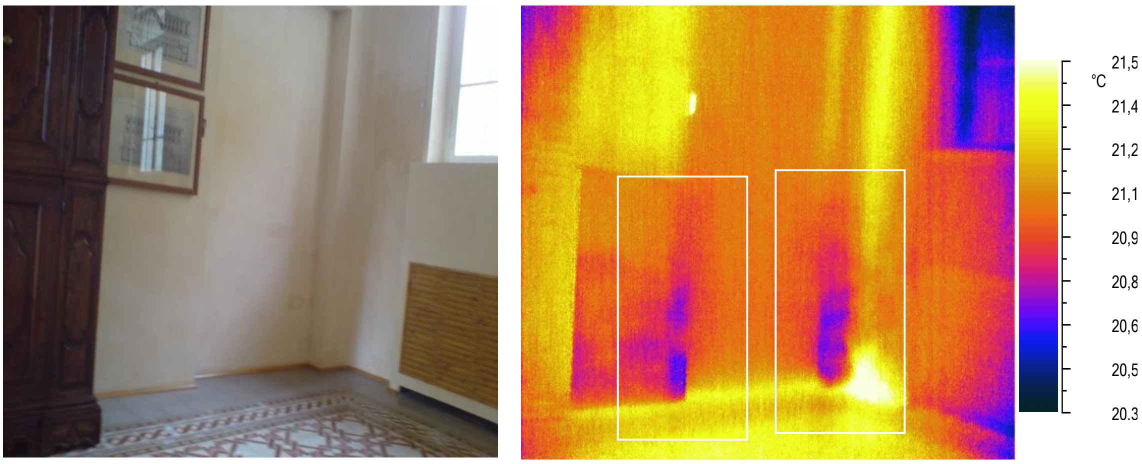

Fig 4.7 – Visual picture of the right side of southwest wall (left) and correspondent thermogram (right), survey of September 9th, 2015

Figure 4.7 represents the west corner of the conference room. In the considered scale it can be identified two cold areas, which are marked with the boxes. As the corners are thicker than the surrounding wall, the water rises higher by capillary. The scale range is very strict, the difference between the darker area and the orange zone is approximately 1ºC.

The warmer areas on the left side of the wall, are due to the reflectance of the glass, from the paintings placed there.

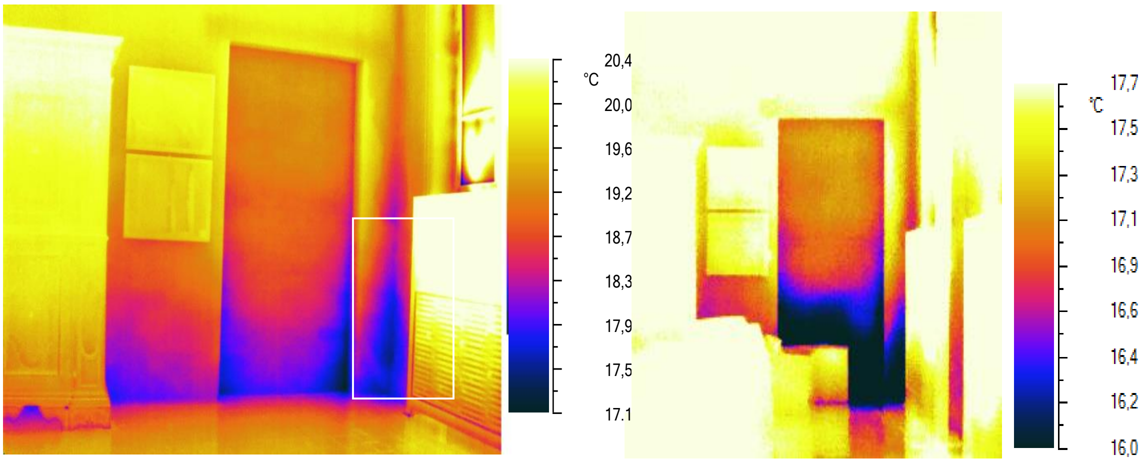

Fig 4.8. - Thermogram of right side of the south west wall on the survey of November 11th, 2015 (left) and March 14th, 2016 (right).

On November 11th and March 14th, the picture taken is more representative of the problem (Figure 4.8). The temperatures are lower in general and the difference from the floor to the celling is almost 3ºC. Beside the two areas that also appeared in the previous thermogram, at this point it could also be noticed the existence of moisture in the corner on the right (marked with a white box). Once again, in the corners, the height that the water reaches is higher than in the surrounding wall. From the distribution of the temperature, it can also be concluded that the damaged area enlarged and now, it also appears in the middle of the niche.

The warmer square, that can be seen in the lower area of the thermogram took in March, concerns to a box that was placed in front of the wall and could not be moved.

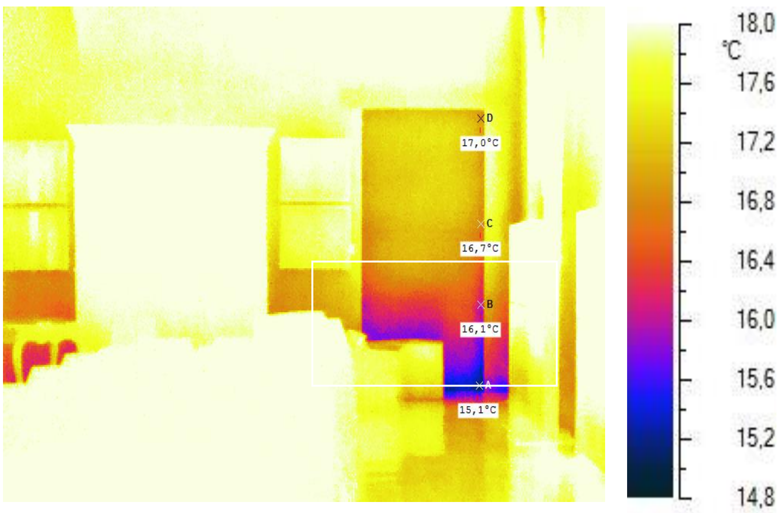

Fig 4.9 – Thermogram of the south west wall with temperature points, survey of March 24th, 2016

The last thermogram of the same wall (figure 4.9), shows that the temperature increases along the height of the wall.

Because of the difference of environmental temperature since the previous test, it was set a different range of temperature to detect their differences between the lower and higher area. From the identified points it can be concluded that the difference is about 2ºC. Because the temperature of the floor is similar to the one on the upper part of the wall, and it can be excluded other possible cause of cooling down of the bottom of the wall, the lower temperature is indicative of water evaporation. Therefore, the colder areas are indicative of the distribution of moisture. The further measures of the water content in these areas will verify the presence of water.

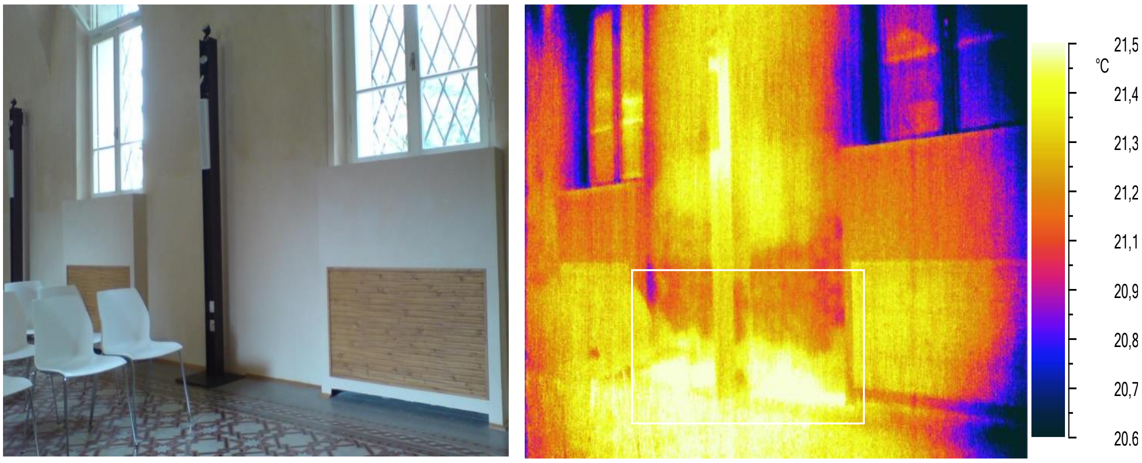

Fig 4.10 – Visual picture of the north west wall, between the 3th and 4th window (left) and correspondent thermogram from September 9th (right)

In September, the thermograms of the wall facing the square does not indicate a clear presence of rising damp. However, a darker area (figure 4.10, in the white rectangle) can be seen at the bottom of the wall. The cause can be the heating that was on in the days before the survey. The thermal inertia in the bottom of the wall lead to the warmer area, that can be seen in the thermogram.

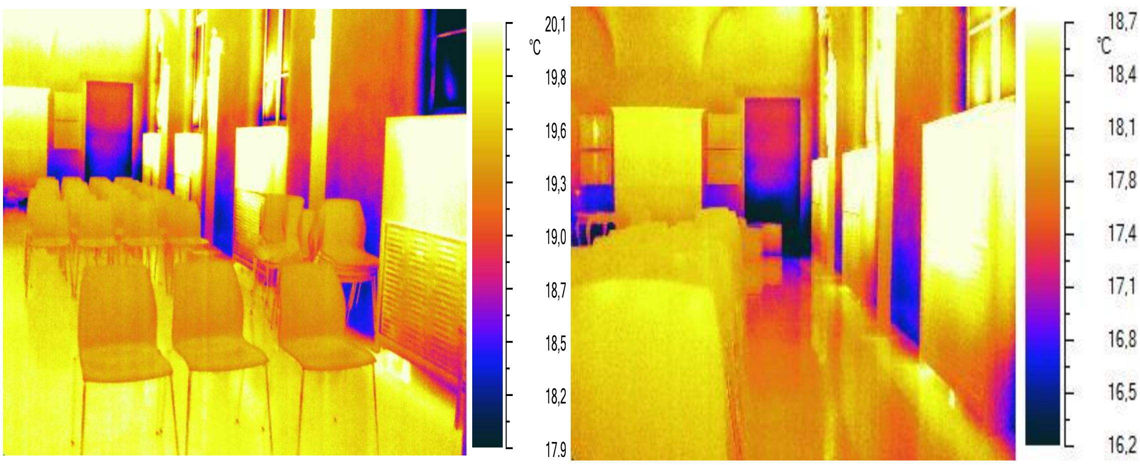

Fig 4.11 – Thermograms of the left side of the northwest wall, survey of November 11th,2015 (left) and March 24th, 2016 (right)

On the other hand, on the thermograms took in November and March (figure 4.11), this side of the room presents a very dark band close to the floor. Although the scale range is different, on both situations there is a difference of 2ºC along the height of the wall because of the lower values of

RH at that time, that lead to a higher evaporative flux and a lower temperature of the surfaces. The dry winter of 2015/2016 is one of the causes for the low RH in both surveys.

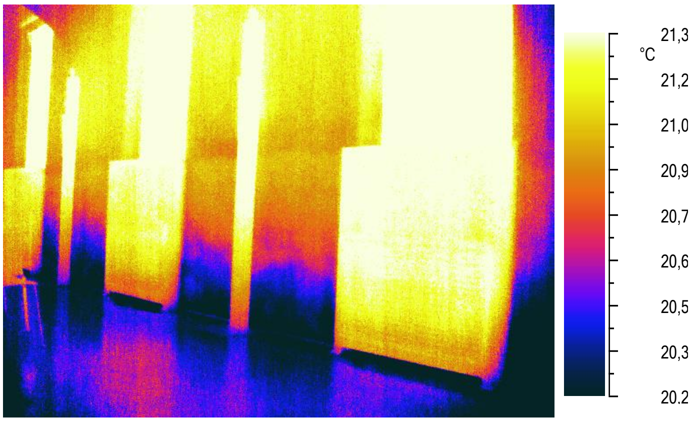

Fig 4.12 – Thermogram from the north west wall from June 16th, 2016

In June (figure 4.12), the thermogram shows a general increase of temperature and the high RH (around 80%) in the conference room during the IRT, reduced the evaporative flux on the wet areas, therefore their cooling down.

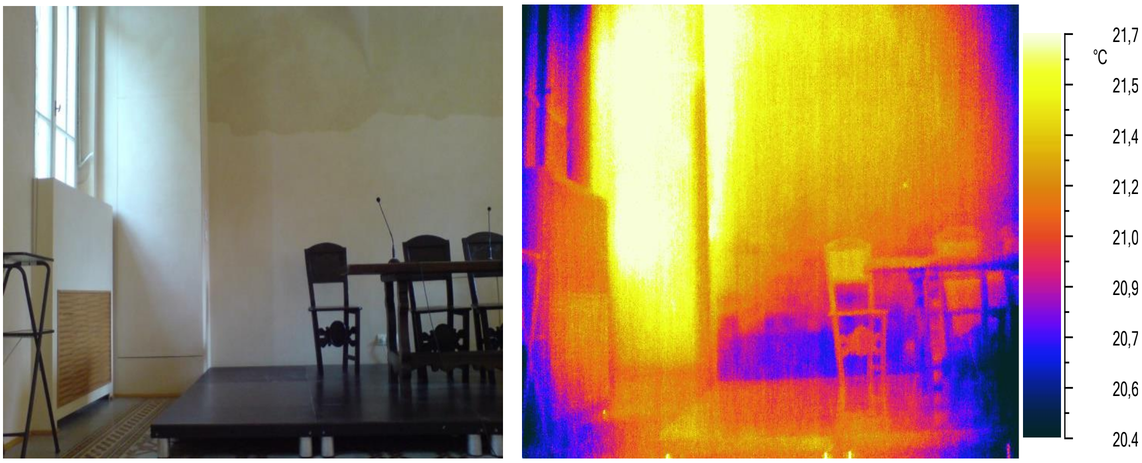

Fig 4.13– Visual picture of the left side of the northeast wall (left) and correspondent thermogram of September 9th,2015 (right)

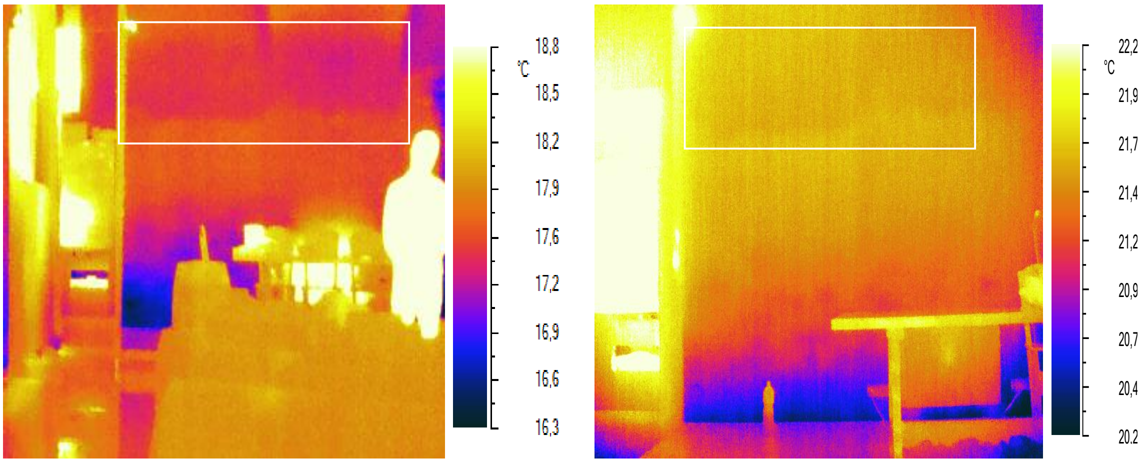

Fig 4.14 – Thermogram of the left side of the northeast wall from the survey of March 24th, 2016 (left) and June 16th,2016 (right).

In figure 4.14, the part of the northeast wall in the white rectangle shows a darker band, compared with the remaining wall. This situation is even more evident in the surveys from September, 2015 (figure 4.13) and March, 2016 (figure 4.14 left), in which the temperatures are lower and the height of the darker band is bigger than in the first test. Regarding the thermogram from June (figure 4.14 right), it can be noticed the colder area in the bottom of the wall is indicative of the presence of water in that area. The gravimetric test performed in this wall, on the same date, validates this diagnosis showing high values of water content in the sample from the lower hole.

In the thermograms from figure 4.14 it can be seen the influence of the heating sources on the left side, regarding the electrical equipment, that do not allow to take any conclusions about the temperature of the wall in that area.

Fig 4.15 – Visual picture of the northeast wall, November 11th, 2015

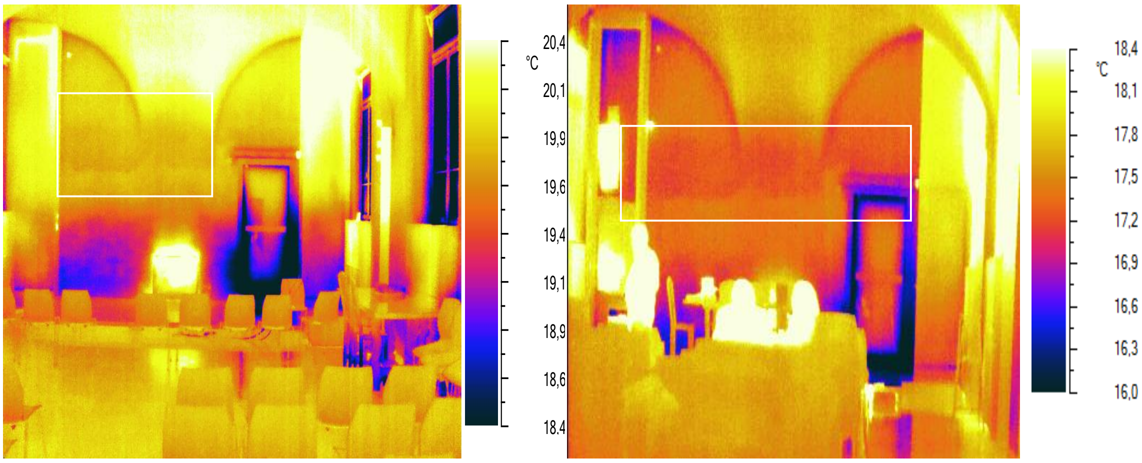

Fig 4.16 – Thermograms of the northeast wall from the survey of November 11, 2015 (left) and March 24th, 2016 (right)

The north east wall, shown in figure 4.15, beside the problems mentioned before, has different temperature alongside the doorframe, due to the air draught resultant of the poor sealing of the door, and it is apparent in the thermograms taken in November and March (figure 4.16), when the differences of air temperature inside and outside are wider.

In addition, in the thermograms represented by figure 4.16, it can also be distinguished a slightly darker area in the upper zone of the wall. This area inside the box goes colder from November to March and is consistent with the stains that can be seen in figure 4.15. The explanation for this phenomenon can be due the soluble salts distribution remaining in the older plaster underneath the recent one, that migrated towards the surface due to the high and variable values of RH.[48] Another reason can be the difference of colour on the surface that affects the absorption of the radiation, or the thickness of the plaster, as the location of the stain is coincident with the new plaster applied during the refurbishment.

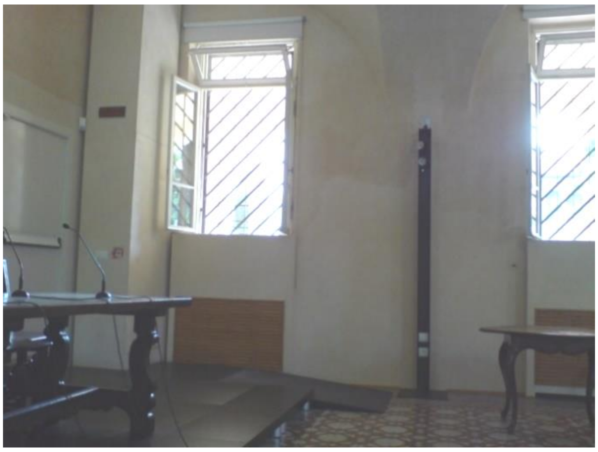

Fig 4.17– Visual picture of the southeast wall between the 4th and 5th window, November 11th, 2015

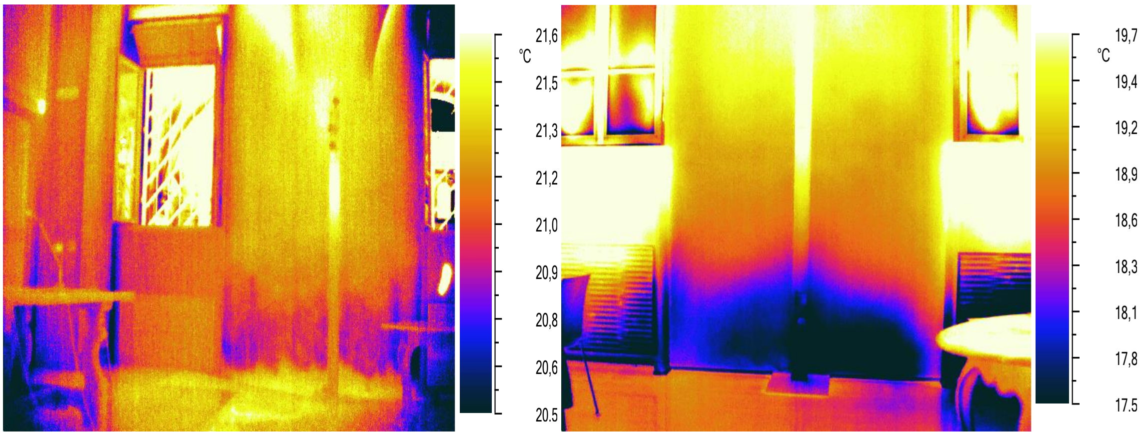

Fig 4.18– Thermograms of the southeast wall, between the 4th and 5th wall, from the surveys of September 9th, 2015 (left) and November 11th, 2015 (right)

Similarly, also the thermograms (figure 4.18) of the wall facing the cloister (figure 4.17), show the same temperature distribution. However, the temperatures on the bottom of this wall are lower than the first one. This is more evident in November, where the scale has lower values of temperature.

Fig 4.19 – Visual picture of the southeast wall, between 3rd and 4th window, (left) and correspondent thermogram from the survey of September 9th, 2015 (right)

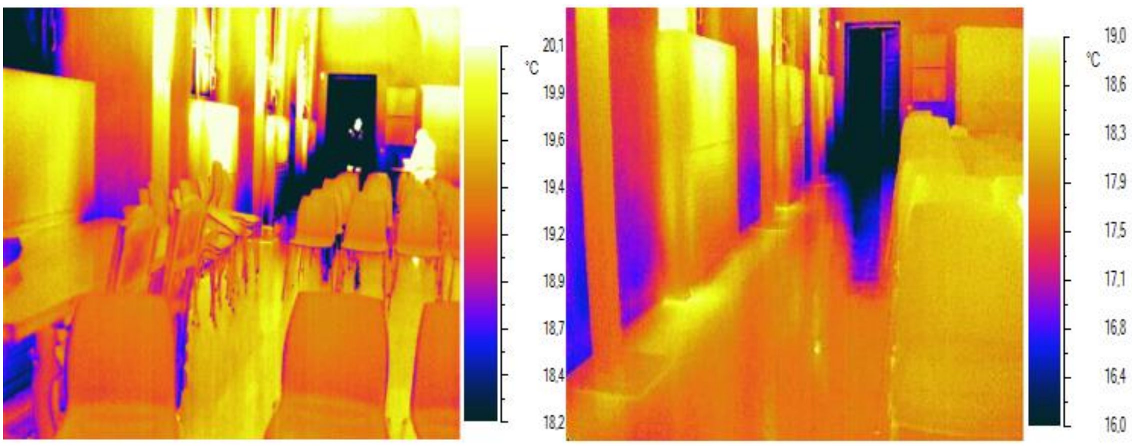

Fig 4.20 – Southeast wall thermograms, from the surveys of November 11th,2015 (left) and March 24th, 2016 (right)

In figure 4.19 and 4.20, as in the rest of the walls, the scale acquires lower values from the first survey to the last and, as it was said before, it is easy to see the gradual change of temperature from the floor to the top of the wall, indicating the existence of water inside the masonry in the colder area. The high temperature of the floor is, possibly, due to the heating occurred before the test: on march the heat spread on all the interior surface of the room, whereas in June (figure 4.21, right) the floor has a lower temperature due to the contact with the soil, colder than the air.

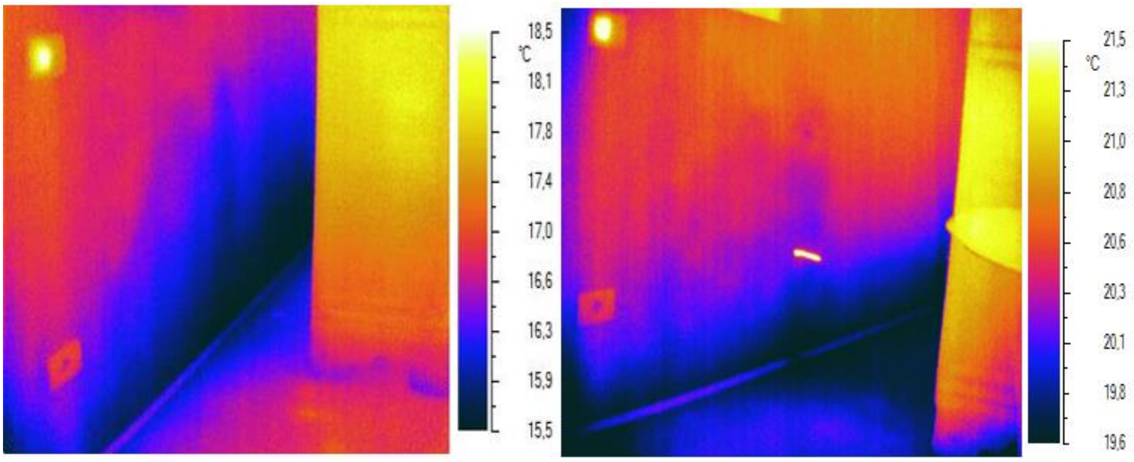

Fig 4.21 – Thermogram of the southwest wall, behind the closet, survey of March 24th, 2016 (left) and June 16th, 2016 (right).

Figure 4.21 corresponds to the wall behind the closet situated in southwest wall. Here it can be seen the temperature change, the colder area corresponds to a situation of rising damp, as it was confirmed by the gravimetric test. Comparing the thermograms of March and June, it can be seen a general increase of the surface temperature, correspondent with the warmer season of the year. However, the colder area in the lower part of the wall remains approximately the same height. The wall remains very wet because it has the closet in front of it.

In both thermograms to hot squares can be seen in the left side of the image. When collecting the data, it was noticed that they correspond to a light switch and a socket.

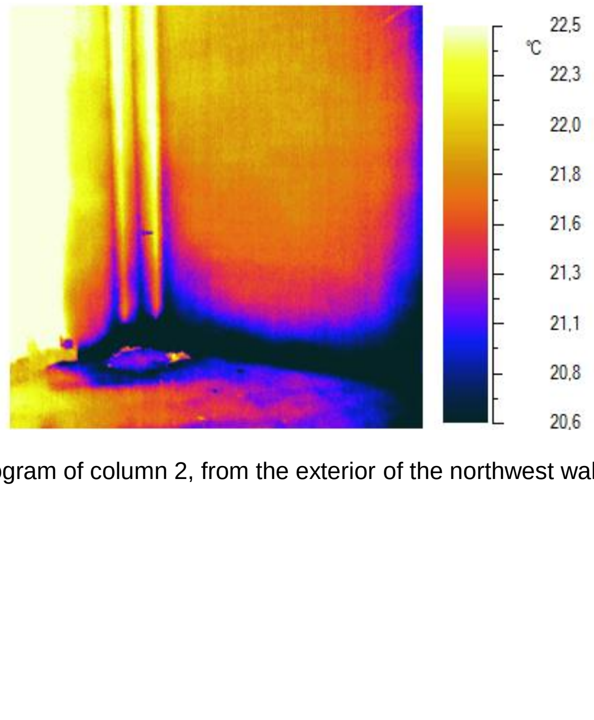

Fig 4.22 – Thermogram of column 2, from the exterior of the northwest wall, June 16th, 2016.

The thermograms of June (figure 4.22) also presents a colder strip on the exterior elevation of the conference room, confirming the results of the diagnostic already done (figures 4.8 and 4.21).

4.4.2. PSYCHROMETRY

4.4.2.1. Introduction

For the psychrometric study, were used measurements done in a previous survey, in fact, the collected data concerns to February 7th, 2014. Additionally, the maps do not concern only to the conference room, but also to other rooms in the museum.

The purpose of the psychrometric measurements is to obtain the internal microclimate map to verify if the conditions are ideal to the conservation of the historical artefact and, if they are not, to rehabilitate the building in order to improve the conditions for the preservation of the construction. The selection of the areas with anomalies in the relative humidity, specific humidity and temperature allows the comparison between the discontinuities and the climate changes during the analysed period.

4.4.2.2. Applied procedure

To perform the measurements, it was used a psychrometer with electrical resistance, as it allows the time in which the device becomes in equilibrium with the air to be short and, consequently, the reading of a big number of points to be brief. It is important to make sure that the measure of the different values is done fast, preferable only with seconds apart, so that the confront of the results is as exact as possible. Some parameter adjustments were made without making any considerable changes to the external and internal conditions. Several procedures were executed to the correct measure of the parameters, starting from doing a regular grid (1.0x1.0m) as a guide to the registration of the important values of temperature and relative humidity, with the objective of transforming the numeric data into a map composed by isolines representative of the values obtained. [26] The final maps were inserted in the building plants, making easier to localize the areas with evident anomalies correspondent to the structure, as windows or installations. Another situation to have in mind is to make measurements also close to the walls.

The measurements were done two times in the same day, instead of the three recommended [26], because each one took a considerable amount of time. Despite that, the result was two maps for each level of the building, one for the first measurement at 9.30 am and the second for the one at 4.30 pm.

The laboratory phase includes the following steps:

1°) processing and transference of the obtain values of T, RH and SH through an appropriated software dedicated to linearly interpolate the values acquired and to connect them with the grid of points.

2°) production of the maps correspondent to the three parameters with highlight to the isolines showing the trend variables.

It is important to be careful during the reading of the results, because the software is not able to automatically enter in the calculous the physical variables that effect the values and, therefore, not able to discern a physical constraint in the geometry of the building from a simple secondary nature constraint. On the other hand, the software offers a vast option of colours, that allow the choice of the most representative to highlight the anomalies investigated and the option to select a fitted scale and interval between isolines.

4.4.2.3. Equipment used

The procedure was effectuated with a digital psychrometer PW600 Tecnoel.

Measuring range of the two annealing transducers of dry bulb and wet bulb temperature: 0-50°C

Maximum error of non-linearity of the two transducers: +/- 0.15°C

4.4.2.4. Regulations

The test was performed following the UNI 10829/99 norm [25;26]

4.4.2.5. Environmental conditions

The average temperatures and relative humidity, at the time of each measurement, are presented on table 4.2.

Table 4.2 – Average temperature and relative humidity on February 7^{th}, 2014 outside

	February 7^{th} 2014	
	9.30 h	16.30 h
	exterior	
Relative Humidity (%)	81.5	72.7
Temperature (ºC)	9.5	10.2

4.4.2.6. Obtained results

The following results regard to psychrometric maps of temperature, relative humidity and specific humidity, made to several rooms in the museum from the ground level and first floor.

Fig 4.23 – Ground floor Temperature map from the 9.30h measure, from the February 4th, 2015, survey.

Fig 4.24 – Ground floor Temperature map from the 16.30h measure, from the February 4th, 2015, survey.

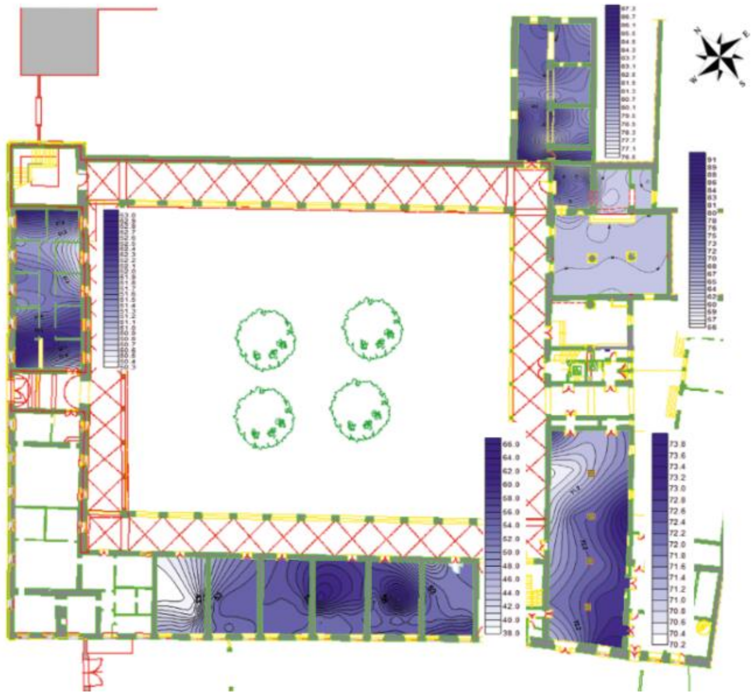

Fig 4.25 – Ground floor Relative Humidity map from the 9.30h measure, from the February 4th, 2015, survey

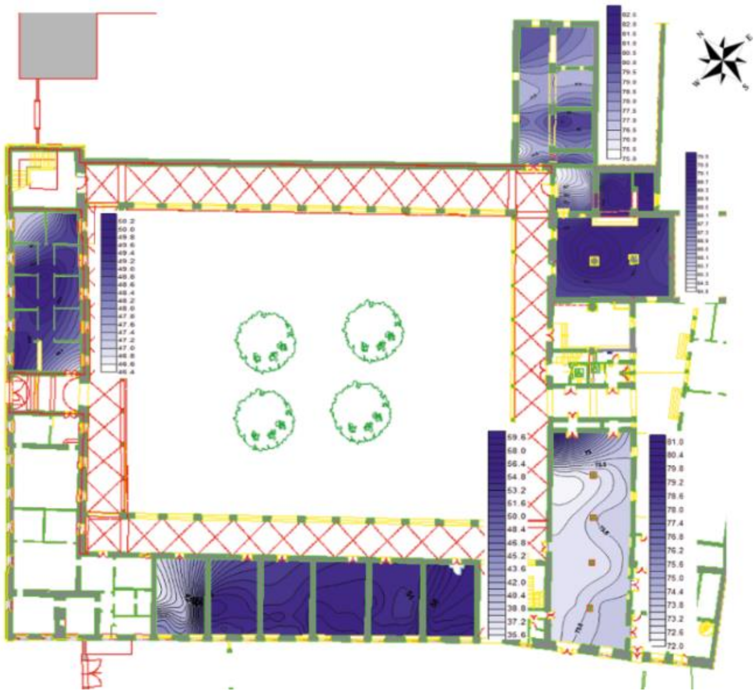

Fig 4.26 – Ground floor Relative Humidity map from the 16.30h measure, from the February 4th, 2015, survey.

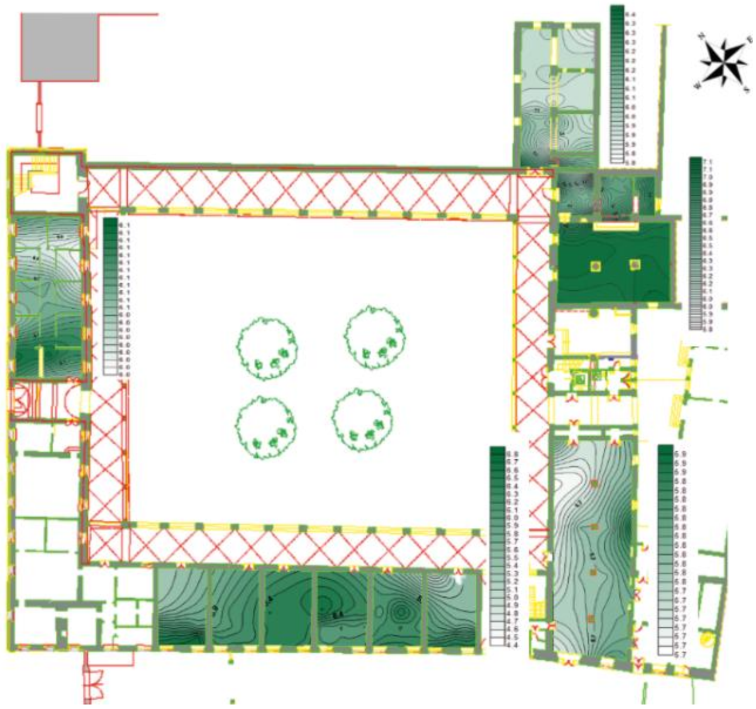

Fig 4.27 – Ground floor Specific Humidity map from the 9.30h measure, from the February 4th, 2015, survey

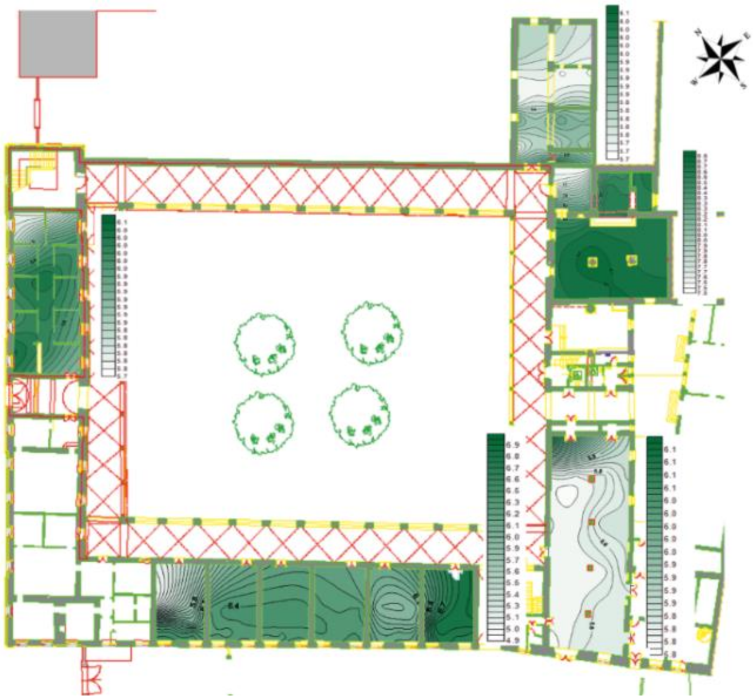

Fig 4.28 – Ground floor Specific Humidity map from the 16.30h measure, from the February 4th, 2015, survey.

Looking generally to the morning temperature map from the ground floor, in figure 4.23, it can be noticed that the temperature between the several rooms varies very much. That difference can be specially noticed between the two rooms in the south west side, where the left one has a scale comprehended from 14 to 28ºC and the right one from 10.7 to 11.1ºC, a very steady temperature.

The high temperatures in those rooms can be explained by the turning on of the heating, as the external temperature is much lower than the internal. A point where this can be seen is in the south west room, in which, besides the almost steady values throughout the room, it can be seen a pic of 20.4ºC close to the wall. Comparing the measurements preformed in the afternoon, figure 4.24, the values are close to each other.

Regarding the distributions of relative humidity (figures 4.25 and 4.26) and specific humidity (figure 4.27 and 4.28), it can be said that they are very similar, being the values in both maps higher in the rooms from the south east side, especially in the ones from the east, having numbers from 56 to 91% of RH. In this case the higher moisture content corresponds, as expected, to the lower temperatures and vice-versa. In fact, in the rooms where the heating is on, the values of humidity can acquire low percentages as 30 or 40%, which can result in poor conditions to the conservation of the timber surfaces. In relation to the afternoon measures the maps are very similar to the morning ones.

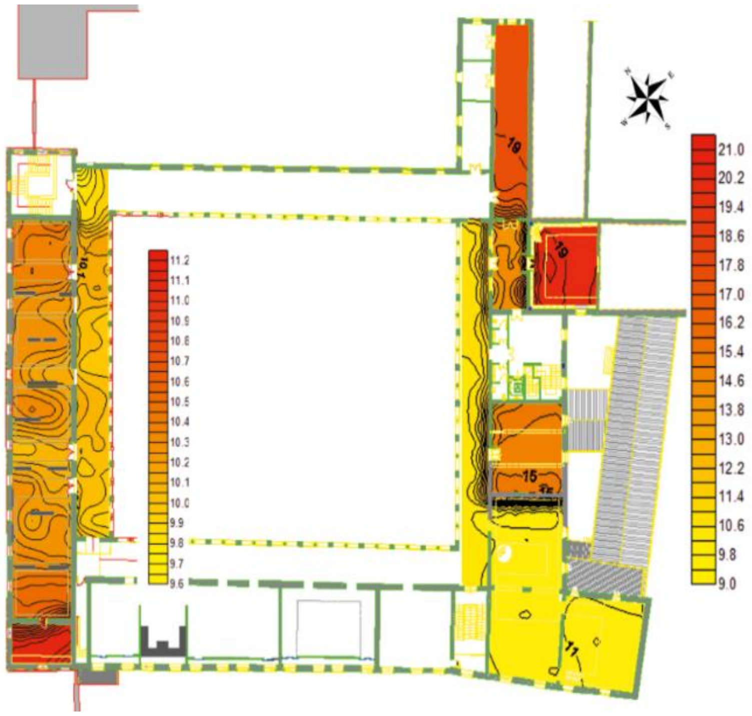

Fig 4.29 – First floor Temperature map from the 9.30h measure, from the February 4th, 2015, survey.

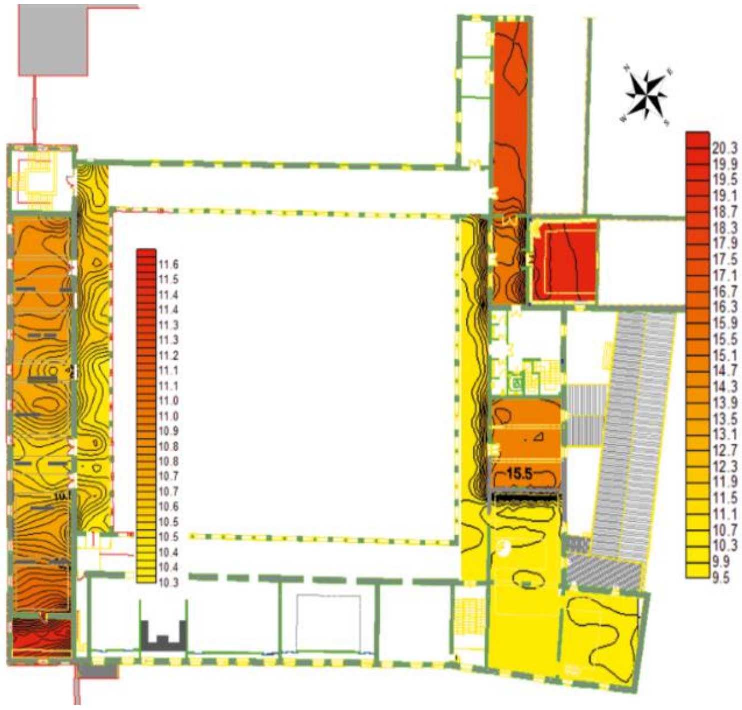

Fig 4.30 – First floor Temperature map from the 16.30h measure, from the February 4th, 2015, survey.

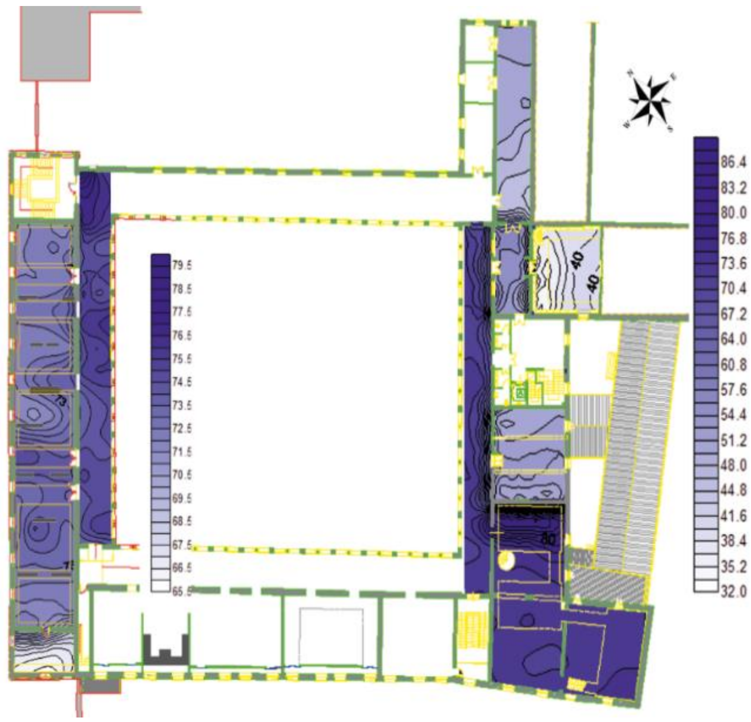

Fig 4.31 – First floor Relative Humidity map from the 9.30h measure, from the February 4th, 2015, survey.

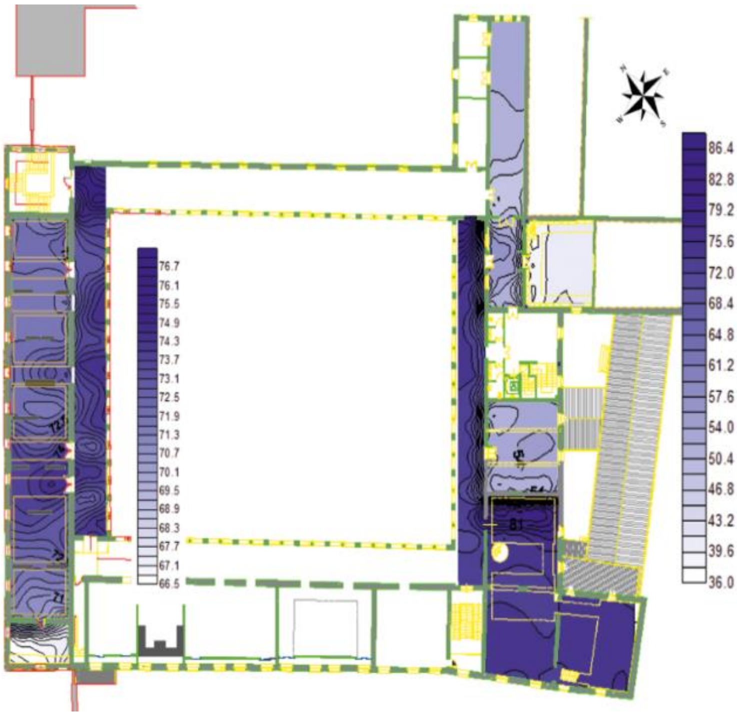

Fig 4.32 – First floor Relative Humidity map from the 16.30h measure, from the February 4th, 2015, survey.

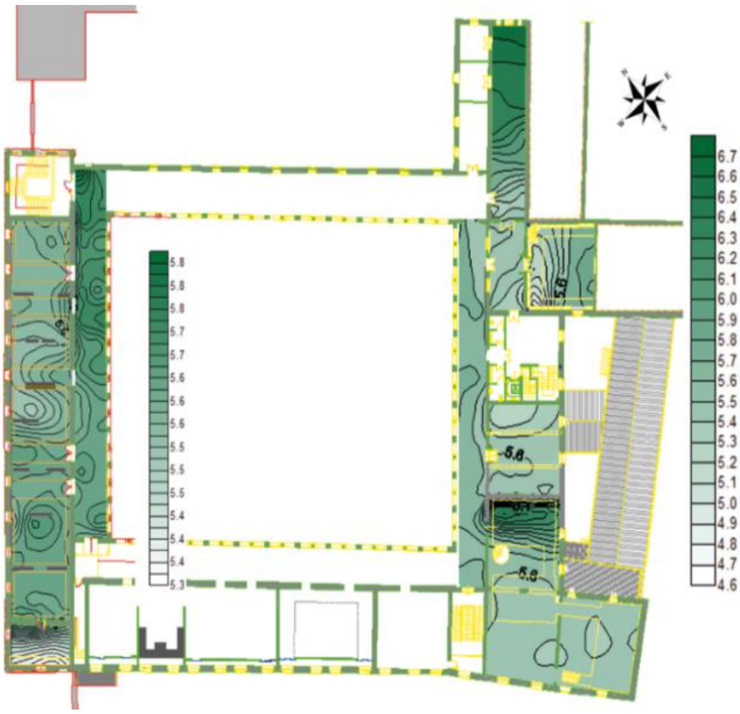

Fig 4.33 – First floor Specific Humidity map from the 9.30h measure, from the February 4th, 2015, survey.

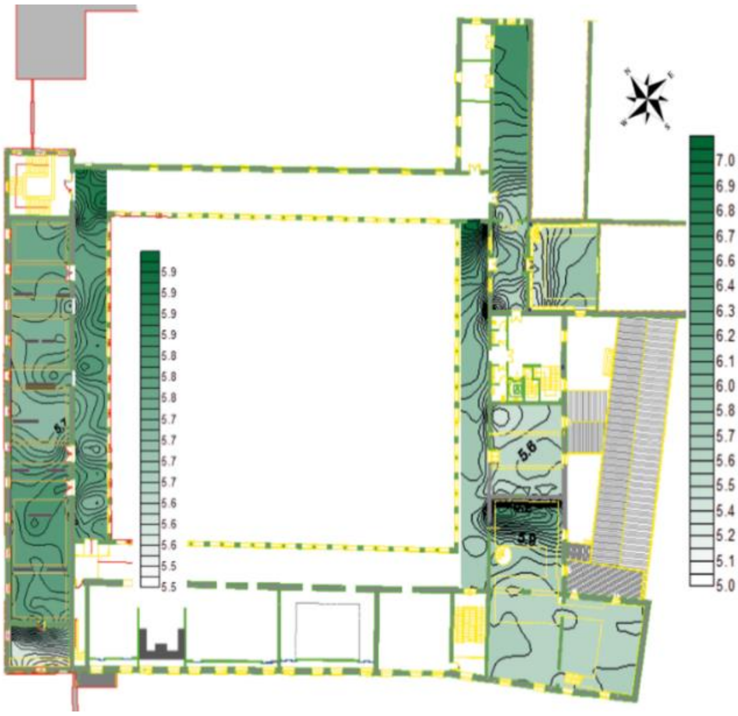

Fig 4.34 – First floor Specific Humidity map from the 16.30h measure, from the February 4th, 2015, survey.

On the 1st floor the differences between the rooms where the heating is turned on and the others, like the corridors, are very accentuated. It is easy to notice, in figures 4.29 and 4.30, the heating flow through the walls in the rooms from the east side, where the isolines are much closer to each other, indicating a quick change of temperature. Between the heated room in the east and the corridor, there is a difference of approximately 10ºC. However, on the west side the temperatures do not vary as much, being the average values of 10.5ºC.

The maps of RH (figures 4.31 and 4.32) and specific humidity, SH, (figure 3.33 and 3.34) are very similar, the higher temperatures also correspond to the lower percentages of moisture. As in the ground level, in the places where the heating is off, the percentage of moisture is dangerously high compared with the heated rooms, where, in this floor, the average of percentage is 40 or 50%, a value that is perfect for the conservation of the historic surfaces. Both morning and afternoon measurements are very similar.

4.4.3. Gravimetric test

4.4.3.1. Introduction

The collection of the samples took place on November 11th, 2015, March 24th and June 16th, 2016. The gravimetric test has the purpose of measuring the water content in the masonry, being an effective test to validate any conclusions taken in the thermography test.

4.4.3.2. Applied Procedure

First of all, it is important to try to be as most delicate as possible, so the depth of the samples taken from the masonry is always the same. Besides that, it is also important to collect homogeneous samples so they can be compared correctly in their different environmental conditions.

The procedure involves the use of a chisel to collect 2 to 3 grams of plaster and mortar. However, to do withdrawals in depth, it is needed a drill, equipped with a tip with 12 mm diameter and 40 cm length, which was chosen according to the type of material. To cause the minimum influence in the state of the samples, the drill bit has to be replaced every time it gets warm. The heat of the equipment can cause the alteration of the hygrometric characteristics of the specimen and change completely the results. [27]

Small polyethylene containers with pressure cap are used to store the dust collected from the drills.

The water content measurement is made by double weighing the sample; in the moment of the withdrawal and after being dried in a thermobalance.[27]

Concerning to historic mortars, the most common in ancient buildings is lime mortar, which is characterized by the low percentages of physically bound water, with values of absorbed water lower than 1% w/w, and a relatively low percentage of structurally bound water, with values above 3 % w/w. Their total porosity is higher than 30%, while their tensile strength does not exceed 0.35 MPa. [46]

As for porous materials, as mortar and lime, the percentage of water of the dry material is close to 1-3%, depending on the method chosen to measure the water content in the wall, it is usual to set a maximum limit for water content. By using the gravimetric test, in Diocesan Museum, it was defined the limit as 5%, due to the interference of the procedure techniques, as for example the heating caused by the drill when extracting the sample.

4.4.3.3. Equipment used

The tools used to perform this test include a thermobalance, a chisel, a drill and containers (air tight) to collect the dust. In addition, it is also used water to decrease the temperature of the drill, in order to not compromise the moisture content in the samples.

4.4.3.4. Regulations

For the gravimetric test the standards followed were UNI 11085/2003 “Cultural Heritage”, natural and artificial stone. Determination of water content: weighing method. [27]

4.4.3.5. Obtained Results

In figure 4.35 it is presented a design of the conference room in which are represented the several locations where the samples were extracted.

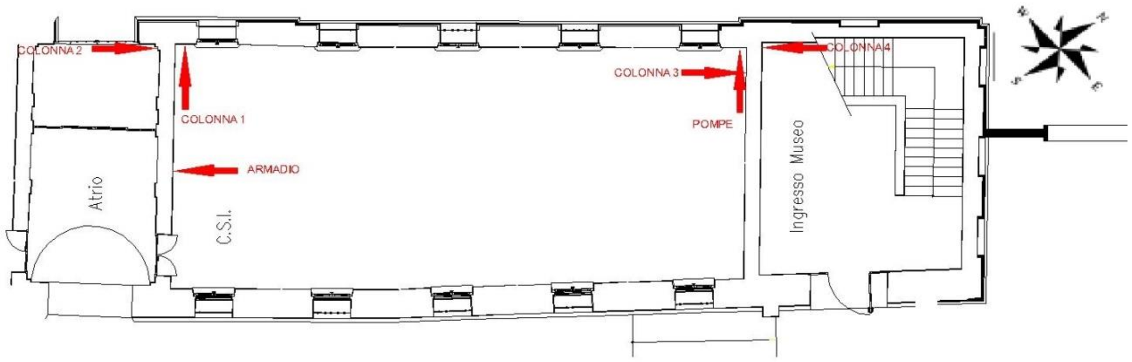

Fig 4.35 – Design of the conference room with the location of the studied points

The table 4.3 regards the results of the gravimetric test performed by Renoxa, the company that installed the SMERALDO device. The results concern to the pump column at 20, 40, 80, 60, 100 and 130 cm from the ground level. All the samples were collected from a deep hole in the masonry wall.

Table 4.3 – Results from the gravimetric test performed by Renoxa company, July 8th, 2015.

Renoxa results (08/07/2015)					
Point		H from floor [cm]	Depth [cm]	W [%]	Material
pumps	20p	20	10	7,2	Brick
pumps	40p	40	10	7,0	Brick
pumps	80p	80	10	4,4	Brick
pumps	60p	60	10	7,6	Brick
pumps	100p	100	10	2,6	Brick
pumps	130p	130	10	4,0	Brick

The table 4.4 regard the values collected by the ABC department of Polimi. The results presented include samples from the surface of each column, as well as from a profound hole. For each column, two holes where made at different heights. For column 1, 1.1 is situated at 7 cm from the floor and 1.2 at 51 cm. The holes 2.1 and 2.1 are, respectively, at 12 cm and 51 cm from the floor. In column 3, the point 3.1 is at 44 cm and 3.2 at 90 cm. The points from column 4 are at 15 cm and 65 cm. For the pump, the extractions where made from the same levels used by Renoxa. Finally, for the column behind the closet, the samples were collected from 40 cm, 80 cm and 130 cm above the ground.

Table 4.4 – Results from the gravimetric test performed by Polimi, November 11th, 2015

Polimi Results (11/11/2015)					
Points	**Wet weight [g]**	**Time [min]**	**Wc [%]**	**Dry weight [g]**	**Material**
Internal south west					
1.1 s	2,186	5,4	3,5	2,113	Lime
1.1 p	2,224	9,0	15,6	1,873	Brick + clay
1.2 s	1,456	2,2	2,6	1,421	Lime
1.2 p	2,143	5,0	8,8	1,952	brick
External south west					
2.1 s	2,485	3,0	2,4	2,427	Lime plaster
2.1 p	2,965	3,0	2,1	2,904	Brick + Lime
2.2 s	2,238	5,4	12,5	1,956	brick
2.2 p	2,079	2,2	5,5	1,969	Malta
Internal north east					
3.1 s	1,764	3,0	4,8	1,682	Lime mortar
3.1 p	2,139	3,0	7,4	1,982	Lime mortar
3.2 s	2,409	2,6	1,0	2,378	Lime mortar
3.2 p	1,796	1,4	1,5	1,765	Lime mortar
External north east					
4.1 s	2,667	3,0	4,5	2,547	Mortar
4.1 p	1,771	2,6	6,1	1,661	Mortar
4.2 s	2,741	2,6	3,3	2,649	Mortar
4.2 p	1,763	1,8	4,0	1,690	Mortar

On November 11 of 2015, despite the hole in column 2, all the values are higher in depth than at the surface (Table 4.4). As it was expected, in general the water content values are superior in the lower areas of the wall. However, again in the column 2 this do not happen. In fact, the value in the surface of the upper hole has an enormous percentage of water, especially compared with the other measurements in the same column.

On March 23rd, the samples collected correspond to the values of water content presented on table 4.5.

Table 4.5 – Results from the gravimetric test performed by Polimi, March 23rd, 2016

Polimi Results (23/03/2016)					
Points	**Wet weight [g]**	**Time [min]**	**Wc [%]**	**Dry weight [g]**	**Material**
Internal south west					
1.1 s	1,130	2,2	3,2	1,093	plaster
1.1 p	1,414	2,6	5,2	1,338	lime mortar
1.2 s	2,593	2,2	1,7	2,549	plaster
1.2 p	1,256	2,2	9,8	1,139	brick/mortar
External south west					
2.1 s	1,679	2,5	5,0	1,610	plaster
2.1 p	1,456	2,2	6,9	1,341	brick/mortar
2.2 s	1,692	1,8	3,0	1,645	plaster
2.2 p	1,995	3,4	5,8	1,871	lime mortar
Internal north east					
3.1 s	2,083	4,2	6,8	1,943	plaster
3.1 p	1,956	4,6	10,4	1,755	brick
3.2 s	1,302	3,0	1,6	1,283	plaster
3.2 p	1,768	1,8	1,1	1,750	lime mortar
External north east					
4.1 s	0,980	1,8	6,2	0,926	plaster
4.1 p	0,959	2,6	8,4	0,881	mortar/ brick
4.2 s	2,450	2,6	5,1	2,328	plaster
4.2 p	1,351	1,0	3,8	1,304	mortar/ brick
Internal north west					
pump 20 s	1,258	4,2	2,8	1,225	plaster cement
pump 20 p	2,463	4,2	9,8	2,220	brick
pump 60 s	2,084	4,2	6,3	1,056	plaster cement
pump 60 p	1,173	2,2	8,0	1,083	brick
pump 100 s	1,487	3,0	2,7	1,449	plaster cement
pump 100 p	2,143	2,6	4,4	2,055	lime mortar
Internal south west					
closet 40 s	1,452	2,2	4,7	1,386	plaster
closet 40 p	1,500	5,0	7,4	1,390	mortar
closet 80 s	1,747	2,6	5,8	1,653	plaster
closet 80 p	1,072	2,6	11,2	0,945	brick
closet 130 s	2,091	2,2	2,2	2,051	plaster
closet 130 p	1,122	1,4	2,6	1,102	brick

In general, the values in table 4.5, are above the appropriate established of 5% as limit. [46] Through all the columns the surface values are lower than the deep ones, except on column 3 and 4, on the upper hole.

In all the measurers the holes near the floor have higher percentage of water, except on the closet where the highest is at 80 cm. Except column 1, where the values decreased, all the results are higher than the previous measurement.

Table 4.6 – Results from the gravimetric test performed by Polimi, June 16th, 2016

Polimi Results (16/06/2016)					
Points	**Wet weight [g]**	**Time [min]**	**Wc [%]**	**Dry weight [g]**	**Material**
Internal south west					
1.1.s	2,539	3,0	6,6	2,374	plaster
1.1 p	1,849	2,6	8,7	1,682	brick/mortar
1.2 s	2,198	3,4	3,1	2,128	plaster
1.2 p	1,896	2,6	5,1	1,796	brick/mortar
External south west					
2.1s	2,040	3,0	3,6	1,966	plaster
2.1 p	2,006	3,4	13,5	1,732	brick
2.2 s	2,092	3,0	1,9	2,054	plaster
2.2 p	2,065	2,6	4,9	1,961	brick/mortar
Internal north east					
3.1s	2,038	3,0	6,3	1,912	plaster
3.1 p	1,814	2,6	8,0	1,669	brick/mortar
3.2 s	2,729	2,6	1,5	2,692	plaster
3.2 p	1,981	2,2	1,2	1,957	plaster
External north east					
4.1s	2,053	3,0	4,2	1,965	lime mortar
4.1 p	2,116	3,4	7,9	1,949	mortar/ brick
4.2 s	2,042	2,6	3,5	1,969	lime mortar
4.2 p	2,056	2,2	4,0	1,971	mortar/ brick
Internal north west					
pump 20 s	2,244	2,2	3,5	2,164	plaster cement
pump 20 p	2,155	3,0	7,9	1,985	Plaster cement
pump 60 s	1,751	3,0	3,8	1,684	plaster cement
pump 60 p	1,626	4,6	9,5	1,477	brick
pump 100 s	1,773	2,6	4,5	1,731	plaster cement
pump 100p	1,812	2,6	4,6	1,729	plaster cement
Internal south west					
closet 40 s	1,200	2,2	4,8	1,141	plaster
closet 40 p	2,107	3,0	9,6	1,904	mortar/ brick
closet 80 s	2,427	3,0	3,3	2,346	plaster
closet 80 p	1,525	3,0	11,9	1,344	brick
closet 130s	1,882	1,8	1,3	1,858	plaster
closet 130p	1,774	2,6	4,8	1,689	mortar/ brick

The measures made in June, table 4.6, confirm the presence of water in the walls. The lower points have higher values of water content than the above ones, as well as the samples collected from deeper holes. The column behind the closet continues to be the one with higher percentage of water content, increasing since March.

These results show that the device installed did not work as expected by Renoxa company. Instead of reducing the presence of humidity and despite the dry winter, the water content increased.

Concerning the results from Renoxa company (table 4.3), they proved out to be unclear, since the table given does not include values from the surface of the walls. However, from what it can be understood, it can be done a comparison between the results from July with the recent obtained data. Comparing the water content values from the depth of the holes it can be concluded that almost all measurements are higher than the previous one. On the pump column the water content from the lower holes is higher than in July. Contradictory, the water content at 100 cm is slightly lower than before. The same effect occurs in the closet results, at 40 cm the increase is low, however at 80 cm the value goes from 4.4% to 11.2%. As in the previous column, the water content in the higher hole decreased. Another inconsistent result is the material of the samples, despite the company has claimed that they have only worked with brick, the results from Polimi show that in the closet column the samples also included lime mortar.

4.4.4. Microclimate monitoring

4.4.4.1. Introduction

On May 2013, 16 probes were installed in several locations of the Diocesan Museum, including one in the exterior figure 4.36, placed in the first floor. This ongoing monitoring has the objective of evaluating the variations of temperature and relative humidity and compare them with the imbalances of water content on the walls. Furthermore, the monitoring helps to understand the influence of the restoration work and functioning of the air conditioning system.

The probe collecting the data inside the conference room is the one represented in figures 4.37 and 4.38 right. To the interest of this project, another probe was installed on March 24, 2016, in the exterior of the conference room with the purpose of a more correct relation with the measurements did inside this room (figure 4.38 left).

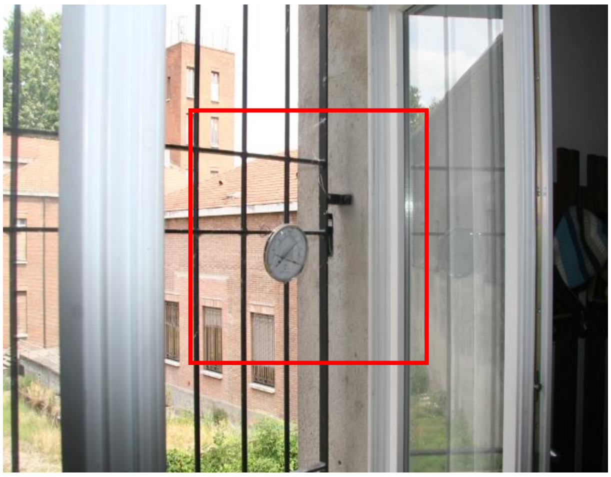

Fig 4.36 – Location of the external probe, nº4.

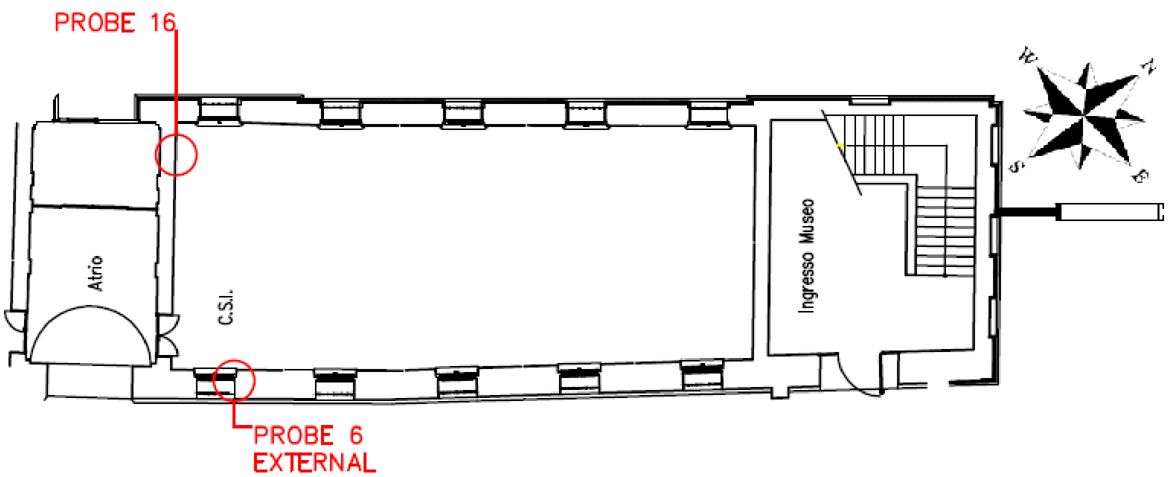

Fig 4.37 – Location of the probes 16 and 6 in the conference room.

Fig.4.38 – Visual images of the location of the probes 6 (left) and 16 (right)

4.4.4.2. Applied procedure

The probes were programed to register information every hour and obtain the maximum and minimum values in the monitored period. The results obtained give us a trend of temperature and relative humidity that can be analysed and compared with other measurements done in the room.

4.4.4.3. Equipment used

The probes used are the DATALOGGEREasylog USB-2, for temperature and relative humidity measurement range.

4.4.4.4. Regulations

The standards followed to the correct monitoring of the microclimate in the conference room where UNI 11120/2004, for measurements in the field of air temperature and the surface of the workpieces [28]. To measure the air humidity, it was followed UNI 11131/2005 [29]

Both standards where substituted and, regarding procedures and instruments for measuring humidity and temperatures, the ones used at the present are EN 16242/2013 [31] and UNI EN 15758/2010 [30]

4.4.4.5. Obtained Results

Before the refurbishment, the data from the conference room was processed with the other rooms of the museum. Comparing the values between 2013 and 2014, time where the renewal happened, it can be notice that the values in the Autumn from the first year are very instable (14-24ºC) and higher than the exterior, whereas in 2014 they remain stable and close to 20ºC. However, on October 21st, 2014, a huge sudden decrease of relative humidity happens that does not relate with any alterations of temperature in the room, except for the decrease in the exterior. After the renovation, the temperature values became more stable than before and the relative humidity went from having a range between 30 and 80% in the winter and 40 to 75% in the spring and summer, to more approximated values as 40 to 60% in the winter and 50 to 80% in the spring.

On July 7th, 2015 the data processing of the conference room started to be done separately from the other divisions of the building. The following results regard to data monitoring from July 1st to August 31st of 2015, September 1st until November 30th of 2015, November 1st until December 31st of 2015, January 1st until February 29th of 2016, March 1st to May 10th, 2016 and from May 11th to June 16th, 2016. The graphs presented concern to the average temperature for each day of the studied period, collected by the external probe, nº4, and by the probe in the conference room, nº16.

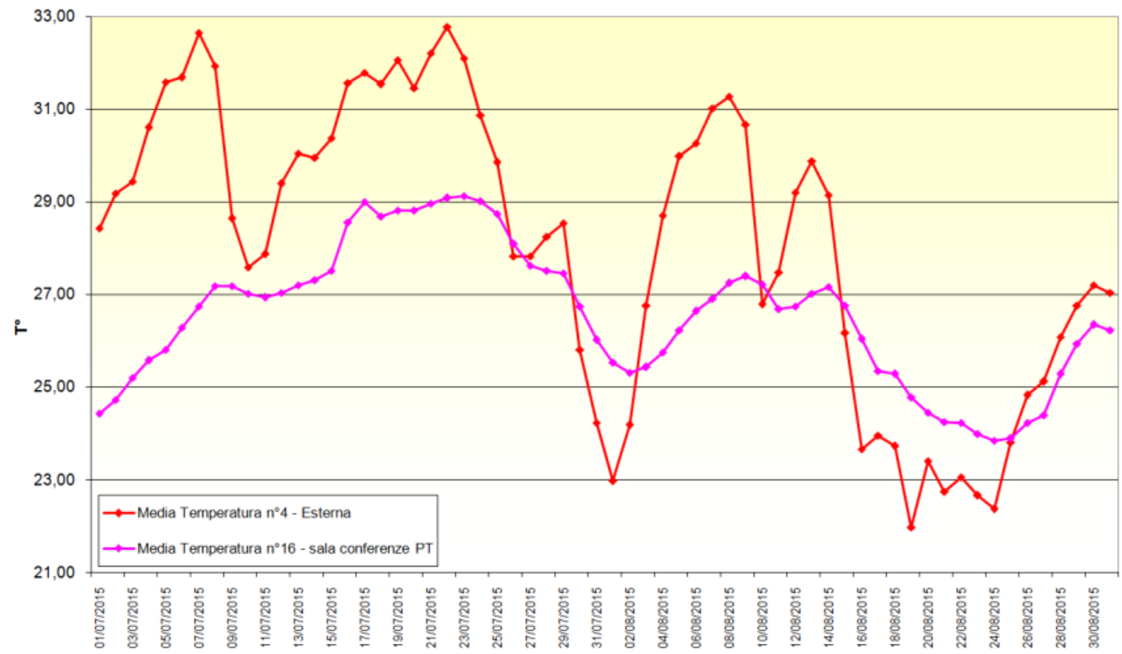

Fig 4.39 – Temperature in conference room, from July 1st to August 31st, 2015.

The temperatures inside the room are, in the majority, lower than in the exterior (figure 4.39). The daily medium values are between 24 and 29ºC. From the end of July until the first week of august, it was observed a big sudden variation. However, it is only a few degrees of difference. From the ground floor, this room was the one where the lower temperatures were registered.

In general, the variation of temperature inside de room is connected with the variation of temperature from the exterior.

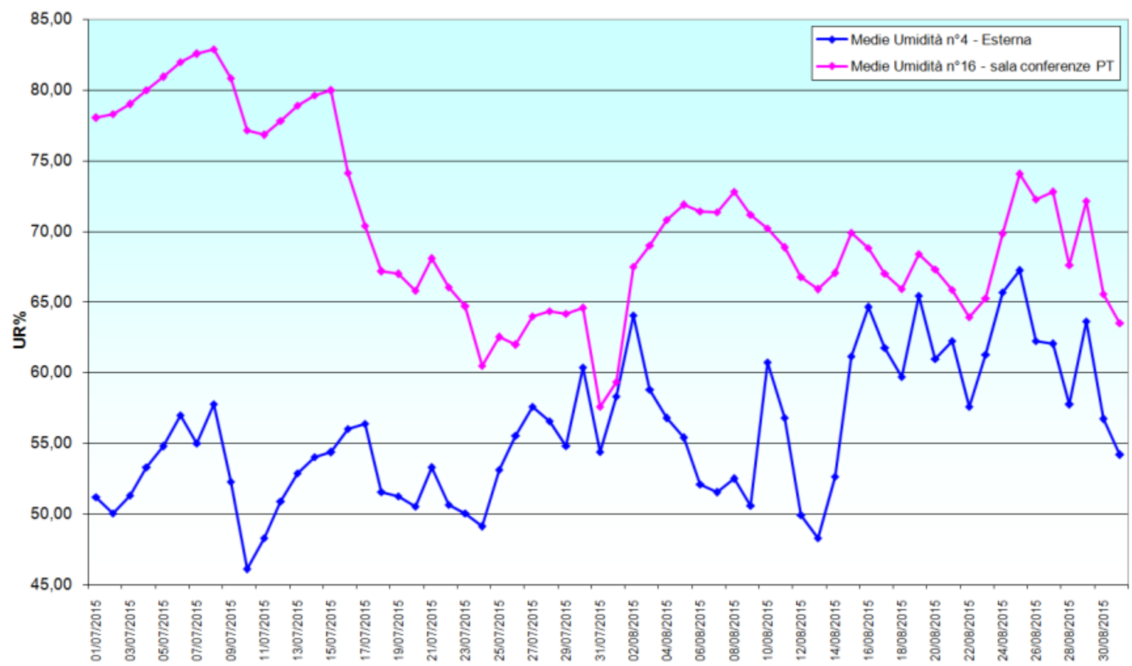

Fig 4.40 – Relative humidity in conference room, from July 1st to August 31st, 2015.

In this two months, figure 4.40, the relative humidity is between 57 and 82 %, which can be considered much higher values than the recommended for conservation of trim work.

The values are not always consistent with the exterior, which can indicate that another source of humidity is inside the room. This situation is more accentuated from 1 to 17 of July when, despite the increasing of temperature, the relative humidity keeps growing until the saturation of the air inside the room. An explanation to this situation can be the evaporation of the water content on the surfaces of the masonry affected by the rising damp. This trend is visible until the end of the moth, time when the humidity drops approximately 8% and stablishes an interconnection with the external values, especially from august 16 and forward, the variations are extremely similar.

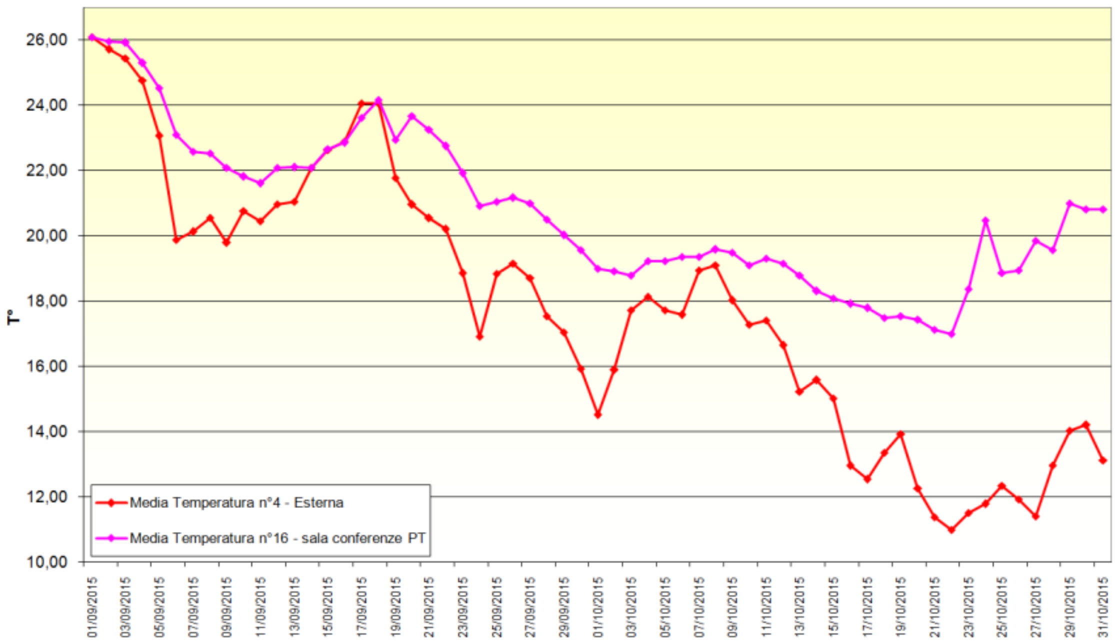

Fig 4.41– Temperature in conference room, from September 1st to October 30th, 2015.

The temperatures from the inside of the room, figure 4.41, are always higher than the external values, but consistent with them. From the beginning of September to October 22nd, the temperatures decrease slowly 9ºC, from 26 to 17ºC. In the following week the interior temperatures increase, probably due the starting of the heating.

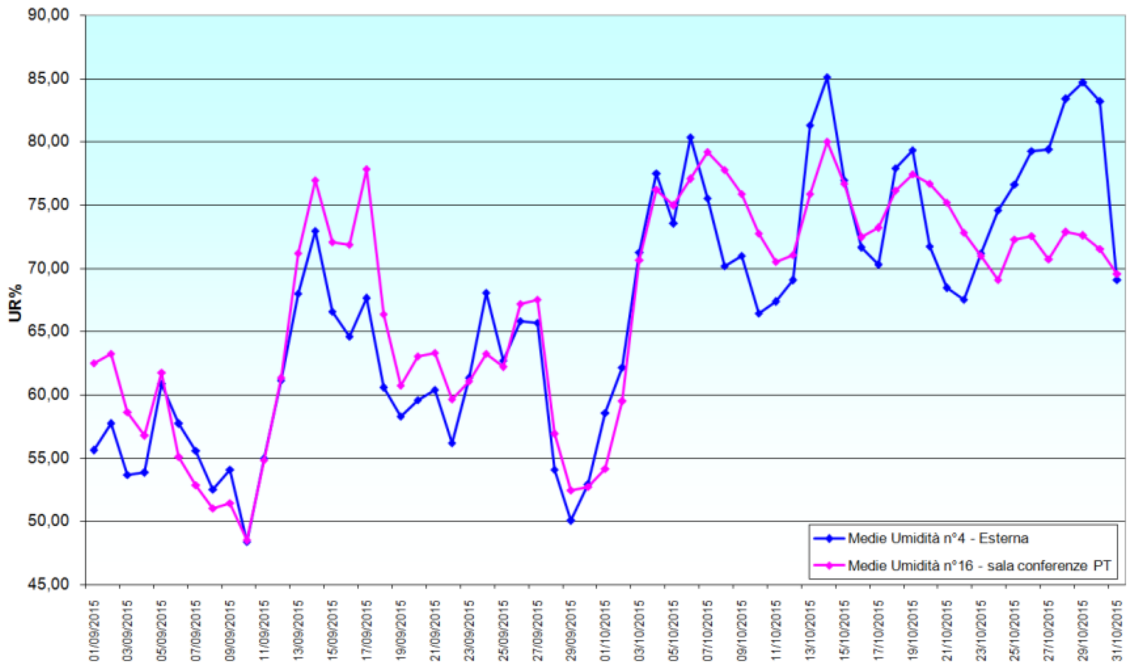

Fig 4.42 – Relative humidity in conference room, from September 1st to October 30th, 2015.

As can be seen in figure 4.42, both values, interior and exterior, are extremely connected in this moth, especially until October 17th. The probe installed inside, registered several large variations, the most sudden in the middle of September, approximately of 30%.

The average values are between 47% and 80%, being the higher values measured in October.

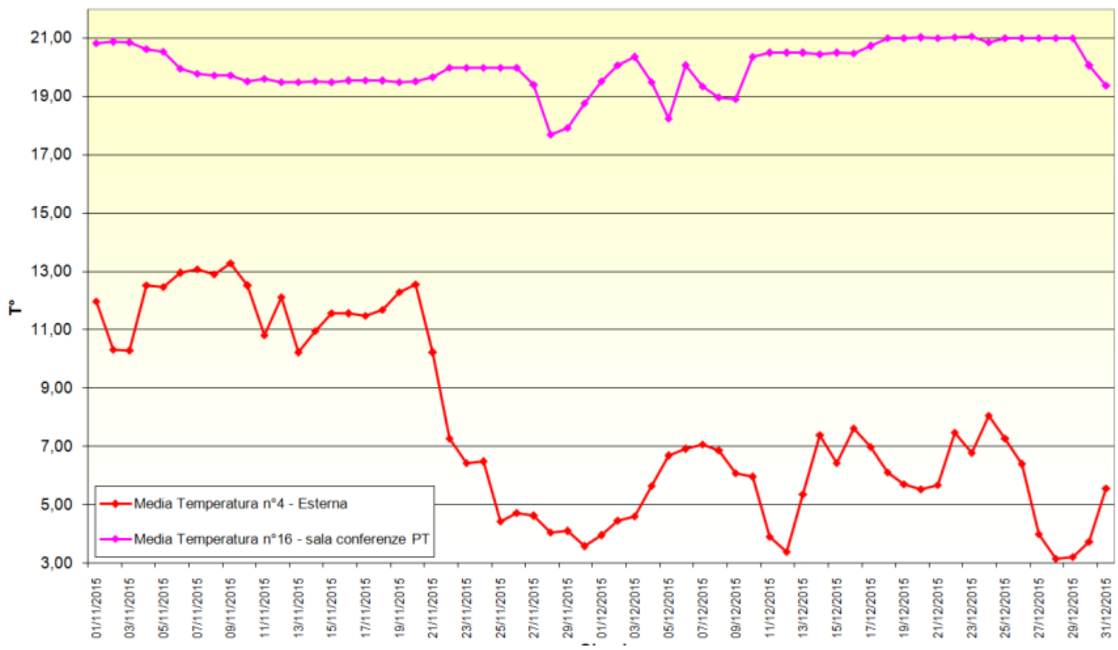

Fig 4.43 – Temperature in conference room, from November 1st to December 31st, 2015.

The trend along the two months is almost steady, figure 4.43, varying between 20 and 21ºC, except in the last week of November and the first of December, when were registered three small decreases of 2ºC.

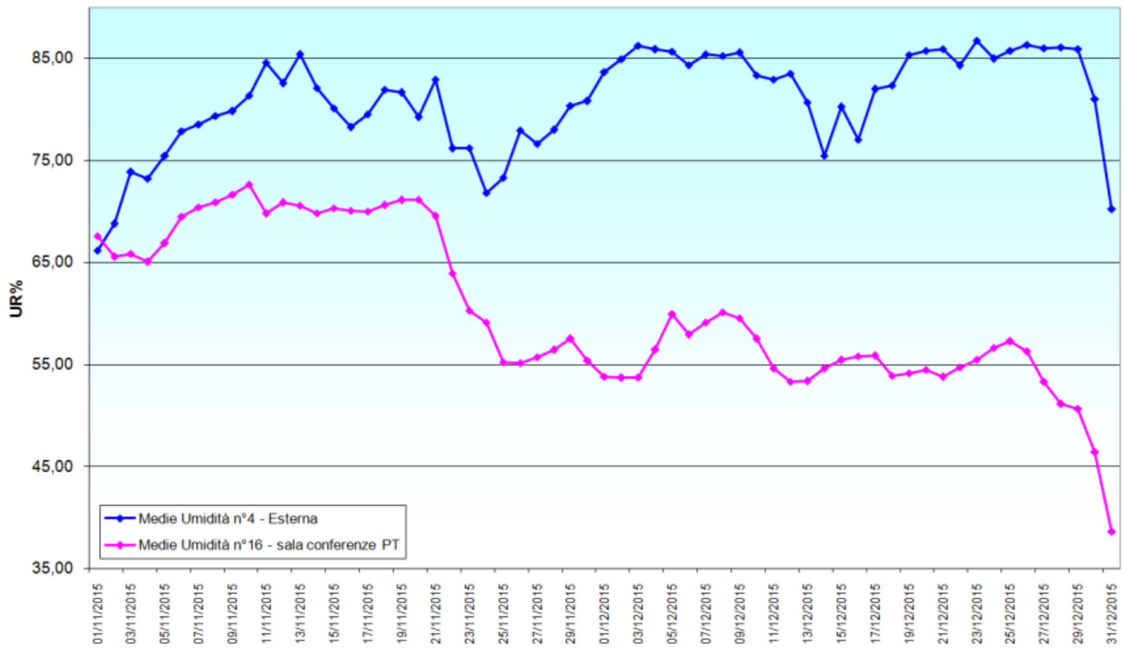

Fig 4.44– Relative Humidity in conference room, from November 1st to December 31st, 2015.

Through both months, the relative humidity is lower inside the room, figure 4.44. The values are steady at 70% until November 21, when it decreases 15%, staying approximately constant at 55% during the rest of the analysed time.

The external values do not influence the relative humidity in the room.

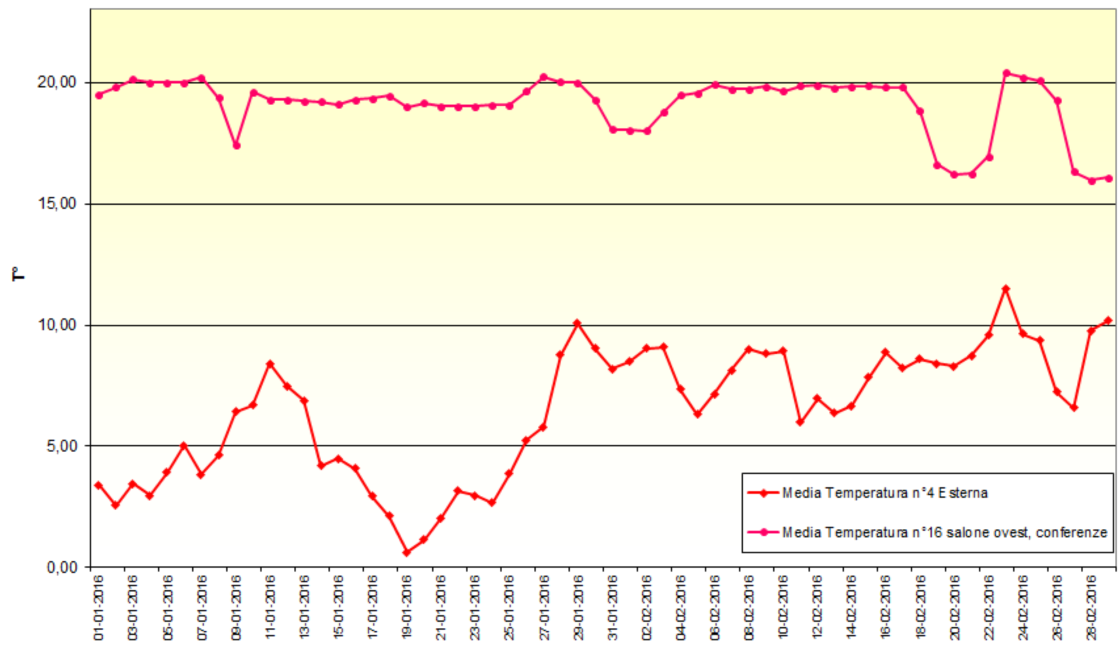

Fig 4.45 – Temperature in conference room, from January 1st to February 29th, 2016.

The interior temperature, figure 4.45, is almost stationary through the two months, the variation being between 19 and 20ºC. In the last week of February, the probe registered some variations of 4ºC with short duration.

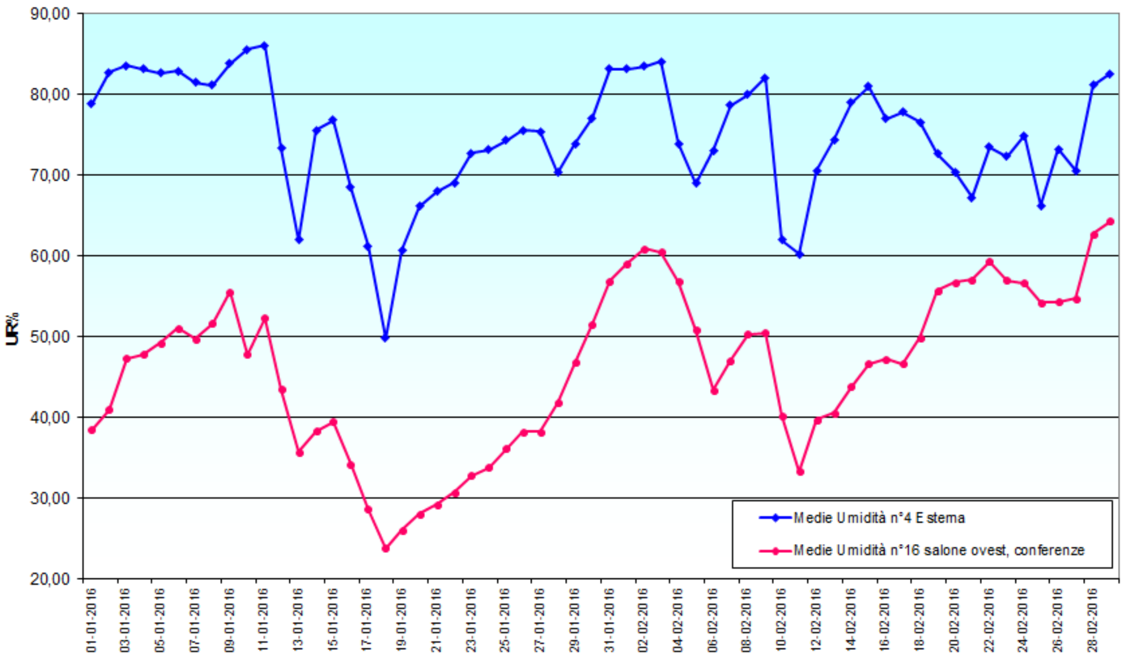

Fig 4.46 – Relative Humidity in conference room, from January 1st to February 29th, 2016.

The values of relative humidity are comprehended between 24 and 65% in all the analysed period, figure 4.46. Variations are interconnected with the external values measured. In the middle of January, a sudden decrease of relative humidity is registered as well as in the middle of February, more specifically from 10 to 12 of February.

Generally, the RH values are low, which can constitute a high risk of evaporation for the water content on the walls, resulting on their degradation.

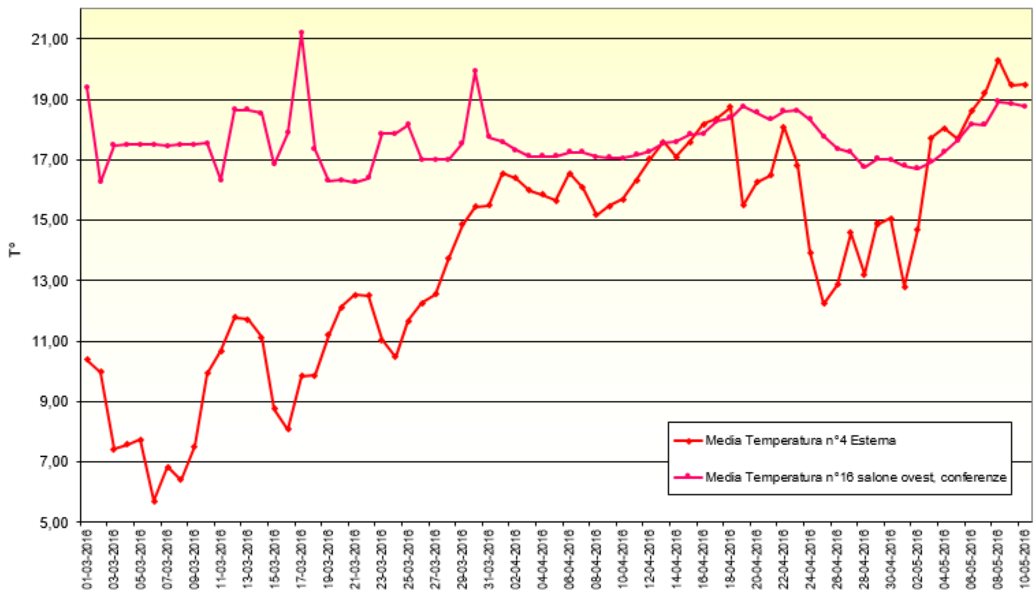

Fig 4.47 – Temperature in conference room, from March 1st to May 10th, 2016

The temperature, figure 4.47, has very steady values through the first two weeks of March, varying between 16 and 19ºC. On march 16th an increase of 4ºC is registered, followed by an extremely sudden decrease of 5ºC on March 17th.

The interior temperature is not connected with the external values, which are approximately 9/10ºC lower than the temperature in the room during March and then very much closer to the internal values during the following months.

During April and May the interior temperatures don't vary much, being the average difference approximately 2ºC.

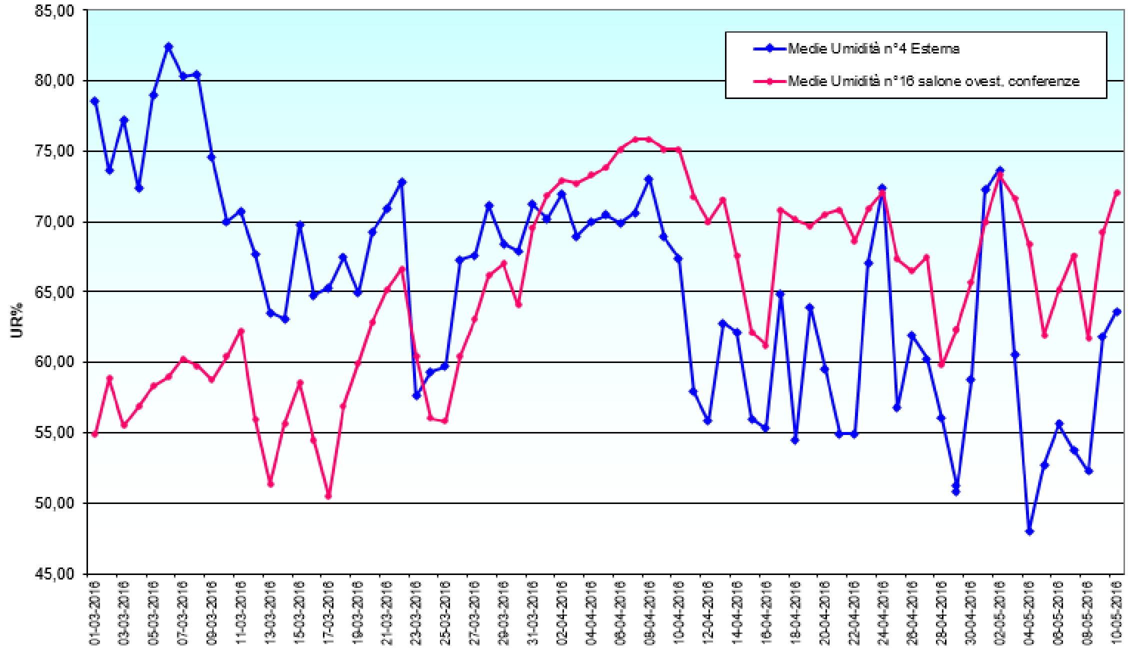

Fig 4.48 – Relative Humidity in conference room, from March 1st to May 10th, 2016

The room's relative humidity, figure 4.48, is under the external values through the entire month of March, however, in the following moths it gets higher. Both trends are interconnected, especially in March. The variation on March 17th is consistent with the pic of temperature described before. On March 22nd a decrease of 20% is registered by the probe, consistent with the simultaneous reduction of the external values. Despite the decrease of the external values on April 22nd, the interior relative humidity remains almost steady, which can be explain by the steady inside temperature, that is not influenced by the exterior. The big pics throughout April and May are not only consistent to the external values but are also connected with the sudden decreases of temperature outside the museum.

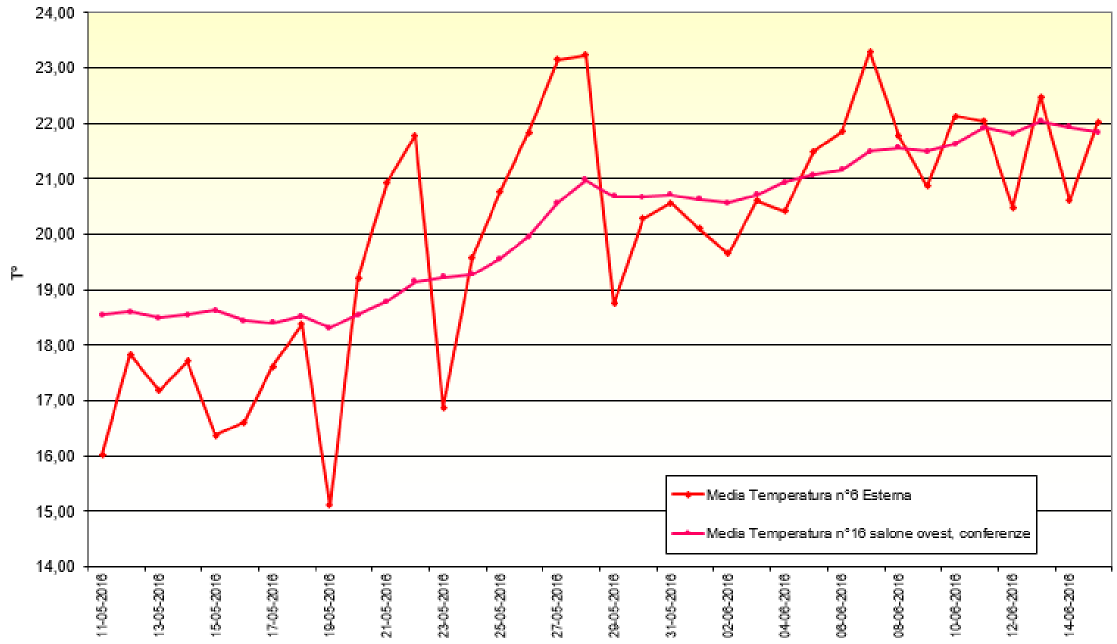

Fig 4.49 – Temperature in conference room, from May 11th to June 16th, 2016

The environmental data represented in the figure 4.49 have been registered by probe nº16, installed in March at the ground level, outside one of the window of the conference room, in the cloister. The data monitoring during this to month shows that the temperature inside the room did not suffer noticeable variations, increasing at an almost steady state from 18 ºC to 22ºC. The trend of the inside values is not interconnected with the exterior one and its values are higher than the external until May 19th, during the rest of the measurement the exterior temperature have several large variations, from 7ºC to 5ºC.

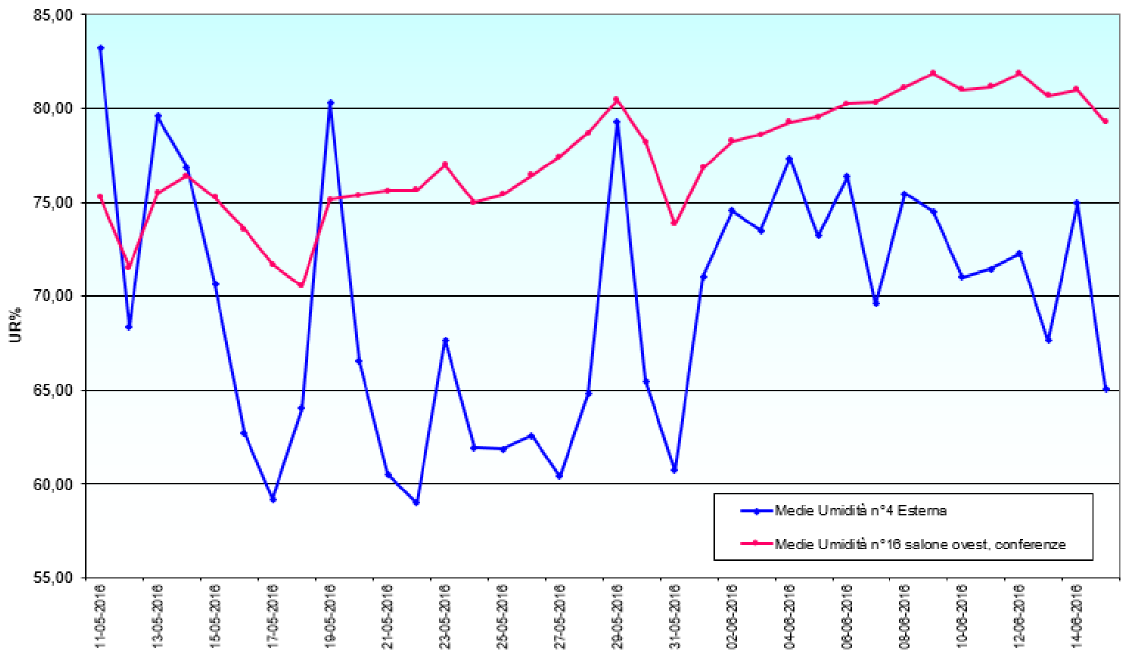

Fig 4.50 – Relative Humidity in conference room, from May 11th to June 16th, 2016

The data collected on May-June, figure 4.50, show very high values of relative humidity inside the conference room. The Relative Humidity values increased almost 30 % since the last survey, due to having turned off the heating system. The environmental variations scarcely affect the trend of RH values inside the room, only huge and prolonged changes outside influence some smoother and delayed variations inside, due to the thickness of the wall and the lack of frequent exchange with the exterior climate.

5
DEVICES AGAINST RISING DAMP

5.1. INTRODUCTION

Currently, the Italian market is filled with dehumidification devices with alternative technologies to the traditional methods. This need of creating new techniques appeared when the old procedures started being too invasive for the constructions, especially for ancient buildings in which using a method that involves changing the structure of the building could lead to a loss of the cultural heritage. Adding to that, the incredible business created around these companies have by selling the equipment to misinformed building owners and managers, plus the lower costs of setting the device comparing to the cost of a real intervention. However, some of the devices created do not have sufficient scientific background to support them, being the results usually doubtful. The devices that the companies claim to have developed, are based in the evolution of some principles of physics. The main principles that they rely on are the electro osmosis, which, in the traditional method, consists in creating an electrical potential opposite to the capillary potential by introducing a set of conductive probes that act as anodes connected to an earthed socked which acts as the cathode; radiation from the universe; the electromagnetic field; magnetic induction; vibrations of 'magneto-gravitational'; and others.

In 2013 a project, leaded by Prof. Nicola Ludwig, tested the application of several devices of this kind in ancient buildings, in order to determine their efficiency and functioning. The following devices are the ones tested during his project. [7]

5.2. EXISTENT DEVICES

5.2.1. ECODRY DEHUMIDIFICATION SYSTEM

Ecodry is a dehumidification system based on IR technology (Impuls resonance technology) (figure 5.1). Due to capillarity, the potential difference and the osmotic pressure gradient, occurs the ascension of the water inside the masonry; acting directly on the geometric structure of the molecules, these electromagnetic pulses reverse the effect of the ascent of water. Ecodry devices emit pulses of electromagnetic radio, a longwave associated with an appropriate oscillating magnetic field, and provide the individual water molecules excitation energy; the energy absorbed creates an important geometric disharmony that results in the loss of the major chemical and physical properties of the water. More specific, the pulses emitted by these devices have a characteristic frequency that is able to expand with periodic regularity of the angle between the hydrogen atoms in the water molecule. This is due to the fact that the bland magnetic field associated to these electromagnetic waves behaves as an inductor field, to which water reacts encouraging the phenomenon of precession of Larmor (i.e. when a magnetic moment is placed in a magnetic field, it experiences a torque which can be expressed in the form of a vector product, more specifically it represents the lowest energy configuration of the magnetic field). Various experiments performed led to the conclusion that water increases its diamagnetism, this happens due to distortions of electron orbitals and then the entire molecular structure.

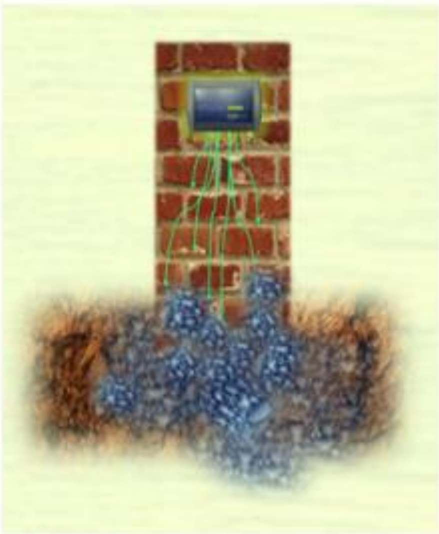

Fig 5.1 – Representation of the method of ECODRY (left); ECODRY device (right); [51]

The expected results are:

i. The inhibition of capillary rise, as the cohesion forces predominate frequently over those with adhesion.

ii. The water lost some its electrical and solvent properties, due to the salt transport, hiding the rising through saline osmosis.

After that, for the water to fall back toward the ground, dragging with it also the salts dissolved in ionic form. The elimination is not only due to the decline, but also because of the evaporation.

The magnetic field is generated inside the wall structure and must be properly addressed and calibrated according to the constituent materials of the wall. This is not harmful to people and does not require an invasive intervention during the installation.

5.2.2. Kalibra dry system

Kalibra dry system, figure 5.2, is a new technology of dehumidification of the environment that part of the electromagnetic field study, which depends on the gravity force and the electric and magnetic repulsion force in the water. By appropriate circuits, which are released into the environment by an apparatus placed directly on the walls, the emission of a weak magnetic field inductor is activated which interacts with the electromagnetic field inducing magnetic dipoles of water, creating a further electromagnetic force repelling the dipoles of water in the soil. For this to happen it is necessary to maintain an induced magnetic field that interacts with water dipoles, localized in the ground and in the masonry, having a hardware configuration that enables the device to power the field required and without the necessity of a faraday cage. The device is installed inside the building to a height equal to the maximum level of visible moisture. The intervention is non-invasive and completely reversible.

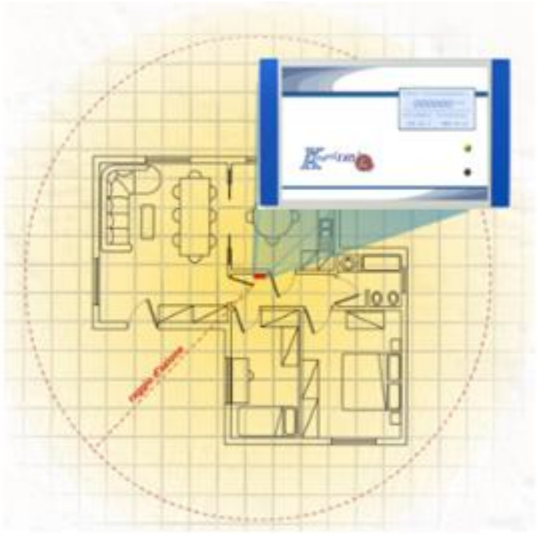

Fig 5.2 – Representation of Kalibra [52]

5.2.3. Kappa 3000

Kappa 3000 is a magnetic inductive system who can counter, using radio frequencies, the potential flow of the water molecule combined with salt ions. The walls start to get rid of moisture excess, with the advantage of percolating also the salts into the ground, now in liquid form, avoiding the crystallization.

5.2.4. Primat Mur Tronic

Primat Mur tronic is a dehumidification system non-invasive, does not in fact have the need of using any type of material in the wall, not even the help of external power supply. The system is composed of a high sensitivity passive electronic circuit incorporated in an insulating resin, which gets the necessary energy for its operation from the electronic fields present in the natural environment. Once installed reacts against the natural magnetic field creating an electromagnetic field identical to the one that generates, according to the Lenz Law (the time variation in a magnetic field generates an electromotive force which contrasts with the variation).

5.2.5. Aquapol

Aquapol is a completely non-invasive device, does not require use of electricity and does not develop electromagnetic fields. It is a device composed of an electrical conductor equipped with a reel spool twisted, inserted in a container: the inner coil is a wound in a spiral with increasingly smaller diameter. The cone-shaped device is composed of receiving and transmitting antennas made of a non-perishable material, does not have electrical parts and is able to pick up with these antennas, vibrations of ‘magneto-gravitational’ which, according to the manufacturer, are created by Earth. Inside the device it is present a biasing unit that reserves the direction of waves picked up by the receiving antenna. Through the transmitting antennas, the energy has been polarized in the opposite direction, it is retransmitted in the environment for a certain radius action. In addition to this energy, flows in the superior part of the device, free cosmic energy. All walls, which lie within this range of action, are interested to the phenomenon of deviation flow of water present in the interior of the wall to the basement. The moisture tends to rise in the wall by capillary action, as explained in the previous chapters. After the installation of the device, the water molecules go down and the wall starts to dry. The action of this instrument is based on the fact that through certain magnetic fields and frequencies, in a high frequency of the microwave field in the porous materials, the force of adhesion between the molecules of the material and the moisture it is disturbed, leading to a decrease of the moisture spectrum.

5.3. COMPARISON OF THE RESULTS

According to what was explained, it can be said that, this new devices work based in the same principle, that the rising damp problem is due to a potential difference in the electric field inside the pores of the materials. Despite the unclear functioning and physical explanation by the companies, in general, the solutions presented by the manufactures are based in the principles of active electric osmosis or the compensation of charges.

The results obtained in Ludwig's search, by the application of diagnostic tests, in the several ancient buildings, where the devices were installed, lead to the conclusion that, in general, the water content decreased since the beginning of the study. However, it was not clear, for some of them, if the reason was due to the devices or to environmental reasons, as in some cases there were not done measures of water content before the installation of the devices, nor collected data about the environment.

Aquapol, resulted in clear diminution of water content, however, it is not possible to be sure if the reduction is not due to the dry climate outside, as the exterior temperature and relative humidity were not registered. In addition, some of the surveys where done one year apart. Without knowing the variations of the microclimate it cannot be done a correct diagnosis about the reason for the decrease of water content.

5.4. DEVICE IN DIOCESAN MUSEUM

To decrease the moisture content in the conference room of the Diocesan Museum it was installed the SMERALDO^{88TM}, a device manufactured by Renoxa (figure 5.3).

The SMERALDO^{88TM} device is based on Gauss' theorem, which states that the flow of the electromagnetic field through a closed surface or volume depends only on the internal charges to the surface. It is a reservoir of these charges, that are responsible for interrupting the water from going upwards and promoting drying of the wall by evaporation and absorption by osmotic effect of other water and mineral salts. [21]

The information given by the company does not allow to take any conclusion about the principle of the machine. Not only it was given a file in which the principles are a poor translation of an English document, but also it contains several physical errors. « The canaliculi in which occurs the rising capillary action are very few compared to the percentage of porosity of building materials value but are distributed widely throughout the material , for which they are able to ensure that the entire solid phase (wall) to behave like a vehicle the canaliculi are more as high thin note is the ascent to the phenomenon of communicating vessels : this migration occurs through all the constituents of the canaliculi porosity and not affected by capillarity . Boost inside canaliculi due to the electronic noise of eddy currents creeps water and the salts dissolved in it.». This affirmation taken from the brochure of Smeraldo88TM claims that the water rises on the wall due to the principle of the communicating vessels, which is not true, as it is currently known that the reason is the capillarity. Communicating vessels are two or more containers open at the top and interconnected, in a way that a fluid can flow between them. When this vessels, with diameters large enough to negate the capillary effect, are filled with the same fluid, its levels are of the same height regardless the shape of the vessels. As the capilars in the masonry are too thin to apply this effect, the principle does not work here, is the capillarity explained in chapter 2 that is the cause for the rising of the water. Another error in this extract and throughout the text is the reference to ‘noise’ as an element that influences the functioning of the device, however, physically ‘noise’ is something that cannot be considered in the measurements.

Another incorrect reference is the fact that the salts are said to be suspended, but it does not say where they are suspended. Also the explanation given for the delamination of the plaster is that the salts go to the surface searching for water, which is not the correct description of the process.

The presence of salts in the water content is a factor that influences the degradation of the walls, because when the salts crystallise, there volume increases, which leads to a higher pressure in the vessels walls and a consequent degradation in the material. [10] This problem has even worst consequences if the material is submitted to a crystallization and dissolution cycle.

In conclusion, among many confusing information, the company does not give a reliable explanation for the working principles of the device or even a description of the components inside the metallic frame that can be seen by the eye. That way, the decision on the functioning of the device is only based on the data collected in the conference room.

Fig 5.3 – Smeraldo device inside the conference room.

6
CONCLUSIONS

The conclusions resulted from this project focus in three areas: the application of gravimetric test and microclimate monitoring in addition to the infrared thermography method, the diagnosis of Diocesan building and the application of the non-invasive devices studied to stop rising damp.

Performing the gravimetric test as a confirmation of the diagnosis obtained in the thermographic procedure gives a reliable validation of the presence of water or not.

However, the application of the gravimetric test has its disadvantages. The first one is the fact that it is a destructive test. As the study concerns to an historic building, the necessity to extract several samples from the wall to measure the water content was not a positive aspect regarding the preservation of the cultural heritage. In addition, the procedure itself has some problems, as, for instance, the heating of the drill with which the sample is collected. The contact of this equipment with the dust taken from the wall dries the sample and influences the result, which translates in a lower value of water content than the real percentage present in the wall.

The precision of the procedure was compromised due to the fact that the masonry structure of the building comprehends an arrangement of bricks with different sizes and shapes and with a non-symmetrical organization, that is typical from fourteen century buildings. Adding to that fact, the very constitution of this bricks is inhomogeneous. Therefore, it was difficult to collect the same material in every sample and the different hygroscopic characteristics of these materials can alter the results registered by the thermo balance. Thus, the comparison between samples from different holes may have been impaired because, the exact characteristics of each sample are unknown, as well as their state of degradation.

Nevertheless, it remains the only method to have water content measurements, under standard, feasible and at a low price.

The monitoring of the temperature and RH was essential for the study of thermograms and comprehension of the microclimate inside the room. As an addition to thermography, the monitoring of the microclimate, is helpful to set the temperature parameter for the process of the thermograms and to understand how the evaporative flux variations are connected with the microclimate in the room, and consequently with the surface temperature.

To perform the IRT method it is extremely important to understand the exchange of heating between the building and the surrounding environment. Thus, the analyses of the thermograms must be done considering all the information regarding the heating of the room, the RH, solar radiation, etc. In the conference room, during the winter months, the heating system was on, however, this did not result in an inhomogeneous heating of the surfaces. Knowing that the temperature was high and the RH low, it was possible to connect the cold surfaces in the lower part of the walls to the increase of evaporative flux of the water content inside the masonry.

Regarding the diagnosis of Diocesan museum, after analyzing the data collected, it could be concluded that the reason for the degradation of the walls is rising damp and high air humidity and its variations. The source of this problem is believed to be the lack of draining system for the rain water. The water infiltrates in the soil due to the penetration of the exterior draining pipes in the ground and, as the foundations are not protected against the water and are made of such a porous material as masonry, the water rises by capillary. The result are the visible stains present in the covering plaster in the interior walls of the conference room and the high RH level in the exterior and interior of the room, that has much higher levels than the adequate for conservation of materials and for human comfort.

The appearance of a colder stain at 2 meters from the floor in the northeast wall were concluded to be caused by the presence of salts [48]. During the refurbishment of the room, the plaster was only changed until 2 m from the floor, leaving in the upper part, old plaster that was under aggressive agents for many years.

After the study of the values collected by the probes in the conference room it can be concluded that the values of RH are higher than the 55% favorable for the preservation of materials [26], as they are in most of the months higher than 70%. As for the temperature, in the winter months where the heating is turned off, the temperatures do not suffer high variations, being the average approximately 20ºC. On the other hand, between July and August, the temperatures can reach maximums of 29ºC, and often suffer large variations harmful for the materials [26]. In addition, the study of the microclimate in the museum allowed to detect situations where the values of relative humidity were high inside the conference room, although the conditions in the exterior where low RH and high temperatures. Therefore, the conclusion is that a source of water vapour was present in the room, most likely to be a result of the evaporation of the water content present in the walls.

Accordingly, with the conclusions taken from the study of the building, and more specifically the conference room, the suggested refurbishment measures are, for instance, the correction of the downspouts, separating them from the soil and altering their drain to the municipal sew system for rain water. Another intervention that should be done is creating a space, with air flow, between the walls and the soil, which is a traditional technique, that is successful also at the present. The extraction of the salts from the plaster is a solution that should be done after stopping the rising of the water. Although it relies in a technique that takes a long time to process, the results in the conservation of the materials of the walls can show significant differences.

Finally, concerning the SMERALDO device. Although the physic principals of the equipment where not completely understood, by comparing the water content values in the conference room, the conclusion is that it did not work. Throughout the months of study, there was not a generalized decrease of water content in the walls of the conference room. In fact, almost all the values increased since the first measurement and the slightly decrease between some of them can be explained by the dry winter of 2015/2016.

Despite the results, from the installation of this devices, are almost never favorable, there market continues to increase. First, the installation of this kind of solution is much more affordable then a full refurbishment of the buildings and secondly, for a person who is not familiar with the concept of moisture and capillary it is easy to believe in the facts and common explanations given by these companies, although they are not physically correct.

BIBLIOGRAPHIC REFERENCES

[1] Franzen, C., Troi, A. *Position Paper on Criteria regarding the assessment of energy efficiency measures regarding their compatibility with conservation issues*. European commission DG research and Innovation. 2014.

[2] Camuffo, D. *Microclimate for Cultural Heritage.* ELSEVIER, 1998.

[3] Togkalidou, T, Moropoulou, A., Karoglou, M., Padouvas, E. & Chandakas, B. *System for conservation management of Historic Buildings incorporating quality control principles*, Proc. Innovative Technologies and Materials for the Protection of Cultural Heritage. Industry, Research, Education: European Acts and Perspectives, Technical Chamber of Greece, Athens, Greece, 16-17 December, 2003.

[4] Bosiljkov, V., Uranjek, M., Žarnić, R., Bokan-Bosiljkov, V. An integrated diagnostic approach for the assessment of historic masonry structures. In *Journal of Cultural heritage,* Volume 11, Issue 3, pages 239-249, July–September 2010. ELSEVIER

[5] Barreira, E., Almeida, R., Delgado, J. *Infrared thermography for assessing moisture related phenomena in building components.* Construction and Building Materials. 2016. pages 251–269. ELSEVIER.

[6] prEN 16682. *Conservation of cultural heritage - Methods of measurement of moisture content, or water content, in materials constituting immovable cultural heritage.* European Committee for Standardization.

[7] Rogora, F. *Risanamento di ambienti di interesse storico-artistico dall'umidità. Confronto di nuove tecnologie, case applicativi in área lombarda*. Master Thesis, Università degli studi di Milano, 2013.

[8] Camuffo, D. *Microclimate for Cultural Heritage.* ELSEVIER, Amsterdam, 2014.

[9] Sansonetti, A., Rosina, E., Ludwig, N, *Moisture Damage. New tools for the protection of cultural heritage on Italy: Innovative Techniques for In-situ Diagnosis*. Materials Evaluation, January, 2011, pages 41-46, The America Society for Nondestructive testing, Columbus, Ohio.

[10] Freitas, V., Torres, M., Guimarães, A. *Humidade Ascensional*. FEUP edições, Porto, 2008.

[11] Rosina E., Ludwig, N. *Optimal thermographic procedures for moisture analysis in buildings materials.* Dipartimento di Conservazione e Storia dell'Architettura, Politecnico di Milano, www.brera.unimi.it

[12] Barreira, E. *Aplicação da Termografia ao Estudo do Comportamento Higrotérmico dos Edifícios*. Dissertação de Doutoramento, FEUP, 2004.

[13] Cortizo, E., Barbosa, M., Souza, L. Estado de Arte da Termografia. In *FÓRUM PATRIMÔNIO– Ambiente Construído e Patrimônio Sustentável*, Volume 11, Issue 3, pages 158-193, May - August 2008. Belo Horizonte.

[14] http://www.mech.hku.hk/bse/MEBS6006/DencoCH1.pdf. 20/05/2016

[15] Jones, T., Kaplan, H. Fundamentals of Infrared and Thermal Testing: Part 1. In *Non-Destructive Testing Handbook: Infrared and Thermal Testing.* pages 32-39, Columbus, Ohio, 2001.

[16] Maldague, X. Fundamentals of Infrared and Thermal Testing: Part 2. In *Non-Destructive Testing Handbook: Infrared and Thermal Testing.* pages 40-46, Columbus, Ohio, 2001.

[17] Weil, G. Infrastructure and Conservation Applications of Infrared and Thermal Testing: Part 1. In *Non Destructive Testing Handbook: Infrared and Thermal Testing.* pages 602-605, Columbus, Ohio, 2001.
[18] Okamoto, Y. Infrastructure and Conservation Applications of Infrared and Thermal Testing: Part 2. In *Non Destructive Testing Handbook: Infrared and Thermal Testing.* pages 609-612, Columbus, Ohio, 2001.
[19] Grinzato, E., Rosina, E. Infrastructure and Conservation Applications of Infrared and Thermal Testing: Part 5. In *Non Destructive Testing Handbook: Infrared and Thermal Testing.* pages 624-646, Columbus, Ohio, 2001.
[20] Glicksman, L., *Air Water Vapor Mixtures: Psychrometrics* MIT, 2010
[21] Smeraldo[88] , *Scheda lavoro per installazione e controlli*. Renoxa, 2015
[22] Zivcàk, J., Madarsdsz, L., Hudák, R., Rudas, I. *Methodology, Models and Algorithms in Thermographic Diagnostics*. Springer, Berlin, 2013.
[24] Moropoulou, A, Delegou, E., Avdelidis, N. P., Athanasiadou, A., *Integrated diagnostics using advanced in situ measuring technology*. 10DBMC International Conférence On Durability of Building Materials and Components, France, April 2005.
[25]http://www.brescianisrl.it/newsite/ita/xprodotti.php?sub_content=20&sub_prodotto=47&hash=bf021ea37d4f9c09c1297fbfb54b3c57, 26/05/2016
[26] UNI 10829/99 - *Goods of historical and artistic interest. Environmental Storage: Measurement and analysis.* ICS : [91.120.01] [91.120.99] [17.180.20] [17.200.99]
[27] UNI 11085/2003 - *Cultural heritage. Natural and artificial stones: Moisture content determination. Gravimetric method*. ICS : [91.100.15]
[28] UNI 11120/2004 - *Cultural heritage: Measurement in the field of air temperature and the surface of the workpieces*
[29] UNI 11131/2005 - *Cultural heritage: Measurement in the field of air humidity.*
[30] UNI EN 15758/2010 - *Conservation of Cultural Property - Procedures and instruments for measuring temperatures of the air and the surfaces of objects.* ICS : [97.195]
[31] EN 16242: 2013 - *Conservation of cultural property: Procedures and instruments for measuring humidity and vapor exchange between the air and the cultural heritage.* ICS : [97.195]
[32] ISO 760:1978, *Determination of water — Karl Fischer method (General method)*
[33] Park, S. *Holding the Line: Controlling Unwanted Moisture in Historic Buildings.* Preservation Briefs – Technical preservation services. www.nps.gov. 2/06/2016
[34] Moyers, C., Baldwin, G., *Psychrometry, Evaporative Cooling, and Solids Drying*. The Macgraw Hill Companies, 1999.
[35] EN 13183-1:2002 - Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method [ISC 79.040]
[36] EN 772-10:1999 - Methods of test for masonry units - Part 10: Determination of moisture content of calcium silicate and autoclaved aerated concrete units
[37] https://weather-and-climate.com/, 12/05/2016
[38] Theodorakeas, P. Cheilakou, E., *Passive and active infrared thermography: An overview of applications for the inspection of mosaic structures*. 33rd UIT Heat Transfer Conference, At L'Aquila, Italy, 22-24 June, 2015
[39] Barreira, E., Freitas, V, Delgado, J., Ramos, N., *Thermography Applications in the Study of Buildings Hygrothermal Behaviour*, Faculty of Engineering, University of Porto

[40] Mecklenburg, M., Tumosa, C., *Temperature and relative humidity effects on the mechanical and chemical stability of collections.* ASHRAE Journal, April 1999.

[41] http://www.msc-sahc.org/upload/docs/new.docs/2011_cmeehan.pdf

[42] L. Capineri, D. Capitani, U. Casellato, P. Faroldi, E. Grinzato, N. Ludwig, R. Olmi, S. Priori, N. Proietti, E.Rosina, R. Ruggeri, A. Sansonetti, L. Soroldoniand M. Valentin, *Limits and Advantages of Different Techniques for Testing Moisture Content in Masonry*. Materials Evaluation, January, 2011, pages 112-116, The America Society for Nondestructive testing, Columbus, Ohio.

[43] Marca, G., *Consulenze geologiche e ambientali*. *Studio geologico-tecnico. Parte prima – relazione geologica generale,* Comune di mantova-Direzione sviluppo del territorio e tutela dell'ambiente, November 2012

[45] Fabozzi, G., Rosina E., *Vicenze edilizie, stato consistenza e indicazioni per il restauro di corte castiglioni a casatico, Mantova*. Facoltà di Architettura, Politecnico di Milano, 1998

[46] Moropoulou, A., Bakolas, A., Anagnostopoulou, S., *Composite materials in ancient structures* ELSEVIER, 2004

[47] Vitruvius, M. Amati, C. *Dell' Architettura*, Milano, Giacomo Pirola, 1829

[48] Sawdy, A, Price, C., *Novel approaches to the control of salt damage.* Archaeology international, 2004

[49] Barreira, E., Freitas, V., *Evaluation of building materials using infrared thermograph*, Constr. Build. Mater, pages 218-224, 2007.

[50] ISO 1026:1982, *Fruit and vegetable products — Determination of dry matter content by drying under reduced pressure and of water content by azeotropic distillation*

[51] http://www.ecodryitalia.it/pagine2/tecnologia.asp, 20/06/2016

[52] http://www.skm-italia.eu/KDComeSiInterviene.aspx. 20/06/2016

[53] http://www.primatsrl.it/it/sistema-mur-tronic.php , 20/06/2016

[54] http://www.aquapol.it/ ,20/06/2016

[55] Rosina. E; Spodek, J., *Moisture detection in masonry using infrared thermography: case study of the masonic temple,* vol. xxxiv, no. 1, 2003, Mount ida press, Albany (NY), USA

[56] Rosina, E., *Le analisi microclimatiche e termoigrometriche dal 1986 al 2003, in "l'oratorio di santo stefano a lentate. il restauro",* Silvana Editoriale, Milano, 2007

[57] Rosina, E., *Curatrice di: contributi di ricerca e didattica per la conservazione del castello di malpaga,* silvana ed, 2008, pp. volume 195

[58] Rosina, E., Fabozzi, G., Valentini, M, *Thermography and gravimetric tests in moisture analysis,* 20° congresso nazionale aicat – gicat, workshop metodi chimici, fisici e biologici per la salvaguardia dei beni culturali roma 1998

[59] Rosina, E., Fabozzi, G., Grossi, A, Schiavetti, S., *Il rilievo del complesso cortivo di corte castiglioni a casatico di marcaria (mantova),* Il rilievo dei beni architettonici per la conservazione, Napol,i 1999

[60] ISO 11461:2001 - Soil quality - Determination of soil water content as a volume fraction using coring sleeves - Gravimetric method

[61] EN 15801:2009 - Conservation of cultural property - Test methods - Determination of water absorption by capillarity [ICS: 97.195]

[62] EN 15757:2010 - Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials [ICS: 97.195]

[63] CEN/TR 14748:2004 - Non-destructive testing - Methodology for qualification of non-destructive tests [ICS:19.100]