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Original Research Article

DIAGNOSTICS AND RENOVATION OF MOISTURE AFFECTED HISTORIC BUILDINGS

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A b s t r a c t

The work concerns issues related to the diagnostics of moisture in historic buildings. Moisture content is one of the basic physical properties of materials. Excessive and undesirable growth of moisture in masonry causes considerable damage to masonry wall assemblies. It reduces the load-bearing capacity of structural elements, causes difficulties with heating and contributes to the development of mould and fungi. The article describes diagnostic procedures, provides available drying methods for walls in buildings and the applied method of renovation based on the example of damage caused by moisture in an examined historic facility.

Keywords: diagnostics of masonry, technological moisture, drying of masonry, renovation works, non-invasive methods, invasive methods, historic buildings

1. INTRODUCTION

Buildings erected over thousands of years differ in terms of materials used and technology applied. Renovation of historic buildings is an extremely difficult and

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delicate task. In the renovation process, the designer should strive to minimize the interference with cultural heritage objects so as not to impoverish their authenticity. When deciding on a specific renovation technology, the feasibility of its application and the intensity of found damage should be considered. Since the consequences of failure to renovate lead to further degradation of buildings, it is important to properly run the renovation management system when the facility is used [16-18]. It is estimated that about 50-60% cases of corrosion of structural elements are related to excessive moisture. Controlling of moisture content in building partitions is essential for the comfortable use of buildings as well as for maintaining their good technical condition. Thermal interactions are closely related to this issue [23,24]. Moisture condition is a state illustrating the current spatial distribution of moisture in building partitions and the tendencies towards predicted changes i.e., periodic or progressive moisture content, drying of materials from construction and technological moisture. Material moisture content is defined as relative water content in a particular material. It can be caused naturally or by external factors. Moisture in building materials is classified as chemically, physicochemically and physicomechanically bound water [25].

2. CONSTRUCTION DIAGNOSTICS

As part of renovation works aimed at removing moisture from a building, it is required to carry out a technical analysis of the facility in question. The assessment of technical condition, supplemented with environmental data, is the starting point for developing a drying and renovation plan. In Poland, guidelines, technical conditions as well as ITB instructions for execution and acceptance of works do not comprehensively solve the problem of construction diagnostics. Contractors use, for example, WTA studies. WTA instruction No. 4-5-99 [28] lists the following tests that should be carried out for masonry diagnostics during the visual inspection:

- tests of masonry structure, detection of voids
- tests of cracks (width and depth of cracks and their changes),
- determination of moisture content (mass moisture content, determination of possible occurrence of water vapour condensation),
- designation of capillary absorption (using a Karsten tube),
- designation of the presence of salts,
- determination of hygrothermal conditions,
- tests for strength parameters (i.e. Schmidt hammer, "pull-off method"),
- surveys of surrounding soil/ geological surveys.

The process of removing moisture is closely related to the cause of its formation. Preliminary tests determining the source of moisture allow for an unambiguous and precise determination of the causes of moisture occurrence. The most frequent sources of moisture in buildings are [9,10,25]:

- water found in the ground,
- rainwater,
- water and moisture from water supply and sewage systems,
- moisture of condensation origin,
- moisture due to hygroscopic uptake.

Each building to be renovated has its own specificity and, depending on its technical condition, requires a different scope of tests.

Construction diagnostics offers a very wide spectrum of securing the right path of conduct in developing technologies for renovation and repair works. The diagnostic procedure is described thoroughly in the Austrian standard ÖNORM B 3355-1 Drying of masonry - Construction diagnostics, planning procedures, execution and monitoring [19].

According to the standard [6] the analysis of a facility should include two stages. Stage 1 is an inventory of a building and its surroundings, which consists of its design, information on the material the building was constructed of, completion date, information on the level of surrounding groundwater and the direction of water inflow, as well as identification of the causes of moisture occurrence.

The first element of waterproofing assessment in buildings are macroscopic examinations, analysis of documentation and appropriately drilled sample holes. Wall excavations, floor point sample holes, wall chasing allow for determining the presence of waterproofing, its type or insulating material used. The inspection carried out in sample holes allows only for local assessment of the condition of insulation and does not provide any answers as to the condition of the entire structure.

The assessment of the quality of waterproofing in buildings is based on macroscopic examination and mass moisture content tests [13,15,26]. In most cases, we perceive the lack of tightness in insulation as the effects of moisture, such as damage to plaster and paint, salt and biological corrosion.

Stage 2 includes diagnostic tests i.e., a basic test of moisture content and salinity of walls (quantitative), a qualitative test on the type of salts present (sulphates, chlorides, nitrates), a test for the difference of pH between the wall and plaster, a test for water vapour condensation on the wall surface and in the masonry core.

The basis of construction diagnostics is, among others, the correct selection of physical and chemical tests for materials used in the structure.

Particularly important is to measure moisture content of both building partitions and surrounding air. Measurement should be carried out before and during the drying process, and its purpose is to create a pre-drying baseline that can be referenced at a later date when assessing the effectiveness of the drying systems used. An additional goal is to check the conditions prevailing in the wall (some drying methods are limited by the level of moisture content to which they can be applied) and to create a moisture balance for the tested structure.

2.1. Testing methods for moisture content in building materials

Testing methods are most often differentiated according to whether the value is measured directly or indirectly. Table 1 lists the methods used for testing moisture content in building materials.

Table 1. Classification of methods for testing moisture content in building materials

Method group	Method name	Measured parameter
chemical methods	indicator	a change in colour of the indicator paper due to moisture content in the material
	carbide (known as CM)	pressure of acetylene (formed by the reaction of carbide with water) in an airtight container
electro-physical methods	electrical resistive	a change in the electrical resistance of the material as a result of a change in moisture content
	dielectric	a change of the dielectric constant of the material as a result of a change in moisture content
	microwave	suppression of microwaves passing through the damp material
nuclear	neutron	a number of neutrons slowed down by collisions with hydrogen atoms
	x-ray radiation γ	a change in the intensity of radiation γ after passing through the tested material

However, the European standard PN-EN 16682:2017-05 [22] lists only four methods adopted to obtain reliable measurements of moisture or water content in building materials (incl. bricks, stones, concrete, plaster, mortar, wood, etc.) affected by weathering, pest infestation, salt migration and other changes over time:

- gravimetric (also known as Darr method),
- Karl Fischer titration (analogous to the carbide method),
- azeotropic distillation (preferred for wood),
- calcium carbide (also known as CM method, calibration required each time).

Other methods, including electrical, nuclear and thermometric systems, are treated by the standard [22] as indicative, burdened with high uncertainty resulting from misinterpretation of the reading of parameters of measured quantities appearing on devices. A more detailed list of methods for testing moisture content in building materials is given in [5].

2.2. Diagnostic methods for historic buildings

The provisions and resolutions of the 1st International Congress of Architects and Monuments Technicians in Venice in 1964 reads: "restoration (...) consists in respecting the old substance and elements that are the authentic documentation of the past". In order to protect movable and immovable goods, the appropriate drying method of wet building partitions should be selected. For this, diagnostics must be performed in accordance with the guidelines provided in the Austrian standard [19] or optionally on the basis of the WTA instructions [28]. The guidelines for testing methods with regard to historic buildings were collected and specified in the standard [22]. In order to reduce the possibility of misinterpretation, the standard presents procedural nomograms. Incorrect determination of the causes of moisture content and undertaking wrong actions may, in the worst scenario, lead to the intensification of destructive processes. Non-invasive methods of moisture content testing only indicate the problem, however the determination of the exact value of moisture content in cultural heritage objects requires the use of destructive solutions: the oven-dry method and CM. Sampling sites should enable the development of maps of moisture (distribution) in masonry, thus they must be carefully documented. Samples should always be collected in a representative number and taken in horizontal and vertical profiles. Insufficient number of samples and their too insufficient sizes do not reflect the heterogeneity of masonry and the actual conditions that prevail in it.

3. DRYING METHODS

Referring to the already invalid standard PN-82/B-02020 [21], due to the lack of other applicable standardized classification, the permissible moisture content in walls made of ceramic bricks and ceramic hollow bricks should not exceed 3%, whereas for walls made of cellular concrete the maximum value of moisture content is 12% [2]. The classification in terms of mass moisture content in walls is as follows [23]:

- dry walls (with permissible moisture content) ≤ 3%,
- walls with higher moisture content 3-5%,
- moderately moist walls 5-8%,
- heavily moist walls 8-12%,
- wet walls >12%.

Drying is a process of both heat and mass flow, the purpose of which is to remove moisture from the dried material by means of a drying agent. This process can be carried out in two ways i.e., artificially and naturally. The first method consists in generating heat using an external energy carrier, the latter assumes that the heat comes directly from surrounding air [14].

The methods of masonry drying can be divided according to the following classification:

1. Natural drying (does not require any devices)

The process of natural drying is long and complex, depends on the temperature and humidity conditions inside and outside buildings as well as on the type of building structures. Additionally, its effectiveness depends on the velocity of air flow within the dried area or surface. The velocity can be increased by using different solutions, including blowers, fans, or by creating a draft. The method is not effective at high humidity of the outside air [20].

2. Artificial drying (with the use of additional devices)

2.1. Non-invasive methods (not interfering with the structure of masonry):

- hot air drying. Drying masonry with heaters is simple. It consists in increasing the temperature in the dried room with heaters to a temperature of several dozen degrees Celsius, which leads to increased evaporation of moisture from the surface layers of masonry. In order to effectively perform drying with this method, it is necessary to use a mechanical fan or natural ventilation, as water vapour is generated and must be removed [12].
- condensation drying. The condensation method consists in drying the air inside a given room by condensing water vapour contained in the air. As a result, the relative air humidity in the room is reduced, so it is possible to evaporate the moisture contained in masonry to the air inside [14].
- absorption drying. Absorption drying is a physical phenomenon that consists in absorbing water from masonry by suction through dry air. This process is based on the assumption that moisture in the air is exchanged as it flows through the slowly rotating rotor (filter), equipped with numerous channels containing hygroscopic materials, such as: lithium chloride, silicone gel or silica gel. Moisture in the air is absorbed by absorbents and discharged outside by the hot air [1,12].
- microwave drying. This method uses a phenomenon of changing the energy of the electromagnetic field into heat in the humid environment, in the area of microwave radiation. The energy is provided by a microwave generator attached to the wall, emitting a field with 2.45 GHz frequency, that sets water molecules in masonry in motion with a similar frequency. As a result, the temperature of masonry increases, both in its external and internal part [12].
- infrared drying. This method consists in heating a given partition with an infrared heater. It sends a beam of invisible electromagnetic waves of an appropriate length towards the wall. As a result, the temperature of the partition increases, and moisture contained inside the wall goes

to its face, from where it is evaporated. It is advisable to combine this method with condensation drying to increase its efficiency.

- magnetokinesis. This system is based on the use of the natural magnetic field of the Earth properly polarized by the installed device, which blocks the process of capillary rising deep into masonry, by changing unfavourable electric potential, which, before using this method, causes the movement of electric charges and water molecules filling capillaries, resulting in masonry getting damp. The result is a change in the equilibrium state of the forces holding water in the structure of masonry directing it towards the foundation of the building. At the same time, water from the areas with lower moisture content in the building evaporates by diffusion [7].
- electrosmosis. The phenomenon of electroosmosis can take place only when porous channels have very small cross-sections and form interconnected capillaries. The main cause of the upward movement of water molecules in masonry is the difference in electric potential, namely the base of masonry, i.e. the Earth has a positive charge, while the upper part of masonry has a negative charge. Water particles contained in capillaries always move towards the negative pole, therefore capillary rise occurs. Devices used for this drying method generate electromagnetic waves of the appropriate shape and intensity, causing the poles to reverse and after installing such a device, the base of masonry has a negative charge, i.e. water moves downwards, and hence the drying of masonry takes place [11,27].

2.2. Invasive methods (interfering with the structure of masonry):

- Knappen siphons. The method consists in drilling holes in masonry to increase the surface of moisture evaporation. The holes have a diameter of 3 to 5 cm and a depth of up to ¾ of masonry's width. There are ordinary single holes or connected by a heating groove, in two rows, drilled from the external part of masonry, from the lower area to the top. For faster drying, the holes in the lower row are connected with a small groove through which a heating cable is led, it is a 24 V power source that speeds up the entire process [1].
- active ventilation screens. Ventilation screens are 1 brick-thick walls, made both inside and outside the building, with an L-shaped cross-section. They can be made of solid ceramic full bricks, hollow bricks or concrete blocks. External screens are built on horizontal waterproofing, at a distance of approx. 6 to 14 cm from the damp wall. The height of such a screen should ensure that moist air can be discharged outside the building. Fans force air to move in the tunnel created between the new and old partition. Air is introduced through air

outlets located in the lower parts of masonry approx. 10 cm from the floor level, and it is blown out through air outlets located higher, i.e. approx. 30 cm from the floor. Drying is the effect of air movement in the gap between the damp wall and the added screen [20].

4. CASE STUDY

The paper presents a historic building (Fig.1) constructed in 1910 in the style of Art Nouveau architecture, distinguished by rich floral ornamentation. Currently, the building is under renovation, the walls of the basement and ground floor show significant damage caused by moisture. Geotechnical tests have shown that the building is set in fine, compacted sands, and the existing foundation level is above the groundwater table.

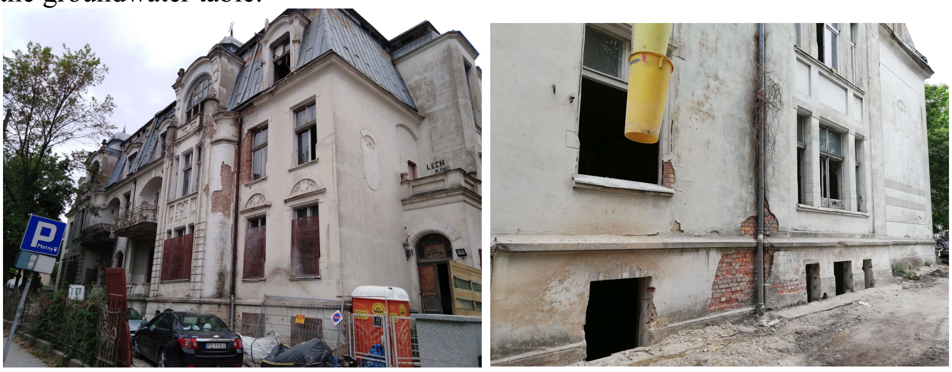

Fig. 1. The facades of the analysed object

4.1. Description of measuring devices

In order to determine the choice of drying methods, the building was diagnosed with a series of moisture content tests. In order to minimize the damage to the walls caused by invasive tests recommended for the proper diagnostics of the building, first the site was inspected and examined with masonry moisture measurements using a non-invasive method (Fig. 2). Then it was decided to make sample holes (Fig. 3, 4). Moisture content and temperature measurements were made using the Logger Termio Termoprodukt recorder, and the former was verified with the T610 dielectric meter.

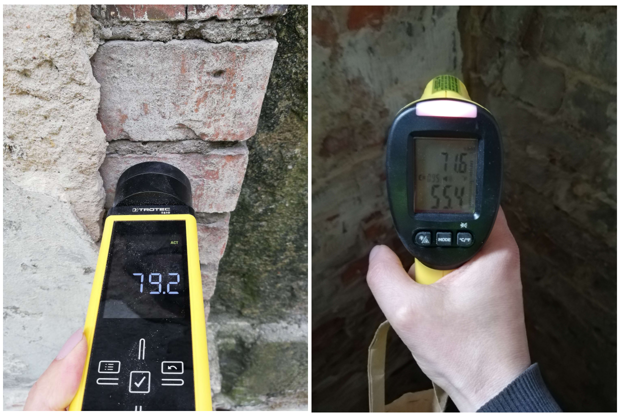

Fig. 2. Measurement of moisture content in masonry (non-invasive method)

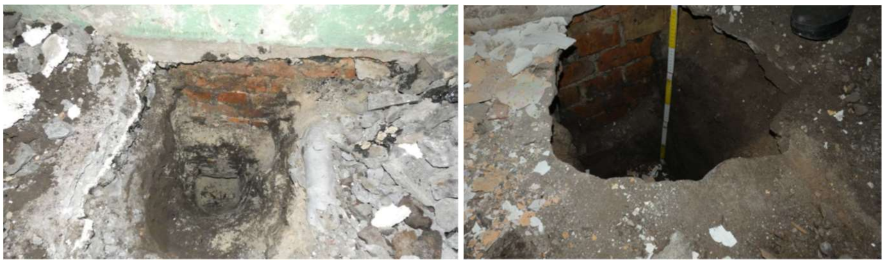

Fig. 3. Internal sample hole in the wall and basement floor

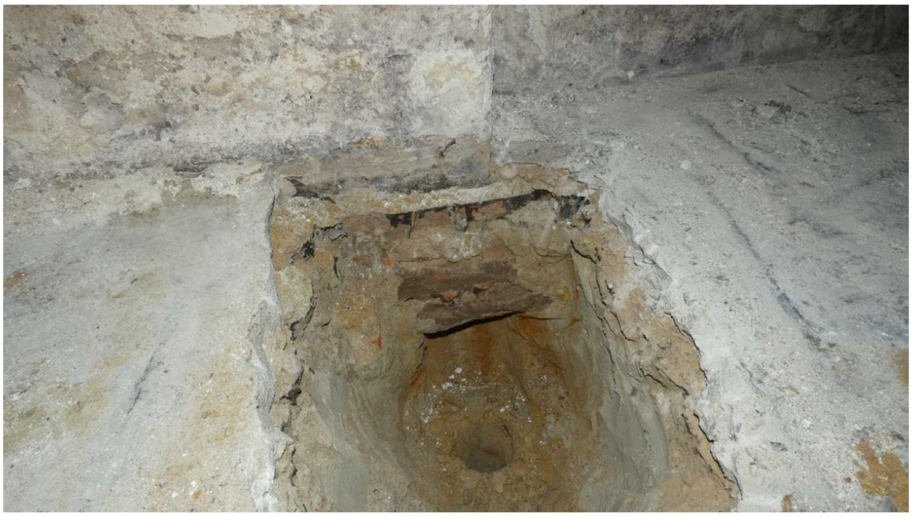

Fig. 4. Sample hole in the foundation under the inner wall

After identifying the representative sites for further tests, measurement was carried out using an invasive method. Invasive tests of mass moisture content in the wall were carried out in 13 selected points called measurement profiles (exemplary measurement holes are shown in Fig. 3, 4, 5). Samples were taken from min. 20 cm using a slow-speed drill and a drill with a diameter of Ø12 mm, at selected levels from the floor or the surrounding area. The temperature of the drill bit did not exceed 37°C, the measurement was made with Trotec T-250. Then the drill cuttings weighing min. 2.5 g were placed in a weighing dryer and subjected to a moisture percentage determination process. The mass moisture content tests were made with the use of a RADWAG weighing-dryer. The RADWAG WPS-30S weighing-dryer is a device consisting of a microprocessor and a precise balance that calculates the moisture content in a sample. The obtained result comes from the measurement of the weight loss of the evaporated moisture from the sample drill cuttings. In order to determine the percentage of moisture, the formula (4.1) provided in for [18] was used.

$$F = \frac{m_m - m_s}{m_s} \cdot 100\% \tag{4.1}$$

where:
m_m – mass of the sample before drying,
m_s – mass of the sample after drying.

In order to analyse the obtained results of wall moisture content, the relative air humidity and temperature inside and outside the building were measured with TROTEC T250. The temperature inside the rooms was additionally verified with TROTEC T610.

The selection of an appropriate hydro-renovation method required the examination of the masonry and plaster samples in order to determine the content and types of salts as well as their pH values. A semi-qualitative method was used with Merckoquant® analytical strips.

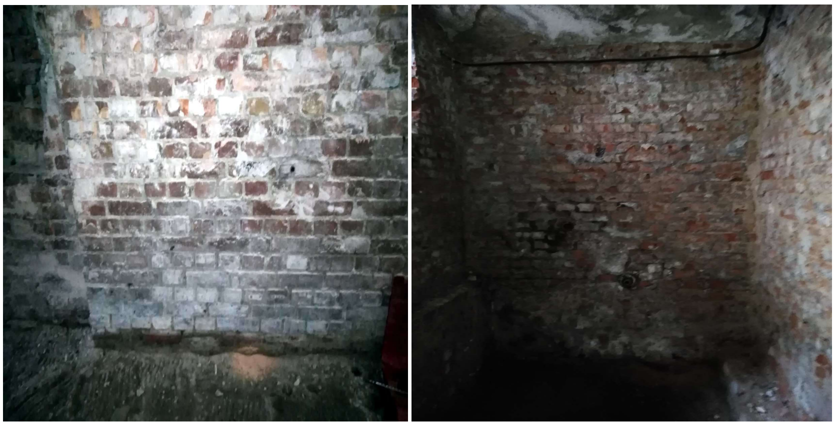

Fig. 5. Measurement profiles for invasive analysis

4.2. Comparative scales for moisture content and salinity

The degrees of moisture content in brick walls were determined in accordance with the DIN classification relating to walls made of bricks produced in standard conditions, with standardized hygroscopic and sorption characteristics, used as an auxiliary tool for the assessment of old walls (Table 2).

Table 2. Classification of moisture content according to DIN

Degree	Mass moisture U_m [%]	Classification of moisture content in masonry
I	0 ↔ 3	masonry wall with permissible moisture content - dry
II	3 ↔ 5	masonry wall with increased moisture content
III	5 ↔ 8	masonry wall with average moisture content
IV	8 ↔ 12	masonry wall with high moisture content
V	>12	wet masonry wall
	18 ↔ 25	maximum mass moisture of ceramic bricks

The analysis of salinity levels was determined according to classification by WTA 4-11-02 Messung der Feuchte von mineralischem Baustoffen instruction [29] (Table 3).

Table 3. Classification of salinity levels according to DIN

Concentration	low	medium	high
chlorides	< 0,2 %	0,2-0,5 %	> 0,5%
nitrates	< 0,1 %	0,1-0,3 %	> 0,3 %
sulphates	< 0,5 %	0,5-1,5 %	> 1,5 %

4.3. Analysis of the obtained results

4.3.1. Climate tests on the day of measurements

Air humidity outside the building, given by the Metrology Institute in the city of Poznań on the day of measurements was: 87% in the morning (from 5.00 to 11.00 am) and 95% in the afternoon (from 1.00 to 5.00 pm). In the analysed case it was 94% during rain and 74% in the morning hours. For comparison, it can be stated that permissible humidity in the room with efficient ventilation should be 50-60%.

4.3.2. Salinity tests

The study of the walls of the building in terms of salinity showed small amounts of nitrates ranging from 0.005% to 0.013%, small amounts of sulphates from 0.1%

to 0.4%, and no chlorides. According to the classification given above, the salinity found in the walls was low. This implies the use of light lime-cement or two-layer renovation plasters. However, it is inadvisable to use gypsum in any form or drywall in the cellar. This also applies to filling electrical conduits and processing electrical system boxes.

4.4. Moisture content tests

The masonry is characterised by high moisture content. Depending on the U_m profiles, the moisture content reached 15.3%. The main reason behind the result is capillary moisture penetrating from the side of the ground adjacent to the wall and caused by the inoperability or non-existence of external vertical waterproofing or a blocked or contaminated wall ventilation duct.

4.5. Research results

The walls have been soaked with moisture, thus the places where water have penetrated from the inside of the building should be drained before modernisation. In order to eliminate the problem of musty smell and dampness in the rooms, it is necessary to dry the walls. The procedure should be carried out with great care, since sudden changes in technical parameters may have a destructive effect on the work of the structure, plus their further deterioration may significantly reduce structural strength parameters.
The natural drying time of a wall with a thickness of two bricks (54 cm) is:

$$t = (0,4 \div 0,8) \text{ x } (50/2)^2 = 250 \div 500 \text{ days.}$$

Approx. 30% of the time a year (autumn and winter) does not have a positive effect on the natural drying of masonry (the process practically stops then), thus the total drying time of a 54 cm thick wall would take around 1000 days (three years). The above calculations are confirmed in practice. The moisture tests of ceramic walls carried out between July and October showed that:

- the decrease in moisture content after removing the plasters was 1.5-2% per month,
- since September, the walls practically did not dry out, and even in some cases the moisture content increased - after intense rainfall and during wet (rainy) days and nights.

Thick walls, practically over 40 cm thick, will dry out for many years, with an assumption that a given building has horizontal and vertical insulation of its basement walls. It will be completely different when there is no horizontal or vertical insulation in walls, and when capillary rising of water from the ground occurs. In this case, the efficiency of masonry drying will be very limited, because rainwater from the surface of the wall will be replaced with moisture from its depths or from below. This water transports salts that crystallize during drying on the surface of the wall. In the case of the building being described, the phenomenon of salt crystallization is very intense, because the drying of the walls creates favourable conditions for this phenomenon. Therefore, it is necessary to use such a technology of masonry drying that will ensure its sufficiency against capillary moisture and will permanently and effectively protect all walls of the building against it in the future. The drying effect of the walls should be confirmed in laboratory tests (moisture analyser or CM). In the analysed case, non-invasive drying methods that does not interfere with the wall structure are recommended i.e., based on magnetokinesis or absorption.

5. CONCLUSIONS

Choosing the right method of masonry protection and drying is an important task in preserving and maintaining historic buildings. Usually, the first step in renovation is to remove plaster and expose the masonry structure. However, in the case of historic buildings, this is not a recommended option. Authors of scientific papers on the subject consider natural drying with the use of fans or heaters (still highly preferred by contractors) as highly dangerous [3,4,6,8,25]. In masonry without properly functioning waterproofing, during the process of drying, very intense salt crystallization occurs and leads to rapid degradation of the dried element. In addition to masonry insulation treatments i.e., the use of secondary waterproofing, a proper renovation concept should also include the selection of an appropriate drying method. The more so since some modern methods of waterproofing require preliminary drying of partitions. Different methods work well in different diagnosed situations. There is no panacea for everything, the designer should always try to minimize the interference with cultural heritage objects.

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