Optimal Indoor Air Parameters in Historical Buildings: Determination Technique

IURII A. TABUNSHCHIKOV
Doctor of Engineering, Professor at the Moscow Architecture Institute (State Academy), President of ABOK

MARIANNA BRODACH
Candidate of Engineering, Professor at Moscow Institute of Architecture (State Academy), Vice President of ABOK

NIKOLAI SHILKIN
Candidate of Engineering, Professor at Moscow Institute of Architecture (State Academy)

Analysis of the literature sources dedicated to studies of historical buildings, including museum and churches, has shown that the most disputed question in monitoring of historical buildings is "optimal indoor air parameters" that must ensure long-term preservation of the works of art [1-9].

Keywords: museum, historic building, church, indoor air temperature, humidity, microclimate, optimal indoor air parameters, permissible indoor air parameters

We will introduce the term "historic building" – meaning a church, museum or church-museum building, including the items indoor of it, that has architectural and/or historical-artistic value. The problem with defining "optimal indoor air parameters" is relevant for historic as well as numerous modern museum buildings. Curators of almost every museum have their own strong conviction in this matter that "is not a subject to criticism and discussion". As a result, the reference literature contains numerous "tables" recommending the "optimal indoor air parameters" that often differ from each other significantly. Most of the researchers recommend the following range of parameters for historic buildings, including museum and church buildings, equipped with an air conditioning system: indoor air temperature 16–22°C and indoor air humidity 45–55% [1–3].

It is assumed that the reasons for such situation lies in the lack of a scientifically justified technique for determination of the "optimal indoor air parameters" that should ensure long-term preservation of historic buildings. It is also assumed that these values depend on numerous factors: building age, type of exhibited items, climate control system, indoor temperature and humidity conditions, building operation mode, climatic conditions at the building's location, etc.

According to ABOK standard "Russian Churches and Cathedrals. Heating, Ventilation, Air Conditioning" the terms "optimal indoor air parameters" and "permissible indoor air parameters", if you ignore the parts related to people, have the following definition: **optimal indoor air parameters** do not cause moisture or temperature related deformations that have a negative impact on the long-term preservation of easel paintings, art paintings, decorative finish and objects of worship practices with historical and cultural value; **permissible indoor air parameters** do not cause moisture or temperature related deformations leading to fast deterioration of easel paintings, art paintings, decorative finish and objects of worship practices with historical and cultural value.

A special case is unheated museum and church buildings; the known reference literature does not have any definition of the "optimal and permissible indoor air parameters" for them and, thus, does not offer any numerical values for them.

Let's give a definition for the term: **permissible indoor air parameters in unheated church-museum purpose temples** – upper and lower limits of indoor air temperature and humidity range that does result in systematic occurrence of significant humidity and temperature related deformations leading to fast irreparable deterioration of wall fresco paintings, wooden iconostasis, icons and other church ornaments with historical and cultural value.

Therefore, from the definitions given above it follows that determination of the optimal and permissible indoor air parameters is related to determination of the minimum deformation values that ensure long-term preservation of art objects. Here we will present the basic provisions of the technique of determination of the optimal indoor air parameters of historic buildings based on the studies of deformation properties of art objects.

Each museum, church or museum-church building, when considered as a single complex from the perspective of the temperature and humidity conditions analysis, consists of a building envelope and various exhibition items: paintings, sculptures, interior decorations, or for churches: icons, fresco paintings, wooden iconostasis, churchware. All of the historic building components listed above have one common characteristic: they are capillary-porous objects containing moisture.

Interior of the Cathedral of the Dormition.

Photo by markrhiggins / depositphotos.com

Interior of the Sistine chapel. "The Last Judgment" by Michelangelo.

Table 1 and **Table 2** [10] present typical values of porosity and normal moisture content of some construction materials.

In the process of building operation with indoor air temperature and humidity fluctuations the indoor surfaces of building envelope, as well as exhibition objects with historical and artistic value indoor the building take up moisture from air in the form of vapors. This process is called sorption.

Relation between material moisture content by mass* and relative humidity of air is plotted as sorption isotherms. Sorption isotherms for wood (**Figure 1**) and brick (**Figure 2**) show that material moisture content by mass increases as the relative humidity of air goes up [10].

We will refer to brick and wood, the sorption indicators of which are shown above, as the new construction materials as opposed to "old construction materials" in the building envelope constructions, icons and wooden iconostasis, the age of which can reach several centuries. Is was determined that sorption, and thus deformation characteristics of old construction materials and things made of them significantly differ from similar new construction materials and things made of them [11].

Studies of the temperature and humidity conditions and thermophysical properties of envelope constructions of the Moscow Kremlin Cathedrals during construction of air conditioning systems have identified the following specifics of sorption properties of old construction materials used in envelope constructions [11]:

- sorption curves of brick samples taken from the walls of the Assumption and the Archangel Cathedrals (old construction materials) have higher equilibrium moisture content than similar modern materials. Thus, the maximum hygroscopic moisture content (i.e. moisture content corresponding to full saturation of air at the given temperature) of red brick taken from the walls of cathedrals of the Moscow Kremlin is 9–18%. This parameter for modern red brick, including brick used for restoration works in the Moscow Kremlin, does not exceed 1–1,8%. Higher sorption capacity is obviously caused by significant contents of minerals in the construction materials that were in operation for several centuries. To verify

* Material moisture content by mass w_B, % is determined by ratio of moisture mass in the material sample to the dry sample weight.

Table 1. *Common porosity values of some typical construction materials.*

Material	Density, kg/m³	Porosity, %
Red brick	2100	20
	1700	37
Oak	700	58
Pine	500	65
Birch	600	57
Aspen	400	75

Table 2. *Normal values of materials moisture content in building envelope constructions.*

Material	Density, kg/m³	Material moisture content, %	
		by weight	volumetric
Red brick in solid walls	1800	1.5	2.7
Lime-sand plaster	1600	1	1.6
Wood (pine)	500	15	7.5

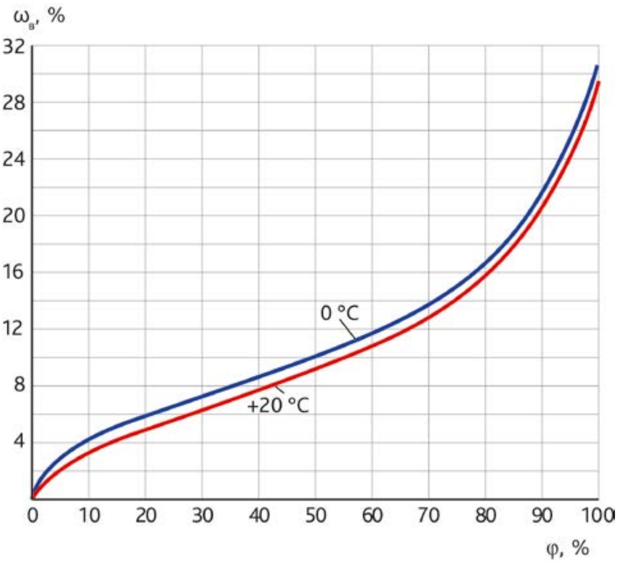

Figure 1. Water vapor sorption isotherm for wood.

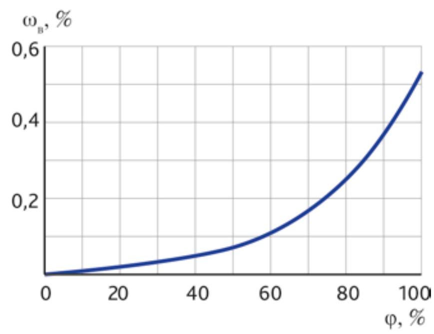

Figure 2. Water vapor sorption isotherm for regular brick.

this assumption the researches have determined the sorption properties of samples of bricks specially produced for restoration of envelope constructions of Kremlin cathedrals that were previously saturated with Na2SU4 and MgSO4 salts. Sorption properties of the materials taken from cathedral walls and materials that were subjected to artificial salinization were quite similar, as seen in **Figure 3**.

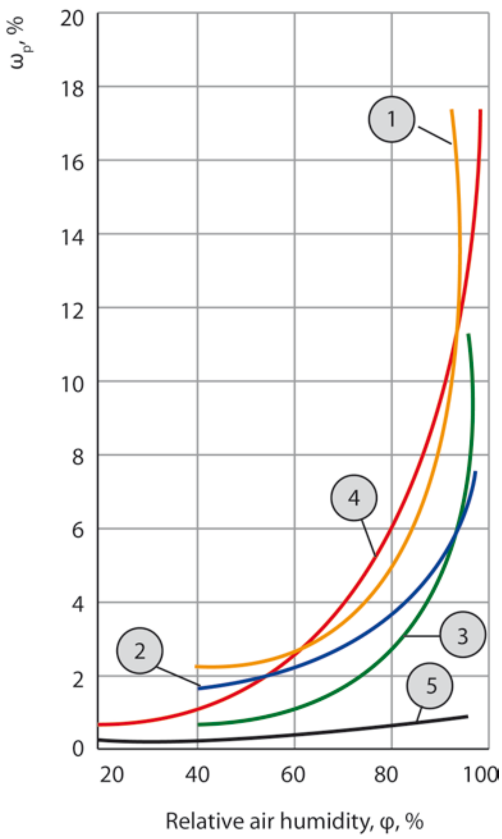

Figure 3. Sorption isotherms for red brick samples. 1, 2, 3 = samples taken from cathedral walls; 4 = sample of restoration material artificially salinized with mixture of Na_2SO_4 and $MgSO_4$; 5 = restoration non-salinized material sample.

The following circumstance should be noted. Since "old construction materials" contain salts accumulated over extended period of their operation, i.e. are "salinized", the dew point temperature on the inner surface of envelope constructions will be higher compared to the dew point temperature of structures made of "new construction materials".

Graphs of relative deformation of plaster samples taken from the walls of the Assumption Cathedral and Museum are presented in **Figure 4**. Relative deformation is the ratio of change in the linear dimension of a sample Δl in mm to its linear dimension in absolutely dry air (φ = 0%). From **Figure 4** it is seen that the biggest increase in the relative deformation of this material is observed in the relative air humidity variation range from 60 to 90% in the process of sorption humidification. During moisture desorption from plaster samples, i.e. during material drying loss, the situation is somewhat different: in the relative air humidity variation range from 40 to 90% the magnitude of relative deformation changes insignificantly, while in the relative air humidity variation range from 20 to 40%, we observe significant changes in the relative deformation. It was also determined that graphs of relative deformation of limestone have similar but not as prominent nature. Also, it was determined, and this is very important, that moisture related deformations are multiple time higher than temperature related deformations of plaster and limestone samples.

Therefore, the reason for deterioration of long-term preservation of museum and church exhibitions, as well as fresco paintings, is moisture and temperature related deformation of the materials of exhibitions and fresco paintings.

So, the objective of ensuring long-term preservation of the works of art is to determine and maintain such

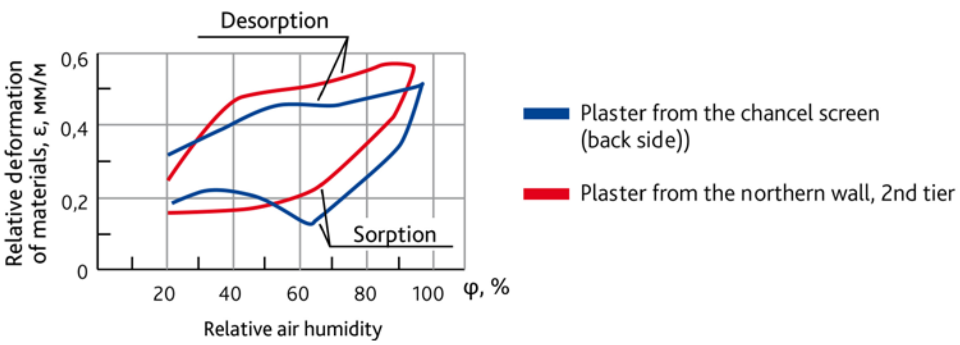

Figure 4. Graphs of relative deformation of plaster material from the walls of the Assumption Cathedral.

Cathedral of the Dormition (Uspensky sobor) in Moscow.

parameters of indoor air during operation that will prevent deformation or keep it within permissible limits.

If a building is equipped with an air conditioning system than, according to **Figure 4**, it would be possible to recommend maintaining relative humidity of indoor air in 40–55% range. However, this result is only preliminary: to make a final decision on the range of relative humidity variations we need to analyse deformation indicators of samples of other materials from the historical building that have architectural or historical-artistic value.

If a historic building is equipped with an air conditioning system, it will be possible to maintain the humidity condition of indoor air at the required level. The humidity conditions of indoor air in a heated building equipped with an air conditioning system are directly linked to the humidity of outside air due to natural or forced ventilation air exchange. In the summer period outside air has high moisture content (Table 3) and, as it freely enters the building interior the moisture is absorbed by internal surfaces of envelope constructions, iconostasis and icons, while in the winter period the outside air has significantly lower moisture content, i.e. is practically dry, so when the building is heated the difference between partial pressure of vapor in humid air and on the internal surface of building envelope or surfaces of objects with historical-artistic value drives the intensive drying process. **Table 3** presents approximate value of moisture content of outside air in g/kg during summer (June-August) and winter (December-February) periods for the following cities: Moscow, Saint Petersburg, Yaroslavl, Rostov-on-Don.

Saturation of a "dry" capillary-porous object with moisture during summer leads to the so called swelling process, i.e. increase in the object size, which in turn is responsible for occurrence of deformations, called moisture related deformations; if the magnitude of deformation is significant, it can result in destruction of the material structure. Evaporation of moisture from "wet" capillary-porous object in winter leads to the

Table 3. *Approximate value of moisture content of outside air in g/kg during summer and winter periods of the year.*

Year period	Moisture content of outside air in g/kg for cities			
	Moscow	Saint Petersburg	Yaroslavl	Rostov-on-Don
Winter	1.1	1.5	1.1	1.3
Summer	10	9.5	10	10.5

reverse process called "drying shrinkage"; if the process is intensive or extensive, it also causes deformations and can result in destruction of the structure of material or objects made of it. Similar phenomena take place when the material temperature changes.

Therefore, if a building is only equipped with a heating and ventilation system, regular "swelling" in summer and "drying shrinkage" in winter will lead to alternating deformation resulting in deterioration of long-term preservation of historic buildings and objects of historical-artistic value located inside of them.

Conclusions

1. Optimal or permissible indoor air parameters for historic buildings including church and museum-church buildings should be determined on the basis of analysis of changes in the sorption and deformation properties of the materials of inner surface of the building envelope and materials of the works of art.
2. It is expected that the optimal indoor air parameters will differ for every individual historic building or may be identical for some of them, and will depend on a number of factors, including the building age, nature of exhibition items, specifics of the building use conditions, climate control system, etc.

The information presented above allows to recommend the following step-be-step technique of determining the optimal indoor air temperature parameters for historic buildings.

- Take samples of the materials of exhibits from historic buildings, and materials of inner surfaces of the building envelope constructions. Considering the artistic value of the exhibits, the samples should be of the minimum size required for analysis.
- Determine the sorption indicators of material samples using, for example, the methods from GOST 24816–14 "International Standard. Building Materials. Method of equilibrium hygroscopic moisture determination" as guidelines.
- Study the deformation indicators of materials using, for examples, methods and equipment described in [2] or other more modern methods or equipment as guidelines.
- Perform comparative analysis of the deformation and sorption graphs of the material samples and select their values which only result in insignificant changes in indicators when they vary. This values will determine the optimal values of the indoor air temperature for a historic building. ■

References

[1] Camuffo D. Microclimate for Cultural Heritage. Developments in Atmospheric Science, 23, Elsever, 1998, 420 p.

[2] Camuffo D., Bernardi A. The Microclimate of the Sistine Chapel, Rome BOLLETTINO GEOFISICO. Anno 18, Numero 2, Aprile–Giugno, January, 1995, p. 7–33.

[3] Negroa E., Cardinaleb T., Cardinalea N., Rospi G. Italian guidelines for energy performance of cultural heritage and historical buildings: the case study of the Sassi of Matera. European Geosciences Union General Assembly 2016, EGU Division Energy, Resources & Environment, ERE. Energy Procedia 97 (2016), p. 7–14.

[4] Popper R., Niemz P., Croptier S. Adsorption and desorption measurements on selected exotic wood species analysis with the Hailwood – Horrobin model to describe the sorption hysteresis. WOOD RESEARCH 54 (4):200943–56.

[5] Camuffo D., Bertolin C., Fassina V. Microclimate monitoring in a Church. Environmental chapter 3. Environment 01/06/10 10.24 Pagina 43.

[6] Vasilyev G. P., Lichman V. A., Peskov N.V., Brodach M. M., Tabunshchikov Y. A., Kolesova M.V. Simulation of heat and moisture transfer in a multiplex structure, Energy and Buildings 86 (2015), p. 803–807.

[7] Cardinale T., Rospi G., Cardinale N. The influence of indoor microclimate on thermal comfort and conservation of artworks: the case study of the Cathedral of Matera (South Italy). Energy Procedia 59 (2014), p. 425–432.

[8] Brodach Marianna Heating of Cathedrals - Alternative practices // ABOK. – 2004. – No. 2.

[9] Sizov B.T. Thermophysical Aspects of Preservation of Architecture Landmarks // ABOK. – 2002. – No. 1. pp. 24–31.

[10] Fokin K. F. Construction Heat Engineering of Building Envelopes. M.: ABOK-PRESS, 2006

[11] Tabunshchikov Iurii. A. Dahno V.N., Melnikova I. S., Protsenko V.N. Thermal Conditions in Architecture Monuments (using cathedrals-museum of the Moscow Kremlin as an examples: compil. "Building Thermal Physics (Microclimate and Thermal Insulation of Buildings"). M.: NIISF, 1979.