Determination of Humidity Conditions of Enclosing Structures by the Color Indicator Method

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Abstract. The necessity of specification of the operational humidity and its distribution in enclosing structures is justified. It is revealed that the existing experimental methods for estimating the moisture state of structures can lead to errors and require scientific development. An experimental method for determining the pattern of moistening of enclosing structures by the color indicator method is proposed. The results of experimental research and numerical calculations of the hygrothermal state of the wall fragment tested in the laboratory climate chamber are presented. It was found that the distribution of moisture can be uneven in a homogeneous structure and can be related to the surface texture of materials.

1. Introduction

To perform calculations on durability, thermal protection of buildings, protection of enclosing structures against moisture accumulation, corrosion of metal parts, and others, one must have an idea of the operational humidity of their material layers. In particular, the coefficients of thermal conductivity ($\lambda$) and vapor permeability ($\mu$) used in the existing standards of steady-state [1] and transient [2] methods for estimating the hygrothermal performance of structures depends on the values of the operational humidity of the materials. On the basis of field studies of the moisture content of enclosing structures in various climatic regions of the Russian Federation, the values of the operational humidity of materials (A and B) were compiled, which are presented in the Standards. These data have not actually been updated since the 1960s, when complex studies of the moisture state of enclosing structures were carried out [3, 4]. The results of studies of moisture content of enclosing structures, carried out by individual researches of NIISF RAASN (Research Institute for Building Physics of the Russian Academy of Architecture and Building Sciences) in the period from 2013–2015 [5] and others [6, 7] confirmed the loss of relevance of operational humidity values indicated in the Standards. The authors emphasize the essential dependence of operational humidity values not only on climatic conditions, but also on the type of construction [5, 6, 7]. The calculation results of steady-state [1] and transient [2] hygrothermal conditions of the enclosing structures are completely dependent on the experimental data such as operational humidity, capillary suction, moisture conductivity of materials etc. However, these experimental data strictly depend on the type of construction, which is not taken into account. Therefore, the calculation methods are unreliable to determine the distribution of moisture in the wall structures and must be confirmed by the field tests. An example of the steady-state hygrothermal conditions of the enclosing structure is shown in figure 1. The structure design and boundary conditions are shown in figure 1a. According to the calculation, a condensation is formed in the structure between the outer and thermal insulation layers (figure 1b), however, it is impossible to determine the further distribution of moisture. Thus, the moisture distribution pattern in the enclosing structure requires scientific investigation.
Figure 1. Calculation of steady-state hygrothermal conditions of the enclosing structure.

a) structure design and boundary conditions; b) distribution of partial pressures of water vapor along the lateral section of the structure.

The only reliable way to determine the operational humidity of material layers of structures is through field studies. The most common measurement methods are gravimetric method and surface moisture meters. Gravimetric method implies sampling the structure (e.g., by a hole saw tool) and weighing it before and after drying process [8]. The gravimetric method is one of the most accurate methods for measuring the moisture content of a material. The disadvantage of the method is in its locality - the humidity values can be known only in the cut out sections, intermediate sections are mentally completed at the discretion of the researcher. The high laboriousness of extracting a sample from the wall, requiring the skill of using dry drilling tools. Moreover, heating the material while drilling can be significant and, therefore, cause drying of the core samples. The high complexity of the assessment and low resolution of moisture distribution data across the sections of the structure, associated with the need to cut the sample into many parts.

Surface moisture meters function by measuring the electrical properties of the material (e.g., dielectric [9], neutron scattering technique [10] etc.). The advantage of the method is the ability to monitor data over a long period. The disadvantage is the localization of the measurements, due to the limited range of the sensor (a few centimeters). In addition, violation of the integrity of the wall when the sensor and its wire are embedded into the structure, which leads to distortion of mass transfer processes in the enclosing structures.

Thus, there is a need to create an experimental method that allows the determination of moisture distribution in the enclosing structures that is free from the issues mentioned above. For these purposes, we proposed a method aimed at the experimental determination of moisture distribution pattern in the enclosing structures by using the water-sensitive indicator (hereinafter referred to as "WSI") [11]. "WSI" is a cotton gauze, treated with a special chemical composition. When "WSI" gets wet, it changes its color. Thus, according to the color change of "WSI", it is judged on the fact of moistening and on the moisture fields along the wall section. "WSI" can be made in the form of a plane or a thread. The "WSI-plane" is placed perpendicular to the flow of water vapor, i.e., over the whole plane of the investigated fragment of the enclosing structure. "WSI-thread" is placed along the water vapor flow in the enclosing structure.

2. Experimental research

In laboratory conditions of the climatic chamber with the use of “WSI”, as well as temperature and relative humidity sensors, the hygrothermal state of the structure fragment was studied. Design of the structure, the arrangement of sensors and “WSI” are shown in figure 2. “WSI-plane” is located in two sections perpendicular to the water vapor flow: between the outer plaster and thermal insulation layer, and in the thermal insulation layer at a distance of 112.5 mm from the inner surface, figure 2. “WSI-thread” is located along the water vapor flow in the lateral section of the structure, figure 2 a. In the cold and warm chamber of the installation, the temperature was maintained at −18 °C and +27 °C, respectively. The steady state occurred after 7 days from the beginning of the experiment.
3. Test Results

The results of the experiment, obtained from the temperature and humidity sensors, are shown in figure 3 a. It can be seen that the values of the relative humidity ($\varphi$) sensors along the section of the structure did not reach 100 %, where the maximum value was equal to 86 %.

![Figure 3](image)

**Figure 3.** a) Distribution of temperatures and rel. air humidity along the lateral section of the structure; b) The fact of moistening due to coloring of “WSI”.

This fact indicates the absence of moisture in the structure. However, the dismantling of the structure showed the presence of condensed moisture in it. The fact of wetting and distribution of moisture along the sections of the structure was determined by the “WSI” coloration, figure 3 b. The thickness of moistening was determined from the length of the colored part of the “WSI-thread” (figure 4 a), which turned out to be in the interval 25–30 mm, as indicated by the shaded area in figure 4 b.

The intensity of coloring of “WSI-plane” turned out to be uneven (figure 5 a). The unevenness of coloring is a consequence of the varying degree of wetting of “WSI-plane”. It can be assumed that a different intensity of coloring is a fact of uneven distribution of moisture across the cross-section of the structure.
Figure 4. a) Length of the colored part of the “WSI-thread” (shown in the rectangle); b) Thickness of moistening (shaded area).

Comparison of the images (a) and (b) in figure 5 shows that the intensity of the coloring was greatest along the sensor wires fixed in the structure for the duration of the experiment. The reason for this is that wire sensors leads to the occurrence of thermotechnical heterogeneity, because of which the structure was unevenly moistened. Also during the experiment, it was noticed that the greatest intensity of color was found in those areas where the most dense contact between “WSI” and the surfaces of material layers occurs.

Figure 5. a) The moisture fields obtained on the “WSI-plane” between the external plaster and thermal insulation layers; b) Location of the sensors during the test.

Figure 6 shows how the surface texture of the mineral wool formed the corresponding pattern on the “WSI-plane”. Apparently, in areas with a more dense contact between “WSI-plane” and the material, the greatest moisture exchange was achieved. Thus, the obtained color humidity field can be not only a reflection of the distribution of moisture, but also a "map" of areas with the most intensive moisture exchange at the junction of material layers of the enclosing structure. At the same time, a different distribution of moisture requires additional investigation.
Figure 6. Influence of the surface texture of a mineral wool on the intensity of coloring of “WSI-plane”.

a) contact of mineral wool with the plaster layer
b) intensity of coloring of “WSI-plane”;
The arrows indicate how areas with tight junction resulted in a more intensive coloring of “WSI-plane”.

4. Conclusions
The fact and the pattern of moisture distribution in enclosing structures can be easily determined by the proposed color indicator method. Wired sensors (inside the structure) significantly affect the distribution of moisture in the structure due to a violation of its integrity. Therefore, the use of wire sensors to study the moisture state of structures can lead to errors. The degree of uneven distribution of moisture in the structure depends on the surface texture of the materials. Features of the surface texture of the layers lead to the formation of areas at the junction of materials with a dense and non-dense junction, which can affect the degree and nature of moisture exchange.

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