Energy and Buildings 158 (2018) 77–85

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Impact of paper and wooden collections on humidity stability and energy consumption in museums and libraries

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ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form
25 September 2017
Accepted 2 October 2017
Available online 5 October 2017

Keywords:
Moisture buffering
Modelling
Relative humidity
Energy consumption
Paper
Wood
Museums
Libraries

ABSTRACT

Much research has been focused on maintaining stable humidity conditions in buildings housing heritage collections while reducing energy use. Moisture buffering by collections themselves can have a marked effect on the stabilisation of relative humidity (RH), the key parameter for preservation. Modelling of moisture transport using COMSOL Multiphysics was applied to transform three-dimensional paper and wooden objects into their one-dimensional representations, without changing the moisture uptake and release characteristics. The results were coupled to the modelling of indoor microclimate and energy consumption in collection storage spaces with the use of WUFI® Plus software. The study revealed the crucial impact of air exchange rate of the building on the stability of indoor RH and the humidification and dehumidification loads required to maintain it. In the adequately air-tight library store, a sizeable paper collection was found to reduce the RH fluctuations from ±9% to ±6% around the yearly average and the energy consumption due to the humidification and dehumidification load by 38% when compared with the empty space, for a high-quality climate control scenario. In turn, a wooden collection, occupying a realistic fraction of a museum store was not large enough to significantly narrow down the RH variations and reduce the energy consumption.

1. Introduction

In recent years, considerable attention has been given to managing indoor environments in museums, libraries and archives in a responsible manner, particularly in terms of reducing energy use and carbon emissions [1,2]. Indoor microclimates are an outcome of many factors, of which construction materials used, air-tightness of the building envelope, its thermal insulation, installed climate control systems of ventilation, heating, humidification or dehumidification, and the collections housed in the building are the most important. A lot of effort has been put into assessing energy consumption in the specific buildings housing collections while taking into account different indoor climate control scenarios [3–6]. While temperature specifications generally aim at providing thermal comfort to visitors and staff, humidity control aims to provide adequate conditions to preserve the collections. The approaches to modelling the indoor humidity conditions included also estimation of the buffering effect by hygroscopic heritage objects housed in a building. The most reliable approach involved modelling fully coupled 1D heat and moisture transport in materials. To use the approach, Steeman et al. [7] modelled books on a library rack as a 1D system of parallel paper and air layers through which water vapour is transported and almost immediately absorbed by the paper sheets so that a 1D moisture front is attained in the paper. As the complex numerical simulations of moisture transport require detailed knowledge of considerable number of material properties and high computational load, the moisture uptake and release by materials have been commonly simplified by adopting the effective moisture penetration depth or the effective capacitance models [8].

The effective moisture capacity approach was favoured in two studies of the buffering effects of the collections [7,9]. The approach assumes that the moisture mass in the objects is always in equilibrium with the room air. This allows the moisture buffering capacity of the objects and the room air to be integrated by multiplying the moisture capacity of the interior air by a constant multiplication factor. Janssen and Roels [8] proposed a method to calculate the multiplication factor for interior finishes and objects based on standardized measurements of the moisture buffer values (MBVs). The

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https://doi.org/10.1016/j.enbuild.2017.10.005

method takes into account various time-scales of relative humidity (RH) variations in the room.

In this study, we propose an improved approach which allows water vapour diffusion in 3D objects to be accurately analysed using 1D moisture transport equations so that the buffering effects of paper and wooden collections can be precisely integrated into the building model. WUFI® Plus and COMSOL Multiphysics software codes were used for the modelling [10,11]. WUFI® Plus allows fully coupled heat and moisture transport problems to be modelled for different building components, such as exterior or interior walls, ceilings and floors. Additionally, the software takes into account the heat and moisture sources and sinks located inside rooms, including ventilation, heating, cooling, dehumidification and humidification processes. The simulations can be further used to determine energy consumption under selected scenarios of microclimate control, based on recommendations or specifications for managing environmental conditions for heritage asset collections. WUFI® Plus however, is not able to solve 3D diffusion processes in objects of complex forms absorbing water vapour from the surrounding environment through many surfaces. For this reason, an ability to analyse complex 3D geometries in the COMSOL Multiphysics software turned out to be useful.

2. Modelling the moisture uptake and release

The general approach to investigating the buffering effect of cultural heritage objects on humidity conditions is divided in this work into two steps. In the first one, a detailed numerical simulation of water vapour uptake or release by heritage objects of given dimensions is performed with the use of COMSOL Multiphysics. The results of the simulation constitute an input into the WUFI® Plus modelling, as the second step of the approach. The buffering impact of collections on the indoor humidity, and on the energy consumption for humidification and dehumidification, are investigated in the second step, depending on a selected climate control scenario.

Two types of hygroscopic materials were analysed – paper and wood. Material properties of the materials used in the model can be found in Table 1. The water vapour permeability was measured in paper stacks imitating a book in the direction parallel to the paper sheets using the approach of Massoquete et al. [12]. The sorption isotherms were measured at 24 °C and described by the Guggenheim-Anderson-de Boer three-parameter sorption equation [13].

Investigation of paper collections gave the opportunity to look closer at the buffering capacity of books stored in a library or paper documents housed in an archive. Looking closer at decorated wooden objects – exemplified by wooden polychrome sculptures – as moisture-absorbing materials most frequently found in museum collections of various kinds, gave the opportunity to study the impact of wooden artefacts on the indoor humidity in a museum store.

2.1. Modelling paper collections

For the purpose of approximating paper collections in archives or libraries, a statistical book was created based on the measurements of sizes of 384 books from the storage of the National Library in Warsaw. The obtained average dimensions were $261 \times 186\,mm^2$. The width of a block of books can take any value, to represent the required number of books placed next to each other on a bookshelf. For such statistically determined book dimensions, a numerical model of time-dependent water vapour uptake by books was prepared in the COMSOL Multiphysics environment. Material properties of the paper used in the model can be found in Table 1. Surface emission coefficient was taken as 2.5E–8 kg/m^2sPa.

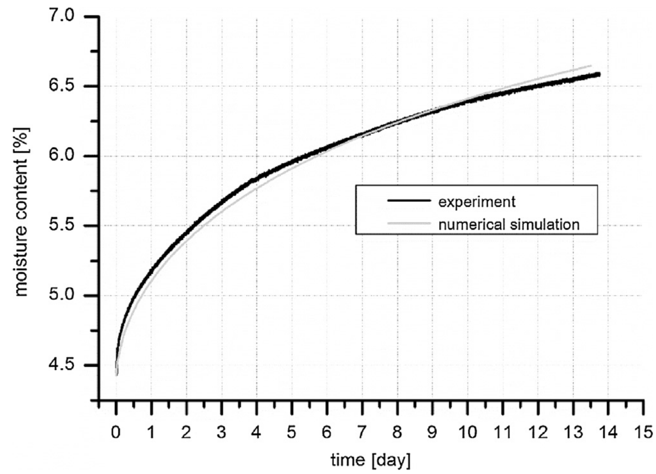

Fig. 1. Gravimetrically measured uptake of water vapour by a twentieth-century book, subjected to a step RH change from 30% to 70%, compared with the numerical simulation.

To validate the model, an uptake of water vapour by a real contemporary book in response to an RH step change from 30% to 70% was measured gravimetrically. Prior to the experiment, the book was kept for two months in a climatic chamber under 30% RH to assure the constant moisture content. In both the computer model and the book tested, the covers and spines were considered to be impermeable to water vapour so that the water vapour uptake through these surfaces was blocked and only three remaining surfaces were left open to the water vapour penetration. The obtained experimental results agreed very well with the numerical simulation, giving the maximum relative error of less than 1.5% (Fig. 1).

The computer model of books thus validated was used to investigate the moisture buffering capacity of paper collections, as well as the impact of buffering on the energy consumption. In the computer simulations of books placed next to each other on a bookshelf, only two of six book surfaces were assumed to significantly absorb/desorb water vapour from the surrounding space. Close packing of books on the bookshelves and book covers block the water vapour penetration through two side surfaces. Book spine and the bookshelf itself isolate the back and the bottom surfaces of a book. These conditions leave altogether only two surfaces, which are open to water vapour transport. Since WUFI® Plus cannot model two-dimensional (2D) sorption process, the statistical book was transformed into a set of three cuboids, having their total absorption surface and volume unchanged, but with only one side open to water vapour transport, making the problem one-dimensional (1D) (Fig. 2a).

The three cuboids, with different thicknesses, allowed us to mimic the fact that the kinetics of water vapour uptake/release changes depending on how far beneath the external absorbing surfaces of the book the moisture front reaches. The effect is due to changing ratio of the area to the volume through and into which the water vapour flows, the larger this ratio the more efficient the diffusion in penetrating the volume. To illustrate this, the 2D water vapour diffusion into the statistical book in response to a simple step RH change from 50% to 75% is considered as depicted in Fig. 2a. At the outset of the step change, the ratio of the area of the outer absorbing surfaces of the book to its volume is approximately 0.01. As the diffusion continues, the front of equilibrium moisture content corresponding to 75% RH shifts deeper into the book, and the analysed ratio of the internal area through which water vapour flows to reach the remaining book volume – where the equilibrium has not yet been reached – increases. For example, 0.1 was