EECHB 2016
on Energy Efficiency and
Comfort of Historic Buildings

Modelling impact of collections on indoor climate and energy consumption in libraries and archives

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Abstract – COMSOL Multiphysics was used to model the moisture uptake and release for library and archival collections in response to variations of temperature and relative humidity (RH) in their environment. These results were coupled to the modelling of indoor climate and energy consumption in collection storage spaces with the use of the WUFI®Plus software. The study revealed the crucial impact of air-tightness of the building on the indoor climate stability and the humidification and dehumidification loads required to provide selected climate control classes. In the adequately air-tight storage spaces, sizeable paper collections were found to diminish the energy consumption by at least 22%. For the 'cool storage' conditions, optimal for the preservation of library and archival materials, the impact of the collection on the energy consumption was reduced due to high average RH levels which required considerable dehumidification year round. The research was supported by Grant PBS2/A9/24/2013 from the Polish National Centre for Research and Development.

Keywords – hygrothermal modelling; indoor climate; energy consumption; libraries and archives; moisture buffering

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 while taking into account different indoor climate control scenarios (the recent publications comprise refs. [3-5]). And yet, all approaches to modelling the indoor climate lack any precise estimations of the buffering effect by hygroscopic heritage objects housed in a building. Only approximations have been used so far to tackle this issue ([6,7] and references quoted therein).

In this study, WUFI®Plus and COMSOL Multiphysics software codes were used to investigate the buffering effects of paper collections in libraries and archives on the indoor microclimate conditions [8,9]. 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, has limitations in simulating objects other than walls or ceilings, for which heat and moisture transport proceeds through more than one surfaces. In such cases, COMSOL Multiphysics turns out to be useful, as it can precisely simulate heat and moisture transport in objects of complex geometries. In fact museum, library and archival collections comprise objects of complex forms absorbing water vapour from the surrounding environment through many surfaces.

2. METHODOLOGY

The general approach to investigating the buffering effect of cultural heritage objects on indoor microclimate in this work is divided into two steps. First, 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 procedure. The buffering impact of collections on the indoor climate, and on the energy consumption for cooling, heating, humidification or dehumidification, are investigated in the second step, depending on the selected climate control scenario.

2.1 COLLECTIONS INVESTIGATED AND CLIMATE CONTROL SCENARIOS

For the purpose of approximating paper collections in archives or libraries, a statistical book was created basing on the measurements of sizes of 384 books from the storage of the National Library in Warsaw. The average obtained dimensions were 261×186 mm^2. Thickness 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 simulation of water vapour sorption was carried out using COMSOL Multiphysics. A relative humidity (RH) step from 30% to 70% was considered. The following material properties of paper were used: density of 690 kg/m^3, water vapour permeability of 9.6E-11 kg/msPa, measured in specimens imitating a book in the direction parallel to the paper sheets, surface emission coefficient of 3E-8 kg/m^{2}sPa, sorption isotherm measured at 24 ^{o}C and described by the Guggenheim-Anderson-de Boer three-parameter sorption equation with the constants v=5.23%, c=15.03, k=0.6 [10]. Sorption of water vapour by a real book in response to the same RH step change was measured gravimetrically and the results agreed very well with the numerical simulation.

In computer simulations of books placed next to each other on a bookshelf, only two of six book surfaces are 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, and the book spine and the bookshelf itself isolate the back and bottom surfaces of a book. Since WUFI®Plus cannot model any two-dimensional (2D) sorption process, the statistical book was represented by another cuboid, with the same volume and only one side open to water vapour transport. The surface of this new side is the sum of two surfaces of the initial statistical book. The obtained dimensions of the new 'equivalent' book are 447 × 109 mm^2. This change has led to the shortening of time needed for the material to reach the new equilibrium moisture content, in response to a step change of RH. To correct this effect, the original diffusion coefficient was systematically decreased. A perfect agreement between the 'true' 2D water vapour diffusion and sorption in the books, and their 1D approximation was achieved when the diffusion coefficient was divided by 1.5 that is to say was taken to be 6.4E-11 kg/msPa. Such 1D model of a statistical book with the modified diffusion coefficient was implemented in the WUFI®Plus simulations.

Four climate control scenarios based on the ASHRAE specifications for classes of climate quality in museums, libraries and archives were analysed [11]. First, the ASHRAE highest class of climate control AA was considered reflecting the conventional 'ideal' option, and a single value RH target of 50% with conservative tolerance of variations of ± 5% was selected. The ASHRAE B class of control was selected as the second case, in which RH was allowed to vary between 40-60%. This class of control is a moderate-cost strategy in historic buildings – also in use by museums – of limited potential for tighter climate control. At the same time, class B constitutes little risk to most paintings or artefacts and no risk to most books. International Institute of Conservation IIC and ICOM Conservation Committee recommended the 40 – 60% RH range as acceptable for loaning objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue) to international exhibitions [12]. The ASHRAE class of control C, in which RH was assumed only to stay within the 25-75% RH range all year round, was selected as an option in which just high risk extremes are prevented. In all three climate control scenarios described, the temperature was maintained at a constant level of 21 ^oC all year round to ensure human comfort. The ASHRAE 'cool storage' recommendations optimal for the preservation of library and archival material, were the last climate control scenario. The RH range between 30 and 50% and natural yearly temperature cycle, but not dropping below 10 ^oC, was assumed.

2.2 MODELLING OF INDOOR CLIMATE

A typical storage space of 14 × 15 × 2.5 m^3 (volume of 525 m^3) in a historic building housing a library or an archive was considered. The building envelope was modelled with the following materials (interior to exterior): walls – cement plaster (0.015 m), ceramic brick (0.51 m), sandstone (0.1 m); floor – stone (0.05 m), cement base (0.05 m), reinforced concrete (0.3 m); celling – cement plaster (0.015 m), reinforced concrete (0.15 m), mineral wool (0.05 m), cement finish plaster (0.05 m), asphalt roofing felt (0.005 m). The water and heat transport properties for these materials were taken from the WUFI®Plus database.

Basing on a typical capacity of storage spaces for paper collections, it was assumed that the storage room housed shelves of the total length of 1780 m. Books of statistical dimensions of 447 ×

109 mm^2, placed next to each other on the shelves, took up 16% of the room space. Half of that space occupancy, 8%, was also considered in the simulation.

Natural ventilation of the storage space, typical of most historical buildings, was assumed. Two aspects controlling the natural ventilation - the air tightness of a building and its pattern of use – are reflected in the air changes per hour (ACH). Five libraries studied in the UK showed a range of ACHs between 0.28 and 0.93 h^{-1} [13]. Two extreme values of 0.3 and 0.9 h^{-1} were considered for the climate control scenarios in which temperature was maintained at the human comfort level of 21 ^{o}C, therefore, in which the conditions are suitable for people visiting the storage rooms or working in them.

In contrast, low ACH of 0.04 h^{-1} was assumed for the 'cool storage' conditions as they can be established at low running costs if the storage space is kept tight and the human traffic and work is kept to a minimum. Such ACH level was estimated in a storage facility at Vejle, Denmark, in which the concept of passive climate control through air tightness of the building supported by the auxiliary dehumidification was implemented [14]. A statistical climatic data for Krakow were taken as outside weather conditions. The energy required to remove or add 1 kg of water by dehumidification (desiccant wheel) or humidification was assumed to be 1.3 and 0.6 kWh, respectively. The moisture content in the building shell or paper was assumed to correspond to 60% RH at the start of the simulation. To avoid the effect of this initial condition on the results, two yearly cycles were considered in the simulations, whereas the results analysed come only from the second year.

3. RESULTS

3.1 BUFFERING EFFECT OF THE COLLECTIONS

Figs. 1 and 2 show the indoor RH in an empty room and in the same room when paper collections of increasing volumes were introduced, for two different ACH values and the constant temperature of 21 ^{o}C. The stationery heating regime bringing the indoor temperature to a human comfort level caused low RH indoors in cold periods as the cold air outside is drawn in and heated. As a result, the ASHRAE lowest class of climate control D (RH below 75% all year round) was attained in the empty room. The buffering effect of the paper objects begins to be meaningful only when ACH is lower than 0.3 h^{-1} in which case the minimum RH in winter is brought within the boundaries of ASHRAE class of climate control C when the amount of paper stored is sufficient. Increasing ACH to a level of 0.9 h^{-1} rises the rate of outdoor air ingress into the building, which decreases the impact of the paper collections.

For the building with ACH=0.04 h^{-1} and the "cool storage" climate conditions, the indoor average RH levels are around 60% RH. Therefore, dehumidification needs to be continually operated to ensure the required RH range between 30 and 50% RH. The buffering effect of the paper collection only minutely reduces the maximum RH level in the summer (Fig. 3) and therefore plays an insignificant role in bringing climate to the optimal conservation conditions selected.

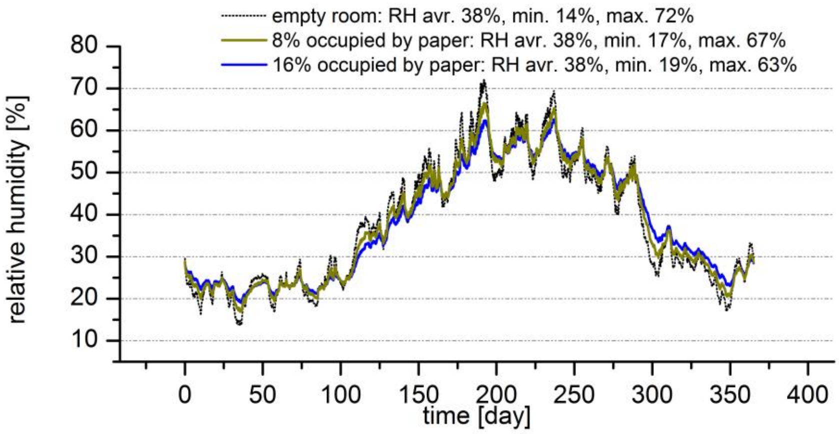

Figure 1. Buffering of indoor climate by paper collections for ACH=0.3 h^{-1} and temperature of 21 ºC.

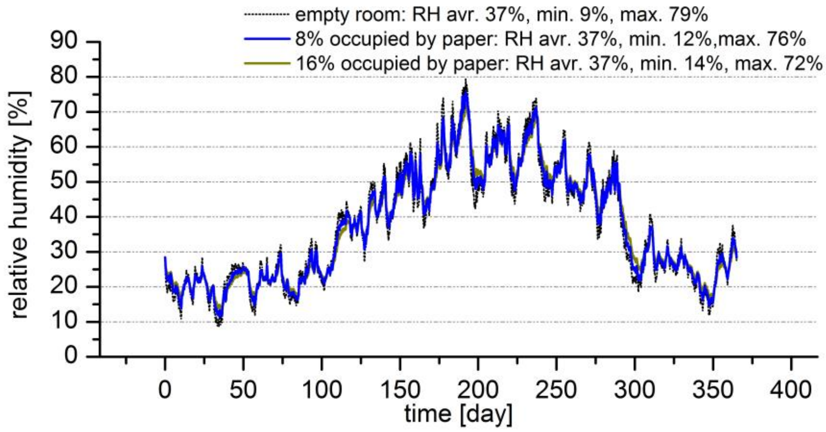

Figure 2. Buffering of indoor climate by paper collections for ACH=0.9 h^{-1} and temperature of 21 ºC.

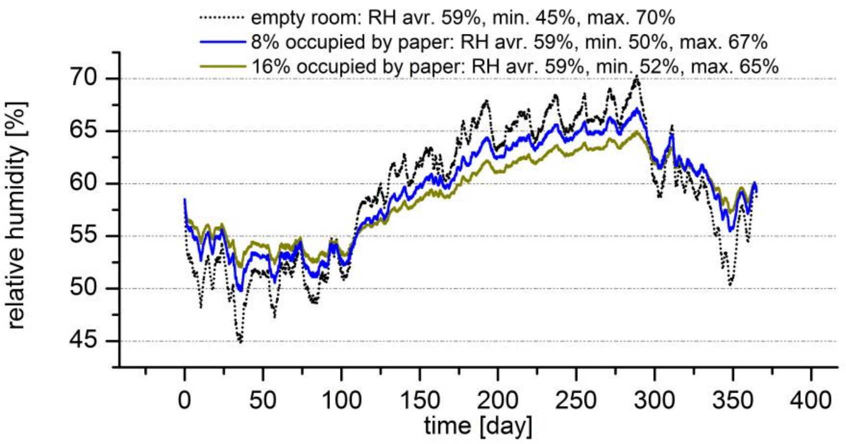

Figure 3. Buffering of indoor climate by paper collections for ACH=0.04 h^{-1} and the natural yearly temperature cycle between 10 and 21 ºC.

3.2 ENERGY CONSUMPTION UNDER VARIOUS CLIMATE CONTROL SCENARIOS

The energy demands for dehumidification and humidification calculated for various climate control scenarios and ACHs are collected in Tables 1 and 2.

Table 1. Energy consumption for humidification (Hu) and dehumidification (De) of a 210 m^2 storage space with varying volume of paper collections, for different climate control scenarios and ACH levels.

Percentage of storage space occupied by paper	ASHRAE AA (45-55% RH)		ASHRAE B (40-60% RH)		ASHRAE C (25-75% RH)	
	Hu [kWh]	De [kWh]	Hu [kWh]	De [kWh]	Hu [kWh]	De [kWh]
ACH=0.3 h^{-1}						
0	1981	530	1446	236	227	0
8%	1796	417	1306	142	175	0
16%	1625	335	1168	76	127	0
ACH=0.9 h^{-1}						
0	6063	1831	4499	975	932	33
8%	5499	1523	4082	757	779	1
16%	4974	1274	3690	585	658	0

Table 2. Energy consumption for humidification and dehumidification for the "cool storage" climate control scenario (210 m^2 of storage space).

Percentage of storage space occupied by paper	"Cool storage" (30-50% RH), ACH=0.04 h^{-1},	
	Humidification [kWh]	Dehumidification [kWh]
0	0	469
8%	0	429
16%	0	394

The data in Table 1 confirms entirely the expectation that maintaining the ASHRAE rigorous climate control scenario AA is the most demanding energetically whilst the ASHRAE most relaxed climate control class C practically does not require energy input when the storage space contains paper collections of sufficient volume. The data reveal the crucial impact of air-tightness of the building, reflected in the ACH values, on the humidification and dehumidification loads required to provide selected climate control classes. The total energy consumption is reduced by a sizeable paper collection by at least 21% when compared with the empty space (the worst case of the climate control class AA combined with high ACH of 0.9). Lower reduction of 16% in the energy consumption is caused by the collection in the case of the 'cool storage' conditions as the moisture buffering by paper has merely a smoothing effect on the yearly variations of the indoor RH around high average level of approximately 60% (Fig. 3). Therefore, a considerable dehumidification all year round is required to maintain the desired 30-50% RH range.

4. CONCLUSIONS

Although a lot of effort has been put into assessing energy consumption to maintain stable indoor microclimate in the memory institutions preserving cultural heritage collections, so far heat and moisture buffering by the stored collections has not been integrated into the simulations. This study analysed quantitatively the impact of paper collections on indoor climate and energy consumption in libraries and archives by implementing a model of a paper 'wall' equivalent to the library collection in the simulations. The results indicated that the collections can have a visible although not significant effect on stabilising the relative humidity, by absorbing and releasing moisture, only when air exchange rates are low. However, the impact of collections on the humidification and dehumidification loads and the related energy consumption crucially depends on the climate control scenarios and need to be assessed individually for each specific case.

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