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Energy use optimization in the building of National Library

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Abstract: The analysis of inner climate parameters and energy use was carried out in the Krasinski Palace in Warsaw: seat of The Polish National Library. The building includes books stores, conservation workshops, reading rooms and offices. Central hydronic heating system and sporadically used local air dryers are the only active systems. The purpose of the analysis was to check at which extent actual microclimate and energy management can be improved. Several alternative scenarios, not compromising climatic protection level of valuable collections, to optimize energy use were elaborated. It turned out, that only improving of heating control and doubling of thermal insulation thickness of ceiling to attic allows for up to 30% of energy savings. Application of extended HVAC systems is not necessary due to high hygrothermal inertia of the building. WUFI®PLUS software was used for the building simulations. The calculation model was first validated against energy use for heating and inner climate measurement results. A special module was used to account for moisture exchange between books and inner air.

1 Introduction

The building, called Krasinski Palace in Warsaw, was built 1677 ÷ 1682 by polish magnate family in the Baroque style. In 1765 the Government of the Republic of Poland repurchased the Palace and placed in it some state institutions and offices. Before the II WW it was the seat of The Supreme Court. During the Warsaw Uprising, the building was destroyed in about 80%. Its reconstruction works began in 1948. In 1961 the building was handed over to the needs of the National Library, where the remaining library collections were placed. On July 1, 1965, the Palace was entered into the register of monuments. In the years 2014 ÷ 2016 the building underwent a thorough revitalization. Currently, the Palace houses collections of manuscripts and old prints of the National Library. Beside book storage rooms there are also conservation workshops, reading rooms and offices [1].

Extended research on the building was carried out in the years 2015 ÷ 2017. The main aim was to find solutions for reduction of energy use while preserving appropriate microclimate for valuable books and manuscripts. According to conservator's suggestion, relative humidity of inner air should be maintained in the range 30 ÷ 50%. This is in line with the ASHRAE recommendations [2].

Long term measurement results were used for validation of calculation model, then several, alternative control scenarios were considered to improve inner climate and to optimize energy use. WUFI®PLUS software was used for the building simulations. The software had been extensively validated for hygrothermal building simulations [3] and already applied to calculations of microclimate development and energy aspects in archive depots [4].

2 Material and methods

2.1 Building

The Krasinski Palace (Figure 1a) has a massive brick construction. It has 3 floors, cellar and hip roof. Roof is covered with painted metal sheets. The heating consists of central hydronic system powered from the municipal heating network. Heating elements are traditional cast, iron radiators. Cellar and attic are not heated.

Outer walls are 95 cm thick (ground floor, cellar) and 70 cm (remaining floors), covered by 2 cm lime-cement plaster. Thickness of inner walls varies between 12 ÷ 140 cm depending on type (partition or supporting). There is cross vault (bricks and sandstone) over cellar. Remaining ceilings consist of ceramic plates reinforced by steel flat bars (so called Klein's construction), approximately 24 cm thick, supported by steel girders. Concrete screed (5 ÷ 8 cm thick) and boards on joists is basic floor structure. Ceiling to not heated attic is poorly insulated by only 10 cm EPS or mineral wool. Windows consists of double glass box with one additional glass pane, put at inner side, to reduce heat loss.

The building comprises rooms of diverse functions and dimensions (Table 1). Almost 40% of total floor area is taken by book magazines (Figure 1b). The total length of book shelfs in storage rooms is estimated to 27 km, the volume of books amounts to about 12% of magazine space. Local air driers are sporadically applied to avoid, hazardous for paper collections, too high air humidity.

The most representative element is so called "Wilanow room" in the central part of the building. It is an open space, starting with its own staircase at the ground floor, stretching from the first to the second floor. The interior is rented for external and internal events, like readings, concerts etc.

About 60 people (researches, conservators, office workers and other stuff) occupy the building at working time. National Library is closed to the public. Catalogue and reading room are irregularly visited by small groups of students and researchers.

a)

b)

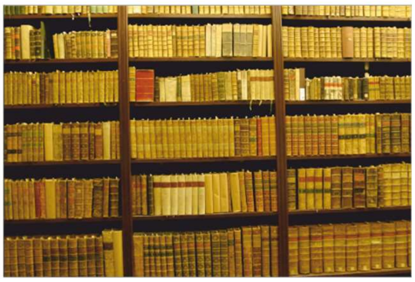

Figure 1. Krasinski Palace: south-west façade (a), collections of antique books in the building (b)

2.2 Measurements

In most of the rooms temperature and relative humidity are constantly monitored. Figure 2 shows yearly pattern (hourly values, averaged for rooms of magazines and offices) of these parameters in book depots, Wilanow room and office rooms in the period Mai 2015 to April 2016.

Outside air temperature and RH were also measured near the building. Data of solar radiation (global and diffuse) was obtained from the nearest weather station Bielany, located about 4,6 km away.

Energy used for heating was determined by monthly readings from heat meter. The heat consumption by the whole building, in the heating period 2015 ÷ 2016, was 1678 GJ, i.e. 466111 kWh. Electricity use was determined from monthly bills.

To define air infiltration, several measurements of CO_2 decay was made. On this basis, the average air exchange rate for the building was estimated to 0.13 ± 0.06 h^{-1}. The measurements were taken after working hours, after employees left the building.

Table 1. Rooms in Krasinski Palace

Room/destiny	Floor area, [m^2]	Net volume, [m^3]
Book magazines		
- ground floor	573.5	2752.8
- 1st floor	220.3	991.4
- 2nd floor	482.1	1470.4
Conservation workshops		
- ground floor	84.2	404.0
- 1st floor	97.0	519.0
- 2nd floor	153.2	467.2
Office rooms		
- ground floor	263.1	1177.3
- 1st floor	307.5	1441.2
- 2nd floor	307.3	1224.6
Catalog and reading room. 1st floor	220.3	1178.6
Representative “Wilanow room”	636.6	4873.7
Corridors. stair cases	176.4	846.0
Attic	1569.0	2982.0
Cellar	1873.8	4506.6
Total without attic and cellar	3521.5	13503.1

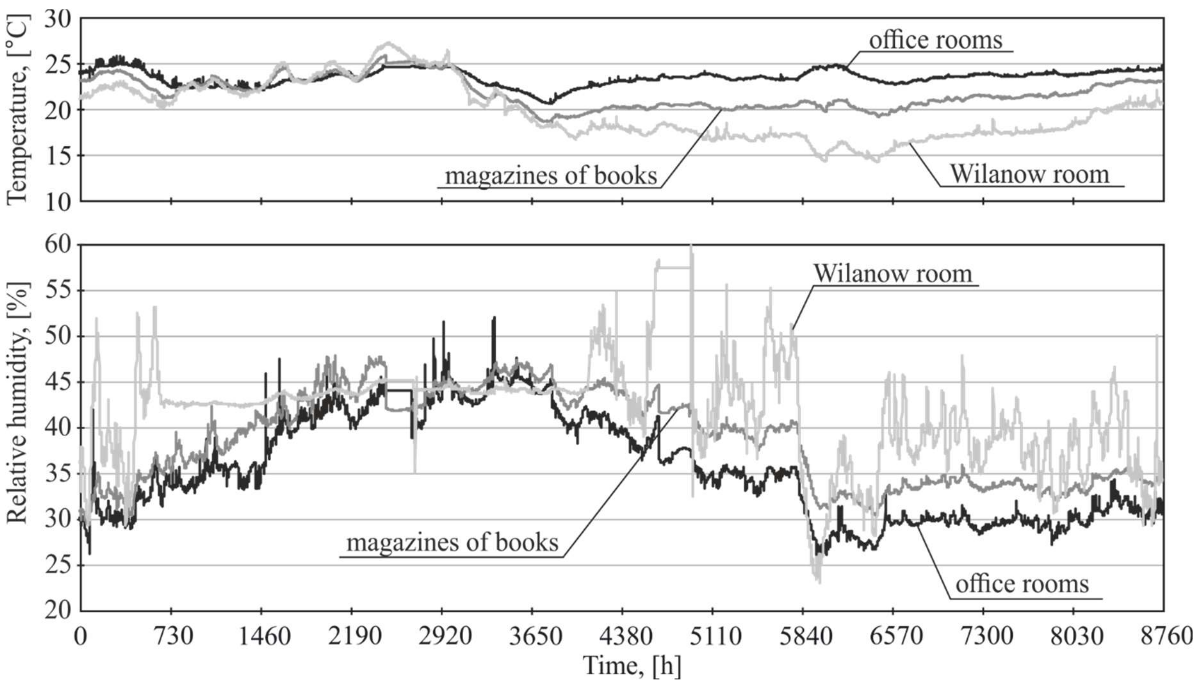

Figure 2. Measured average air temperature and RH in book magazines. office rooms and Wilanow room

2.3 Calculation model

Based on architectural plans. building 3D model was prepared in the SkechUp© software. and then imported into the WUFI®PLUS program. The model includes relevant opaque and transparent assemblies. which have impact on transient microclimate formation. The cubature of individual rooms and area of partitions had been exactly reflected. Based on specific usage of rooms and façade orientation. the building was divided into 18 zones including attic and cellar. Free floating air temperature and RH were assumed in the attic and sinusoidal yearly pattern of this parameters in the cellar. Figure 3. shows the visualization of whole building (all zones) and book magazines.

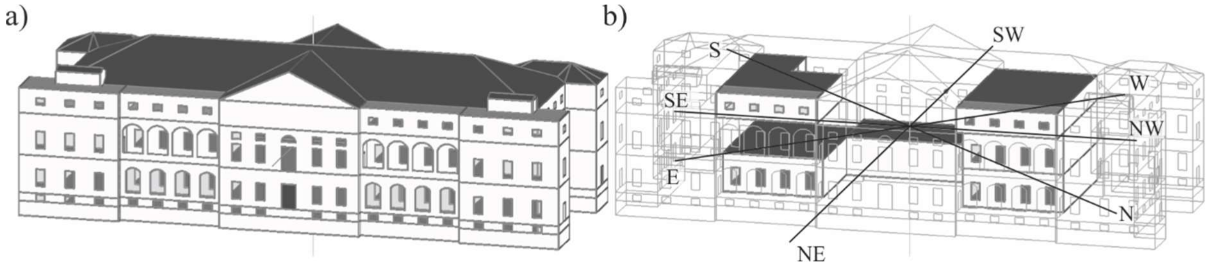

Figure 3. Building visualization in WUFI®PLUS software: a – whole building (all zones), b – book magazines.

Magazines are filled with books up to 12% of inner space. Special attention was then paid to calculation of buffering of heat and moisture in books. WUFI®PLUS can calculate 3D objects only thermally. Development of an algorithm estimating the dynamics of water vapor sorption and consequently the impact of library collections on climatic conditions was necessary. For this purpose. a statistical model of a book standing on a shelf next to other books was developed. First. the size of 384 old prints stored in one of the National Library's magazines was measured. Based on these measurements. an equivalent cuboidal block of paper cards was created assuming that the volume of this block is equal to the sum of the volumes of individual books. and the surface is equal to the sum of the surface of the respective sides of the books standing side by side. An additional condition imposed on the dimensions of the model block was the height-to-width ratio of the books. which has a good approximation of 0.71. The height and width of the statistical book included in the model block obtained on the basis of such accepted criteria are 261 and 186 mm respectively. The simulation of water vapor sorption by a row of books implies the diffusion of the vapor through the two sides of the book - upper and lateral. Access of water vapor to the other lateral side is usually blocked by a firmly glued spine. Based on this diffusion model. the statistical implementation of the book to the WUFI®PLUS module has been adjusted. In the model. the statistical book was changed into cuboid. with the same volume. but with one side diffusion open. which is the sum of the two diffusion-open face surfaces in the output book. The height and width of the modified statistical book are finally 447 and 109 mm, respectively (see Figure 4). In order to obtain agreement between the simulation results for the original (2D moisture flow) and modified statistical books (1D flow). a parametric adjustment of the diffusion coefficient was carried out. The best fit was obtained by division of the original diffusion coefficient by 1.5. COMSOL Multiphysics software was used for 2D moisture flow analysis [5]. Similar algorithm was also used in adjustment for other museum collections (e.g. wooden sculptures) [6]. Consequently. WUFI®PLUS calculated heat exchange with cuboid of books using 3D thermal calculation. and moisture exchange using geometrical and diffusive adjustment to 1D calculation. Material data for books is shown in Figure 5. Moisture storage function has been determined experimentally for several paper types and averaged to best reflect of the paper properties of book collections in the National Library [7]. Remaining data was assumed based on literature study and WUFI®PLUS database.

Assemblies of walls. ceilings as well as roof structures. in particular; layer types and thickness. were assumed based on available building documentation and own observations. Material parameters were defined from material database of WUFI®PLUS. U value of windows was estimated to 1.1 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and average solar radiation transmittance (g-value) to 0.6. Windows in book magazines were curtained to reduce potentially harmful effect of intensive light on the state of books. Hence. average g-value of windows in storage rooms was reduced to 0.1.

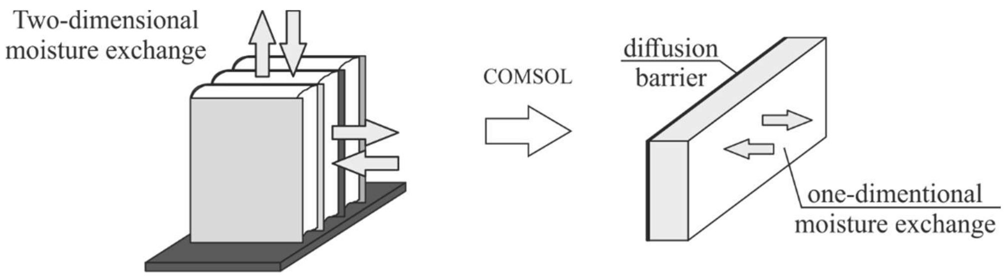

Figure 4. Adjustment of two to one dimensional moisture exchange with books

Bulk desity	[kg·m^{-3}]	618
Porosity	[m^3·m^{-3}]	0,6
Specific heat capacity	[J·kg^{-1}·K^{-1}]	850
Thermal conductivity, dry	[W·m^{-1}·K^{-1}]	0.73
Water vapor diffusion resistance factor	[-]	3.6

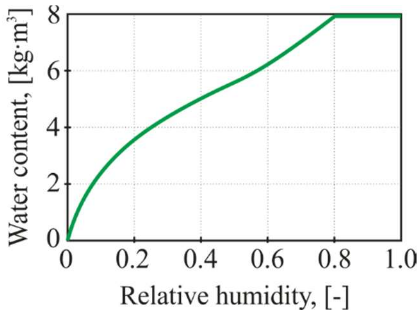

Figure 5. Material properties of books cuboid used for calculation

During work time. for all rooms excluding book magazines. air change rate (ACH) was assumed to 1 h^{-1}. Outer work time. ACH in all rooms. was assumed to 0.13 h^{-1} (based on CO_2 decay measurements). Windows in book magazines are not opened. so ACH in this rooms was assumed also 0.13 h^{-1} for the whole calculation time.

Heat gains from 60 people (convection 4800 W and radiation 2460 W. corresponding to human activity at 1.2 met – an adult performing work in a sitting position) were distributed proportionally to the floor area in all rooms except magazines and corridors. The source of moisture (3540 g·h^{-1}) were similarly assumed and distributed. Heat and moisture gains from visitors were omitted.

Electricity use was also added to heat gains proportionally to floor area. according to monthly power consumption. It was assumed that 75% of the total electricity consumption is a heat gain. of this 90% is consumed during the day at working days and 10% at night. On days off. the heat gain from lighting is constant and amounts to 500 W. It has been assumed that the radiative and convective part of electricity heat source is both 50%.

3 Calculative analysis

3.1 Model validation

Due to the lack of real data of instantaneous heat and moisture sources in individual rooms. poor heating control and uncertainty of air exchange during working time. it is very difficult to make calculations for direct comparison of air temperature and humidity patterns with measured data. Therefore. the model adequacy check was made indirectly. performing calculations with the assumption of measured air temperature and humidity in the zones. The program calculates the values of heat and moisture sources from active systems necessary to maintain the assumed air parameters. There is only heating in the zones. hence the amount of cooling. humidification and drying should be zero. Non-zero values are a measure of the (un)accuracy of the model.

Due to the valuable book collections. special attention was paid to computational simulations of storage rooms. Figure 6 shows the virtual humidification and dehumidification in magazine room on the ground floor. These values. combined with air temperature. allow to estimate the extent to which virtual dehumidification/humidification would change the relative humidity. The average deviation in this aspect for all storage rooms is under 1%. Nonetheless. temporary deviations can amount to several percent. The same analysis for air temperature (cooling impact) gave average deviation of 0.9ºC.

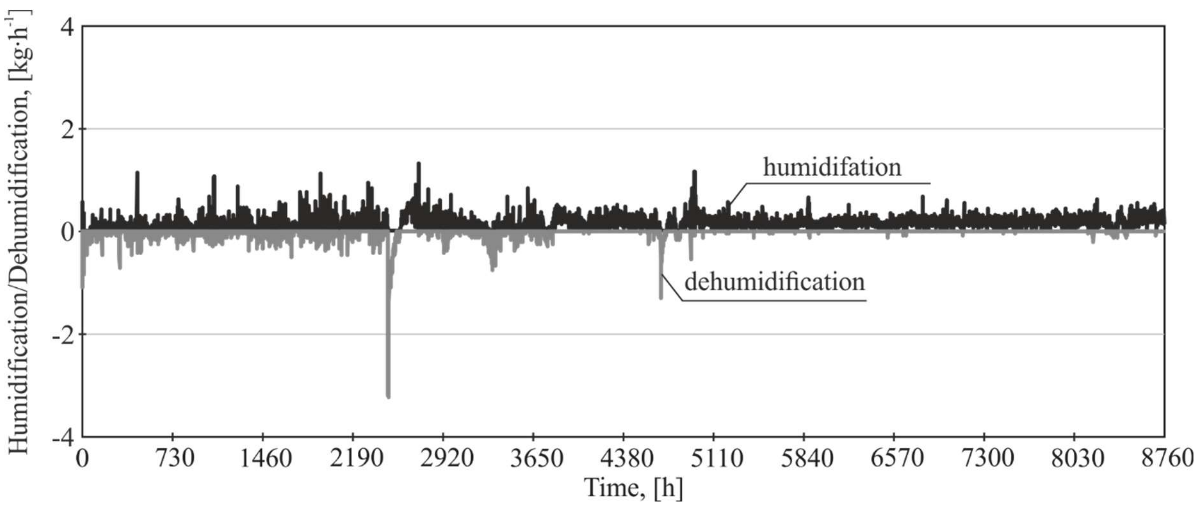

Figure 6. Virtual humidification/dehumidification of storage room on ground floor as a measure of (in)accuracy of the calculation model

Calculated heat energy. necessary to maintain measured inner air parameters in building. was 417952 kWh. The difference to real heat amount used is 10.9%. The discrepancy is due to approximate assumptions and definition of energy. Real consumption is final energy. which includes heat losses of supply pipes. Whereas energy calculated (useful energy) is the heat given off by radiators to indoor air in a convective way.

3.2 Energy optimization calculations

The only structure change proposed is improving of the thermal insulation of ceiling to unheated attic by increasing of the thickness of mineral wool from 10 to 20 cm. to mitigate influence of attics high temperature in the summer on neighboring rooms and to reduce heat loss in winter. It is an easy. low cost change. without significant intrusion into the historic character of the building. Assuming this change. three alternative climate control scenarios. to reduce energy use not compromising climatic protection level of valuable collections. were designed and tested:

I. In office rooms a minimum air temperature of 20ºC is maintained. In other rooms (including book magazines) the minimum temperature is 18°C. Air humidity in all zones is free floating depending on the transient heat and moisture balance.
II. The book magazines are heated to only 7°C (protection against freezing). Other rooms heated according to scenario I. Humidity in rooms is shaped passively.
III. Heating according to scenario II. In book magazines relative humidity is maintained below 50%. In other rooms the humidity is shaped passively.

Figure 7 shows resulting temperature and RH pattern in book magazines in scenario II. Due to lower air temperature in book magazines in winter time. values of RH higher than 50% occur temporarily. This makes dehumidification from time to time necessary in this rooms (scenario III). Moisture to be removed is relatively small (see Figure 8). within drying power of portable devices used in the library. Calculation results of energy use and dehumidification. according to alternative scenarios. are comprised in Table 2.

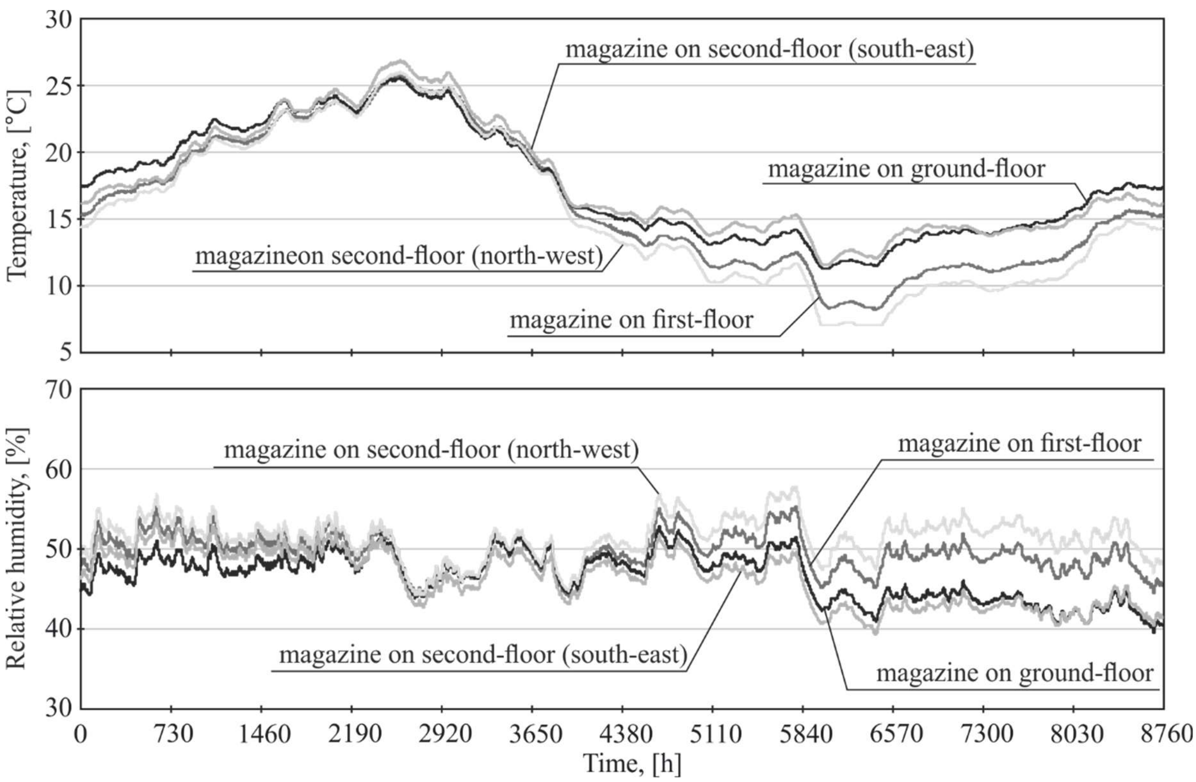

Figure 7. Inner climate pattern in magazine rooms for scenario II

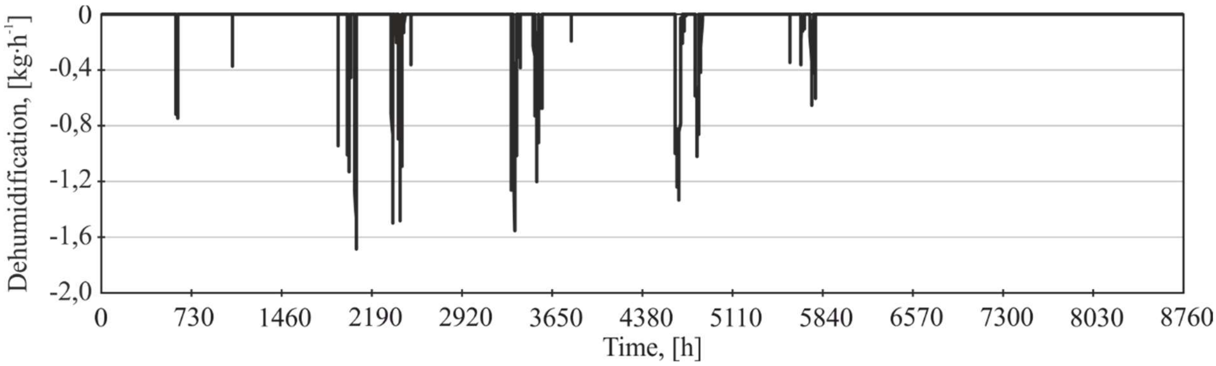

Figure 8. Dehumidification of book magazine on the ground floor. scenario III

Table 2. Energy use and dehumidification in Krasinski Palace

Specification	Energy for heating [kWh·yr^{-1}]	Dehumidification [kg·yr^{-1}]
Real energy use (measurement)	466 111	–
Energy use. model validation	417 952	–
Alternative scenario I	331 525	0
Alternative scenario II	286 427	0
Alternative scenario III	286 260	1 036

4 Summary and conclusions

Long-term measurements results of inner and outer climate parameters were used to validate calculation results in the Krasinski Palace. Uncertainty about air exchange and poor control of heating system made standard inner climate validation very difficult. Instead indirect check of calculation adequacy was applied. Using measured temperature and humidity of inner air transient heating. cooling. humidification and dehumidification loads were calculated. As only heating was available remaining loads is regarded as a measure for calculation (in)accuracy. Mean discrepancy for cooling. humidification and dehumidification was below 1%. The difference between measured and calculated energy demand for heating season 2015/2016 was about 11% for the whole building. Consequently. quantitative results of overall calculations of alternative scenarios to optimize energy use may differ within these errors. Nevertheless. the Authors believe. that following conclusions are justified considering the analysis.

Perfect heating control. 20ºC in office rooms and 18ºC in remaining rooms and improving the thermal insulation by double thickening of mineral wool on ceilings to the attic can save about 20% of energy for yearly heating.

As people only sporadically enter book storage rooms. they don't need to be heated for comfort. Exclusion magazine rooms from regular heating while preserving only frost protection (setpoint 7ºC) as well as precise heating control in other rooms. can bring about 30% of heat savings. Lower air temperature in storage rooms will cause higher heat flow from neighboring rooms (heating trough partition walls). These rooms will acquire higher heating load power.

Due to the massive construction of the walls and ceilings of the building as well as the large mass of books. the relative humidity of the air in storage rooms is subject to much lower fluctuations than the humidity of the outdoor air. Lower air temperature in the absence of heating means higher relative humidity. The optimum RH range for book collections is 30 ÷ 50%. To maintain this range. it is necessary to dehumidify of inner air. Calculation results indicate. that instantaneous dehumidification power in largest storage room does not exceed 1.7 $kg \cdot h^{-1}$. The annual total dehumidification for all book magazines is not much above 1000 kg. Nonetheless. the energy needed for drying is much lower than energy used for regular heating.

5 Acknowledgments

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6 Literature

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