SIMULATION OF ENERGY CONSUMPTION FOR DEHUMIDIFICATION WITH COOLING IN NATIONAL MUSEUM IN KRAKÓW

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ABSTRACT

It has been monitored, that about 35 % of all energy in the main building of the National Museum in Kraków is used in the summer period for cooling and dehumidification. To refine the process and possibly reduce energy demand, a series of simulations has been carried out. The main calculative tool was the WUFI®PLUS software, developed at the Fraunhofer-Institute for Building Physics, to model the hygrothermal performance of the multi-zone building.

In the analyzed building, dehumidification of the air is performed by cooler-heater coils integrated into the mechanical ventilation system. The process alters temperature and the humidity of ventilation and recirculated air significantly thereby also affecting the energy and heat balance of the simulated zones. The building and HVAC must therefore be regarded as a one coupled system.

To account for the dehumidification process in the museum in a more realistic way, a simulation model for a cooler-heater coil was built and set into the main loop of zone iteration process. The model is based on design assumptions (contact factor, temperature of cooling coil, reheating temperature). The model includes heat recovery from outlet air, mixing of ventilation air with recirculation air, dehumidification with cooling and reheating.

Simulation results allowed us to obtain the annual amount of moisture, which must be condensed from the air and energy demands of different indoor environment scenarios including 3 relative humidity ranges and 3 air change rates.

Keywords

Museum, Dehumidification, Cooling, Energy use, Simulation

1. Introduction

Managing indoor environments in historical buildings, especially museums, is regarded as energy- and cost-intensive. The increasing costs of energy and budget cuts promotes the search for reducing energy use and operating costs.

Passive inner climate in a museum is a result of interaction between building assemblies with outer climate and inner air including internal and external heat and moisture sources. Since inner climate parameters do not meet conservative requirements and cannot provide comfort for visitors, active ventilating, heating, cooling, humidifying and dehumidifying systems must be used in most existing museums.

There is a universal consensus that the museum building and the HVAC should be regarded as a single system. Appropriate adjustment of active systems to hygrothermal building performance and their efficiency obviously has a great impact on energy use in museums [2][5]. The climate control scenario, defining allowed temperature and humidity range [6], is the primary influences on energy use. As a consequence, modeling museum buildings in terms of energy, needs clear understanding of building envelopes and functions of the climate control systems, but at the same time equally clear understanding of climate control strategies to maintain high standards of collection care.

This paper presents the modeling of inner climate and energy use in the main building of the National Museum in Kraków. Since a lot of energy (about 35 % of all energy) was used in recent years for cooling and dehumidification in summer periods in this building, there is a special focus on this processes.

The main calculation tool is the WUFI®PLUS software, developed, to model the hygrothermal performance of the multi-zone building exposed to real climate conditions [11]. The software, however, can calculate active systems using simplified, idealistic model. Therefore a calculation model for cooling and dehumidification was developed and applied to reflect cooling and dehumidification processes in analyzed museum buildings in a more realistic way.

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2. Building and climate control system

The Main Building of the National Museum in Krakow was designed in 1934 as a monumental brick/stone structure (Figure 1). The design was clearly driven by the function of the building – among others, thick walls with small windows providing a good isolation of the exhibitions rooms from the direct impact of the external environment and the advantageous thermal inertia were the design's characteristic features. The project of Krakow National Museum was presented during "General Conference on Architecture and Development of Art Museums" in Madrid 1934. The committee of experts from eighteen countries emphasized the modern character of technical solutions adapted especially in the design of lighting, ventilation and communication in the building.

Figure 1 Main façade of National Museum in Kraków

The first part of the building, encompassing approximately one third of the entire design, was accomplished by 1939 when further construction was interrupted by the outbreak of World War 2. The second part of the museum was finished between 1970 and 1989, according to a modified design increasing the interior floor area to 19,500 m^2 (interior volume of 68,600 m^3). The modification was made using materials similar to those used in the original construction and involved among other additions that of a vast expanse of glass on the northern façade, making the modified design arguably less energy-efficient than the original one. Air conditioning was introduced to control stability of the climate in the 80s. Further expansion and modernization of the climatic control machinery was carried out at the beginning of 2000s. As a result, the HVAC system in the Main Building consists of 11 independently controlled units (Figure 2).

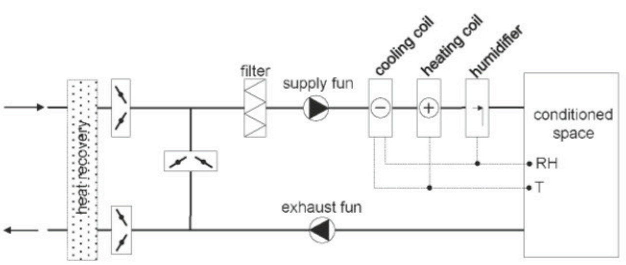

Figure 2 HVAC units operating in the National Museum Main Building.

Humidifying or dehumidifying of the air is obtained by steam humidifiers and cooler-heater coils, respectively. Heater coils are also used in winter to aid the hot water radiator heating system operating in the building. Mechanical ventilation both distributes the air conditioned in the climatic units and provides fresh air from outside. The level of air recirculation in the building can be adjusted and energy from exhaust air is partially re used thanks to recuperators with 50-80% effective thermal efficiency. Not every unit has HRV. It has been estimated, that about 18% of ventilation energy is effectively recovered from exhaust air in the whole building.

3. Modeling

3.1 Calculation tool

WUFI®PLUS is a holistic model based on the hygrothermal envelope calculation model developed by Künzel [10]. The hygrothermal behavior of the building envelope affects the overall performance of a building. WUFI®Plus is a building performance simulation tool which computes the coupled heat and moisture transfer in the building envelope. Moisture sources or sinks inside the rooms or building components, input from the envelope due to capillary action, diffusion and vapour ab- and desorption as a response to the exterior and interior climate conditions, as well as the thermal parameters are taken into account.

A stable and efficient numerical solver had been designed for the solution of the coupled and highly nonlinear equations. The conductive heat and enthalpy flow by vapour diffusion with phase changes in the energy equation are strongly dependent on the moisture fields. The vapour flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapour pressure with temperature. The differential equations are discretized by means of an implicit finite volume method.

The model was validated by comparing its simulation results to the measured data of extensive field experiments [1][3][8][11]. The indoor climate is user appointed with minimal and maximal design conditions. The software can calculate heat and moisture balances for more than one building zone, with all the sources, sinks and transfers. As long as heat and moisture balance is not equal to zero during the calculation step, the interior temperature and humidity is adapted. For example, if the heat loss through the building envelope and ventilation is more than the internal heat gains, plus space heating capacity, the interior temperature is iteratively decreased as long as the loss and the gain is the same.

3.2 Building model

As far as the climate control is concerned, the building can be divided into three distinct zones: unheated zone at the vehicle entrance to the museum and reloading area, partially heated zone in the basement of the building and heated/air conditioned zone encompassing most of the building – the floor area of 19.500 m^2 and volume of 68,600 m^3. The heated/air conditioned premises house several permanent galleries, a space for temporary exhibitions, stores, offices, the library, conservation studios and technical workshops. The collections range from paintings on canvas, decorative art objects and militaria to mixed-media modern works of art.

The model of the Main Building of the National Museum in Krakow took into account its most important features, including the building materials and technologies used in the building's two-phase construction. The external walls were represented in the model as multilayer structures in accordance with the energy audit performed. The partitions and floors were taken into account in the calculations as thermal and moisture reservoirs instantaneously interacting with the indoor air.

Each building material was selected from WUFI®PLUS database and was characterized, among others, by thermal and moisture conductivity and sorption isotherms. Calculations took into account not only the construction of the building envelope, but also heat and moisture gains from people working in and visiting the building. The latter number was assessed based on the number of tickets sold during 2010-2012 and the assumption that a visitor spends 2 hours on average in the museum.

The analysed building has a heavyweight type of construction with great heat and moisture capacity. It has been observed, that initial conditions, especially initial moisture content of assemblies, has a great impact on moisture balance and relative humidity. To obtain proper initial conditions, calculations started on 1st July and lasted 18 months, but only results for the last year were evaluated.

Figure 3 shows visualisation of the building in WUFI®PLUS software. The most important building parameters are summarized in Table 1. Moisture storage functions for building materials are shown in Figure 4.

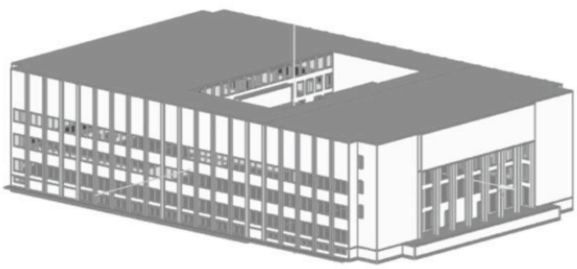

Figure 3 Visualization of National Museum Building in WUFI®PLUS software.

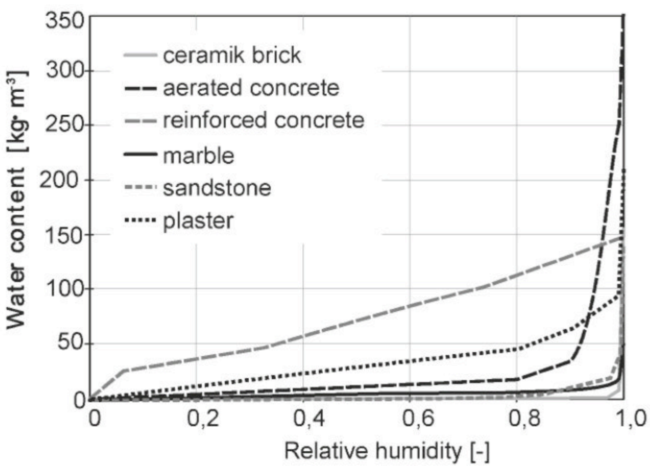

Figure 4 Moisture storage functions for building materials.

Table 1 Main building parameters

Specification		Value
Zones		
Conditioned zone (exhibition rooms)	net volume [m^3]	68601
	floor area [m^2]	19500
Partially heated basement	net volume [m^3]	15073
	floor area [m^2]	5980
Unheated space (vehicle entrance, reloading area)	net volume [m^3]	2612
	floor area [m^2]	503
Assemblies		
Outer wall old part (by the year 1939), (plaster, ceramic bricks 51 cm, cladding sandstone 10 cm)	area [m^2]	2050
	U [W/m^{2}K]	1.1
	λ [W/mK] [1]	0,8/0,8/1,7
	μ [-] [2]	19/22/73
Outer wall newer part (by the year 1989), (plaster, aerated concrete 51 cm, cladding sandstone 10 cm)	area [m^2]	4147
	U [W/m^{2}K]	0.83
	λ [W/mK] [1]	0,8/0,5/1,7
	μ [-] [2]	19/8/73
Roof (plaster, reinforced concrete 15 cm, mineral wool 5cm)	area [m^2]	5928
	U [W/m^{2}K]	0.78
	λ [W/mK] [1]	0,8/1,8/0,04
	μ [-] [2]	19/76/1,3
Ceiling to basement (cladding marble 5 cm, reinforced concrete 15 cm, plaster)	area [m^2]	5234
	U [W/m^{2}K]	1.68
	λ [W/mK] [1]	1,7/1,8/0,8
	μ [-] [2]	54/76/19
Inner wall (plaster, bricks 12 cm, plaster)	area [m^2]	3500
	λ [W/mK] [1]	0,8/0,8/0,8
	μ [-] [2]	19/22/19
Inner wall (plaster, concrete 20 cm, plaster)	area [m^2]	1627
	λ [W/mK] [1]	0,8/1,8/0.8
	μ [-] [2]	19/76/19
Inner wall (plaster, concrete 40 cm, plaster)	area [m^2]	8359
	λ [W/mK] [1]	0,8/1,8/0.8
	μ [-] [2]	19/76/19
Windows	area [m^2]	2418,0
	U [W/m^{2}K]	3.0/(5,0)
	g-Value [-]	0,60/(0,73)

[1] – thermal conductivity
[2] – water vapor diffusion resistance factor

3.3 HVAC modeling

As already mentioned WUFI®LUS software models HVAC in an idealized way. According to defined system capacities, the appropriate heat and moisture amount is provided or removed from inner air. As the dehumidification process applied in the museum alters not only humidity, but also the temperature of ventilation and recirculated air, the simplified model cannot be used efficiently. Therefore a more detailed model for air conditioning process in the museum was developed and integrated into the software.

According to the ventilation system (Figure 2) inlet air regains energy from exhausted air. Then the air is mixed with recirculated air. It is assumed, that recirculation is constant in time with 4 ACH (274404 m³/h). If relative humidity of inner air exceeds the upper limit (eg. 60 %), the coil is cooled down and, if its temperature drops below dew point of flowing air, some amount of vapour is condensed. This process can be linearly depicted on the Mollier chart [10]. Figure 5 shows exemplary dehumidification with cooling for inlet air of 26 °C and 60 % rel. humidity (point 1) and 9 °C (3a), 12 °C (3b) and 14°C (3c) cooling coil temperature. Point 2 (a,b,c) can be calculated from the contact factor between cooling coil and air. The contact factor was assumed to be 80 %.

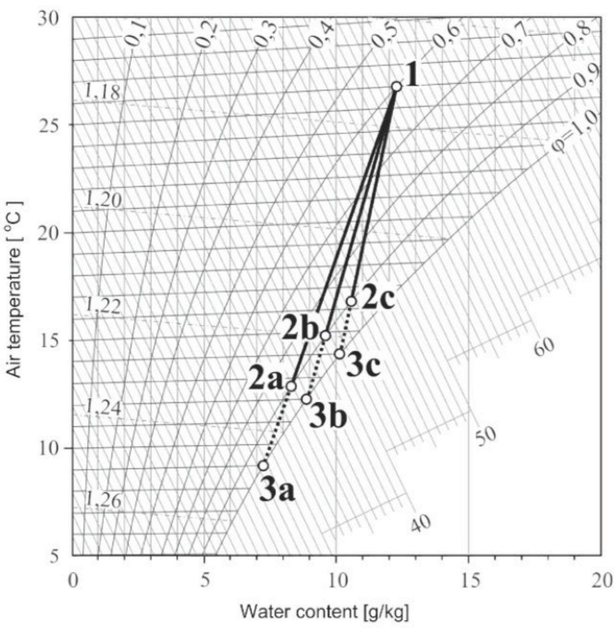

Figure 5 Exemplary dehumidification with cooling

The amount of condensed water is equal to absolute moisture content difference between points 1 and 2 (Figure 5). Dehumidification efficiency depends significantly on cooling coil temperature. If the coil temperature is too high, then too little or no moisture is condensed and the upper humidity limit of inner air cannot be maintained.

After cooling with dehumidification, the air is reheated to 19°C. The heating coil is used in winter together with water radiators for heating and in summer for reheating.

If relative humidity of inner air drops below the lower limit (eg. 35%), the air is humidified by spraying water from the humidifier.

Calculations were carried out using an explicit model with maximal time step 1 min. During each time step, inner and outer air parameters are constant and enthalpy change in every process (heat recovery, mixing, cooling with dehumidification, reheating, and humidification) is accordingly accounted for. After every time step, heat and moisture balance of the inner air is made and new temperature and relative humidity calculated (initial conditions for the next time step). Figure 6 shows the simplified algorithm for the calculations.

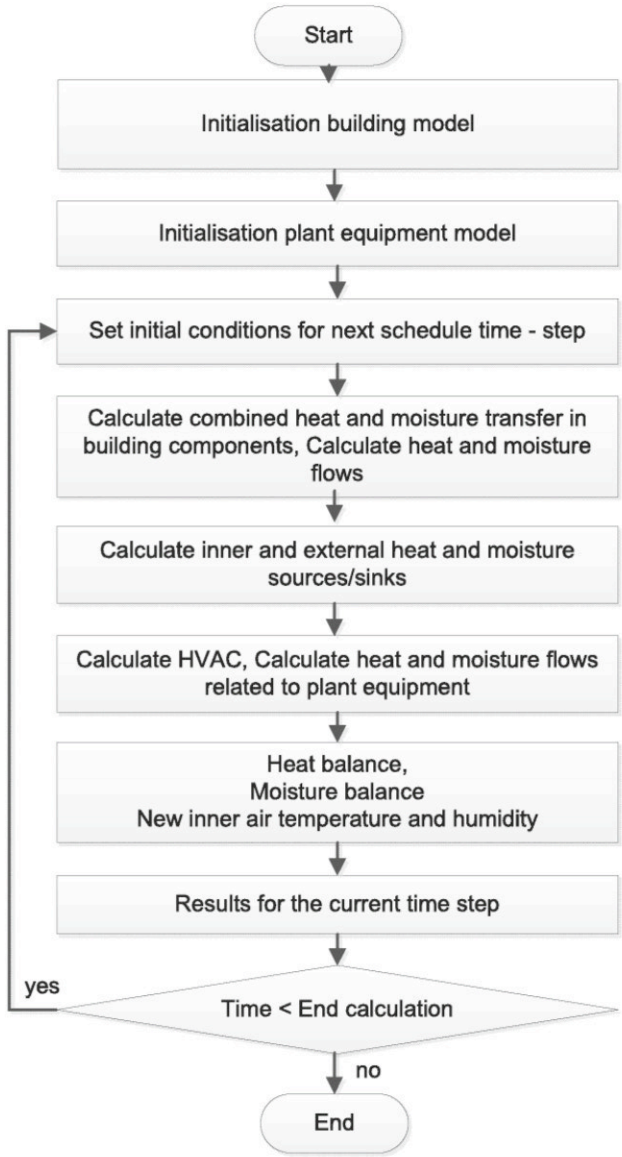

Figure 6 Simplified calculation algorithm for building and HVAC

3.4 Outdoor climate

For the outdoor climate, the test Reference Year (TRY) data for Krakow, provided by the Technical University of Lodz, Poland was used [7]. The most important parameters of the Krakow climate are summarized in Table 2.

Table 2 Features of the TRY outdoor climate for Krakow

Specification	Value
Minimum temperature	- 20.1°C
Maximum temperature	31.0°C
Yearly average temperature	8.3°C
Average temperature (V-IX)	15.8°C
Average temperature (X-IV)	3.0°C
Temperatures higher than 26.0 °C	1.86% of the year
Average rel. humidity	77.7%
Minimum rel. humidity	22%
Maximum rel. humidity	100%

Design climates were also used to account for the conditions in the unheated and partially heated zones of the building. Yearly sinusoidal variability of the temperature was assumed with the amplitude of 5 °C (maximum on August 1) and the yearly average temperatures of 10 °C and 15 °C in the unheated and partially heated zones, respectively.

4. Results and discussion

According to the presented calculation model, a series of simulations was carried out to find out the impact of control strategy (allowed RH band), air change rate and cooling coil temperature on energy use for dehumidification with cooling in the main building of the National Museum in Kraków.

The following climate control scenarios in the heated/air conditioned part of the building were used in the simulations. The temperature was assumed to be in the range of 19°C to 25°C, that is, the heating and cooling systems were operated when the temperature dropped below 19°C or surpassed 25°C, respectively. Three different bands of allowable RH variations were analysed: 45-60%, 35-60%, and 35-65% [6]. Various ventilation rates (0 - 2,5 ACH) in the museum building were also considered. Mean ACH measured in the last 2 years gave 0.7 1/h. Measurements were made twice a year (in spring and autumn) in two week cycles, using CO_2 as a tracer.

Every calculation was made for 18 months, but only results for the last 12 months were evaluated. Figure 7 shows exemplary results of inner air temperature and relative humidity, heating/cooling, humidification and dehumidification in the main zone by 35-60% RH-control, 19-25° C temperature-control, cooling coil temperature 9°C and ACH 0,7 1/h. It can be observed that both temperature and humidity of inner air are maintained within assumed ranges. No additional cooling was necessary to keep air temperature below 25°C. Whereas humidification and dehumidification had to be applied in winter and summer time respectively.

Moreover, the allowed RH variations in air change rate has a great impact on energy use for dehumidification. Therefore, a series of calculations was carried out assuming different RH variations and air change rates from 0 to 2,5 1/h. Figure 8 shows the yearly sum of condensed water and net energy demand for cooling and reheating. Cooling coil temperature was set to 9 °C for all calculations. Net energy means the heat

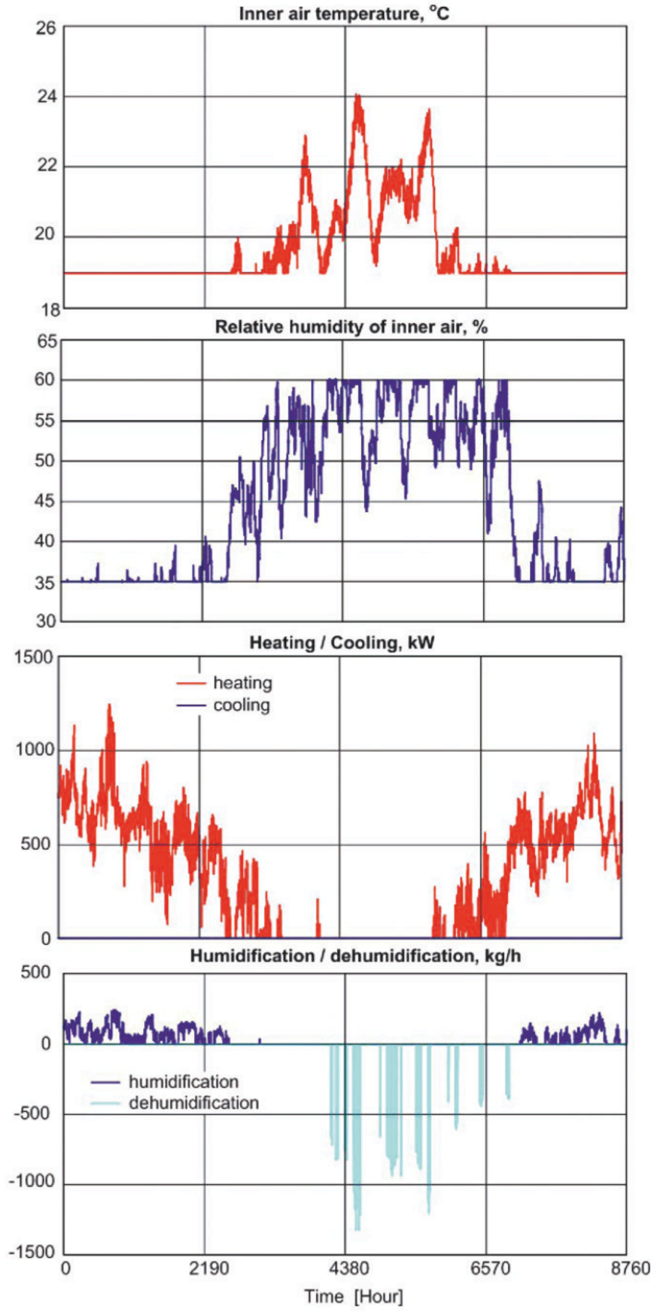

Figure 7 Yearly patterns of inner air temperature, relative humidity, heating/cooling and humidification/dehumidification.

removed from air for cooling down and vapor condensing (enthalpy change) or heat provided to reheat air up to 19 °C. Energy performance of the cooling system (heat pump, circulations, etc.) or reheating system was not modeled in detail.

As can be seen (Figure 8), ACH = 0.05 amount of condensed water and energy use takes the minimum to nearly zero. Then both condensed water and energy grow almost linearly with air change rate. RH band of 45-60% and 35-60% give nearly the same results. It means that the lower RH limit has no effect on energy for dehumidification.

Relaxing the upper limit from 60 to 65% (only 5 %) caused a reduction of both condensed water amount and energy consumed by more than 60 %. The zero energy range extended to 0.5 ACH. The RH range above 60 % is also very

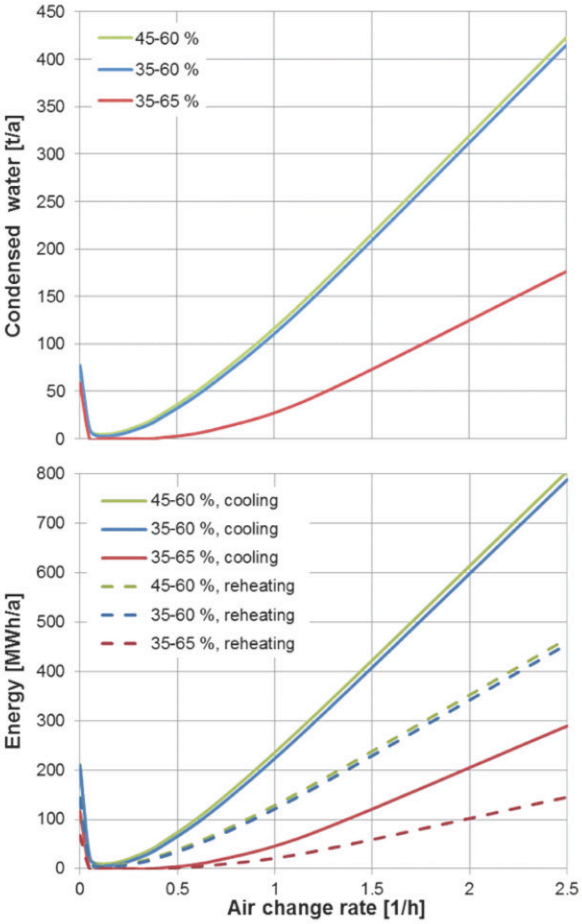

Figure 8 Amount of condensed water and net energy used for cooling and reheating depending on climate control scenarios (RH band and air change rate).

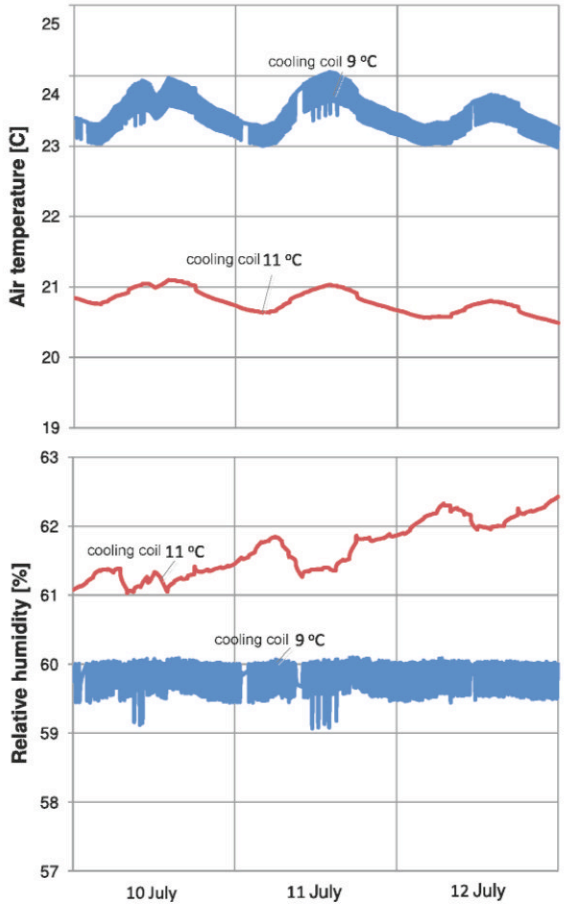

Figure 9 Air temperature and relative humidity by cooling coil temperature 9 - 11°C.

sensitive to energy use but also regarded as favourable for mould grow and biological impact. The results show, that even one percent RH above the upper limit means significant energy saving in the analysed building.

Hitherto calculations assumed cooling coil temperature to be 9 °C. This value seems to be the highest acceptable temperature by which dehumidification is sufficient. Assuming higher cooling coil temperature results in surpassing the upper RH limit. Figure 9 shows patterns of temperature and relative humidity inside the building for

3 consecutive days in July for cooling coil temperature 9 and 11 °C. It can be clearly seen that relative humidity exceeds 60 % when cooling coil temperature is equal to 11 °C. In this case the dehumidification system is working constantly and ineffectively in contrast to the highly effective, intermittent dehumidification obtained by the system with low temperature cooling coil. Paradoxically, inner air temperature is lower (Figure 9) when cooling coil temperature is higher. Recirculated and ventilation air is cooled down and reheated regardless of the dehumidification efficiency.

Lower air temperature increases relative humidity. This causes even more moisture to be condensed in comparison with lower coil temperature.

To show how cooling coil temperature influences energy use for dehumidification, the next simulations were carried out for cooling coil temperature 9-14 °C and ACH 0,4;0,7 and 1,2 1/h. The results are shown in Figure 10. Energy use increases moderately with cooling coil temperature till 11-12°C then grows rapidly achieving maximum at about 13°C (0,71,2ACH). For lower ACH (0,4 1/h) the maximum is shifted beyond 14°C. It can be assessed that for 1,2 ACH maximum energy use is about 3 times higher in comparison with energy use by 9°C cooling coil temperature. For ACH = 0.7 1/h the difference is about 5 times and for ACH = 0.4 more than 12 times respectively.

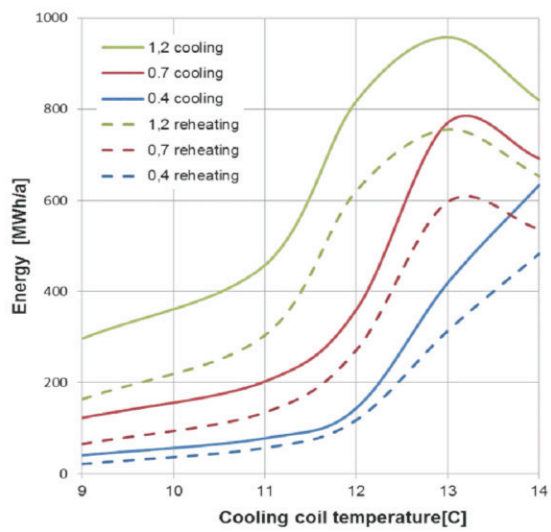

Figure 10 Energy demand depending on cooling coil temperature and air change rate

As already mentioned, cooling coil temperature higher than 9 °C should not be applied in analyzed building because upper RH limit cannot be preserved. Furthermore too high cooling coil temperature can cause huge energy consumption for dehumidification if control system does not work properly.

5. Conclusions

The paper presents a calculation model of a mechanical system with air treatment coupled with a building. All relevant processes in the system, such as heat recovery, recirculation/mixing, dehumidification by cooling coil, reheating and humidification are accounted for. The model has been integrated into hygrothermal building simulation software WUFI®PLUS. Exemplary calculations were made for the main building of the National Museum in Kraków. The results obtained allowed the quantitative assessment of the influence of assumed microclimate control strategies and some system parameters on net energy use for dehumidification.

It could be observed, that the upper RH limit and air change rate have significant impact on energy consumption for dehumidification. At about ACH = 0.05 1/h amount of condensed water and energy takes minimum to nearly zero, then grows almost linearly with air change rate.

Relaxing the upper RH limit from 60% to 65% gives over 60% energy reductions, regardless of ACH.

The highest, acceptable cooling coil temperature for the analysed museum building is 9°C. Increasing cooling coil temperature means inefficient dehumidification (surpass upper RH zone limit) and increase in energy use. For the analyzed building, the maximum energy use, depending on ACH, can be from 3 to more than 12 times higher than energy used by the acceptable cooling coil temperature.

6. Acknowledgements

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