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# Adaptive Ventilation Towards Better IEQ: A Case Study of the Pilgrimage Chapel of Holy Stairs

**Adaptivní větrání jako nástroj ke zlepšení kvality vnitřního prostředí: případová studie poutní kaple Svatých schodů**

*Reviewer*
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*The paper presents the problem of unsatisfactory indoor environmental quality in the Chapel of Holy Stairs in the north of the Czech Republic, which is represented by a high value of air moisture leading to the degradation of the historic interior and frescoes. In order to understand the overall hygro-thermal properties of the airflow in the chapel, monitoring of the air temperature and relative humidity in the chapel and the cloister was carried out. The monitoring data, which provides a basis for examining the initial condition of the Chapel, is used for the calibration of the numerical model developed within the current research. The model is created in a simplified form based on physical principles and the heat balance method. The numerical model enables one to find a suitable control algorithm for the adaptive ventilation system*
*The main aim of this work is to present the benefits and limitations of adaptive ventilation. The analysis highlights the influence of the controlled air supply on the indoor environmental quality and the overall reduction in the amount of air moisture.*
***Keywords:*** *adaptive ventilation, indoor environmental quality, heat balance method, regression-based numerical model, historic interior*

*V příspěvku je prezentována studie Poutní kaple Svatých schodů v Rumburku, která se potýká s problémem nevyhovující kvality vnitřního prostředí z hlediska vysokých hodnot vzdušné vlhkosti. Vysoká míra vlhkosti vede k degradaci historického interiéru a fresky na stropě kaple. Za účelem stanovení počátečních podmínek a pochopení tepelně vlhkostních procesů byl proveden monitoring teploty vzduchu a relativní vlhkosti v kapli a přilehlých chodbách. Naměřená data posloužila jako základ pro kalibraci zjednodušeného numerického modelu, který funguje na fyzikálních principech zachování energie. Cílem modelu je najít a ověřit vhodný algoritmus pro přívod venkovního vzduchu do interiéru, který by vedl ke zlepšení podmínek v kapli.*
*Tato práce si dává za cíl poukázat na přínosy a limity aplikace adaptivního větrání. Prezentovaná analýza ukazuje vliv kontroly přísunu venkovního vzduchu na kvalitu vnitřního prostředí a celkové snížení množství vzdušné vlhkosti v interiéru.*
***Klíčová slova:*** *adaptivní větrání, kvalita vnitřního prostředí, metoda tepelné rovnováhy, regresní metoda, historický interiér*

## INTRODUCTION

Historically valuable interiors require special attention in terms of the indoor environmental quality, where hygro-thermal properties of the indoor air play a significant role. The level of the air temperature and relative humidity, and, in particular, their sudden fluctuation over the time, have wide implications on the preservation of the interior. Unfortunately, in many cases, the indoor air properties are far beyond the tolerance zone given by the relevant standards.

Most of the historic interiors contend with problems related to high moisture level, which can lead to cultural heritage deterioration [1]. Leaving aside the structural faults, one of the most common problems is condensation on the internal surfaces, which occurs due to the high accumulation capability of the heavy historical construction. Especially in spring, the surface temperature of the walls is still under the dew point of the inlet outdoor air and the condensation of water vapours in the air can appear. As a result, the historic frescoes can be irreversibly damaged.

The ideal solution for maintaining appropriate internal conditions in order to preserve the artefacts is the installation of an air conditioning system. Nevertheless, this solution may be unacceptable for two main reasons: the high investment and maintenance cost and the high impact on the historical interior related with the new addition of the air conditioning system, which is in contradiction with the preservation attempts. [2]. Therefore, this solution is not a preferable option for most historical buildings. Adaptive ventilation is potentially a low-energy and low impact alternative. By using sensor technology, a ventilation system only runs when the outdoor air has the potential to improve hygro-thermal properties in the interior [8].

An adaptive ventilation strategy is provided via controlled openings, air dampers or fans. This strategy takes the change of the air temperature and the level of the air moisture in the exterior and the interior into account. Based on the evaluation of the current conditions, the control algorithm recommends an action to achieve the desired airflow of the outdoor air. The actuation can be executed manually by an operator, who manually opens the window or automatically opens the window via a servomechanism [5]. If the wind and buoyancy effects are not sufficient enough for providing the right amount of outdoor air, fans are utilised. [6, 7].

The goals of the adaptive ventilation strategy are to:
- adjust the indoor conditions (air temperature and relative humidity) as close as possible to the required (tolerated) zone, which is defined in the ASHRAE standard [10];
- minimise the risk of condensation associated with natural ventilation;

- minimise the intensive fluctuation of the relative humidity associated with natural ventilation [8].

The paper represents a feasibility study which evaluates the potential of the adaptive ventilation strategy and its influence to the hygro-thermal properties of the air in the pavilion with an historic fresco. The simplified numerical model was developed for the assessment of the ventilation strategy. The aim of the paper is to evaluate the influence of the timing ventilation to the conservation risk reduction for the historic frescoes.

## THE CASE STUDY

### Object description

The Pilgrimage Chapel of the Holy Stairs is part of the important cultural monument called the Loreto in Rumburk in the north of the Czech Republic. Since 2014, it has been included as one of the significant places on the "Via Sacra" Pilgrims' Way [3]. The Chapel was built between 1767 and 1770 and its staircase is surrounded by unique sculptural decorations and historical ceiling frescoes, which underwent a complete renovation between 2007 and 2012 [3, 4]. However, shortly after the renovation, the fresco painting and artefacts began to show signs of damage. The presumed reason for this damage is the unsatisfactory indoor environmental quality. The damage is likely caused by the recurring conditions of the higher air humidity combined with the lower air and surface temperatures, resulting in the condensation of water vapour on the ceilings with the frescoes. Moreover, during the winter period, the air temperature often falls below zero, causing the condensed water vapour to freeze and ice to develop on the surfaces. (Fig. 1)

The previous analysis described in [12] evaluated the hygro-thermal conditions in the chapel based on the monitoring data. The analysis confirmed the assumption of a moisture ingress from the adjacent corridor. On the basis of a comparison of the results from the previous analysis and the available literature describing an adaptive ventilation application [6, 7, 8], it is possible to assume the positive effects of the adaptive ventilation for the reduction of air moisture in the chapel. These publications suggest adaptive ventilation as a possible solution for similar interiors like the Chapel of Holy Stairs.

### Monitoring data

In order to understand the hygro-thermal conditions in the interior, the monitoring of the air temperature and the relative humidity of the interior and the exterior was carried out during the period of November 2012 to June 2013 with 15-minute time steps. 14 dataloggers were used in the chapel and the adjacent cloister (Fig. 2).

*Fig. 1 The Pilgrimage Chapel of Holy Stairs [3], frost on the frescoes.*

The comparison between the results of the air temperature and relative humidity in the north-facing corridor, south-facing corridor of the ambit and the area of Holy Stairs indicates an interesting finding. Although the values of the air temperature do not indicate significant differences (except a slight fluctuation due to solar radiation), the values of the relative humidity show considerable dissimilarities. The extremely high value of the relative humidity in the north-facing corridor has a direct impact on the relative humidity values in the area of the Holy Stairs with the historic fresco. Based on these results, an additional source of moisture is expected in some parts of the cloister. This fact is supported by a visual inspection.

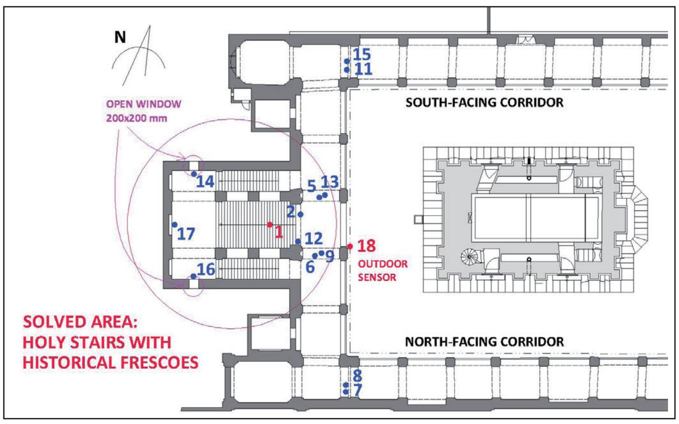


*Fig. 2 Position of the sensors in the Chapel and Cloister during the measurements. Sensor No. 1 is located under the ceiling in space of the Holy staircase. Outdoor sensor No. 18 is placed out of direct sunlight.*

## NUMERICAL MODEL

### Modelling method

In order to assess the ventilation strategy, a simplified model was created in Microsoft Excel. For the determination of the hydro-thermal microclimate properties, the variables of the indoor temperature, the indoor humidity ratio and the surface temperature, $T_i$, $x_i$ and $T_m$, respectively, must be calculated. To indicate the dependency with the other variables and parameters in the numerical model, the key variables are represented as functions (1), (2) and (3). The model is governed by these systems of equations.

The calculation of the indoor air temperature and the temperature of mass (representing the temperature of the walls) is influenced by several properties. These properties, where it is possible to determine more of less exactly, represent $c_a$ (the specific heat capacity of the air), $c_m$ (the specific heat capacity of the mass), $A$ (the area of the mass), $U_i$ (the individual heat transfer coefficient), $T_e$ (the exterior air temperature), $\rho_a$ (the density of the air), $\rho_m$ (the density of the mass), $V_e$ (the volume of the exterior air), $V_i$ (the volume of the interior air). Other properties $h$ (the convection heat transfer coefficient) and $d$ (the effective thickness) are the subject of calibration.

The calculation of the air moisture is represented by $T$ (the air temperature), $\rho_a$ (the density of the air), $x_e$ (the exterior humidity ratio), $p_v''$ (the saturation vapour pressure), $V_e$ (the volume of the exterior air), $V_i$ (the volume of the interior air). It is possible to determine these properties more or less exactly and they are the subject of the explicit calculation. $G$ (the accumulation moisture uptake) represents the amount of moisture, which is possible to be absorbed by the mass. The calculation of the accumulation moisture uptake is a complex process; thus it is the subject of the regression method.

$$T_{i,\tau(x)} = T_{i,\tau(x-1)} + f\left(c,A,U,T_e,T_m,h,\rho,d,V_e,V_i\right) \tag{1}$$

$$x_{i,\tau(x)} = x_{i,\tau(x-1)} + f\left(\rho,G,x_e,T_i,p_v'',V_i,V_e\right) \tag{2}$$

$$T_{m,i,\tau(x)} = T_{m,\tau(x-1)} + f\left(c,A,h,U,T_e,T_i,\rho,d,V_i,V_e\right) \tag{3}$$

The variables $T_i$ and $T_m$ were determined by the explicit method based on the principle of the heat balance method, which forms the basis of all load estimation methods [14]. The most important assumption is that the temperature of the air in the thermal zone is homogeneous. The other important assumptions are that the surfaces (walls, windows, floors, ceilings, etc.) have a uniform temperature. Based on these assumptions, the heat balance can be set up. The convective heat balance is calculated for the room air by (4) [9].

$$m_i c_i \frac{dT_i}{d\tau} = Q_{conv} + Q_{iv} + Q_{ce} \tag{4}$$

where:

$m_i c_i \frac{dT_i}{d\tau}$ the rate of the increase of the heat stored in the room [W]

$Q_{conv}$ the convective heat transfer from the surfaces [W]

$Q_{iv}$ the load caused by the infiltration and ventilation air [W]

$Q_{ce}$ the convective parts of the internal loads [W][14]

Contrary to the temperature calculation, the variable $x_i$ is calculated by using the regression method. The regression formula is used to describe the complex process related to the accumulation of the moisture in the structures. The calculation takes the outdoor air humidity entering the space with the ventilation and the infiltration, as well as the ability of the material to absorb the moisture, into account.

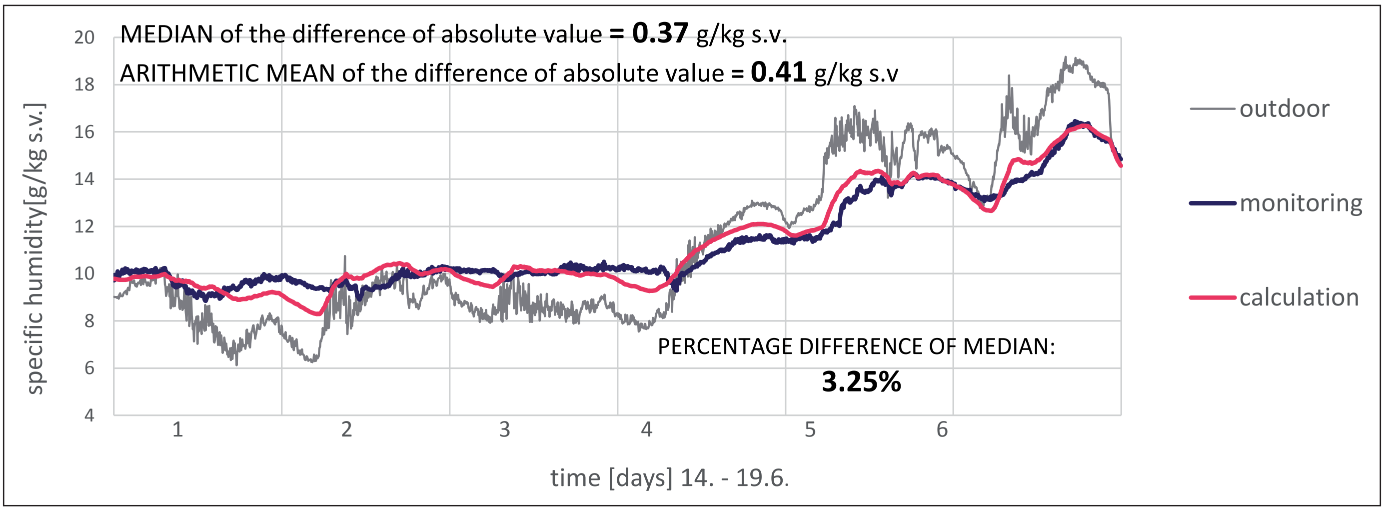


*Fig. 3 Comparison of the measured and calculated air temperature values in the chapel.*

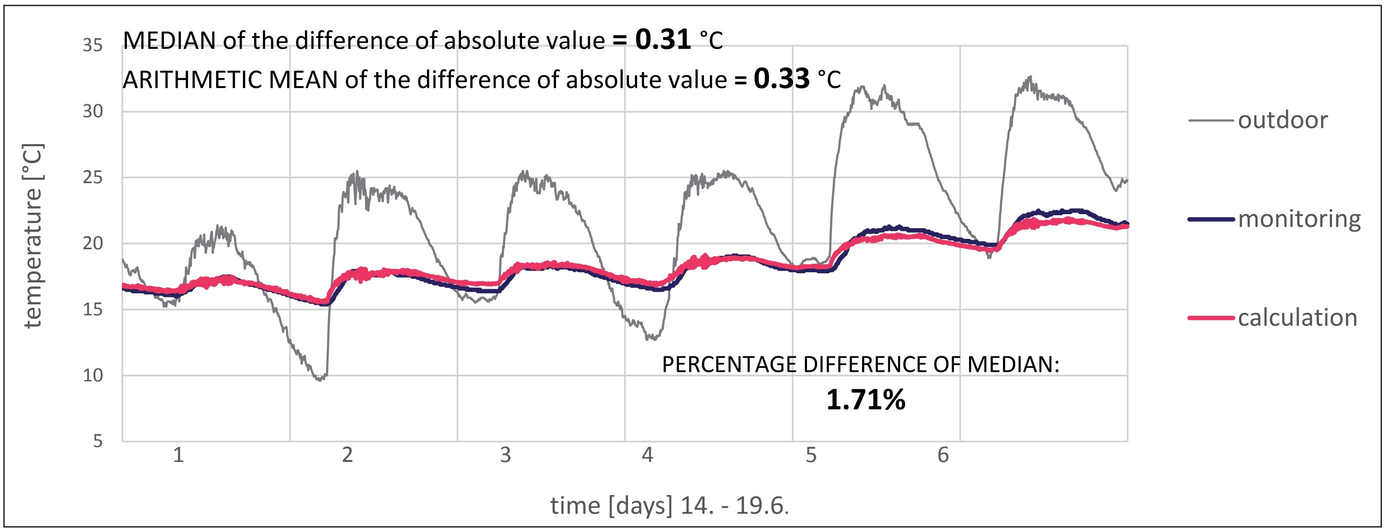


*Fig. 4 Comparison of the measured and calculated specific humidity values in the chapel.*

The principle of the numerical model is based on the calculation dependent variables $T_i$, $T_m$ and $x_i$ in specific time steps. The transient simulation is an iterative process, where the calculated values at the end of the time step enter the calculation of the next time step as the initial values. Therefore, the selection of the appropriate time step is essential. The numerical model works with a 5-minute time step. This interval is short enough for the elimination of computational errors. These errors are caused as a result of the calculation of several equations within one time-step, where they are interdependent.

The model is not able to take the possibilities and limits of natural ventilation in terms of buoyancy driven and wind driven ventilation into account. The task of the model is to verify the influence of the timing for the outdoor air supplied to the interior. The way of supplying outdoor air to the interior (fan or natural ventilation) is not the subject of the study.

### Model calibration

The model was calibrated based on the measured data for a period of 6 days and subsequently validated for other periods using the measured data for the calibration as reference.

The graphs (Fig. 3 and 4), show the results of the model verification for the randomly selected period of 6 days. The air temperature results are almost identical to the measured values in all periods that have been verified after calibration. The average absolute errors between the monitored and calculated data is 0.31 °C, which represents 1.71% from the average value of the monitored air temperature. The specific humidity values show acceptable deviations, where they are represented by the median of the difference of the absolute value between the monitored and calculated values The median was calculated to be 0.37 g/kg, which means a 3.25% difference from the average value of the monitored specific humidity. These differences can be attributed to the considerable simplification of the extensive problems of moisture accumulation in the masonry, and the non-linear influence of the measured values by the additional air humidity coming from the adjacent corridor.

## CONTROL ALGORITHM FOR THE ADAPTIVE VENTILATION

After validation of the model, the control algorithm for the adaptive ventilation were applied to determine the appropriate time for increasing the outdoor air supply. The two conditions mentioned in (5) and (6) were applied in order to move the parameters of air temperature and relative humidity closer to the tolerance zone. The control algorithm (7) avoids undesirable fluctuations in the relative humidity in the interior during the day. The last one (8) prevents the increase in the risk of condensation on the interior surfaces.

$$T_i < T_e \wedge T_i < 25 \Leftrightarrow \text{"OPEN"} \tag{5}$$

$$x_i > x_e \wedge RH_i > 60 \Leftrightarrow \text{"OPEN"} \tag{6}$$

$$|\max(RH_{\tau,0} - RH_{\tau,30min}) - min\left(RH_{\tau,0} - RH_{\tau,30min}\right)|\rangle 1.5 \Leftrightarrow \text{"CLOSE"} \tag{7}$$

$$T_{dp,ex} > T_m \Leftrightarrow \text{"CLOSE"} \tag{8}$$

In case the model evaluated at least one of the conditions as a “CLOSE” mode, it only considers infiltration.

The results of the impact of the adaptive ventilation on the interior, were evaluated in terms of three criteria: the fluctuation of the relative humidity, the risk of condensation and the reduction of air moisture.

The three ventilated modes are presented for assessment (in ach – air changes per hour):
- only infiltration: constant 0.2 ach;
- permanent ventilation: constant 1.5 ach;
- adaptive ventilation: 0.2 or 1.5 ach (depending on the boundary conditions).

In reality, of course, the air change in the interior will not be constant. On the other hand, the exact value of air change in the interior is not essential to assess the effect of adaptive ventilation. It is only necessary to determine what happens if the outdoor air supply will suddenly increase or decrease.

## RESULTS

### Prevention of high fluctuation during the day

Figure 5 represents the comparison of the relative humidity results. Even though more than half a year was measured, the graph only shows a short period (10 days) for visualisation purposes. The results with the infiltration mode only (blue line) indicate minimal fluctuation, however, these values, in just a few cases, fall over the critical value of 75 % RH. On the other hand, the permanent ventilation results (green line) show extreme daily fluctuations reaching almost 30 % RH. Moreover, in some

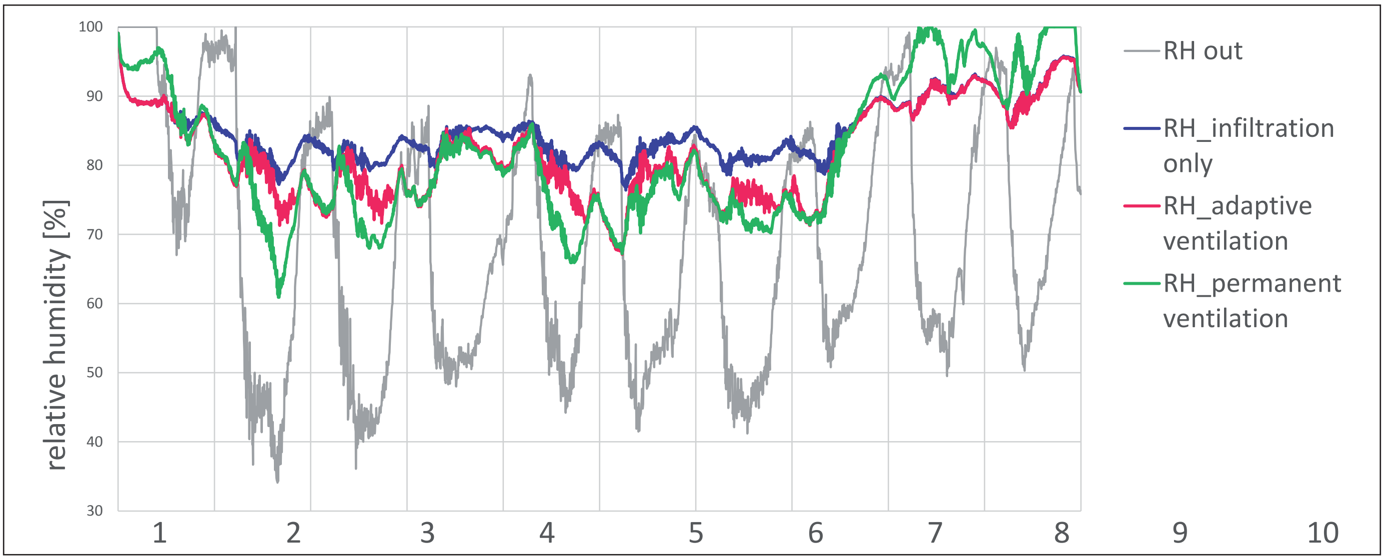


*Fig. 5 Comparison of the relative humidity values for the different ventilation modes during the selected period of 10 days.*

cases it could also lead to increased values. The adaptive ventilation (red line) represents an acceptable rate in the relative humidity decrease, and leads to an overall decrease in the relative humidity values.

**Reduction of the risk of the condensation on surfaces**

The graphs in Fig. 6 assess the degree of condensation risk during the year for the individual modes of ventilation. The percentage of time in which the indoor dew point temperature drops below the surface temperature of the walls is indicated in the red region.

The spring season represents the critical periods for all the variants. In spring, the surface temperature is still low, caused by the high heat capacity of the massive walls, and the warm wet outdoor air together with the moisture from the corridor, caused the condition for condensation. Due to the lower relative humidity in the interior, the adaptive ventilation reaches the conditions with the lower condensation risk in the infiltration mode only. As was expected, the highest potential for condensation risk, is represented by the constant ventilation.

**Reduction of the relative humidity fluctuation**

The assessment of the adaptive ventilation mode was based on the Performance Index (PI) defined as the percentage of time in which the indoor air conditions (air temperature and relative humidity) lie within the required range [13]. The parameters of the indoor environment for the historical interior are defined in the ASHRAE standard [10], which divides the indoor environment into several categories according to the degree of preservation risk. An acceptable risk is defined by the values with ±10 % RH and ±5 K deflection from the ideal values of 50 % RH and 20 °C. An extremely high risk is defined for the relative humidity values higher than 75 % [10].

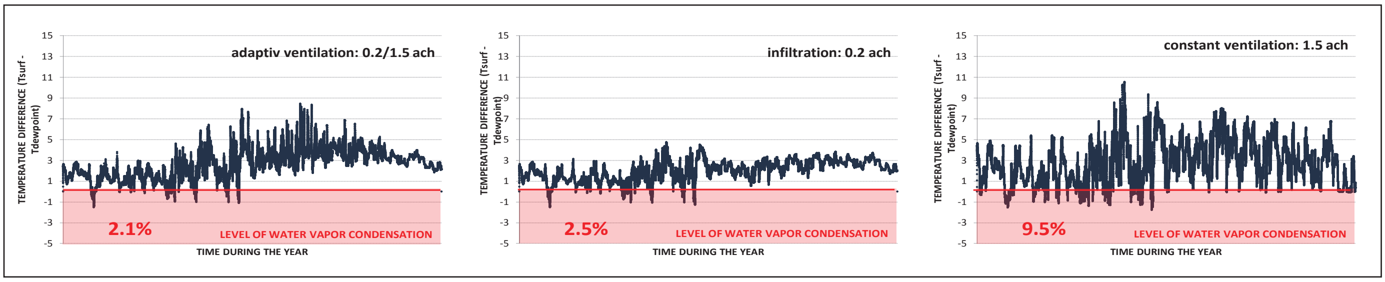


*Fig. 6 Comparison of the condensation risk for the different ventilation modes during the year.*

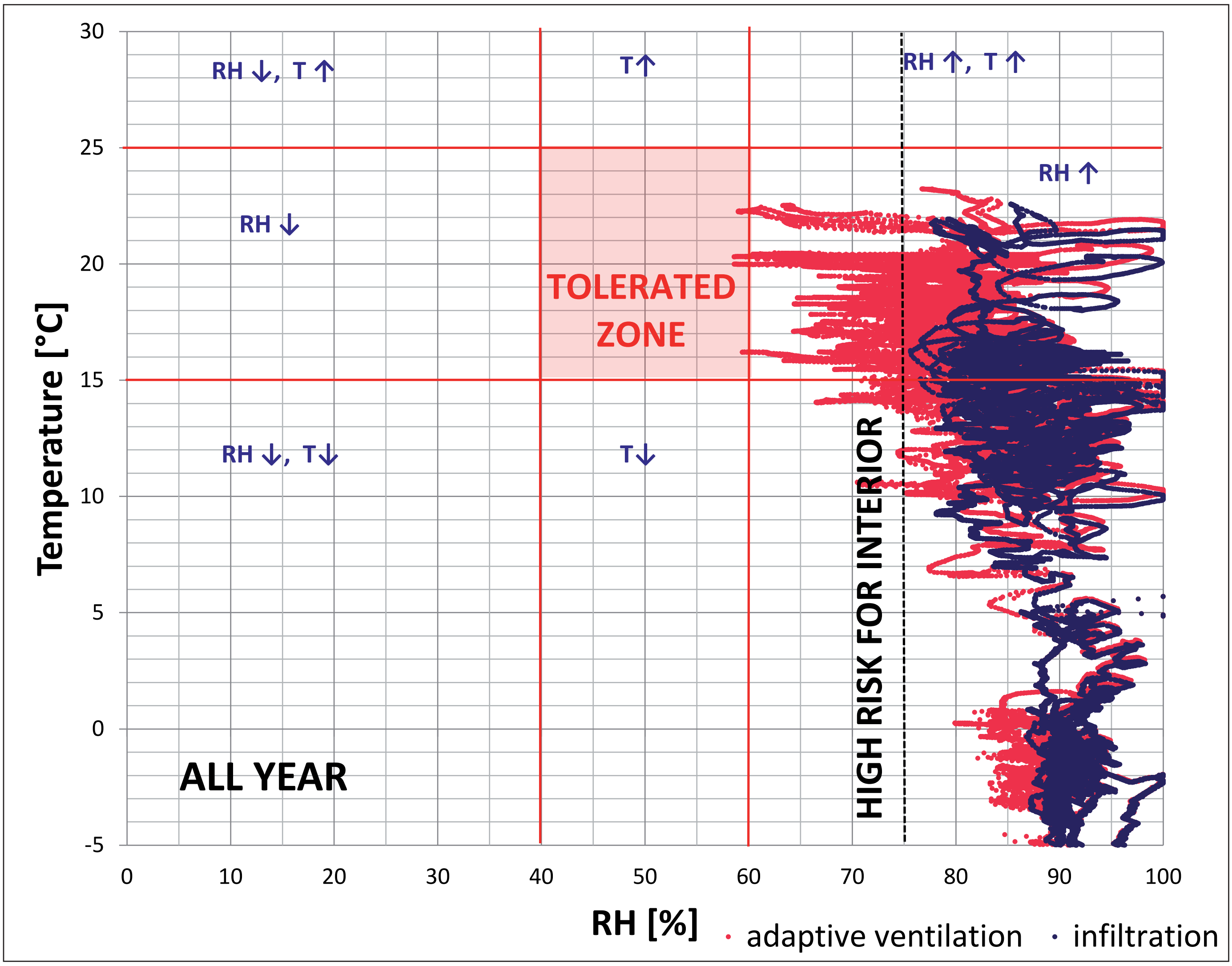


*Fig. 7 Comparison of the calculated air temperature and the relative humidity values (blue dots: with infiltration only, red dots: with adaptive ventilation).*

The red dots in Fig. 7 representing the performance of the adaptive ventilation indicate the improvements, where the values of the relative humidity are shifted towards the tolerated zone. On the other hand, no improvements can be observed in some periods. For example, the values in the winter period only show a slight improvement due to the low outdoor temperature, which prevents the use ventilation most of the time.

## DISCUSSION

In order to maintain the indoor environmental parameters in the historic interior, especially with the air moisture reduction, these interiors are often manually ventilated. However, there is the possibility that the outdoor air supply could have a negative impact on the interior. It depends on the climatic conditions. For this reason, in depth knowledge regarding ventilation of the interiors is necessary.

As expected, adaptive ventilation can only partially satisfy the quality requirements of the indoor environment. However, the results of the adaptive ventilation have shown the improvement in the indoor air quality. Minimal energy use of this system can be expected when compared to the energy use of the mechanical air-conditioning systems. It can be assumed that the influence of the adaptive ventilation on the quality of the indoor environment will not be similar for buildings with different operations. A positive effect is especially expected in buildings with some added source of moisture, which can be caused by the occupants or a structural defect. In this case, adaptive ventilation is able to provide a cheap solution to achieve acceptable conditions that preserve the historical interior.

However, the results for one-year study presented in this paper reveal that the adaptive ventilation strategy can have a positive effect over a longer period of time. The results show that the adaptive ventilation strategy reduces the specific humidity by 12% on average over the one-year period. Thus, further reduction of the moisture in the indoor air can be expected in the following years.

## CONCLUSION

The presented simulation using a simplified numerical model demonstrates that the selection of a suitable control algorithm for adaptive ventilation can have a positive effect on the quality of the indoor environment. The model was created by the regression method using the measured data of the air temperature and relative humidity in the interior and exterior. The paper describes the boundary conditions ensuring that the interior will not be damaged due to the sudden change of internal conditions and a large amount of outside air. The results of the numerical model confirmed the positive effect of adaptive ventilation on buildings with some additional source of moisture (e.g., occupants or structural defects). At the same time, the assumption of a different efficiency in the individual periods was verified, proving that the influence on the parameters in winter is minimal.

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## LIST OF SYMBOLS

$c$ specific heat capacity [$J.kg^{-1}.K^{-1}$]
$T_i$ indoor air temperature [°C]
$T_e$ outdoor air temperature [°C]
$T_m$ temperature of the mass [°C]
$T_{dp}$ dew point temperature [°C]
$RH$ relative humidity [%]
$\rho$ density [$kg.m^{-3}$]
$A$ area [$m^2$]
$V_i$ volume of indoor air [$m^3$]
$V_e$ volume of outdoor air [$m^3$]
$U$ overall heat transfer coefficient [$W.m^{-2}.K^{-1}$]
$d$ effective thickness [m ]
$h$ convection heat transfer coefficient [$W.m^{-2}.K^{-1}$]
$x_i$ indoor humidity ratio [$kg.kg^{-1}$]
$x_e$ outdoor humidity ratio [$kg.kg^{-1}$]
$\tau$ time [s]
$G$ accumulation moisture uptake [$kg/m^2$]