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Hygrothermal Interaction in Romanesque Rotunda in Znojmo

IBPSA-CZ

Tepelně-vlhkostní interakce v románské rotundě ve Znojmě

The contribution is aimed at the hygrothermal interaction of an indoor climate with an original mural painting in the Romanesque Rotunda in Znojmo. This hygrothermal interaction has been analysed through impact of the heating, ventilation, and number of visitors on the indoor climate with the subsequent impact on the mural painting. This triple parametrical numerical simulation was performed in the WUFI®Plus 3.0 software and independently in the BSim 2000 software and CalA 4.0 software. The numerical simulation of the indoor climate is validated with real long-term measurements from 2011 – 2015 in hourly time steps. A correlation of 99 % was obtained for the WUFI®Plus 3.0 software with the BSim 2000 software for the indoor climate and a correlation of 97 % was obtained for the hygrothermal diffusion in the peripheral wall with the CalA 4.0 software. The obtained results show that a thermal stress up to 2.6 K and a dryness effect up to 18.3 kg/m^3 caused by the intensive heating act on the mural painting. A thermal stress up to 1.4 K and a dryness effect up to 26.8 kg/m^3 was also obtained by the intensive ventilation on the mural painting. This obtained knowledge shows that a natural indoor climate in combination with conservation heating should be preferred over a controlled indoor climate in the Romanesque Rotunda in Znojmo.
Keywords: *numerical simulation; hygrothermal diffusion; preventive conservation*

Příspěvek je zaměřen na tepelně-vlhkostní interakci vnitřního prostředí s původní nástěnnou malbou v románské rotundě ve Znojmě. Zmíněná tepelně-vlhkostní interakce je analyzována vlivem vytápění, větrání a počtem návštěvníků na vnitřní prostředí s následným dopadem na nástěnnou malbu. Uvedená triple parametrická numerická simulace je provedena v softwaru WUFI®Plus 3.0 a nezávisle v softwaru BSim 2000 a softwaru CalA 4.0. Provedená numerická simulace vnitřního prostředí je validována se skutečným dlouhodobým měřením v období 2011 – 2015 v hodinovém kroku. Korelace softwaru WUFI®Plus 3.0 se softwarem BSim 2000 je dosažena na 99 % pro vnitřní prostředí a tepelně-vlhkostní difúze v obvodové stěně koreluje se softwarem CalA 4.0 na 97 %. Získaný výsledek ukazuje teplotní napětí v nástěnné malbě až 2.6 K a efekt vysušování až 18.3 kg/m^3 způsobený intenzivním vytápěním. Teplotní napětí v nástěnné malbě až 1.4 K a efekt vysušování až 26.8 kg/m^3 je způsoben také intenzivním větráním. Získané poznání upřednostňuje přirozené vnitřní prostředí v kombinaci s konzervačním vytápěním před řízeným vnitřním prostředím v románské rotundě ve Znojmě.
Klíčová slova: *numerická simulace; tepelně-vlhkostní difuse; preventivní konzervace*

INTRODUCTION

The Romanesque Rotunda in Znojmo was built in the 11th century as a part of the Znojmo Castle in the Czech Republic. This rotunda, with an outer diameter of 9.2 m and a total height of 12.6 m, includes an original layer of lime plaster with a fresco-secco mural painting. The upper part of the mural painting presents personages of the Premyslid genealogical cycle and combines secular iconography with a religious theme. The lower religious part is composed of typical scenes from the life of Jesus Christ and the Virgin Mary. This unique combination of secular iconography with a religious theme legitimates the sovereignty of the Premyslid dynasty.

The peripheral wall with the mural painting is built from granite stones and lime mortar in a thickness of about 1.10 m. This masonry is composed from two faces of quarry stone and is filled by a lime mortar with granite stone residue in an *opus implectum* type in between. The internal surface of the masonry is covered by lime plaster in two layers. The bottom layer of the lime plaster covers the unevenness of the stones in a thickness of up to 8 cm and the fine surface layer of the lime plaster includes an *intonaco*. This *intonaco* includes the fresco-secco technique. The fresco type is applied on the fresh surface and painting's colours are dissolved in the plaster, but the secco type is applied on the dry plaster surface, see also [1].

Research Aim

The main research aim is the analysis of the hygrothermal impact of the heating, ventilation, and number of visitors on the indoor climate with the subsequent impact on the mural painting. This hygrothermal interaction was studied through numerical simulations in WUFI®Plus 3.0 and also independently in the BSim 2000 software and the CalA 4.0 software. The numerical simulation of the indoor climate was validated with real long-term measurements provided in hourly time step over the period of 2011 – 2015. The result of numerical simulation is assessed by preventive conservation method of Target range, Historical climate method [2], and according to mandatory Decision [3]. The unacceptable indoor climate, known as the "Frost risk", the "Dryness effect" and "Microbiology risk", has been evaluated according to the ASHRAE Handbook [4].

METHODS

The hygrothermal impact of the heating, ventilation and number of visitors on the indoor climate with the subsequent impact on the surface of the mural painting has been analysed in two different independent calculation ways, see Fig. 1. The first calculation is coupled in WUFI®Plus 3.0. The second calculation is composed from BSim 2000 designed for the numerical simulation of indoor climates and CalA 4.0 designed for the hygrothermal diffusion. The hygrothermal diffusion in the peripheral

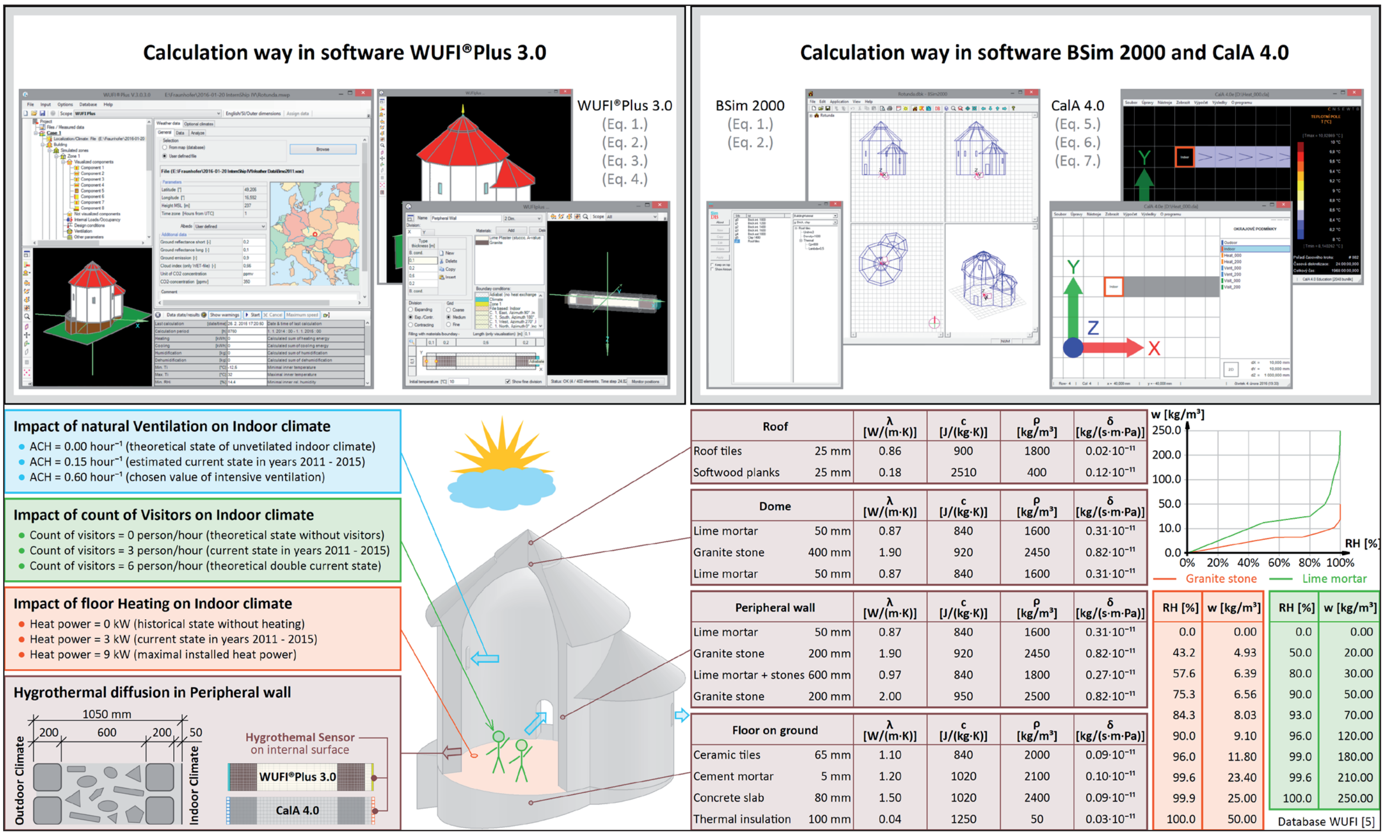

Figure 1 Hygrothermal numerical simulation in WUFI®Plus 3.0 and BSim 2000 with CalA 4.0.

wall is run with nonlinear material characteristics for the water content of the granite stone and lime mortar. The numerical simulation of the indoor climate has been validated with real long-term measurements in the Romanesque Rotunda in Znojmo, see Fig. 2.

WUFI®Plus 3.0 Software

The software WUFI®Plus 3.0 was developed at the Fraunhofer IBP for unsteady hygrothermal numerical simulations of a whole building, as well as the building components, see [5]. The hygrothermal balance of an indoor climate is calculated in each thermal zone by Equations (1) and (2), see [6] for more information. The heat and moisture transport in a multilayer building component is solved by Differential Equations (3) and (4), see [7] for more information. The right side of Equations (3) and (4) contain the storage term and the left side includes the heat flux and moisture transfer. The heat and moisture transfer are solved by a fully implicit scheme in a variable grid.

$$\dot{Q}_{\text{cond}} + \dot{Q}_{\text{vent}} + \dot{Q}_{\text{solar}} + \dot{Q}_{\text{source}} = V \rho_{\text{air}} c_{\text{air}} \frac{\partial T_{\text{int}}}{\partial \tau} \qquad (1)$$

$$\dot{G}_{\text{diff}} + \dot{G}_{\text{vent}} + \dot{G}_{\text{source}} = V \frac{\partial x_{\text{int}}}{\partial \tau} \qquad (2)$$

$$\nabla(\lambda \nabla T) + l_{\text{wv}} \nabla\left(\delta \nabla(\phi p_{\text{sat}})\right) = \frac{\partial T}{\partial \tau}\left(\frac{\partial H}{\partial T} + \rho c\right) \qquad (3)$$

$$\nabla\left(D \nabla \phi + \delta \nabla(\phi p_{\text{sat}})\right) = \frac{\partial \phi}{\partial \tau} \frac{\partial w}{\partial \phi} \qquad (4)$$

BSim 2000 Software

The software BSim 2000 from the Danish University at Aalborg is designed for unsteady hygrothermal numerical simulations of indoor climates with variable internal loads defined in the thermal zone. The numerical simulation of the indoor climate is based on a weighted average of the heat and moisture balance according to Equations (1) and (2) in each thermal zone, see [8] for more information.

CalA 4.0 Software

The software CalA 4.0 is developed at the Brno University of Technology for unsteady hygrothermal diffusion in inorganic porous materials. The heat and moisture transport are driven by three differential equations solved by the finite volume method with respect to the nonlinear material characteristics in aa regular orthogonal grid. The thermal diffusion in the material is based on a temperature gradient, see (5). The moisture diffusion is solved on the pressure gradient for water vapour (6) and separately for liquid water (7), similar in [9]. This software is designed for the numerical simulation of building components, see [10].

$$\nabla(\lambda \nabla T) + \dot{f} l_{\text{wv}} + \dot{Q}_{\text{source}} = \frac{\partial T}{\partial \tau} \rho c \qquad (5)$$

$$\nabla(\delta \nabla p_{\text{v}}) - \dot{f} + \dot{G}_{\text{source}} = \frac{\partial w_{\text{v}}}{\partial \tau} \qquad (6)$$

$$\nabla(\kappa \nabla p_{\text{w}}) + \dot{f} + \dot{L}_{\text{source}} = \frac{\partial w_{\text{w}}}{\partial \tau} \qquad (7)$$

RESULTS

The hygrothermal impact of the heating, intensity of the ventilation, and number of visitors on the indoor climate was analysed in 43,824 hourly time steps by a numerical simulation with nonlinear material characteristics. The numerical simulation correlated with the real long-term measurements by 98 % for the air temperature and by 89 % for the

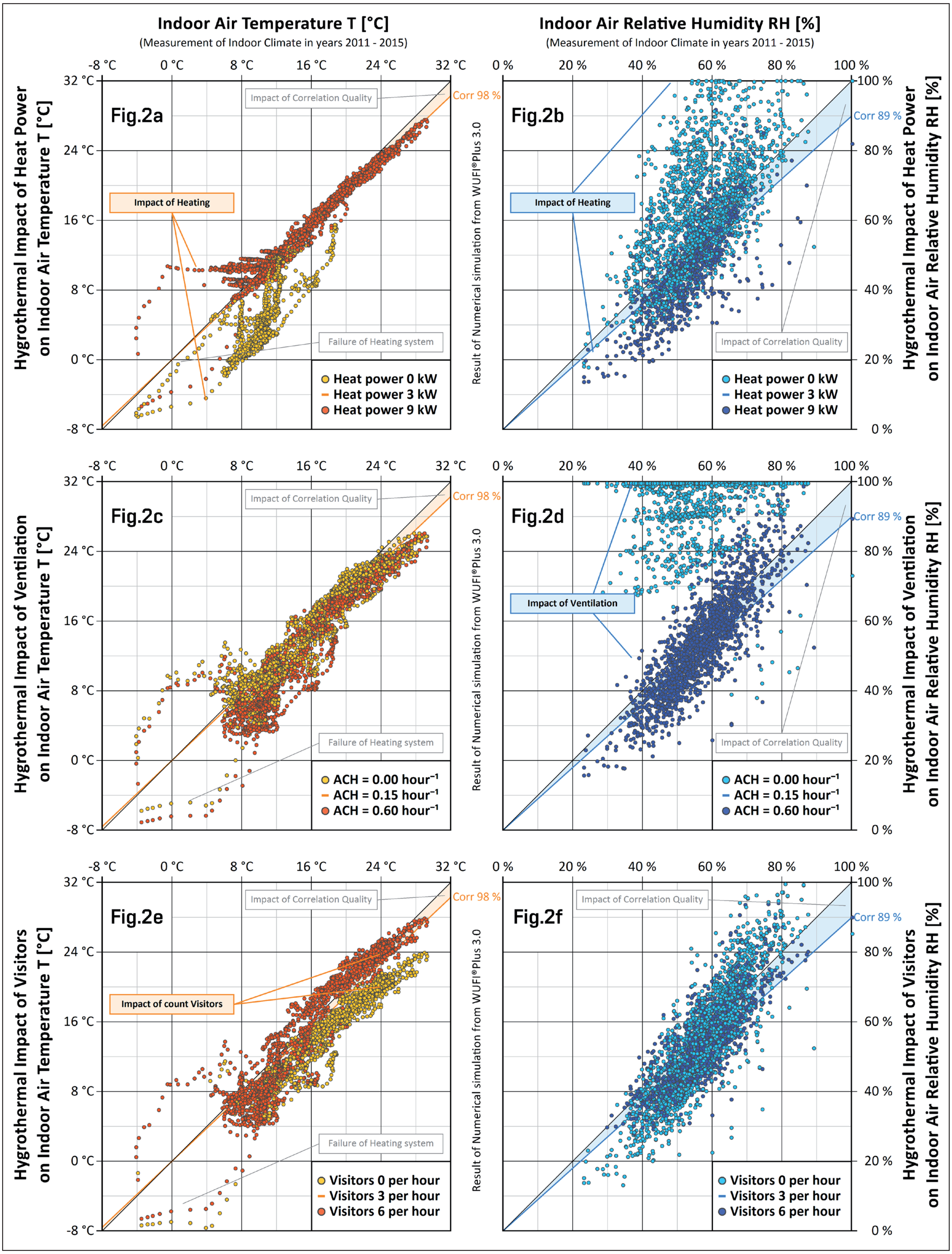

Figure 2 Hygrothermal impact of the heating, ventilation and number visitors on the indoor climate.

indoor air relative humidity, see Fig. 2. The indoor climate was applied as the boundary condition in the hygrothermal diffusion. The hygrothermal diffusion is analysed by the hygrothermal difference between the indoor climate and the surface monitoring of the mural painting, see Fig. 3.

Impact of Heating on Indoor climate

The impact of the floor heating on the indoor climate was studied for the historical state before year 1997 without any heating, and the current state in the years 2011 – 2015 with a heat power of 3 kW and a maximal installed heat power of 9 kW, see Fig. 2a | 2b. The heating system is set at a temperature of 8 ± 2 °C and the electric floor heating uses a power of 3 kW in the current state.

a) The historical state without the floor heating shows an appropriate indoor climate in a frequency of 38 % of the days for the Target range and a frequency of 51 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 25 % of the days which is caused by a Frost risk in 3 % of the days, the Dryness effect in 7 % of the days and a Microbiology risk in 15 % of the days.
b) The current state with a heat power of 3 kW shows an appropriate indoor climate in a frequency of 67 % of the days for the Target range and a frequency of 73 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 12 % of the days, which is caused by a Frost risk in 0.8 % of the days, the Dryness effect in 7 % of the days and a Microbiology risk in 4 % of the days.
c) The maximal heating from a heat power of 9 kW shows an appropriate indoor climate in a frequency of 49 % of the days for the Target range and a frequency of 56 % of the days according to Historical climate method. An unacceptable indoor climate is reached in a frequency of 20 % of the days, which is caused by a Frost risk in 0.4 % of the days, the Dryness effect in 19 % of the days and a Microbiology risk in 0.8 % of the days.

In summary, the hygrothermal impact of the floor heating on the indoor climate shows a positive effect with the lower Microbiology risk and Frost risk, but a negative effect with the increased Dryness effect in the indoor climate. The maximal heating from the installed heat power of 9 kW increases the annual heat energy consumption about 21 %. The impact of the floor heating on the mural painting is shown in the section Impact of Heating on Mural painting.

Impact of Ventilation on Indoor climate

The impact of the intensity of the ventilation on the indoor climate was studied for the theoretical unventilated state by the ACH = 0.00 h^{-1} (0 m^3/h), the current state in the years 2011 – 2015 (see the preview result) with the previously estimated ACH = 0.15 h^{-1} (45 m^3/hour) and intensive ventilation with ACH = 0.60 h^{-1} (180 m^3/hour), see Fig. 2c | 2d.

a) The unventilated indoor climate shows an appropriate indoor climate in a frequency of 0.3 % of the days for the Target range and a frequency of 0.4 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 94 % of the days, which is caused by a Frost risk in 0.4 % of the days, the Dryness effect in 0.1 % of the days and a Microbiology risk in 93 % of the days.
b) The intensive ventilation shows an appropriate indoor climate in a frequency of 52 % of the days for the Target range and a frequency of 56 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 21 % of the days, which is caused by a Frost risk in 0.8 % of the days, the Dryness effect in 16 % of the days and a Microbiology risk in 4 % of the days.

In summary, the hygrothermal impact of the ventilation on the indoor climate shows a positive effect with the lower Microbiology risk. Nevertheless, the intensive heating used for the elimination of the Frost risk increases the Dryness effect. The hygrothermal impact of the intensive ventilation on the mural painting is shown in the section Impact of Ventilation on Mural painting.

Impact of Visitors on Indoor climate

The hygrothermal impact of the number of visitors on the indoor climate was studied for a theoretical state without visitors, the current state according to the real amount of tickets sold in the years 2011 – 2015 with a monthly average of 3 visitors per hour (see the preview result) and double the current state with 6 visitors per hour, see Fig. 2e | 2f.

a) The state without any visitors shows an appropriate indoor climate in a frequency of 49 % of the days for the Target range and a frequency of 53 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 25 % of the days, which is caused by a Frost risk in 0.7 % of the days, the Dryness effect in 18 % of the days and a Microbiology risk in 4 % of the days.
b) Double the number of visitors shows an appropriate indoor climate in a frequency of 54 % of the days for the Target range and a frequency of 58 % of the days according to the Historical climate method. An unacceptable indoor climate is reached in a frequency of 22 % of the days, which is caused by a Frost risk in 0.7 % of the days, the Dryness effect in 17 % of the days and a Microbiology risk in 7 % of the days.

In summary, the hygrothermal impact of the number of visitors on the indoor climate shows a positive effect with the lower Dryness effect, but a negative effect can be seen with an increased Microbiology risk and an increased indoor air temperature in the summer season. The impact of the visitors on the indoor climate is minor in comparison with the floor heating and ventilation effects.

Impact of Heating on Mural painting

The hygrothermal impact of the heating on the surface of the mural painting was studied for the historical state before the year 1997 without any floor heating, the current state in the years 2011 – 2015 with a heat power of 3 kW and a maximal installed heat power of 9 kW. The impact of the floor heating on the surface of the mural painting is expressed by the hygrothermal difference between the indoor climate and the surface monitoring on the mural painting, see Fig. 3a.

a) The historical state without any heating shows a stable indoor climate with a temperature difference of -0.11 ± 0.10 °C (up to -0.88 °C) and a median difference in the water content of -0.69 ± 1.51 kg/m^3 (up to -9.78 kg/m^3). Nevertheless, the floor heating in a historical building is necessary to eliminate the Frost risk, see 3.1a.
b) The current state in the years 2011 – 2015 with a heat power 3 kW shows a temperature difference of -0.16 ± 0.28 °C (up to -1.09 °C) and a median difference in the water content of -0.69 ± 3.29 kg/m^3 (up to -18.3 kg/m^3) with a dependence on the heating season.
c) The maximal installed electric heat power of 9 kW shows a temperature difference of -0.24 ± 0.35 °C (up to -2.61 °C) and a median difference in the water content of -5.72 ± 3.98 kg/m^3 (up to -18.3 kg/m^3). This impact of the floor heating on the median difference in the water content is significant in the winter heating season, see Fig. 3a.

In summary, the intensive heating of the indoor climate increases the risk of a fractal failure in the mural painting and this historically new hygrothermal gradient causes mechanical tension in the original lime plaster layer. Nevertheless, the heating of the indoor climate in the historical building is suitable on the low heat power on the low set-point temperature.

Impact of Ventilation on Mural painting

The hygrothermal impact of the ventilation on the mural painting was studied for the unventilated indoor climate with $ACH = 0.00\ h^{-1}$, current state in the years 2011 – 2015 (see result 3.5b) with the previously estimated $ACH = 0.15\ h^{-1}$ and an intensive ventilation with $ACH =$ $= 0.60\ h^{-1}$. The impact of the ventilation on the original mural painting is expressed by the hygrothermal difference between the indoor climate and the surface monitoring on the mural painting, see Fig. 3b.

a) The unventilated indoor climate shows a temperature difference of -0.2 ± 0.33 °C (up to -1.59 °C) and a median difference in the water content of -0.57 ± 1.70 kg/m³ (up to -5.63 kg/m³). This small fluctuation in the water content is positive, but the relative humidity of the indoor air over 90 % RH increases the Microbiology risk, as well as the dissolving the colour pigments in the mural painting.

b) The intensive ventilation shows a median temperature difference of -0.04 ± 0.29 °C (up to -1.39 °C) and a difference in the water content of -10.6 ± 10.2 kg/m³ (up to -26.8 kg/m³). The intensive ventilation of the indoor climate increases Dryness effect, which is caused by the intensive heating to eliminate the Frost risk.

In summary, the current state in the years 2011 – 2015 with an estimated $ACH = 0.15\ h^{-1}$ (45 m³/hour) is suitable and this natural ventilation respects the natural hygrothermal response of the historical building.

CONCLUSION

The hygrothermal interaction of the indoor climate with an original mural painting in the Romanesque Rotunda in Znojmo was analysed by a numerical simulation in WUFI®Plus 3.0 and BSim 2000 + CalA 4.0

Numerical simulation

The 99 % correlation of the WUFI®Plus 3.0 with BSim 2000 software is caused by the identical geometry, identical calculation model, material characteristics, user profile in the zone, and weather file. A range of -0.3 K to -0.1 K was obtained in the difference in the indoor air temperature. A range of 0.5 % RH to 0.7 % RH was obtained in the difference in the indoor air relative humidity . A 98 % and 89 % correlation quality was obtained with the real long-term measurements and for the relative humidity of the air temperature for the indoor climate, respectively.

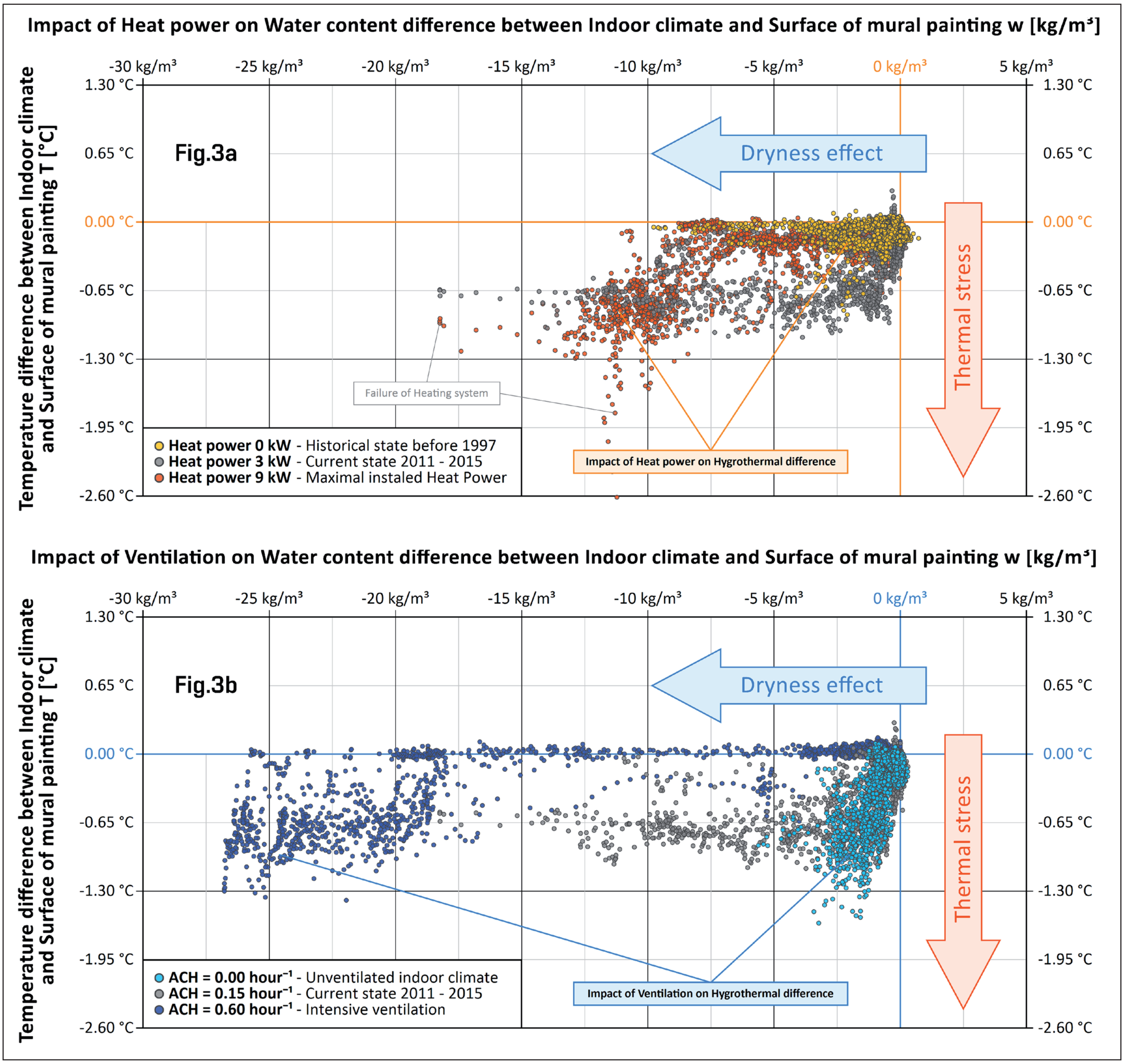

Figure 3 Hygrothermal impact of the heating and ventilation on the surface of the mural painting.

The 97 % correlation of the WUFI®Plus 3.0 with CalA 4.0 software is caused by the identical model, material characteristics and boundary conditions. The obtained difference is caused by the equidistant calculation grid in the CalA 4.0 (336 elements) software versus the adaptive grid in the WUFI®Plus 3.0 (376 elements) software. The diffusion of the liquid moisture according to Equation (7) in CalA 4.0 software was not obtained. A range of -0.2 K to 0.1 K was obtained for the difference in the temperature distribution. A range of -4 % RH to 3 % RH was obtained for the difference in the relative humidity.

Hygrothermal interaction

The hygrothermal numerical simulation for the years 2011 – 2015 shows the impact of the floor heating, natural ventilation and number of visitors on the indoor climate with the subsequent impact on the mural painting.

It is suitable to heat the historical building on a low heat power on the heating system's low set-point temperature. Overheating the indoor climate increases the Dryness effect and the Thermal stress in the mural painting. Oppositely, the historical state without any heating increases the Microbiology risk and the Frost risk.

It is suitable to ventilate the historical building with respect to the natural hygrothermal response of the historical building. The intensive ventilation causes a short-term fluctuation in the indoor climate with a negative impact on the mural painting. Oppositely, the reduced ventilation of the indoor climate increases the Microbiology risk.

The number of visitors to the building increase the Microbiology risk and the indoor air temperature in the summer tourist season. Nevertheless, the hygrothermal impact of the visitors is minor in comparison with the impact of the ventilation and heating on the indoor climate. A strictly defined tourist season and a limited number of visitors to the Romanesque Rotunda in Znojmo is supported.

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Nomenclature

c	thermal capacity [J·kg^{-1}·K^{-1}]
D	conduction coefficient [kg·m^{-1}·s^{-1}]
f	mass condensation [kg·s^{-1}]
G	mass flux of water vapour [kg·s^{-1}·m^{-3}]
H	total enthalpy [J·m^{-3}]
l	latent heat of phase change [J·kg^{-1}]
L	mass flux of liquid water [kg·s^{-1}·m^{-3}]
p	pressure [Pa]
Q	bulk heat flux [J·s^{-1}·m^{-3}]
T	thermodynamics temperature [K]
V	net volume [m^3]
w	moisture content [kg·m^{-3}]
x	absolute humidity [kg·m^{-3}]
δ	permeability of water vapour [kg·s^{-1}·m^{-1}·Pa^{-1}]
κ	permeability of liquid water [kg·s^{-1}·m^{-1}·Pa^{-1}]
λ	thermal conductivity [W·m^{-1}·K^{-1}]
ρ	bulk density [kg·m^{-3}]
τ	time [s]
φ	relative humidity [-]

Subscripts

air	properties of air
cond	conduction
diff	diffusion
int	internal
sat	saturation
solar	solar
source	source
v	water vapour
vent	ventilation
w	liquid water