Natural indoor climate in St. Charles Borromeo chapel in Telc

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Abstract: The memorial chapel of St. Charles Borromeo from 1664 in town Telc includes the fresco-secco mural painting in the dome. The natural indoor climate with a height of 12.1 m is analysed for the preventive conservation of the original mural painting. This hygrothermal analysis in the period 2018 - 2021 shows the average indoor air temperature of 10.2 °C and indoor air relative humidity of 75.1 % r.h. This natural indoor climate shows the frequency of Frost risk in 10.72 % days per year, Microbiology risk in 4.85 % days per year, and Dryness effect in 0.01 % days per year. The vertical stratification of indoor climate is obtained for air temperature up to 5.2 K and -24.1 % r.h. for relative humidity. This natural indoor climate in the St. Charles Borromeo chapel is significantly dependent on outdoor weather with time-lag 2 hours.

Keywords: natural indoor climate; mural painting; preventive conservation; measurement
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1. Introduction

The chapel of St. Charles Borromeo near town Telc in the Czech Republic is built in 1664 as the memorial chapel on 13th October 1653. On this date, the son Charles of Countess Frantiska Slavatova von Meggau fell to the wolf-pit with a depth of 5 m. The thirteen years old Charles survived October night in the wolf-pit. He was rescued in the next morning by forest workers. This historical legend is the motive of mural painting in the dome, see Fig. 1.

Fig. 1 - *The original photo of mural painting in the dome of the St. Charles Borromeo chapel with the motive of Charles's rescue on day 13th October 1653 is painted about the year 1730 by Heinrich Herwig Hoff.*

1.1 Research Aim

This research study is focused on the preventive conservation of original fresco-secco mural painting in the dome of St. Charles Borromeo chapel in Telc. The hygrothermal analysis of natural indoor climate with a height of 12.1 m is based on experimental measurement over 3 years.

2. Chapel of St. Charles Borromeo

This memorial chapel of St. Charles Borromeo on the hill above Telc is connected with the town by eight stations on the Way of the Cross since 1670, more [1]. This Borromeo chapel is built by the builder Stefano Perti in 1664, see Fig. 2. The polygonal floor plan is composed of a regular octagon with an outer diameter of 9.47 m and the entrance leeward, see Fig. 3. The internal height of the St. Charles Borromeo chapel is 12.1 m (exterior height 16.1 m), and the chapel basement (original wolf-pit) is God's grave with a relics of statue. The peripheral wall with thickness of 1.0 m is built by ceramic bricks up to 9.10 m. This peripheral wall includes four wooden windows (1.25 × 2.50 m) with shutters and double wooden doors (1.34 × 2.60 m). The internal wooden dome with a radius of 3.60 m is created in the octagonal pyramid roof and extended by the lighting lantern. The inner surface of the wooden dome is lime plaster layer with the fresco-secco mural painting. The natural indoor climate is formed only by outdoor weather and natural infiltration. The

liturgical ceremony in the St. Charles Borromeo chapel is organized in summer one time per year.

Fig. 2 - *Photo of St. Borromeo chapel in town Telc* [2].

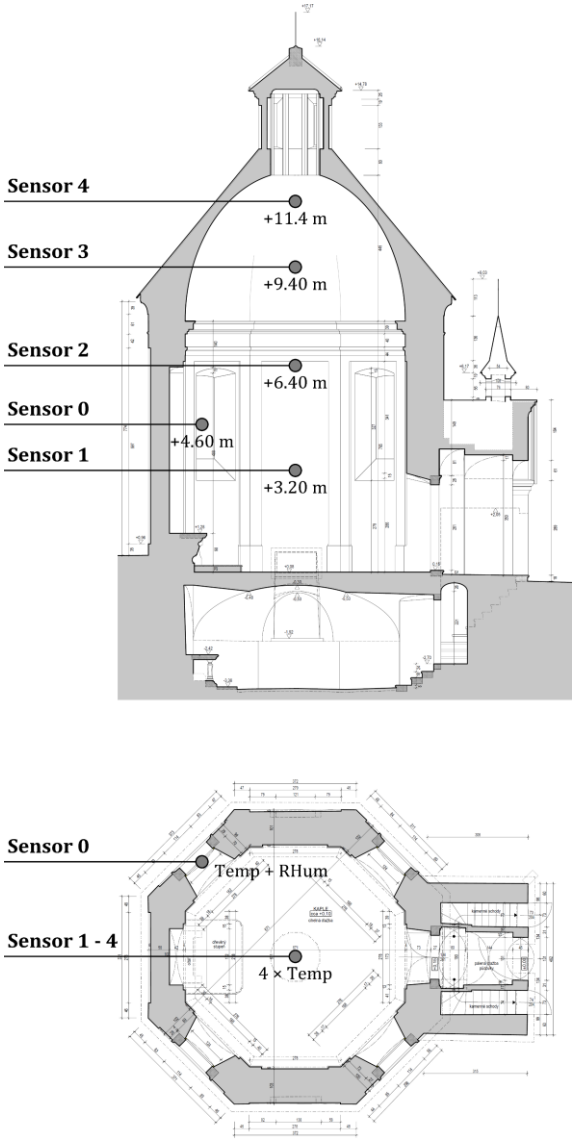


Fig. 3 - *Floor plan and vertical cut of St. Borromeo chapel with the location of hygrothermal probes* [3].

3. Experimental measurement

The natural indoor climate in the St. Charles Borromeo chapel is monitored by a hygrothermal sensor and four temperature probes from 18th June 2018 to 16th October 2021. The hygrothermal data-logger is COMET S3120 with a sensitivity ±0.10 K for air temperature in interval <-30; 70 °C> and the sensitivity ±0.1 % r.h for relative humidity in interval <0; 100 % r.h.>. This hygrothermal data-logger is located on the window (Northwest) with a closed shutter on level 4.60 m (Sensor 0) above the floor. The vertical temperature distribution of natural indoor climate is monitored by four temperature probes COMET Pt1000/3850 ppm with a sensitivity ±0.15 K for air temperature in interval <-30; 180 °C>, more [4]. These temperature probes are suspended in level 3.2 m (Sensor 1), 6.4 m (Sensor 2), 9.4 m (Sensor 3), and 11.4 m (Sensor 4) above the floor, see Fig. 3. The outdoor climate is monitored by professional weather station ITAM (Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences) in town Telc. The straight distance between the St. Charles Borromeo chapel and this professional weather station ITAM is 2080 m.

4. Results

The natural indoor climate in St. Charles Borromeo chapel is analysed from 4 temperature probes and one hygrothermal sensor (over 28 939 hours) from 18th June 2018 to 16th October 2021 with the respect to mural painting.

4.1 Method of Target range

The appropriate indoor climate for preventive conservation of original fresco-secco mural painting recommends technical standard and scientific studies, see [5-7]. This appropriate natural indoor climate defines a hygrothermal range of indoor air temperature and indoor air relative humidity. The other way is American standard ASHRAE [8] with defined unacceptable indoor climate for the preventive conservation of artefacts.

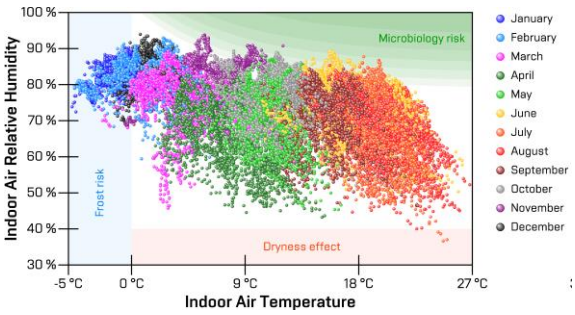


Fig. 4 - *Hygrothermal analysis of natural indoor climate by preventive conservation method of Target range in period from 18th June 2018 to 16th October 2021. The unacceptable indoor climate is defined as Dryness effect (RH < 40 % r.h.), Frost risk (T < 0 °C), and Microbiology risk, according to* [9].

Table 1 - *Frequency of indoor climate in Target range.*

Target range	Frequency	
M.BB.CC. 2001 [5]	2097 hours	7.28 % days
UNI 10829:1999 [6]	2726 hours	9.42 % days
Kadijsky in [7]	617 hours	2.31 % days
Frost risk [8]	4 hours	0.01 % days
Dryness risk [8]	3255 hours	10.7 % days
Microbiology risk [9]	1404 hours	4.85 % days

The year frequency of appropriate indoor climate is 7.28 % days in M.BB.CC. 2001 [5] (range 6-25 °C and 45-60 % r.h.), 9.42 % days in UNI 10829:1999 [6] (range 10-24 °C and 45-65 % r.h.), and 2.31 % days in Kadijsky [7] (range 6-25 °C and 50-55 % r.h.). The year frequency of unacceptable indoor climate is 0.01 % days in the Dryness effect (RH < 40 % r.h.), 10.72 % days in the Frost risk (T < 0 °C), and 4.85 % days in the Microbiology risk [9]. This total year frequency of Microbiology risk is aggregated from risk 3.04 % days in 32 days, risk 1.39 % days in 16 days, risk 0.38 % days in 8 days, and risk 0.04 % days in 4 days. In summary, the natural indoor climate in the St. Charles Borromeo chapel is over 84.4 % days per year without Frost risk, Dryness effect, and Microbiology risk.

4.2 Method of Historical climate

The preventive conservation method of Historical climate respects the natural hygrothermal response of the building. The appropriate indoor climate for preventive conservation is calculated as a 30-days centred moving average (CMA) over a year, and the hygrothermal fluctuation of indoor climate is limited by a lower (7th)/upper(93rd) percentile, more [10].

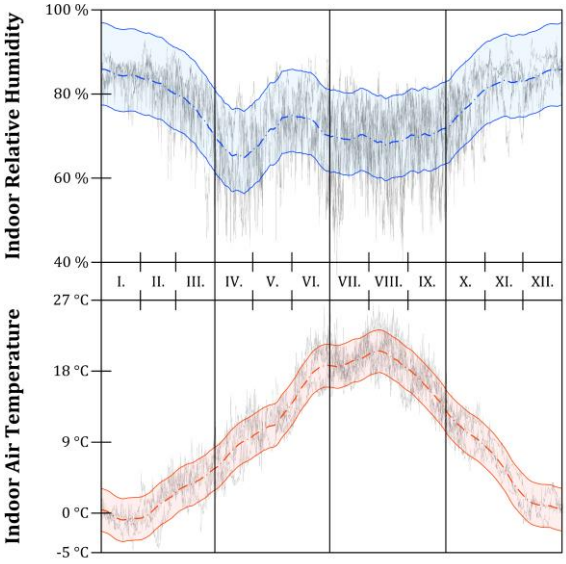


Fig. 5 - *Hygrothermal analysis of natural indoor climate by Historical climate method in period from 18th June 2018 to 16th October 2021.*

The average indoor air temperature is 10.2 °C, and the average indoor air relative humidity is 75.1 % r.h. The CMA of indoor air temperature is calculated in the range from -0.85 °C (18th January at 8 am) to 20.6 °C (8th August at 9 pm) with fluctuation from -2.7 K to 2.7 K. The CMA of indoor air relative humidity is obtained in a range from 64.9 % r.h. (24th April at 6 am) to 85.9 % r.h. (31st December at 23 pm) with fluctuation from -11.0 % r.h. to 8.5 % r.h. This hygrothermal fluctuation of natural indoor climate is caused by natural ventilation through the lighting lantern in the dome.

4.3 Vertical stratification of Indoor climate

The vertical stratification of natural indoor climate show hygrothermal difference between sensors, see Fig. 6. The temperature difference between levels 6.4 m and 3.2 m (red dots) is 0.05 ± 0.26 K in a range from -0.9 to 1.3 K, and the relative humidity shows a median difference -3.7 ± 1.9 % r.h. in a range from -1.2 to -9.4 % r.h. The temperature difference between levels 9.4 m and 3.2 m (grey dots) is 0.10 ± 0.42 K in a range from -1.1 to 2.0 K, and the relative humidity shows a median difference -7.1 ± 3.7 % r.h. in a range from -2.4 to -18.2 % r.h. The temperature difference between levels 11.4 m and 3.2 m (yellow dots) is 0.43 ± 0.74 K in a range from -0.7 to 5.2 K, and the relative humidity shows a median difference -9.4 ± 4.9 % r.h. in a range from -3.2 to -24.1 % r.h. This hygrothermal fluctuation of natural indoor climate increases with the level above the floor, see Fig. 6.

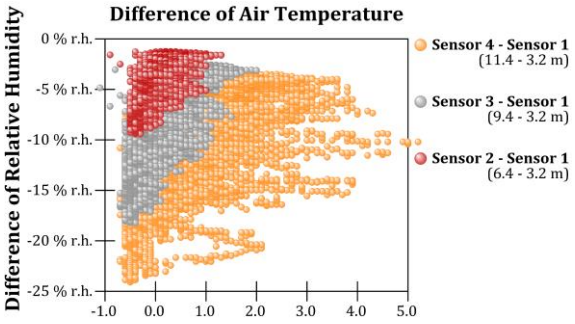


Fig. 6 - *Hygrothermal difference in natural indoor climate between sensors in the period from 18th June 2018 to 16th October 2021.*

The hygrothermal vertical stratification of natural indoor climate shows the temperature gradient 0.136 ± 0.033 K/m in a range from 0.01 to 0.63 K/m, and the relative humidity shows the gradient of 1.49 ± 0.97 % r.h./m in a range from 0.39 to 2.94 % r.h.

4.4 Dependence of Indoor on Outdoor climate

The hygrothermal time-lag between outdoor and indoor climate is calculated for 2 hours by the Fourier transform method with a correlation of 90.2 % for air temperature, 63.3 % for relative humidity, and 95.1 % for specific humidity. The hygrothermal attenuation in the brick envelope of St. Charles Borromeo chapel is obtained by the Root mean square method on a value of 3.87 K for temperature, 13.1 % r.h. for relative humidity, and 0.913 g/kg for specific humidity. This hygrothermal interaction of natural indoor climate with outdoor

climate is plotted for air temperature and specific humidity, see Fig. 7.

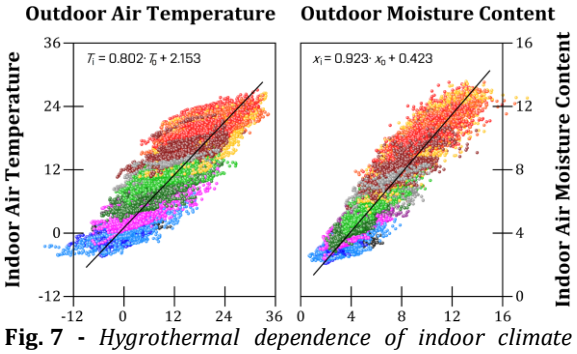


Fig. 7 - *Hygrothermal dependence of indoor climate on outdoor weather in period from 18th June 2018 to 16th October 2021.*

The linear regress between indoor climate (T_i [°C] and x_i [g/kg]) and outdoor weather (T_o [°C] and x_o [g/kg]) is obtained $T_i = 0.802 \cdot T_o + 2.153$ [°C] for air temperature (R^2 value 84 %) and $x_i = 0.923 \cdot x_o + 0.423$ [g/kg] for air specific humidity (R^2 value 92 %). The slope parameter of linear regression close to 1.0 (100 %) shows the hygrothermal dependence of indoor climate on outdoor weather. The intercept parameter of linear regression close to 0 (without gains) shows the hygrothermal source in indoor climate in the St. Charles Borromeo chapel. This hygrothermal source is the impact of heat/moisture loads and heat/moisture storage, sun radiation, etc.

5. Visualisation of Measurement

The colour visualization of hygrothermal behaviour of natural indoor climate in the St. Borromeo chapel uses linear interpolation (colour-map in the figure) between real measured values (numerical value in the figure).

5.1 Spring season

The outdoor weather on 21st April 2019 shows a daily temperature fluctuation from 4.4 °C at 7 am to 20.6 °C at 6 pm. This daily temperature fluctuation (16.2 K per 11 hours) is coupled with the outdoor air relative humidity in a range from 77 % r.h. at 7 am to 25 % r.h. at 3 pm. This hygrothermal fluctuation of outdoor climate is detected in the dome up to 2.1 K and 9 % r.h (Sensor 4) and up to 0.8 K and 4.6 % r.h. in level 3.20 m (Sensor 1). The hygrothermal response of the St. Charles Borromeo chapel shows a stable natural indoor climate during the day, see Fig. 8.

5.2 Summer season

The outdoor weather from 21st June 2018 to 23rd June 2018 shows a sunny warm day with afternoon rain and a following cloudy day. The outdoor air temperature on 21st June 2018 is increased from 16.2 °C at 7 am to 28.8 °C at 3 pm. The indoor air temperature in the dome (Sensor 4) is detected from 20.4 to 20.8 °C. The indoor air specific humidity is obtained from 9.6 to 10.1 g/kg, see Fig. 9.

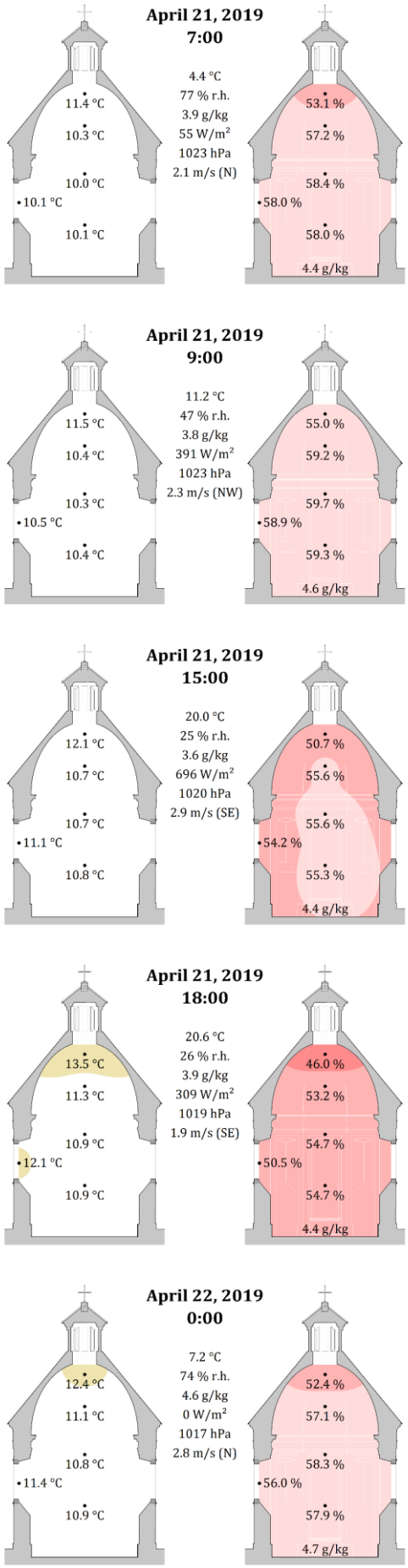


Fig. 8 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the spring season.*

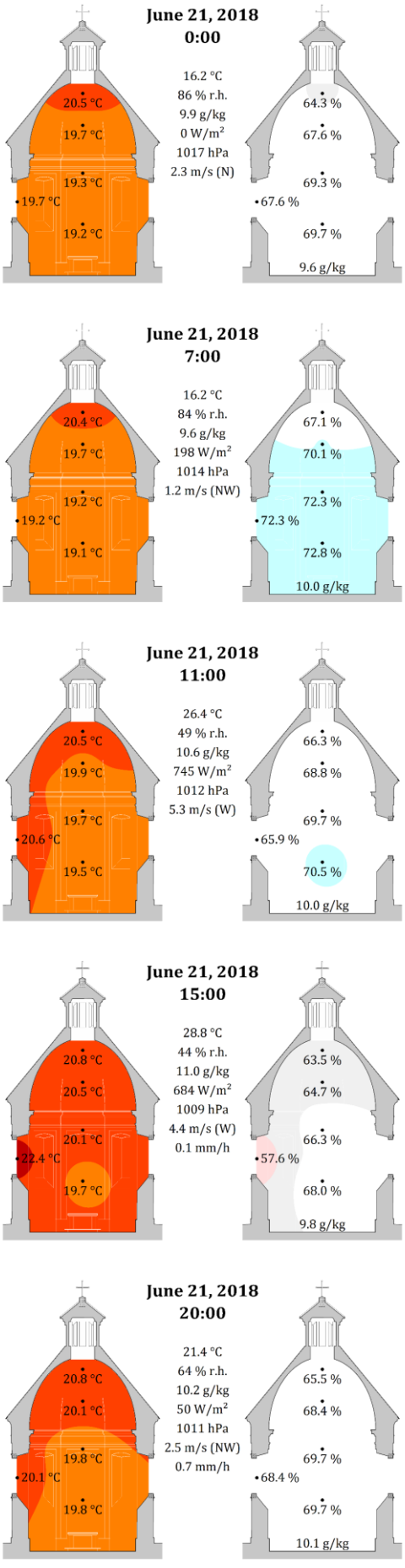


Fig. 9 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the summer season.*

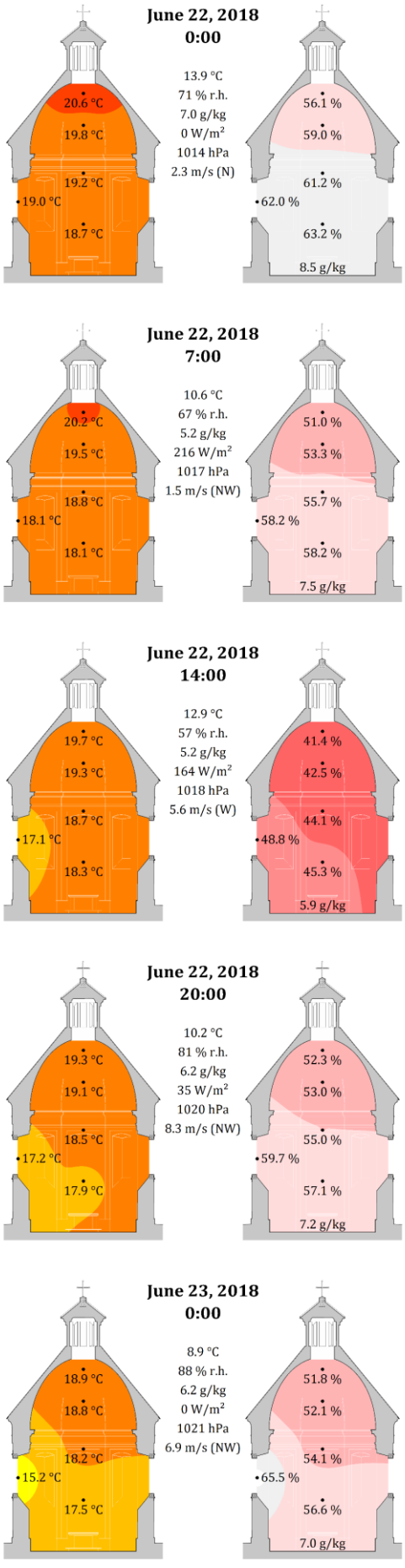


Fig. 10 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the summer season.*

The outdoor weather on 22nd June 2018 is a windy and cloudy day, see Fig. 10. The outdoor air temperature decreases from 13.9 to 8.9 °C, but the indoor air temperature is over 18 °C. This combination of a warm indoor climate and increased wind speed up to 8.3 m/s at 8 pm causes a drying effect in the St. Charles Borromeo chapel. The indoor air relative humidity decreases up to 41.4 % r.h. in the dome at 2 pm, and the indoor air specific humidity is decreased also from 10.1 g/kg at 8 pm on 21st June 2018 to 5.9 g/kg at 2 pm on 22nd June 2018. This dryness effect of indoor climate is the impact of the natural hygrothermal response of St. Charles Borromeo chapel on the outdoor weather.

5.3 Autumn season

The outdoor weather on 2nd October 2019 shows a windy and cloudy day. The wind speed is measured from 3.6 to 6.5 m/s. The outdoor air relative humidity is obtained from 85 to 90 % r.h. This high outdoor air relative humidity caused by light rain of 0.10 mm/hour is detected in the dome (Sensor 4) by 76.9 % r.h. at 11 am, 80.4 % at 1 pm, 79.2 % r.h. at 3 pm, 79.3 % r.h. at 5 pm, and 69.3 % r.h. at 8 pm after the end of the rain. The indoor air temperature in the dome shows a stable value from 14.1 to 14.2 °C. This hygrothermal response of the St. Charles Borromeo chapel shows the impact of wind on the natural indoor climate.

5.4 Winter season

The natural indoor climate in St. Charles Borromeo shows a low indoor air temperature of -4.7 °C on the northwest window on 26th January 2019 at 4 am. The indoor air temperature is obtained for the outdoor air temperature at -4.8 °C in combination with the northwest wind with a wind speed of 5.2 m/s. This natural indoor climate with the Frost risk on 26th January at 4 am shows indoor air relative humidity in a range from 65.6 % r.h. (Sensor 1) to 73.8 % r.h. (Sensor 0). After the sunrise on 26th January 2019 at 7:33 am, the outdoor air temperature is increased up to 2.1 °C and the wind speed is growing up to 7.4 m/s. The snow layer is melting and the combination with a light rain of about 0.10 mm/hour at 11 am, and 3 - 5 pm increases the indoor air relative humidity up to 88.4 % r.h. (Sensor 3), see Fig. 13 at midnight on 27th January 2019. This obtained result shows the impact of a windy day and high outdoor air relative humidity on the natural indoor climate in St. Charles Borromeo chapel.

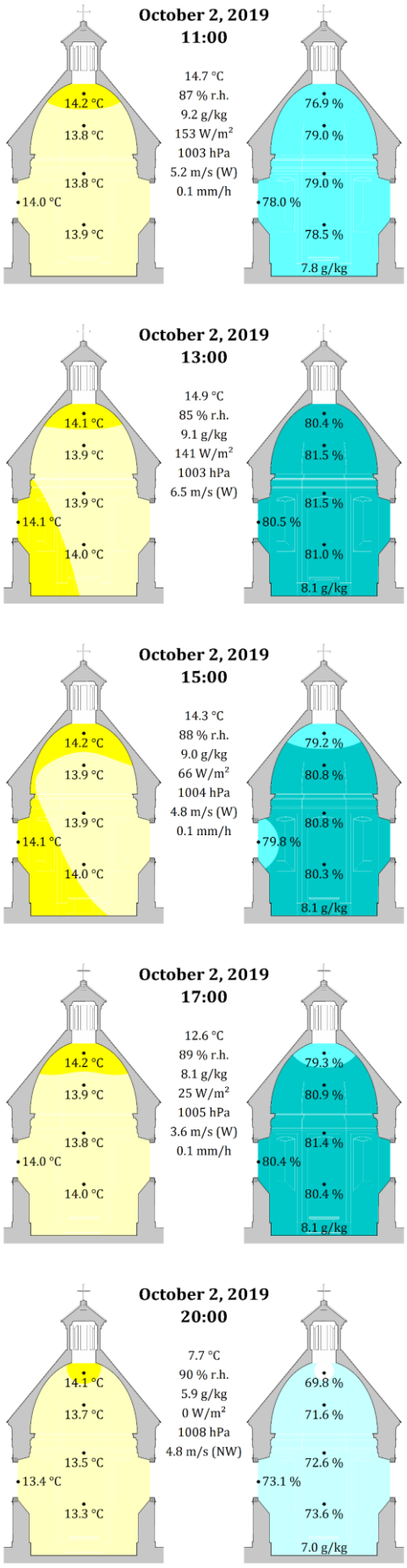
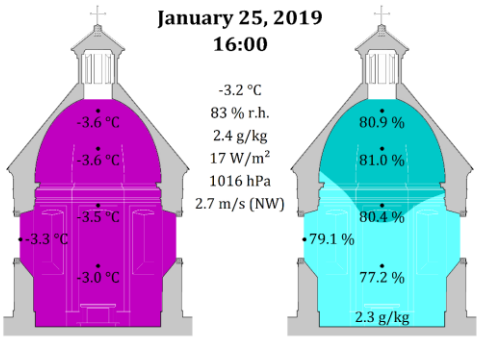
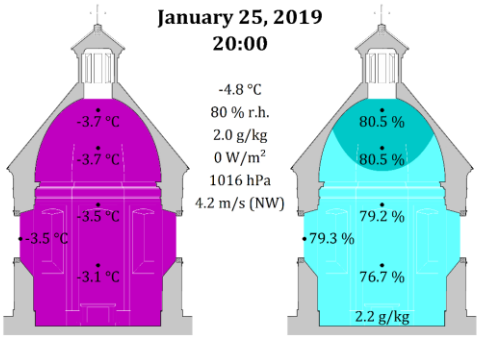
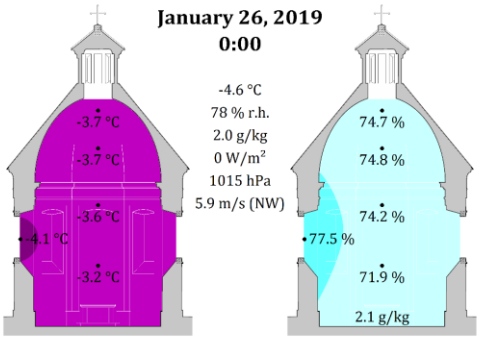
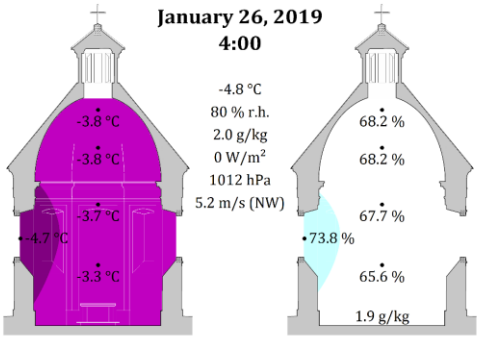


Fig. 11 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the autumn season.*









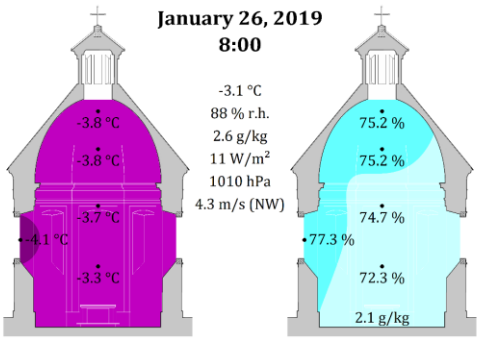
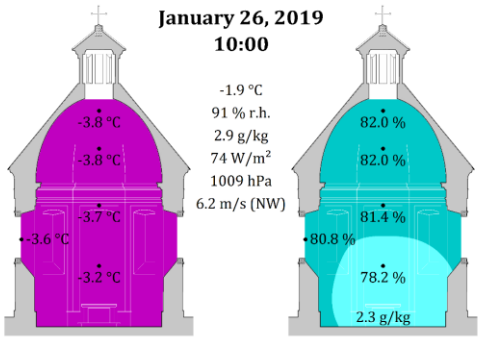
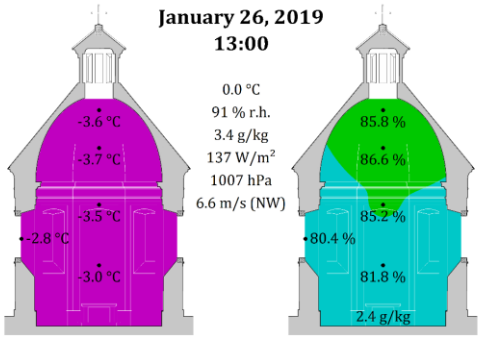
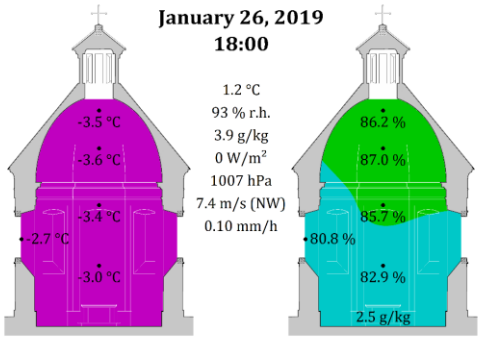
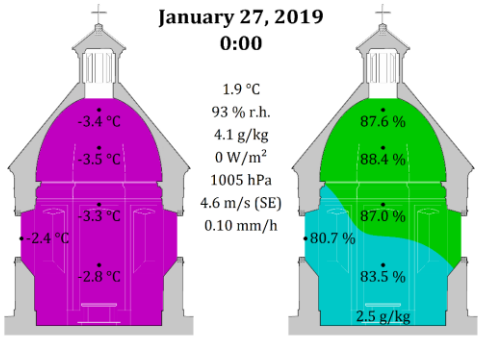


Fig. 12 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the winter season.*









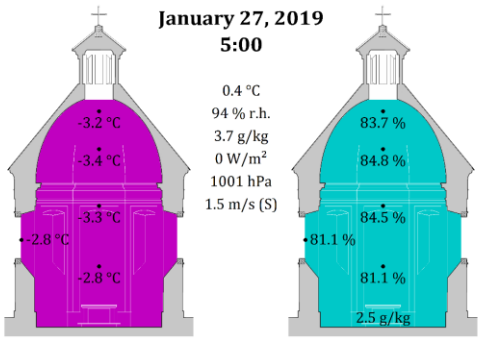


Fig. 13 - *Hygrothermal behaviour of indoor climate in the St. Charles Borromeo chapel in the winter season.*

6. Conclusion

The natural indoor climate in the St. Charles Borromeo chapel is analysed over 28 939 hours in the year 2018 - 2021. This natural indoor climate shows an average air temperature of 10.2 °C and average relative humidity of 75.1 % r.h. The hygrothermal vertical stratification of indoor climate is obtained for air temperature up to 5.2 K and 24.1 % r.h. for relative humidity. These hygrothermal parameters of indoor climate show the Microbiology risk in 4.85 % days per year, the Dryness effect in 0.01 % days per year, and the Frost risk in 10.72 % days per year. Finally, this natural indoor climate isn't a risk for the preventive conservation of original mural painting over 84.4 % days per year.

Acknowledgement

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