Adaptive Bricks: Potentials of Evaporative Cooling in Brick Building Envelopes to Enhance Urban Microclimate

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Abstract

Over the history of human settlements, approximately 30% of the world's population lived in brick made structures by 1990. It is also projected that the brick product segments will raise 3.5% during 2017-2027 and it is anticipated to dominate over the forecast period. So far, energy regulations have pushed the innovation of bricks towards better U-values especially in northern and central Europe however there has been less attention to see brick as a climate active material able to improve microclimate conditions. Within this regard this research is investigating the potentials of irrigated solid bricks as a component for climate adaptive façades able to enhance urban microclimate in urban canyons. The study shaped in two layers including field measurements and simulations. An experiment setup of façade panel is demonstrated to test different irrigation scenarios under varying environmental conditions and hours of the day to quantify surface temperatures and intensity of evaporative cooling effect. The results are validated with transient hygro-thermal simulation models in WUFI. The results show that in average wet bricks can have 7 °C lower surface temperatures compared to dry ones. Also the color of the bricks is influencing the temperature curve where the difference of 5.4 °C recorded between light and dark colored ones.

Keywords

irrigated bricks, microclimate, outdoor comfort, evapotranspiration

1 INTRODUCTION

"When we talk about brick, people think that we talk about tradition but it is all about innovative approach giving the brick a new meaning and new appearance."

Wang Shu, Brick Award 14

In the last centuries, history of human settlement was very much related to the use of brick as a key element for shelter as structure of architectural space (Serena, 2012). Since the very beginning of human settlement, sun dried mud and later burned bricks made out of clay have been used to build shelter and buildings all over the globe. Sun dried mud bricks are a common building material across the globe, found in many archaeological sites in the Old World over ca. 11000 years ago (Friesem, Karkanas, Tsartsidou, & Shahack-Gross, 2014). First traces are reported from Neolithic settlements in Anatolia and the Levant (Cauvin, 2000). Clay was the predominant building material in architecture of the Neolithic era which has been called the "Age of Clay" (Schmandt-Besserat, 2015; Stevanović, 1997). Due to their robustness, bricks have been widely used as waterproof materials in aqueducts, bridge sand cisterns since early Hellenistic time (Uğurlu & Böke, 2009). Later, bricks have been further developed and especially the invention of burned bricks round 4000 BC, durability, resistance and structural performance has increased the use of this technology. The widely use of mud-bricks as a key element in prehistoric architecture and the following centuries is related to its modular and highly flexible use and adaptability to various applications allowing for a high degree of design freedom and structural performance (Oates, 1990).

According to statistics in 1990, approximately 30% of the world's population lived in earthen brick made structures (Coffman, Agnewl, Austin, & Doehnel, 1990). In the last years brick architecture has experienced a revival and will grow even further. As said by Compound Annual Growth Rate, (CAGR) for the brick product segment the estimation is to raise 3.5% during 2017-2027 and it is anticipated to dominate over the forecast period (TMRGL, 2017).

This success of monolithic walls built from a single material as an approach captivates builders and planners by its simplicity and the avoidance of complicated details (Wernery, Ben-Ishai, Binder, & Brunner, 2017). The mentioned advantages of brick construction are also subject of further research in digital fabrication with robots enabling architects to directly control complex geometries in construction. Due to its close relation to common construction practice, digital fabrication allows for the control of the micro and macro structure of a building component, performance optimization through the design of the cross section (Bonswetch, Kobel, Gramazio, & Kohler, 2006). Therefore, this technology is supposed to increase the spread of brick construction in architectural context. However, since the 1980s, energy regulations have pushed the innovation of bricks towards better U-values especially in northern and central Europe. Thus, the latest developments have been pushed towards insulating bricks since they incorporate both the structural and the thermal functions of the building envelope (Wernery et al., 2017).

The work of this research focuses on the potentials of brick as a climate active material improving urban (thermal) comfort conditions. Research and practice has already proved that brick is one of well performing material for climate control due to its high thermal capacity and thermal mass effect (Al-Sanea, Zedan, & Al-Hussain, 2012, 2013) nevertheless energy regulations have limited the innovation of bricks towards better thermal performance only. There have been various studies performed to understand thermal and optical performance of façade and pavement materials on microclimate of cities. The issue is important due to urban heat island phenomena described as temperature differences between downtown and suburbs. Due to decreased sky view factor in urban canyons as function of compactness and increased density of cities, the trapped heat and solar radiation keeps surface temperatures high even during night time. As consequence, the buildings that are dependent on night time cooling cannot recover and they cause significant health issues. The summer of 2003 could be relevant instance in Europe for the extreme heat wave that caused 15000 additional deaths in France (Ata Chokhachian, Santucci, & Auer, 2017).

Addressing the mention problems, this paper investigates application of innovative approach on the potentials of irrigated solid bricks as a component for climate adaptive façades aiming to enhance urban microclimate and outdoor comfort. The study shaped in two layers including field measurements and simulations. An experiment setup of façade panel is demonstrated to test different irrigation scenarios under varying environmental conditions and hours of the day to quantify surface temperatures and intensity of evaporative cooling effect. The results are validated with transient simulation models in WUFI.

2 BUILDING ENVELOPES AND IMPACT ON MICROCLIMATE

The phenomena of urbanization and industrialization concerning its effect on environmental change has been known and studied for many centuries all over the world. Addressing the topic of environmental change, we need to refer to relevant metrics depending on the context and scale. Urban Heat Island effect (UHI) is one of the widely investigated phenomena to measure the effect of urbanization and built environment on the climate of cities. It is one of the most common manifestations on urban climate studies and since its advent by Luke Howard (1818), it is still the topic of researchers in different regions of the world. UHI by definition is known as higher temperatures or heat content stored in urban areas caused due to the anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources, and due to the heat stored and re-radiated by massive and complex urban structures which leads to deterioration of living environment and increase in energy consumptions (Rizwan, Dennis, & Liu, 2008).

As an example, Analysis of temperature trends for the last 100 years in several large U.S. cities indicate that, since ~1940, temperatures in urban areas have increased by about 0.5 - 3.0 °C. Typically, electricity demand in cities increases by 2 - 4 % for each 1 °C increase in temperature. Hence, we estimate that 5 - 10 % of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5 - 3.0 °C in urban temperatures (Akbari, Pomerantz, & Taha, 2001; Jandaghian & Akbari, 2018). It is found that for the city of Athens, where the mean heat island intensity exceeds 10 °C, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum COP value of air conditioners may be decreased up to 25% because of the higher ambient temperatures (Mofidi & Akbari, 2017; Santamouris et al., 2001).

There has been several approaches toward UHI mitigation by designing proportional aspect ratio for street canyons which allows enough sky exposure for night time cooling or choosing proper materials for building envelopes depending on context and orientation of each façade. Studies show that brick façades with low reflectivity in comparison with heavily insulated envelopes can decrease extreme heat stress for pedestrians by 26% during the day time (Ata Chokhachian, Perini, Dong, & Auer, 2017). Additionally, there has been several studies about evaporative cooling potential of building envelopes where Han, Xu, and Qing (2017) explored the effect of two passive cooling systems, water-retaining bricks on roof and radiation shield on roof concluding that the maximum cooling capability can be achieved through on-roof water-retaining bricks. Another study explores the effects of a Moist Void-brick wall as passive microclimatic converter and the results show that the wall surface temperature are averagely lower than ambient air temperature by 5 °C over day time

(He & Liu, 2012). Addressing the wide spread of brick buildings as well as the mentioned problems with urban heat island and outdoor comfort, this paper proposes an architectural investigation on innovative approaches on the potentials of irrigated solid bricks as a component for climate adaptive façades. It is understood that the focus on this research is clearly an investigation as an architectural approach rather than an emphasis on building physics.

3 RESEARCH METHODOLOGY

The study approached with two complimentary methods of experiments and validation modeling. In order to evaluate the potentials of evaporative cooling with irrigated bricks following steps conducted: Measurements: In-situ measurements on evaporation cooling effects of irrigated bricks were taken on two different summer days in Munich. The measured data served as a base for thermal simulations in part 2 (Simulations).

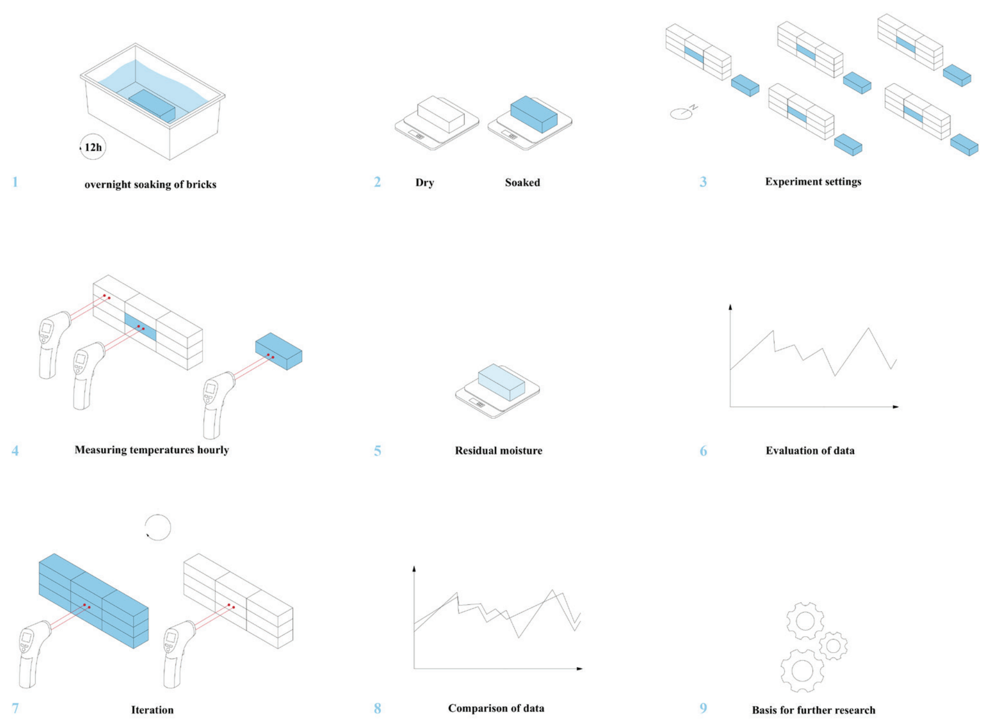

FIG. 1 Experiment setup and process of measurements

Numerical simulation: In order to validate the experiments thermal simulations in WUFI (Lengsfeld & Holm, 2007), a software developed by Fraunhofer institute were set up based on boundary conditions of the measurements. WUFI allows realistic calculations of heat and moisture transport in walls and other multi-layer building components exposed to varying environmental conditions. The outcome of the measurements and simulations lead to an investigation in constructive solutions for façade application of irrigated brick walls. Summary of methodology is illustrated in fig. 1.

3.1 MEASUREMENTS AND EXPERIMENT SETUP

The first investigation was an in-situ testing setup to measure and monitor evaporation potential of irrigated bricks exposed to solar radiation in an urban context. For this reason experiment setup of different brick types are built and tested over a day. The objects were monitored on two summer sunny days (03.07.2018 and 14.07.2018) on the rooftop terrace at 28 meters height above ground floor in the city center of Munich (48.135125 - 11.581981). The setup is done for different colors and densities of bricks based on concrete soil ground in full south orientation. Fig. 2 shows the experiment setup demonstration with 5 different brick types as: solid porous bricks in white (Passo), black (Pescara) Yellow (Lagoni), and red (Bologna) as well as red (Bologna) containing holes, each brick sized 240 mm x 115 mm x 71 mm.

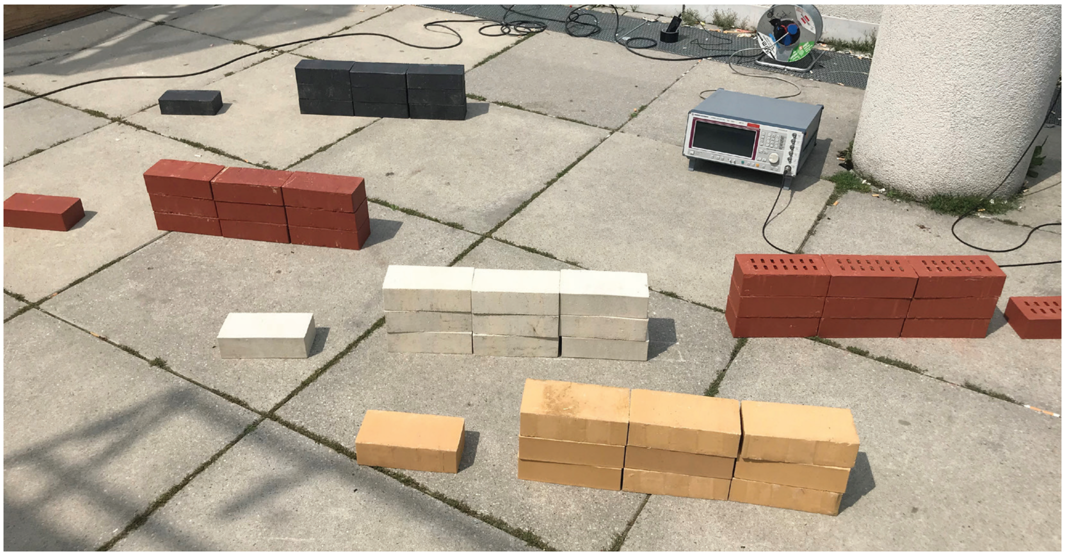

FIG. 2 Experiment setup and process of measurements

The water suction capacity was varying between 1 – 7 % depending on the color of bricks: white and black: 2% - light red: 4%. A small wall was layered in a row of three bricks in length and three layers in height. The tenth brick was placed besides allowing more solar exposure of surfaces. The middle bricks as of each series as well as the isolated one laying aside were watered in a bucket for twelve hours (Fig. 3) and they were weighted before and after they were soaked. A parallel recording of weather data was done using Ahlborn Almemo System, and WinControl V6 Software. In order to validate the measured data, a second weather station has been used which is installed on the roof top at same height of an adjacent building in 300m distance. (https://www.meteo.physik.uni-muenchen.de/wetter/index.html). The recorded weather data included: global radiation, diffuse radiation air temperature, wind speed, relative humidity. Measurements as test series were taken on two different days, 3rd and 14th of July 2018 from 9 am till 5 pm with time step of 2 minutes (Fig. 3).

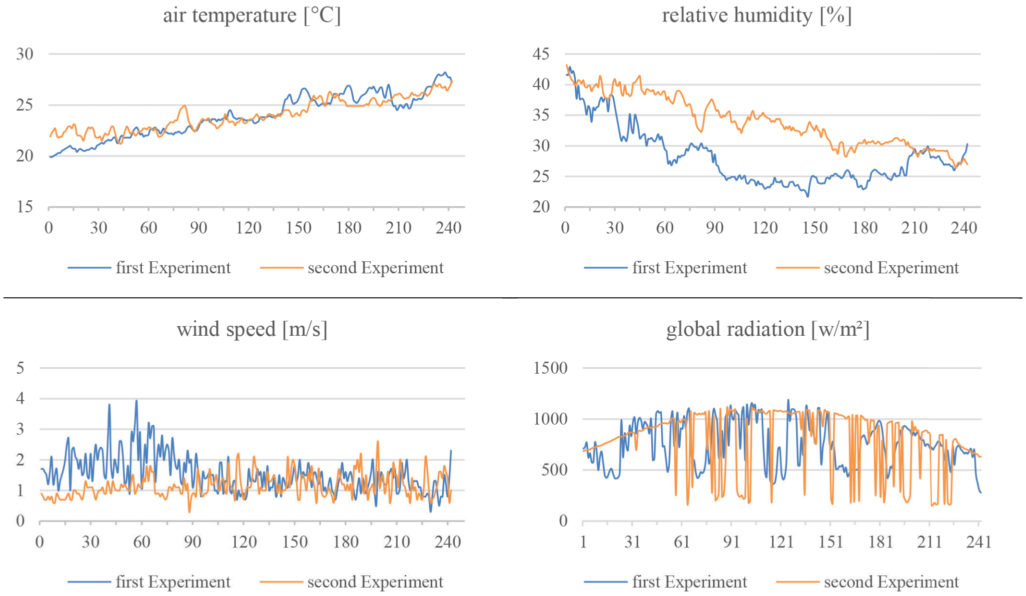

FIG. 3 Recorded weather data for 2 experiment days

For the experiment setup five walls out of different bricks were positioned on concrete base. Each experiment unit consisted of 10 bricks; of which 9 made up the tested wall and one was tested independently under the same boundary conditions to see the full evaporative capabilities of a singular brick. Therefore, two bricks were left to soak in water tub overnight to have a maximum water content. The bricks were weighted before and after they were soaked. One soaked brick was positioned centrally in the wall surrounded by 8 briefly wetted bricks. The other soaked brick was tested individually. The brick in the upper left corner of the 9 bricks in a wall was also measured (Fig. 4). Surface temperature of wet and dry bricks was measured with infrared thermometer for each brick in the middle of a 9-brick-wall (Fig. 5). Instead of hourly measurements to increase the accuracy of the experiment the bricks were monitored every half hour, including the weight.

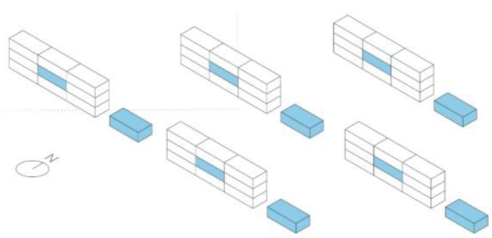

FIG. 4 Experiment configuration and location of wet bricks

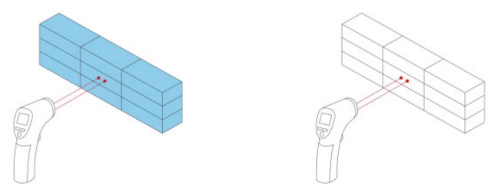

FIG. 5 Surface temperature was measure by infrared thermometer for both wet and dry bricks

On the first day (3rd of July), the air temperature showed a slow increase from 20 °C in the morning until 28 °C in the afternoon. In average the wind speed was 2 m/s in the morning with more variations compared to afternoon with average speed of 1.5 m/s. Several wind gusts were recorded showing a speeds of 3.8 m/s in the morning. The radiation was from time to time slightly overcast by some clouds. The global radiation, addition of direct and diffused, raised its maximum at 13:07 with 1178 W/m2. Highest direct solar radiation was recorded at 13:29 up to 937 W/m^2. The indirect radiation reached its maximum at 11:11 with 462 W/m^2. The values for relative humidity was decreasing until 12 and was increasing by late afternoon. Since the temperature was still raising, the absolute humidity was increasing significantly.

On the second round of experiment (14th of July) temperature values showed to be slightly higher in the beginning of the measurements, however, over the course of day it was comparable with the first day. In the morning of the first experiment, the wind was stronger, whereas the day of the second experiment had calmer wind speeds with less variations. Overall, the difference in weather on both experiment days was not exceptionally significant. The global radiation reached high levels very quickly, due to the clear sky before 11 am. Later on, the clouds reduced the radiation down to 200 W/m2. Overall, the solar radiation showed higher values in comparison to the first day. Relative humidity was decreasing continuously and the absolute humidity has likely remained similar. This was different in comparison to values of relative humidity received during the first experiment.

3.2 NUMERICAL SIMULATIONS

In order to certify the experiments, the modeling approach was deployed. The goal was to compare the simulation results with those of the detailed measurements for validating the simulation considering the surface temperature and the humidity within the bricks. After validation of the experiment, in the second step the simulation is transferred to another climate zones in order to estimate maximum potential of wet bricks in terms of evaporative cooling. Within this regard, in order to demonstrate the potential of improved microclimate with irrigated brick, the city of Madrid in Spain was chosen since it's known as a dense city and has hot summers. The method can be transferred to other potential climate zones and cities but this was not the main scope of this research. Fig. 6 show the overall process of coupling through measurements and simulations.

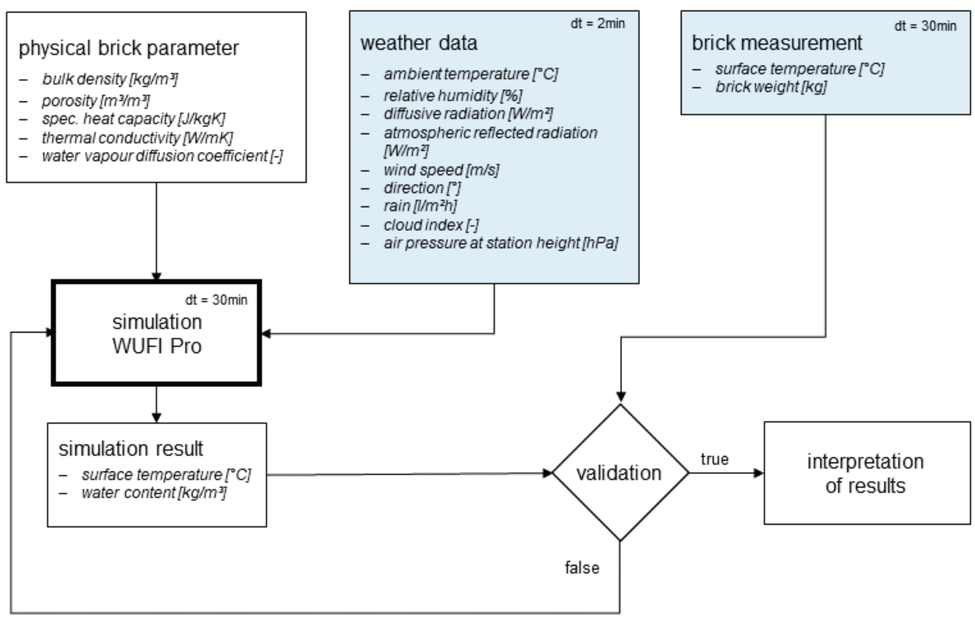

FIG. 6 The process of measurement validation with WUFI simulations

$$\frac{dH}{d\vartheta}\frac{\partial\vartheta}{\partial t} = \nabla * (\lambda\nabla\vartheta) + h_V \nabla * \left(\delta_p \nabla(\varphi\, p_{sat})\right) \qquad (1)$$

$$\frac{dw}{d\varphi}\frac{\partial\varphi}{\partial t} = \nabla * \left(D_\varphi \nabla\varphi + \delta_p \nabla(\varphi\, p_{sat})\right) \qquad (2)$$

$dH/d\vartheta$	[J/m³K]	heat capacity of the wet material
$dw/d\varphi$	[kg/m³]	humidity capacity of the wet material
λ	[W/mK]	thermal conductivity of the wet material
D_φ	[kg/ms]	fluid/ liquid conduction coefficient
δ_p	[kg/msPa]	water vapour permeability of the material
h_V	[J/kg]	evaporation enthalpy
p_{sat}	[Pa]	water vapour saturation pressure
ϑ	[°C]	temperature
φ	[-]	relative humidity

WUFI Pro is used as simulation engine to model surface temperature of bricks for both wet and dry scenarios. WUFI uses the necessary hygro-thermal differential equations and delivers the needed output parameters as surface temperature (°C) and the water content within the construction. WUFI Pro is able to simule every detailed construction component specifically. The material of the brick with the greatest potential to be observed in the measurement was chosen for the simulation. A red unsealed brick type “Bologna” was used, which has the best suction characteristics compared to the other measured bricks. The measured brick is modelled as a single, one-dimensional material layer, consisting of 115 mm thick brick elements (λ=0.68 W/mK; μ=5.00; ρ=1.600 kg/m^3; c¬p=1.00 kJ/kgK; water suction capacity: 6.4 vol.%). For reasons of comparison, the same measured weather data are used from the nearby weather station TUM, located next to the testing area as an input. These measured data were hourly interpolated, because WUFI just imports hourly weather data. A south orientation was chosen for the simulation and the resolution of the time steps set to 30 minutes, to compare it with the measured data. For boundary conditions the measured initial surface temperatures of the bricks were used. The initial relative humidity for the dry brick was set up to 45% and for the wet brick to 96.5%, according to its measured initial weight. Soaking the bricks overnight mainly reduces the initial temperature. Another approach for minimizing temperature peaks in summer is to irrigate the brick surfaces with the help of a targeted control signals using local weather dependent parameters. The outside air temperatures (threshold >20 °C, >25 °C, >30 °C) and the global radiation (threshold >400 W/m^2, >500 W/m^2, >600 W/m^2) were used as the control signal for irrigation. As a result, 30 different variants depending on the amount of water (4 L/m^{2}h, 5 L/m^{2}h, 6 L/m^{2}h) were simulated with WUFI and lead to differing irrigation frequencies. For comparing these simulation variants, average temperature difference for the whole year and for summer period (3.300 – 6.500 h) during the day and the maximum temperature difference were chosen as output values.

4 RESULTS

4.1 RESULTS OF IN-SITU MEASUREMENTS

As mentioned before for the discussion part red unsealed brick type “Bologna” is selected as an example due to better suction performance compared to the other brick types. The results of experiment shows that soaked bricks can decrease surface temperature significantly by daily average of about 7 °C. However, the color of the bricks is also influencing the temperature curve. Between the white and the black brick there was an average temperature difference of 5.4 °C. Fig. 7 illustrates the measured surface temperatures on the second day for dry and wet bricks.

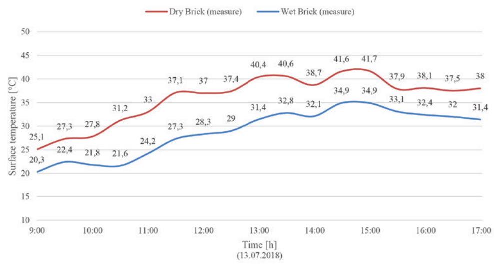

FIG. 7 Results of in-situ measurements second day for brick type Bologna

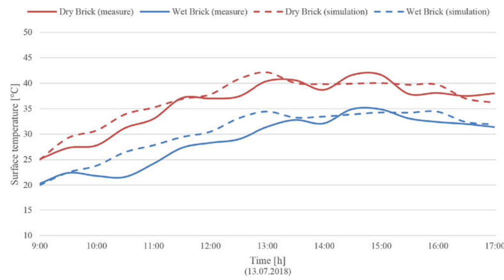

FIG. 8 Comparison measure results vs. simulation results

4.2 RESULTS OF NUMERICAL SIMULATIONS

The first part of the results compares the measures of the experiment with those of the WUFI simulation. The results are still different, as the time step had to be reduced to 30 min with the interpolated weather data and the water suction properties of bricks cannot be depicted more precisely for this transient hygro-thermal calculation method. The potential of the average temperature difference of 7.09 K (measure) was proved by the average temperature difference of the simulation (6.37 K). A more precise validation of the simulation results is not possible due to the limits of the existing simulation approaches and software tools and the limits of measurements under practical (not laboratory) conditions. For the second part of the simulation, the yearly results of the irrigation of the brick wall in Madrid (Spain) are shown in Tab. 2 and Tab. 3. The results of the simulation are shown on the average year and the average summer hours, as well as maximum temperature difference values.

THRESHOLD TEMPERATURE [°C]	20	25	30	30	30
Threshold global Radiation [W/m²]	400	400	400	500	600
Irrigation frequency [h/a]	3151	2361	2032	1565	1249
Maximum temperature difference [K]	15.11	14.27	13.72	13.50	13.47
Average temperature difference (summer, daytime) [K]	5.83	4.95	4.56	4.3	3.4

TABLE 1 Influence of different threshold temperatures and global radiation for the irrigation control on the temperature difference of the dry and wet bricks (boundary conditions irrigation intensity 4 L/m²h)

The simulation results in Tab. 2 show the influence of different control variants depending on different parameters of the threshold temperature and threshold global radiation. The goal was to minimize the amount of water (represented by the irrigation frequency) used for the irrigation and to reach still rewarding temperature differences between the dry brick wall and the irrigated brick wall.

IRRIGATION INTENSITY [L/M²H]	4	5	6	7
Irrigation frequency [h/a]	1249	1249	1249	1249
Maximum temperature difference [K]	13.47	14.08	15.45	16.18
Average temperature difference (summer, daytime) [K]	3.4	4.56	5.04	5.46

TABLE 2 Influence of different threshold temperatures and global radiation for the irrigation control on the temperature difference of the dry and wet bricks (boundary conditions: Threshold temperature 30°C, Threshold global radiation 600 W/m²)

In a second step (Tab. 3), the irrigation intensity was increased from 4 L/m²h to 7 L/m²h while the irrigation frequency doesn't change due to the same boundary conditions of temperature and global radiation thresholds. The effect is that temperature differences increase significantly.

5 DISCUSSION

The in-situ measurements show a significant potential for evaporative cooling effects of irrigated brick façades. However, the effect of soaking bricks in their entire mass shows no advantage in comparison to surface watering of bricks. Especially in dry climate zones where use of water needs to be regulated, an optimized surface watering in specific times can significantly contribute to improved microclimate.

In order to ensure a watered surface of urban brick façades, an irrigation system of pipes distributing collected and filtered rainwater of the rooftop is proposed. Based on weather data, water is circulated through the pipes providing punctual irrigation of brick façades. Addressing a constructive approach, different façade typologies are classified. Basically, two application scenarios could be demonstrated: Retrofit application for existing buildings and Façade construction with irrigation system and optimized design. For new buildings, a unitized cladding system containing an optimized geometry of the bricks could be implemented as a first design strategy.

6 CONCLUSIONS

The potential of watered bricks decreasing surface temperature of building envelopes can significantly contribute to an improved microclimate and better thermal comfort. An average decrease of about 7°C due to evaporative cooling alone and the use of brighter colors of the bricks can also strongly influence the temperature curve, which is shown by the temperature difference of 5.4 °C between white and black bricks seen in the first experiment. Therefore, it can be assumed that both characteristics (water absorption capacity of bricks that enables evaporative cooling and color) can reduce the surface temperature of bricks even greater when combined together and could contribute towards a positive impact on micro-climate. Based on the measurements and simulations, a constructive experiment setup needs to be build and evaluated on a larger scale. The experiment setup needs to contain the integrated pipework for irrigation as well as a control strategy based on weather data to allow an efficient use of water in dry and hot climate zones.

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