Non-stationary thermal performance evaluation of external façade walls under central European summer conditions

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Abstract

Thermal response of building envelope exerts a substantial influence on the formation of overall indoor comfort conditions as well as on the energy performance of buildings. For the majority of Central and Northern European countries it can be said that legislators as well as designers focus primarily on the optimization of building performance in heating season. Nevertheless, predictions for the future show the potential for large increase in cooling demand due to overheating of buildings. In this context, the focus of the presented work was to evaluate the non-stationary performance of different façade walls (lightweight and heavyweight construction systems) during typical Central European summer conditions. In addition to the influence of wall composition, the impact of orientation and high intensity passive cooling on thermal response was also investigated. The results showed differences in the summer time performance of lightweight and heavyweight envelopes, whereas lightweight façade walls had worse summer time thermal response. Furthermore, substantial differences in thermal behaviour of east, south and west faced walls were identified, with wall orientation having greater effect in the cases of walls with higher thermal transmittance and when constant ventilation regimes were used. However, among all the analysed parameters, high intensity passive cooling was identified to have the greatest influence on the summer time thermal behaviour of façade walls.

Keywords: external façade walls, transient thermal performance, night-time ventilation, thermal mass, FEM thermal analysis, Central European climate

1. Introduction

Indoor thermal environment in buildings during cooling season is becoming an ever more increasing concern in EU due to projected increase in the application of active cooling in the decades to come (STRATEGO, 2015). Current statistical data for EU (RESCUE, 2014) show that active cooling systems are installed in 7% of the total floor area in case of residential buildings, while the share for the tertiary sector is 40%. In the light of increasing influence of climate change and ever-higher demands for indoor occupant comfort, the growth in space cooling applications and their potential influence on energy consumption could be substantial. As an alternative, less energy demanding solutions for providing adequate indoor thermal conditions during summer time should be investigated in order to evaluate their overall efficiency. Best results can be attained by passive solutions on the level of building envelope, such as high thermal mass, and on the level of building functioning, for example night-time ventilation (Santamouris et al., 2010). Both approaches have a large potential in reduction of overheating occurrence, especially in temperate (i.e. Central Europe) and cold (i.e. Northern Europe) parts of Europe. In order to evaluate the potential influence of such passive solutions during free-run conditions (i.e. building is not mechanically cooled), a non-stationary analysis must be used due to the dynamic nature of the thermo-physical problem.

Several studies have investigated summer time thermal response of different construction types, with most of them studying lightweight constructions (i.e. constructions that lack or have low thermal mass). The overheating of buildings during cooling season most likely occurs in timber buildings (Adekunle and Nikolopoulou, 2016), in buildings located in highly urbanized environments (due to the occurrence of heat islands) (Paolini et al.,

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2016), in hot climates (Stazi et al., 2017) or in the case of a combination of all the stated. Pekdogan and Basaran (2017) investigated thermal performance of external walls during winter and summer. They emphasized that heat loss and gain values were significantly reduced with thicker insulation and that different thermal insulation positions (external, internal, sandwich) and wall orientations influenced the heat flow through the wall. Similar study was also conducted by Tzoulis and Kontoleon (2017), which highlighted that varying wall orientation has lower effect on the value of decrement factor compared to the time lag. Therefore, the composition and orientation of building's external wall are extremely important in the context of overheating prevention.

The objective of the analysis presented in this paper was to evaluate the thermal response of selected typical external façade walls under Central European (i.e. Ljubljana, Slovenia) summer time climatic conditions. The importance of thermal insulation position and wall composition, especially the presence or absence of thermal mass, was already emphasized by Al-Sanea and Zedan (2011). In this context, the executed study focused on the investigation of the influence of multi-layer wall composition on its non-stationary thermal response and consequential indoor conditions. Special focus was on the performance of walls with low U values (U = 0.20 $Wm^{-2}K^{-1}$), which are becoming a standard in Central Europe for the newly constructed as well renovated buildings. Simultaneously, the effect of high intensity passive cooling (i.e. night-time ventilation) and façade orientation was included in the analysis and their effect on thermal response of walls was evaluated. Calculations were conducted by an in-house developed finite element method.

2. Methodology

2.1. Selection of wall construction systems

The selected heavyweight (HWC) and lightweight (LWC) external wall construction types were analysed. As a representative construction of typical LWC envelope systems, a wall used in timber-framed buildings was selected. Such wall construction consists of an external thermal insulation and additional thermal insulation between elements of the wood load-bearing construction. Both the internal and external surfaces are finished with a construction board (e.g. OSB board). For a HWC, multiple materials, such as brick, reinforced concrete (RC), stone and hollow brick as a load bearing construction layer were investigated (Hudobivnik et al., 2016). Nonetheless, for the purpose of the presented analysis only the HWC with RC load bearing construction will be presented. In the case of RC, HWC thermal insulation is placed on external (RC_E) or internal surface (RC_I) of the load bearing construction. Because all the analysed façade walls and results of their thermal performance simulation have to be directly comparable, each construction system was, unless otherwise specified, insulated with appropriate thermal insulation thickness in order to have identical overall thermal transmittance of 0.20 $Wm^{-2}K^{-1}$.

2.2. Climate data and time interval of analysis

Calculations were made using climate data for the city of Ljubljana (46°03'N, 14°30'E), Slovenia. Necessary weather parameters (i.e. hourly air temperatures and solar radiation data) were obtained from EnergyPlus weather files (EnergyPlus, 2016) and were directly transferred into the numerical model. Ljubljana has a typical Central European climate with slight influence of northern Mediterranean due to the relative proximity of the Adriatic Sea. According to Köppen-Geiger climatic classification, it is classified as Cfb and can be described as a fully humid, warm temperate climate with cold winters and warm summers. According to ASHRAE Standards 90.1 and 90.2 (ASHRAE Standards 90.1-2004, 2004; ASHRAE Standards 90.2-2004, 2004) the climate of Ljubljana may be designated as type 5A. The average monthly air temperature (T_{avg}) varies between 20.4°C in July and – 1.2°C in January, while the average monthly maximum air temperatures ($T_{max,avg}$) reach up to 26.4°C, and minimum monthly average air temperatures ($T_{min,avg}$) reach down to – 4.9°C. The average daily global horizontal solar irradiation (G_{sol}) varies between the maximum values of 359 Whm^{-2} (July) and 73 Whm^{-2} (December). The climatological averages of Ljubljana for the period between 2005 and 2014 are presented in Figure 1. If the historical overview of trends in the average yearly values of T_{avg}, $T_{max,avg}$ and $T_{min,avg}$ are observed for the last 54 years (Fig. 2), it becomes evident that ambient air temperatures are on the rise. In regards to the observed trend it can be concluded that for the location of Ljubljana the importance of overheating protection is on the rise, while the duration of heating period is being reduced (Pajek and Košir, 2017). The stated underlines the importance of the proposed study.

The executed analysis was conducted for the summer period between the 21st of June and 11th of August with a model’s 10 days warm up period. In order to clearly present the calculated results, only a short period between the 2nd and 10th of August will be presented. During this time the external air temperatures were extremely high with daily maximums reaching above 30°C, while the last three days mark the beginning of a cooler period.

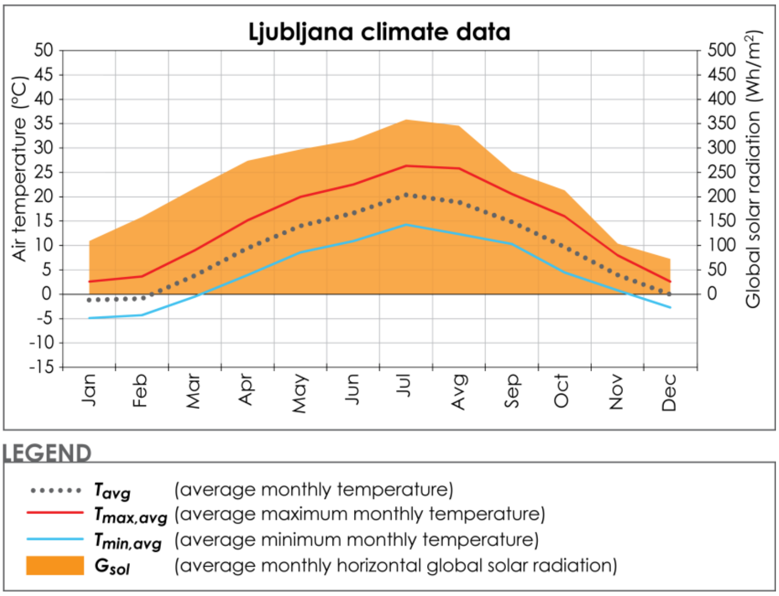

Fig. 1: Climate characteristics of Ljubljana (2005-2014 period).

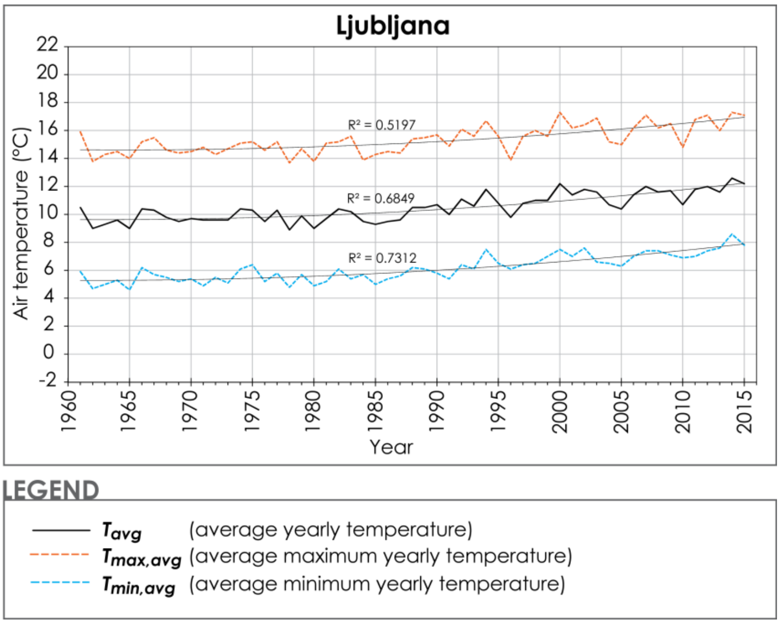

Fig. 2: Historical (1961-2015) overview of increase in average temperatures in Ljubljana.

2.3. Model and boundary conditions

The numerical model used to study the non-stationary response of the selected wall constructions was modelled in computer algebra system Mathematica (Wolfram Research, Inc., 2013) with finite element code derived using AceGen (Korelc, 2011) and finite model solved by AceFEM (Korelc, 2011). The model represents a 1 m^2 (i.e. 1 m by 1 m) of the external wall with an associated building interior of 2 m^3 and a 3.6 mm thick air boundary layer. The mass of internal partitions and furnishing as well as all internal heat gains were appropriately scaled in order to represent a typical residential house. The numerical model characteristics are presented in Figure 3 and in more depth also in a paper by Hudobivnik et al. (2016).

Additional model boundary conditions were defined in order to accurately study the non-stationary thermal behaviour of selected wall types. Solar radiation heat gains on wall’s external surface were calculated, and the constant solar absorptivity of the exterior surface was set as $\alpha = 0.40$ (solar reflectance $\rho = 0.60$), as suggested by Al-Sanea and Zedan (2011) for light-coloured surfaces (e.g. beige, cream, sand, etc.), commonly used in External Thermal Insulation Composite System (ETICS) façade renderings. In addition, the radiation losses to the environment were considered. Heat gains from occupants and appliances (including their intensity and timetable of occurrence) in internal space were defined in accordance with the values stated for residential buildings (living rooms and kitchens) in EN ISO 13790, Annex G (EN ISO 13790:2008, 2008, p. 137). Natural ventilation (0.7 ACH) as well as high intensity passive cooling (0.7/7.0 ACH) were taken into account, because ventilation regime has a significant impact on internal thermal conditions, consequently affecting heat flow through wall construction. When high intensity passive cooling is used, it is presumed that, during periods when external air temperatures are higher than internal, lower values of ventilation rates are applied (i.e. 0.7 ACH). The value of minimal ventilation rate in the simulations was defined in accordance to EN 15251 (EN 15251:2010, 2010) standard recommendation for residential buildings. In addition to the above, the orientation of façade walls was modified as well in order to evaluate the influence of received solar radiation on the thermal response of analysed walls. Orientations from east-northeast (azimuth 75°) through south (azimuth 180°) to west-northwest (azimuth 285°) were calculated in 15° steps (Fig. 3).

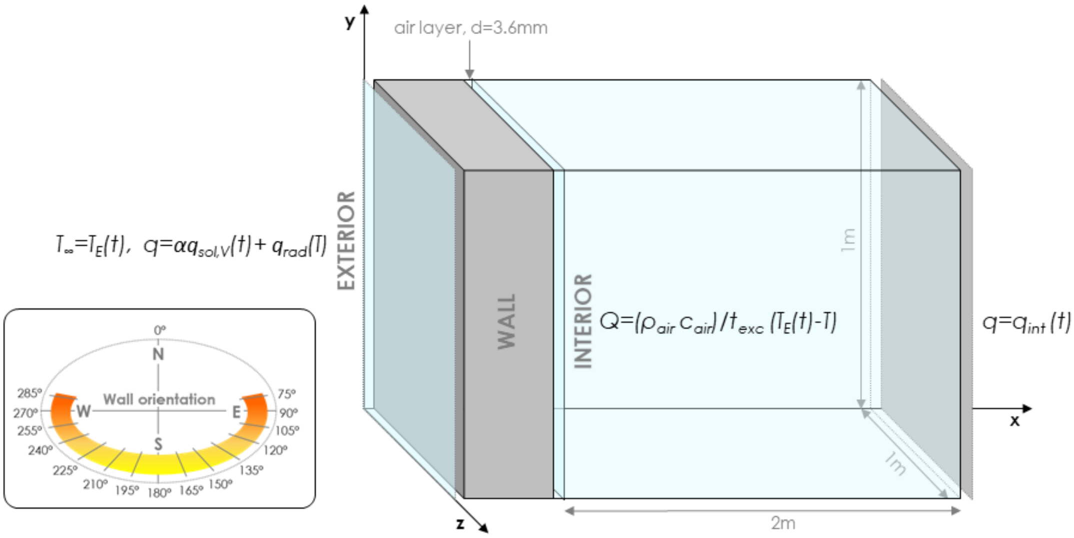

Fig. 3: Numerical model and boundary conditions with representation of analysed wall orientations.

3. Results and discussion of non-stationary analysis

The objective of the executed study was to evaluate the thermal performance of three different external façade walls (i.e. LWC, RC_E and RC_I) in relation to their loadbearing construction system type and thermal insulation position as well as wall orientation and the influence of ventilation regime (i.e. constant or high intensity passive cooling natural ventilation). The numerical model used to simulate the thermal response of the analysed external walls was run under summer climatic conditions in Central Europe (Ljubljana, Slovenia) with presumption that the building is not actively cooled and is therefore in a free-run mode. The latter enabled a study on the influence of the analysed passive strategies (i.e. wall composition, orientation and ventilation mode) on the internal temperatures. Specifically, the internal wall surface temperature was monitored (T_{surf}).

3.1. Influence of high intensity passive cooling on the internal temperatures

The results (Fig. 4) showed that indoor air change intensity has a significant impact on heat flow through external multi-layer building envelopes and the corresponding internal surface temperatures. Therefore, the effect of (natural) ventilation should not be neglected in the evaluation of the thermal response of building envelopes, especially when high intensity night ventilation is used as a passive cooling strategy (i.e. buildings in a free-run mode). When using constant ventilation rates (i.e. 0.7 ACH) for the south faced wall (i.e. azimuth 180°), the highest average T_{surf}, during the analysed period of 28.9°C was reached equivalently in the case of LWC and RC_I (Fig. 4). In the case of RC_E the average T_{surf} is 1.8 K lower (i.e. 27.1°C). In the case of externally insulated wall RC_E the average daily surface temperature fluctuations are the lowest ($\Delta T_{surf\_mean,RCE,0.7ACH} = 0.82$

K), which is the consequence of high thermal mass positioned on the internal side of the building envelope. In the other two cases, where thermal mass is positioned on the external side (RC_I) or there is overall lack of thermal mass (LWC), the average daily surface temperature fluctuations are higher and are $\Delta T_{surf\_mean,LWC,0.7ACH}$ = 1.58 K and $\Delta T_{surf\_mean,RCI,0.7ACH}$ = 1.68 K for LWC and RC_I, respectively.

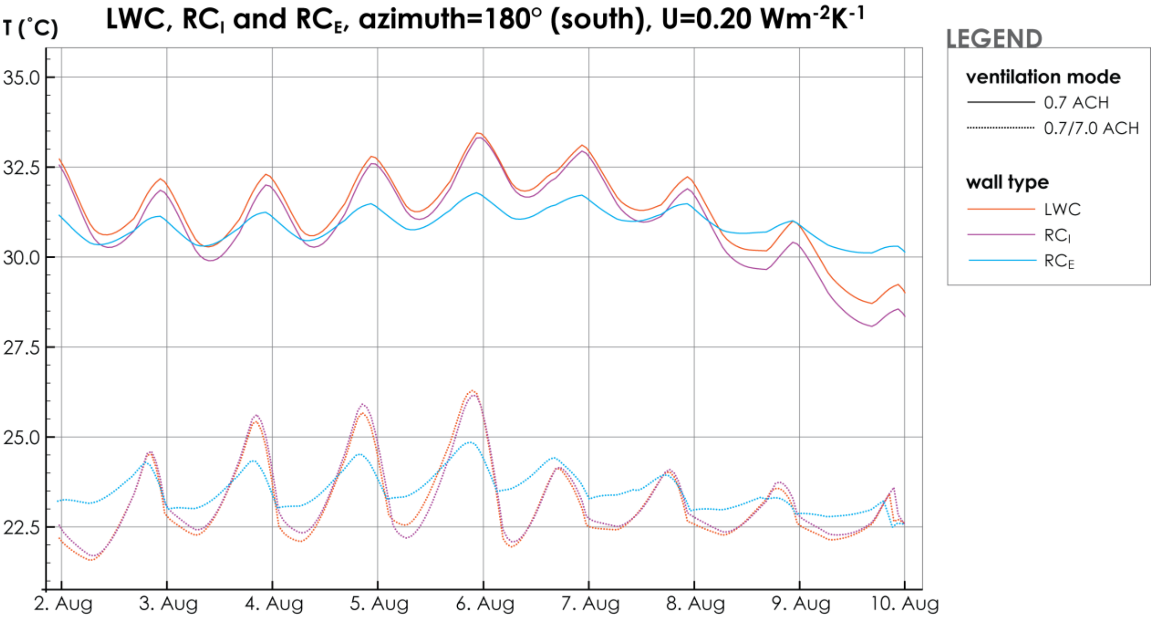

Fig. 4: Impact of high intensity passive cooling (0.7/7.0 ACH) in comparison to constant ventilation (0.7 ACH) on the internal surface temperatures for RC_E, RC_I and LWC at $U = 0.2$ Wm^{-2}K^{-1} and azimuth 180° (south).

Observing the thermal response of the same three constructions under high intensity ventilation regime (i.e. 0.7/7.0 ACH) in Fig. 4, it can be noticed that the maximum T_{surf} in each case drops by approximately 7 K, compared to the case with constant ventilation. Nonetheless, all three constructions exhibit higher average fluctuations of surface temperature under high intensity ventilation regime, which amount to $\Delta T_{surf\_mean,RCE,0.7/7ACH}$ = 0.96 K, $\Delta T_{surf\_mean,LWC,\ 0.7/7\ ACH}$ = 2.23 K and $\Delta T_{surf\_mean,RCI,\ 0.7/7\ ACH}$ = 2.39 K. However, the mentioned increase in ΔT_{surf_mean} is most pronounced in the cases of LWC and RC_I constructions, which lack thermal mass on the internal side. The comparison between LWC (i.e. timber framed wall), RC_E and RC_I façade envelopes with and without the application of high intensity passive cooling demonstrated that, although passive cooling is beneficial in all cases, its absolute effectiveness on the indoor thermal conditions is, however, primarily still dependent on the selection of building envelope type. For example, observing Fig. 4 it can be seen that RC_E exhibits lower surface temperature fluctuations in both cases, whereas the maximum T_{surf} is always reached in the case of LWC, which is 33.3°C and 26.2°C without and with high intensity ventilation, respectively. This means that passive cooling was far more efficient in the case of RC_E than it was with LWC as well as RC_I façade walls, as a result of internally positioned thermal storage capacity in case of RC_E.

3.2. Influence of wall orientation on the internal temperatures

In the next stage of the analysis the influence of wall orientation was investigated for each of the three wall compositions using constant and high intensity ventilation mode. The main point of interest was to study how the combination of external temperatures and received solar radiation influences the internal surface temperatures with respect to the ventilation mode. Wall orientation as a variable was altered from east-northeast (i.e. azimuth = 75°) and west-northwest (i.e. azimuth = 285°) in steps of 15°. The results for each of the constructions are presented in Figs. 5–7.

The results in Fig. 5 represent variations of T_{surf} for RC_E wall construction as a function of orientation and ventilation regime. During the entire analysed period, the maximum T_{surf} in the case of RC_E with constant ventilation (i.e. 0.7 ACH) was reached at azimuth 255° and amounted to 33.5°C, while the minimum T_{surf} of 29.1°C was achieved at azimuth 75°. The mentioned orientations define the upper and lower boundary of a family of curves defining the extent of T_{surf} for all analysed orientations. The average difference between the upper and lower boundary of the defined envelope is 1.7 K. Moreover, several orientations presented in Fig. 5

give similar results. For instance, such orientations are western azimuths between 240° and 270° and east-southeast to south azimuths between 105° and 180°. In the case of RC_E with high intensity ventilation (0.7/7.0 ACH), the overall maximum and minimum T_{surf} of 25.3°C and 22.4°C are reached at different orientations of 240° and at azimuths between 90° and 150°, respectively. The average difference between the upper and the bottom line of a family of curves during the entire analysed period is 0.2 K. From the results presented in Fig. 5 it becomes evident that in the case of high intensity ventilation the impact of wall orientation is no longer significant.

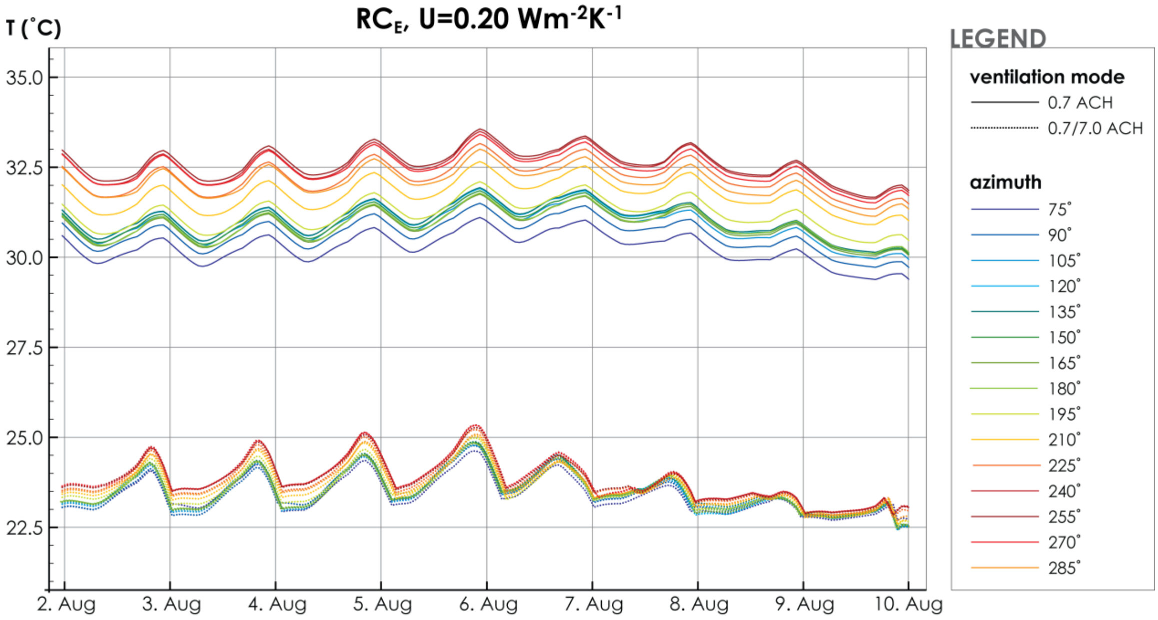

Fig. 5: Impact of wall orientation and ventilation mode (0.7 or 0.7/7.0 ACH) on the internal surface temperatures of RC_E with U value of 0.2 Wm^{-2}K^{-1}.

Fig. 6 shows the results for the RC_I construction, where variations of T_{surf} as a function of wall orientation and ventilation regime can be examined. During the entire analysed period, the maximum and minimum reached temperatures for RC_I in the case of constant ventilation (0.7 ACH) and at different orientations are 35.0°C (at azimuth 240°) and 27.1°C (at azimuth 75°), respectively. The average difference between the upper and the bottom line of a family of curves for RC_I during the entire analysed period is 2.0 K. In the same manner as it was observed in the case of RC_E, several orientations for RC_I construction presented in Fig. 6 give similar results. These orientations are again western azimuths between 240°and 270° (maximum T_{surf}) and eastern-southern azimuths between 105°and 180° (minimum T_{surf}). In the case of high intensity ventilation (0.7/7.0 ACH), the maximum and minimum reached temperatures at different orientations for RC_I are 26.6°C (at azimuths 240° and 270°) and 21.4°C (at azimuth 90°), respectively. The average difference between the upper and the bottom line of a family of curves is 0.4 K, effectively making orientation irrelevant when high intensity ventilation is used.

Finally, the results for the LWC wall construction are presented in Fig. 7, where variations of T_{surf} as a function of wall orientation and ventilation regime can be observed. During the entire analysed period, the maximum and minimum reached T_{surf} for LWC in the case of constant, 0.7 ACH ventilation and at different orientations are 35.1°C (at azimuth 255°) and 27.7°C (at azimuth 75°), respectively, while the average difference between the upper and the bottom line of a family of curves for LWC during the entire analysed period is 1.9 K. The same as in the cases of RC_E and RC_I, several orientations for LWC construction presented in Fig. 7 give similar results. These orientations are western azimuths between 240° and 255° and eastern-southeastern azimuths between 105° and 180°. In the case of high intensity ventilation (0.7/7.0 ACH), the maximum (i.e. 26.5°C) and minimum (i.e. 21.4°C) T_{surf} are reached at azimuths between 240° and 255° and at azimuth 105°, respectively, while the average difference between the upper and the bottom line of a family of curves is 0.3 K. Altogether, the results for LWC and RC_I are almost identical.

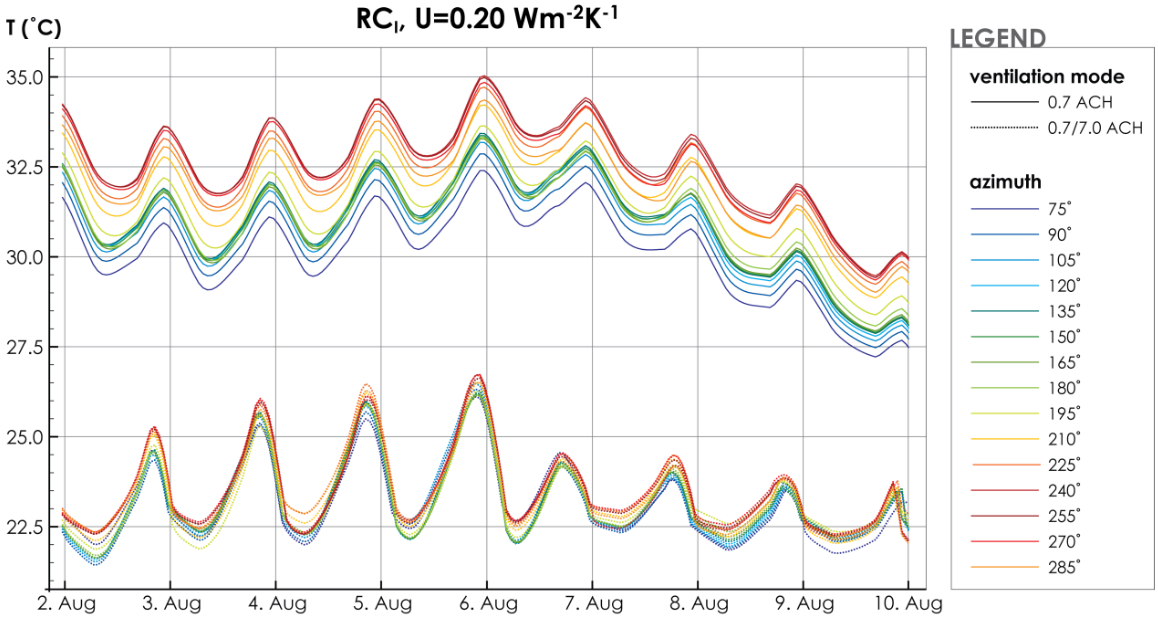

Fig. 6: Impact of wall orientation and ventilation mode (0.7 or 0.7/7.0 ACH) on the internal surface temperatures of RC$_I$ with *U* value of 0.2 Wm^{-2}K^{-1}.

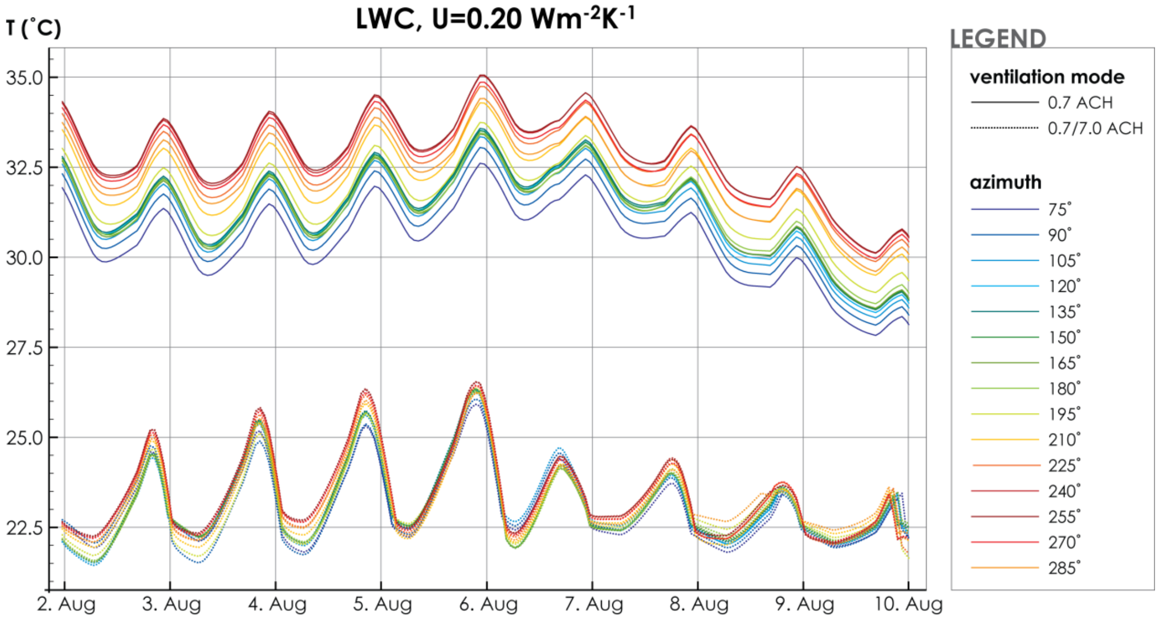

Fig. 7: Impact of wall orientation and ventilation mode (0.7 or 0.7/7.0 ACH) on the internal surface temperatures of LWC with *U* value of 0.2 Wm^{-2}K^{-1}.

The influence of wall orientation plays a role in performance of the analysed constructions as clear differences in internal surface temperatures can be identified at different orientations (Figs. 5–7). In general, for cases with constant natural ventilation (0.7 ACH), eastern orientations (i.e. azimuths 75–90°) exhibited up to 3 K lower T_{surf} in comparison to western oriented walls (i.e. azimuths 240–270°), while southern orientations fall between the two extremes. The orientation plays an insignificant role when high intensity passive cooling is used (Figs. 5–7) as average differences between minimum and maximum T_{surf} for all three analysed cases do not exceed 0.3 K, which is a tenfold reduction in comparison to constant ventilation mode. In general, the externally insulated wall with internally positioned thermal mass (i.e. RC$_E$) outperforms both lightweight (i.e. LWC) as well as internally insulated (i.e. RC$_I$) wall constructions in regards to their thermal response. Despite this fact, it should be stressed that constructions with higher thermal mass on the internal side cool down much slower when constant ventilation is applied. This effect can be observed if the results for RC$_E$ and RC$_I$ (or LWC) are compared (Figs. 4–7) for the days from 8th till 10th of August. Such thermal behaviour is in this case unfavourable. However, if high intensity ventilation is used, the RC_E wall construction outperforms LWC and RCI even in this respect.

In the case of well insulated envelopes, solar gains through façade walls generally have moderate impact on the overall thermal performance. The results presented above were made for constructions with thermal transmittance of 0.2 $Wm^{-2}K^{-1}$. However, thermal response would be different if higher thermal transmittance of the wall was used, as was demonstrated by a study conducted by Corrado and Paduos (2016). Therefore, section 3.3 discusses this issue on the example of RC_E.

3.3. Discussion

Because the analyses presented in previous chapters were made with a fixed U value of 0.2 $Wm^{-2}K^{-1}$, it was of further interest to investigate how higher U value would influence the thermal response of the wall construction in regards to its orientation and ventilation mode. Therefore, an additional study was made with the RC_E wall construction, where its U value was set to 0.6 $Wm^{-2}K^{-1}$. The results presented in Fig. 8 are plotted as an envelope of a family of curves made for the wall orientations with azimuths between 75° and 285° for U values of 0.2 and 0.6 $Wm^{-2}K^{-1}$. The results in Fig. 8 show that wall orientation plays much greater role, when thermal transmittance of the construction is higher and even more so, if constant ventilation regime (i.e. 0.7 ACH) is used. In particular, the average difference between the upper and the bottom line of a family of curves for constant ventilation and U = 0.6 $Wm^{-2}K^{-1}$ is 3.3 K, while for U = 0.2 $Wm^{-2}K^{-1}$ this value is equal to 1.7 K. In the case of high intensity ventilation (i.e. 0.7/7.0 ACH) the average difference between the upper and the bottom line of a family of curves for U = 0.6 $Wm^{-2}K^{-1}$ is 0.8 K, while for U = 0.2 $Wm^{-2}K^{-1}$ this value is equal to 0.2 K. Comparing RC_E constructions in Fig. 8 at azimuth 180° (i.e. south) it can be said that in the case of constant ventilation higher U values of walls can results in lower T_{surf} and faster thermal response (e.g. the T_{surf} is reduced faster during the cooling down period from 8th to 10th of August). However, the situation is reversed when high intensity ventilation is used.

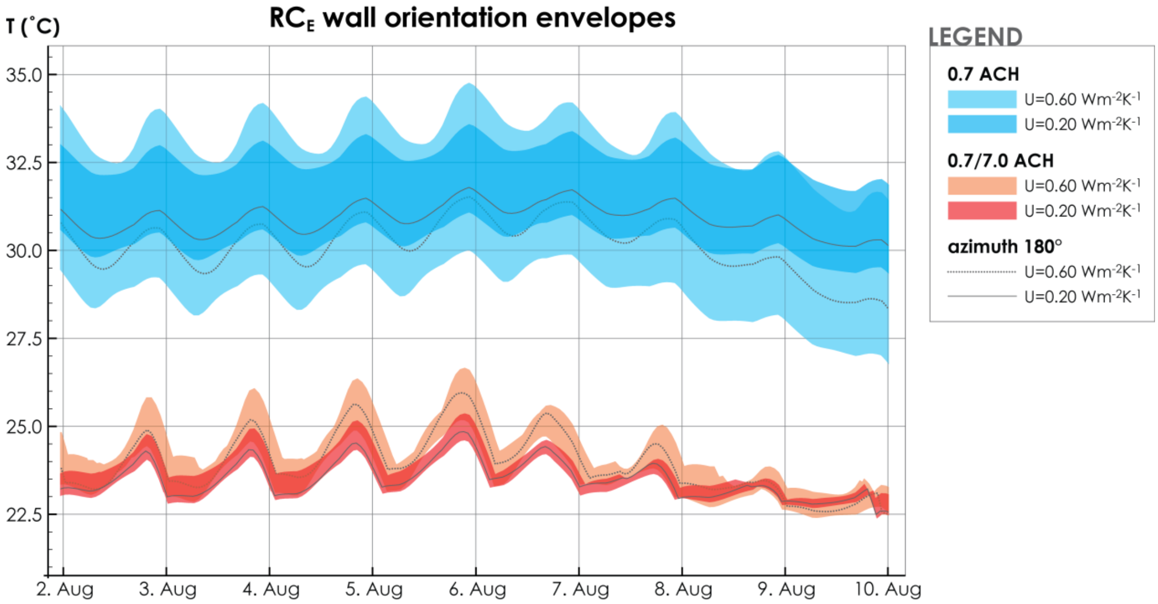

Fig. 8: Comparison of wall orientation envelopes of internal surface temperatures for RC_E at different ventilation modes (0.7 and 0.7/7.0 ACH) and different U values (0.60 and 0.20 $Wm^{-2}K^{-1}$).

Observing Fig. 8 it can be concluded that in temperate climate it would be better to use higher thermal transmittance of walls in order to better control indoor wall surface temperatures during summer. Conversely, buildings in such climate zones are mostly optimized for the winter conditions, thus having low or extremely low U values. The latter is also prescribed by the legislation. Therefore, high intensity cooling can play a vital role in enhancing the summer time thermal performance od wall constructions with low U values, as using it results in a better performing construction (i.e. lower T_{surf}) (Fig. 8). This specifically applies to all the considered orientations under the presumption that high intensity ventilation (passive cooling) is used.

The results of the conducted study showed that even in cases with low *U* values of the walls, orientation of the façade has an impact on the thermal response of non-transparent building envelope elements. In particular, substantial differences between east, south and west orientations were identified. Especially the south-west orientation of the façade was shown as extremely unfavourable in the case of LWC and RC_I. Although wall composition (especially thermal mass) and orientation play a role in the thermal response of the analysed façade walls, high intensity passive cooling proved as the most decisive factor, whereas the potential of diurnal temperature fluctuations is used to passively cool down buildings. Nevertheless, even here the effectiveness is linked to the configuration and type of the façade wall.

4. Conclusions

The trend of using lightweight building envelope components, especially in residential buildings, will probably continue during the forthcoming years (Kitek Kuzman et al., 2013). The biggest growth is expected in the market of timber framed and cross-laminated construction systems. Consequentially, the importance of assuring satisfactory thermal response of such envelope systems during summer conditions will become crucial. The latter is highlighted through the presented study as LWC external façade wall systems have been shown to exhibit inferior thermal performance in comparison to externally insulated heavy weight envelopes (HWCs). In the light of EU policies for the reduction of building stock’s influence on the energy consumption and the decrease of environmental impact, it is crucial to develop and implement passive solutions for the reduction of cooling loads. Results of the conducted analysis show that lack of thermal mass in lightweight construction systems should be addressed. In addition, it was shown that, although both wall composition and orientation influence the thermal response of the façade envelope, the greatest effect can be achieved by using appropriate passive cooling ventilation technique. After all, prospective solutions can be found in applications of materials with high thermal storage potential and relatively small thickness in the form of interior cladding (Jeanjean et al., 2013). However, in this context the appropriate use of PCMs (Kheradmand et al., 2016) and/or other efficient enhancements of thermal performance of lightweight constructions (Pajek et al., 2017) can be a viable alternative as well. The findings of the conducted study can represent guidelines for design decisions when the objective is to design better performing buildings. Although each building is unique, set in its individual environmental context, the general performance principle of selected wall constructions remains the same.

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