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Evaluation of the thermal comfort and indoor air quality in a military shelter under summer conditions

Evaluarea confortului termic și a calității aerului interior într-un adapost militar în condiții de vară

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Abstract. *The present paper presents a study of thermal comfort in a military tent, through numerical analysis using dynamic simulations, under summer climatic conditions. The topic was chosen based on the increasing importance of temporary structures in military activities, operational interventions, training camps or situations in which personnel must carry out activities in open field. The main goal was to evaluate thermal comfort in a military tent, by comparing several operational scenarios and by identifying solutions that can reduce overheating and improve the quality of the indoor environment. The results obtained are promising and should be confirmed by an experimental campaign.*

Key words: *thermal comfort, indoor air quality, military tents*

Rezumat. *Prezenta lucrare are ca obiectiv studiul confortului termic în corturi militare, prin analiza numerică a unui cort utilizat ca adăpost temporar pentru personalul militar, în condiții climatice de vară. Tema a fost aleasă pornind de la importanța structurilor temporare în activități militare, intervenții operative sau situații în care personalul trebuie să desfășoare activități în teren deschis. Scopul principal al lucrării a fost evaluarea confortului termic într-un cort militar, prin compararea mai multor scenarii de simulare și prin identificarea soluțiilor care pot reduce supraîncălzirea și pot îmbunătăți calitatea mediului interior. Rezultatele obținute sunt încurajatoare și vor trebui confirmate printr-o campanie experimentală.*

Cuvinte cheie: *confort termic, calitatea aerului interior, corturi militare*

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1. Introduction

The study of thermal comfort in military tents and temporary shelters has become increasingly important in recent years due to the current geopolitical context marked by regional conflicts and humanitarian crises, facts that emphasize the need for more efficient temporary shelter solutions. Although these structures were created, in principle, for short-term use, in practice, they end up being used for long periods when returning to a permanent home is slow or impossible. Under these conditions, thermal comfort parameters and accumulated pollutant concentrations indoors no longer represent just a singular comfort issue, but one of health, safety and functionality of the occupied space.

Zheng et al. [1] selected and studied over 100 representative articles from a broad analysis of thermal comfort in temporary buildings, producing a synthesis that aims to organize the entire field of thermal comfort in temporary shelters. The article is not limited to a single type of shelter, but synthesizes the existing literature for temporary buildings, including tents, modular shelters, containers and other lightweight structures. The aim of the research was to find problems related to thermal comfort, assessment methods used in practice and improvement measures reported in different climatic zones. The users of these spaces are frequently dissatisfied with the quality of the indoor environment, and this problem occurs recurrently in most climatic zones. Thermal discomfort rates reach approximately 75% in hot and humid climates, 86.7% in hot and dry climates, 51% in temperate climates and 85% in cold climates. For example, in temperate climates, the authors showed that temperatures inside temporary buildings can vary between 7°C and 41°C throughout the year, with predicted mean vote (PMV) values outside the comfort range 60% of the time. These data show that temporary structures have very poor thermal performance and present difficulties in maintaining a comfortable indoor environment.

Crawford et al. [2] studied temporary shelters in cold climates by experimentally testing two shelter prototypes under controlled conditions, with the external temperature maintained at -20°C and compared the measurement results with numerical simulations in the ESP-r program. The aim of the research was twofold - on the one hand, to compare the performance of two constructive solutions (the total thermal conductance of one shelter was 54.29 W/K, and 63.82 W/K for the second prototype), and on the other hand, to develop well-calibrated evaluation tools that could be used to correctly simulate these structures under different conditions. An important result of the work was related to the thermal stratification of the air: both tents showed a significant variation in temperature with increasing height, the temperature difference between the lower and middle areas reaching up to 17°C. This shows that the average internal temperature is not an accurate parameter and can hide severe discomfort.

Cornaro et al. [3] analysed an emergency tent produced in collaboration with the Solar and Organic Energy Center. The authors studied the performance of a tent in both hot and cold climates, using an IDA Indoor Climate and Energy 4.5 dynamic simulation model calibrated using field data collected near Rome. The tent studied is constructed of a steel structure, covered with a material composed of 50% cotton and 50% modacrylic synthetic fiber. Six photovoltaic panels with a power of 780 Wp were installed on the roof of the tent, which will produce between 300Wh/day and 4 kWh/day depending on the season. Cornaro's study [3] shows the levels of poor performance of a tent in winter and how much these effects can be improved by using thermal insulation of the tent envelope structure. In addition, in hot climates, the study proves that in addition to using insulation, reflective shading elements are needed to reduce daily solar gains.

Y. Jiang [4] directly assessed the thermal comfort of soldiers in military tents during summer. The study was conducted in Tianjin, for four outdoor military tents, with 30 investigations being carried out between 8 am and 6 pm to study the effects of the indoor environment on soldiers during the hot period. The study consisted of questionnaires being completed by groups of 10 people, with almost 100 soldiers being interviewed for this experiment. Also, in addition to the questionnaires completed by the soldiers, the author measured indoor parameters such as temperature, relative humidity and air velocity to correlate the physical parameters with the direct perception of people. Jiang defined a scale with values ranging from -3 (very cold feeling) to +3 (very hot feeling), with the value 0 being for the thermal neutral zone. The indoor air temperature ranged between 22.06°C and 33.4°C, while the outside temperature ranged between 22.8°C and 26°C, so the temperatures inside the tent were higher than those outside; the average relative humidity was 61.97%. The study shows that the vote for thermal sensation 0, i.e. neutral, was for the range 26-28°C.

At the same time, Liu et al. [5] studied a simple passive solution to increase thermal comfort by installing textile shade nets over a military tent. For this experiment, two shade nets were compared, one with a shade rate of 75% and the other with a shade rate of 96%, both mounted one meter above the tent. The test took place in Tianjin city, on a day when the outside temperature varied between 20°C and 28°C. To conduct the experiment, the authors used 25 thermometers placed at five different heights: 0.1m, 0.5m, 1m, 1.5m, 2m. In addition, the authors measured the relative humidity both inside and outside and monitored the temperature on the inner surfaces of the envelope. The study's conclusions show that the 96% shading net should be preferred, as it reduces solar gain much better and thermal stratification is less pronounced. The authors propose extending the shading surface to the tent walls, as well as optimizing the position and size of the windows.

Tan and Tan [6] compared the performance of a tent with that of a standard temporary shelter configuration (container type) under subtropical summer conditions in Taiwan, using both experimental measurements and computational analysis. During the time interval 9:30-14:30 in the center of the tent, the air temperatures at heights of 0.1m, 1.1m, 1.7m were 3.1°C, 5.5°C and 6°C higher than the outdoor temperature. In contrast, in the standard shelter configuration, the temperatures measured at the same points were 1.2°C, 0.5°C and 0.7°C lower than the same outdoor temperature. In other words, the tent enhanced the heating of the indoor air, while the standard shelter configuration was able to maintain temperatures below the outdoor temperature. In terms of PMV and PPD (Predicted Percentage of Dissatisfied) indices, the standard configuration recorded an average PMV of 3.14 and PPD of 100%, while the tent had a PMV of 5.03 and the same PPD of 100%. Neither was the shelter able to maintain a comfortable indoor environment, but the level of heat stress was significantly more severe in the tent.

The PhD thesis of R. Poschl [7] is one of the most consistent works in literature on thermal comfort in humanitarian tents. The study included field monitoring for six months, dynamic thermal modelling and CFD modelling. The author used a real standardized tent, installed in the UK, then calibrated numerical models that were subsequently applied for cold, temperate and warm climates. For the cold climate, one of the most important conclusions is that changing the material for the walls and roof increases the difference between the indoor and outdoor temperature from 30 K to 39 K, i.e. by 9 K. In addition, the number of hours of thermal comfort according to the PMV-PPD index criteria increased from 10.50 hours to 23.00 hours. This is a very large increase and shows that improving the envelope material has a direct effect on the real possibility of achieving a thermal state closer to optimal comfort. Interestingly, the number of hours in which a state of good thermal comfort is observed assessed only by the indoor air temperature decreased from 17.25 to 16.00 hours, which shows that assessing comfort based only on-air temperature is incorrect and that changing the material also changes other comfort parameters.

For hot climates, Poschl [7] shows that simply increasing the ventilation openings does not solve the problem. In the best-case scenario of increased opening, the PMV range improved from +1.7…+3 to +1.5…+3, i.e. by only 0.2 units. The maximum PPD value decreased from 72.4% to 62.4%, i.e. by 10 percentage points, and the interior temperature in the hottest part of the day decreased from 75.2°C to 72.5°C. In other words, the additional ventilation helps a little, but the thermal comfort in the tent does not improve significantly.

In contrast, changing the shading strategy and increasing the reflectance of the envelope material had much greater effects. The author shows that the PMV index improved from 2.9 to 2.6, and the maximum PPD value decreased from 95.7% to 91.2%. The most important finding is the reduction of the indoor air temperature by 23 K compared to the basic tent. Even so, the results summarized by the author show that even the optimized variant does not provide acceptable hours according to the PMV/PPD criteria in very hot climates: both the basic tent and the "large opening" and "modified shading" variants have 0 hours of comfortable environment.

The important conclusion of the thesis is that some solutions clearly work better than others, but in very severe climates even good solutions are not enough to transform the tent into a thermally comfortable space. In cold climates, improving the envelope can double the acceptable hours after PMV/PPD, and in warm climates the use of reflective materials can lower the interior temperature. However, in extreme climates additional measures are also needed – for example, additional blankets and clothing for the cold or active cooling solutions in very hot environments.

Lee et al. [8] reached the same conclusion, showing that advanced materials used for tent envelope insulation and shading can bring modest improvements to the thermal comfort during the warm season, and correct infiltration modelling can have a greater impact on thermal comfort in the cold season.

The study conducted in this paper aims to evaluate the thermal behaviour and indoor air quality for a small, lightweight military tent-type structure, typical of the Romanian Army, through numerical simulations performed for a standard (reference) tent, as well as for an identical tent for which different scenarios for improving the indoor environment in Bucharest summer conditions were applied. It follows the main hypothesis carried out in the paper entitled: "Analysis of possible overheating countermeasures applied to a Romanian military tent by means of numerical simulations", which was accepted for the presentation at the RoomVent 2026 Conference, to be held in Prague, between 15th and 18th September 2026 [9]. The present paper will focus on the influence of improved ventilation scenarios related to those presented in [9], as well as on the indoor air quality (IAQ) obtained indoors by using these scenarios.

2. Description of the investigation method and case studies

The analysis of the thermal comfort presented in this paper relies on the PMV-PPD Fanger theory, certified by the European standard EN 7730 [10]. Therefore, we performed dynamic simulations with the Design Builder simulation software, during a one-week summer period (1st-7th July, corresponding to the weather file for Bucharest, Romania, available within the Design Builder weather database), to assess the variation of the thermal comfort index PMV within a temporary military shelter, while assuming two methods to counteract excessive overheating: shading and mechanical ventilation with outdoor air.

The Design Builder simulation program (educational license) was used to perform numerical simulations of shading and ventilation scenarios for a military shelter located in the city of Bucharest, Romania. This program was conceived to analyse thermal building behaviour, energy performance of the systems linked to buildings (heating, ventilation, air-conditioning) through dynamic simulations, which allows also the assessment of thermal comfort and the verification of the influence of different comfort improvement solutions on the indoor environment, using dynamic calculations based on the Energy Plus simulation engine.

To model the military tent thermal regime, the most important categories of input data entered into Design Builder interface are the building envelope (walls, windows, slabs), the schedules for daily human occupancy, for occupant's activities, properties of opaque and transparent materials, lighting systems, HVAC systems and their operating schedules. Each of these categories influences the results of the simulation, either through internal heat gains, heat transfer through the envelope, or air exchange between the outdoor and indoor environment.

The analysed tent is a real one, in terms of shape, materials and dimensions, typically used by the Romanian army within latest decades, with plan dimensions of 3.60×3.60 m and a two-slopes pitched roof (Fig. 1). The height of the side walls is

1.60 m, and the maximum height in the ridge area is 2.30 m. The tent has a surface area of 12.96 m^2 and a volume of 25.27 m^3.

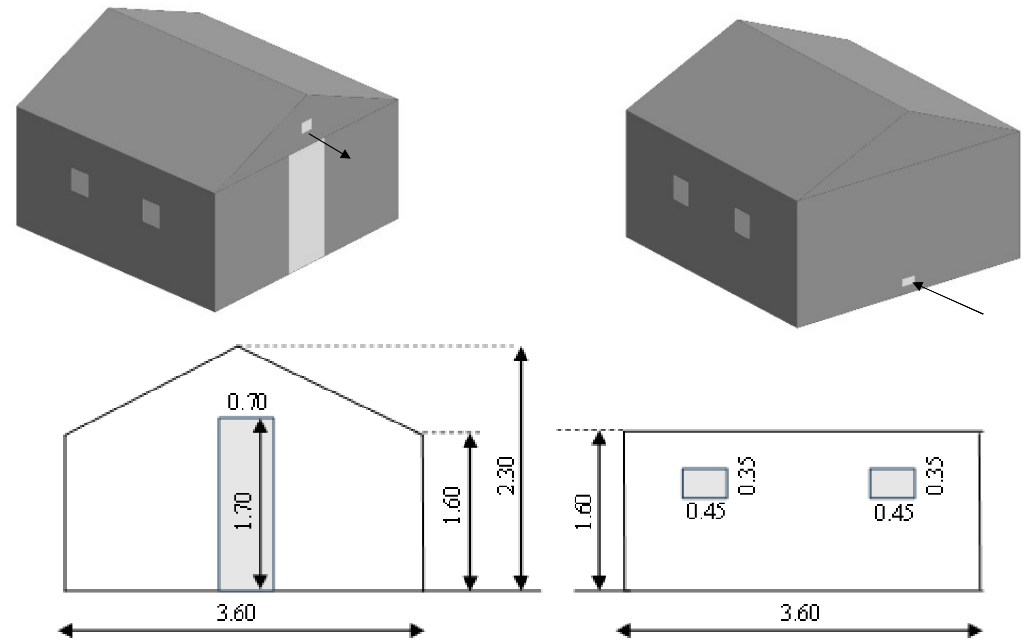

Fig. 1. Sketch-up of the simulated tent and its geometric dimensions (m) [9]

The material of the tent envelope is textile fabric, and its behaviour is not only influenced by the thermal conductivity of the material, but also by the way in which the material reflects or absorbs solar radiation. The textile fabric has a thermal conductivity of 0.04 W/m·K and a solar radiation absorption coefficient of 0.90. The tent envelope contains 4 windows (made of plexiglass) mounted on opposite facades, with a thickness of 3mm and a thermal conductivity of 0.19 W/m·K. In terms of optical properties, the plexiglass was defined as a solar transmittance of 0.90, and the external and internal solar reflectance was 0.08. These values show that the material allows a very large proportion of the incident solar radiation to pass through to the interior, while only a small part is reflected by the external or internal surface.

The internal heat gains were considered as follows: for lighting 5 LED bulbs, each with a power of 5 Wp, resulting in a total installed power of 25 Wp (operating only in the evening, between 19:00 and 22:00) and a maximum occupancy of 8 people. During the day, the heat gain from people inside was 125 W/person (light physical activity), respectively 70 W/person during nighttime, due to the reduced activity inside the tent (sleeping). During a day, training, rest and administrative activities are considered (Table 1). The total installed power for lighting being low in relation to the occupants' emissions and the effects of solar radiation on the envelope, the lighting did not have a visible influence on the internal environment but was included to more accurately represent the way the tent is used.

Table 1

Daily occupation schedule for the analysed tent [9]

Period of the day	Type of activity	Number of people present in the tent	Metabolic heat emitted (W/person) [10]
6:00 – 7:00	Wake-up time	Eight	125 (light physical activity)
7:00 – 8:00	Breakfast time	No people	0
8:00 – 12:30	Training activities	No people	0
12:30 – 13:30	Lunch time	No people	0
13:30 – 19:00	Mixed activities	Four	125 (light physical activity)
19:00 – 20:00	Dinner time	No people	0
20:00 – 21:00	Administrative activities	Six	125 (light physical activity)
21:00 – 6:00	Rest during nighttime (sleeping)	Eight	70 (low activity, sleep)

In table 2 are presented the three improved mechanical ventilation scenarios imagined for the simulations of thermal comfort and indoor air quality, as related to [9]. In fact, the V2 scenario remains the same as the similar V2 presented in [9], while the V3 scenario suppose a double airflow rate reported to V2 (200 m^3/h), more appropriate to remove the excess heat from the tent during the high solar gains period (daytime). The scenario V1 is similar with the correspondent V3 from [9], with the single difference in the airflow rate during periods of human absence, which is doubled (50 m^3/h- 2 ach, instead of 25 m^3/h-1 ach) also for reasons of a better excess heat removal. Concerning the airflow rates corresponding to the period of human presence, they are calculated according to the equation (2), given by the Romanian norm for design, execution and commissioning of the ventilation and air-conditioning installations, I5-2022, for non-residential buildings [11]:

$$q_{fa} = N_p * q_A + A_o * q_B \qquad (1)$$

where:

q_{fa} - the fresh airflow rate for ventilation purposes, supplied from outdoor (m^3/h),

N_p – number of people present indoors (0 to 8), variable upon the schedule (Table 1),

q_A – specific airflow rate depending on the ambiance category (m^3/h*person),

A_o – occupied area (m^2), equal to 14 m^2,

q_B – specific airflow rate depending on the ambiance category as well as on the potential pollution issued by the building itself ($m^3/h*m^2$).

Table 2

Ventilation scenarios proposed for the simulations

Ventilation scenario number	Airflow rate	Schedule
Ventilation scenario No.1 (V1)	Variable according to the schedule and calculated with equation (2)	25 m^3/h – during nighttime 50 m^3/h – during absence 120 m^3/h – 4 people present 170 m^3/h – 6 people present 220 m^3/h – 8 people present (excepting nighttime)
Ventilation scenario No.2 (V2)	100 m^3/h (4 ach), or 25 m^3/h (1 ach)	100 m^3/h (4 ach) during daytime (7:00-21:00), 25 m^3/h (1 ach) during nighttime (21:00-7:00)
Ventilation scenario No.3 (V3)	200 m^3/h (8 ach), or 25 m^3/h (1 ach)	200 m^3/h (8 ach) during daytime (7:00-21:00), 25 m^3/h (1 ach) during nighttime (21:00-7:00)

Concerning the shading measures to be taken, we proposed the same two solutions for the tent pitched roof covering, as in [9], outlined in table 3.

Table 3

Shading solutions proposed and characteristics [9]

Thermal and optical characteristics	Shading solution No.1 (U1) (Aluminium foil)	Shading solution No.2 (U2) (Shade net)
Thermal conductivity (W/m*K)	237	0.5
Specific heat mass (J/kg*K)	900	930
Mass density (kg/m^3)	2700	1300
Thermal absorptance (-)	0.05	0.4
Solar absorptance (-)	0.1	0.4
Visible absorptance (-)	0.1	0.4
Transmissivity (-)	0.0	0.4
Reflectance (-)	0.9	0.2

3. Results and discussion

In figures 2 and 3 we present the 7-days (equivalent to 168 hours) variation of indoor operative temperatures and PMV indexes obtained by numerical simulations, for the three shading situations assumed (no shading, shading U1 and shading U2), along with the variation of the outdoor temperature. The ventilation scenario applied for this simulation was V1, according to Table 2. We could notice from these figures that, during the warmest day periods, corresponding to the superposed effect between outdoor temperature and solar radiation (11:00 to 17:00), the indoor operative temperatures exceed 35 °C (excepting day 7, the coldest of the week), while PMV-s exceed the value of +3 (hot, according to the Fanger comfort scale [10]), for the same time intervals. Moreover, it appears clearly that the ”no shading case” is the worst related to thermal comfort, while the shading case U1 (Aluminium foil) seems to be the most favourable one. As expected, the shading case U2 (shade net with 40% solar transmittance) lies between these two extreme cases. This behaviour could be explained by the high reflectance (0.9) of incident solar radiation that characterises the Aluminium foil. Meanwhile, for the shade net solution, the reduced transmittivity of light lowers the temperature increase of the tent roof material compared with the “no shading case”, but with a lower efficiency of heat transmission indoors compared with the Aluminium foil case.

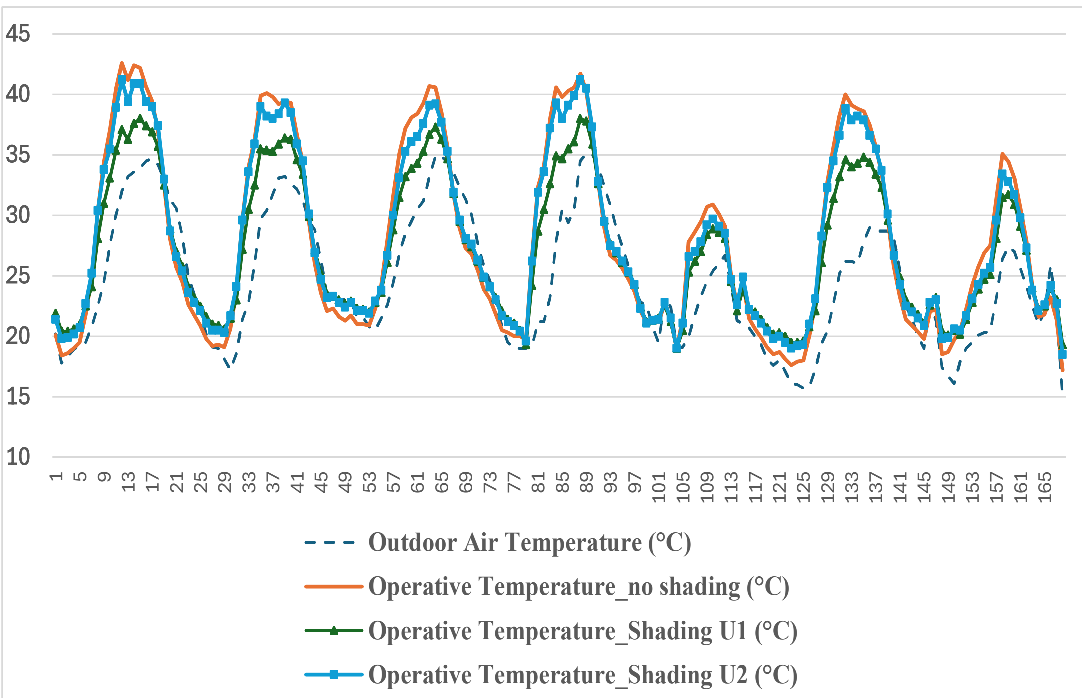

Fig. 2. Comparison between indoor operative temperatures obtained by applying the ventilation scenario V1 for the two types of shading (U1 and U2) and the ”no shading case”.

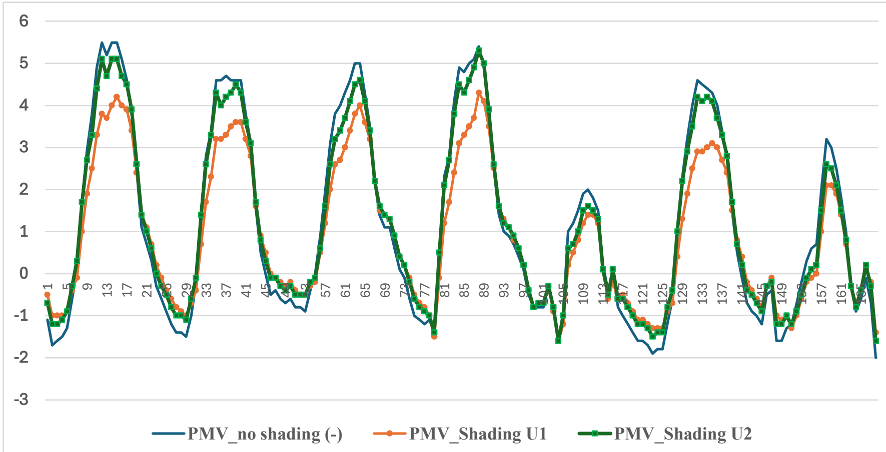

Fig. 3. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V1 for the two types of shading (U1 and U2) and the "no shading case".

In fig 4. is presented the comparison between indoor operative temperatures obtained by applying the best ventilation scenario, V3 (8 air changes per hour during daytime and 1 ach during nighttime) for the two types of shading (U1 and U2) and the "no shading case", while in fig.5 is outlined the similar variation of the PMV-s obtained under the same hypothesis.

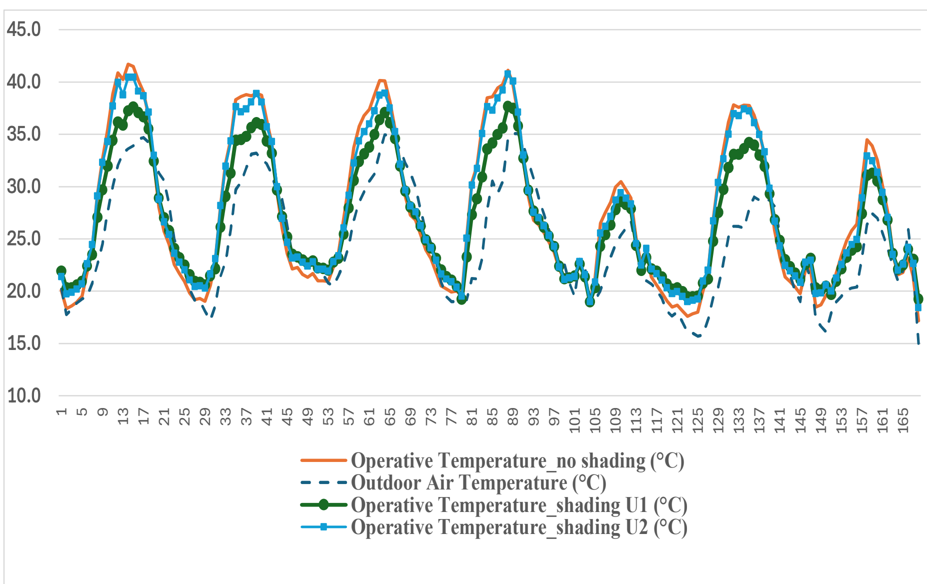

Fig. 4. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V3 for the two types of shading (U1 and U2) and the "no shading case".

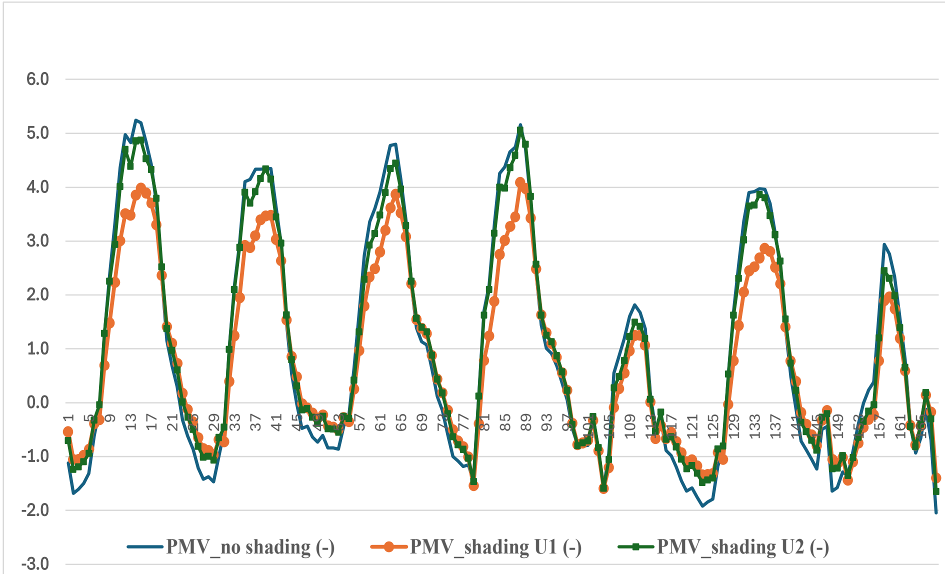

Fig. 5. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V3 for the two types of shading (U1 and U2) and the "no shading case".

The conclusions emerging from these two graphs are similar to those explained for the ventilation scenario V1, with the single difference in the lowest peaks of operative temperatures and PMV-s, which is due to the highest airflow ventilation rate (Table 2), which is supposed to evacuate more excess heat from the analysed tent.

In the figures 6 and 7 are represented the variations of the operative temperatures and PMV-s, assuming the same shading case (U2 in fig.6 and U1 in fig.7), but three different mechanical ventilation scenarios (V1, V2 and V3). We could observe from each of these graphs that the scenario V3 (green line) is the best (lowest peaks of operative temperatures and PMV-s), while the scenario V2 (constant airflow rate of 100 m^3/h during daytime) appears to be the be slightly worse than V1, but very close to it. However, the differences between the peaks obtained by the simulation of these scenarios are quite low, keeping thus in mind that the influence of the ventilation rate with outdoor air doesn't bring a substantial improvement on the thermal comfort, in the absence of any active or passive cooling method.

However, when comparing fig.6 to fig.7, we could notice that the peaks of operative temperatures and PMV-s for the shading case U1 are sensibly lower that those obtained for the shading case U1. Therefore, it is obvious that the efficiency of the shading method has much more influence on the thermal comfort than the ventilation airflow rate during the daytime, when the thermal load is heavy (temperature and solar radiation).

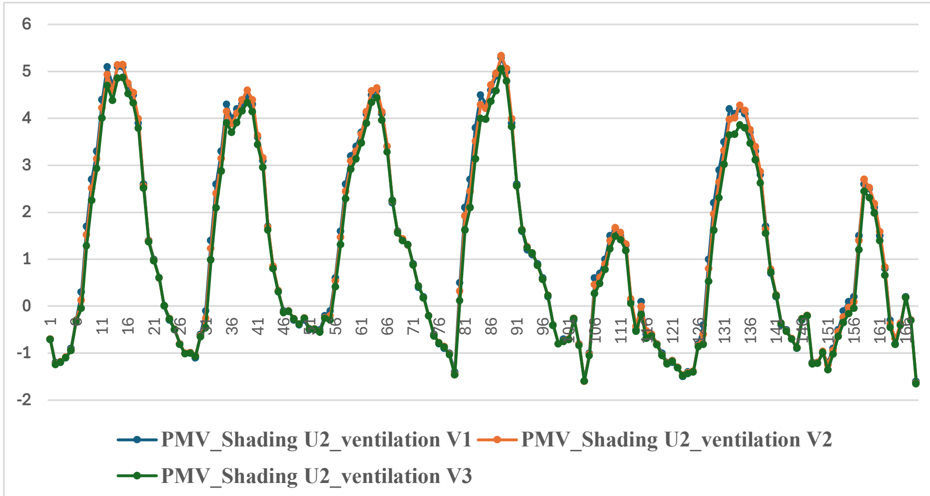

Fig. 6. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U2

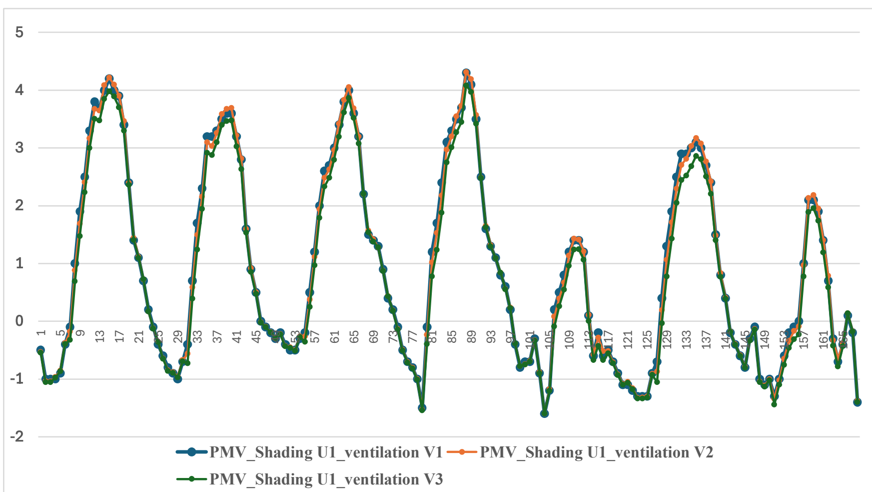

Fig. 7. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U1

Concerning the influence of the ventilation scenarios on the indoor air quality (IAQ) related to CO_2 indoor concentrations (in ppm unit), we represented in fig.8 a comparison between the V1, V2 and V3 scenarios, for the shading case U2, for the whole 7-days simulation period. We can notice from this figure that the best scenario for IAQ is V3 (with the highest airflow rate), where the maximum CO_2 indoor concentration (green line) reaches approximately 900 ppm, when for the other two scenarios (V1 and V2), the concentrations are very close and the peaks are slightly surpassing the threshold limit of 1000 ppm, at the hour with maximum occupancy. During nighttime we could notice that indoor CO_2 concentrations decrease at 400-500 ppm values (very good IAQ), which could be explained by very low CO_2 emissions through respiration, by the sleeping occupants, as well as by the outside CO2 concentration, equal to 350 ppm. A similar concentrations behaviour was observed for the shading case U1.

Therefore, we could assess that all the ventilation scenarios imagined are satisfying the IAQ condition related to CO_2 concentration, regardless of the shading solutions adopted.

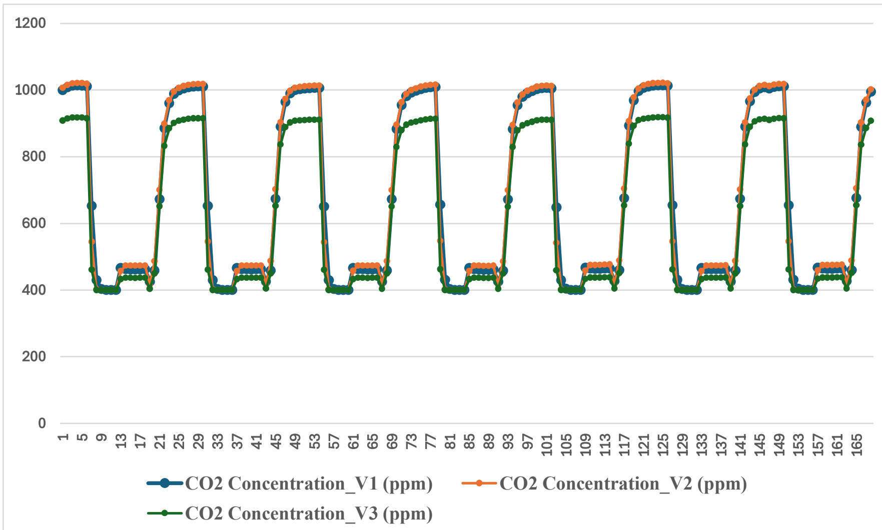

Fig. 8. Comparison between indoor CO2 concentrations by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U2

4. Conclusions

The main conclusions that could be highlighted from this numerical study are:

- The efficiency of the shading method is crucial in regard with the indoor thermal comfort, but could not alone reduce the PMV values below ”+3” (sensation of Hot environment) during daytime (highest cooling loads), in the absence of any passive or active cooling system;
- The mechanical ventilation plays an important role in maintaining CO_2 concentrations indoors below the threshold value of 1000 ppm, considered as the maximum limit of the ”fresh air state”; however, any ventilation scenario chosen, even with the highest airflow rates (8 air changes per hour during daytime) could not assure indoor thermal comfort when outdoor temperatures reach peak values as high as 35 °C or bigger;
- Even that the ventilation scenarios could not ensure the thermal comfort sensation during daytime, the increase of outdoor airflow rate leads to the decrease of indoor operative temperatures peaks, as well as of PMV-s peaks;
- During nighttime, the situation changes, in the sense that the thermal comfort improves considerably after 8:00 PM, while after 2:00 AM and 6:00 AM the calculated PMV-s could reach even ”-2” values (sensation of

Coldness), knowing that the occupants are wearing light clothes (0.5 clo thermal resistance, equivalent to summer period) and their internal metabolism is very low (sleeping period); this rapid change in thermal sensation during the day cycle could be explained obviously by the very low thermal inertia of the tent structure.

The research presented in this paper will be completed with results issued from an experimental campaign performed during the summer 2026 (July-August 2026), corresponding to an identical tent with the one described in Figure 1, and considering similar scenarios of mechanical ventilation and shading.

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