SUMMER OUTDOOR THERMAL COMFORT IN MULTI-FAMILY HOUSING
Combining Microclimate Indicators with Human Thermal Sensation

by

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The paper examines outdoor thermal comfort in summer in the multi-family housing area Duvanište in the city of Niš, Serbia, combining objective and subjective evaluation assessments. Objective evaluation obtained field measurements of microclimatic parameters at selected sites and mean radiant temperature, predicted mean vote, and psychological equivalent temperature calculation using RayMan software. Subjective methodology assessment is performed using survey questionnaires based on thermal sensation vote and overall comfort vote. The paper aims to find the correlation between measured and calculated parameters on one side and Thermal Sensation Vote values. The results show that air temperature significantly correlates to human thermal sensation in the subject area. Obtained results also indicate high prediction accuracy of psychological equivalent temperature in the outdoor thermal comfort evaluation in summer. Finally, to feel comfortable, neither warm nor cold, in continental climate regions with hot summer conditions, the neutral psychological equivalent temperature should be between 15-24.3 °C.

Key words*: outdoor thermal comfort, multi-family housing, RayMan model, mean radiant temperature, psychological equivalent temperature, thermal sensation vote, overall comfort vote, predicted mean vote*

Introduction

Suitable outdoor thermal comfort is a significant precondition for high-quality and environmentally friendly urban areas. Compared to indoor environments, outdoor urban spaces are more complex due to variations in climatic characteristics, users' physical and socio-cultural adaptation, and activities [1]. Different microclimatic conditions and urban morphology defined by the geometry of buildings, vegetation, and other urban elements, can affect the use of open areas and users' behavior. Due to the expansion of urbanization, the effect of global warming, and the appearance of urban heat islands, the issue of achieving adequate thermal comfort and overcoming heat stress in outdoor environments is particularly pronounced after the 2000s [2]. The first outdoor thermal comfort studies were initiated in the 1940s, but realization dropped until Penwarden 1973 tried to systematize external thermal conditions by introducing solar radiation as an important factor [3]. Further, Fanger [4] determined human thermal conditions by a heat exchange model based on physical (air temperature, air velocity, air humidity, mean radiant temperature) and physiological indicators (metabolism and clothing level). Fanger's predicted mean

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vote (PMV) model aims to predict the mean value of thermal comfort of a group of occupants, measured by a thermal sensation scale [5, 6]. In the absence of official standards for outdoor thermal comfort, the model has remained one of the bases for studies [7].

In the last two decades, researchers emphasized the importance of psychological and behavioral mechanisms in outdoor thermal comfort assessment [3, 8]. Generally, steady-state assessment methods are applied in outdoor thermal comfort evaluation based *on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium* [8]. In addition to PMV, the most widely used thermal indices in research are standard effective temperature (SET), universal thermal climate index (UTCI), and physiological equivalent temperature (PET) [2, 3, 7, 9]. Many studies promote thermal comfort sensation marked as thermal sensation vote (TSV), applying a seven-point ASHRAE standard 55 scale through questionnaire, described as subjective data, and their comparison objective predicted thermal condition (PMV, PET) [2, 9].

Many authors dealt with the relationship between human thermal sensation and microclimate conditions in high-density warm and humid tropical and sub-tropical climates [10, 11]. These studies have shown that air temperature and mean radiant temperature are the main factors influencing the users' thermal sensation. Recently, several researchers have tackled the same problem in severe cold regions, proving the importance of human thermal sensation in low air temperature conditions [7, 12]. Due to drastic differences in air temperature concerning other seasons, there is an issue of achieving preferred outdoor thermal comfort in summer in continental climates. A few authors dealt with this challenge [6, 9], opening the need for new studies. Given the type of open spaces, previous research was mainly focused on outdoor thermal comfort evaluation of squares [9, 13, 14], pedestrian streets and urban canyons [2], urban blocks of different morphology [7, 15], urban parks [16, 17], and university campuses [6, 12, 18, 19]. One group of authors tackled the issue of outdoor thermal comfort in housing areas [20-22]. These papers compare microclimate indicators with a human thermal sensation integrating objective and subjective evaluation assessments to calculate the neutral range of thermal indices.

The paper examines the outdoor thermal comfort in a multi-family housing area in Serbia, a region with a continental climate. For the research, the residential block in Duvanište, in the city of Niš, is chosen. Outdoor thermal comfort evaluation integrates microclimatic indicators and calculation of the thermal indices PET and PMV with subjective human thermal sensation assessment. The research aims to provide correlation analysis of data gains from theoretically predictive values, using the RayMan software model, with human thermal sensation data provided by field survey. The main goal is to calculate the neutral PET and neutral PET range for the continental climate region in the summer.

Materials and methods

Study area

This study is carried out in an outdoor area of a multi-family housing block in Duvanište, in Niš, in the southeastern part of Serbia, located at 43°19 ′ North latitude and 21°54′ East longitude, at an altitude of 194 m [23]. The climate is continental with hot summers, cold winters, and an average annual temperature of 11.8 °C [24]. The hottest is July, with a mean temperature of 21.3 °C, and the coldest is January, measuring a mean temperature of 0.2 °C [25]. The influence of wind from the northwest is constant, while breezes from the north and east are frequent in the summer. Climate change is measured by a meteorological station located at 202 m in the Fortress near the city center [26].

Duvanište is located in the eastern urban periphery and has strong traffic connections with the city center. After the fall of socialism, multi-family housing developed intensively in the northern part of the settlement. The scope of the area consists of five parallel tracts of seven floors multi-family buildings at the ground floor level interrupted by pedestrian passages. The tracts extend northeast-southwest, relying on the boulevard in the north, and the sports and recreational facilities in the south, fig. 1. Open spaces appear as playgrounds, sports fields, parking spaces, greenery, pedestrian paths, and common areas near buildings. Five sites were selected between the buildings, which differ in purpose, orientation, urban design, and surface type, fig. 1 and tab. 1. Site A is in the shadow of Buildings (I) in the morning, with grass greenery. This children's playground is equipped with benches and swings. Site B is a resting place near Buildings (II) with greenery and benches. Site D is partly in the shadow due to the tall park greenery, while site E is a children's playground with different equipment. Tall trees form sun protection during the day. Table 1 shows the type and degree of possible activities for each measurement site, additionally expressed in metabolic equivalents (1 met = 58.2 W/m²) [27].

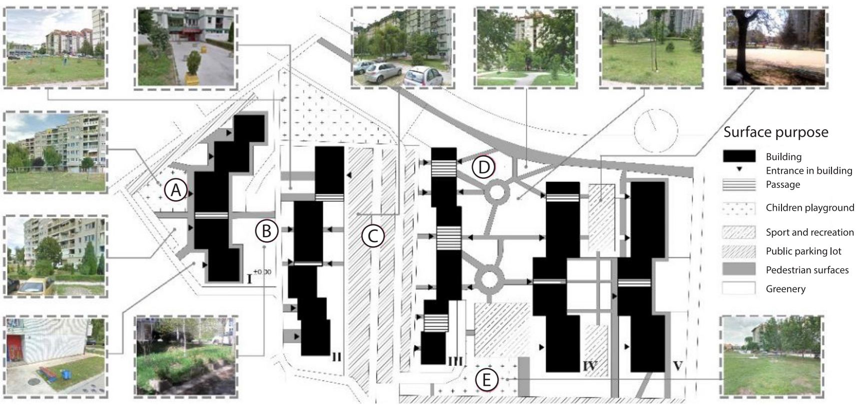

Figure 1. View of the subject area (source: [23] using authors photographs)

Table 1. Description of measurement sites

	Purpose	Shadow	Surface material	Activity	Metabolic rate [27]
A	Playground	From I in the morning	Grass, no trees	Sitting, playing	1.0, 3.0-4.0
B	Rest place	From II in the morning	Grass and asphalt	Sitting	1.0
C	Parking	No protection	Asphalt	Walking	2.0-2.6
D	Park	From trees	Grass and asphalt	Sitting, walking	1.0, 2.0-2.6
E	Playground	From trees	Grass and asphalt	Playing, running	4.0, 5.0-7.6

Research methodology

The research methodology combines objective and subjective outdoor thermal comfort evaluation assessment, as is shown in fig. 2.

Phase 1 – Field study

The first phase obtained field monitoring and survey collection tools to evaluate outdoor thermal comfort. The field monitoring uses equipment to measure thermal comfort condi-

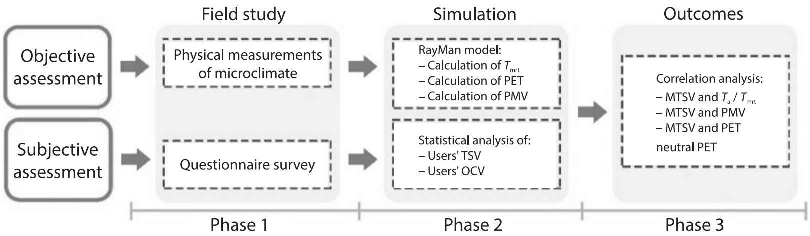

Figure 2. View of research methodology (source: authors)

tions as part of an objective research assessment, while a field survey uses questionnaires as a subjective assessment. The field study was conducted in the summer of 2016, between July 15 and August 15, as the warmest year period in continental climate zones. Microclimatic parameters of air temperature, T_a, relative air humidity, RH, and air-flow, V_a, were measured every hour between 8 a. m. and 8 p. m. every day. For this study, we have chosen three typical days for further analysis of outdoor thermal comfort July 14 (extremely high air temperatures exceeding 35 °C), July 21 (as an example of a typical sunny summer day), and August 9 (a cloudy day with lower temperatures). Microclimatic monitoring was performed using the portable instrument TESTO 435-2 while the surface temperature was measured using the contact infrared thermometer EBRO TFI 420, tab. 2. Experts tested equipment to determine its accuracy. The instruments were placed at 1.1 m, as recommended height of the sensors [1].

Table 2. Information on the measurement instruments

Instrument	Physical factors	Range	Accuracy
TESTO 435-2	Air temperature	–20 °C/+70 °C	+/– 0.3 °C
	Air humidity	0-100%	+/– 2%
	Air-flow	0- 20 m/s	+/–0.03 m/s
EBRO TFI 420	Surface temperature	–30 °C/+300 °C	+/–2 °C

Human thermal sensation data was obtained through a field survey using a questionnaire, fig. 3. Given the differentiation between people's adaptation transit routes and resting places, the survey was not conducted at site C. It was carried out simultaneously with microclimatic measurements on July 14, July 21, and August 9, during the morning (from 8 a. m. to 9 a. m.), the noon (from 12 p. m. to 1 p. m.), the afternoon (from 3 p. m. to 4 p. m.), and the evening (from 7 p. m. to 8 p. m.). A total of 480 valid questionnaires were collected, 160 per day, and 40 per every site. The respondents, who share 5-10% of the area population, were randomly sampled to provide the collection of the most comprehensive data. Given the time needed to adapt to conditions, the users filled out the questionnaire if they had been outside in the vicinity of the sites for at least 30 minutes. Each questionnaire took 5 minutes to complete.

The scope of the questionnaire was structured based on the ASHRAE standard 55 [5], the recommendations in the field of outdoor thermal comfort [1], and previous studies [2, 11,12, 15-18]. The first section obtains the information regarding date, time, and measuring points, filled out by the researcher. The questionnaire consisted of nine questions, mostly with offered answers. Questions No. 1-5 included general information on age, gender, weight, height, level of activity (metabolic rate), and clothing (measuring unit 1 clo = 0.1555 °Cm^2/W), as defined by the ASHRAE standard [5]. Questions No. 6-9 were related to the thermal sensation of users, their degree of comfort, and preferences. Question No. 6 was asked in order to check if filled questionnaire is valid. The TSV is defined by the seven-point scale of the

ASHRAE standard (–3 cold, –2 cool, –1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) [5], while the determination of overall comfort vote (OCV) uses a 3-point scale expresses a comfortable, neutral, and uncomfortable state, fig. 3. The 3-point McIntyre scale (higher/stronger, unchanged, lower/weaker) was used to express thermal preferences [28].

Outdooor Thermal Comfort Questionnarie

Date: ___/___/___ Time: ______ Measuring point: _____

Please circle or fill up the appropriate answer.

1. Age group:	a) <18	b) 18-35	c) 36-55	d) 56-65	e) >65
2. Gender:	a) male	b) female			
3. Weight:	________kg	Height: ________m			
4. During the last half hour, what was your main activity?					
	a) sleeping	b) sitting	c) standing	d) walking	e) running
5. What are you wearing now? (*multiple choice*)					
	a) bare foot shoe	b) covered foot shoe	c) socks	d) tights	
	e) short skirt	f) dress	g) shorts	h) long pants/skirt	
	i) tank top	j) T-shirt	k) long sleeve shirt	l) jacket	m)_______
6. At the moment, do you feel comfortable?					
	a) comfortable	b) sligthly comfortable	c) sligthly uncomfortable	d) uncomfortable	
7. How do you feel at this moment in terms of thermal sensation?					
-3 cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm / +3 hot
8. What are your preferences regarding microclimate parameters?					
temperature	+1 higher	0 unchanged	-1 lower		
air flow	+1 stronger	0 unchanged	-1 weaker		
solar radiation	+1 stronger	0 unchanged	-1 weaker		
9. At the moment, what is your overall comfort level?					
	+1 comfortable	0 neutral	-1 uncomfortable		

Figure 3. View of the questionnaire form (source: authors, originally in Serbian)

Phase 2 – Simulation and calculation using RayMan

The RayMan 2.3 Pro bioclimatic model developed by Matzarakis [29] was used to calculate the mean radiant temperature, T_{mrt}, and the thermal index PET for the selected measuring points. The RayMan calculates complex radiation fluxes and thermal indices given the existing environmental structure. It is based on German standards VDI 3789-Part 2 and VDI 3787 – Part 2 [30, 31]. Data on the date and time, longitude and latitude, altitude, meteorology (air temperature, air humidity, air-flow), surface temperature, and degree of cloud cover were entered as input parameters. The degree of cloudiness for clear days is zero octus and for semi-cloudy is four octus. Ambient parameters are defined by the 3-D model of buildings, vegetation, and topography. Subjective data was adopted as parameters characteristic of the average European male, age 35, height 1.75 m, and weight 75 kg [32].

The T_{mrt} as a parameter affecting the human energy balance during sunny weather conditions [29], summarizes all the short and long waves of radiation flux to which the human body is exposed. It is determined using Stefan-Boltzmann's law:

$$T_{\mathrm{mrt}} = \sqrt[4]{\frac{S_{\mathrm{str}}}{al\,\sigma}} - 273.2 \tag{1}$$

where σ [$5.67\cdot10^{-8}$ Wm^{-2}K^{-1}] is the Stefan-Boltzmann constant [31, 33] and S_{str} is the mean radiation flux densities of the human body [34]. For T_{mrt} RayMan uses [27, 29, 32]:

$$T_{\mathrm{mrt}} = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(Ei + ak\frac{Di}{\varepsilon p}\right)Fi\right]^{0.25} \tag{2}$$

where *Ei* and *Di* are long- and short-wave radiation, *Fi* – the angle factor, *ak* – the absorption coefficient of the irradiated body surface area, and *εp* – the emission coefficient of the human body.

In the summer, T_{mrt} has a significant impact on PET, defined as *air temperature at a given location, equivalent to the air temperature of typical interior space, for a person whose body temperature is equal to that under the estimated conditions* [34]. The PET is based on the Munich energy balance model for individuals and is linked to the thermal sensitivity scale of PMV, depending on the climate zone [32], tab. 3. Unlike PMV [4], PET is independent of clothing and activity.

Table 3. The PMV and PET ranges for different human sensations and thermal stress level [9, 35]

PET [°C]	*PMV*	Human sensation	Thermal/Heat stress level
2-4		Very cold	Extreme cold stress
4-8	–3	Cold	Strong cold stress
8-13	–2	Cool	Moderate cold stress
13-18	–1	Slightly cool	Slight cold stress
18-23	0	Comfortable	No thermal stress
23-29	+1	Slightly warm	Slight heat stress
29-35	+2	Warm	Moderate heat stress
35-41	+3	Hot	Strong heat stress
>41		Very hot	Extreme heat stress

Results and discussion

Objective assessment – thermal comfort analysis based on microclimatic parameters and PET

Table 4 gives an overview of the microclimatic parameters and mean radiant temperature mean values for three measurement days at each site. It also summarizes values for the sky view factor (SVF) calculated using RayMan. The SVF determines *the ratio of sky hemisphere visible from the ground and related to long-wave radiation* [33]. The wind speeds, V_a, were relatively small and varied between 0.21 m/s and 3.06 m/s. The smallest average values for V_a were recorded for sites D and E (under 1 m/s), while average V_a at site C was the highest on July 14 (only 2 m/s). The relative air humidity, fluctuates between 21.1% (on July 14 at C) and 89.7% (on August 9 at D). The results show that when the air temperature is extremely high, as on July 14, there is a low difference in average RH between sites. On other days RH at site D is significantly higher due to the greenery.

Table 4. Average microclimatic parameters and calculated mean radiant temperature for sites

	July 14				July 21				August 9				
	T_a [°C]	RH [%]	V_a [ms^{-1}]	T_{mrt} [°C]	T_a [°C]	RH [%]	V_a [ms^{-1}]	T_{mrt} [°C]	T_a [°C]	RH [%]	V_a [ms^{-1}]	T_{mrt} [°C]	SVF
A	34.9	27.2	1.66	47.6	28.0	35.8	0.99	40.8	23.8	58.2	0.5	35.9	0.781
B	35.1	26.2	1.6	51.2	28.1	34.5	0.9	43.4	25.4	61.3	1.2	34.9	0.321
C	35.4	26.4	2.0	52.8	28.5	34.9	1.0	44.5	27.1	58.8	0.7	41.6	0.831
D	33.9	29.1	0.5	46.4	26.2	51.6	0.6	40.3	23.7	69.9	0.4	34.3	0.574
E	35.1	26.5	0.9	34.3	29.2	35.0	0.7	43.0	26.3	60.2	0.8	38.8	0.841

The highest average T_a and T_{mrt} were recorded for site C. In contrast, the lowest was recorded at site D. The highest T_a was measured on July 14, at 3 p. m. at site C (39.2 °C). At the same time, values of the T_a were similar at sites A, B, and E, but at site D, T_a was 2.2 °C lower, fig. 4. The reason was that site C is a parking lot with no greenery, directly exposed to the sun, while site D is rich in tall vegetation and creates significant shade. Further, site D has a smaller SVF value ($SVF_D = 0.574$ and $SVF_C = 0.831$). The highest T_a was recorded for site E, while the T_a at site D was the smallest on July 21. Although site B had the smallest SVF value ($SVF_B = 0.321$), on sunny summer days, the lowest T_a and T_{mrt} were recorded at site D, fig. 4. On August 9, when it was cloudy and when the temperatures were lower than typical for the summer period, in the first half of the day, site B had the smallest T_{mrt} values. The SVF values at points C and E are similar ($SVF_C = 0.831$ and $SVF_E = 0.841$), but there is a variation in T_{mrt} values, especially for July 14, due to the greenery at site E, fig. 4. On sunny days, sites A and B had similar microclimatic conditions as their environmental structures have the same character. Nevertheless, the variation of SVF values ($SVF_A = 0.781$ and $SVF_B = 0.321$) and degree of cloudiness result in differences in T_{mrt}. The lowest T_a was recorded on August 9 at 8 a. m. at site D (17.4 °C). The values of T_a were quite similar for sites B, C, D, and E in the morning, with the highest T_a during the afternoon on site B. On sunny days A and E had similar T_{mrt}.

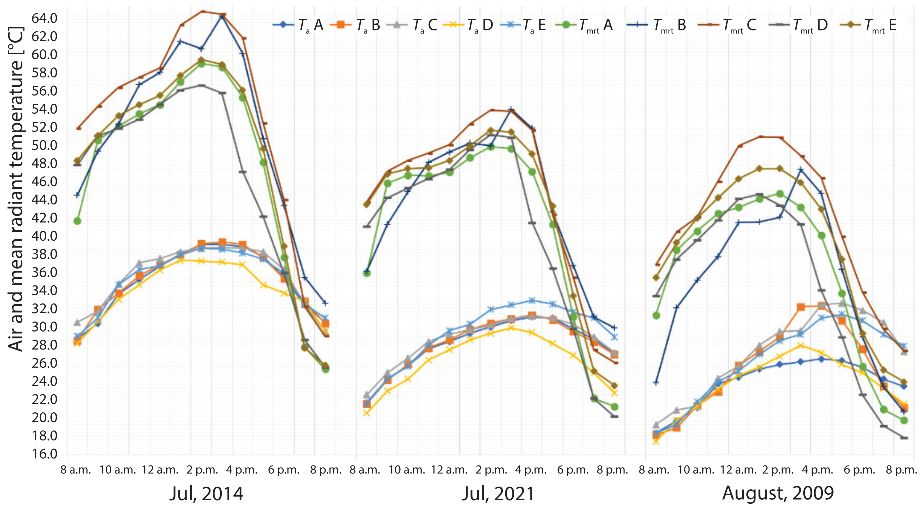

Figure 4. View of daily variation of T_a [°C] and T_{mrt} [°C] in different sites for three days

The calculated PET and different heat stress levels for three measurement days are present in fig. 5. The temperature limits of heat stress levels were applied based on the studies regarding thermal sensation classification [9, 35]. On July 14, between 10 a. m., and 6 p. m., an extreme level of heat stress was at all sites, with PET values exceeding 41 °C. The highest PET value was recorded at site B (50.4 °C) due to the combined effect of very high T_a and T_{mrt}. In the morning, moderate heat stress characterized only sites A and B, as they were in the shadow of the buildings. Between 4 p. m. and 7 p. m., the PET values for site D were slightly lower due to tall vegetation and lower T_a and T_{mrt} values. On the same day, slight heat stress was identified after 7 p. m., in all points except B, where heat stress was moderate due to higher values of T_{mrt}. On July 21, the maximum PET value was at sites B, C, and D (40.1 °C). The slight heat stress was in the early morning at A and B due to the shadow and between 6 p. m. and 8 p. m. on all sites. The comfortable sensation was calculated only for site D after 7 p. m., fig. 5.

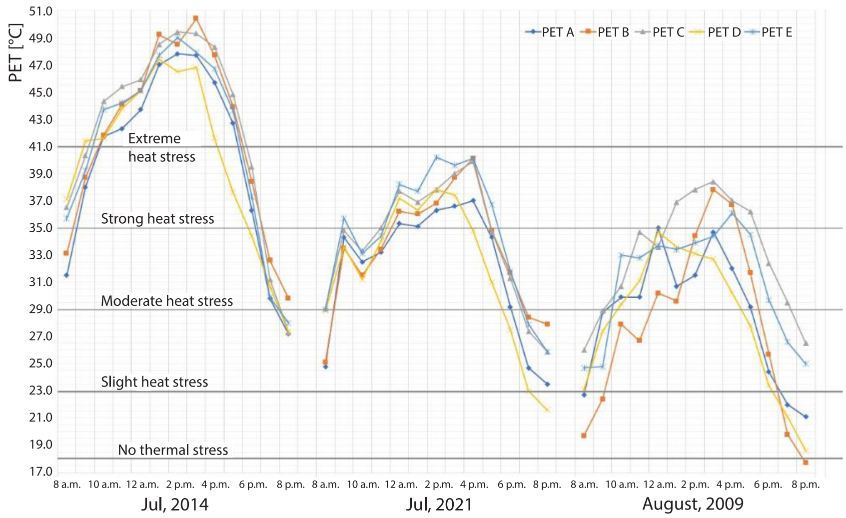

Figure 5. Daily variation of calculated PET [°C] and heat stress levels

On August 9, the absence of thermal stress was at site B till 11 a. m. and after 6 p. m. at all sites. During the day, the highest PET value was calculated for sites B (37.8 °C) and C (38.4 °C). Generally, the environmental structure of site D, as a park area with tall vegetation, seems to be a positive example of urban design of the outdoor multi-family housing block, which can contribute to overcoming heat stress in summer in the continental climate zone. Nevertheless, PET values for all sites were above the upper comfort range of 23 °C.

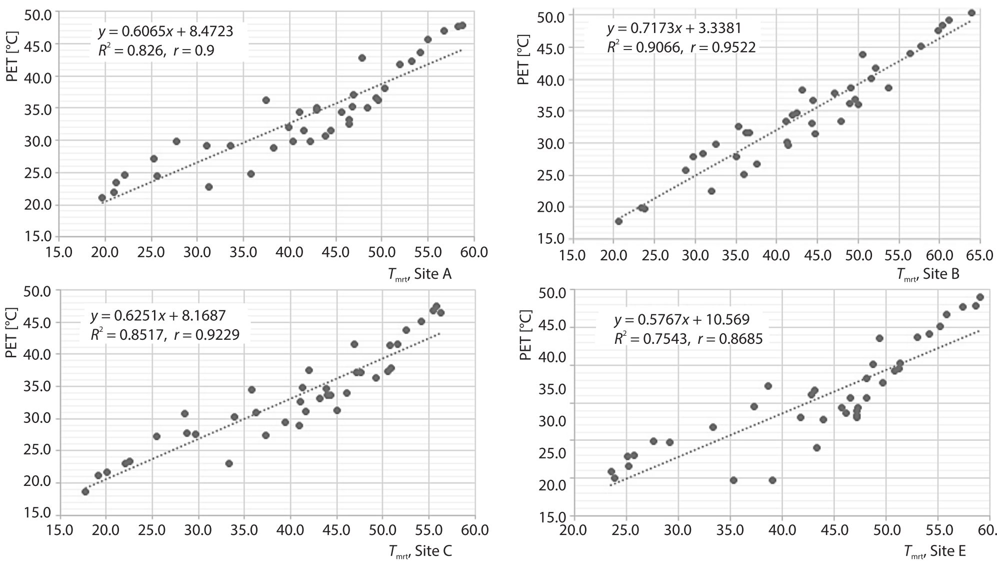

Figure 6. Linear regression of PET [°C] and T_{mrt} [°C] for measuring sites A, B, D, and E

Figure 6 shows the relationship between the PET and T_{mrt} on measuring sites marked as resting places, analyzed using a simple linear regression method. The results indicate that PET increased with T_{mrt} with a robust correlation defined by the Pearson correlation coefficient (r > 0.9 for sites A, B, and D), and the coefficient of determination, R^2, exceeded 0.8 at all sites. The strongest correlation is identified in site B ($r_B = 0.9522$, $R^2 = 0.9066$, $p_B = 1.17182 \cdot 10^{-20} < 0.00001$) due to the smallest SVF value.

Subjective assessment – human thermal sensation and overall thermal comfort

Male and female users accounted for 226 (47.1%) and 254 (52.9%). The highest number of respondents belonged to the age category from 36 to 55 (33.96%), while the lowest number was people over 65 (5.2%). The 18.96% of users belonged to persons under 18 years, and 30% of persons from 18 to 35 years. The average weight of the users was 73 kg, and the average height was 1.74 m, corresponding to the values adopted in the software. The highest number of users mentioned sitting as an activity (56.85%) and walking (40%), while a small percentage participated in sports (3.15%). Most users (89.96%) wore a T-shirt, and open shoes, with an average level of clothing of 0.30 clo. Table 5 summarizes the basic information of respondents in relation to gender (Questions No. 1-5).

Table 5. Summary of basic information of respondents

			Age [%]					Average			
	Gender	No.	<18	18-35	35-55	56-65	>65	Height [m]	Weight [kg]	Clothing [clo]	Activity [met]
July14	Male	71	18.3	29.6	35.2	12.7	4.2	1.81	83.5	0.28	1.44
	Female	89	11.2	33.7	39.3	11.3	4.5	1.66	59.7	0.25	1.62
July21	Male	74	18.9	25.7	40.5	8.1	6.8	1.82	84.4	0.31	1.71
	Female	86	20.9	30.2	36.1	8.1	4.7	1.68	63.7	0.27	1.65
August 9	Male	81	23.5	32.1	22.2	16	6.2	1.78	85.8	0.38	2.10
	Female	79	21.5	27.8	30.4	15.2	5.1	1.69	60.7	0.35	1.95

Table 6 summarizes the responses of the users to the questions related to thermal sensation, overall comfort and preferences for three measuring days (Questions No. 7-9). Figure 7 presents the distribution of TSV, while fig. 8 shows the distribution of the OCV concerning subject sites. On July 14, overall, the main thermal sensation recorded was *hot* (47.5%), followed by *warm* (36.25%). Two different TSV were identified at A, B, and E ($TSV = 2$ and $TSV = 3$), while three were characteristic for site D, including a *slightly warm* thermal sensation ($TSV = 1$). On July 21, the main TSV was *warm* (40%), followed by *slightly warm* (33.75%) and *hot* (21.25%). A few respondents felt *neutral* at site D (5%). That could be due to the lower T_a and T_{mrt} values. On August 9, the main TSV was *slightly warm* (43.75%), followed by *neutral* (32.5%). Due to the lower T_a than typical for summer, 13.75% of respondents felt *slightly cool* in the morning. The most comfortable were users at site D, who felt *neutral* to *slightly warm*. The most common TSV at B and E was *hot* on sunny days, accounting for 50% and 55%. Overall, there was a high percentage of *hot* and *warm* votes with a rate of 34.37% and 38.12%, fig. 7.

On July 14, 68.125% of respondents felt *uncomfortable*, while on July 21, 42.5% of respondents felt *uncomfortable* and 45% felt *neutral*. On August 9, 53.125% of respondents felt *neutral*, while 31.875% felt *comfortable*. Regarding each measuring point, on sunny days, the most common OCV at sites A, B, and E was *uncomfortable* with a rate of 60%, 70%, and 66.25%, respectively. At site D most common OCV was *neutral* with a rate of 53.33% during three measuring days, fig. 8.

Table 6. Summary of responses to the questions

Question	Offered answer	Statistics of responses [No. %]					
		July 14		July 21		August 9	
How do you feel at this moment in terms of thermal sensation? (No votes for –2 cool and –3 cold)	+3 hot	76	47.5%	34	21.25%	0	–
	+2 warm	58	36.25%	64	40%	16	10%
	+1 slightly warm	24	15%	54	33.75%	70	43.75%
	0 neutral	2	1.25%	8	5%	52	32.5%
	–1 slightly cool	0	–	0	–	22	13.75%
What are your preferences for air temperature?	+1 higher	0	–	0	–	24	15%
	0 unchanged	26	16.25%	64	40%	94	58.75%
	–1 lower	134	83.75%	96	60%	42	26.25%
For air-flow	+1 stronger	111	69.37%	102	63.75%	32	20%
	0 unchanged	49	30.63%	50	31.25%	112	70%
	–1 weaker	0	–	8	5%	16	10%
For solar radiation	+1 stronger	0	–	2	1.25%	85	53.13%
	0 unchanged	12	7.5%	64	40%	67	41.87%
	–1 weaker	148	92.5%	94	58.75%	8	5%
At the moment, what is your overall comfort level?	+1 comfortable	4	2.5%	20	12.5%	51	31.87%
	0 neutral	47	29.37%	72	45%	85	53.13%
	–1 uncomfortab	109	68.13%	68	42.5%	24	15%

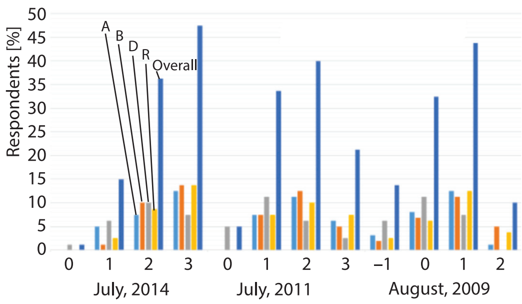

Figure 7. The percentage of TSV at each site

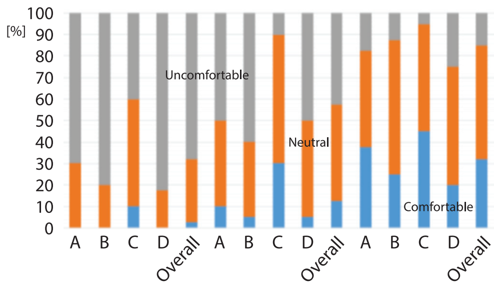

Figure 8. The percentage of OCV at each site

Phase 3 – Outcomes: combining microclimate indicators with human thermal sensation

This section analyzes correlations between microclimate parameters, PET and PMV, and TSV as subjective data. For each interval during the survey (8-9 a. m., 12-1 p. m., 3-5 p. m., 7-8 p. m.), the mean thermal sensation vote (MTSV) is calculated and compared with obtained parameters.

The relationship between the MTSV and parameters of T_a and T_{mrt} for resting sites is analyzed using the linear regression method, fig. 9. The results show that T_a significantly correlates to human thermal sensation at each site, with the Pearson coefficient, r, around 0.9. The strongest correlation between T_{mrt} and MTSV is identified in site B ($r_B = 0.80$, $R^2 = 0.6452$, $p_B = < 0.001$), with the smallest SVF value. At sites A, D, and E, the medium correlation is identified ($r_A = 0.56$, $r_D = 0.488$, $r_E = 0.48$), revealing that air temperature has a greater effect on thermal sensation in summer in continental climates. The sensitivity of the MTSV to the meteorological parameters, represented by slope in the regression equation, is highest for sites D and E, with the slope of 5.05 and 4.76 for T_a, and 5.46 and 5.306 for T_{mrt}, respectively, fig. 9. Thus, for example, at site E, the Ta needs a change of 4.76 °C and T_{mrt} a change of 5.306 °C, to change thermal sensation by one scale point. No strong relationship is found between human thermal sensation and SVF.

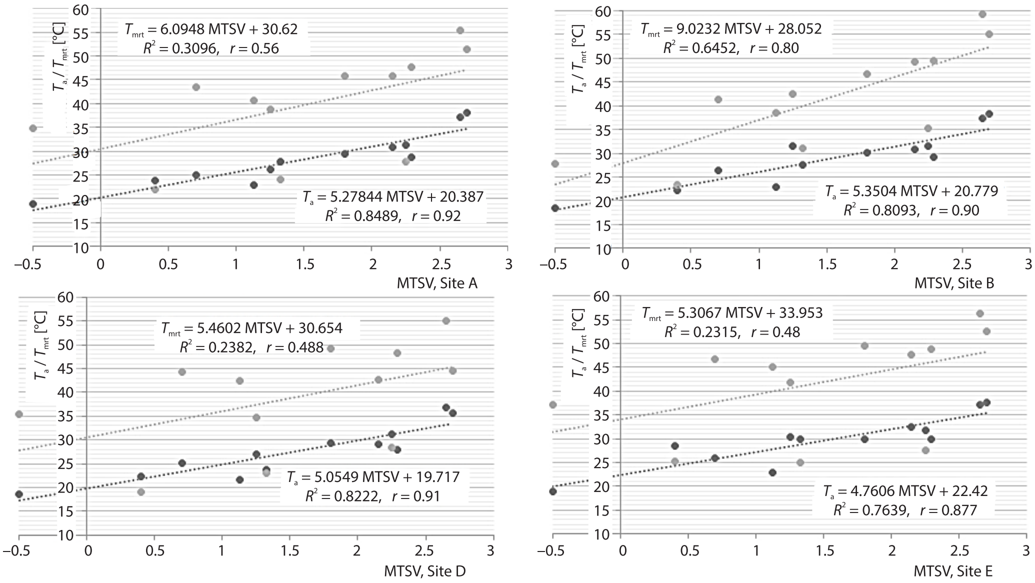

Figure 9. Correlation analysis between T_a [°C] and T_{mrt} [°C] and MTSV sites A, B, D, and E

In the next step of correlation analysis, MTSV from the questionary was compared to PMV, calculated via RayMan, for the subject area. Figure 10 presents the differences in MTSV and PMV distribution for each interval during the days. As PMV is related to indoor environments, its values for the warmest period of July 14 exceed the limit of +3 scale points. The PMV values were slightly higher than MTSV values in the noons and afternoons, probably because people prepared themselves for the hot weather conditions. In the evenings, PMV was lower than MTSV. The significant difference is noticed in the morning on August 9, when T_a was lower than typical for the summer. The subjective thermal sensation moves towards *slightly cold* while PMV values refer to a *neutral* feeling.

Finally, the relationship between the MTSV and PET for the subject area is analyzed using a linear regression method to determine neutral temperature when people feel comfortable, fig. 11. The MTSV is calculated for every PET interval of 1 °C, and the regression-line is defined:

$$MTSV = 0.1134\,PET - 2.2518 \quad (R^2 = 0.78,\ r = 0.93) \tag{3}$$

The obtained slope of the regression equation is 0.11, which means that when PET changes by 0.11 °C, TSV will change by one point scale, with high sensitivity. Pearson coefficient (r = 0.93) shows a strong correlation between MTSV and PET. In contrast, a high determination coefficient (R^2 = 0.78) indicates high prediction accuracy of PET in the outdoor thermal comfort evaluation in continental climates in summer. By substituting $MTSV$ = 0 in eq.

3, the neutral temperature of the summer season is obtained as 20.5 °C PET, fig. 11. Assuming that the neutral comfort range at the seven-point scale is the MTSV interval (–0.5, +0.5), given eq. 3, the neutral PET range in summer is from 15.4-24.3 °C.

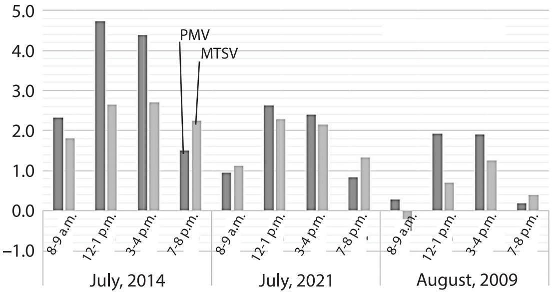

Figure 10. Differences in MTSV and PMV values

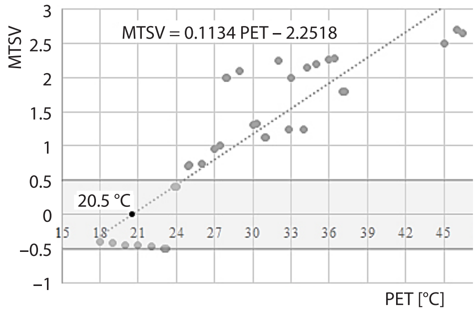

Figure 11. The MTSV and PET correlation

Conclusions

This study accessed outdoor thermal comfort in the multi-family housing area in Niš, Serbia. The research combines the measurement of microclimate parameters and calculated PET and PMV indices with a questionnaire survey to understand the effects of microclimate on human thermal sensation in a continental climate with hot summer conditions. Analysis of data provides the following conclusions.

- Environmental structures with tall vegetation can contribute to overcoming heat stress in summer when PET values are above the theoretically set comfort range. This type of area is most comfortable for users, with a *neutral* vote of 53.33% of respondents in different weather conditions.
- *Hot* (*TSV* = 3) and *warm* (*TSV* = 2) are the most common TSV of residents, with a rate of 34.37% and 38.12%, due to the different sites directly exposed to the Sun.
- Air temperature has a more significant effect on human thermal sensation than the mean radiant temperature in summer in continental climate regions intended for multi-family housing. Further researches are necessary to examine this conclusion in other urban functional areas.
- When microclimate parameters are lower than typical for the summer period, subjective thermal sensation values are significantly lower than predictive ones, as people over time adapt their bodies to hot weather conditions. Thus, future research must be focused on the influence of psychological and behavioral factors on thermal comfort in terms of thermal adaptation.
- No strong relationship is found between human thermal sensation and SVF, but this parameter was confirmed to impact mean radiant temperature values on different sites significantly.
- The PET has a strong prediction accuracy in the outdoor thermal comfort evaluation during summer. The sensitivity of human thermal sensation PET is high, with a correlation coefficient of $r = 0.93$.
- The neutral temperature of the summer is 20.5 °C PET. The neutral PET range is 15.4-24.3 °C, more expansive than the theoretically set comfortable PET range (18-23 °C). The findings indicate a need for more research in continental climate regions of South-Eastern Europe to determine a new thermal sensitivity scale.

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Nomenclature

I, II, III, IV, V – building trackt
A, B, C, D, E – measuring sites
clo – clothing level, [1 clo = 0.1555 °Cm^{2}W^{-1}]
met – metabolic rate, [1 met = 58.2 Wm^{-2}]
MTSV – mean value of thermal sensation vote, [–]
OCV – overall comfort vote, [–]
*PE*T – physiological equivalent temperature, [°C]
PMV – predicted mean vote, [–]
RH – air humidity, [%]
SET – standard effective temperature, [°C]
SVF – sky view factor, [–]
T_a – air temperature, [°C]
T_{mrt} – mean radiant temperature, [°C]
TSV – thermal sensation vote, [–]
UTCI – Univeral Thermal Climate Index, [°C]
V_a – air-flow, [ms^{-1}]

Greek symbol

σ – Stefan-Boltzmann constant, [Wm^{-2}K^{-1}]

References

[1] Johansson, E., *et al*., Instruments and Methods in Outdoor Thermal Comfort Studies – The Need for Standardization, *Urban Climate*, *10* (2014), Part 2, pp. 346-366
[2] Zhu, Z., *et al*., Summer Outdoor Thermal Comfort in Urban Commercial Pedestrian Streets in Severe Cold Regions of China, *Sustainability*, *12* (2020), 5, 1876
[3] Nikolopoulou, M., *et al*., Thermal Comfort in Outdoor Urban Spaces: Understanding the Human Parameter, *Solar Energy*, *70* (2001), 3, pp. 227-235
[4] Fanger, P. O., *Thermal Comfort*, Danish Technical Press, Copenhagen, Denmark, 1970
[5] ***, ASHRAE standard 55 Thermal Environmental Conditions for Human Occupancy, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2017
[6] Kajtar, L., et al., Objective and Subjective Thermal Comfort Evaluation in Hungary, *Thermal Science*, *21* (2017), 3, pp. 1409-1418
[7] Taleghani, M., *et al*., Outdoor Thermal Comfort within Five Different Urban Forms in the Netherlands, *Building, and Environmen*t, *83* (2015), Jan., pp. 65-78
[8] Chen, L., Ng, E., Outdoor Thermal Comfort and Outdoor Activities: A Review of Research in the Past Decade, *Cities*, *29* (2012), 2, pp. 118-125
[9] Kantor, N., *et al*., Human Bioclimatological Evaluation with an Objective and Subjective Approaches on the Thermal Conditions of a Square in the Center of Szeged, *Acta Climatologica et Chronologica*, *40-41* (2007), Jan., pp. 47-58
[10] Zhao, L., *et al*., Study on Outdoor Thermal Comfort on Campus in a Subtropical Urban Area in Summer, *Sustainable Cities and Society*, *22* (2016), Apr., pp. 164-170
[11] Huang, J., *et al*., Outdoor Thermal Environments and Activities in Open Space: An Experiment Study in Humid Subtropical Climates, *Building and Environment*, *103* (2016), July, pp. 238-249
[12] Yin, Q., *et al*., Research on Outdoor Thermal Comfort of High-ensity Urban Center in Severe Cold Area, *Building and Environment*, *200* (2021), 107938
[13] Cortesao, J., *et al*., Photographic Comparison: A Method for Qualitative Outdoor Thermal Perception Surveys, *International Journal of Biometeorology*, *64* (2020), Jan., pp. 173-185
[14] Tian, Y., *et al.*, Factors Influencing Resident and Tourist Outdoor Thermal Comfort: A Comparative Study in China's Cold Region, *Science of the Total Environment*, *808* (2022), 152079
[15] Lai, D., *et al.*, Studies of Outdoor Thermal Comfort in Northern China, *Building and Environment*, *77* (2014), July, pp. 110-118
[16] Zhang, L., *et al*., Outdoor Thermal Comfort of Urban Park – A Case Study, *Sustainability*, *12* (2020), 1961
[17] Wei, D., *et al*., Variations in Outdoor Thermal Comfort in an Urban Park in the Hot-Summer and Cold-Winter Region of China, *Sustainable Cities and Society*, *77* (2022), 103535

[18] Zhen, M., *et al*., Urban Outdoor Thermal Comfort in Western China, *Journal of Asian Architecture and Building Engineering*, *20* (2021), 2, pp. 222-236
[19] Xi, T., *et al.*, Study on Outdoor Thermal Comfort on a Campus in a Subtropical Urban Area in Summer, *Building and Environment*, *52* (2012), Apr., pp. 162-170
[20] Adunola, A. O., Evaluation of Urban Residential Thermal Comfort in Relation Indoor and Outdoor Air Temperatures in Ibadan, Nigeria, *Building and Environment*, *75* (2014), May, pp. 190-205
[21] Matallah, M. E., *et al*., Prediction of Climate Change Effect on Outdoor Thermal Comfort in Arid Region, *Energies*, *14* (2021), 4710
[22] Elshafei, G., *et al*., Green Building Outdoor Thermal Comfort in Hot-Desert Climatic Region, *Cogent Engineering*, *9* (2022), 1, 2046681
[23] Brankov, B., Stanojević, A., Differentiation of the Usability of Common Outdoor Spaces in Multi-Family Housing (in Serbian), *Proceedings*, International Scientific-Professional Conference 16th Summer School of Urbanism, Prolom Banja, Serbia, 2020, pp. 143-152
[24] Lukić, M., *et al.*, Assessment of Outdoor Thermal Comfort in Serbia's Urban Environments during Different Seasons, *Atmosphere*, *12* (2021), 1084
[25] Đekić, J., *et al*., Thermal Comfort of Pedestrian Spaces and the Influence of Pavement Materials on Warming Up during Summer, *Energy and Buildings*, *159* (2018), Jan., pp. 474-485
[26] Bogdanović-Protić, I. S., *et al*., Forecasting of Outdoor Thermal Comfort Index in Urban Open Spaces: The Nis Fortress Case Study, *Thermal Scienc*e, *20* (2016), 5, pp. 1531-1539
[27] Auliciems, A., Szokolay, S. V., *Thermal Comfort*, 2nd ed., Department of Architecture, The University of Queensland, Brisbane, Australia, 2007
[28] McIntyre, D. A., *Indoor Climate*, Applied Science Publishers, London, UK, 1980
[29] Matzarakis, A., *et al*., Modelling Radiation Fluxes in Simple and Complex Environments – Application of the RayMan Model, *Int. J. Biometeorol*., *51* (2007), 4, pp. 323-334
[30] ***, Guideline VDI 3789, Part 2, Environmental Meteorology – Interactions between Atmosphere and Surfaces, VDI-Handbuch Reinhaltung der Luft, Bd. 1, Beuth, Berlin, Germany, 1994
[31] ***, Guideline VDI 3787, Part 2, Environmental Meteorology - Methods for the Human Biometeorological Evaluation of Climate and Air Quality for Urban and Regional Planning at Regional Level, Part 1: Climate. Beuth, Berlin, 2008
[32] Matzarakis, A., *et al*., Developments and Applications of Thermal Indices in Urban Structures by RayMan and Sky Helios Model, *Proceedings*, ICUC9 9th Inter. Conf. on Urban Climate, Touluse, France, 2018, pp. 1-6
[33] Bernard, J., *et al*., Sky View Factor Calculation in Urban Context: Computational Performance and Accuracy Analysis of Two Open and Free GIS Tools, *Climate*, *6* (2018), 3, 60
[34] Hoppe, P., The Physiological Equivalent Temperature: A Universal Index for the Biometeorological Assessment of the Thermal Environment, *Intern. Jour. of Biometeor*., *43* (1999), 2, pp. 71-75
[35] Matzarakis, A., Mayer, H., Another Kind of Environmental Stress: Thermal Stress, WHO Collaborating Centre for Air Quality Management and Air Pollution Control, *NEWSLETTERS*, *18* (1996), Jan., pp. 7-10

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