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SIMULATION OF THE THERMAL COMFORT CONDITIONS OF URBAN AREAS: A CASE STUDY IN KYIV

О. Г. Шевченко, С. І. Сніжко, М. О. Матвієнко. МОДЕЛЮВАННЯ БІОКЛІМАТИЧНИХ УМОВ УРБАНІЗОВАНОГО СЕРЕДОВИЩА (НА ПРИКЛАДІ МІСТА КИЄВА). *Дослідження біокліматичних умов урбанізованих територій в теплий період є дуже актуальними, адже, достовірні результати оцінки інтенсивності теплового стресу є підґрунтям для розробки та впровадження заходів адаптації до спеки. Крім того, моделювання біоклімату важливо застосовувати на етапі проектування міської забудови для підбору оптимальної структури, що допоможе підвищити комфортність міських районів. Метою даного дослідження є моделювання біоклімату урбанізованого середовища для визначення теплового навантаження на людський організм в літній період з використанням сучасних біокліматичних індексів та програмних продуктів. Для реалізації мети дослідження було обрано частину території житлового масиву Осокорки (м. Київ). Значення основних метеорологічних параметрів на досліджуваній ділянці отримані з використанням прогностичної тривимірної моделі «ENVI-met», а фізіологічно-еквівалентної температури (ФЕТ) – за допомогою моделі «RayMan». Аналіз результатів моделювання свідчить, що значення температури та вологості повітря, характеристик вітру та ФЕТ характеризується значною простою-часовою мінливістю навіть на незначних за розмірами ділянках в межах міської забудови. Амплітуди значень ФЕТ були максимальними в денні години і становили 12°–15℃. Найсильнішого теплового стресу мешканці урбанізованих територій зазнають перебуваючи на відкритих заасфальтованих ділянках в денні години. Зменшення амплітуди температури повітря на досліджуваних ділянках у вечірні та нічні години призвело до помітного зниження амплітуди ФЕТ на обраній території – до 2°–3℃. Порівняння змодельованих значень ФЕТ для досліджуваної території та для АМСЦ «Київ» показало, що значення ФЕТ, змодельовані за даними метеорологічної станції, не відображають реальних біокліматичних умов в межах складної міської забудови.*

Ключові слова: *урбанізоване середовище, біоклімат, тепловий комфорт, фізіологічно-еквівалентна температура, модель «ENVI-met», модель «RayMan».*

О. Г. Шевченко, С. И. Снижко, М. О. Матвиенко. МОДЕЛИРОВАНИЕ БИОКЛИМАТИЧЕСКИХ УСЛОВИЙ УРБАНИЗИРОВАННОЙ СРЕДЫ (НА ПРИМЕРЕ ГОРОДА КИЕВА). *Исследование биоклиматических условий урбанизированной среды в теплый период является очень актуальными, ведь, достоверные результаты оценки интенсивности теплового стресса являются основой для разработки и внедрения мероприятий адаптации к жаре. Кроме того, моделирование биоклимата важно применять на этапе проектирования городской застройки с целью подбора оптимальной структуры, которая поможет повысить комфортность городских районов. Целью данного исследования является моделирование биоклимата урбанизированной среды для определения тепловой нагрузки на организм человека в летний период с использованием современных биоклиматических индексов и программных продуктов. Для реализации поставленной цели была выбрана часть территории жилого массива Осокорки (г. Киев). Значения основных метеорологических параметров на исследуемом участке получены с использованием прогностической трехмерной модели «ENVI-met», а физиологически-эквивалентной температуры (ФЭТ) – с помощью модели «RayMan». Анализ результатов моделирования показывает, что значение температуры и влажности воздуха, характеристик ветра и ФЭТ характеризуется значительной пространственно-временной изменчивостью даже на незначительных по размерам участках городской застройки. Амплитуды значений ФЭТ были максимальными в дневные часы и составили 12°–15℃. Самый сильный тепловой стресс жители урбанизированных территорий испытывают находясь на открытых заасфальтированных участках в дневное время. Уменьшение амплитуды температуры воздуха на исследуемом участке в вечерние и ночные часы приводит к заметному снижению амплитуды ФЭТ на выбранной территории – до 2°–3°С. Сравнение смоделированных значений ФЭТ для исследуемой территории и для АМСГ «Киев» показало, что значение ФЭТ, рассчитанные по данным метеорологической станции, не отражают реальных биоклиматических условий в пределах сложной городской застройки.*

Ключевые слова: *урбанизированная среда, биоклимат, тепловой комфорт, физиологически-эквивалентная температура, модель «ENVI-met», модель «RayMan».*

Introduction. The climatic conditions of a territory affect human health and well-being, recreational activity and rest. This influence is caused by the effects of weather and climate on the human body and the conditions of its heat exchange with the environment. Studies of bioclimate of a territory are aimed at determining the favourable and adverse impacts of various climatic factors and their aggregates on the human body.

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According to the United Nations Department of Economic and Social Affairs, more than half of the world's population lives in cities today, and by 2050 the share of urban residents will increase and exceed 66%. Rapid urbanization will exacerbate urban environmental problems.

Complex urban morphology has a significant impact on microclimate and, accordingly, on thermal comfort conditions. Housing development parameters such as the height of buildings, street orientation, and distance between buildings alter the solar energy inlet, affect thermal conditions, have distinct modifying effects on wind speed and direction at the street level. Central parts of cities are normally characterized by higher air temperature – occurrence of an urban heat island (UHI) phenomenon is their characteristic feature. An impact the high intensity of UHI on the human is especially dangerous during summertime. The adverse effects of this urban phenomenon have been documented in many studies – they are associated with increased blood circulation and cause higher mortality rates in the cities [1, 2]. Most notable is the adverse impact of UHI on urban ecosystem and urban residents during heat wave cases in summer. Such a complex impact can significantly increase the heat load on urban residents and reduce the human comfort in the city.

Studies of the bioclimatic conditions of urban areas during the warm season are highly relevant as they provide an opportunity to evaluate human thermal sensations in the city, as well as the potential effectiveness of adaptation measures to heat stress (especially, architectural measures and measures based on the use of green areas and water bodies).

Analysis of recent research and publications. In recent years, increasing attention has been paid to the study of heat stress, as it can pose a significant health risk [3–4]. Over the last decade, a series of studies at bioclimatic assessment of urban areas has been carried out: K.S. Ahmed [5] explored the bioclimate of the tropical city of Dhaka, Bangladesh; R. Emmanuel and E. Johansson conducted research for the city of Colombo, Sri Lanka [6]; N. Gaitan et al. [7] studied outdoor thermal comfort of the Athens region. M. Fahmy and S. Sharples [8] investigated the effect of city morphology on thermal comfort with the case of Cairo, Egypt, [9–10] analyzed the effect of green spaces and street orientation on air temperature and wind speed decrease. A. Carfan, E. Galvani, and J. Nery compared thermal comfort in two areas varying in building densities and in number of green spaces in the city of Sao Paulo [11]. Studies conducted in Freiburg, Germany focused on the study of street parameters effect of on thermal comfort conditions [12–13]. In their work, F. Ali-Toudert and H. Mayer studied the influence of street design, i.e. aspect ratio (or height-width ratio) and axis orientation, towards the development of a comfortable microclimate at street level for pedestrians in the city of Ghardaia, Algeria [14].

Bioclimatic studies conducted by Ukrainian scientists, although initiated relatively long ago (for example, the assessment of Kyiv bioclimate was carried out by B.A. Ayzenshtat and L.I. Sakali back in the late 1970s – in the 1980s), unfortunately, they have not developed to the same level as in the European countries and the United States of America. The simplest bioclimatic indices (BI) (effective temperature, equivalent and effective temperature, radiation equivalent and effective temperature, normal equivalent and effective temperature, biologically active temperature, etc.) are used for the bioclimate assessment in Ukraine nowadays. Most of these indices are quite old, some of them were developed over fifty years ago. These indices are very simple to calculate, but mainly take into account the impact on human thermal sensation of meteorological parameters only, while the indices based on human energy balance have been used globally for bioclimatic assessment throughout the last decades. In addition, bioclimatic studies in Ukraine are mostly limited to the use of data obtained at meteorological stations (i.e., in open space areas with natural vegetation). It is natural that the BI obtained with the use of such input data can not reflect objective thermal sensation of a person within a complex urban environment.

Formulating the purpose of the article. The aim of this research is to simulate the bioclimate of an urban environment to determine the human thermal load in summer months based on modern bioclimatic indices and software.

Materials and methods of the research. For the purpose of this study, a part of the territory of the Osokorky residential area of Kyiv was selected. Osokorky residential area is located in Darnytskyi district, between the Dnipro river, Mykoly Bazhana avenue and lake Vyrlytsya. This paper studies the 9th residential district located in the north of this area, between the streets of Larysy Rudenko, Solomiyi Krushelnytskoyi, Oleksandra Mishugy and the avenue of Petra Hryhorenka. The simulation area includes the territory of the residential area near the Poznyaky metro station. The site selected for the simulation is located in the "dormitory area" of the city, characterized by developed infrastructure, high-rise buildings and relatively small areas of green space.

To get values of the main meteorological parameters of the researched area, a three-dimensional, prognostic, microscale model ENVI-met (version 4.3.2 Summer 18) was used. The model was downloaded (following the sign-up, free of charge) from the official site: https://www.envi-met.com/. ENVI-met, which is a CFD model (*computation fluid dynamics model*), was developed by M. Bruce at Ruhr-University Bochum, Germany, and is one of the few microscale models that meet the criteria for an accurate simulation of physical processes and resulting micro-meteorological phenomena within the urban canopy and boundary layer [15–17].

The model is widely used to address scientific and practical issues in countries with various climates – from tropics to polar regions (Egypt [8], Sri Lanka [6], Brazil [11], England [18], Italy [19], Germany [20], the Netherlands [21]). In total, over three thousand studies have been carried out to date in more than 145 countries. ENVI-Met is designed for microscales with a horizontal resolution from 0.5 to 10 m and a time step of 10 seconds maximum. Physical basis of the model is explained in detail in [14, 17, 22–23]. Maximum simulation period is 48 hours.

Simulations in ENVI-met require two sets of input data: IN-file (input file) and CF-file (main configuration file). The IN-file contains information on dimensional properties of the area, such as geographical location, construction materials of the buildings, height of the buildings and types of vegetation. For this study, the dimensions of the research area were set to be 370×400 m.

The CF file contains meteorological inputs – air temperature and humidity, wind speed, as well as the measurement date and time. Data obtained from the Civil Aviation Weather Station “Kyiv” (CAWS Kyiv) located at Kyiv Sikorsky International Airport, 8 km southwest of the city center, were used to create the CF file.

The PET calculation was performed using the RayMan model [24], which was downloaded (following the sign-up, free of charge) from https://www.urbanclimate.net/rayman/index.htm. This model uses the following data groups to obtain PET values: date and time for which the calculation will be made; geographical data (geographical coordinates, time zone and altitude); meteorological data (air temperature (°C), water vapour pressure (hPa) or relative humidity (%), wind speed (m/s) and degree of cloud cover); human personal data and parameters that can affect the thermal sensation (clothing and activity). In this study the simulations were referred to a standard parameters of the person which use for such type of the researches: 35-year-old man, 1.75 m high, 75 kg weight, wearing clothing with a heat resistance of 0.9 clo, sedentary, with heat producing is equivalent to 80 W.

Research results. In the context of considering the impact of climate on the human body, the key term is “bioclimate”, which is a set of climate characteristics that determine its complex impact on the human body in a certain territory [25]. To evaluate the bioclimatic features of a territory, comprehensive indicators called bioclimatic indices are used most often. Among European scientists, one of the most popular BI is currently the Physiologically Equivalent Temperature (PET), which is based on the energy balance of the human body. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. The typical indoor setting is an indoor room, with wind speed is 0.1 m/s, vapour pressure is 12 hPa (approximately equal to 50% relative humidity at 20.0°C) and mean radiant temperature equal to the air temperature [13, 26]. The basis for the PET calculation is «The Munich energy balance model for individuals» (MEMI). The PET units are °C, which makes this index very easy to use. Comfortable conditions correspond to PET values within the range of 18.1–23.0°C (Table 1).

Table 1

Ranges of the physiologically equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings [27]

PET, °C	Thermal perception	Grade of physiological stress
<4	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
>41.1	Very hot	Extreme heat stress

H. Lee et al. [13] note that bioclimate in different parts of our planet has been assessed using PET. Having carried out an analytical review of BI, S. Tkachuk [28] also came to the conclusion that PET is a very appropriate universal bioclimatic index, because it takes into account the complete energy balance equation, core temperature, sweat rate, skin wetness and meteorological parameters. In our previous studies [25], we presented the results of a comparative analysis of the BI most used in the former Soviet Union (equivalent and effective temperature, normal equivalent and effective temperature, radiation equivalent and effective temperature, biologically active temperature) and the PET and showed the significant advantages of the latter for bioclimatic assessment of the urban environment during the warm period.

Human thermal perception in a complex urban environment is determined by the combined influence of weather conditions at the regional level and the microclimatic features that are formed under the influence of a number of factors [29]. Characteristics of urban geometry (street direction, height of buildings and width of streets) do not only contribute to the formation of UHI, but also directly affect the thermal perceptions of city residents. F. Ali-Toudert and H. Mayer [14] note that urban canyon geometry affects strongly magnitude of energy regime of its individual surfaces. The main descriptors of the canyon include the height/width ratio, the canyon axis orientation and the sky view factor (SVF), which is a proportion of the sky dome that is "seen" by a surface, either from an observation point on that surface or integrated over its area [31]. The above descriptors can be in fact applied not only to the canyon, but also to other types of urban space. Increased shading through change in the ratio between the height of the buildings and the distance between them leads to a significant decrease in PET (or other bioclimatic indices) values, which, accordingly, reflects an increase in thermal comfort [32]. A. Matzarakis and H. Mayer [33] note that the closure of the horizon within an urban structure (which in urban meteorology is expressed through the SVF) is the most important factor that determines the formation of differences in the bioclimate within a complex urban environment. The lower the SVF value for a certain point, the lower the thermal stress for a person there, since the main effect from the tree crowns or tall buildings during the daytime is the reduction of direct solar radiation. In addition to urban geometry, thermal comfort conditions are influenced by facing materials of the walls, and the type and characteristics of the underlying surface [34–35].

The complex urban geometry and the multitude of factors that can influence the values of air temperature and PET define the significant differences in thermal comfort conditions, even within small sites of the urban environment [5, 7–14, 29–35].

To assess the heat load on a human in an urban environment, 7 points were selected within the researched area. The points were selected in a manner that they differed in microclimatic conditions, the parameters of the surrounding buildings and the underlying surface. For instance, point number 1 is located on an open paved area (on the parking lot), point number 4 – in the area covered in lawn grass, point number 5 – inside the well courtyard of High School for International Affairs, etc. (Fig. 1).

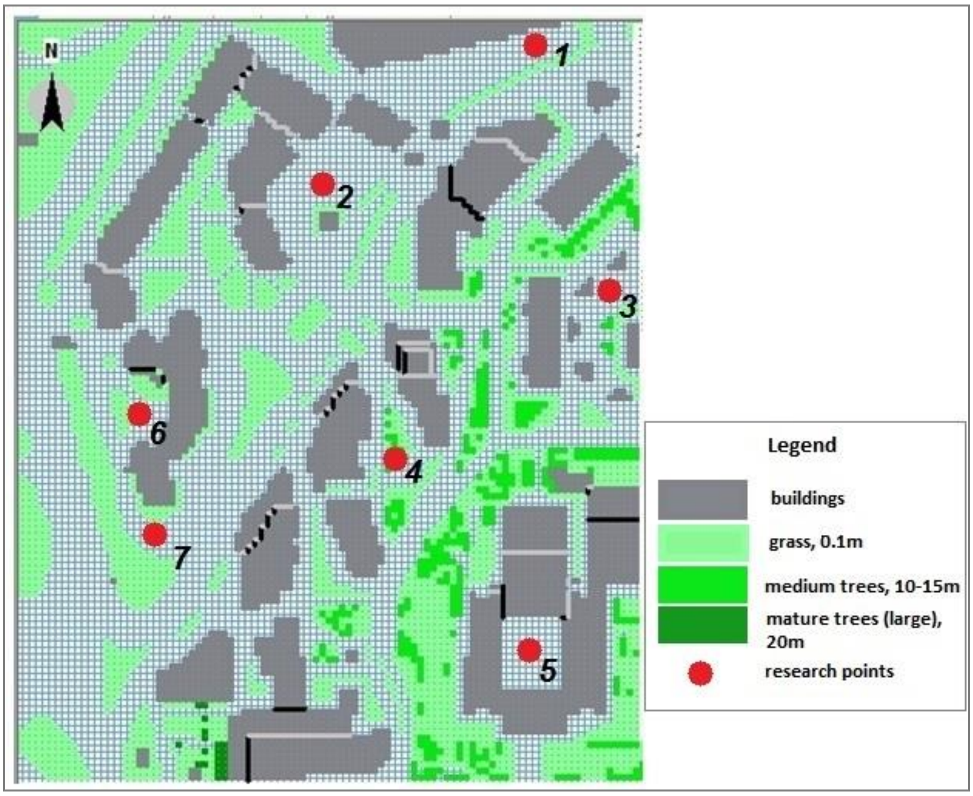

Fig. 1. Simulation domain and locations of research points

Most studies of the microclimate and thermal comfort conditions of an urban areas are based on simulations for short time periods of 5–6 to 24 hours. Since cloudiness significantly affects the formation of a temperature field in the city, and the maximum differences in meteorological parameter and thermal indexes values across the area are observed during clear hot weather, for the simulation purpose, most often selection is a summer day with high air temperature and the simulation hours are selected in a manner to capture the period with the highest daily air temperature, as well as several hours before and after the maximum [14, 36]. Thus, the simulation results enable setting both maximum amplitudes within the territory, and the maximum thermal load on the human body within the researched area.

C. S. Gusson and D. H. S. Duarte [37], and F. Ali-Toudert [38] indicate that simulations using ENVI-met is best started at predawn hours, around 6 am, because at that time the earth's surface receives a much smaller amount of solar radiation and the intensity of some atmospheric processes in the urban canopy layer is lower than in the afternoon. This helps to reduce the inaccuracy of the obtained results that can occur if the simulation starts at high Sun altitudes. Therefore, a lot of simulations start at 5 am to 7 am [17, 38–39].

In this study, a clear hot day was chosen for the simulation (04 August 2017). According to the CAWS Kyiv, the maximum air temperature of +34.0°C was recorded at 16:00 EEST this day. During the day, the wind speed ranged from 2 m/s to 7 m/s. The simulation was carried out from 6:00 Eastern European Summer Time (EEST) (EEST=UTC+3) on 4 August till 6:00 EEST the next day (interval of the results output – 1 hour).

The results of the air temperature simulation for the selected area showed that the daytime temperature within the urban areas may vary significantly on a clear summer day. For example, at 12:00 EEST the value of the amplitude was 5.0°C. The highest air temperature was over the open asphalt-paved sections of the researched area. The results of the microclimate studies in other cities also show that there are major differences in air temperature over small areas during daytime. For example, the air temperature amplitude in the central part of the city of Teramo, Italy can reach 8.0ºC in the daytime, 4.0ºC in the night [40]. For Colombo, the air temperature difference recorded between the areas of the city having complex geometry made 7.0°C [6], for Sao Paulo (Brazil) – 6.0°C [41].

In the evening and night hours (Fig. 2), the amplitude of temperature values within the researched area decreased and at midnight the temperature differences did not exceed 3.0°C. The highest air temperatures were naturally recorded above the asphalted parking areas and in the well courtyard, the lowest – above the areas with dense vegetation.

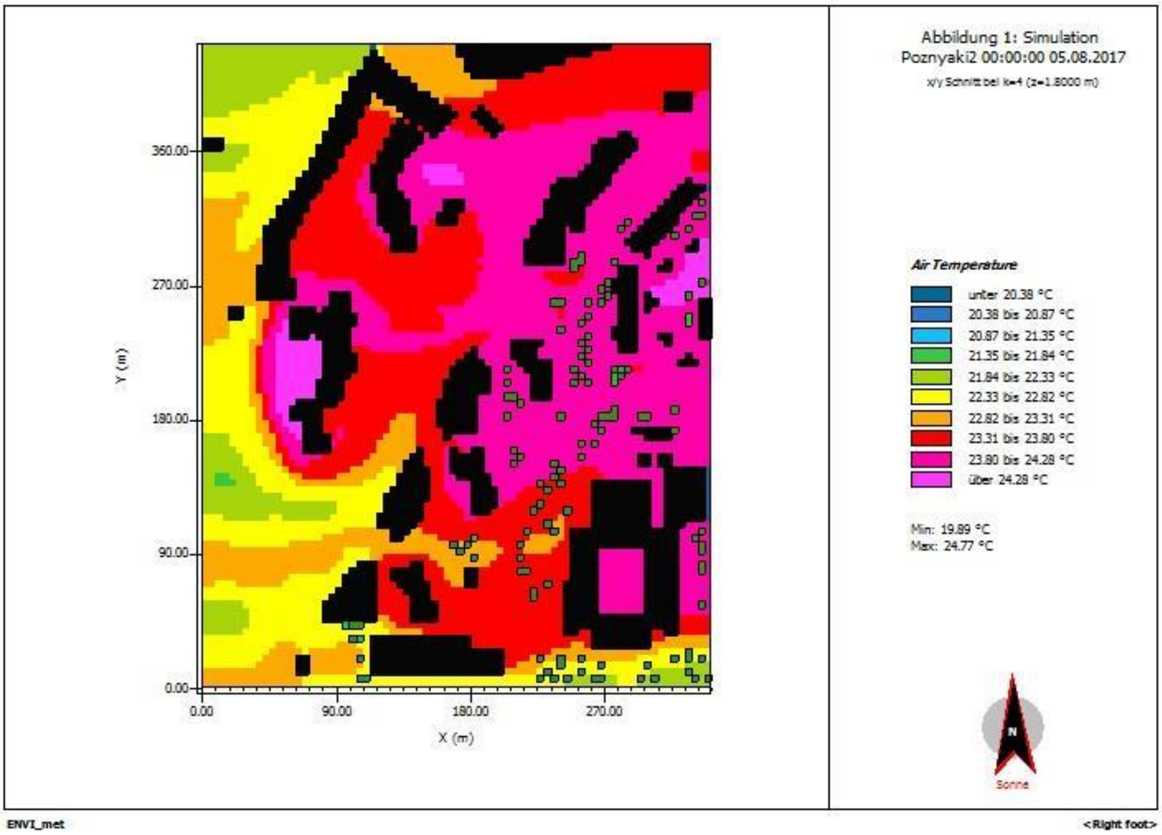

Fig. 2. The results of air temperature simulation at 00:00 EEST of 5 August 2017

Changing the properties of the underlying surface in cities (prevalence of roofs and asphalt roads, which are waterproof and facilitate the most rapid removal of runoff and discharge of precipitation into sewers) is one of the reasons for the change in the relative humidity in the city and the transformation of the humidity field across its territory [38–39]. The simulation results show that notable differences in relative humidity are observed even over a small part of urban area on a clear day. The lowest values are observed over the paved territories, the highest – over the areas with vegetation, i.e. the influence of the underlying surface on the formation of the humidity field within the urban development is observed, as well as a clear inverse relationship between air temperature and humidity.

The results of the wind field simulation showed that low wind speed are observed in enclosed courts and tall vegetation areas, while the space between some buildings are characterized by a local increase in wind speed (Fig. 3), which is caused by the Venturi effect.

Thus, the analysis of the simulation results has confirmed once again that the values of the main meteorological parameters (air temperature and humidity, wind characteristics) differ significantly within the complex urban structures, even in small areas.

In this study, a bioclimatic index of physiologically equivalent temperature is used to evaluate the thermal load on the human. Simulation of PET values was performed utilizing the RayMan model with 1-hour interval (Table 2).

The simulation results show that on 4 August, residents of the researched area experienced slight heat stress at all research points already since 6:00 EEST (at the air temperature of 21.5°C, measured on the meteorological station). At 9:00 EEST, points 1, 3, 4, 5 record intense heat stress, while at other points it is moderate because they are still in the shade. Extreme heat stress was observed at points 2–6 from 10:00 EEST to 15:00 EEST, however, the highest PET values were recorded at 11:00 EEST at points 4 and 5 (48.7° and 49.9°C). Before noon, the open paved areas are exposed to more heat than the rest of the territory. In the afternoon, the decrease in PET values is observed first in points 4 and 3, and after 15:00 EEST – in the rest of the territory. From 18:00 EEST, the residents experience slight heat stress. Comfortable conditions across the area last from 22:00 EEST through midnight. At night, a person in the area would experience slight cold stress and moderate cold stress. Starting as early as at 5:00 EEST the following day, comfortable conditions were observed for points 1–2 and 6–7, and from 6:00 EEST (for points 2 and 6) such conditions would change to moderate heat stress. The highest amplitude of PET values in the researched area was recorded at 11:00 EEST and made 15.6°C. At night, when comfortable conditions and cold stress are observed, the amplitudes are much lower – from 1.8°C (at 23:00 EEST) to 4.5°C (4:00 EEST on 5

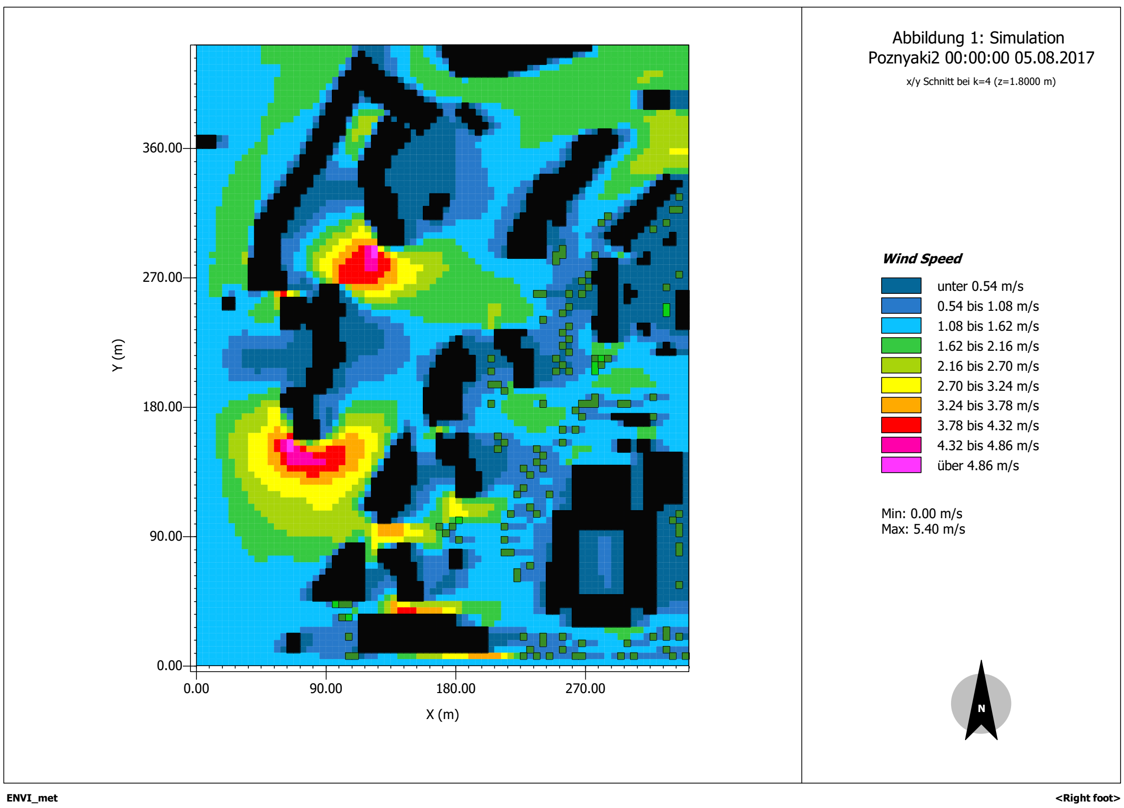

Fig. 3. The results of wind regime simulation for 00:00 EEST on 5 August 2017

Table 2

PET values (°C) in different research points for 4–5 August 2017

Number of study point	1	2	3	4	5	6	7	Amplitude of the territory	CAWS Kyiv
Time (EEST)	PET	PET	PET	PET	PET	PET	PET	PET	PET
6:00	24,8	24,2	25,5	26,9	26,9	27,4	24,1	3,3	27,0
7:00	24,9	28,4	28,0	30,4	29,0	32,1	27,6	7,2	31,2
8:00	32,4	28,4	32,0	34,4	34,2	33,5	31,4	6,0	31,0
9:00	35,5	33,5	36,5	39,6	39,0	37,9	32,9	6,7	30,9
10:00	36,3	34,7	38,8	42,6	42,6	37,6	32,2	10,4	32,4
11:00	38,9	37,9	44,0	48,7	49,9	41,8	34,3	15,6	34,2
12:00	36,6	42,8	41,9	38,5	41,8	43,5	31,4	12,1	34,1
13:00	34,6	44,8	45,0	38,6	40,8	40,7	30,6	14,4	37,8
14:00	37,1	44,9	40,7	38,1	41,5	40,6	33,4	11,5	37,6
15:00	30,4	42,8	39,3	37,9	40,2	40,3	33,3	12,4	36,8
16:00	32,1	37,9	35,3	33,7	35,3	36,5	29,6	8,3	36,7
17:00	30,1	32,7	31,1	30,4	31,5	32,1	27,8	4,9	34,6
18:00	26,0	26,3	25,8	25,7	26,0	26,5	24,6	1,9	30,4
19:00	25,4	25,5	25,4	25,5	25,7	25,8	24,8	1,0	28,5
20:00	25,0	25,1	25,0	25,1	25,1	25,2	24,4	0,8	25,5
21:00	24,5	24,8	24,5	24,7	24,7	24,9	23,8	1,1	23,2
22:00	18,0	20,2	19,6	19,2	19,2	20,2	17,4	2,8	20,6
23:00	18,0	20,2	19,6	19,1	19,2	20,1	17,4	1,8	18,5
0:00	17,9	20,1	19,6	18,9	19,4	20,0	17,4	2,7	17,4
1:00	14,8	15,7	14,3	14,8	14,5	16,8	16,5	2,5	16,4
2:00	14,1	14,1	13,6	14,1	13,7	16,7	15,8	3,1	16,4
3:00	13,7	15,5	13,1	13,6	13,3	16,7	14,9	3,6	18,5
4:00	13,7	15,6	12,7	13,2	13,0	17,2	15,7	4,5	18,7
5:00	17,0	19,7	12,7	13,1	12,8	22,9	19,7	10,2	20,9
6:00	21,4	23,5	13,7	14,6	14,1	28,3	22,8	14,6	24,3

*the red color corresponds to the values of heat stress of different grades; green – to comfortable conditions; blue – cold stress of different grades.

August). This is obviously due to the decrease in the air temperature amplitude in the evening and night hours, which is defined by the decrease (evening hours) and the absence (night time) of the solar radiation (due to which temperature contrasts are formed within the complex geometry of urban areas).

In order to study the differences in thermal comfort conditions within the complex urban structures and meteorological station (in an open area with natural vegetation), PET values for CAWS Kyiv were also simulated using the RayMan model. This weather station was chosen for comparison because of the appropriate time of the observations. Meteorological elements measured hourly on this station, whereas the Joint Hydrometeorological Station "Kyiv" located at Nauky avenue the observations are carried out once every three hours, at air pollution observation posts (which also measure meteorological parameters) – once every 6 hours. On the CAWS Kyiv air temperature and relative humidity are measured using Viasala HUMICAP HMP 155 sensor, wind speed – using Vaisala WAA252 sensor. This make possible to get the values of meteorological parameters with the required frequency.

The analysis of the simulated PET values for the weather station shows that from 6:00 EEST until 20:00 EEST the values of this BI at the weather station also correspond to the heat stress. Starting at 22:00 EEST, the PET values at the weather station correspond to comfortable conditions, same as in the researched urban area. However, cold stress at the weather station occurs an hour earlier than in the researched area, which confirms the well-known fact that the natural surfaces after the sunset cool down faster and the air temperature above them decreases also, while the artificial ones (asphalt, concrete) continue to emit heat (Fig. 4).

The amplitude of the time course of PET values at the CAWS Kyiv was 21.4ºC, at different points of the researched area it ranged from 19.4° (at point No. 7) to 37.1°C (at point No. 5, located in the well courtyard).

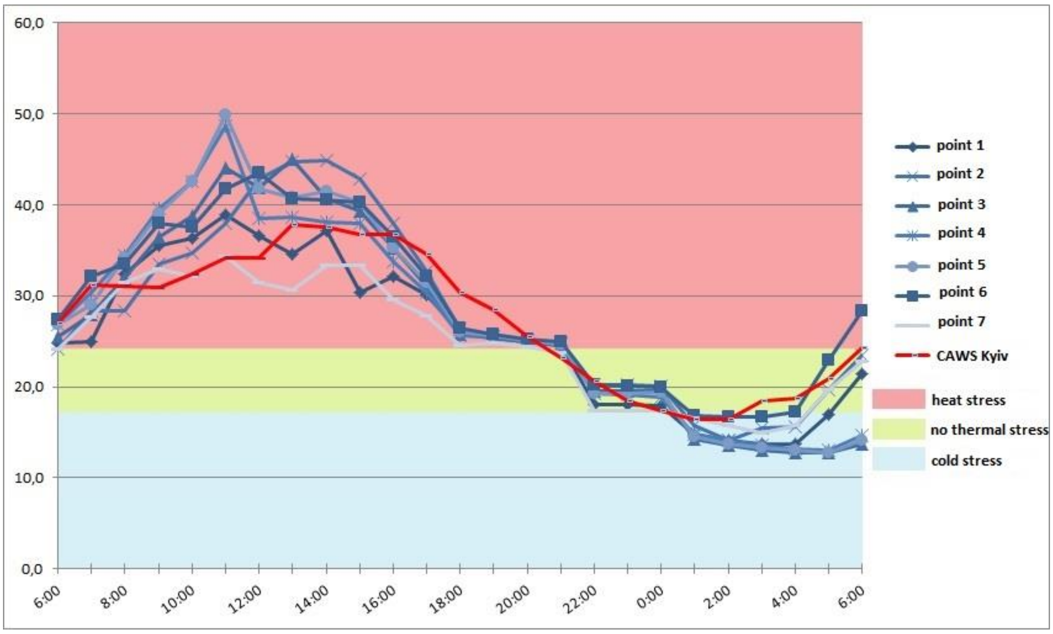

Fig. 4. Time course of PET values (°C) within the researched area and at the CAWS Kyiv

Conclusions. Thus, the article shows modern methods and approaches of bioclimatic studies of an urbanized environment. On the example of an area located within the Osokorky residential area, Kyiv, it is shown that the values of the basic meteorological parameters (air temperature and humidity, wind characteristics) and physiologically equivalent temperature differ significantly within the urban spaces, even across small areas. The amplitudes of PET value were maximum in the daytime and made 12°–15°C. The decrease in the amplitude of the air temperature in the researched areas in the evening and night hours led to a notable decrease in the PET amplitude at the selected area – up to 2°–3°C. Analysis of the simulated PET values for the researched area confirmed that residents of urban areas face the most severe heat stress while staying in the open asphalt-paved areas during the daytime. The duration of the period with comfortable conditions during the day was very short – from 22:00 EEST through midnight.

Based on the PET values simulated for the researched area and for CAWS Kyiv was found the significant differences between thermal comfort conditions within the complex urban spaces and at the weather station. The PET values at different times of the day at different points of the researched area significantly exceeded the value of this BI for the weather station (maximum – by 15.7°C) or was significantly lower (maximum – by 10.6°C). Therefore, the values of bioclimatic indices simulated based on the weather station data can not be applied with any approximation to solve scientific and applied tasks that require information on the bioclimate at particular points in the urbanized environment. To solve such tasks, it is recommended to apply modern methods – ENVI-met and RayMan models.

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SIMULATION OF THE THERMAL COMFORT CONDITIONS OF URBAN AREAS: A CASE STUDY IN KYIV

Formulation of the problem. Studies of bioclimate of a territory are aimed at determining the favorable and adverse impacts of various climatic factors and their combinations on the human body. Complex urban morphology has a significant impact on microclimate and, accordingly, on thermal comfort of a person in such an environment. The height of buildings, street orientation, and distance between buildings alter the solar energy inlet, affect thermal regime, transform the wind speed and direction at the street level. Studies of the bioclimatic conditions of urban areas during the warm season are highly relevant as they provide an opportunity to evaluate human thermal sensations in the city, as well as the potential effectiveness of adaptation measures to heat stress (architectural measures and measures based on the use of green areas and water bodies).

The purpose of the article. The aim of this research is to simulate the bioclimate of an urban environment to determine the human thermal load in summer months based on modern bioclimatic indices and software.

Methods. For the purpose of this study, a part of the territory of the Osokorky residential area of Kyiv was selected. To get values of the main meteorological parameters of the researched area, a three-dimensional, prognostic, microscale model ENVI-met was used. ENVI-met pertains to the CFD-models (computation fluid dynamics model) and is designed for microscales with a horizontal resolution from 0.5 to 10 m and with a time step of 10 seconds as maximum. The PET calculation was performed using the RayMan model.

Results. A clear hot summer day (04 August 2017) was chosen for the simulation. The simulation was performed from 6:00 EEST on 4 August till 6:00 EEST the next day (output interval – 1 hour). The simulation results show that the values of the main meteorological parameters (air temperature and humidity, wind characteristics) and physiologically equivalent temperature differ significantly within urban spaces, even across small areas. The amplitudes of PET value were maximum in the daytime and made 12°–15°C. The decrease in the amplitude of the air temperature within the researched area in the evening and night hours led to a notable decrease in the PET amplitude to 2°–3°C. The analysis of the simulated PET values for the researched area confirmed that the residents of the urban areas experience the most intense heat stress while staying in the open asphalted areas during the daytime. The duration of the period with comfortable conditions during the researched day was very short – from 22:00 EEST through midnight. The range of the daily course of PET values at different points of the researched area varied from 19.4° (at point No. 7) to 37.1°C (at point No. 5 located in the well courtyard).

Based on the PET values simulated for the researched area and for CAWS Kyiv was found the significant differences between thermal comfort conditions within the complex urban spaces and at the weather station. Therefore, the values of bioclimatic indices simulated based on the weather station data can not be applied with any approximation to solve scientific and applied tasks that require information on the bioclimate at particular points in the urbanized environment. To solve such tasks, it is recommended to apply modern methods – ENVI-met and RayMan models.

Scientific novelty and practical significance. For the first time in Ukraine, microclimate and thermal comfort conditions within the complex urban environment has been simulated using ENVI-met and RayMan models. The results of such simulation can be used to choose heat adaptation measures which would help to increase the

comfort of the urban areas. The simulation of microclimate and thermal comfort conditions of some parts of the city territory is important stage of design of the buildings, in order to choose the optimal location for buildings and trees and to create the most comfortable conditions for people.

Keywords: urban area, thermal bioclimate, thermal comfort, physiologically equivalent temperature, «ENVI-met» model, «RayMan» model.

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