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THE ASSESSMENT OF MICROCLIMATIC CONDITIONS IN A WELL-SPACED URBAN STRUCTURE

OCENA WARUNKÓW MIKROKLIMATYCZNYCH W DOBRZE ROZMIESZCZONEJ STRUKTURZE MIEJSKIEJ

A b s t r a c t

A proposed assessment method for microclimatic conditions in urban structures is presented in the paper. The assessment model defines the quantitative and qualitative features of the study area. The three main elements of the urban environment – local climate, urban development, and the type of the area surfaces – are all evaluated. The proposed method constitutes an approximation. Parameters such as the location, shadow fall, or heat loss by the external surfaces of the building were not included.

Keywords: microclimate, human comfort, CFD

S t r e s z c z e n i e

W pracy przedstawiono metodę szacowania warunków mikroklimatu w strukturze miejskiej. Model szacowania definiuje jakościowe i ilościowe cechy rozpatrywanego obszaru. Oceniane są trzy główne elementy środowiska miejskiego – klimat lokalny, rozwój zabudowy oraz rodzaj powierzchni obszaru. Proponowana metoda stanowi przybliżenie. Nie zostały uwzględnione parametry takie jak położenie, zacienienie, czy utrata ciepła przez zewnętrzne powierzchnie budynku.

Słowa kluczowe: mikroklimat, komfort ludzki, CFD

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1. Introduction

The external environment, determined by natural conditions such as climate or topography, and also by anthropogenic factors, that is; urban development, the density of urban structures or the size of green areas, have a major impact on living conditions. Dense urban structures in city areas affect unique microclimatic conditions that greatly influence residents' comfort. In some situations, local problems connected with excessive air flow in the vicinity of the buildings or the formation of strong turbulences, may arise. At the same time, tall, concentrated buildings sometimes cause a significant decrease in urban ventilation. This may lead to a deterioration in hygienic conditions and encourage local accumulations of snow or pollution. The ventilation degree of urban areas also depends on the climatic conditions of individual residential districts, as these may enhance or counteract the influence of urban development.

Analysis of the human body's heat balance shows that in order to create comfortable wind conditions it is essential to take into account thermal factors. This is especially important when the temperature is below -5°C and wind speed is greater than 1 m/s, and also in cases when the temperature is greater than +25°C but wind speed is less then 3 m/s. In the above circumstances, discomfort is caused by a deficiency of heat exceeding 40 W/m^2 and in the case of temperature above zero by a heat surplus above 40 W/m^2, [8].

Knowledge of environmental conditions and an appropriate application of assessment results greatly contribute to increasing residents' living comfort.

2. The assessment of microclimatic conditions in urban areas

2.1. Criteria and general model of microclimatic conditions assessment

The assessment of environmental impacts on human presence is a complex issue, as the consideration of the great number of variables that characterise individual occurrences is necessary. The descriptive method and the model method are the most frequently used for these purposes. In the latter, a model that comprehensively characterises environmental functions is constructed. It constitutes a certain physical or mathematical pattern that incorporates the greatest number of variables affecting individual occurrences.

The quantitative and qualitative structure of the external environment should be considered in the assessment of microclimatic conditions. For this purpose two models: an exponential function model and a model analogous to Ohm's law can be used. In the exponential function model, the function base characterises quantitative features of the environment $y = x^z$, while the index exponent – its qualitative features. The value of the function y ranges between 0 and 1. No favourable features of the environment occur for $y = 0$, and the ideal state is recorded for $y = 1$. Values x fall within the range of variable between 0 and 1 whereas z may range between 0 and $+\infty$. For the most favourable qualitative features $z = 0$ the function y equals 1, [9]. The second model can be described by:

$$y_i = \frac{P_i}{R_i} \tag{1}$$

where: y_i – value of a given parameter, P_i – potential, treated as favourable features of the environment, R_i – resistance, treated as the conditions that make long-term human occupation difficult or impossible.

Finally, the proposed model is a combination of two above mentioned models and has the following form:

$$y = \left(\frac{P_x}{R_x}\right)^{\frac{R_z}{P_z}} \tag{2}$$

where: P_x, R_x – potential and resistance of quantitative features, P_z, R_z – potential and resistance of qualitative features.

2.2. Human comfort criteria

The comfort sensation is associated with changes in body temperature caused by an increase or decrease in ambient temperature, the cooling effect of wind, and the convective and the radiative heat loss from the body. There are a number of factors which affect the heat exchange between man and the external environment. The most important physical parameters include: air temperature, wind speed, solar radiation, relative humidity and radiation temperature. Equally important are the parameters related to the individual person, such as the activity, exposure time, clothing thermal insulation and finally the psychological factors associated with the level of adaptation, expectations or previous experiences [11, 12].

Human comfort studies carried out over many years have resulted in the development of about 100 indices which assess the influence of the atmospheric environment on a human being. Most of the indices are not strongly correlated with physiological reaction in human. They are based on single or composite meteorological parameters, such as wet – bulb or equivalent temperature. Since the 1970s the psychological relevant indices derived from the human energy balance have become more popular. The MEMI model (Munich energy balance for the individual) and the derived thermal assessment index PET (physiologically equivalent temperature) proposed by Höppe [7] were commonly used. Other models are the predicted mean vote (PMV) Fanger [5], Klima-Michel Model and PT index (Perceived Temperature) by Jendritzky (1990), standard effective temperature (SET*) Gagge et al. [6] and MENEX_2005 by Błażejczyk [2] with PST (Physiological Subjective Temperature) and PS (Physiological Strain) indexes. Recent years have brought a new generation of models – multi node models that consider all mechanisms of thermoregulation. Among them the most popular is the UTCI (Universal Thermal Climate Index) derived from the Fiala multi-node model of human heat balance. The UTCI is defined as the air temperature of the reference condition causing the same model response as actual conditions. The UTCI was developed in 2009 by international experts within the COST Action 730 Błażejczyk et al. [3]. All of the models presented require detailed input information both meteorological and physiological which in practice are sometimes difficult to obtain, like mean radiant temperature or skin temperature. As a result there is a need for a more simplified method of determining the individual components of the heat balance equation.

$$M + R + Q_C + Q_E + Q_K + Q_L + Q_R = \Delta Q \tag{3}$$

where: M – metabolic rate, R – absorbed solar radiation, Q_c – heat transfer by convection, Q_E – heat transfer by evaporation, Q_K – heat transfer by conduction, Q_L – heat transfer by long wave radiation, Q_R – heat loss by respiration.

In the light of extensive research carried out in many countries, described by Błażejczyk [1], it can be demonstrated that there is a correlation between the intensity of heat fluxes with air temperature and wind speed, which allows approximations to be applied.

In the author's proposed method comfort criteria were based on the heat balance equation and the aforementioned findings. In order to specify the individual components some assumptions have been made based on standard values for a typical human and long term meteorological data of the analysed location (solar radiation):

- Metabolism M – 70 W/m^2
- Thermal insulation of the cloths 1 clo
- Solar radiations absorption R – 30 W/m^2
- Heat exchange through evaporation Q_E – 8 W/m^2 for $T_a < +5^{o}C$, 20 W/m^2 for $T_a \geq +5^{o}C$
- Heat exchange through conduction Q_K is not taken into account
- Heat loss caused by respiration Q_R – 8 W/m^2

Both human body parameters and solar radiation absorption can take different values depending on local conditions.

The remaining components of the heat balance equation i.e. heat transfer by convection and long wave radiation were determined analytically using Błażejczyk's [1] observation.

Furthermore heat transfer by convection and long wave radiation, based on temperature and wind speed, are specified thus:

For weather conditions where wind speed $U \leq 4$ m/s and temperature $T_a \geq +5^{o}C$

$$Q_C + Q_L = 3,4T_a + 0,2\overline{U} - 118,8 \tag{4}$$

Where the wind speed $U \leq 4$ m/s and temperature $T_a < +5^{o}C$

$$Q_C + Q_L = 1,7T_a + 6,0\overline{U} - 101,4 \tag{5}$$

Where the wind speed $U > 4$ m/s and temperature $T_a \geq +5^{o}C$

$$Q_C + Q_L = 3,3T_a + 0,2\overline{U} - 127,8 \tag{6}$$

Where the wind speed $U > 4$ m/s and temperature $T_a < +5^{o}C$

$$Q_C + Q_L = -1,5T_a + 0,3\overline{U} - 126 \tag{7}$$

By applying the above equations (4–7) and assumptions to the heat balance equation, thermal loads on the body were derived for specified ranges of temperature and wind speed [4]. The parameter can be used for the relative comparison of different environmental conditions.

In weather conditions where wind speed $U \leq 4$ m/s and temperature $T_a \geq +5^{o}C$

$$\Delta Q = 2,8T_a - 4,8\overline{U} - 29,8 \tag{8}$$

Where the wind speed $U \leq 4$ m/s and temperature $T_a < +5^{o}C$

$$\Delta Q = 1,7T_a - 6,0\overline{U} - 23,0 \tag{9}$$

Where the wind speed $U > 4$ m/s and temperature $T_a \geq +5^{o}C$

$$\Delta Q = 2,3T_a - 3,5\overline{U} - 35,4 \tag{10}$$

Where the wind speed $U > 4$ m/s and temperature $T_a < +5^{o}C$

$$\Delta Q = 1,5T_a - 3,0\overline{U} - 34,0 \tag{11}$$

Taking into account the efficiency ranges of the thermoregulatory systems, which are applied in thermophysiology, it is assumed that $|\Delta Q| <$ 20 W/m^2 does not trigger system loads. However, where there is deficiency and excess heat ΔQ equal to 20–40 W/m^2 then unfavourable loads will affect the body. Strong heat load can be observed when ΔQ is between 40–80 W/m^2. Higher values than the threshold value 90 W/m^2 can trigger disturbances in the proper function of the thermoregulatory system, which consequently can lead to dangerous overheating or conversely hypothermia.

Finally the criteria for thermal comfort were established based on the following thresholds for heat loads on the body ΔQ.

- $|\Delta Q| <$ 20 W/m^2 – comfortable condition,
- $|\Delta Q|$ in ranges 20 – 40 W/m^2 – unfavourable loads on the body,
- $|\Delta Q|$ in ranges 40 – 80 W/m^2 – strong unfavourable loads on the body,
- $|\Delta Q| >$ 80 W/m^2 – dangerous loads on the body.

The proposed criteria were the basis for weather typology used in the assessment of weather conditions of the urban structure analysed.

Fig. 1. presents the relationship between ΔQ and air temperature T_a and wind speed as well as body heat load thresholds.

The detailed analysis of body heat loads with the corresponding ranges in temperature and wind speed are presented in Klemm [9].

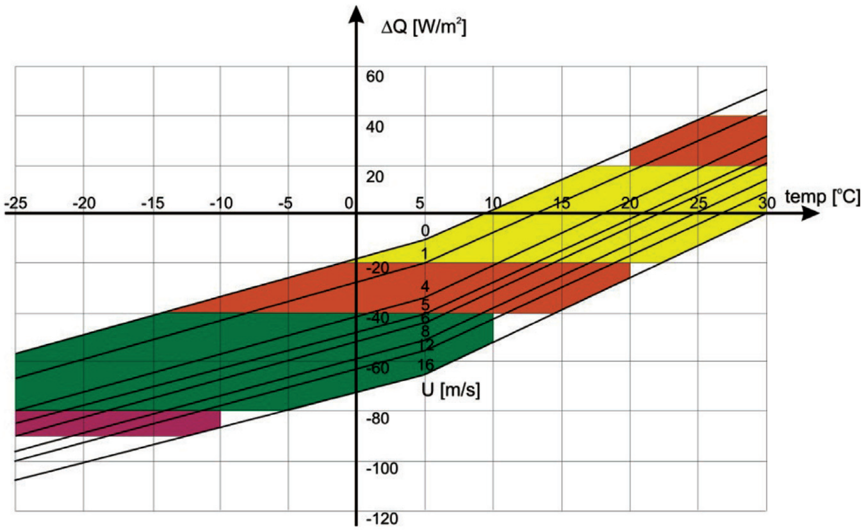

Fig.1. Threshold values of the thermal loads on the body

2.3. Assessment of weather conditions

For the purpose of the study, a weather typology was proposed. As the basic feature of the weather type, human thermal sensation caused by the reaction of the thermoregulatory system to atmospheric stimuli (air temperature, wind speed) were used. Three types of weather conditions and twenty groups were determined.

Type A includes weather situations in which wind conditions allow a human to spend a long period of time outdoors. Wind speed is lower than 8 m/s, and the thermal conditions are perceived as comfortable $\Delta Q \leq 20$ W/m^2.

Type B includes weather situations not conducive to relaxation, walks or cycling, but allowing work in the open air. Thermal conditions are perceived as causing adverse thermal load on the body. The physical influences of the wind are crucial, wind speed exceeds the threshold of 5m/s. Type B also includes the situation where wind speed is less than 5 m/s and a thermal effect is pronounced due to very unfavourable thermal conditions of the body, loss or excess heat at 20–40 W/m^2.

Type C includes situations of definitely unfavourable windy weather. Thermal influences are clear, a strong thermal load on the body, heat loss from 40 to 80 W/m^2 and over 80 W/m^2. The detailed typology of weather conditions including body heat loads with the corresponding ranges in temperature and wind speed are presented in Klemm [9].

In the assessment of weather conditions, quantitative features are represented by the occurrence of favourable and unfavourable weather types from a human comfort point of view. Qualitative features of weather conditions may be described by the parameters of the intensity of wind speed, wind direction and air temperature changes. Intensity changes were defined as the relation of a standard deviation to mean value.

$$K_w = \left[\frac{cA_1 + cA_2 + cA_3 + cA_4 + cA_5}{1 + \left(cC_1 + cC_2 + cC_3 + ...cC_8 \right)} \right]^{\left[\frac{\left(1+I_U^C\right)\left(1+I_k^C\right)\left(1+I_T^C\right)}{\left(1+I_U^A\right)\left(1+I_k^A\right)\left(1+I_T^A\right)} \right]} \tag{12}$$

where: cA_1, cA_2, cA_3, cA_4, cA_5 – occurrence frequency of favourable weather conditions, defined by groups A_1, A_2, A_3, A_4, A_5, cC_1, cC_2, ...cC_8 – occurrence frequency of unfavourable weather conditions, defined by groups C_1, C_2, ...C_8, I_U^A , I_U^C – intensity of wind speed changes in A and C weather groups, I_k^A , I_k^C – intensity of wind direction changes in A and C weather groups, I_T^A , I_T^C – intensity of air temperature changes in A and C weather groups.

2.4. Assessment of urban development

The second important element with an effect on the final assessment of microclimatic conditions is the structure of the urban area i.e. participation of various urban structures, tall vegetation, and open area in the total surface, as well as zones with wind comfort and discomfort. The above estimation is carried out using numerical simulations, assuming wind speed 4 m/s and by simultaneously taking into account frequencies of wind flow occurring from 8 or 12 directions and also its related temperature.

The participation of the open area Z_w in the total surface was considered to be the potential of quantitative features of the land development coefficient Z_t and the participation of various urban structures and green areas in relation to the study area was considered to be their resistance (Z_m).

$$Z_m = \frac{S_m}{S_o}, \quad Z_w=1-Z_m,$$

where: S_m – surface area of buildings and tall vegetation [m^2], S_o – study area [m^2].

Then quantitative features may be described by:

$$x = \frac{Z_w}{1 + Z_m} \tag{13}$$

The qualitative features z may be described by:

$$z = \left[\frac{1 + Z_1^C}{1 + Z_1^A} . \frac{1 + Z_2^C}{1 + Z_2^A} ..... \frac{1 + Z_8^C}{1 + Z_8^A} \right] \tag{14}$$

From the human sensation point of view, uncomfortable conditions are influenced by wind flow and air temperature. Weak air flow in built-up areas leads to deterioration of hygienic conditions and encourages local accumulation of pollution, whereas increased speeds can trigger dynamic loads. Simultaneously even at moderate wind conditions local discomfort may appear due to low or high temperatures. High temperatures especially can cause serious problems in big cities. Nowadays heat islands and poor ventilation as a result of inappropriate urban planning become the most serious factors which influence human health and comfort. This fact was considered in the qualitative features proposed.

The resistance of qualitative features was determined from the equation

$$Z_k^C = Z_k^{C(U)} + Z_k^{C(T)} \tag{15}$$

The first element in the equation describes situations in which, due to low wind speed, ventilation of the area is problematic ($U < 1$ m/s) and situations in which high wind speed can cause discomfort ($U > 4$ m/s). In order to assess wind flow conditions around buildings and determine the sizes of zones in which wind speed reaches values lower than 1 m/s and over 4 m/s numerical simulations can be used.

$$Z_k^{C(U)} = \left[\frac{S_k^{U<1}}{S_{Lg}} + \frac{S_k^{U>4}}{S_{Lg}} \right] \cdot f_k^{U=4} \tag{16}$$

where: $\frac{S_k^{U<1}}{S_{Lg}}$ and $\frac{S_k^{U>4}}{S_{Lg}}$ – ratios of the areas of zones in which wind speed $U < 1$ m/s and $U > 4$ m/s to the surface S_{Lg}, which is characterised by clear fluctuations in wind speed caused by buildings.

Surface size S_{Lg} is determined on the basis of the principle proposed by Bottema [4]. The length L_g is specified using the formula

$$L_g / H = \frac{W/H}{1 + 0,5 W/H} \tag{17}$$

where: L_g – geometrical influence scale [m], W – building width [m], H – building height [m].

Since the wind speed $U_{ref} = 4$ m/s (wind speed measured at the meteorological station at a height of 10m) assumed in the numerical simulation as the inflow wind speed occurs with different probabilities in different directions, it was necessary to introduce a weighting coefficient $f_k^{U=4}$, resulting from meteorological data analysis.

The second element in eq. 15 refers to conditions when, despite comfortable wind speed, thermal loads of human body exceeded 40 W/m^2.

$$Z_k^{C(T)} = \left(\frac{S_k^{1 \le U \le 4}}{S_{Lg}} \right) \cdot f_k^{U=4} f_k^{U=4, \Delta Q>40} \tag{18}$$

where: $f_k^{U=4, \Delta Q>40}$ – weighting coefficient taking into account the thermal conditions in the direction of k, when the heat loss of the body exceeds 40 W/m^2, and the inflow wind speed is at the level of 4 m/s.

The potential of qualitative features Z_k^A describes situations in which human comfort is achieved through moderate wind speed ($1 \le U \le 4$) and temperature which guarantee thermal loads $\Delta Q \le 20$ W/m^2.

$$Z_k^A = \left(\frac{S_k^{1 \le U \le 4}}{S_{Lg}} \right) f_k^{U=4} f_k^{U=4, \Delta Q \le 20} \tag{19}$$

where: $f_k^{U=4,\Delta Q \le 20}$ – weighting coefficient taking into account the thermal conditions considered as comfortable in the direction of *k*, when the thermal loads $\Delta Q \le 20$ W/m^2 and the inflow wind speed is at the level of 4 m/s.

The above mentioned qualitative features were determined using numerical simulations of wind flow around buildings and analysis of meteorological data.

The urban development coefficient was finally described by:

$$Z_t = \left(\frac{Z_w}{1 + Z_m} \right)^{\left[\frac{1+Z_1^C}{1+Z_1^A} \cdot \frac{1+Z_2^C}{1+Z_2^A} \cdots \frac{1+Z_8^C}{1+Z_8^A} \right]} \tag{20}$$

2.5. Assessment of surface

An equally important element in the analysis of microclimatic conditions is assessment of the surface in the vicinity of the urban area being examined. Special attention was paid to the size and thermal characteristics of the surface and also to the impact of direct solar radiation, air temperature and wind speed. Taking into account the aforementioned elements has allowed the partial inclusion of thermal turbulence, caused by solar radiation in the above analysis.

The great participation of artificial areas in urban environment, characterised by low albedo contributes to an increase in the thermal turbulence and the air temperature. This phenomenon has a major impact on heat island formation and worsening human comfort.

In order to create a comfortable environment, conditions increasing the participation of natural areas (low vegetation, water areas) characterized by maximum albedo are recommended.

The quantitative features of the surface coefficient were determined taking into account participation of surfaces with different albedo in the general area.

$$x = \frac{Z_{A_l > 0,25}}{1 + Z_{A_l < 0,25}} \tag{21}$$

The qualitative features may be described using the refractive index structure coefficient, one of the main parameters describing turbulent fluctuations caused by sensible heat fluxes:

$$z = \left[\frac{1 + Z_{0<R\le30}^{A_l<0,25}}{1 + Z_{0<R\le30}^{A_l>0,25}} \cdot \frac{1 + Z_{30<R\le60}^{A_l<0,25}}{1 + Z_{30<R\le60}^{A_l>0,25}} \cdot \frac{1 + Z_{60<R\le90}^{A_l<0,25}}{1 + Z_{60<R\le90}^{A_l>0,25}} \cdot \frac{1 + Z_{R>90}^{A_l<0,25}}{1 + Z_{R>90}^{A_l>0,25}} \right] \tag{22}$$

$Z_R^{A_l<0,25}$ and $Z_R^{A_l>0,25}$ where determined for four ranges of direct solar radiation $0 < R \le 30$, $30 < R \le 60$, $60 < R \le 90$ and $R > 90$ W/m^2 using equations:

$$Z_R^{A_l<0,25} = C_n^* \cdot f_R \quad \text{and} \quad Z_R^{A_l>0,25} = C_n^* \cdot f_R \tag{23}$$

where: C_n^* – normalized value of refractive index structure coefficient dependent on albedo and direct solar radiation for analysed for ranges $0 < R \leq 30$, $30 < R \leq 60$, $60 < R \leq 90$ and $R > 90$ W/m^2, f_R – weighting coefficient of direct solar radiation incidence for four ranges $0 < R \leq 30$, $30 < R \leq 60$, $60 < R \leq 90$ and $R > 90$ W/m^2 (determined on the basis of the typical meteorological tear), C_n – refractive index structure coefficient which characterise fluctuation of turbulent air flow

Refractive index structure coefficient can be determined based on wind tunnel measurement by the use of narrow laser beam. The optical properties of the air on the path of the laser beam are subject to constant changes caused by turbulent air flow. In the method described it is possible to gain 1000 to 2000 records in a short period of time (10^{-9} s). This allows for accurate analyses of turbulence phenomena. Detailed information on this method is presented in Klemm [9]. It is also possible to define the refractive index structure coefficient in an analytical way using Monin Obuchov theory, the aerodynamic characteristic, and wind profile of analysed location Klemm [10].

2.6. Overall assessment of microclimatic conditions

The overall assessment of environmental conditions may be described by the coefficient B_k, expressed by:

$$B_k = \left[0,2K_w + 0,5Z_t + 0,3Z_n\right] \tag{24}$$

The highest coefficient weight was attributed to urban development due to the fact that the layout of the buildings can be controlled to a greater extent in comparison with macroclimatic conditions. The lower value of the surface coefficient results from taking into account only horizontal surfaces. In real conditions vertical elements can play a major role the in radiation and heat balance of complex urban structures. This problem will be developed in future research.

3. Conclusions

The paper presents a proposal for an assessment method for microclimatic conditions in the urban environment. An assessment model defines quantitative and qualitative features of the study area from the human comfort aspect. Three main elements of the urban environment – local climate, urban development, and surface characteristic – are evaluated. Apart from local scale analyses it also takes into account long term climatic characteristics.

In the case of weather condition assessment a typical meteorological year can be used as the base for weather typology.

The second important element having an effect on the final assessment of microclimatic conditions is the structure of the urban area, i.e. the participation of various urban structures, tall vegetation and open area in the total surface, as well as zones with wind comfort and discomfort. The above estimation is carried out using numerical simulations, assuming wind speed 4 m/s (mean value for analysed location) and by simultaneously taking into account frequencies of wind flow occurring from 8 or 12 directions and also its related temperature. The combined consideration of temperature and wind speed is very important in the case of human comfort. Taking into account the above elements allows for estimation of the impact of the urban structure, especially building geometry, their location in relation to each other, and to compass directions on wind comfort. The above assessment answers the question of whether the assumed urban development can be treated as comfortable or not from the wind conditions point of view.

An equally important element in the analysis of microclimatic conditions is assessment of the surface in the vicinity of the examined urban area. Special attention was paid to the size and thermal characteristics of the surface and also to the impact of direct solar radiation, air temperature, and wind speed. Taking into account these elements has allowed the partially inclusion of thermal turbulence caused by solar radiation into the above analysis.

The proposed method constitutes a certain approximation due to many parameters not included, such as the lay of the land, shadow fall, or heat lost by the external surfaces of the building. The construction of the model also allows other elements to be taken into account. Preliminary verification of the model regarding urban development and surface assessment conducted by the use of numerical simulation and wind tunnel tests shows consistent results. However, more detailed analysis are still under way.

References

[1] Błażejczyk K., *Heat exchange between man and his surroundings in different kinds of geographical environment*, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Geographical Studies, 159, 1993 [in polish].

[2] Błażejczyk K., *Bioklimatyczne uwarunkowania rekreacji i turystyki w Polsce*, Prace Geograficzne, IGiPZ PAN, 192, 2004 [in polish].

[3] Błażejczyk K., Jendritzky G., Bröde P., Fiala D., Havenith G., Epstein Y., Psikuta A., Kampmann B., *An introduction to the Universal Thermal Climate Index (UTCI)*, Geographia Polonica, Vol. 86(1), 2013, 5-10.

[4] Bottema M., *Wind climate and urban geometry*, Ph.D. Thesis, FAGO, Technical University of Eindhoven, 1993.

[5] Fanger P.O. *Thermal comfort*. McGraw-Hill, New York, 1972.

[6] Gagge A.P., Fobelets A.P., Berglund L.G. *A standard predictive index of human response to the thermal environment*, ASHRAE Trans, Vol. 92, 1986, 709-731.

[7] Höppe P., *The physiological equivalent temperature in a universal index for the biometeorological assessment of the thermal environment*, International Journal of Biometeorology, Vol. 43, 1999 71-75.

[8] Klemm K., *Kryterium komfortu człowieka w terenach zabudowanych*, Budownictwo i Architektura, Vol.12 (2), 2013, 127-133 [in polish].

[9] Klemm K., *The complex assessment of microclimatic conditions in well-spaced and dense urban structures*, Studia z Zakresu Inżynierii PAN, Warszawa 2011 [in polish].

[10] Klemm K., *Wykorzystanie badań modelowych w przybliżonej ocenie strumienia ciepła jawnego z powierzchni zabudowanej*, Fizyka Budowli w Teorii i Praktyce, Łódź 2015 (accepted for publication) [in polish].

[11] Koss H., Sahlmen J., *Method in pedestrian wind comfort assessment; Theoretical and practical comparisons,* Proc. of COST Action C14 Workshop, Nantes 2002.

[12] Nikolopoulou M., Steemers K., *Thermal comfort and psychological adaptation as a guide for designing urban spaces*, Energy and Building, Vol. 35, 2003, 95-101.