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Assessment of human thermal comfort in street canyons. An example of typical structures (Lodz, Poland)

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Abstract: An urban form has undeniable influence on microclimatic and human thermal conditions in strongly urbanized areas. In this context, this paper aims at evaluating the ability of the layout of street canyons to provide proper outdoor conditions in the human realm. The research is focused on the assessment of human thermal comfort depending on the configuration of the selected streets, which are located in the main city's area of the revitalization process. The ENVI-met application, which is widely used in urban climatology, is applied to estimate the impact of the street's layout on human comfort. Thermal indices such as: SET, PMV, PET and UTCI are implemented to describe conditions prevailing in the street canyons. Furthermore, the results are compared with the literature findings.

Keywords: urban planning, city structure, thermal comfort, numerical simulation

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Introduction

Urban layout plays an important role in creating citizen-friendly outdoor microclimatic conditions. Thus, it has a direct impact on thermal comfort. The assessment of the impact of environmental parameters on humans is extremely complicated in outdoor conditions. This is related to sudden changes in meteorological parameters, in particular solar radiation and wind (Coccolo et al., 2016). The exposure time to microclimatic parameters can range from a few minutes to several hours. Depending on the thermal sensations, a person has the possibility to modify their clothing, as well as the type of physical activity performed. What is more, thermal impressions are the result of physical and mental conditions of a person. Satisfaction with the thermal environment also results from expectations, choices and previous experiences related to exposure to environmental factors (Auliciems, 1998).

1. Thermal comfort

One of the basic definitions, created by the American Society of Heating, Refrigeration and Air Conditioning Engineers, describes the state of mind that expresses satisfaction with the thermal environment (ASHRAE55) as thermal comfort. According to the Polish standard ISO 7730, the state of satisfaction with the thermal environment occurs when the amount of heat generated inside the body is equal to the loss of heat to the environment. This means that it appears when a so-called heat balance occurs. Then the physical parameters of the human body, i.e. skin temperature, sweat rate and/or core temperature, are in a state of thermal equilibrium (Fanger, 1970).

2. Outdoor comfort indices

Literature research shows that there are more than 165 indicators for assessing thermal comfort. They are divided into two categories: empirical and rational indices (de Freitas et al., 2017). In the first case, the assessment is only a component of the influence of meteorological parameters (temperature, humidity and airflow) on the human body. The latter, rational indices, are used to assess the thermal comfort of a person in an external environment. Their application has become popular with the development of computer techniques. Currently used CFD software (Computational Fluid Dynamics) allows the simulation of the distribution of meteorological parameters in a highly urbanized environment on the basis of a 3D model of buildings. Finally, the assessment of human thermal comfort is carried out on the basis of the simulation's output data. Thanks to the implementation of heat balance equations in the software, it is possible to estimate the values of thermal comfort indices for various combinations of physical human parameters.

According to Pochter et al. (2018), the most commonly used empirical indices are Effective Temperature (ET) and Operative Temperature (T_{op}). Standard Effective Temperature (SET), Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) are mentioned as commonly used rational indices. In this paper we will discuss the above mentioned rational indices due to their application in the empirical part of this study in order to assess the thermal comfort of humans in typical street canyons.

2.1. Standard Effective Temperature (SET)

The Effective Temperature Standard was developed by modifying the Effective Temperature (ET) index, which was used to estimate the working conditions in industrial and service facilities. The index is defined as a temperature in a standard environment (relative humidity = 50%, air temperature = radiant temperature, wind velocity < 0.15 m/s) at which the human being will have the same average skin temperature and humidity as in a real environment. Thanks to the implementation of the Gagge's two-nodes model equation, it is possible to use it to assess the thermal comfort of a human being in an outdoor environment.

2.2. Predicted Mean Vote (PMV)

Predicted Mean Vote is defined as the average score of a group of people expressing their satisfaction or dissatisfaction with thermal conditions. Sensations are determined by a seven-step rating scale (typically from [–3] to [+3]). Initially, it was used to assess the thermal comfort of people living inside buildings. Thanks to modification of the Fanger's heat balance equation used in the model, it was applied in the research on external environment. The modified version of this model is called 'Klima-Michel-Modell'. Currently, this index takes into account the influence of meteorological parameters, long-wave and short-wave radiation flows, typical physical activity and human clothing (Jendritzky & Nübler, 1981).

2.3. Physiological Equivalent Temperature (PET)

Currently, the most frequently used comfort index is the Physiological Equivalent Temperature. It is defined as the 'air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed' (Höppe, 1999). The MEMI model (Munich Energy-Balance Model for Individuals) is used as a thermal balance equation, taking into account meteorological parameters, physiological factors and information on thermal insulation properties of clothing.

2.4. Universal Thermal Climate Index (UTCI)

Under the European programme COST Action 730 (Cooperation in Science and Technical Development), the Universal Thermal Climate Index has been developed. It was the result of several years of cooperation between an interdisciplinary expert group in the field of thermophysiology, occupational medicine, physics, meteorology, biometeorology and environmental science. The Universal Thermal Climate Index is defined as the equivalent air temperature at which, under reference conditions, the basic physiological parameters of an organism assume the same values as under real conditions. It is universally applicable in relation to different microclimatic conditions (taking into account the seasonality of microclimate), as well as the scale and objective of research. In addition, it takes into account information of complex thermophysical processes. Human energy balance is determined by the Fiala model.

3. Model of street canyons in the city of Lodz – the case study

Poland is a country located in Central Europe. Lodz is the third largest city in the central zone. Currently, all of the city's planning activities are focused on transformations within the Historic Urban Core, which is defined as the densest urban fabric in the city. The inner structure is the most vulnerable part of the city to the occurrence of uncomfortable thermal conditions. According to Fortuniak & Kłysik (2008) the most intense thermal phenomenon (Urban Heat Island) in the country was observed in the city of Lodz. Furthermore, this area is subject to the process of revitalization and there are the most intensive investment activities ongoing. The main objective of the strategic document (Strategy for Spatial Development of Lodz 2020+) connected with spatial planning processes is to create citizen-friendly areas. Special attention has been paid to public spaces classed as street canyons.

In this study, the typical urban spaces that have been selected as research areas are, a north-south oriented canyon and an east-west oriented canyon that were transformed within the revitalization process. The typical characteristics of the street canyons was determined on the basis of information acquired from the public authorities (the Geodesy Office). Parameters of buildings located along the city roads, as well as information on street dimensions (Aspect Ratio and Sky View Factor) were determined. Canyons characterized by average values of coefficients (AR and SVF) were selected for analysis. Their geometry is presented in Figure 1. In addition, the choice of the terrain depended on its location. Spaces located in the area of revitalization projects were selected for the study.

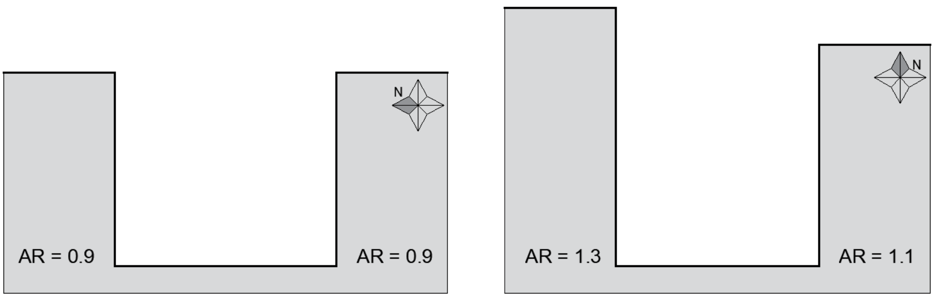

Fig. 1. Geometry of selected street canyons (the aspect ratio of the east-west oriented canyon – left; the aspect ratio of the north-south oriented canyon – right), (*own elaboration*)

Thermal comfort was evaluated with the use of CFD software, ENVI-met. This tool was used to create three-dimensional, non-hydrostatic microclimatic models for the selected street canyons. Initially, 3D models of the building structure were made. In the first case, the east-west oriented canyon, the dimensions were 60 x 30 x 30 units with a resolution of 4 m x 4 m x 1 m. A model of 60 x 75 x 30 units with a resolution of 4 m x 4 m x 1 m was created for the north-south oriented canyon. Next, the meteorological conditions prevailing in the area of revitalization activities undertaken in the city were determined. For this purpose, the parameters of a Typical Meteorological Year were assessed in accordance with the European standard

PN-EN ISO 15927-4. This data reflects the long-term average conditions for the warm period prevailing in the external environment. On the basis of the procedure described in (Bochenek & Klemm, 2019), the warm period for the city was determined from May 14th to September 24th. Information was used as input data for the simulation of atmospheric processes. Having the output data in the form of meteorological parameters occurring in street canyons, selected indicators of thermal comfort, i.e. SET, PMV, PET and UTCI, were calculated. Thermal comfort was estimated for an adult with a height of 1.75 m and weight of 75 kg, metabolic rate of 1.48 met and clothing heat resistance of 0.50 clo.

4. Outdoor human thermal comfort in the analysed street canyons

The urban form of public spaces, including street canyons, has an influence on microclimatic parameters. Thus, it shapes the thermal conditions in the external environment. The values of comfort indices for typical street canyons obtained by computer simulation are presented in Figure 2.

Studies have shown that greater differentiation of thermal conditions occurred in the area of the street canyon of north-south orientation. The average SET index value was 18.15°C. In the case of the east-west oriented canyon it was 16.61°C. This means that in both cases, the canyons were for the most part 'slightly cool' or 'cool'. The conducted analyses show that the conditions described as 'comfortable' occurred between 10 a.m. and 2 p.m. only in the north-south oriented canyon area.

The values of PMV index significantly exceeded the typical scale [–3], [+3]. This was related to the calculation of index value based on variable atmospheric conditions, as well as average scores of people expressing their satisfaction with the thermal environment. In addition, the discrepancy between theoretical (seven-degree scale) and empirical studies resulted from the lack of restrictions as to minimum/maximum PMV values in the ENVI-met software. The scale was the result of input data entered into the model (initial atmospheric conditions depending on geographical location). In this case, the average value of the index was [–2.83] for the north-south oriented canyon and also [–2.68] for the east-west oriented canyon. The conditions in both public spaces were described as 'slightly cool', 'cool', 'cold'.

PET is the most commonly used indicator for the assessment of thermal comfort in an external environment. The average index value ranged from 11.04 to 27.16°C (north-south canyon) and from 9.96 to 22.36°C (east-west canyon). Comfortable conditions occurred between 9 a.m. and 5 p.m., as well as between 8 a.m. and 5 p.m., respectively. For most of the time, both areas recorded conditions known as 'slightly cool', 'cool'.

According to the last of the applied indicators, the conditions in both public spaces were described as 'comfortable'. The average index value was 17.32°C (east-west canyon), 17.72°C (north-south canyon). A greater variation in thermal conditions was observed in the east-west canyon.

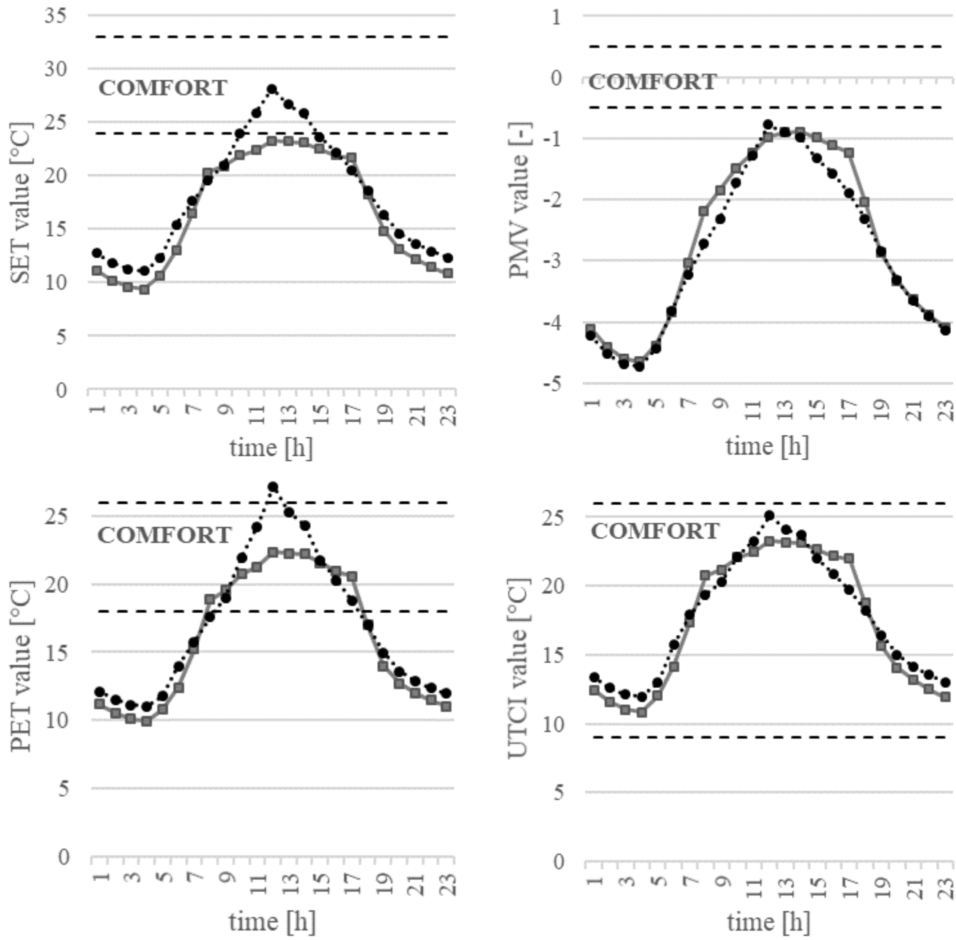

Fig. 2. Values of thermal comfort indices for the warm period in the selected street canyons (grey solid line – values for the east-west oriented canyon, black dotted line – values for the north-south oriented canyon), (*own elaboration*)

Conclusions

This research is focused on the assessment of human thermal comfort in street canyons with the use of computational modelling. In this case, rational indices such as SET, PMV, PET and UTCI were used, which are widely applied in urban climatology. The results clearly showed that urban layout has an undeniable influence on thermal sensations.

Both the north-south and east-west canyons were characterized by ‘cool’ and ‘slightly cool’ conditions for most of the time. In the analysed cases the average SET value was 16.61°C (east-west canyon), 18.15°C (north-south canyon). Literature research has shown that ‘comfortable’ conditions occur when it oscillates between 23.9 and 33°C (Lin et al., 2011; Yahia & Johansson, 2013; Zhao et al., 2016). The average value of the PMV index was [–2.68] (east-west canyon),

[–2.83] (north-south canyon). Neutral conditions occur in a range from [–0.5] to [+0.5]. The air temperature is between 17.5 and 22.5°C and the wind speed does not exceed 5 m/s (Metje et al., 2008). In the studied cases, the average air temperature ranged from 13.84 to 21.02°C (east-west canyon) and from 13.60 to 20.67°C (north-south canyon). Therefore, the comfort conditions were not achieved. Also in the case of using the PET indicator (estimation using CFD software), the conditions in both areas were considered as 'cool' and 'slightly cool' (9.96-22.36°C for the east-west canyon; 11.04-27.16°C for the north-south canyon). However, according to Potchter et al. (2018), the comfort conditions for temperate climates oscillate between 10 and 31°C (the authors carried out comparative studies, i.e. computer method vs. field surveys). Taking into account the results of Potchter et al. studies, it can be concluded that comfortable conditions prevail in the area of both street canyons. This fact is confirmed by the study with the use of the UTCI index. The values occurring in the area of both street canyons ranged from 9 to 26°C, which indicates the occurrence of comfortable conditions.

Selection of an indicator enabling the assessment of thermal comfort of a person living in an outdoor environment is a problematic issue. Many authors emphasize the fact that the results of studies are not comparable. This is due to the fact that the inhabitants adapt to the local microclimate conditions. Within a single climate zone, different thermal sensations may occur (Eludoyin & Adelekan, 2013). Therefore, in order to assess thermal comfort, it is necessary to determine both the index value and to conduct surveys. The results are then compared. Finally, a neutral value is determined, as well as a scale of thermal comfort coefficients depending on the geographical location.

The urban form influences the microclimatic conditions and thus the thermal comfort felt by the human being. The research showed that higher values of indicators, and thus more comfortable conditions, were recorded in the north-south oriented canyon (SET – 9 a.m. – 4 p.m.; PMV – 12 p.m. – 3 p.m.; PET – 10 p.m. – 3 p.m.; UTCI – 10 p.m. – 2 p.m.). This was related to the strong radiation of the canyon resulting from its orientation, north-south (no shadow cast by the buildings during the day). Surfaces absorbed radiation, maintaining a higher air temperature in the canyon. According to Taleghani et al. (2015), it is not only the orientation of canyons that affects the prevailing thermal conditions. Building geometry may significantly contribute to the modification of microclimatic parameters. Through appropriate shaping of building parameters (Aspect Ratio Index, Sky View Factor) it is possible to maintain desired microclimatic parameters in public spaces. This fact is confirmed by the studies conducted by Tumini & Garcia (2016), Martinelli & Matzarakis (2017) and De & Mukherjee (2018).

Information

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