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EVALUATION OF THERMAL COMFORT OF THE CITY'S PUBLIC SPACES BY THE USE OF NUMERICAL SIMULATIONS

Decision making by those who play a key role in urban transformation can be supported by computer techniques. 3D-4D spatial simulations provide reliable information on the impact of spatial development changes on urban composition, microclimatic conditions and thermal comfort. Comprehensive approach to the subject of spatial changes during revitalization activities can contribute to guarantee high quality of life for people in urbanized areas, especially within public spaces. However, the current activities do not take into account microclimate issues, due to higher costs. As a result, an aim of this work was to evaluate microclimatic conditions and thermal sensation of people occupying two public spaces, i.e. Old Marketplace and Urban Square, which have been identified as priority areas in the process of city revitalization (Lodz). Results of studies may be presented to the local authorities to enrich analytical part of the urban development study, thus to enable appropriate decisions to be taken on land conversion.
Conducted studies have shown that microclimate of areas is strongly dependent on spatial planning method. Greater diversity of meteorological parameters, i.e. temperature and relative humidity of air is observed in the Old Marketplace. In both areas there are microclimatic conditions described as uncomfortable. In order to guarantee appropriate thermal conditions for users, it is necessary to implement changes in their structure. The authors proposed potential planning strategies aimed to alleviate the discomfort related to human presence in both public spaces.

Keywords: CFD simulator, urban environment, revitalization, comfort

1. Introduction

In recent decades, there have been a growing number of studies on the thermal comfort of man in the external environment. Rapid population growth causes the occurrence of negative phenomena, i.e. density and degradation of

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urban tissue, sealing of natural operative surfaces and thus modification of microclimate conditions [1]. In order to ensure the comfort and quality of life of the urban population, it becomes necessary to undertake comprehensive spatial planning activities. Therefore, it is necessary to provide stakeholders reliable and detailed information about the given area, i.e. population, economic development and changes in spatial planning. This data can be acquired from direct field studies, public digital databases (e.g. GIS system) and numerical simulations [2]. Currently, the most common methods are simulation analysis based on information from field measurements. This technique obtains in a relatively short period of time the data necessary to assess microclimate in urbanized areas. It enables comprehensive analysis of the impact of spatial development on the comfort in an external environment. It provides graphical presentation of the study results. As a result, the stakeholders are informed about required changes on the given area in an accessible way [3].

2. Thermal comfort

Thermal comfort is defined as "a state of mind that expresses satisfaction from thermal environment" (ASHRAE 55) [4]. According to Auliciems, thermal comfort is dependent on the physical and psychological feelings of man generated by a type of physical activity, exposure to environmental factors, expectations and previous experiences [5]. In addition, research shows that man adapts to changing conditions by acclimatization and clothing modification [6].

PMV (Predicted Mean Vote) is one of the most commonly used indicators to evaluate the thermal comfort of man. At first, it was used for testing indoor thermal comfort. By modifying the Fanger's thermal balance equation by Jendritzky and Nübler, it has been adapted to the external environment [7]. PMV is dependent on the metabolism rate (M) and body thermal load (L), i.e. difference between the amount of heat produced by the body and its losses in the external environment. The parameter of body thermal loads takes into account metabolism rate, type of physical activity, water vapor pressure, air speed and temperature, average radiation temperature, clothing thermal insulation, as well as convection heat transfer coefficient [8].

According to ASHRAE-55 standard, PMV is defined as the average evaluation of the group of people determining their thermal impressions on a seven-stage scale. PMV values exceed much beyond this scale with regard to conducting study in the external environment. It results from the fact of calculating the index on the basis of initial data of atmospheric process simulation and average predicted thermal sensations of man. Divergence between data obtained in the questionnaire survey (seven-stage scale) and empirical results from lack of restrictions concerning minimum and maximum PMV values. In addition, this index depends on the local microclimate conditions, and therefore its values vary depending on the climate zone.

This fact is confirmed by the research conducted by Jihad and Tahiri. The authors showed that the value of PMV index depended on local microclimatic conditions, season of the year and spatial planning method, in particular on the ratio of buildings height forming the pedestrian area to the width of streets. The average value of index varied from [-4] to [11] per year, depending on the building geometry [9]. Thorsson et al. conducted research on the largest green area complex in Gothenburg, Sweden (moderate zone). In this case, the value of thermal comfort index ranged from [-11] to [11]. Thus, they have shown that there is a discrepancy between PMV values obtained during the questionnaire survey and those obtained from simulation (40% of cases) [10].

3. Characteristic of research area

Lodz is the third largest city in terms of population numbers (693 797 persons) and fourth in terms of area (29 325 ha) in Poland (51°46′36″N 19°27′17″E). Currently the most urbanized part of the city is undergoing major transformations. Twenty areas were selected in the downtown zone, which were included in "Revitalization of Lodz Centre Area". One of the project's objectives is to "create a friendly, lively and interesting living and working space for the residents". Refurbishment of buildings, transformation of areas in the immediate vicinity of facilities and change in the way of management of areas open to the general public, i.e. plazas and greenery areas, will be direct measures aimed to implementation of tasks.

Taking microclimate issues into account in the revitalization process can contribute to improvement of the quality of life of people in the city. Appropriate modification of the spatial planning can alleviate the thermal discomfort experienced by humans in the external environment. Therefore, the main objective of this study was to assess microclimatic conditions and thermal comfort within selected public spaces.

Two of the oldest spaces in the city were provided with analyses, which were selected as priority areas within the revitalization program. The first one – Old Marketplace – is located in the centre-north part of Lodz. Its shape is similar to a rectangle of 105 m x 85 m. The frontage of the square is formed by residential buildings with services on the ground floor with an average height of 3 storeys. From the southern side it is adjacent to a large complex of greenery. Concrete and asphalt are the dominant surface types. The second public space – Urban Square – is located by the city's main street – Piotrkowska. This square was created by withdrawal of one of the service buildings in the east direction. Its dimensions are about 43 m x 34 m. From all sides it is surrounded by residential and commercial buildings. The height of buildings varies from 3 to 5 storeys. In this case, concrete is the dominant type of surface.

Fig. 1. Priority area of revitalization in Lodz (1 – Old Marketplace, 2 – Urban Square)

Fig. 2. Old Marketplace (view the South-East)

Fig. 3. Urban Square (view from the South)

4. Meteorological data

The model's input data was obtained from digital databases of Lodz-Lublinek meteorological station located in the south-western part of the city. Information stored as part of station activity concerned the values of meteorological parameters such as: temperature, air humidity, dew point temperature, atmospheric pressure, direction, speed and wind blast, precipitation and Wind Chill Index. The digital data format (.xls) enabled their adaption to the requirements of ENVI-met application, i.e. calculation of hourly meteorological parameters. The study concerned four cloudless days: 31/12/15, 02/04/16, 24/06/16 and 30/09/16. At first, spatial diversity of meteorological parameters was evaluated. In order to estimate the thermal comfort of man in the external environment, the PMV index was calculated for selected cloudless days within one year.

5. Simulations of atmospheric processes

Development of atmospheric process models requires specialized tools. Currently, one of the most popular is ENVI-met program, which enables to create three-dimensional, non-hydrostatic models taking into account the principles of fluid mechanics and heat flows [11]. It enables thermal simulations of surface – vegetation – air interaction in urbanized areas on a daily cycle (from 24 h to 48 h) [12]. The atmospheric processes were simulated for selected public spaces located in the centre of Lodz, within the area covered by revitalization program. At first, geographical location of each site was defined in order to determine the amount of solar radiation on the Earth's surface. Microclimate conditions in the external environment were determined on the basis of data obtained from Lodz-Lublinek meteorological station in the hourly interval. Three-dimensional models of public spaces were then created by defining the geometry of buildings, building materials and surface types. For the Old Marketplace, the model size was 80 x 80 x 30 units with a resolution of 2 m x 2 m x 1 m. The basic materials used for modeling of buildings were concrete and glass. Concrete and biologically active surfaces were used as substrates. A significant area was covered with impermeable surfaces (86%). The size of the city square model was 90 x 80 x 30 units with a resolution of 1 m x 1 m x 1 m. The dominant types of building materials were concrete and glass. In this case, the substrate was entirely covered with impermeable materials.

6. Analysis of results

The first stage of study consisted in estimating spatial diversity of microclimatic conditions in the area of analyzed public spaces depending on the season of year. For this purpose, detailed analyses were carried out at four characteristic points located at the corners of buildings (point: 1, 4) and on the main square (point: 2, 3) (measuring stands are presented on Figures 6–9). The range of values of basic meteorological parameters, i.e. temperature and relative humidity of the air in an hourly interval, is presented on Figure 4–5.

The analysis of simulation results showed that greater diversity of microclimatic conditions prevails in the Old Marketplace. Extreme values of parameters, i.e. temperature and relative humidity of the air are observed in the first and fourth measuring point for each of analyzed periods. The highest average daily air temperature was recorded in the first point at the corner of the northern frontage building. This point also had the lowest average daily relative humidity value. This may result from the fact that concrete surface of substrate has been strongly heated; the space is closed from the west with a multi-family building block limiting the air flow and lack of greenery. The fourth measurement point was located at the corner of a building on the eastern frontage in immediate vicinity of a large greenery complex – Old Town Park. As a result, the minimum average daily temperature value was observed. Additionally, this area was characterized by the highest average daily relative humidity of air.

A similar outline of the spatial distribution of meteorological parameters is observed in the Urban Square. Maximum daily average air temperatures and minimum daily average relative humidity are noted in the first point. It results from the fact that the control point is protected from the west by a compact multi-family structure. Location of buildings in close proximity to each other contributes to weakening the air exchange in the northern part of square. The opposite situation is observed within the fourth point. It is located next to a communication line running from east to west, parallel to the dominant wind direction. Therefore, in the southern part of square a lower average daily air temperature value and higher average daily relative humidity are observed.

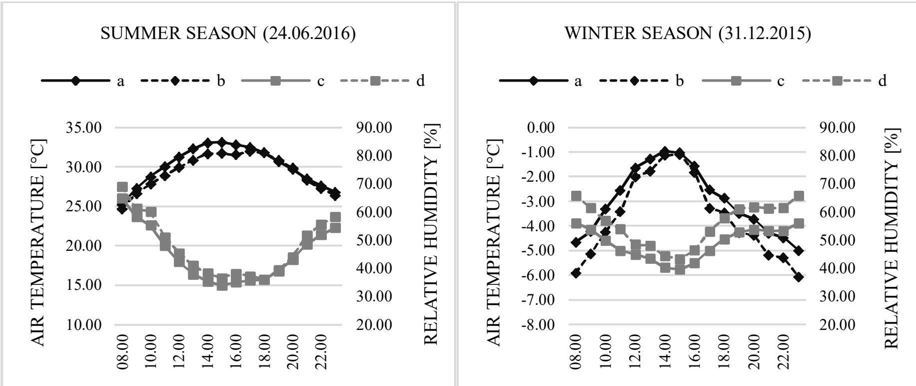

Fig. 4. Daily average values of meteorological parameters on the area of Old Marketplace (a – air temperature in point 1, b – air temperature in point 4, c – relative humidity in point 1, d – relative humidity in point 4)

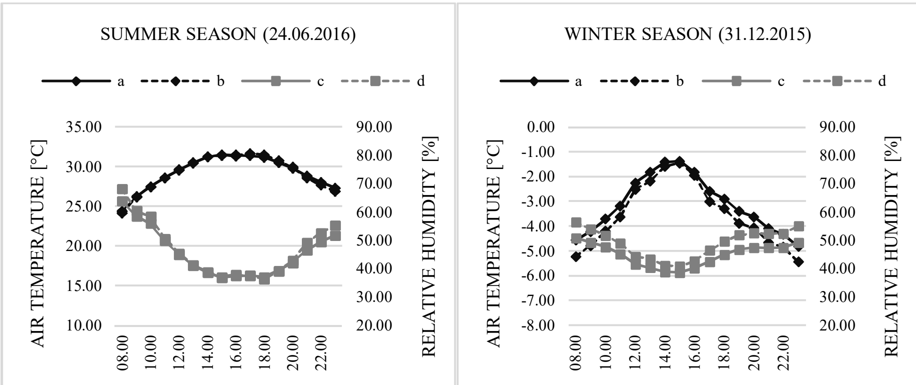

Fig. 5. Daily average values of meteorological parameters on the area of Urban Square (a – air temperature in point 1, b – air temperature in point 4, c – relative humidity in point 1, d – relative humidity in point 4)

The last stage of study consisted in estimating the thermal comfort in areas of selected public spaces. PMV index was calculated on the basis of obtained output data of atmospheric process simulation with an hourly interval. Additionally, it was necessary to determine the individual characteristics of humans, their clothes and type of physical activity. Thermal comfort was estimated for a 35-year-old man with a height of 1.75 m and weight of 75 kg, which moved at a speed of 1.21 m/s (average man's walking speed) [13]. Results of thermal sensations are presented on Figure 6-9.

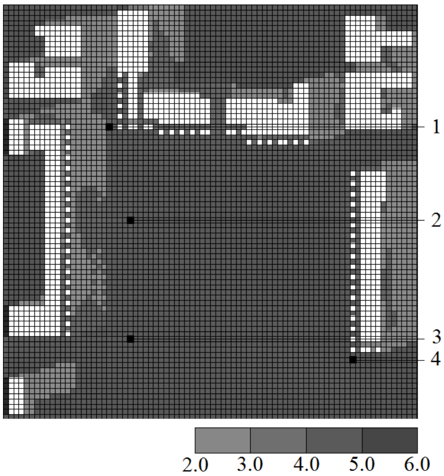

Fig. 6. PMV index – Old Marketplace (24/06/16)

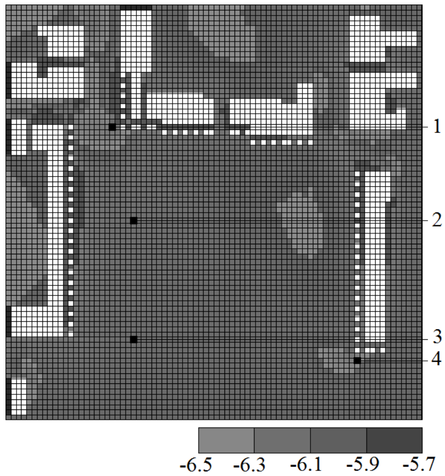

Fig. 7. PMV index – Old Marketplace (31/12/15)

Based on obtained research results, it can be concluded that similar values of the index were observed in both public spaces. During the summer period, the index significantly exceeded the theoretical scale between [3] and [+3]. According to ASHRAE-55 standard, this indicates the presence of microclimatic conditions known as “neutral”, “slightly warm” and “hot”. The most favorable thermal conditions were observed in the morning and late evening. During the day, the lowest PMV values were recorded on the leeward side of buildings and in the backyards surrounded by dense stone buildings (so-called manhole courtyard). It should be noted that this is an aerodynamic shadow zone. Conditions described as “discomfort” were found in strongly sunny areas.

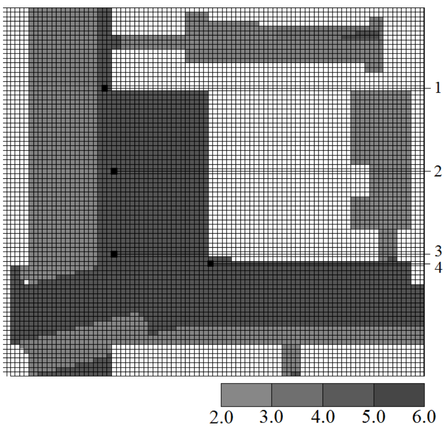

Fig. 8. PMV index – Urban Square (24/06/16)

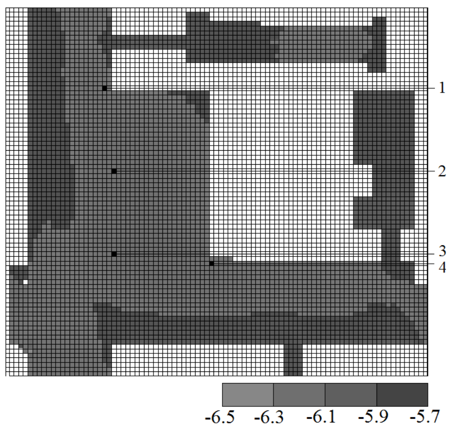

Fig. 9. PMV index – Urban Square (31/12/15)

In the winter period, the index values ranged from -7.21 to -5.21. In this case, the least favorable thermal conditions were observed around the corners of buildings, which were caused by an increase in the air flow in their vicinity. The most favorable conditions have been recorded on the leeward side of facilities.

7. Changes in spatial planning to ensure thermal comfort

Convenient conditions in the external environment can be ensured by modification of spatial planning on the given area. It is worth considering changing the location and geometry of facilities. Appropriate location of buildings in relation to each other ensures correct airflow. It is necessary to take into account the prevailing direction of wind flowing to the area. This ensures a cooling effect in high temperatures that reduces discomfort in the outdoor environment. The change of the height of objects can contribute to a decrease in the value of air temperature. Higher structures of buildings will reduce the amount of solar radiation reaching the ground atmospheric layers [14]. Studies conducted by Jihad et al. confirm that thermal comfort is dependent on the area morphology. The authors have shown that proportions of street canyons have an impact on microclimatic conditions in the given area. Comfort can be ensured by changing the installation parameters forming the street canyon or modifying its width [9].

Chatzidimitriou and Yannas have shown that the use of natural materials as a basic type of substrate can reduce the air temperature in the summer period – cooling effect, and cause its increase in winter period. The use of materials with a high albedo value can have a positive impact on the area’s microclimate. Their application will reduce the amount of solar radiation absorbed by vertical and horizontal surfaces. A similar effect will be achieved by using materials with bright tinges [15].

According to Axarli and Chatzmidimitriou, high greenery contributes to reducing the amount of sunlight reaching the earth’s surface. This reduces the temperature of horizontal surfaces, especially those made of materials with high thermal capacity. On the other hand, it increases relative humidity. Due to the appropriate location of green elements, it is possible to ensure thermal comfort in the external environment, especially in the summer period [16].

8. Conclusion

Simulation analyses conducted with programs of CFD type constitute the future alternative to traditional testing methods of microclimate and thermal comfort in urbanized areas. They enable obtaining information on meteorological parameters in a relatively short time and reduce financial outlays for research. Finally, there is an option to visually present the results of study.

In this way, information on the necessary changes in spatial planning method is provided in a way that is accessible to everyone – not only specialists.

Comparative analysis of research results showed that spatial diversity of microclimatic parameters occurs in the area of both public spaces. It results from the spatial planning method, i.e. geometry of building development, their location in relation to each other and existing vegetation. The research has shown that it is larger in the Old Marketplace.

PMV index enables the evaluation of the thermal comfort of humans in an external environment. Determination of the parameter supports taking a decision on the spatial planning method.

Transformation of downtown areas, in particular areas of historical meanings, requires additional arrangements with the historic conservationists. Interference with geometry of buildings is in many cases impossible due to their architectural qualities. The objects forming frontages of both squares have been entered into the municipal register of monuments. Therefore, consideration should be given to increasing the amount of greenery and permeable surfaces, which will not only improve thermal comfort, but also improve the microclimate. It will help to reduce the heat island, reduce concentration of pollutants and will also have a positive impact on the user's psyche. In tight urban interiors, green walls or green roofs can be a good solution. Improvement of conditions in the summer period can be achieved by placing water elements in the form of fountain or a water curtain.

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