Measurement and modelling of the cumulated thermal stress in Leipzig

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Abstract

This paper shows first results of mobile measurements, which carried out in summer 2009 to evaluate the thermal comfort for a ‘standardized’ pedestrian in several urban areas of Leipzig. The analysis of the obtained data was conducted by calculating the mean radiant temperature as well as the Predicted Mean Vote (PMV). The results were compared to simulations applying the RayMan-program. Additionally to these findings to short-term stress, a study to the cumulated thermal stress was implemented into the analysis for the first time. Thereby, the thermal stress was considered which is perceived by a healthy ’standardized’ person during a one hour walk. As a first step a time rate of change of the PMV was defined for a measurement period. Using the example of the 20th August, 2009 in Leipzig, urban district Lößnig, a cumulated PMV-aggregation of 0.7 was calculated and hence, a total (cumulated) PMV of 3.4 results in comparison to an arithmetically averaged PMV of only 2.7 for all measurement points along the route that were taken that day. Thus, a person perceives a severe thermal stress when walking the typical pedestrian route in Leipzig-Lößnig in one hour.

Introduction

Urban areas represent only 0.2 percent of the earth´s surface [Fezer, 1995], but nevertheless over 70 percent of the world population are living in cities [Hupfer und Kuttler, 2006].

The growing population density in urban areas and hence the enhanced urbanization influence and modify the climate of a city. Thereby, the co-action of natural (e.g.: relief or altitude) and anthropogenic (e.g.: the form and density of the buildings, heat storage capacity of the building materials or degree of surface sealing) features affect the particular urban climate.

In the past, studies on urban climate in Leipzig have been carried out e.g. by Müller (1997), who made extensive measurements by car and generated urban climate maps (especially temperature maps) for Leipzig. Schwab and Heinz (1997) worked out special maps to evaluate the urban climate and air quality. Also the office of environmental protection of Leipzig carried out urban climate studies. On the 12th and 13th August, 1997 thermal scanner photographs and mobile measurements of the air temperature, humidity and wind velocity were accomplished during calm and almost cloudless weather conditions. The results show for most urban areas in Leipzig a thermal stress situation because of higher temperature values in comparison to surrounding areas [Amt für Umweltschutz, 2007].

The here presented study is also dealing with the thermal factors of the urban climate in Leipzig outgoing from recently measured data. Changed meteorological conditions due to climate changes may have especially an effect on the habitants of a city, because an enhanced thermal stress is expected. This possible impact of the global changes to the local urban climate is interesting for the personal well-being and health status of the people in a city.

The research was focussed on the thermal stress related to a 'standardized' person, who represents the thermal sensibility of the majority of the population. Hence, the focus lied on the methods and results to evaluate the thermal comfort. Furthermore, the following questions should be answered by the study:

1. Which urban area generates stress?
2. What's the amount of the thermal stress?
3. How improvements could be achieved and what significant points should be considered in future landscape design processes?

Characteristics of the urban climate

The climate of a city is characterized by the modification of the meteorological parameters. Well verifiable is the heat island effect, which is characterized by higher air and surface temperatures compared to rural areas [Oke, 1987]. Most of the heating occurs in the urban areas, which are sealed and covered with buildings very densely. These are typically the downtown areas. The intensity of the urban heat island averages 1 to 3 K, especially at night it can reach up to 10 K.

The general temperature anomalies of urban areas in comparison to the rural environment are caused by an interaction of several effects, which are due to the urban structure:

- The reduction of the horizon (sky view factor), reduces the diffuse radiation [Häckel, 2005]. This has an impact on the radiation balance.
- The effect of 'solar trapping', i.e. multiple reflections of the radiation, leads to an additional heating of the air.
- The increased heat conductance of the materials typically used in cities (asphalt, concrete, etc.) influences also the temperature regime. Because these surfaces are quite dark, they absorb most of the visible sun light which is followed by a heating.
- The built surfaces in cities lead to a reduced evaporation and therewith changed energy balance components (enhanced sensible heat fluxes).
- Also the anthropogenically generated heat due to traffic, industry and household results in a warming of the urban air.

Thermal assessment methods

The human organism has the ability to be responsive to atmospheric variations. Changes of meteorological parameters such as air temperature, humidity and wind velocity as well as short-wave and long-wave radiation have an impact on the well-being of the people. To evaluate the thermal impulse on a person, the different fluxes involved in heat exchange have to be regarded. This was realized in several heat balance models [Hupfer and Kuttler, 2006]. The basis for these investigations is the heat balance equation for a human body.

In the VDI-Guideline 3787 Part 2 (1998) the comfort equation according to Fanger (1972) is recommended for standard applications. The result of this equation is the thermal index PMV. This scale of values provides information on the average degree of the thermal stress perceived by a large collection of individuals [VDI, 1998]. The

PMV equation was originally developed for indoor conditions and is a basis to quantify the thermal sensibility based on a psycho-physical scale. Coupling the comfort equation according to Fanger with the short-wave and long-wave radiation fluxes has become widespread as a planning instrument under the name "Klima-Michel-Model" [e.g. Jendritzky et al., 1990; Grätz et al., 1994].
Using the procedure of the above mentioned VDI-Guideline a mean radiation temperature t_{mrt} is calculated from the short-wave and long-wave radiation fluxes. [VDI 3787 Part 2, 1998]. In addition to the meteorological parameters with physiological relevance such as air temperature, water vapour pressure and wind velocity, the PMV also depends on the individual input variables clothing (controls the heat transition resistance of the clothing) and activity (controls the metabolic rate and the energy transformation as a result of the mechanical efficiency).
At PMV = 0, no one should feel uncomfortable. In fact, according to Fanger (1972), even then about 5% of individuals are expected to feel discomfort. Table 1 shows the PMV-values and their thermal perception as well as the corresponding stages of stress.

Table 1: *Predicted Mean Vote PMV, thermal perception and stages of stress [VDI 3787, 1998].*

PMV	Thermal perception	Stages of stress	
> 3.5	very hot	extreme stress	heat stress
> 2.5…3.5	hot	great stress	
> 1.5…2.5	warm	moderate stress	
> 0.5…1.5	slightly warm	slight stress	
-0.5…0.5	comfortable	no stress	
> -0.5…-1.5	slightly cool	slight stress	cold stress
> -1.5…-2.5	cool	moderate stress	
> -2.5…-3.5	cold	great stress	
> -3.5	very cold	extreme stress	

Measurement and analysis methods

The data collection was carried out by mobile measurements. Especially for this study a transport trolley equipped with several devices was developed and used (figure 1). The advantage of this measurement setup was that the instruments were transportable to every measuring point without a car. It was the first time that urban climate studies in Leipzig were made with such a measurement setup.
The values of the air temperature and the humidity as well as the horizontal wind velocity and the short wave radiation fluxes were determined by appropriate instruments on a tripod. Additionally an infrared thermometer was used to measure the surface temperature and to estimate long-wave radiation fluxes. These measurement instruments were connected with a data logger, which recorded and saved the measuring data. To get representative values for the prevailing areas a measuring time of 10 minutes was chosen at one place.

Figure 1: *Measurement setup, positioned at a measuring point in Leipzig-Paunsdorf.*

The interesting areas for the investigations were, beside the downtown area, also the urban areas with many inhabitants, which are at the periphery of the city. It was decided to investigate a developing area in the east of Leipzig (Paunsdorf). Furthermore, the urban area Lößnig and the park area Lößnig-Dölitz were chosen to examine measurement points with natural surfaces as well. The measurements were primarily carried out at sites near public institutions or at places where many citizens often come together. In the 3 studied districts of Leipzig a measurement route was chosen, which contained 6 measuring points characteristically for the district. The total lengths of the measurement routes were about 4 km's. This is a distance which a pedestrian may cover in 1 hour. The measurements were done at various times of the day and were also repeated for different weather conditions to get a general statement about the thermal stress during summer 2009 in Leipzig. Each route contained at least one measuring day at which the solar radiation was maximal due to cloudless conditions. Furthermore, at each route it was tried to get a comparison of the thermal stress of sunny places with shadowed places. Additionally, at several measuring points measurements were taken in the evening to detect cooling rates depending on the kind of surface (densely built or green areas).

To analyze the obtained data several programs were used. To determine the mean radiation temperature a Fortran-program at the basis of VDI 3789 (1994) was developed (see Friedrich, 2010). The incoming long-wave radiation was calculated due to the cloud coverage at different heights. Furthermore, the measured air and surface temperature were used and therewith the outgoing long-wave radiation fluxes were calculated. The measured short-wave radiation fluxes were also used to compute, together with the calculated long-wave radiation fluxes, the mean radiation temperature. Then, the mean radiation temperature is used in a program for determining the thermal stress, i.e. the PMV [VDI 3787 Part 2, 1998]. To compare the measured and calculated data the RayMan-model was used, which is a program for modelling the radiation fluxes and the thermal stress in urban structures [Matzarakis, 2001]. RayMan simulates the short- and long-wave radiation fluxes at a certain time and place using the real urban structures. As one result of the simulations the PMV-value can be calculated.

Results

The results of the thermal comfort analysis show, that already at temperatures of 20°C a slight thermal stress (PMV-values greater than 0.5) exists. At temperatures of about 25°C there result partly PMV-values higher than 2.5. Therefore, a moderate thermal stress occurs most likely, although thermal comfort in the shadowed zones is also possible. On hot summer days (air temperature higher than 30°C) the healthy "standard" person (without additional regulation) feels even in shadowed zones no thermal comfort with its environment. On such days a great, partly extreme thermal stress with PMV-values of about 4.0 can be expected.

To study the influence of shadowed areas on the thermal stress the measured 10-minute averages of the data from all measuring days from Leipzig-Lößnig and the city centre were considered and compared. In both urban districts there were shadowed measuring places during the whole day due to buildings or trees. Independent from the special weather conditions it was discovered, that the PMV-values in shadowed areas were reduced by about 30% in comparison with places, where the sun was shining directly. At PMV-values of 2.0 and greater (in the sun) this reduction of the thermal stress of30 % makes out one entire stage of stress (according to Fanger). It has to be mentioned that the thermal stress can be reduced even by staying for a short period of time in shadowed places.

In the following, additional results of the study are summarized (see also Friedrich, 2010).

Intensity of the Heat Island Effect

The urban heat island is a well-known phenomenon in the urban climate and is formed by the temperature difference between the city centre and the surrounding areas. The intensity depends on the weather conditions and reaches its maximum at calm nights. The intensity of the heat island in Leipzig was verified by comparing the measured air temperatures at the LIM (Leipzig Institute for Meteorology) and at the park in Lößnig for the 20th August, 2009. The observed measuring points are both on a grassland site. The park in Lößnig represents the less sealed areas at the periphery of the city, which cool rapidly down after sunset in comparison to the city centre. The measuring point at the LIM represents the air masses of the centre, which are additionally heated by the released heat of the surrounding buildings.

During the day with the high solar radiation and the cloudless sky the temperature difference between the city centre and the Lößnig park site was 1.1 K. In the evening the temperature difference was even 2 K. This result verifies the findings of other studies that the heat island effect is especially distinctive at night [Häckel, 2005].

Intensity of the nocturnal cooling

On the 20th August, 2009, which was the hottest day in this summer, additional measurements were taken in the evening hours in Lößnig. The aim was to show that the cooling over unsealed surfaces, such as the grassland in the park, is enhanced. The measured air and surface temperatures are plotted in figure 2. During the measurements a difference between the measuring points in the park and those within the blocks of houses became apparent. The air temperature still increases in the evening hours once there was a change in the location away from the grassland to a closed location of buildings. This behavior is caused by the fact that the air masses are heated due to the release of the stored heat of the buildings. This effect is verified by the measured surface temperatures. Specially the sealed surfaces are storing more heat because of their material composition and deliver this heat after sunset to the overlying volume of air. Also, the influence of the 'solar trapping' between the buildings plays a role. Thus the air between the blocks of houses is heated additionally. Whereas natural ground surfaces have a less storage capacity and therefore their cooling is more rapidly.

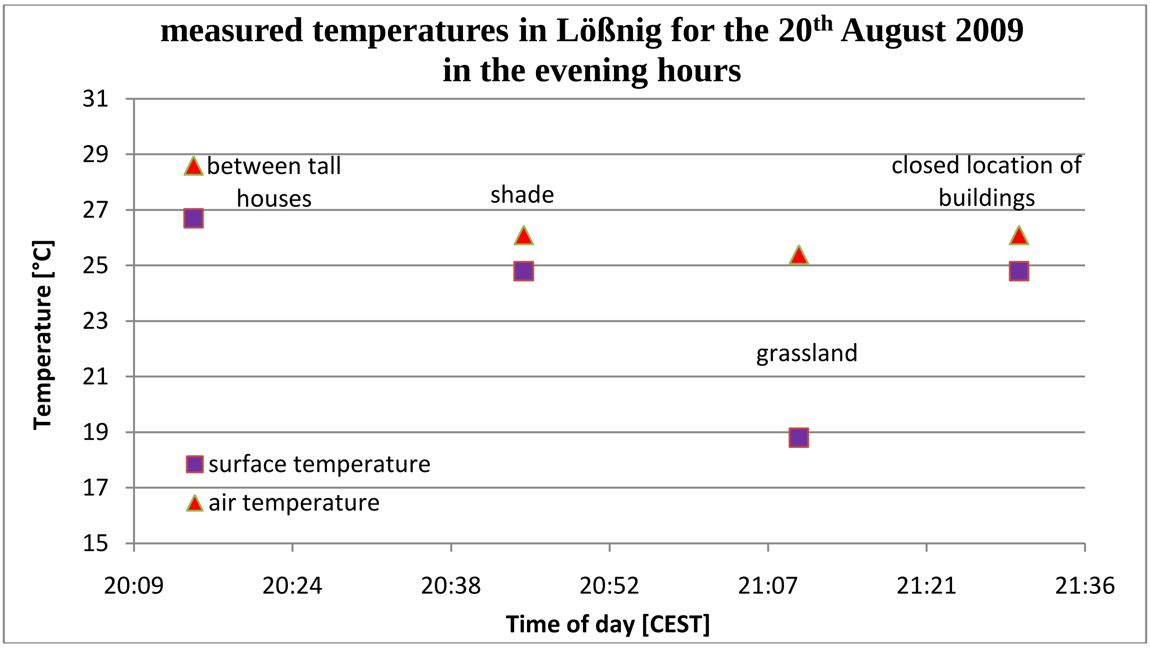

Figure 2: *10-minutes-average of the measured air and surface temperature on the 20th August, 2009 in Lößnig in the evening hours.*

The different cooling effect of different surfaces is also reflected by the values of the PMV (figure 3). Generally, there is a less thermal stress expected in the evening hours, while in contrast the abidance on grassland is already perceived as slightly cool (negative PMV). According to the simulation with the RayMan-program a person standing on the grassland in the park at the measurement time still feels comfortable.

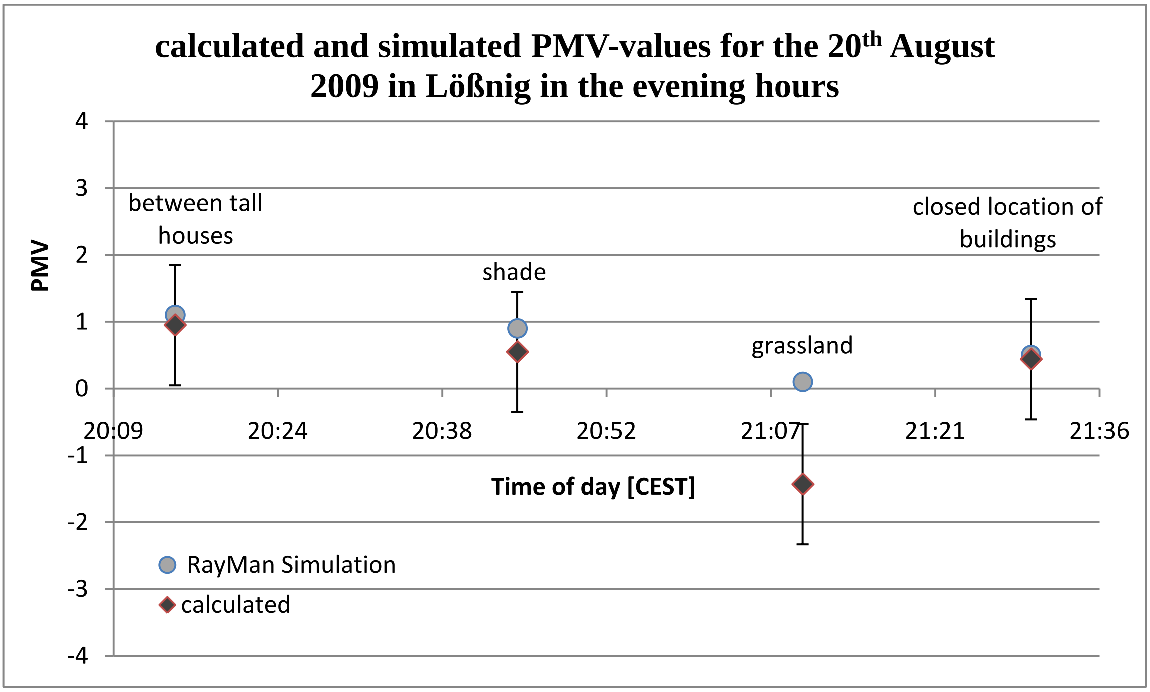

Figure 3: *Calculated/measured (10-minutes-average) and simulated (RayMan) PMV-values on the 20th August, 2009 in Lößnig in the evening hours.*

An error of ±0.9 for the PMV was calculated with the Gaussian propagation of uncertainty method (see fig. 3, error bars). For the measurement point in the park (grassland) the result of the simulated PMV-value by RayMan shows a difference to the calculated result outside the error bar for the measurement, which cannot be explained up to now. It is possible that any prefactor is the reason for the deviation between the simulated and the calculated values of the PMV.
All in all, the example shows that the differing thermal behavior of natural and sealed surfaces is well demonstrated. The unsealed surfaces cool off more rapidly by comparison. This effect is caused, e.g., by the less reduction of the horizon and the additionally released heat of the buildings and the sealed surface.

Cumulated thermal comfort

A person perceives a particular thermal stress when remaining at one place just for a short time. Whereas by walking a certain route over a long time, the person is effected not only by the thermal stress dependent on a position but additionally by the change of the thermal stress dependent on the time of day. What thermal stress perceives a ‘standard’ person by walking a certain distance in one hour?
The study of Fanenbruck (2001) shows approaches of such a cumulated point of view. He not only involved the ’standard’ person in his calculation, but also concentrated on several groups with different age and their variable adaptability. In the calculation algorithm Fanenbruck (2001) uses the thermo-physiological stress [unit °C]. Furthermore, the cumulated thermal stress is the integrated thermo-physiological stress by the time. Hence a time-integrated total exposure can be given. The approaches made by Fanenbruck (2001) could not be assigned for this study because the PMV equation contains a lot of time-dependent parameters, and hence an integration difficulties not operationally applicable.

A likewise method could be to calculate a mean average and afterwards add a defined cumulated aggregation, which is determined by the chronologically change of the PMV-value from one measuring point to the next one. Because the time difference between each measurement of every measuring point is irregular, a change of the PMV per minute was determined. Afterwards this change per minute is generated over the total measurement period. The result is an average of the change of the PMV per minute over a certain measurement time. To derive a statement for the cumulated thermal stress for a certain time range within the measurement time (e.g. one hour), the change of the PMV per minute can be multiplied with the required number of minutes (see also Friedrich, 2010). This calculation formalism shall be shown using the example of the 20th August, 2009, measurements in Lößnig. Therefore, the results of the calculated PMV-values at each measurement point in Lößnig for the current time of the day are presented in figure 4.

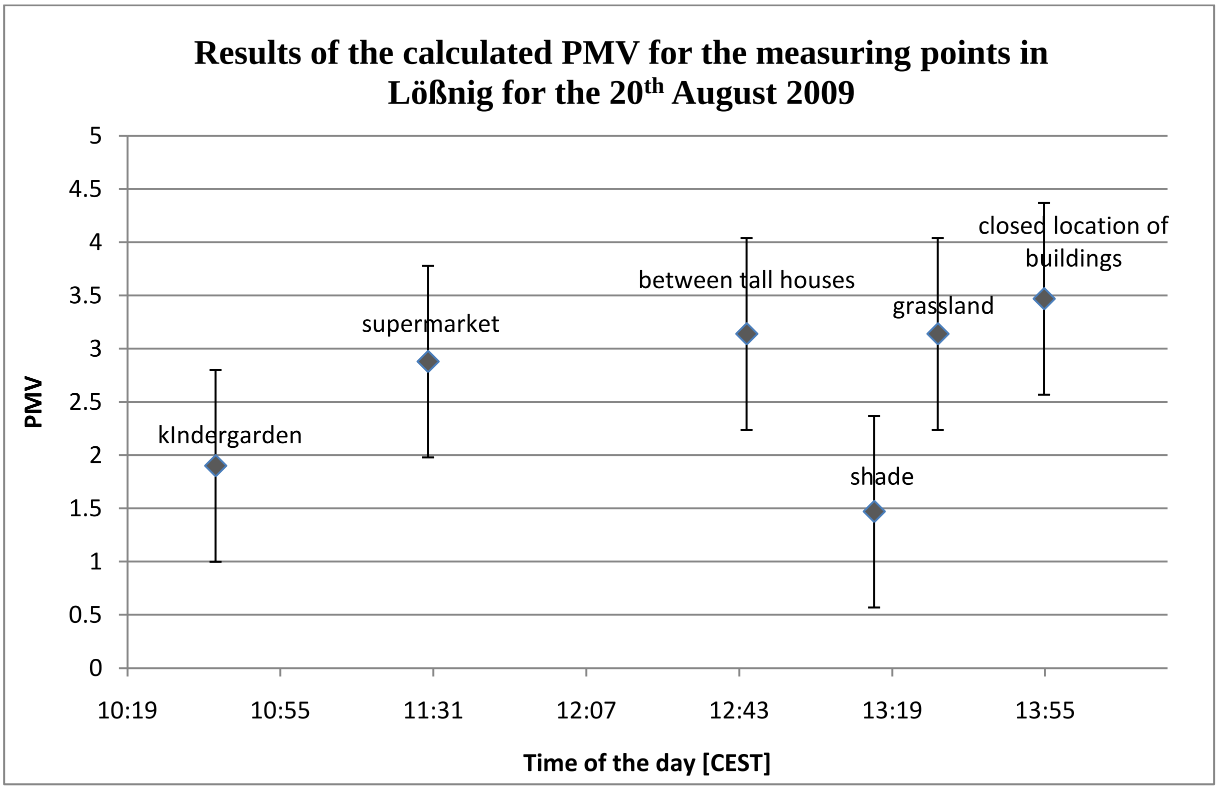

Figure 4: *Calculated/measured (10-minutes-average) PMV-values for the measurement points in Lößnig on the 20th August 2009 in the daytime hours.*

The calculated PMV-values result in an arithmetically averaged value of about 2.7. Table 2 shows the results of the further evaluation. For every time range from one measuring point to another the change of the PMV was determined (column 3, table 2) and divided by the corresponding minutes (column 4, table 2). The resulted changes of the PMV per minute for each measuring point were then averaged. Thereby a negative change of the PMV (decline of the PMV in shady places) was considered. Further, the average change of the total measurement period (3 ½ hours) is multiplied by 60 minutes and hence a cumulated change of the PMV per hour of 0.7 was calculated using the example of the 20th August 2009 in Lößnig. This is the appointed cumulated aggregation, which is added to the calculated average of 2.7. A total mean PMV of 3.4

results, which means, that a person walking along the measuring route in Lößnig in one hour perceives a great thermal stress (see table 1).

Table 2: *Calculated/measured PMV and the results of the change of the PMV-values for every measurement point in Lößnig on the 20th August 2009 in the daytime hours.*

measurement point	calculated PMV	change of the PMV within the time from one measurement point to the next one	change of the PMV per minute
kindergarden	1.90		
supermarket	2.88	+ 0.98 in 45 min	+ 0.0217
between tall houses	3.14	+ 0.26 in 60 min	+ 0.0043
shade	1.47	- 1.67 in 15 min	- 0.111
grassland	3.14	+ 1.67 in 6 min	+ 0.278
closed location of buildings	3.47	+ 0.33 in 15 min	+ 0.022
		average change of the PMV	+ 0.043

The consideration of a time-dependent cumulated change of the PMV is necessary, because the PMV itself can change due to varying environmental as well as meteorological conditions. If a person already feels uncomfortable, a natural increase for example in the air temperature or solar radiation can indicate a higher sensed PMV as currently calculated at one place and moment. An individual perceives an additional thermal stress, although he/she already feels too hot. This was respected with the above chosen approach for the evaluation of the cumulated thermal comfort. The given method for the calculation of an hourly cumulated change of the PMV has to be applied for each measurement period to incorporate possibly changing environmental conditions.

For future studies it should be tried to generalize the method to evaluate the cumulated thermal comfort.

Conclusions and Outlook

The formation of the urban climate is, mostly, due to the high percentage of sealed areas in a city.

In general a thermal stress occurs at air temperatures of 20°C. Only parks and shades provide an adjustment to high thermal impact, which has been proved by means of various sealed areas in Lößnig. During the cooler evening hours, there is still a low thermal stress or thermal comfort between the blocks of houses (PMV-values range from 0.4 to 1.0) whereas in parks and on grassland a PMV of -1.4 was calculated, which is already chilly. According to the statement of Becker (Deutscher Wetterdienst-DWD, 2008) the air temperature rises from 0.3 to 0.4°C with every 10 percent additional degree of surface sealing. Because the climatic radius of operation of planted areas is limited, it is important that rebound (little parks and green spots) is created close to places of residence. Under trees and in shades the thermal stress can decrease by about 30%. The aim of landscape design processes should be to reduce new sealed areas and to utilize grassland or porous pavement more intensive.

To propose the conclusion how high the thermal stress is, a “standard” human perceives during a one hour walk, the PMV-values were being cumulated. Therefore, a cumulated thermal loading was defined, which results in the time rate of change of the meteorological parameters. Using the example of the 20th of August 2009 in Lößnig, a cumulated loading of the PMV of 0.7 was calculated and added to the average of the PMV during the measuring period (2.7). Hence, a total PMV of 3.4 results, which means that a person, who walks the route in Lößnig in one hour senses a great thermal stress.

Finding an adequate calculation formalism for the cumulated thermal stress is very hard in respect of using the Predicted Mean Vote as an index of thermal stress. In following studies the presented approaches should be improved. Also, other indexes such as the Perceived Temperature could be used to define a cumulated thermal stress with the unit of degree Celsius.

In conclusion, the obtained results are still insufficent to make a general statement, which urban area in Leipzig is mostly thermal loaded. For that reason, following studies must be carried out to enhance the data set. Additional and isochronic measurements are necessary to confirm the shown results and to gain an overview of the thermal stress of all areas in Leipzig. Therefore, more urban areas should be embraced. Furthermore measurements at “Neuseenland”, south of Leipzig, are recommendable to pinpoint the contrast between the city centre and the nearby rural areas. Also, for a qualitative analysis of the heat island effect, there should be measurements at night. With more available date there can be made generalized statement of the thermal stress all over the town of Leipzig.

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References

Amt für Umweltschutz: Umweltbericht 2007, Stadt Leipzig, Dezember 2007

Becker Dr. P, 2008: Stadtplanung im Zeichen des Klimawandels, Deutscher Wetterdienst, Kongress Energie.Stadt.Geld Frankfurt

Fanenbruck O., 2001: Ein thermophysiologisches Bewertungsmodell mit Anwendung auf das Leipziger Stadtgebiet, Wiss. Mitteilung aus dem Institut für Meteorologie der Universität Leipzig, Bd. 24, Dissertation, 151 Pages.

Fezer F., 1995: Das Klima der Städte, 1. Auflage, Justus Perthes Verlag Gotha, 199 Pages

Friedrich A., 2010: Messung und Modellierung der kumulierten thermischen Belastung in Leipzig, diploma thesis, 106 Pages

Häckel H., 2005: Meteorologie, 5. Auflage, Verlag Eugen Ulmer Stuttgart. 447 Pages

Helbig A., Baumüller J., Kerscher M. J., 1999: Stadtklima und Luftreinhaltung, 2. Auflage, Springer-Verlag Berlin, 467 Pages

Hupfer P., Kuttler W., 2006: Witterung und Klima: Eine Einführung in die Meteorologie und Klimatologie , 12. Auflage, B. G. Teubner Verlag, 553 Pages

Kratzer P. A., 1956: Das Stadtklima, 2. Auflage Friedr. Vieweg & Sohn Braunschweig, 184 Pages

Matzarakis A., 2001: Die thermische Komponente des Stadtklimas, Ber. Meteor. Inst. Univ. Freiburg Nr. 6, 286 Pages

Müller U., 1997: Stadtklima Leipzig – Ergebnisse experimenteller Untersuchungen, Wiss. Mitteilung aus dem Institut für Meteorologie der Universität Leipzig, Pages 120-125

Müller U., Tetzlaff G., 1999: Zur thermischen Belastung in Innenräumen, Wiss. Mitteilung aus dem Institut für Meteorologie der Universität Leipzig, Pages 142-148

Oke T. R., 1987: Boundary layer climates, 2. Auflage, Routledge Verlag, 435 Pages

Schwab U., STEINICKE & STREIFENDER Freiburg und Heinz P., Amt für Umweltschutz der Stadt Leipzig 1997: Stadtklimauntersuchung Leipzig 1997, Eine klima- und immissionsökologische Bewertung, Wiss. Mitteilung aus dem Institut für Meteorologie der Universität Leipzig, Pages 116-119

Seifert P., 2004: Seminarvortrag Stadtklima, 21 Pages

VDI 3789 Blatt 2, 1994: Umweltmeteorologie - Wechselwirkungen zwischen Atmosphäre und Oberflächen - Berechnung der kurzwelligen und der langwelligen Strahlung, VDI-Richtlinien, 52 Pages

VDI 3787 Blatt 2, 1998: Umweltmeteorologie – Methoden zur human-biometeorologischen Bewertung von Klima und Lufthygiene für die Stadt- und Regionalplanung Teil 1: Klima, VDI-Richtlinien, 29 Pages

Verein Deutscher Ingenieure, 1988: Stadtklima und Luftreinhaltung, Herausgegeben von der VDI-Kommission Reinhaltung der Luft, Springer-Verlag Berlin, 426 Pages