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Some elements for assessing the radiated heat in urban areas

Ivica Kožar*, Krešimir Peša*, Marijana Cuculić* and Neira Torić Malić*
* University of Rijeka Faculty of Civil Engineering, Rijeka, Croatia
ivica.kozar@gradri.uniri.hr

***Abstract* - Heat island describes increase in air temperature between a city and its surrounding area. The air temperature increase significantly endangers the quality and health of life in a city. Radiation plays a crucial role in heating of open surfaces in a town. Solar radiation heats the surface that later cools itself radiating heat during the night. The presented model calculates the amount of daily sunlight for arbitrary location and arbitrary day of year. This is the basis for calculation of shades from buildings and estimation of the heat radiated to the street. This is an input for the second part of the model: calculation of the street surface temperature and heat exchange with the surrounding air. Heat exchange problems involving radiation lead to a non-linear formulation, which can be simplified with careful parameterisation, i.e., contribution of radiation should be expressed through radiated heat instead of direct influence of distant body temperature. That approach requires introduction of a non-linear convective heat transfer coefficient between the pavement and the open air. In order to determine model parameters, small experimental field with several differently paved areas has been established near the Faculty. Some of the recorded data is presented in the paper.**

Key words - heat island; solar radiation; radiated heat; city model; heat transfer coeficient

I. INTRODUCTION

The term "heat island" describes a phenomenon where the air temperature inside a city is significantly higher then air temperature in the area surrounding a city. The exact temperature difference depends on many parameters, city size being one the most relevant. So, Los Angeles is approximately 6˚C hotter then the surrounding area, while Rijeka is only 2˚C hotter. Heat island effect can be very dangerous [9] and should be put under control. Assuming that air conditioning devices could solve the problem is completely wrong [10].

It is believed that the main cause for increased temperature comes from the sun heating the paved areas within the city. Understanding the mechanism of the heating is crucial for taking measures to reduce the heat island effect. Here, we are trying to develop a mathematical model that would put into relation all the relevant parameters and predict the pavement temperature based on the insolation data.

There are two main groups of parameters comprising the model: i) the amount of urban area exposed to direct sunlight and ii) the process of heat exchange between the surface and the surrounding air.

The amount of urban area exposed to direct sunlight is determined from city maps where streets (paved areas) and buildings are treated separately from green (and similar) areas. It is important to assign different convective heat transfer coefficient to different areas. Here, the amount of direct sunlight plays an important role. We have devised a procedure for determination of shade area around a tall building for more precise assessment of the area exposed to direct sunlight.

Regarding the process of heat exchange between the surface and the surrounding air, we have re-parameterized the relevant equations so that convective heat transfer coefficient could be introduced as a parameter. In [8] we have established that the non-linear convective heat transfer coefficient is sufficient for description of the observed phenomena. Namely, there are many parameters that influence radiated heat exchange [1] but the assumption is that, similar to the eddy diffusivity approach in [2], all the contributions could be introduced through one parameter [3]. Presented numerical experiments confirm that hypothesis, opening the way to further investigation of parameter determination from experimental results (like in [4]).

II. ESTIMATION OF RADIATED SOLAR HEAT

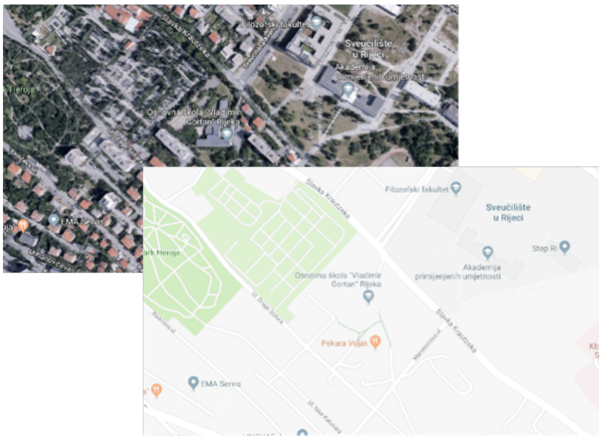

Figure 1. City area used for model parameters, satellite image for surface properties and schematic image for area calculation

A. Terrain model

Terrain model is starting point of our city model. From there, we get areas of various surfaces and streets comprising the city. At this point of development, we are taking into consideration only a small city area (up to 1 square kilometer). Figure 1 presents area from Google Earth map that is used in the example. From satellite photo, we assume terrain reflective properties (street, building, green area or trees) and from schematic image we calculate areas and coordinates.

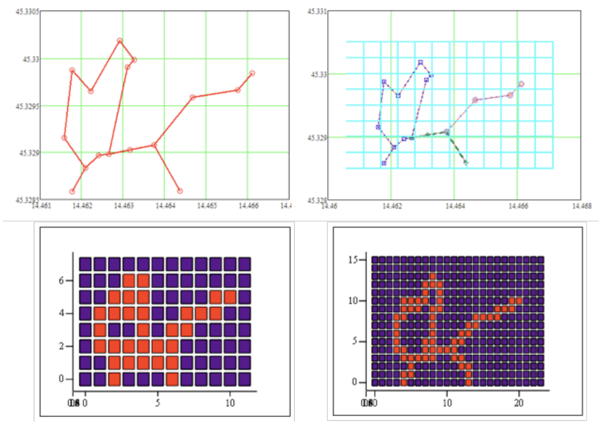

Figure 3. Digitalized streets and the coressponding city area, digitalization resolution is adjustable as needed

In the next step, streets are digitized and digitized surfaces are created, as shown in Figure 3. At this point, digitalization requires human to choose characteristic points that are latter connected into a polygon. Resolution of digitalized surfaces can be adjusted as needed (see Figure 3). For the future development, we are considering use of maps from the Croatian Geo-portal and possibly, automation of the digitalization.

B. Experimental field

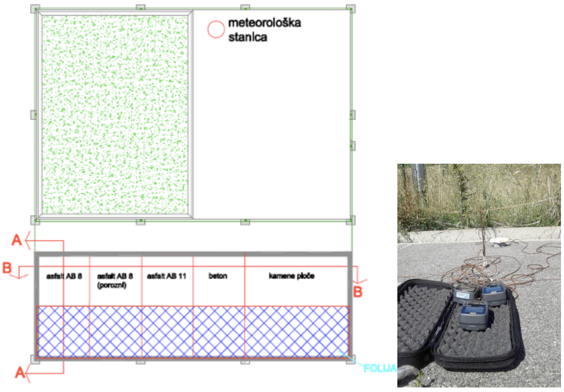

Figure 5. Test field "Kampus" and some measuring devices

In order to get insight into the process of heating and cooling of pavement in urban area measurements have been performed during the summer of 2013. Small area 3x9 m with different pavement materials has been set up at a location just outside of Faculty of Civil Engineering in Rijeka, Croatia. The test field is presented in Figure 5. Measurements comprise temperature at the pavement surface, at the pavement bottom where sub-grade material starts and at the depth of 20 cm. In addition, radiated heat flux has been measured using solar-meter and corrected for the reflexivity parameter (we assume $R_{reflex}=0.5$). Excerpt from the measurement data (about 3 consecutive days) is presented in Figure 2.

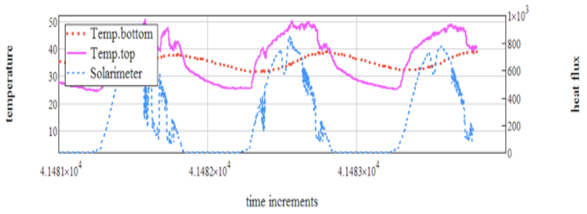

Figure 2. Experimental measurements of the pavement surface and bottom temperatures and radiated heat flux, presented as time series

C. Sun position and shadow calculation

The main source of information for Sun and Moon positions is [13]. Sun position is calculated for various seasons and times of day and shadow length and direction is determined for each corner of a building. Based on that calculation shadow area is estimated. Figure 4 gives schematic illustration of the calculation, where e_0 – Sun elevation angle, Φ - topo-centric azimuth angle, h – building height. During calculation we transfer coordinates between degrees and kilometers (and vice versa).

Calculation has to be performed for each building and its influence on the solar radiation on the street (surface) is estimated. This is one of input variable for our heat exchange mathematical model.

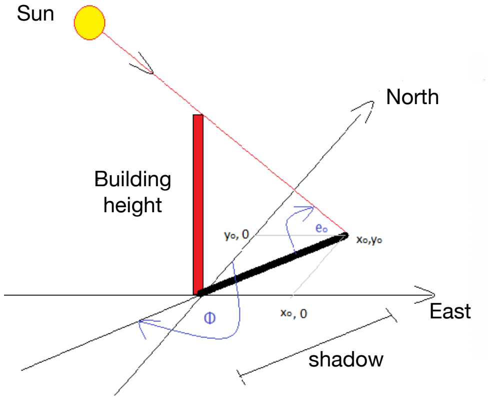

Figure 4. Schematic representation of shadow calculation

III. MODEL OF HEAT EXCHANGE FOR OPEN SURFACES

A. Mathematical model

The work develops a model for heat exchange between the pavement and surrounding air and soil. The mathematical model is based on 1D non-stationary heat differential equation, see [5]

$$\rho c \frac{\partial T_{pav}}{\partial t} - \frac{\partial}{\partial z}\left(k(z)\frac{\partial T_{pav}}{\partial z}\right) = Q \tag{1}$$

Here T_{pav} is (through the depth) pavement temperature filed, t is time, $k(z)$ is diffusivity coefficient, z is pavement depth and Q is rate of heat (coming in or out), ρc is unit mass and heat capacity of the pavement. In our case, Q represents solar radiation (dividing it with the surface area, we obtain radiated heat flux q). The relationship between the pavement surface temperature and the radiated heat is obtained with the introduction of the convective heat transfer coefficient between the pavement and the open air. The equation reads

$$\begin{aligned} &\alpha_{sol} q_{sol} + \epsilon_{IR}\sigma T_{sky}^4 = \\ &= \bar{h}(T_{pav} - T_{air}) + \epsilon_{IR}\sigma T_{pav}^4 \end{aligned} \tag{2}$$

The convective heat transfer coefficient h is related to the eddy diffusivity principle (see e.g., [2,3]) and the thin film coefficient concept (see e.g., [15]). The idea is that a constant cold be replaced with a functional value that incorporates the influence of some other parameter not appearing explicitly in the equation. In the case of eq.(2) it permits us to rewrite the heat flux from radiation in a form similar to the Newton heat exchange law, i.e., $q = h(T)\Delta T$, where $h(T)$ is convective heat transfer coefficient as a function of temperature and ΔT is the temperature difference (here $(T_{pav} - T_{air})$).

Here α_{solar} and ε_{IR} are solar absorptance and infrared emittance for the pavement, q_{solar} is solar radiation in [W/m^2] and $\bar{h}$ is convective heat transfer coefficient between the pavement and the open air. The sky temperature T_{sky} is assessed using empirical relation, as described in [6]

$$T_{sky} = T_{air}\sqrt[4]{0.711 + 0.0056T_{DP} + 7.3\cdot 10^{-5}T_{DP}^2 + 0.013cos(\frac{2\pi t}{24})} \tag{3}$$

Q in eq.(1) is determined from eq.(2); it equals either the left or the right hand side of the eq.(2). We are using the left hand side for calculation of T_{pav} from eq.(1) since we are measuring q_{sol} and calculating T_{sky} from eq.(3). However, when calibrating for convective heat coefficient h we are using the right hand side.

Temperatures are in Kelvin and T_{DP} is dew point temperature, calculated as $T_{DP} = T_{air} - \frac{100 - RH}{5}$ with RH being relative humidity and t is time in hours after midnight [7]. All parameters are functions of time with their value changing during the day. Influence of the wind is taken through dependence of $\bar{h}$ on the wind speed, as in [8].

Data connecting h and various weather conditions could be found in the literature like [14] but due to local conditions it is better to estimate it locally. Due to the eddy diffusivity principle h would reflect the local conditions at the recording time.

The convective heat transfer coefficient h is also a function of position and has to be calibrated for each type of soil that we want to analyse. The key data in the inverse procedure required for assesment of h is change of the surface temperature in time and in various parts of the city it could be obtained with large-scale infrared shooting (e.g., from a plane). Data from larger area would lead to more precise temperature predictions.

The convective heat transfer coefficient h has to be calibrated for each type of soil that it to be analysed. The idea is that each city area has to be calibrated once and that value is then used in all subsequent analysis.

B. *Finite element discretization*

Mathematical model described with Eq.(1) has been discretized using the finite element method with a special finite element for heat flux towards the soil [9]. Special elements are needed in order to avoid measuring the temperature at a certain depth below the pavement. Infinite elements used could have boundary condition expressed in terms of heat flux but that quantity is not measurable. Intermediate temperature measurement is used for determination of the bottom heat flux and is later used only for control purpose. Discretized model equation is as in [2] and in matrix notation reads

$$\mathbf{C}\frac{\Delta T}{\Delta t} + \mathbf{KT} = \mathbf{Q} \tag{4}$$

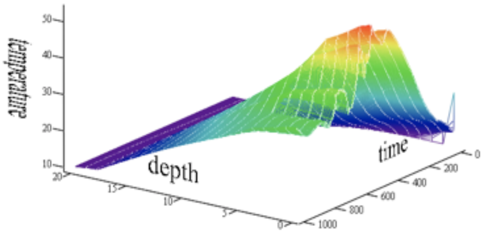

Figure 6. Temperature in space and time for non-calibrated convective heat transfer coefficient.

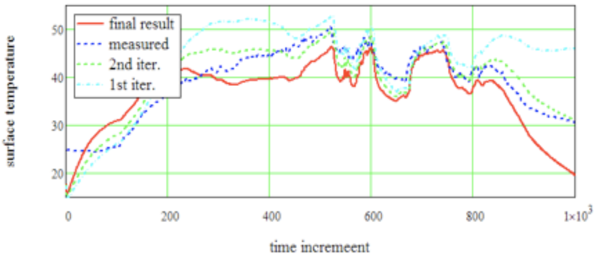

Figure 7. Temperature in space and time during calibration of the convective heat transfer coefficient.

where **C** and **K** are heat capacity and heat conductance matrices respectively and Δt is a time increment used in the simulation. Vector **Q** has only entry at the last element and that one involves convective heat transfer coefficient $\bar{h}$ between the pavement and the open air. Model is calibrated through measurements of q_{solar} on the site and validated through comparison with pavement temperatures. For the purpose of validation, temperatures were measured on the surface and bottom of the pavement for an extended period.

C. *Infinite 3D finite element*

In this work, 3D infinite finite element has been used to enable analysis of large areas of ground. Applying one-dimensional element as in [9] prevents inter-element communication in the surface direction (1D element extends along the depth). This difficulty is overcome by applying 3D infinite elements that extend infinitely into depth direction but are connected with adjacent nodes into a mesh of surface elements. The resulting mesh has only 2 nodes in depth and asymptotically approaches given deep earth temperature while allowing for arbitrary temperature distribution on the surface.

D. *Calibration of the model*

Experimental set-up has been mimicked in a numerical simulation so that numerical results could be compared with measurements. Twenty 1D finite elements and 1000 time increments have been used in the backward-Euler integration procedure. The results of simulations have been compared with measurements and inverse procedure has been applied (Levenberg-Marquardt method, as in [2]) to determine appropriate convective heat transfer coefficient.

E. *Numerical example*

Numerical example uses convective heat transfer coefficient determined in the calibration procedure. Experimental set-up has been mimicked in a numerical simulation so that numerical results could be compared with measurements. Twenty 3D finite elements and 1000 time increments have been used to reproduce results from experimental field measurements. The backward-Euler integration procedure used for solution of this non-linear matrix equation (4). Figure 6 presents, in space and time, the first solution with non-calibrated convective heat transfer coefficient, while Figure 7 presents comparison of measured values and those calculated in the numerical simulation. Good of fitness could be estimated using e.g., least square differences or Pearson correlation coefficient.

IV. CONCLUSION

This work confirms our hypothesis that non-linear (time and temperature dependent) convective heat transfer coefficient $\bar{h}$ between the pavement and the open air suffices for modeling the radiated heat exchange between the pavement and the surrounding air. Further development includes development of an inverse procedure for determination of $\bar{h}$, similar to [4]. In addition, factor analysis of $\bar{h}$ is planned, to obtain insight of possible factors contained in the heat transfer coefficient between the pavement and the open air.

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