Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Vol 2 (10) September 2013: 90-96

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com

ORIGINAL ARTICLE

Modeling Energy Balance over Different Land Covers in Urban Environment

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ABSTRACT

Urban Heat Island (UHI) is detrimental to urban dwellers and energy users because it contributes to cooling loads, thermal discomfort and air pollution. The main objective of this study is modeling energy balance over the different urban land covers such as Asphalt, Cement, Soil, Stone, Water body and Grass. To do so, three OPUS 200/300 Data Loggers with six PT100 sensors were installed in Geophysic Weather Station in University of Tehran in 10 minutes time interval during the year 2012-2013 to measure surface temperature. Then, a one-dimensional mathematical model was developed based on the fundamental energy balance, to calculate the surfaces temperature and heat flux. Finally, the ability of studied land covers in the absorption, reflection and transmission of energy were discussed; then, estimated temperature was calibrated by observed surface temperature data to determine model's accuracy.

Results illustrated that, materials thermo-physical properties are the main effective factor on their thermal behavior and temperature pattern. The result obtained from mathematical modeling demonstrated that asphalt surface has the highest and lowest energy absorption and reflection, respectively. Moreover, the model has sufficient accuracy in estimating of surface temperature, especially for Asphalt, Cement and Soil.
Keywords: *surface temperature, energy balance model, urban environment, Tehran.*

Received 21.07.2013 Accepted 30.08.2013

INTRODUCTION

Many urban and suburban areas experience elevated temperatures compared to their outlying rural surroundings; this difference in temperature is what constitutes an Urban Heat Island (UHI). The intensity of UHI is directly related to the land use and land cover in urban areas and is typically defined as the temperature difference (ΔT) between the urban and suburban locations [1].Therefore, the urban heat island has become one of the largest problems associated with the urbanization and industrialization of human civilization [2]. As a result, urban microclimates, referred to as urban heat islands, with elevated air temperatures of 2-8°F, increased energy demands and elevated pollution concentrations are created [3]. Studies have shown that such an effect will result in higher energy and water consumption [4]. The peak urban electrical demand rises by about 2–4% for each 1°C rise in the daily maximum temperature above a threshold of 15–20°C [5]. Also, Rosenfeld et al (1996) showed that ozone concentration begins to exceed the National Ambient Air Quality Standard (NAAQS) of 120 parts per billion by volume (ppbv) when the daily maximum temperature hits about 22°C, and O_3, often reaches 240 ppbv by 32°C [6]. Obviously, urban materials have different ability for energy absorption and determining these abilities are significant in identifying the favorable areas for formation or expansion of Urban Heat Island (UHI), energy consumption management and urban planning. In this regard, Hall et al (2012) showed that the different pavement thermo-physical properties affect the thermal response of pavement and how their relative behavior changes [7]. Landsberg and Maisel (1972) showed that urban thermal environment is directly related to the urban land covers [8].

Knowledge of surface energy balance is very important not only to obtain boundary conditions of the atmosphere, but also to understand the environmental conditions necessary for human beings [9]. From this point of view, it is also of great significance to measure the surface temperature for predicting and optimally designing the thermal behavior of pavement structures and materials [10]. Hence, research studies have been extensively carried out for finding ways to mitigate and predict the high pavement energy absorption. One such method suggested is utilization of permeable pavements for drainage of urban streets. However, since they allow the exchange of water between the atmosphere and the soil below, evaporation can occur at the surface [11]. Other studies developed mathematical models to simulate and predict the pavement temperatures with varying materials [12-19]. Therefore, the objectives of this study are as below:

1) To evaluate the energy balance over six urban land covers with different thermo-physical properties using one-dimensional heat flux model.
2) Estimate the surface temperature of each land cover based on the energy balance model.
3) Determine the accuracy of simulated surface temperature by measured surface temperature at Geophysic weather station in University of Tehran.

MATERIALS AND METHODS

Surface temperature data measurement

A monitoring station was set-up to collect data on surfaces temperature including Asphalt, Soil, Cement, Stone, Grass and Water. Six PT100 (Platinum Resistance Thermometer) sensors were connected to three OPUS 200/300 2-channel data loggers housed in protection enclosure at Geophysic weather station in University of Tehran (Fig.1).

Fig.1. Measurement points at Geophysic weather station in University of Tehran.

In addition to measuring the surface temperature, the weather data including hourly measured air temperature, dew point temperature, solar radiation, cloudiness and wind speed data were extracted from Geophysic weather station. A one-dimensional mathematical model was then developed, based on the fundamental energy balance, to calculate the surfaces temperature and heat flux. The simulation model proposed in this paper is based on formulas for convection, incoming solar radiation and irradiation as described by Bentz (2000), Qin et al. (2011) and Hermansson (2004) [12, 21].

Energy Balance Model

The heat flux between the air/space and surface is schematically depicted in Fig. 2. Related to Energy balance model, calculations are accomplished by the following equations and then numerical values are extracted from table.1.

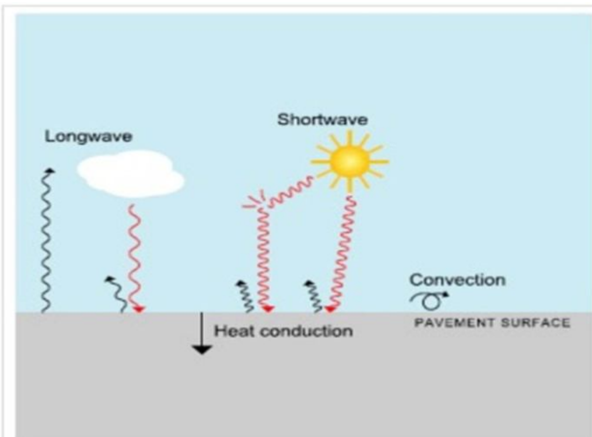


Fig.2. Surface Energy Balance [21]

RESULT AND DISCUSSION

As mentioned before, temperature of the land covers depends on absorption, reflection and transmission of energy; therefore thermo-physical properties of different land covers affect the amount of surface temperature. Hence, in this section, ability of different urban materials in absorption, reflection and transmission of energy were analyzed during December 2012. According to figure 8, total amount of solar radiation in this month varies between 301 and 337 W/m^2 due to variation in cloudiness and the effect of different atmospheric systems which are among the factors affecting incoming solar radiation. As can be seen in figure 3, the highest amount of energy absorption is related to Asphalt, Soil, Grass, Cement, stone and water, respectively. In other words, monthly average of solar radiation of December is 321 W/m^2 which Asphalt, Soil, Grass, Cement, stone and water absorb about 282, 266,240,163,160 and 128 W/m^2, respectively and the rest of incoming energy is reflected or transferred by materials (figure.4). Generally, one can conclude that Asphalt and Soil have higher absorption and less reflection, while Water, Cement and Stone have higher reflection and less absorption based on some properties like albedo and emissivity (table.2).

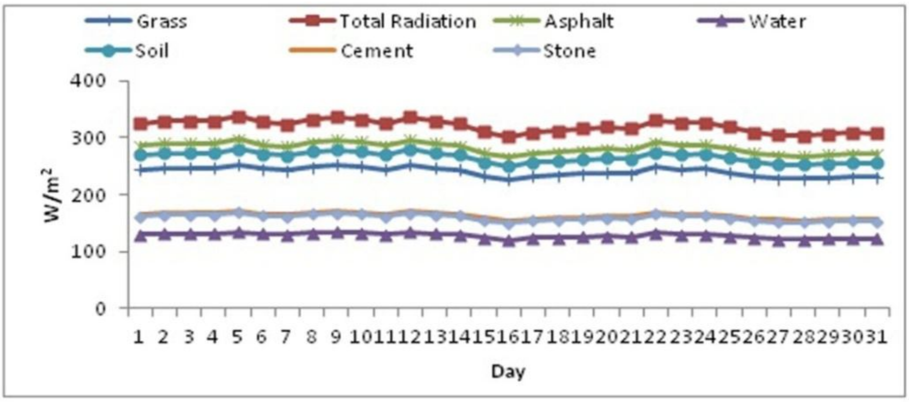
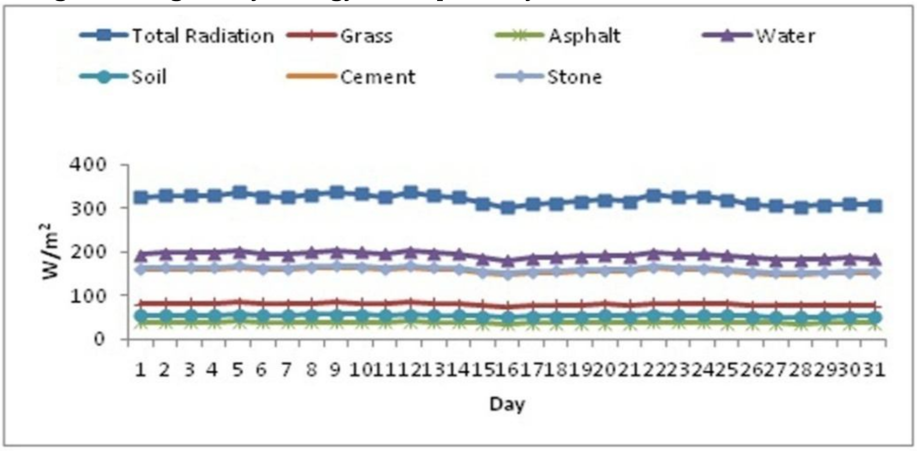


Fig.3.Averege daily energy absorption by Land covers in December 2012



.Fig.4. Reflection and transmission of daily incoming energy by land covers in December2012.

According to the relationship between received energy and land covers temperature, the surface temperature of studied materials were calculated based on emissivity and energy balance between them and surrounding air using equation (5). Then, calculated temperatures were calibrated with observed surface temperature in Geophysic weather station. Finally, the accuracy of the model was determined. As can be seen in figures 5-10, the model has sufficient accuracy in estimating the surface temperature so that correlation coefficient between observed and estimated surface temperature is significant at 0.05 level (table.3).

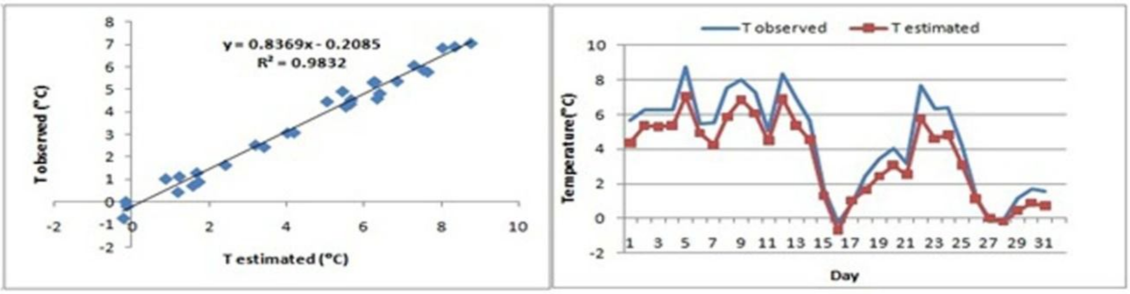


Fig.5.average daily observed and estimated surface temperature in Asphalt in December2012.

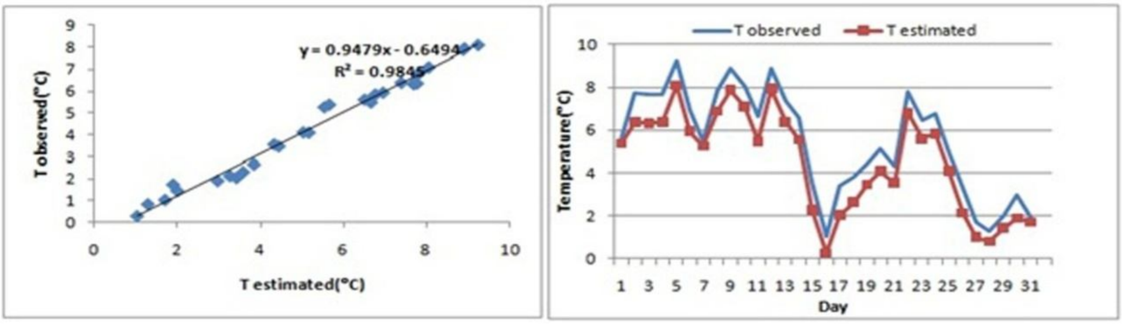


Fig.6.average daily observed and estimated surface temperature in Soil in December2012.

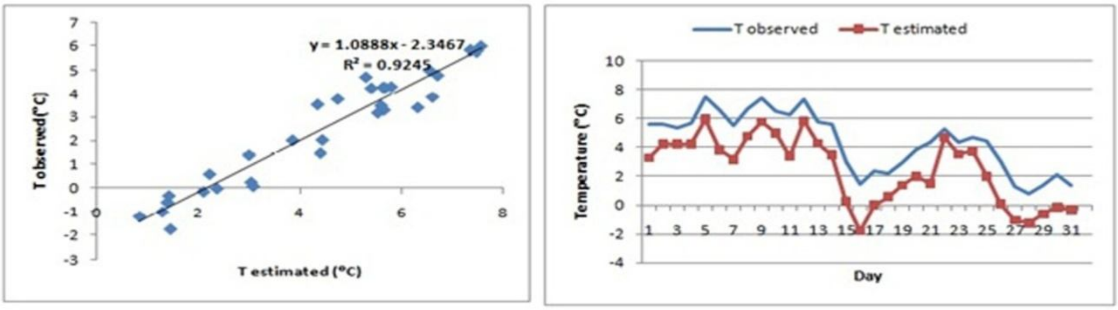


Fig.7.average daily observed and estimated surface temperature in Grass in December2012.

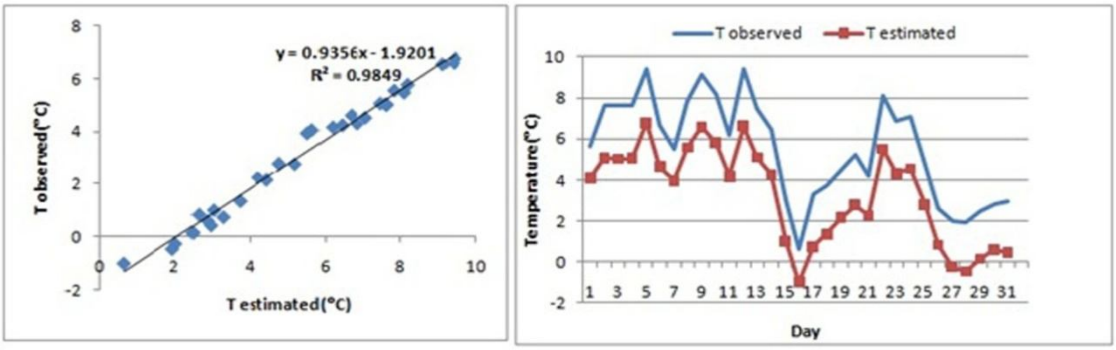


Fig.8.average daily observed and estimated surface temperature in Cement in December2012.

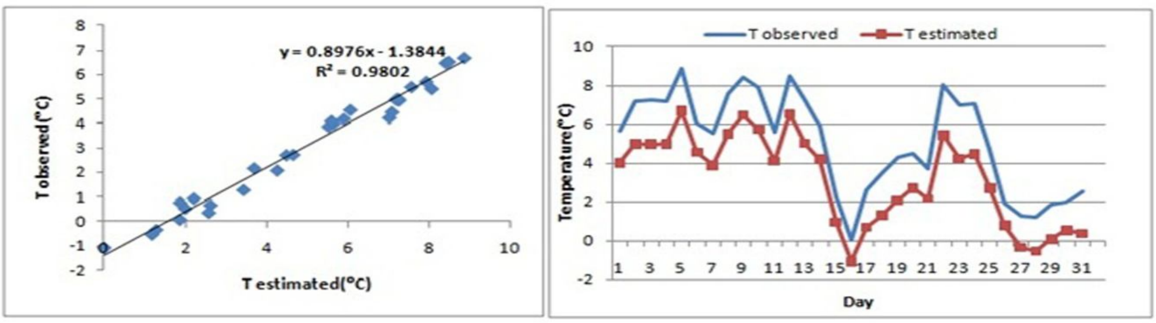


Fig.9.average daily observed and estimated surface temperature in Stone in December2012.

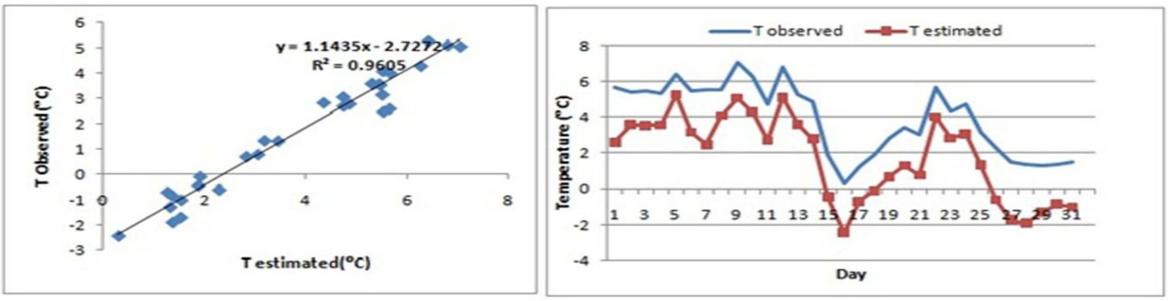


Fig.10.average daily observed and estimated surface temperature in Water in December2012

Table1. Energy balance model calculations

q	Equation[1]
q h_{conv} = 5.6 + 4u_{wind} For $u_{wind} \leq$ 5 M/s h_{conv} = 7.2×$u_{wind}^{0.78}$ For $u_{wind} >$ 5 M/s	Equation[2]
$q_{irr} = \sigma\varepsilon\times(T_s^4 - T_{sky}^4)$ *T* ε *F*	Equation[3]
q γ	Equation[4]
$E = \varepsilon\sigma T^4 \left(W/_{m^{-2}}\right)$, then; $T = \left(\frac{E}{\varepsilon\sigma}\right)^{0.25}$	Equation[5]

q_{total} = total energy balance between the surface and the surrounding air,
q_{conv} = the heat flux due to the convection at the surface
q_{irr} = thermal irradiation from the ground surface to the surrounding air
q_{sun}= amount of energy as a short wave arriving at the ground surface.
T_A and T_S = air and surface temperature in kelvin, respectively
h_{conv} = the convection coefficient, W/m^2 °C
u_{wind} = the measured wind speed in M/s.
σ = Stefan-Boltzmann constant (5.669×10^{-8} WM^{-2}K^{-4})
ε = emissivity of the surface
T_{sky} = the effective sky temperature (°K)
ε_s = the sky emissivity
T_{dew} = dew point (°K)
F_{cloud} = cloud cover factor
N = cloud cover, taking value between 0 to 1.0
γ_{abs} = the solar absorptivity of land covers.
q_{inc} = incident solar radiation (W/m^2)
T = object's temperature (°K),
ε = emissivity of the object

Tabel2. Albedo and Emissivity of different land covers [22].

Land cover	Albedo (%)	Emissivity
Asphalt	12	0.966
Soil	17	0.952
Grass	25	0.981
Stone	50	0.971
Cement	49	0.97
Water	60	0.991

Table3. Correlation coefficient between observed and estimated surface temperature in December2012

Land cover	Asphalt	Soil	Cement	stone	Water	Grass
Correlation Coefficient(R)	0.96	0.96	0.96	0.96	0.92	0.84

CONCLUSION

Since one of the contributors in urban UHI effect is urban building materials and their thermo-physical properties, changes in these properties or attention to them in construction of urban areas can help to reduce the impact of UHI. Results, illustrated materials surface temperature in urban areas and calm weather conditions according to the solar radiation changes during the day, but the amount of received or lost energy during the day and night is related to their thermo-physical properties such as albedo, emissivity, thermal conductivity, thermal inertia and heat capacity. Therefore, material's thermo-physical properties not only are effective in surface temperature patterns of different materials, but they are also effective in absorption, reflection and transmission of energy by different urban building materials so that those with lower albedo, emissivity, heat capacity, thermal inertia show higher absorbency and temperature. Also, it was concluded that the proposed simulation model properly can calculate the land covers surface temperature. Generally, it can be concluded that selection of materials based on their color, composition, texture and etc. and attention to their thermal behavior during the day and different seasons in urban areas, can help to urban designers for identification of regions with high potential of formation or development of Urban Heat Islands (UHI). Also energy consumption managements, urban architecture, application of land cover with lowest thermal fluctuations during the day and night and expansion of water bodies and vegetation covers such as urban parks, lakes, artificial waterfalls and etc., can reduce the impact of UHI impact.

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How to cite this article
Shamsipour Ali Akbar, Azizi, Ghasem, Karimi Ahmad Abad, Mostafa, Moghbel, Masoumeh.Modeling Energy Balance over Different Land Covers in Urban Environment. Bull. Env. Pharmacol. Life Sci., Vol 2 (10) September 2013: 90-96