Comparative analysis of the heat exchange between a green roof and a tile roof under summer conditions

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Abstract: *A mathematical model of the heat exchange through a tile roof has been developed. Based on it and on a similar model for a green roof, a specialized software application has been developed. Using the developed models and the meteorological data for the city of Ruse from 2010, a comparative analysis of the energy loses through the two roof constructions has been carried out. The results are presented graphically.*

Keywords: *green roof, tile roof, mathematical model, evapotranspiration*

INTRODUCTION

The reduction of the energy loses through the building roofs plays an important role in the improvement of their microclimate. There are many studies showing that the green roofs provide notably lower temperature of the roof construction, which reduces both the energy loses for cooling down the building during the summer and the urban heat island effect [6]. This is due to the phenomenon evapotranspiration caused by the water evaporation from the soil and water transpiration from the green parts of the plants. In order to estimate the efficiency of the green roof and a traditional tile roof, it is necessary to model the heat exchange through the two roof constructions and to compare their energy loses.

The goal of this study is to develop a model of the heat exchange of a tile roof and through simulation compare it with an already developed model of the heat exchange and accumulation processes of a green roof [5].

OBJECTS OF THE INVESTIGATION

In Bulgaria the most popular roof construction is the classical red clay tile roofs. They reflect about 26% of the solar radiation and the rest of it is accumulated in them as heat [1]. This leads to a significant increase in their temperature during the summer months, which could go up to 60 $^\circ C$. The energy balance of the heat exchange of a roof tile with the environment can be expressed with (figure 1):

$$Q_{env.tile} = Q_{solar} - Q_{refl} - Q_{rad} - Q_{conv}\,,\; W.m^{-2}, \tag{1}$$

where $Q_{env.tile}$ is the heat flux of the accumulated environmental energy in the tile, $W.m^{-2}$;

Q_{solar} - the heat flux of the solar energy, $W.m^{-2}$;

Q_{refl} - the reflected part of the solar energy, $W.m^{-2}$;

Q_{rad} - the radiative flux towards the environment, $W.m^{-2}$;

Q_{conv} - the convective heat flux to the environment, $W.m^{-2}\,W$.

The radiative flux of a roof tile Q_{rad} can be determined according to:

$$Q_{rad} = \varepsilon.\sigma.(T_{tile}{}^{4} - T_{env}{}^{4})\,,\; W.m^{-2}, \tag{2}$$

where T_{tile} is the temperature of the roof surface, $^\circ K$;

T_{env} - the temperature of the environment, $^\circ K$;

σ - the Stephan-Boltzmann constant, $W.m^{-2}.K^{-4}$;

ε - the thermal emissivity of the roof tile.

In order to calculate the solar radiation Q_{solar} it is necessary to determine the angle θ_i between the sun rays and the tile roof surfaces. It should be considered that this angle is different for the two roof surfaces (fig. 1) and depends on both the azimuth angle and the roof slope angle and could be calculated according to [7]:

$$\cos\theta_i = \sin\delta.\sin\phi.\cos\beta + \sin\delta.\cos\phi.\sin\beta.\cos A_{ZS} + \cos\delta.\cos\phi.\cos\beta.\cos\omega - \\ - \cos\delta.\sin\phi.\sin\beta.\cos A_{ZS}.\cos\omega - \cos\delta.\sin\beta.\sin A_{ZS}.\sin\omega \quad (3)$$

$$\delta = 23.45\frac{\pi}{180}\sin\left[2\pi.\left(\frac{284+n}{356.25}\right)\right], \text{deg} \quad (4)$$

where δ is the declination angle, deg;
ω - the hour angle, deg;
ϕ - the latitude angle, deg;
β - the slope angle of the surface and the horizontal, deg;
A_{ZS} - the azimuth angle (rotation from north), deg;
n - the day of the year.

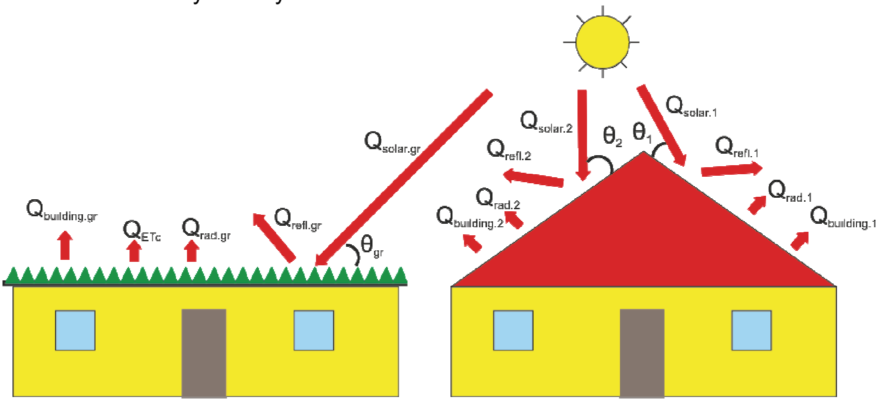


Figure 1. Heat exchange processes of a green and a tile roofs

In order to determine the solar radiation falling on the tile roof, the following equations are used [3]:

$$AM = 1/\cos(90-\delta) + 0.50572.(96.07995-(90-\delta))^{-1.6364}, \ m, \quad (5)$$

$$I_{G.angle} = 1{,}1.1353.0{,}7^{(AM^{0,678})}.\sin(\theta_i), \ W.m^{-2}, \quad (6)$$

$$Q_{solar} = I_{G.angle}.(1 - 0.49.Cl/10), \ W.m^{-2} \quad (7)$$

where AM is the airmass of the atmosphere, m,
$I_{G.angle}$ - the global radiation falling on a surface with angle θ_i, $W.m^{-2}$;
Cl - the sky cloudiness taking values between 0 and 10.

The roof tile temperature T_{tile}^{+t} after a time interval Δt is calculated with:

$$T_{tile}^{+t} = T_{tile} + \Delta t\frac{Q_{roof.tile} + Q_{env.tile}}{C_{tile}.m_{tile}}F, \ ^{\circ}C, \quad (8)$$

where $Q_{roof.tile}$ is the heat flux coming from the ceiling to the tiles, $W.m^{-2}$;
C_{tile} - the specific heat capacity of the roof tiles, $J.kg^{-1}.K^{-1}$;
m_{tile} - the mass of the tiles per square meter, kg;
F - the surface of the exchange surface, m^2;
Δt - the time interval between the previous and the next moment, sec.

SIMULATION AND RESULTS

A software application has been developed using the Visual Studio 2010 environment, which implements the developed mathematical model of the heat exchange through a tile roof. The application also implements the model of the heat exchange and accumulation of a green roof, presented in [5]. For the purpose of the simulation study, the meteorological data for the city of Ruse from year 2010 have been used. The rest of the simulation parameters are presented in table 1 [4,5].

Table 1.
Values of some of the simulation attributes.

Attribute	**Value**
Heat conductivity of the soil	0.35 $W.m^{-1}.K^{-1}$
Specific heat capacity of the soil	1512 $J.kg^{-1}.K^{-1}$
Albedo of the green surface	0.26
Bulk density of the soil	1144 $kg.m^{-3}$
Specific heat capacity of the roof tile	920 $J.kg^{-1}.K^{-1}$
Albedo of the tile roof surface	0.26
Mass of one roof tile	5.5 kg
Number of roof tiles per square meter	10
Surface of the building roof	100 m^2
Width of the concrete roof slab	0.15 m
Heat conductivity of the concrete roof slab	1.63 $W.m^{-1}.K^{-1}$
Width of the insulation	0.05 m
Heat conductivity of the insulation	0.03 $W.m^{-1}.K^{-1}$
Azimuth of the tile roof	0 deg
Slope of the tile roof	60 deg

Through the developed software application, a simulation of the heat exchange processes for green and tile roofs has been carried out, using the meteorological data for May, June, July and August. The temperature variation of the two surfaces of the tile roof is presented in figure 2.

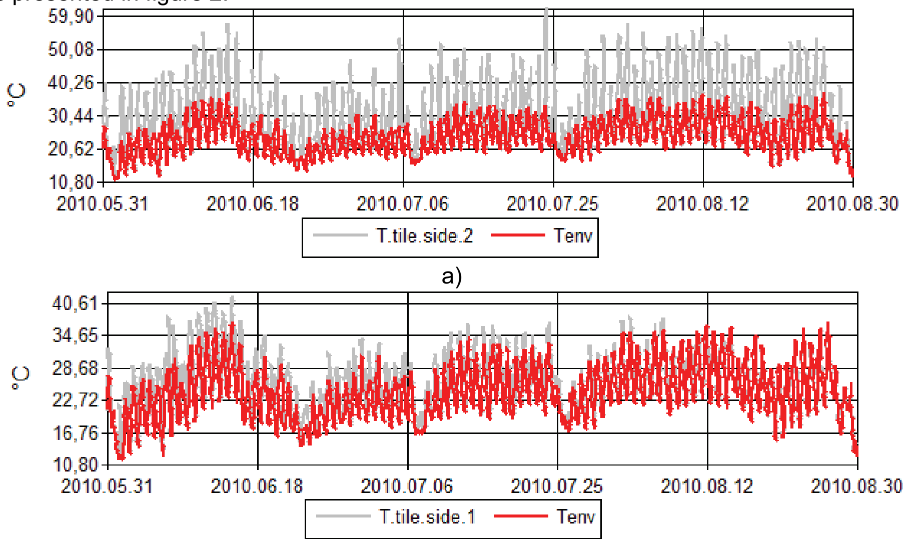
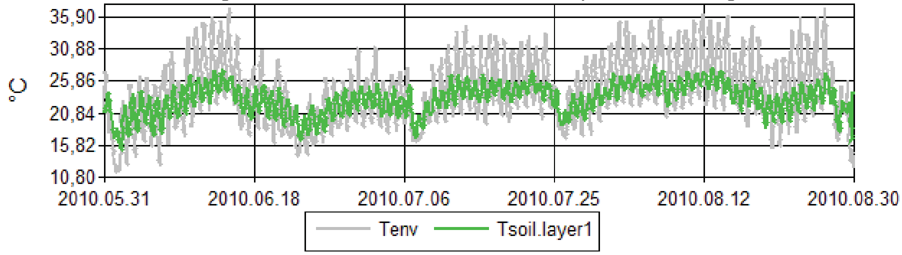


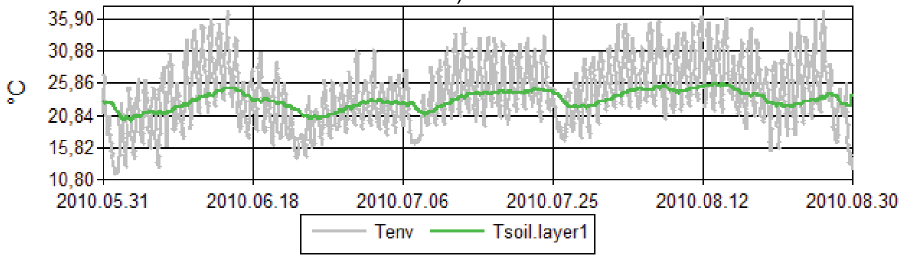
Figure 2. Temperature variation of the environment and of the:
a) south tile roof surface; b) north tile roof surface

It could be noticed that during the summer months when the solar radiation has a peak value the south side of the tile roof goes up to 60 $°C$ during the day, and levels the environment one during the night. The temperature of the north roof side goes up to 40 $°C$ but for most of the time it is close to the environment one.

An analogical simulation has been carried out using the model of heat exchange and accumulation of a green roof, the results of which are presented in figure 3.

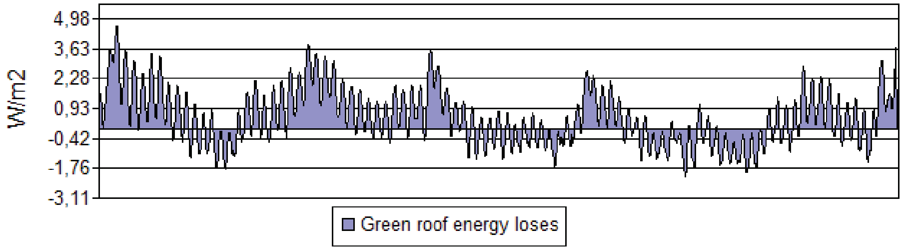


a)

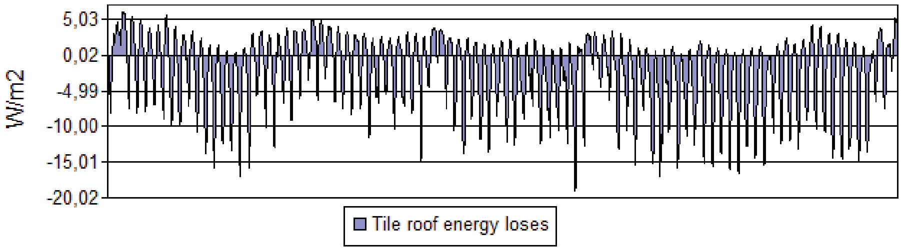


b)

Figure 3. Temperature variation of the environment and the lowest soil layer for soil depth: a) 10 cm; b) 30 cm



a)



b)

Figure 4. Heat flow through: a) the green roof; b) the south side of the tile roof

The green (darker) curve shows the variation of the lowest soil layer (the one on top of the insulation) which forms the energy loses of the building. The simulation has been carried out for two different depths of the soil layer: 0.1 m and 0.3 m. It could be seen that even for a 0.1 m soil layer, the environment temperature has low influence over it's temperature and during the hottest parts of the day the soil temperature is about 10 $°C$ lower.

The heat flux of a green roof and of a tile roof are shown in figure 4. During the summer season, a positive heat flow is preferred because it would reduce the building temperature. In figure 4a could be seen that for green roof the positive sign heat flow prevails over the negative one which is low and doesn't go over -2 $W.m^{-2}$. The total energy loses through the green roof are 244 and 151 $kW.h$, for depths of the soil 0.1 m and 0.3 m respectively. In figure 4b could be seen that the tile roof has a negative sign for the heat flow for the majority of time and the total loses are 1426 $kW.h$. The heat flow varies from 5 $W.m^{-2}$ during the night to almost -20 $W.m^{-2}$ in the noon hours.

CONCLUSIONS

A mathematical model describing the heat exchange processes through a tile roof has been developed. It has been implemented in a specialized software application developed in the Visual Studio 2010 environment. It also implements the model of heat exchange and accumulation of a green roof.

Using the meteorological data for the city of Ruse in the year 2010, a simulation of the models has been carried out for the months May, June, July and August, whose results have been presented graphically. The temperature and heat flow variations have been presented for the two roof construction types.

From the simulation results, it could be concluded that even for a minimal 10 cm depth of the soil layer, the heat exchange through it are 6 times lower than those through a tile roof. Another plus is that the heat flow from the green roof has a predominantly positive sign. This means it is directed from the building towards the environment, which helps to keep the building temperature lower during the summer months.

It is necessary to conduct a similar study for the winter months in order to determine the optimal soil depth of the green roof, which is an object for future investigations.

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Докладът е рецензиран.