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The application of energy balance at the bare soil surface to predict annual soil temperature distribution

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ABSTRACT

A complex model for the prediction of annual soil temperature distribution is presented in the study. This model is based on a transient heat conduction differential equation with the energy balance at the soil surface as a boundary condition. The boundary condition involves both shortwave and longwave radiation energy, convection and latent evaporation energy, which makes the model dependent on meteorological data such as air temperature, air relative humidity, total solar radiation on a horizontal plane, wind velocity, cloud cover and snow cover. The computer program FlexPDE, based on the finite elements numerical solutions of energy flow equations, was used for simulating the soil temperature distribution inside the domain. Next, the model was validated on the basis of the measured soil temperature distribution at depths of 5 cm, 50 cm and 100 cm. The measured and simulated values are in high agreement, as the correlation factor reaches 0.99 [-].

The model is useful for the prediction of thermal performance of the building's partitions in direct contact with soil, like that of green roofs. The model has already been used in the hybrid model for energy demand analysis of earth-sheltered buildings and may be used for buildings with green roofs.

1. Introduction

One of the properties of soil is its very large thermal mass, which causes a slow response to changes in temperature variations at its surface. The large amplitude of the fluctuations is dampened with depth, seeking a constant temperature [1]. This feature causes the temperature of the ground to be cooler than the air in summer and warmer in winter. Also, the amplitude of temperature fluctuations on both sides of the building partitions is smaller, which in turn contributes to improving thermal conditions [2,3]. It is believed that the interest in using soil to improve the heat balance of buildings began to strongly increase with the imposition of an embargo on oil in October 1973. That year brought an energy crisis to the world, which caused a national challenge to reduce energy consumption in buildings for the countries affected by the embargo [4]. However, the initial interest in using soil as a heat reservoir dates back more than 5000 years ago. All primary underground buildings are located in hot arid countries, in which the examples of whole cities built below the soil surface can be found, like the town of Matmata in Tunisia, the Goreme Valley in Turkey or Henan in the Shanxi province in China. The ground was thus first used more for passive cooling rather than heating. This is of particular importance if one takes into account that more than one third (~36%) of total land is located in arid and semi-arid climates and only 12% of the land is situated in a temperate climate [4]. This makes using soil as a cooling element for buildings of particular importance, especially since about 15% of the population lives in the desert [4].

Addressing global warming and climate change issues in cities has recently gained more attention in literature [5–7]. Global warming, projections of increased precipitation and human migration to urban lands [8] causes a number of environmental hazards, including the urban heat island (UHI) [6]. One of the most significant reasons of urban heat island is substitution of green areas with impervious surfaces that limit evapotranspiration [9–11]. The most commonly known, efficient and practiced measures to mitigate the UHI effect includes highly reflective materials to reduce the albedo of cities and the use of additional natural surfaces by green roofs, green walls, parks, roadside trees, etc. [9,12]. Thus, the vegetation placed on the roofs and walls is considered as 'an ecological solution to the concrete jungle in cities' [13–15] and is one of the ways to increase evapotranspiration [9,11,16]. All of this together makes the research on soil temperature distribution and the use of construction covered with soil/sod to mitigate UHI of special importance. Soil temperature is also a critical variable controlling the below-

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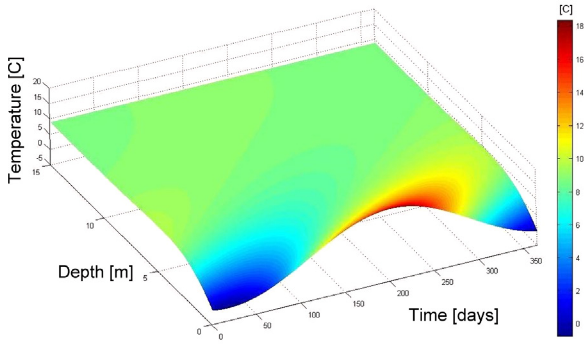

Fig. 1. Simulation results: a 3D plot of annual soil temperature distribution with depth (Legnica, 2005).

ground processes [17]. The soil surface temperature becomes a boundary condition for models used in agriculture field practices to predict the natural soil temperature distribution important for crops development [18], in determining the efficiency of underground heat exchangers [19], in determining soil cooling effect for buildings [20,56], calculating the energy consumption of buildings with green roofs or earth-sheltered buildings [1], in determining effect of vegetation cover in urban ecosystem [21] and many others.

1.1. *Observations of soil temperature*

Soil is a complicated domain in which surface temperature is determined by the interplay of heating (by absorbed solar radiation), cooling (by longwave radiation to the sky), convective exchange between soil and ambient air, energy loss due to evaporation and heat flow between the surface and the deeper layers of soil [18,20]. Years of observation show that the temperature at the ground surface varies harmonically both with diurnal and annual variations [1,2,22–24]. By analyzing the temperature distribution profile, three zones can be distinguished: surface zone (0–1 m), shallow zone (1–10 m) and deep zone (below 10 m) [1]. The *surface zone* extends from the ground surface level to the depth of about 1 m. The temperature profile depends strongly on daily temperature fluctuations at the surface, thus is strongly dependent on the atmospheric conditions [25]. The temperature in *shallow zone* depends mainly on the seasonal cycle, thus the temperature of this layer is more stable (its shape is close to a sine-wave) and close to the annual air temperature [25]. The *deep zone* temperature is almost constant and rises with the depth according to geothermal gradient; which is 1 Centigrade per 30 m [25]. Fig. 1 shows a three-dimensional plot of the calculated annual soil surface temperature and subsurface temperatures at various depths for Polish climate conditions. It clearly shows the ground temperature zoning and phase shift, which is caused by the large thermal mass of soil, and thus the heat accumulated during the summer stays in deeper layers of ground during the winter. This also explains why the soil temperature is typically higher than the air temperature in winter and lower in summer. It can also be noticed that the amplitude of the fluctuations is dampened with depth, seeking a constant temperature [2,26–28].

One of the earliest papers including a temperature distribution in the ground was published by Fluker in 1958 (in Ref. [30]). Due to incomplete and inaccurate measurements of soil temperature, the first comprehensive research and work carried out on the ground temperature was done by Penrod (1960) and Carson (1963) (in Ref. [29]). They showed that at small depths, the ground temperature fluctuates both with annual and diurnal oscillations. Kimball in 1972 presented the results of the annual soil temperature fluctuations for Warrensburg, NY, (USA), which was 10 °C at a depth of 50 cm and only 5 °C at a depth of 300 cm (in Ref. [18]). Their research provided evidence that the temperature in the soil is influenced by many factors, such as the longitude and latitude, weather conditions, season of the year, shading, terrain, soil properties and precipitation. Hence many of these parameters are dependent on seasonal changes and frequent variation in time. The accurate determination of the temperature distribution in soil has become very difficult, especially in the layer near the surface, where temperature fluctuations are stronger.

1.2. *Brief history of empirical models*

One of the first empirical models, developed by Langbein (1949), Fluker (1958) and Parton (1978) (in Ref. [30]), used the Fourier heat conduction equation to predict the temperature of soil as a function of soil surface temperature distribution. In 1959 Carslaw and Jager [31] provided a solution of the equation by using the Laplace transformation, which required initial and boundary conditions. They assumed that the domain is a half-space limited by the upper boundary condition and is time-dependent, hence the knowledge of the surface temperature distribution at time $t = 0$ is required. These formulas gave the beginning for a more comprehensive modification. On the basis of Van Wijk's and De Vries' achievements in the early 1960s (in Ref. [32]), Kusuda and Achenmach (1965) (in Ref. [33]), used a small sample of measurement data collected in the U.S. to prove that the annual soil temperature distribution at various depths can be described by a simple harmonic function using monthly mean values. The researchers use the fact that the air temperature distribution is correlated well with the surface soil temperature and hence may become the upper boundary condition [17,30]. However, due to the large thermal mass of soil, the lag exists between the air and soil surface temperature and thus some models use running averages to correlate the air temperature with the soil temperature [17]. In 1978 a typical lag (approximated to a sine-wave) at depth of 10 cm was described to be 4 h for the minimum temperature and 6 for the maximum temperatures [34]. Assuming constant periodic variation, Carslaw and Jaeger [31] proposed a solution of the Fourier one-direction heat conduction equation, based on the assumption that the soil is a homogeneous half-space, limited with the surface, in which temperature fluctuates harmonically (sinewave). The periods of temperature oscillations are the same at each depth, but with increasing distance from the surface "$z = 0$", the sine wave is delayed. Concurrently, the amplitude of the oscillations becomes smaller. In 1983 Horton et al. [35] examined several models based on the analytical solution of the heat conduction equation, which considered temperature at the soil surface described as a sinusoidal function or Fourier series. They showed that harmonic functions are more reliable than the other examined (linear, non-linear, Fourier series and sinusoidal models) (in Ref. [30]). Sodha [36] and Mihalakakou ([18]) also used the Fourier transformation for soil temperature distribution at various depths, but made it dependent on the soil cover type. As it was noticed by Labs most of the problems and misconceptions related to underground structures stemmed from not completely understanding the heat transfer processes in the soil [3]. It was proved by Bligh and Knothe (1982) (in Ref. [18]) that at a depth of 14 m the soil temperature is constant. Later, Givioni and Katz (1982) (in Ref. [3]) reported that the soil temperature at the deep layer is equal to the annual mean temperature on its surface. This formula was validated in 1997 by Mihalakakou et al. [18] and by Al-Temeemi in 2004 [4]. Based on the measured data, Baggs [37] proposed a semi-analytic solution, which adapted to the conditions of the northern hemisphere and can be used also for soil covered with vegetation [38].

Although the models based on the empirical approach provide good information on parameters that are not measured directly,