Geothermics 53 (2015) 379–384

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

New correlations for the prediction of the undisturbed ground temperature

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ARTICLE INFO

Article history:
Received 14 April 2014
Accepted 4 August 2014
Available online 27 August 2014

Keywords:
Ground source heat pump
Thermal response test
Undisturbed ground temperature
Borehole design

ABSTRACT

The undisturbed ground temperature is an important parameter in the design of the ground heat exchanger connected to the ground source heat pump systems. Based on the heating mode for cold climates, the underestimation of this parameter leads to oversizing the ground heat exchanger length and therefore resulting in the additional cost of the system. Using measured data obtained from thermal response test (TRT) reports for seventeen sites covering a wide range of climates, two different correlations of the undisturbed ground temperature, global and simplified have been developed. The first one, obtained using the least square method, is a function of ambient air temperature, wind velocity, global solar radiation on a horizontal surface and sky temperature. It has been shown by using this correlation that the air ambient temperature is the dominant parameter on the undisturbed ground temperature. Following this conclusion, the simplified correlation which is only a function of the air ambient temperature was developed. Then using this latter correlation, isotherms of the undisturbed ground temperature for Canada were generated.

1. Introduction

The assessment or prediction of the ground temperature is commonly required in various environmental and several energy applications such as ground source heat pumps (GSHPs), agricultural greenhouses and ground energy storage systems. The ground temperature profile is characterized by three different zones: 1 – surface zone (down to 1 m below the ground surface), 2 – shallow zone (from 1 m to 8 m), and 3 – deep zone in which the temperature remains almost constant throughout the year (below about 8 m). This latter temperature is called "undisturbed ground temperature".

In ground source heat pump systems, heat is extracted/rejected from/to the ground via a ground heat exchanger (GHE). The total length of the GHE which involves relatively expensive drilling work represents a very important part of the total cost of the system. Therefore, borehole sizing needs to be done as accurately as possible. The undisturbed ground temperature is a critical parameter for sizing GHE, especially for vertical boreholes.

It is obvious that direct measurement gives accurate values. Often, for large buildings with relatively high cooling and heating loads, one well is drilled to perform thermal response tests (TRTs). In addition to the thermal properties of the soil (conductivity and diffusivity) and the borehole thermal resistance, the TRT gives the undisturbed ground temperature. However, this test results in an additional cost for the GSHP system. Another way to obtain the value of the undisturbed ground temperature is by using theoretical predictions based on the meteorological data and the thermal properties of the ground.

Two of the earliest analytical models were developed by Van Wijk (1963) and Kasuda and Achenbach (1965). Both models are based on Fourier analysis of multi-year measured data. The correlation proposed by Kasuda and Achenbach (1965) is commonly used in several commercial softwares such as TRNSYS (2005), DOE-2 (1982) and RETScreen (2005). It gives the ground temperature as a function of the time of the year and the depth below the ground surface. Among the input data for this correlation is the annual average surface ground temperature which is not often accessible. For this reason, this parameter is often substituted by the annual average air temperature. Such a simplification appears to be rather inaccurate in the design and prediction of GSHP energy performance systems, as shown later in this paper.

By introducing a correction for the daily amplitude of the ground temperature by a sinusoidal function of time rather than a constant

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http://dx.doi.org/10.1016/j.geothermics.2014.08.001
0375-6505/

Nomenclature

h	convective heat transfer coefficient (W/(m^2 K))
R^2	coefficient of determination
t	time (s)
T	temperature (K)
V	velocity (m/s)
z	depth coordinate (m)

Greek symbols

α	absorption coefficient
λ	thermal conductivity (W/(m K))
ε	emissivity
$\dot{\Phi}$	density of heat flux (W/m^2)

Subscripts

amb	ambient
c	convective
dp	dew point
g	ground
gs	ground surface
Lat	latitude
Long	longitude
r	radiative
sky	sky
sol	solar
w	wind

value, Elias et al. (2004) and Smerdon et al. (2006) have improved the model proposed by Van Wijk (1963).

Based on both mean annual surface air temperature (SAT) and the mean ground surface temperature (GST) values measured at meteorological stations, Signorelli and Kohl (2004) generated a useful regional ground surface temperature map for Switzerland. However, GSTs and SATs values were recorded from depths of 5 to 100 cm and 2 m above the ground respectively. SAT is not a common value given by the weather stations and it associates with many uncertainties.

Another category of work has been done, based on the energy balance at the ground surface (Cellier et al., 1996; Khatry et al., 1978; Mihalakakou et al., 1997; Mihalakakou, 2002; Okada and Kusaka, 2013; Thiers, 2008). This category of studies, in which the energy balance is applied as a boundary condition at the ground surface, is applicable anywhere due to the availability of the required data. However, it introduces more modeling complexities. As pointed out by different studies, the boundary condition at the ground surface involves three terms including solar radiation, heat losses to the cold sky by long wave radiation and convective heat transfer between the ambient air and the ground surface.

All the above models involve several assumptions. Many of their inputs are spatially and temporally difficult to collect as well as being costly and time consuming. The main objective of this work is to analyze the effect of the meteorological data on the undisturbed ground temperature taken from the measurements, in order to develop a simple correlation as a function of the ambient temperature.

2. Undisturbed ground temperature

The assessment and/or prediction of the ground temperature profile is commonly required in various environmental and several energy applications such as ground source heat pumps, agricultural greenhouses, heating and cooling of buildings and ground energy storage systems. Temperature changes in the soil are essentially driven by transient conduction resulting from the net heat flux ($\dot{\Phi}_{net}$) on the ground surface (Eqs. (1) and (2)). The different phenomena occurring at the ground surface are presented in Fig. 1. The surface of the ground is heated by solar radiation ($\dot{\Phi}_{sol}$) when the weather is fine. The surface also loses heat to the cold sky by long wave radiation ($\dot{\Phi}_r$). Convective heat exchange occurs between the ground surface and ambient air ($\dot{\Phi}_c$).

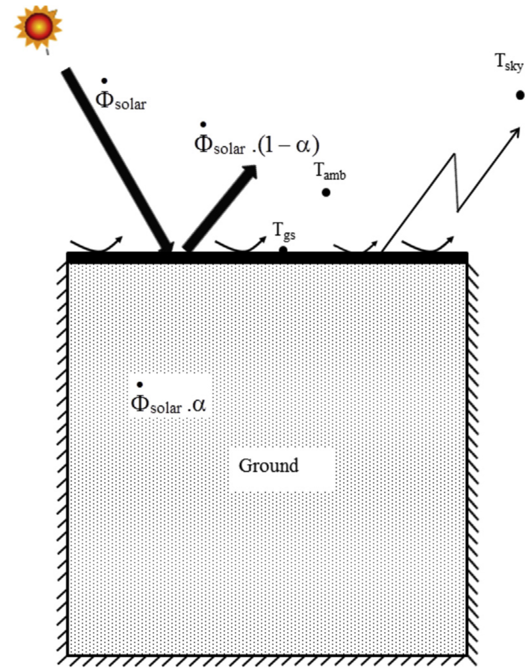

Fig. 1. Energetic exchange phenomena on the ground surface.

$$\dot{\Phi}_{net} = \dot{\Phi}_{sol}\alpha + \dot{\Phi}_c + \dot{\Phi}_r \tag{1}$$

$$\dot{\Phi}_{net} = \lambda_g \cdot \left.\frac{\partial T}{\partial z}\right|_{z=0} = h_c(T_{amb} - T_{gs}) + \dot{\Phi}_{sol}\alpha - h_r(T_{gs} - T_{sky}) \tag{2}$$

The typical daily ground temperature profile is presented in Fig. 2. Due to the temperature fluctuations on the ground surface, the annual variation of the daily ground temperature profile varies from the summer time to the winter time. Because of the high thermal inertia of the soil, the amplitude of its temperature variation diminishes as the depth of the ground increases until it reaches a certain depth where the temperature remains constant (15 m in Fig. 2). This constant temperature is often called “undisturbed ground temperature”.

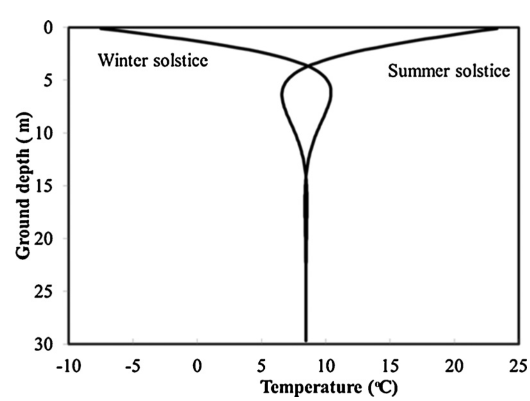

Fig. 2. Typical ground temperature distribution profile.