Renewable Energy 72 (2014) 1–11

Contents lists available at ScienceDirect

Renewable Energy

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

The relative importance of moisture transfer, soil freezing and snow cover on ground temperature predictions

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ARTICLE INFO

Article history:
Received 16 June 2013
Accepted 25 June 2014
Available online

Keywords:
Ground temperature
Moisture transfer
Snow cover
Soil freezing
Equivalent moisture content

ABSTRACT

Predicting ground temperature is an important part of the analysis of geothermal resources assessment and use. Thus, we develop and validate one-dimensional numerical model for heat and mass transfer in partially frozen soils. The model is implemented in HVACSIM Plus and used to simulate the thermal regime of soil profile. In addition to modeling heat conduction, model variations also includes moisture transfer, snow accumulation and melting, and soil freezing and thawing. The results are compared against experimental measurements of ground temperature for three locations in Montana, USA. The differences between simulated depth temperature with and without snow cover and freezing and thawing of soil reveal that ground temperatures are predominantly influenced by these two factors. Considering moisture transfer slightly improves temperature predictions, although it increases computational time by one order of magnitude. To balance computational efficiency with prediction accuracy, we propose an equivalent moisture content of 40–60% saturation in predicting ground temperature.

1. Introduction

Predicting ground temperature is an important part of the analysis of geothermal heat pump systems with significant earth contact. Ground temperatures are often used as boundary conditions for simulations of heat transfer between the ground heat exchanger and the soil [1–3]. Depending on the simulation, ground temperature near the ground heat exchanger may be explicitly calculated. Aside from energy calculations, ground temperature is often required for assessing shallow low enthalpy geothermal resource [4], measuring ground water recharge [5,6], and even analyzing burial sites [7].

Despite this wide use, the availability of ground temperature data for engineers is surprisingly limited. In the US, the most commonly used approach proposed by Kusuda and Achenbach [8] relies on two weather-related parameters: annual average undisturbed ground temperature and annual amplitude of surface temperature variation, both of which are read from very small maps. These maps can be traced back to research in the 1920s and 1950s. The two parameters (along with soil thermal diffusivity and a phase delay parameter) are then used with a simple (one-year period) harmonic relationship that has the amplitude decaying exponentially with depth. This formulation was proposed by Thomson in 1862 [9] with multiple harmonics. ISO 13370 [10] appears to use the same formulation but starts with a sinusoidal representation of annual air temperatures. Periodic heat transfer coefficients and phase lags that apply to the entire air-temperature-to-air-temperature problem are then computed using empirical expressions. All of these approaches assume pure conduction of heat transfer with uniform thermal properties and sinusoidal boundary conditions but neglect moisture transfer, freezing/thawing, and surface conditions.

The increasing availability of computers in the 1970s enabled the development of more comprehensive mathematical models, thereby facilitating the formulation of solutions to heat and mass coupled transfer equations for soil. However, soil temperature is affected by many factors, such as weather conditions, soil properties, surface conditions, and the freezing–thawing cycle. Most of these factors irregularly change, complicating the prediction and estimation of soil temperature.

Many numerical models have been used to solve various heat and mass transfer problems. Freezing–thawing and moisture transfer have been recognized as important in predicting soil temperature. Harlan [11] analyzed the heat–mass transport in soil with freezing and thawing through an analogy between the mechanisms of water transport in partially frozen soil and those in unsaturated soils. Soil freezing significantly affects soil temperature

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http://dx.doi.org/10.1016/j.renene.2014.06.044
0960-1481/

distribution. Guymon and Luthin [12] presented a finite element solution to the same problem. Fuchs et al. [13] indicated that the thermal capacity of water in the liquid–solid phase change range is several orders of magnitude higher than that in either unfrozen or almost completely frozen soil. Lytton et al. [14] performed a sensitivity study using the frost model of the Cold Regions Research and Engineering Laboratory to evaluate the important impact of saturated hydraulic conductivity on soil temperature distribution during freezing. Hansson et al. [15] and Hansson and Lundin [16] tested the sensitivity of the predicted soil temperature in a similar model, namely, the Hydrus-1D model. The results of Hansson's studies verified those of Lytton's, indicating the significant impact of surface conditions on predicting soil temperature. Temperature distribution in unfrozen soil is also closely tied to moisture content [17]. Jansson and Karlberg [18] developed the Coup Model to describe the heat fluxes and water movements of the soil–atmosphere system. The model considers both water and water vapor movement in soil. Based on this model, Jansson et al. [19] pointed out the important influence of water vapor transport through asphalt pavement profiles in warm season (spring and summer). This effect was experimentally verified by Lu et al. [20]. Xing et al. [21] developed a 2-D finite-volume model to evaluate the effect of moisture movement in soil on calculating heat load.

The soil surface temperature regime is also influenced by air temperature, snow presence, and turbulence. Given its low thermal conductivity, snow cover reduces the loss of heat flow from the ground. However, the high albedo of snow cover and the enthalpy of its phase transition limit heat flow from the atmosphere to the ground during thawing [22]. Ellis and Leathers [23] evaluated the effect of snow cover on daily maximum soil surface temperature. Given the low thermal conductivity, snow cover caused midday temperatures to be approximately 1–4 °C cooler than those over surrounding bare ground. Marcos and Garcia-Blanco [24] reported that the impact of snow cover can reduce the number of freezing–thawing cycles in winter. Lin et al. [25] found that the maximum and minimum temperature system shield biases can increase by about 1 °C with snow cover compared with the opposite. Gadek and Leszkiewicz [26] indicated the impact of snow cover depth and density on the delay and amplitude of soil surface temperature throughout winter. Niu and Yang [27] and Zhang et al. [28,29] developed numerical models to improve simulations of snow and soil thermal regimes and found that snow cover significantly affects surface energy fluxes and soil temperature. Mackiewicz [30] used multiple linear regressions with dummy predictor variables to quantify the degree of dampening between air and shallow soil temperatures with and without snow cover.

Although detailed studies of soil thermal regimes are available, especially on partially frozen area, little is known about the relative importance of moisture transfer, snow cover, and soil freezing in predicting soil temperature. A better understanding of the thermal regime of soils in response to snow cover, moisture transfer, and soil freezing/thawing is required because of its possible importance in understanding the impact on assessing and using geothermal resources [31,32].

In the current work, a heat and mass coupled model is developed for the ground temperature prediction in partially frozen soils. In addition to modeling heat transfer, the model also includes the characteristics of mass transfer, snow accumulation and melting, and soil freezing and thawing. The model is implemented in HAVCSIM Plus simulator. Dataset from 3 locations in the northern United States are used to test the model and analyze the relative importance of moisture transfer, snow cover, and soil freezing to ground temperature predictions. To balance prediction accuracy with computational efficiency, equivalent moisture content is proposed to simplify the procedure for computation of ground temperature. Section 2 describes the heat and mass coupled model for partially frozen soils. Data from evaluation and analysis are presented in Section 3. Simulation results and conclusions are given in Sections 4 and 5, respectively.

2. Model description

2.1. Water transport

Variably saturated water flow for above- and subzero temperature is described using the modified Richards equation in Eq. (1) as follows [15]:

$$\frac{\partial \theta_u}{\partial \tau} + \frac{\rho_i}{\rho_w}\frac{\partial \theta_i}{\partial \tau} = \nabla(D_l(\theta_u)\nabla\theta_u) + \nabla(D_l(T)\nabla T) - \frac{\partial K}{\partial y} + \nabla(D_v(\theta_u)\nabla\theta_u) + \nabla(D_v(T)\nabla T) \quad (1)$$

where τ is time (in s); T is the temperature (in K); y is the vertical axis coordinate (in m); ρ_i is the density of ice (in g/m^3); ρ_w is the density of water (in g/m^3); θ_u is the volumetric unfrozen water content (in m^3/m^3); θ_i is the volumetric ice content (m^3/m^3).

In Eq. (1), water flow is assumed to be caused by five different processes for two different flows: (1) liquid flows due to a hydraulic gradient ($D_l(\theta_u)$ isothermal liquid diffusivity, m^2/s), a temperature gradient ($D_l(T)$ nonisothermal liquid diffusivity, m^2/(K-s)) and gravity (K hydraulic conductivity, m/s), respectively; (2) vapor flows due to hydraulic ($D_v(\theta_u)$ isothermal vapor diffusivity, m^2/s) and temperature ($D_v(T)$ nonisothermal vapor diffusivity, m^2/(K-s)) gradients, respectively.

While numerous functions for the unsaturated porous media hydraulic properties may be used, we will in this study invoke the expressions of Brooks and Corey [33], and Mualem [34]:

$$\frac{\theta_u - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi}{\psi_a}\right)^{-a} \quad (2)$$

$$K_{sat}\left(\frac{\theta_u - \theta_r}{\theta_s - \theta_r}\right)^{n+2+\frac{2}{a}} = K \quad (3)$$

where a is the pore size distribution parameter; ψ is the matric potential (in m); ψ_a is the air-entry tension (in m); θ_r is the residual water content (in m^3/m^3); θ_s is the saturated water content (in m^3/m^3); K is the unsaturated hydraulic conductivity (in m/s); K_{sat} is the saturated hydraulic conductivity (in m/s); n is a parameter accounting for pore correlation and path tortuosity.

When the soil is frozen, the presence of ice crystal in voids may lead to an apparent blocking effect. To quantitatively account for this blocking, a parameterization has been developed based on the constitutive relationship between matric potential and liquid moisture content in unfrozen porous media presented by Brooks and Corey [33]:

$$\psi = \psi_a\left(\frac{\theta_u - \theta_r}{\theta_s - \theta_r}\right)^{-1/a}(1 + C_k\theta_i)^2 \quad (4)$$

where C_k is the effect of soil specific surface on matric potential due to the presence of ice. Kulik [35] reported an average value of about 8 for C_k.

The Mualem relation for K is modified by an empirical formula proposed by Jame and Norum [36]:

$$K = 10^{-E_i\theta_i}K_{sat}\left(\frac{\theta_u - \theta_r}{\theta_s - \theta_r}\right)^{n+2+\frac{2}{a}} \quad (5)$$