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A revised thermal resistance and capacity model for the ground heat exchanger under freezing soil conditions and thermal performance analysis

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Abstract

When designing ground source heat pump systems in northern regions, we usually face the problem of soil freezing/melting around ground heat exchanger. The impact of freezing on heat transfer should be evaluated. An improved thermal resistance and capacity model based on the effective heat capacity method is developed in the paper to evaluate the effect. Further comparisons have been carried out against measured data from an experimental set-up, and agreement of the results validates the proposed model when the parameters of the model are set properly. The heat transfer capacity could rise by 30% because of phase change. The quantity of heat transfer could stay at 75 W/m to 80 W/m during three-month operation, which is feasible for a GSHP system to operate normally in such extreme condition.

Keywords: Ground source heat pump; Frozen soil; Ground heat exchanger; Thermal performance; RC model;

1. Introduction

With the global energy crisis and increasingly serious environmental problems, ground source heat pump (GSHP) technology gradually gets more and more attention, since it is considered to be energy-saving and environmental-friendly. GSHP systems use soil as the heat sink and source, and thanks to the relatively stable underground

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temperature, the systems are applied to a wide range of projects including some systems in cold regions. However, under extreme heating operating conditions, the inlet temperature of the ground heat exchanger (GHE) pipes can be below 0 °C in cold regions, thus the soil surrounding the pipes may be frozen. As for the freezing problem, it is actually a moving boundary phase-change problem, and it can be considered that there is a moving interface of two phases, where the latent heat release or absorption occur. The heat exchange per meter and the temperature distribution in the soil would also be affected because of the phase change. Measuring the effects would be valuable for the GSHP system engineers to decide whether it is suitable for the GHE to operate under freezing soil conditions. Therefore, a method for predicting thermal performance of GHE under freezing soil condition is developed to deal with the problem in this paper.

The resistance capacitance (RC) model comes from the field of electrical engineering, and it has been widely used in the field of building load calculation, computer information security, medicine biology and so on. The model can be easy to understand and calculate with good accuracy. Several scholars have applied the RC model to the ground heat exchanger (GHE) heat transfer calculation, the parameterized model has a good calculation accuracy and speed without the need for time-consuming geometric modeling, thus the model is valuable in engineering design. Sharqawy et al. [1] develops an expression of thermal resistance within the borehole, and compares the model with the existing analytical models. Carli and Zarrella [2-4] develops a relatively complete theory of capacity resistance model for single U-tube, double U-tube and coaxial pipes, and the simulation results are validated by a commercial software simulation results, and a ground thermal response test and data from an office building equipped with a GSHP and double U-tube GHE. Bauer et al. [5] adds the thermal capacity of grout to Carli's model, and the modified models are validated by FEM. It is shown that the models are suitable for incorporation into transient energy simulation programs. Pasquier et al. [6] modifies the RC model by the addition of more capacities and resistances within the borehole, and the model presents a significant improvement over the original one. Maestre et al. [7, 8] combines the RC model within the grout with the G - function model in the soil to develop a hybrid one. Compared with the FVM reference model, the relative errors are under 5%. As can be seen from the researches above, RC model for GHE has been studied for several years, and it could achieve good accuracy with proper improvement.

To deal with the phase change problem, there are generally two ways: one is to assume the existence of a thin interface, and heat transfer equations should be listed respectively for either phase, using the Stefan equation to link the two parts. Another method doesn't strictly distinguish the solid and liquid phase, but distinguishes phases by using enthalpy or temperature. The enthalpy method is based on the relationship between temperature and enthalpy to establish a unified energy equation. The effective heat capacity method [9-11] defines that the temperature refers to different heat capacity so as to unify energy equation, and it has been widely applied in recent papers talking about freezing issues. Because it is easy to change the heat capacity in the RC model, the effective heat capacity would be a suitable choice to work as a module for dealing with freezing conditions.

Therefore, this paper provides an efficient method based on thermal resistance and capacity models and effective heat capacity method with relatively high precision to calculate the quantity of heat exchange under the extreme operating condition. And the method is also verified by experimental results.

Nomenclature

c	specific heat (J/(kg·K))
C	volume thermal capacity (J/(m^3·K))
H	latent heat of the liquid (J/kg)
i	ground discretization index in radial direction
j	ground discretization index in vertical direction
l	pipe length (m)
m_w	fluid flow rate (kg/s)
m	maximum discretization index in vertical direction
n	maximum discretization index in radial direction
r_b	borehole radius (m)
r_m	barycentric radius (m)
R	thermal resistance (K/W)