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Estimation of the thermal effect of ground moisture condensation on heat transfer outside a geothermal borehole

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ABSTRACT

Presented in this article are the results of the theoretical research demonstrating the need to consider the changes in the ground heat transfer properties in geothermal borehole heat modelling because of moisture condensation/evaporation in the ground pores. It is our opinion that in the GSHP system design, the quantity of the boreholes is often overestimated and the associated parameters are oversized, while the extent of the ground heat transfer is underestimated. In most cases, the operation and performance of the GSHP design are caused by an incorrect assessment of the ground moisture content, which has the most tangible effect on the ground heat transfer properties. This article demonstrates the need to consider the ground moisture condensation/evaporation in the GSHP system design. Presented in this article is the mathematical simulation of the ground pore moisture condensation at the GSHP boreholes. Additionally, the numerical data derived from the calculations are presented to assess the effect of the ground pore moisture condensation on the borehole heat transfer efficiency. Through analysis and experimentation, it was determined that the ground pore moisture condensation has a substantial impact on the GSHP efficiency.

1. Introduction

GSHP systems are normally used for heating and cooling in temperate climate regions, where the thermal conditions are more or less consistent throughout the year (North America, Europe, and, more recently, China [1]). The main factor limiting GSHP use in other areas is the substantial capital investments associated with geothermal boring [2]. The high costs of geothermal borehole construction are due to the low efficiency in the ground heat transfer at the borehole, which is the result of the ground's low heat transfer properties. However, it is our experience in the practical application and use of the GSHP systems that the quantity and parameters of the boreholes are very often overestimated/oversized, while the extent of the ground heat transfer is underestimated. In most cases, in designing the GSHP operating modes, this effect is caused by an incorrect assessment of the ground moisture content, which has the most tangible effect on the ground heat transfer properties. The mathematical models currently used are far from perfect and do not accurately describe the ground heat transfer process in GSHP systems.

Heat transfer modelling that describes the heat state of a complex system, such as ground, is an extremely elaborate task [3] because it requires consideration for and a mathematical description of various mechanisms: heat transfer within a single particle, heat transfer between particles upon contact, molecular heat transfer properties in the medium between the particles, pore moisture and vapour convection.

Strictly speaking, in projecting the heat transfer of the ground's low-grade heat collection system in addition to considering the heat and mass transfer mechanisms, it is important to account for the chemical and mineralogical nature of the ground base, material structure, degree of dispersion in the medium, shape and size of the particles and pores, number of phases, quantitative relationships between the phases and their positions in the medium that fills the pores as well as many other physical and chemical parameters of the ground. The ground moisture and the moisture migration in the pores and their effect on the heat collection system operation are described below in more detail [2,7].

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In capillary-porous systems, such as the ground in the geothermal heat collection system, the moisture content and migration have a tangible effect on heat propagation. With the delta T present in ground, vapour molecules migrate towards the areas with lower temperatures. This effect will increase under the gravitational pull, causing a directed moisture flow in the liquid phase. This effect is virtually overlooked in the existing mathematical models describing GSHP borehole heat transfer [4–6].

The "INSOLAR" Group has developed a dynamic 3-D physical-mathematical model for an assessment of the heat state in ground heat collection systems (this model was implemented in the "INSOLAR.GSHP.12" software). The model determines the optimal heat collection system specifications based on the climate conditions, thermotechnical properties of the ground, building insulation properties, heat pump and circular pump specifications, heating equipment and operation.

This article focuses on the model blocks related to the ground heat state mechanisms due to the moisture condensation in the pores.

2. Model for ground heat transfer on the exterior of the geothermal borehole

To describe the heat transfer process in the ground around the vertical geothermal borehole of radius r_b, we will use a cylindrical coordinate system, where the z-axis is parallel to the borehole axis. Discounting the heat flow along the z-axis parallel to the borehole, the heat transfer in the ground can be expressed by the equation below:

$$c_g \rho_g \frac{\partial T(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_g \frac{\partial T(r,t)}{\partial r}\right) + q\left(T\left(r,t\right)\right), \qquad (1)$$

where $T(r, t)$ [K]—ground temperature, r[m]—polar radius, and t[h]—time. Ground parameters: c_g [kJ/(kg K)]—isothermal heat capacity, ρ_g [kg/m^3]—density, λ_g [kJ/(h m K)]—coefficient of thermal conductivity. The source term q [kJ/(h m^3)] represents the heat released through water vapour condensation in the ground pores.

Eq. (1) holds in the annular region $r_b < r < r_\infty$ with the boundary conditions below:

$$-r\,\lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_b} = Q(t), \qquad \left.\frac{\partial T}{\partial r}\right|_{r=r_\infty} = 0, \qquad (2)$$

where $Q(t)$ [kJ/(h m)]—given heat flux from ground into the borehole simulating heat collection from ground during heating season. The outside radius of the ring r_∞ should be large enough for Eq. (2) to hold true at the low error margin over the given time interval. Suppose the initial condition is a constant temperature:

$$T(r,0) = T_g, \qquad (3)$$

where T_g (>0 °C)—average natural ground temperature at the heat exchanger depth in the borehole.

Eqs. (1)–(3) will be solved numerically by using the finite difference method. We will introduce a uniform space grid, $r_i = r_b + (i-1/2)h$, $i = 1,2,\ldots,N$, $h = (r_\infty - r_b)/N$ and time grid $t_k = k\tau$, $k = 0,1,2,\ldots$

Eq. (1) is rewritten on the grid, replacing the space derivatives with the finite differences and using an implicit scheme for the approximation of the time derivative:

$$c_g \rho_g r_i h \frac{T_i^{k+1} - T_i^k}{\tau} = -\lambda r_{i-1/2} \frac{T_i^{k+1} - T_{i-1}^{k+1}}{h} + \lambda r_{i+1/2} \frac{T_{i+1}^{k+1} - T_i^{k+1}}{h} + q\left(T_i^{k+1}\right), \qquad (4)$$

where $T_i^k = T(r_i, t_k)$, $r_{i\pm(1/2)} = r_i \pm (1/2)$. The finite difference counterparts of the boundary and initial conditions (2) and (3) are as follows:

$$-\lambda r_{-1/2}(=r_b)\frac{T_1^k - T_0^k}{h} = Q\left(t_k\right), \quad \lambda r_{N+(1/2)}(=r_\infty)\frac{T_{N+1}^k - T_N^k}{h} = 0; \qquad (5)$$

$$T_i^0 = T_g, \quad i = 1,2,\ldots,N. \qquad (6)$$

The main objective of this paper is to introduce a method to obtain a simple ("engineered") estimation of the q value based on the intuitive physical notions [8,9].

It is presumed that air in the ground's pores contains water vapour. The relative humidity of air equals the ratio of the partial pressure of water vapour p_v[Pa] to pressure $P_{sv}(T)$ [Pa] of the saturated water vapour at a given temperature T, $\varphi(T) = p_v/P_{sv}(T)$. For the purpose of this analysis, we will presume that the water vapour pressure is constant and is equal to the pressure at the initial time,

$$p_v = \varphi_0 P_{sv}\left(T_g\right), \qquad (7)$$

where φ_0—predetermined relative humidity of air in ground. It is therefore assumed that the vapour transfer rate in the porous space is high enough to equalize the pressure in the entire area around the borehole relatively fast. Obviously, this assumption will cause an overestimation of the amount of condensation heat in this model.

The dependence of the saturated water vapour pressure on temperature $P_{sv}(T)$ is known, and it decreases as the temperature decreases. Specifically, in this paper, reference manual data were used [10,11]. By gathering the ground heat using a heat exchanger, the ground temperature T near the borehole will decrease, and hence the pressure $P_{sv}(T)$ will decrease. Consequently, air humidity in the pores near the borehole will increase, and at a certain moment will exceed one. The water vapour condensation with water drops formation will then occur in the vicinity of the borehole.

The rate of water vapour condensation W_c [kg/(h m^3)] is hard to calculate. In this model, we use a heuristic formula, where the rate per unit volume of gas is proportional to the excess vapour pressure:

$$W_c = k_c\left(p_v - P_{sv}(T)\right), \qquad (8)$$

where k_c [kg/(Pa m^3 h)]—coefficient (condensation rate constant).

If in layer i at time t_k and temperature T_i^k the saturated vapour pressure is less than the pressure p_v, then the mass of water is

$$\Delta m_i = k_c\left(p_v - P_{sv}\left(T_i^k\right)\right)V_i \tau \qquad (9)$$

and converts from the gaseous state to the liquid state. Here, $V_i = \pi(r_i^2 - r_{i-1}^2)$ is the volume of i-th layer per unit length of the borehole. At that same time in layer i, the heat of condensation is released:

$$q_i^k = q_v \Delta m_i, \qquad (10)$$

where q_v—vapourization latent heat.

3. Numerical example

Estimations of the thermal effect of condensation were performed at the model parameters below:

Study area around the borehole: r_b = 0.05 m, r_∞ = 15 m.Ground properties: density ρ_g = 1500 kg/m^3, isothermal heat capacity c_g = 0.84 kJ/(kg K), thermal conductivity coefficient λ_g = 5.4 kJ/(h m K), porosity σ = 0.5.

Initial ground temperature T_g = 10 °C.

Specific heat of vapour condensation q_v = 2250 kJ/kg