Energy and Buildings 107 (2015) 434–444

Contents lists available at ScienceDirect

Energy and Buildings

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

Design of plane energy geostructures based on laboratory tests and numerical modelling

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 21 May 2015
Accepted 20 August 2015
Available online 24 August 2015

Keywords:
Geothermal energy
Energy geostructures
Laboratory test
Numerical simulation
Thermal resistances

ABSTRACT

Energy geostructures are an up-coming technique for the thermal utilization of the ground. Due to the complexity of the system, it is necessary to apply numerical simulations for a proper design of plane energy geostructures. However, varying scales, different heat transfer mechanisms, and a missing rotational symmetry require complex numerical models and long computing times.

This motivated the authors to develop a semi-analytical calculation model based on thermal resistances. This model was implemented in the general 3D coupled heat and flow transport code SHEMAT-Suite. Large-scale laboratory tests were carried out for verification and validation of the model. The results from the novel numerical approach were compared with results from the laboratory and with results from a fully discretized finite element model. All comparisons show a good agreement. As expected, computing times are significantly smaller than for fully discretized numerical models. Thus, the new approach is suitable for the design of plane energy geostructures. The new model was used for an extensive parameter study. As a result, the flow rate in the heat exchanging system, the ground temperature, the groundwater flow, the pipe arrangement in the structural element and the structure of the element were identified as the decisive parameters.

1. Introduction

Worldwide, the geothermal utilization of the shallow ground has significantly increased over the last years. The installed thermal power increased from 8.9 GW to 48.5 GW between 2000 and 2010 [1]. Borehole heat exchangers (BHE) are the most common system. However, for the installation of BHEs drilling is necessary, implying high installation costs. Therefore, the use of earth-contacted structural elements as a heat exchanger (so-called energy geostructures or thermo-active elements) has gained increasing interest during the last years (e.g. [2]). By the integration of heat exchanging pipes into the structural element two functions can be combined, which significantly reduces the installation costs. Currently, the energy pile is the most commonly used energy geostructure in Europe and all over the world. In Austria, the amount of energy piles increased from about 5500 in 1994 to nearly 23,000 in 2004 [3], for example. Nevertheless, plane structural elements have a high energy potential due to their large contact area to the ground. Therefore, some works in this area exists, i.e. the thermal activation of diaphragm walls and base slabs [3]. Furthermore, since the beginning of the 2000s, research on the thermal activation of tunnels was carried out [4–6]. In this context, the authors developed so-called “thermo-active seal panels” for the thermal activation of basement walls, which are in contact to (streaming) groundwater [7]. In contrast to concrete energy geostructures, where the heat exchanging pipes are attached to the reinforcement, the pipes are incorporated into the sealing layer. Thus, the thermal resistance can be reduced.

Regarding the design of BHEs, and with some restrictions the design of energy piles as well, many calculation approaches exist. These approaches are normally based on the line source theory. In principle, different heat transfer mechanisms and a large number of parameters have to be considered. Thus, numerical methods have to be applied for the design of geothermal systems. However, the different scales between the structural element and the surrounding ground imply very high computing times when running a fully discretized numerical model with sufficient spatial resolution. For

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http://dx.doi.org/10.1016/j.enbuild.2015.08.039
0378-7788/

Nomenclature

a	pipe distance/shank space [m]
$c_{v,F}$	heat capacity of the heat carrier fluid [W/(m^3 K)]
d_1	distance between pipe axis and the outer surface of the pipe layer [m]
d_2	distance between pipe axis and the inner surface of the pipe layer [m]
d_i	inner diameter of the pipe [m]
d_{IS}	thickness of the overlapping layer (insulation) [m]
d_L	thickness of the heat conduction layer [m]
d_o	outer diameter of the pipe [m]
$g_1(s), g_2(s)$	functions for calculating the structural resistance
h	difference in potential [m]
L_p	pipe length [m]
N_1, N_2, R	variables for calculating the structural resistance
Nu	Nusselt number [–]
P	power [W]
Pr	Prandtl number [–]
Q_1	heat flow from the ground (outside) [W/m^2]
Q_2	heat flow from the adjacent room (inside) [W/m^2]
Q_{min}, Q_{max}	heat flow (minimum, maximum) [W/m^2]
Q_v	volumetric flow rate in the heat exchanging system [m^3/s]
R_1, R_2	thermal resistances for the wall (based on a star-connection) [m^2 K/W]
R_a, R_b, R_c	thermal resistances for the structural element (based on a delta-connection) [m^2 K/W]
R_p	pipe resistance (convection and conduction) [m^2 K/W]
R_x	structural resistance [m^2 K/W]
Re	Reynolds number [–]
s	control variable for calculating the structural resistance
T_1	temperature outside (ground) [°C]
T_2	temperature inside (adjacent room) [°C]
T_3	temperature at the outer surface of the pipe [°C]
T_B	ground temperature [°C]
T_C	temperature at the outer surface of the pipe [°C]
T_F	temperature of the heat carrier fluid [°C]
T_{in}	inlet temperature [°C]
T_{out}	return temperature [°C]
U_1	total heat transfer coefficient outside [W/(m^2 K)]
U_2	total heat transfer coefficient inside [W/(m^2 K)]
$\bar{U}_1$	heat transfer coefficient outside (without heat conduction and pipe layer) [W/(m^2 K)]
$\bar{U}_2$	heat transfer coefficient inside (without heat conduction and pipe layer) [W/(m^2 K)]
v_f	groundwater flow velocity [m/d]

Greek symbols

Φ	constant for calculating the structural resistance
α_1	heat transfer coefficient outside [W/(m^2 K)]
α_2	heat transfer coefficient inside [W/(m^2 K)]
λ_C	thermal conductivity of the pipe layer (concrete) [W/(m K)]
λ_{IS}	thermal conductivity of the overlapping layer [W/(m K)]
λ_L	thermal conductivity of the heat conduction layer (sealing panel) [W/(m K)]
λ_p	thermal conductivity of the pipe wall [W/(m K)]
Γ	constant for calculating the structural resistance

reducing computing times, thermal resistance models are often used for the calculation of BHEs. A summary of common approaches is shown in [8,9], for example. By implementing the thermal resistance model into a numerical software tool, the whole system can be modelled with reasonable computing times and without losing accuracy (e.g. [10–12]).

Due to the missing rotational symmetry, these approaches cannot be applied for plane energy geostructures. Currently, there is a lack of corresponding approaches for plane energy geostructures, due to the high complexity and individuality of these systems. Therefore, only a few works exist (e.g. [13–15]). All of these approaches are characterized by simplifications. Particularly, the heat transfer in the pipes is neglected. Thus, the influence of the flow rate, the pipe geometry and the pipe arrangement cannot be considered. In view of these limitations, the authors developed a thermal resistance model for plane energy geostructures, which has been implemented into the finite difference code SHEMAT-Suite [16]. The main characteristics of this new approach are summarized in Sections 2 and 3. For verification, a benchmark study was performed using a fully discretized COMSOL Multiphysics® model. Both numerical models show a very good agreement [16]. For validation and proving the practical applicability, heat extraction tests in a large-scale laboratory test were carried out. These tests and the comparison with the results from the numerical approach are described in Section 4. Additionally, a parametric study was carried out. In this study, the decisive parameters influencing the thermal behaviour of plane energy geostructures were determined. The results are also summarized in Section 4.

2. Calculation approach for plane energy geostructures

For the design of plane energy geostructures, different heat transfer mechanisms in the ground, in the structural element, and in the heat exchanging pipes have to be considered. In our approach, a semi-analytical model is used for the description of the energy geostructure on the one hand. On the other hand, the finite difference method is applied for modelling the surrounding ground. In order to describe the structural element, a thermal resitance model was developed. which is based on the design approach for thermally active building systems (TABS) [17]. This approach was adapted to plane energy geostructures following the work of [18]. The fundamentals of the appoaches are shown below. Details can be found in [8,16].

In principle, the system can be built up via a delta-connection of different thermal resistances as shown in Fig. 1.

The temperature difference between the heat carrier fluid (T_F) and the ground (T_1) and the adjacent room (T_2) respectivly leads to a heat flow from the ground (outside, Q_1) and a heat flow from the room (inside, Q_2). These heat flows are characterized by the corresponding thermal resistances R_a and R_b. Due to the temperature difference between inside (T_2) and outside (T_1), a third heat flow occurs, which can be described by the thermal resistance R_c. The temperature at the outer surface of the pipe (T_3) can be calculated by using the pipe resistance $R_{p.}$ It depends on the convective heat transfer in the heat carrier fluid and the conductive heat transfer in the wall of the pipe.

The delta-connection can be transferred to a star-connection [17], which is more suitable for numerical implementation. The thermal resistances for the pipes and for the strcutural element (R_p, R_1, R_2) can be calculated according to the thermodynamic principles (e.g. [19]). The mathematical formulations are defined as follows:

$$R_p = \frac{a}{2\pi \cdot \lambda_p} \cdot \ln\left(\frac{d_o}{d_i}\right) + \frac{a}{\pi \cdot \lambda_p \cdot Nu} \quad (1)$$