Impact of Seasonal Heat Accumulation on Operation of Geothermal Heat Pump System with Vertical Ground Heat Exchanger

D V Timofeev, E G Malyavina
Department of Heating and Ventilation, National Research Institute Moscow State University of Civil Engineering, 26, Jaroslavskoe Shosse, Moscow 129337, Russia

E-mail: daniil@fastmail.fm

Abstract. The subject of the investigation was to find out the influence of heat pump operation in summer on its function in winter. For this purpose a mathematical model of a ground coupled heat pump system has been developed and programmed. The mathematical model of a system ground heat exchanger uses the finite difference method to describe the heat transfer in soil and the analytical method to specify the heat transfer in the U-tubes heat exchanger. The thermal diffusivity by the heat transfer in the soil changes during gradual freezing of the pore moisture and thus slows soil freezing. The mathematical model of a heat pump includes the description of a scroll compressor and the simplified descriptions of the evaporator and condenser. The analysis showed that heating during the cold season and cooling in the warm season affect the average heat transfer medium temperature in the soil loop in the winter season. It has been also showed that the degree of this effect depends on the clay content in the soil.

1. Introduction
Heat pump systems, which are connected to the vertical ground heat exchanger, are provided for heating and cooling of different buildings. Designing of these systems is complicated by the soil thermal inertia properties, constant and non-linear changing values of the heat carrier temperatures at the inlet and outlet of the heat pump, and consequently, its power. If the system operates in summer, the heat, which has been discharged from the premises of the building during the air conditioning, is transmitted to the ground loop and then to the soil. If the system operates in winter, the heat pump functions for heating of the building rooms and refrigerates the soil. If the system operates all the year round, the soil heating in summer will somehow put an effect on the system’s operation in winter. To investigate the influence degree of the heat pump system operation in summer on its winter functioning, a mathematical model has been developed and a software has been written to simulate the operation of the whole heat pump system.

The computer model consists of submodels of a vertical ground heat exchanger, a heat pump with constant rotation frequency of the scroll compressor drive, as well as the submodels of circulation pumps: both with constant and variable speed drive.

The computer model of the system represents each submodel as an object, which emits streams of events in response to the emitted event streams of the other objects. The climatic data and time’s steps are emitted by a special object, i.e. the environment object. The building, as an object, consumes the
stream only from the environment object, and heats or refrigerates the heat transfer agent according to the heat losses or the heat gain in the building loop.

2. Ground coupled heat pump system model
The mathematical model of the ground heat exchanger is given in the work [1]. The heat transfer inside the soil, as well as between the soil and the heat exchanger—“the exterior task” - is described there using the aggregate implicit transient finite-difference method of balances by the radius in the cylinder coordinates, and by the axis of the hole – in orthogonal coordinates. The temperature changes of the heat carrier along the route in the U-tube heat exchanger – “the inner task” – have been determined at each step of the coordinate analytically. The step borders along the U-tube axis in the heat exchanger corresponded to the nodes of the grid of the finite-difference “exterior task”. The heat transfer process between the heat carrier and the exterior surface of the pipes has been considered as a fixed one at each time step. Within the exterior task the U-shaped heat exchanger is represented as one pipe, which has the surface area equal to this one of all pipes of the U-shaped heat exchanger. To compensate the shape change, the nominal thermal conductivity has been replaced by a fictitious conductivity value. The value of the fictitious thermal conductivity is determined by the heat transfer resistance, which has been calculated according to the procedure [2]. The specificity of the mathematical model is that it takes into account gradual freezing of moisture in the soil by changing the characteristics of the heat capacity of the soil. The mathematical model of the heat pump is described in [3]. It is referred to the class of models, which are based on calculations of the heat pump parameters [4]. As compared to [4] model, which is implement in the EnergyPlus, it differs by the use of a scroll compressor, instead of a reciprocating one. The mathematical model of the scroll compressor has been made on the basis of the works [5,6], and is a simplification of the model [7]. Calculation of the refrigerant parameters at the compression cycle of scroll compressor has been made according to [8-10]. During the simulation procedure the heat pump may operates for heating, cooling, as well as a heat exchanger for free cooling or heating.

The mathematical model of the circulator pump is based on the equations given in [11]. It takes nominal pressure drop and liquid flow rate as a parameters of the model, and calculate pump motor electrical input power. The parameters of pump may be constant as in the case of constant motor speed drive, or controlled, as in the case of variable motor speed drive. In the latter case pump parameters are recalculated to find out the hydraulic power. The latter shall be converted into the pump electric input power by the motor and part load efficiency coefficients.

5. System simulation and discussion
The simulation of the heating dominant ground coupled heat pump system has been performed for a small residential building. The three cases were considered: when the ground heat exchanger is located at sand, or at clays, or at sandy loam soil. For each of these cases system performance was analyzed in two different operation modes: when the system operates only in winter for the building spaces heating, and when it operates in winter for heating and in summer for cooling of the building. A “reference year” of the city of Moscow has been taken as the climatic conditions [12]. The loads on the building has been calculated by RTS procedure [13] with enhancement, presented in [14]. For the results see figure 1. The average temperature values of the heat carrier at the ground loop and the building loop have been taken for the period from November to April. This range has been taken, because there are no Moscow days, when a heat pump shall operates for the building cooling.

Two cases have been examined for sand, sandy loam and clay soils. In the first case the heat pump operates only in winter for the building air heating and is switched off in summer. In the second case the heat pump operates for heating in winter and for cooling in summer. The density of 1.8 g/cm³ and the specific soil water content of 20% have been taken equal for sand, sandy loam and clay soils. The length of the ground heat exchanger is the same in all the cases. The initial temperature of the soil has been taken 4°C at the depth of 20 meters, and has been recalculated using the temperature gradient and the temperature on the ground surface.
Figure 1. Calculation of heating and cooling loads on the building. The
grey line shows the hourly loads. The black line shows the same loads,
but averaged by the double exponential smoothing.

The heat pump operation control has been provided according to the outdoor air temperature. The
heat pump has been switched on for heating, when the outdoor air temperature made 8 °C and lower,
for cooling, when it made 18 °C and higher.

The figure 2 shows the change of the average temperature of the heat carrier in the soil loop within
the heating season of 8 years. It shows, that the sand soil, being of high thermal conductivity in the
first year, becomes refrigerated up to the temperature, under which it will operates within the
remaining 7 years. The sandy loam soil stops to be refrigerated in the fifth year, and the clay – in the
sixth one. It is important to note, that the length of the hole has been taken the same in calculations of
all the three types of soils. It means, that the length of the heat exchangers for sandy loams and
especially for sands has been oversized, so that’s why they are subject to a more quick refrigeration. If
the length of the heat exchanger is made shorter for the sand soil, the result shall be expected the same,
as for sandy loams and clays.

Figure 2. Changes of the
average temperature in April-
November in the soil loop
within 8 years of simulation
of operation only for heating.
Solid line — sand soil, long
dashed line — sandy loam
soils, short dashed line —
clays.

The calculation results of the 8th year of the system service are given in the table 1. The average
values of the heating medium temperature within the building loop are nearly the same, because they
are controlled by automatic facilities of the heat pump. By contrast, the difference of the heating
medium average temperatures within the soil loop grows up during the operation in different modes:
0.47 °C of sands, 0.82 °C of sandy loam and 0.85 °C of clay soils. The average values of the heating
medium temperature within the soil loop are different and decrease, when the soil thermal
conductivity is reducing.
Table 1. Average soil temperatures for November-April in the ground loop and the building loop, if the heat pump of the heat supply system operate only for heating or for heating and cooling of the building premises.

| Soil type and its thermal conductivity, $\lambda$ (W/(m·°C)) | Average temperatures |
|-----------------------------------------------------------|----------------------|
|                                                           | Ground loop (°C)     | Building loop (°C) |
| Sands, $\lambda = 2.67$                                   | Heating 2.99         | 43.64              |
| Sandy loam, $\lambda = 1.86$                              | Heating and cooling 3.46 | 43.62              |
| Clays, $\lambda = 1.57$                                   | Heating 2.24         | 43.79              |
|                                                           | Heating and cooling 3.06 | 43.73              |
|                                                           | Heating 1.84         | 43.81              |
|                                                           | Heating and cooling 2.69 | 43.77              |

Due to a small value of refrigeration loads in Moscow, the total influence of the year-round operation the heat pump is not great. However, even in this case, the bigger content of clay in the soil increases its accumulating capacities. If the system is made as a hybrid one by addition of a heat generating element in the soil loop, for example, a Sun collector, such a solution will be effective in the clay soils.

References
[1] Timofeev D V and Malyavina E G 2015 Bulletin of Civil Engineers pp 196–202
[2] Remund C 1999 ASHRAE Transactions 105(1)
[3] Timofeev D V and Malyavina E G 2017 Proceedings of Moscow State University of Civil Engineering 12 pp 437–45
[4] Jin H and Spitler J 2002 ASHRAE Transactions 108(1) pp 3–17
[5] Duprez M-E, Dumont E and Frere M 2007 International Journal of Refrigeration pp 873–86
[6] Duprez M-E, Dumont E and Frere M 2010 International Journal of Refrigeration pp 721–8
[7] Chen Y, Halm N P, Groll E A and Braun J E 2002 International Journal of Refrigeration 25 pp 731–50
[8] Coquelet C, El Abbadi J and Houriez C 2016 International Journal of Refrigeration 69 pp 418–36
[9] Mulero A, Cachadina I and Tian J 2013 J. Chem. Thermodynamics 61 pp 90–9
[10] Poling B E, Prausnitz J M and O’Connell J P 2001 Properties of gases and liquids (McGRAW-HILL)
[11] Kavanaugh S and Rafferty K 2014 Geothermal heating and cooling: Design of Ground-Source Heat Pump systems (Atlanta: ASHRAE)
[12] Malyavina E G, Ivanov D S and Frolova A A 2013 Industrial and civil engineering pp 26–9
[13] 2013 ASHRAE Handbook Fundamentals
[14] Yan C 2015 Applied Thermal Engineering 77 pp 30–41