14th „Building Services, Mechanical and Building Industry days"
International Conference, 30-31 October 2008, Debrecen, Hungary

COMPARISON BETWEEN SIMPLIFIED AND DETAILED MODELS FOR VERTICAL GROUND-COUPLED HEAT EXCHANGERS

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KEYWORDS: *Ground source heat pumps, ground modelling.*

Abstract:
Geothermal energy is a promising technique for solving greenhouse gases emissions. One of the most interesting application is the use of heat pumps coupled with earth, by the use of close circuits with water flowing inside vertical boreholes. Many installations are addressed to small applications for residential issues, mainly for heating purposes, but many plants can also be applied to commercial users. For both applications the use of suitable tools is required for properly sizing the ground heat exchangers. In this paper two models are investigated and compared: ASHRAE method, a simplified calculation based on simple inputs and a specific model developed by authors, namely CARM (CApacity, Resistance Model). This last tool is presented and a tuning of the model is presented against measured values in a building equipped with ground source heat pump.

1. Introduction

Ground Source Heat Pumps (GSHP) is a promising technique for reducing CO_2 emissions. In the last years the market of heat pumps is increasing and in more buildings this system is going to be installed. Several calculation methods are in the market, but many times the problem can differ from usual solutions. For facing different possible solutions and problems a specific mathematical model has been developed. This model has been compared with measurements on a pilot office building and then compared with the most common ASHRAE method.

2. Mathematical models for ground heat exchange

Many models of ground heat exchangers are available today with different grade of complexity. Most of them are based on the following simplified equation which allows to calculate the heat flux exchanged between fluid and ground:

$$q = L \cdot \frac{(t_g - t_w)}{R} \tag{1}$$

where L is the total length of the borehole, t_g is the undisturbed ground temperature, t_w is the temperature of the fluid and R is the thermal resistance of the ground.

Usually the heat exchange is not in steady state conditions, thus changing the resistance by introducing some variables, e.g. Ingersoll et al. (1954), Eskilson (1987), and many others. Simplified models always give good results in medium-long term. If the behaviour in a short period is wanted to be investigated more complex models have to be used, which present longer calculation time.

2.1 ASHRAE method

In this model two functions $G = G(Fo)$ and $I = I(X)$ have been introduced by Kavanaugh and Rafferty (1997). Two equaions for the heat flux are introduced, if the heating mode (label h) or the cooling mode (label c) are considered:

$$L_c = \frac{q_a \cdot R_{ga} + (q_{lc} - \overline{W}_c) \cdot (R_b + PLF_m \cdot R_{gm} + R_{gd} \cdot F_{sc})}{t_g - \left(\frac{t_{wi} + t_{wo}}{2}\right)_c - t_p} \tag{2}$$

$$L_c = \frac{q_a \cdot R_{ga} + (q_{lc} - \overline{W}_c) \cdot (R_b + PLF_m \cdot R_{gm} + R_{gd} \cdot F_{sc})}{t_g - \left(\frac{t_{wi} + t_{wo}}{2}\right)_c - t_p} \tag{3}$$

where L_c and L_h are the length of the holes needed in the two operating conditions, q_a is the heat flow exchanged in the ground during one year q_{lc} and q_{lh} are the peak loads needed to cool/heat the building, $\overline{W}_c$ and $\overline{W}_h$ are the electrical powers absorbed by the compressor of the heat pump corresponding at the design loads, PLF_m is a reduction factor, F_{sc} is a loss factor due to the thermal short circuit in the pipe, t_g is the temperature of the undisturbed ground, t_p is the penalty temperature (due to other bores), t_{wi} e t_{wo} are the supply and return temperatures in the pipes, R_b is the thermal resistance (per unit length) between fluid and the external surface of the grout, R_{ga} is the annual thermal resistance (per unit length) of the ground, R_{gm} is the monthly thermal resistance (per unit length) of the ground, R_{gd} is the daily thermal resistance (per unit length) of the ground.

2.2 CARM model

For analysing the behaviour of the ground heat pump, a simulation code, called CARM, has been developed. It is based on the electric analogy representation of the thermal masses and resistances of the ground surrounding the pipe heat exchangers. The concrete grout thermal capacity has been neglected (due to its low value compared to the ground’s one) and the resistances between the pipe holes and the grout boundary have been separately calculated trough a detailed finite difference program (Blomberg 1999). This simplification has been assumed in order to have a radial one-dimension resistance-capacity model that describes the ground as a series of shells (Figure 1).

Along the vertical direction the ground can be divided in several layers, each one having its own thermal properties. A sensitivity analysis has been carried out to assess the number of subdivisions required for accurate results. If the thermal properties are constant, the analysis has demonstrated that three or four layers are sufficient. Heat flow in the vertical direction between ground layers has been neglected. The pipes are divided in several elements to study water temperature variation with depth. In Figure 2 the model of the water flowing inside a 2-U tubes heat exchanger is shown in detail. The model does not consider only a single borehole, but it takes into account the influence of other boreholes. If two boreholes are close and at distance d, the present of an adiabatic plane at distance d/2 can be assumed by assuming adiabatic planes at mid way between adjacent boreholes (Figure 3). CaRM model simulates also the heat pump coupled with the boreholes.

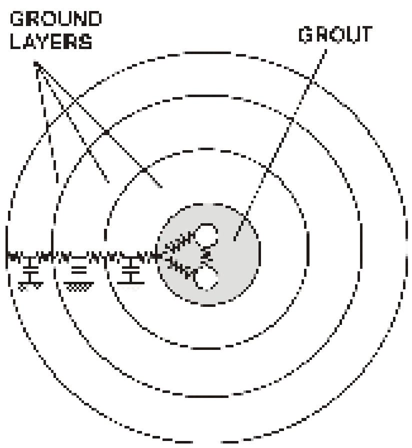


Figure 1 Model for a single U-tube ground heat exchanger (cross section)

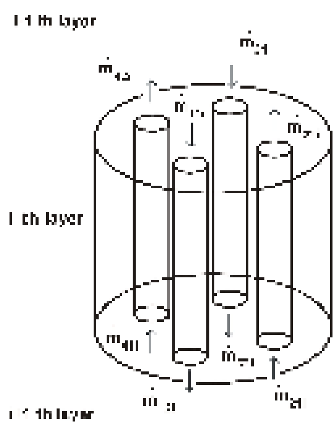


Figure 2 Water modeling of a double U-tube ground heat exchanger

3. Measurements on a pilot system

The system which has been measured is heating/cooling an office building. The geothermal system consists of a heat pump (nominal power of 80 kW), with 16 boreholes (95 m depth 7 m distance) L shape distribution. The heat pump has been specifically designed to work at two different temperature levels: in cooling conditions 5 °C during day-time (for air handling) and 15 °C during night-time, due to TABS (thermo-Active Building System); in heating conditions 35 °C during both day and night. In this way the COP may vary from 3.5 to 5.5 during the day and from 4.4 to 6.9 during the night in summer period, from 3.7 to 4.7 in heating conditions.

Ground properties of the area are reported in Table 1, based on geological analysis and on thermal properties of the ground obtained from literature data (Kavanaugh and Rafferty 1997). No significant aquifer movement is present within the proposed deepness. The temperature of undisturbed ground is 13.3 °C. Pipes have an external diameter of 31 mm and the water flow rate is 0.32 kg/s.

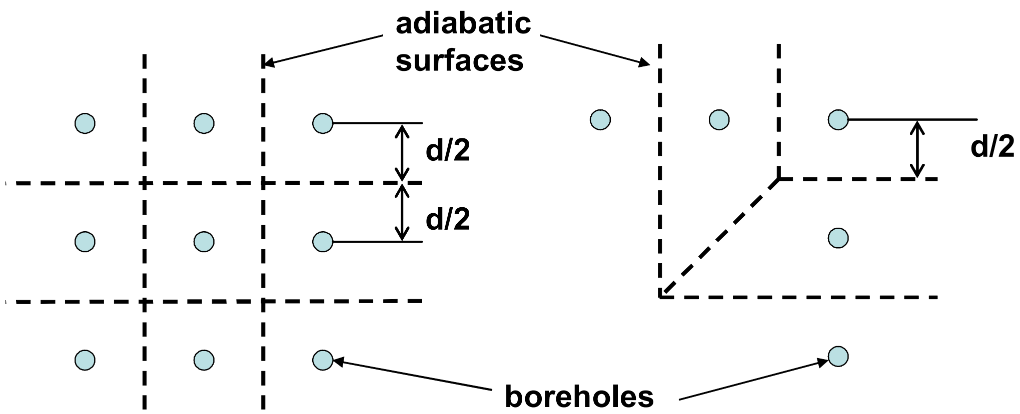


Figure 3 – Possible lay-out of the field: grid (a) and L shape (b) and adiabatic planes

Table 1 *Average characteristics of the considered ground*

Type of ground	Thickness [m]	λ [W/(m K)]	ρ [kg/m^3]	c_p [J/(kg K)]
Mix of clay and sand	90	1.90	1920	1155

4. Validation of the detailed model

4.1 Comparison between the proposed model and detailed simulation 2D model

CARM model has been compared with the detailed program HEAT2. The temperature value given by CARM has to be compared with the mean values on the same area (circular crown) of temperatures given by the detailed program HEAT2. The simulation performed by CARM gave the temperature trend in time domain at the edge of the grout. Such temperatures have been given as input for the detailed program. The mean value of temperatures in the circular crown given by HEAT2 has been compared with the values given by CARM at different time steps (here after 600, 800 and 1000 hours). The results, reported in Table 2, show good agreement between the two models.

4.2 Comparison between detailed model and measurements

Energy flow in the ground has been measured every 5 minutes and it considers both the vertical boreholes as well as the horizontal loop. Measurements have been carried out from end of May to end of July, at the beginning of operation of the building. For considering the horizontal profile, simulations with HEAT2 have been carried out. In Figures 4 and 5 comparison between measured and calculated results are shown for the whole period and in during 4 days in July respectively. Looking at the overall period of investigation, measured energy released into the ground has been 738 MWh, while with the model the calculated value has resulted 764 MWh, i.e. 3.6 % error.

Table 2– Comparison between temperatures in the ground between HEAT2 and CARM

Time step simulation [h]		Mean radius of the circular crown [m]									
		0.060	**0.527**	**1.059**	**1.980**	**2.941**	**3.570**	**4.325**	**5.231**	**6.318**	**7.623**
600	Heat 2	7.86	11.16	12.04	12.65	12.87	12.94	12.98	13.00	13.00	13.00
	CARM	7.86	11.25	12.09	12.67	12.89	12.94	12.98	12.99	13.00	13.00
800	Heat 2	10.66	11.07	11.86	12.53	12.80	12.89	12.96	12.99	13.00	13.00
	CARM	10.66	11.16	11.92	12.56	12.82	12.90	12.95	12.98	13.00	13.00
1000	Heat 2	7.48	11.40	11.83	12.43	12.73	12.84	12.93	12.97	12.99	13.00
	CARM	7.48	11.45	11.89	12.46	12.75	12.85	12.92	12.97	12.99	13.00

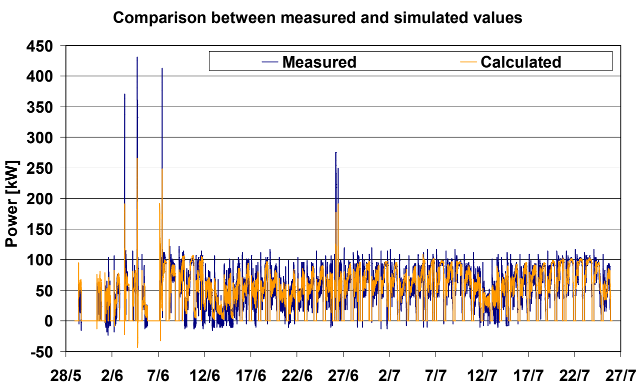


Figure 4 – Comparison between measured and calculated results in the investigated period

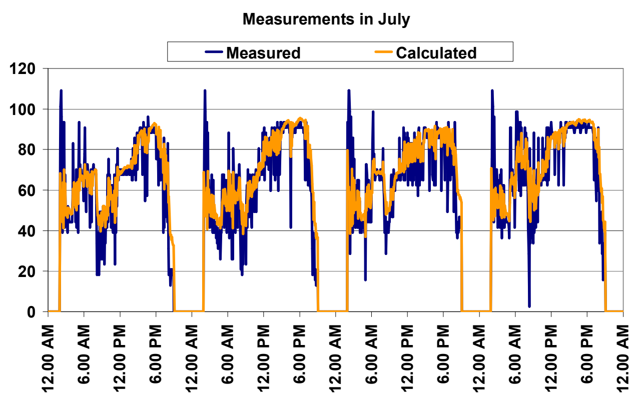


Figure 5 –Comparison between measured and calculated results in 4 days during July

5. Comparison between detailed model and ASHRAE method

In the comparison between detailed and simplified model a typical residential house with two flats (floor area is 160m^2) has been considered, located in the North of Italy. Heating and cooling is provided with radiant floor, while mechanical ventilation system (0.5 Vol/h of outdoor air) with 50% sensible heat recovery has been considered. Opaque walls have U = 0.3 W/(m^2 K), glazing surfaces U = 1.5 W/(m^2 K) and solar factor g = 0.35. Load profiles have been evaluated by means of building simulation via DigiThon model (Bottarel et al. 2008), which is based on transfer function method. Venice TRY has been used and an on/off regulation on the indoor temperature with set-point of 20°C (winter) and 26 °C (summer) has been considered.

In Table 3 design parameters of the building, as well as the yearly energy need for heating and cooling of the considered building are reported. In Table 4 characteristics of heat exchangers and physical properties of the ground (undisturbed temperature 13.2°C) are listed. A single U-tube has been considered, in particular two boreholes of 100 m have been taken into account (parallel connection). A mixture of water and ethylene glycol (25% in volume), with 0.5 kg/s flow rate, has been considered. In CaRM model the thermal resistances of Figure 6 are an input: they have been calculated by a simulation tool based on finite elements; R_{pp} is 1.637 m K/W and R_{p0} is 0.2 m K/W. In this case these thermal resistances take into account also the effect of the thickness of the pipe of the heat exchanger. In Figures 7 a result of the simulation by CaRM tool is reported. Results of CaRM model have been used as input in ASHRAE method (Table 5).

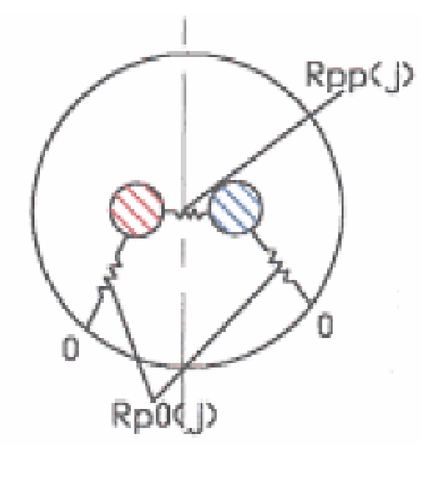


Figure 6 - Thermal resistances used in CaRM

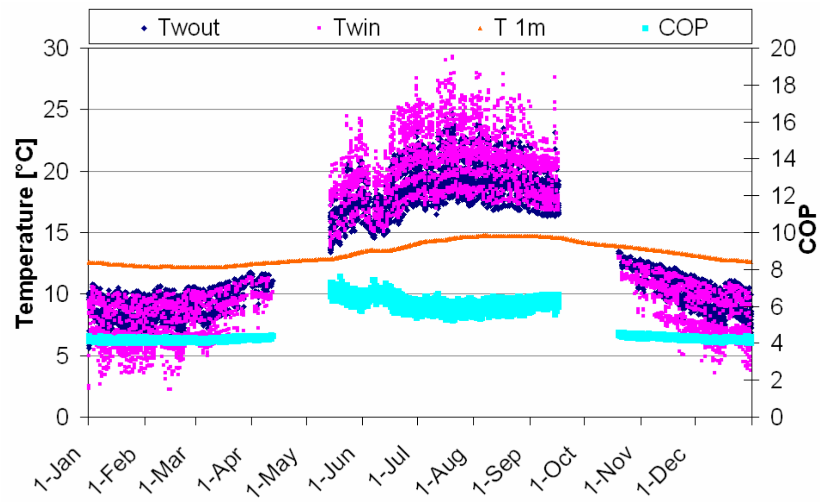


Figure 7 – CaRM output: temperature (supply, return, 1 m distance from grout) and COP of the heat pump

Table 3 - Building design heating/cooling conditions

	Heating	Cooling
Peak load [kW]	8.5	7.7
Yearly energy [kWh]	7600	6200
Working hours	2451	2250
Monthly Peak Load Factor (PLF_m)	0.432	0.395
Supply Temperature to radiant system [°C]	25	20
Return temperature from radiant system [°C]	23	22

Table 4 - Properties of the Simple U (PEAD)system (ground and borehole)

	Pipe	Grout	Ground
Thermal conductivity [W/(m K)]	0.4	1.6	1.7
Diameter [mm]	$d_e = 32$ / $d_i = 26$	120	
Thermal diffusivity of ground [m^2/s]			$8.5\ 10^{-7}$

Table 5 - Output of CaRM tool considered in ASHARAE method

	Heating	Cooling
Supply temperature [°C]	2.24	29.3
Outlet temperature [°C]	5.59	24.67
Ground thermal load [W]	6764	-9006

The thermal resistance of bore R_b of ASHRAE method has been calculated by:

$$R_b = R_{pipe} + R_g \tag{3}$$

where R_{pipe} is the thermal resistance of convection and pipe thickness, R_g is thermal resistance of filling of borehole. R_{pipe} is calculated by classical equation of heat transfer; on the other hand R_g is calculated by semi-empirical relation:

$$R_g = \frac{1}{S_b \cdot \lambda_g} \tag{4}$$

where $S_b = \beta_0 \cdot \left(\frac{d_b}{d_e}\right)^{\beta_1}$, λ_g is thermal conductivity of backfill and β_0 and β_1 are coefficients which are reported in Table 6.

In this work configuration B has been used: in this case R_b is 0.13 m K/W. The net annual average heat transfer to the ground (q_a) is -259.24 W; coefficient F_{sc} has been set 1.04. A temperature penalty for interference of adjacent bores (t_p) has not been taken into account since they are far away. Difference in results between the ASHRAE method and CaRM are reported in Table 7. It can be observed that ASHRAE overestimates the length of pipes to be installed, keeping calculations on the safety side.

Table 6 - Coefficient for evaluating thermal resistance of bore

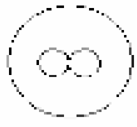
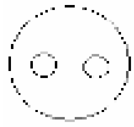
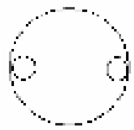
Configuration	 A	 B	 C
β_0	20.10	17.44	21.91
β_1	-0.9447	-0.6052	-0.3796

Table 7 – Comparison between results of the two different methods

	CARM	ASHRAE
Length for heating demand [m]	200	255
Length for cooling demand [m]	200	234

6. Conclusions

In this paper a detailed simulation model has been presented (namely CaRM). This model has been compared to two-dimension detailed finite difference model and with measurements in a pilot building, showing in both cases good agreement. CaRM has been also used in comparison with ASHRAE method, showing that ASHARE method overestimates the length of boreholes.

References

Ingersoll L. R., Zobel O. J., Ingersoll A. C. (1954). Heat conduction: with engineering and geological applications, 2nd edition.

Kavanaugh S. P., Rafferty K. (1997). Ground source heat pumps - Design of geothermal systems for commercial and institutional buildings, A.S.H.R.A.E. Applications Handbook.

Eskilson P. (1987). "Thermal Analysis of Heat Extraction Boreholes", Doctoral Thesis, University of Lund, Department of Physics, Sweden.

Bottarel D., De Carli M., Raisa V., Zarrella A, Zecchin R. 2008. The role of mechanical ventilation for efficient radiant cooling in residential applications. Proceedings of Indoor Air 2008, Copenaghen.