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INFLUENCE OF GROUND HEAT EXCHANGER MODELLING ON THE PREDICTED EFFICIENCY OF THE HEAT PUMP SYSTEM

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ABSTRACT

This paper presents simulations of the integral coefficients of performance of a heat pump system coupled with a vertical ground heat exchanger (GHE). The GHE is simulated using different assumptions concerning the heat transfer in the ground, heat exchange between the ground and the brine and vertical variation of the brine temperature.

The differences in the predicted performance coefficients of the heat pump system using the GHE as the lower energy source are analysed and shown to be significant.

NOMENCLATURE

General

c_p	- thermal capacity of ground in J / (kg × K)
dl	- length of GHE's segment in m
$r_{0,IN}$	- inner radius of the GHE's pipes in m
r_0	- outer radius of the GHE's pipes in m
r_1	- borehole radius in m
r_{MAX}	- maximal radius, the outer boundary in m
r_Q	- dimensionless position of point heat source
r_S	- dimensionless position of the image sink
z	- z-coordinate of the point source in m
z'	- z-coordinate of the image sink in m
H_m	- length of the GHE in m

Latin

g	- function
$\dot{q}$	- specific heat flux in W/m
r	- position relative to GHE's centre in m
rz	- radial position of the calculation node in m
t	- time in s
P	- electrical power consumption in W
$\dot{Q}$	- heat flux in W
R	- thermal resistance in (m^2 K) / W
T	- temperature in °C

Greek

α	- thermal diffusivity of the ground in m^2/s
β	- integral coefficient of performance
γ	- $\gamma = r / H_m$
η	- $\eta = z' / H_m$
λ	- thermal conductivity in W / (m × K)
ρ	- density of the ground in kg / m^3
ξ	- $\xi = z / H_m$

Subscripts

hp1	- beginning of the heating period
hp2	- end of the heating period
a	- external
i	- internal
init	- initial condition
sys	- global property of the system
A	- auxiliary devices except for the pump of the heating system
C	- compressor
Cont	- control units
HP	- heat pump
S	- storage tank

INTRODUCTION

Heat pump systems need a lower energy source to operate in the heating mode. The higher the temperature of the lower energy source the better the efficiency of the heat pump system.

The lower energy source may be constituted by outside air, water or ground. Air is the coldest when the heating demand is the biggest and water reservoir is not always available therefore we concentrate on the ground as the most universal source. Heat can be extracted from it by means of a collector or a vertical borehole. This paper discusses the modelling of a vertical double U-tube ground heat exchanger (GHE) which is quite a popular solution. The temperature of the brine leaving the GHE is decisive for the efficiency of the heat pump. This temperature depends on the temperature of brine which enters GHE, length of GHE, the properties of the ground surrounding it and the presence and strength of sources or sinks of heat (other GHE's) in the proximity of GHE. There is an ample number of models describing the different heat transfer phenomena in and around the GHE. Those phenomena can be divided into three groups:

1. heat transfer in the ground – which can be modelled in a great number of ways,

2. heat exchange between the brine, the grout and the ground in the immediate contact with the GHE – which is either assumed quasi-steady-state phenomenon or solved by means of different configurations of thermal RC-networks,

3. heat transport in the brine – which may or may not account for the temperature variation along the direction of the flow.

Little has been done in the way of reviewing those models. The influence they have on the predicted efficiency of the heat pump system is almost never reported. The primary objective of his paper is to close this gap by simulating the integral coefficients of performance (as defined later) of the heat pump system coupled with GHE. The GHE is simulated using different assumptions concerning the above mentioned points. The common assumptions for all investigated models are:

1. heat transfer in vertical direction is negligible

2. heat exchange with ground surface and the ground under GHE can be neglected

3. moisture transport and ground water flow are not accounted for

4. the equivalent temperature of the grout can be used to couple the heat transfer in ground with the heat transfer from brine and grout to the ground.

The second aim is to propose some extensions to the existing models of heat exchange in the ground.

SIMULATIONS

Heat pump and building characteristics

The geometry of the heated building is presented in figure 10. It is a well insulated detached house that meets the requirements of the German standard [EnEv 2004] which means that its annual predicted energy consumption does not exceed 50 kWh/a/m^2 (15848 BTU/a/ft^2). It is heated with a radiator heating system with operating temperatures of 45/35/20°C. That means that in steady state conditions, at the outside design temperature of -14°C the temperature in heating system will reach 45°C in supply, 35°C in the return pipe and the room temperature will stay at 20°C. Each radiator is fitted with a thermostatic control valve with the throttling range of 4K. The heating load is covered by the water-brine heat pump (B0/W35=6.9/1.6kW according to [DIN 2008]). The hydraulic circuit containing also a 200 litres parallel storage tank is presented in the figure 1. All the above components have been modelled in the version 14.2 of TRNSYS® that has been adapted, further developed and validated at the TU Dresden.

GHE geometry and discretization

The lower energy source of the heat pump is constituted by the vertical double U-tube ground heat exchanger. It consists of two pipes (outer radius r_0= 0.016 m; inner radius $r_{0,IN}$= 0.0131 m) placed in a H_m=100m deep vertical borehole with radius r_1= 0.055 m. The space between the pipes and the walls of the borehole is filled with betonite. The GHE is sketched in the figure 2 along with the thermal RC-network by means of which it is modelled.

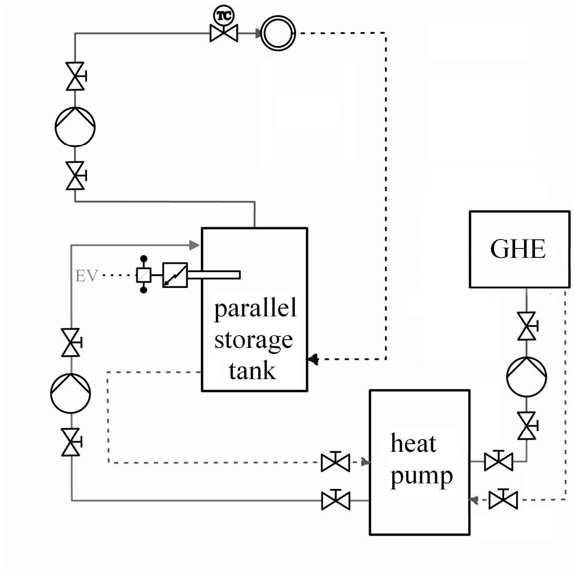

Figure 1 The hydraulic circuit of the heating system

For the sake of simplicity the brine flowing down in two pipes is assumed to have exactly the same temperature at any chosen depth and is modelled as a single node. The same assumption is applied to the brine flowing up. The heat transferred to and from the brine has to come through the pipes and then through the grout and only then can reach the ground.

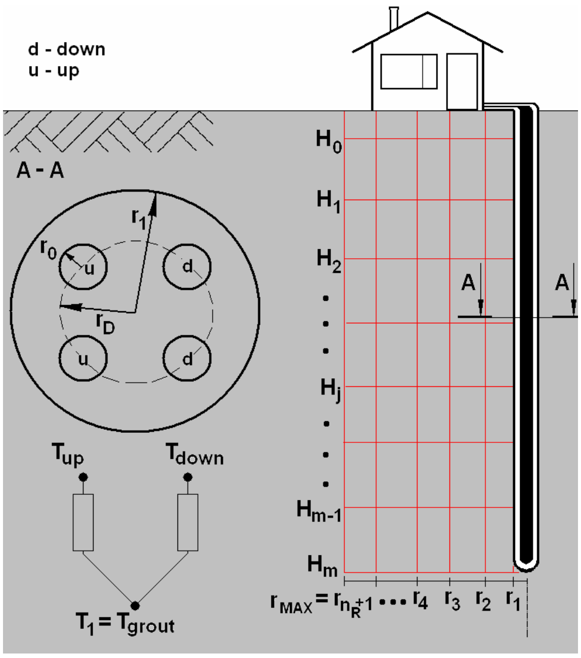

Figure 2 Geometry and discretization of GHE

That is because only the grout has contact with the ground surrounding the borehole. The temperatures of the grout (T_1) and the ground (T_2, T_3, … ,T_{nR}) are calculated in the nodes positioned at radiuses rz_1, rz_2, rz_3, … , rz_{nR+1} respectively. These radii are calculated from the following equation

$$rz_i = \sqrt{\frac{r_{i-1}^2 + r_i^2}{2}}$$

The radius of the last node is assumed equal to the outer boundary of the simulated domain: $rz_{nR+1}=r_{MAX}$. This node has no thermal capacity and its temperature is calculated according to the far ground model.

Overall program structure

The inputs of the GHE module are the temperature of the brine entering the GHE and the mass flow of the brine. The main output is the temperature of brine leaving the GHE but it is also possible to give out the temperatures of brine and ground. The brine entering the GHE comes directly from the heat exchanger of the heat pump. The brine leaving GHE goes directly back to the very same exchanger.

The brine exchanges the heat with the piping, grout and the ground surrounding the GHE. The thermal behaviour of ground is simulated at the radius of 2.0 m from the centre of the GHE. The boundary condition at this radius is determined every 21 600 seconds (every 6 hours) using various analytical solutions which are presented in the next paragraph. The time step for the whole simulation is determined by the reaction time of the control appliances and is fixed at 360 s.

Far ground models

The thermal behaviour of the ground between the grout and the outer boundary (radius r_{MAX}) is simulated by means of numerical explicit one-dimensional finite differences scheme. The conditions at outer radius are modelled by the following models of the long-time ground behaviour (radius $r = r_{MAX} = 2.0$ m):

1. The outer boundary of the simulation domain can be assumed to be an **adiabatic** surface as proposed in [Glück 2008] which means that:

$$\dot{q}(r = r_{MAX}) = \left.\frac{\partial T}{\partial r}\right|_{r=R_{MAX}} = 0 \qquad (1)$$

2. **Zeng** et al. in [Zeng et al.2002] proposed a more accurate and analytical formulation for the Eskilson's [Eskilson 1987] g-function

$$g_1(t,\gamma) = \frac{1}{2}\cdot\int_0^1\int_0^1 \left(\frac{erfc\left(\frac{H_m \cdot r_S}{\sqrt{4\alpha\cdot t}}\right)}{r_S} - \frac{erfc\left(\frac{H_m \cdot r_Q}{\sqrt{4\alpha\cdot t}}\right)}{r_Q} \right)\cdot d\eta\cdot d\xi \qquad (2)$$

by means of which the boundary temperature averaged along the borehole's length can be calculated from:

$$T(r = r_{MAX}) = T_{init} + \sum_{i=1}^{n}\left[\frac{\dot{q}_i - \dot{q}_{i-1}}{2\cdot\pi\cdot\lambda}\cdot g_1\left(t_n - t_{i-1}; \frac{r_{MAX}}{H_m}\right)\right] \qquad (3)$$

where

$$r_S = \sqrt{\gamma^2 + (\eta - \xi)^2} \quad , \quad r_Q = \sqrt{\gamma^2 + (\eta + \xi)^2} \quad ,$$

and the heat extraction from the borehole is assumed to be constant along the length of the GHE and a piecewise constant function in the time as depicted in figure 3.

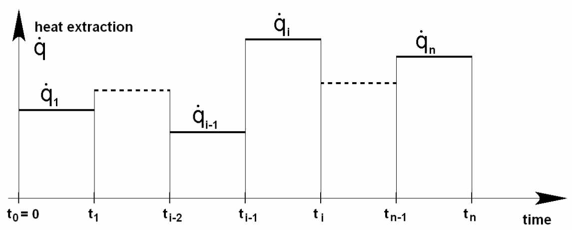

Figure 3 Heat extraction regime for g_1-function

This analytical solution is derived by using the method of images and integration of the point-source solution (both described in [Carslaw and Jaeger 1959]) along the length of the GHE. Such an approach is considered (see [Eskilson 1987]) to be sufficiently accurate only for the time steps larger than $\Delta\tau_{min} \geq 5 \times r_1^2 / \alpha$ (Ingersoll in [Ingersoll et al. 1954] demands even greater time steps of $\Delta\tau_{min} \geq 20 \times r_1^2 / \alpha$) as it does not exactly account for the difference between the thermal properties of ground and the grout within the borehole. This deficiency is compensated by the use of the numerical simulation of heat transfer in the ground near GHE for time periods shorter than $\Delta\tau_{min}$. Similar models are presented in [Yavuzturk and Spitler 1999], [Yavuzturk 1999], [LaMarche and Beauchamp 2007], [Xu and Spitler 2006], [Zhang and Murphy 2003], [Zeng et al. 2002], [Zeng et al. 2003], [Diao et al. 2004] and [Liu and Hellström]. Dobson in [Dobson et al. 1994] prefers the "infinite cylinder" solution given by [Carslaw and Jaeger 1942] and supported as the best fit by [Ingersoll et al 1954]. However, the analysis carried out by [Diao et al. 2004] and [Lamarche and Beauchamp 2007] suggests that cylinder solution gives slightly more accurate results for the times lower than $20 \times r_1^2 / \alpha$ and significantly worse solutions for times exceeding $10^5 \times r_1^2 / \alpha$ (when H_m/r_1=2500). For our specific case of α=8.8×10^{-7} m^2/s, H_m=100 m and r_1=0.055 m the linear model gives us worse results for the first 19.1 hours and is bound to still work properly after 10.9 years.

3. Our own proposal is to assume the heat extraction to be continuous and piecewise linear function of time and discontinuous, piecewise constant function of the depth as depicted in figure 4. We still use the same point source solution integrated in time and space so that the above mentioned limitations on the accuracy are also valid here. The temperature at the boundary of the k-th segment starting at the depth H_{k-1} and ending at the depth H_k is given by:

$$T_k(r = r_{MAX}) = T_{init} + \sum_{i=1}^{n}\left\{ -\sum_{j=1}^{m}\left[\frac{d_{i,j} - d_{i-1,j}}{2\cdot\pi\cdot\lambda}\cdot g_3\left(t_n - t_{i-1}; \frac{r_{MAX}}{H_m}\right)\right] + \sum_{j=1}^{m}\left[\frac{c_{i,j} - c_{i-1,j} + \left(d_{i,j} - d_{i-1,j}\right)\cdot t_n}{2\cdot\pi\cdot\lambda}\cdot g_2\left(t_n - t_{i-1}; \frac{r_{MAX}}{H_m}\right)\right]\right\} \qquad (4)$$

with

$$g_2(t,\gamma)=\frac{F}{2}\cdot\int_{\frac{H_{k-1}}{H_m}}^{\frac{H_k}{H_m}}\int_{\frac{H_{j-1}}{H_m}}^{\frac{H_j}{H_m}}\left(\frac{erfc\left(\frac{H_m\cdot r_S}{\sqrt{4\alpha\cdot t}}\right)}{r_S}-\frac{erfc\left(\frac{H_m\cdot r_Q}{\sqrt{4\alpha\cdot t}}\right)}{r_Q}\right)\cdot d\xi\cdot d\eta \quad (5)$$

$$g_3(t,\gamma)=\frac{G}{8\cdot\alpha\cdot\sqrt{\pi}}\cdot\int_{\frac{H_{k-1}}{H_m}}^{\frac{H_k}{H_m}}\int_{\frac{H_{j-1}}{H_m}}^{\frac{H_j}{H_m}}\left[r_S\cdot Ei\left(-\frac{H_m^2\cdot r_S^2}{4\cdot\alpha\cdot t}\right)\right.$$

$$\left.-r_Q\cdot Ei\left(-\frac{H_m^2\cdot r_Q^2}{4\cdot\alpha\cdot t}\right)\right]\cdot d\xi\cdot d\eta \quad (6)$$

where

$$c_{i,j}=\frac{1}{\rho\cdot c_p}\cdot\frac{\dot{q}_{i-1,j}\cdot t_i-\dot{q}_{i,j}\cdot t_{i-1}}{t_{i+1}-\cdot t_i}$$

$$d_{i,j}=\frac{1}{\rho\cdot c_p}\cdot\frac{\dot{q}_{i,j}-\dot{q}_{i-1,j}}{t_1-\cdot t_{i-1}}$$

and

$$F=\frac{H_m}{H_k-H_{k-1}}, \qquad G=\frac{H_m^3}{H_k-H_{k-1}}$$

r_S and r_Q are equal to those from g_1-function.

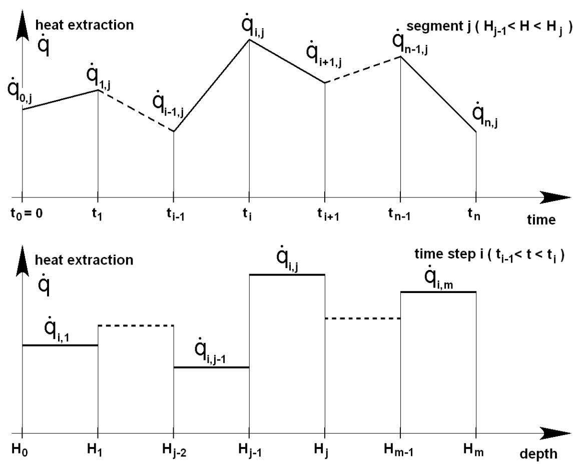

Figure 4 Heat extraction regime for new g-function

In all the above functions the values of error function erfc(x) have been calculated using Ooura's [Ooura 2006] mathematical package and formula given in [Abramowitz and Stegun 1967]. The exponential integral (function Ei(x)) has been calculated with algorithms given in [Thompson 1997].

Brine models

Following models are used to obtain the temperature profile of brine along the GHE:

1. **Constant profile** - the temperature of brine travelling down is assumed to be constant within each simulated pipe segment and equal to the average temperature of brine that travels down in this segment of GHE. The brine travelling up is treated in the analogous way. The temperatures of brine travelling down and up can differ.

2. **Linear profile** - the temperature of brine travelling down is assumed to have a linear profile within each simulated pipe segment. The average temperature of brine that travels down in this segment of GHE equals the arithmetic average of the temperatures of brine entering and leaving this pipe segment. The brine travelling up is treated in the same way. The temperatures of brine travelling down and up can differ. This approach has been used among others by Dobson et al. [Dobson et al. 1994]

Coupling between ground and brine

Following coupling methods are used to calculate the heat transfer between the GHE and the surrounding ground:

1. **Huber1** – Huber in [Huber and Pahud 1999] and [Huber 2005] proposed a one-dimensional model of coupling using the thermal RC-network from figure 5.

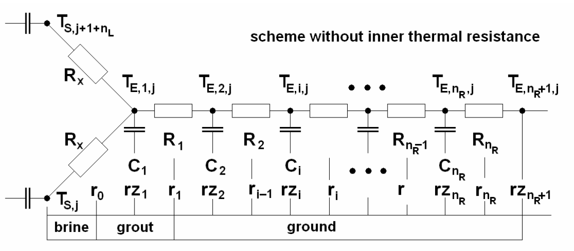

Figure 5 RC-network in first (1D) model of Huber

The resistances are

$$R_X=\frac{1}{4}\left(\frac{1}{2\pi\alpha r_0 dl}+\frac{\ln\left(\frac{r_1-rz_1}{r_0}\right)}{2\pi\lambda_{GROUT}dl}\right)+\frac{\ln\left(\frac{r_0}{r_{0,IN}}\right)}{2\pi\lambda_{PIPE}dl} \quad (7)$$

$$R_1=\frac{1}{2\pi\cdot dl}\left(\frac{\ln\left(\frac{r_1}{rz_1}\right)}{\lambda_{GROUT}}+\frac{\ln\left(\frac{rz_2}{r_1}\right)}{\lambda_{GROUND}}\right) \quad (8)$$

The thermal capacity of the grout is modelled as:

$C_1=C_{GROUT}=c_{GROUT}\times\rho_{GROUT}\times\pi\times dl\times(r_1^2-4r_0^2)$

Similar models are presented by [Xu and Spitler 2006] and [Zeng 2003].

2. **Huber2** - Hellström in [Hellström 1991] and Bennet at el. in [Bennet et al. 1987] proposed an analytical, two-dimensional method of determining the resistances between the brine and ground. Their method does not account for the thermal capacity of the grout and gives the resistance between the brine and an equivalent average temperature of the borehole wall. Huber in [Huber 2005] has modified a single U-tube formulation given by Hellström to account for the thermal capacity of the grout. Zeng et al. in [Zeng et al. 2003] has given a formulation for double U-tube without thermal capacity of the grout. By combining the formulas of Zeng with the method

of Huber a thermal RC-network depicted in figure 6 is created.

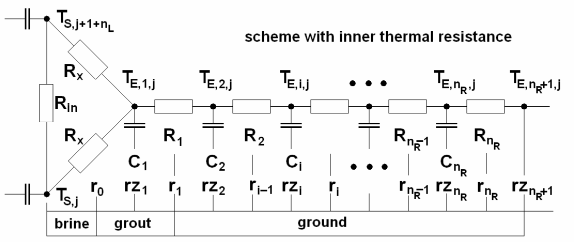

Figure 6 RC-network in second (2D) model of Huber

with

$$R_X = \frac{R_A}{2} - \frac{1}{2\pi\lambda_{GROUT}\,dl}\cdot\ln\left(\frac{r_1}{rz_1}\right) \qquad (9)$$

$$R_{IN} = \frac{1}{2\cdot\left(\frac{1}{R_B}+\frac{1}{R_C}\right)} \qquad (10)$$

where

$$R_A = \frac{1}{2\pi\lambda_{GROUT}\,dl}\left(\ln\left(\frac{r_1}{r_0}\right) - \frac{\lambda_{GROUT}-\lambda_{GROUND}}{\lambda_{GROUT}+\lambda_{GROUND}}\cdot\ln\left(\frac{r_1^2-r_D^2}{r_1^2}\right)\right)$$
$$+\frac{1}{2\pi\alpha\cdot r_{0,IN}\,dl} + \frac{1}{2\pi\lambda_{PIPE}\,dl}\cdot\ln\left(\frac{r_0}{r_{0,IN}}\right)$$

$$R_B = \frac{1}{2\pi\lambda_{GROUT}\,dl}\left(\ln\left(\frac{r_1}{\sqrt{2}r_D}\right) - \frac{\lambda_{GROUT}-\lambda_{GROUND}}{2(\lambda_{GROUT}+\lambda_{GROUND})}\cdot\ln\left(\frac{r_1^4-r_D^4}{r_1^4}\right)\right)$$

$$R_C = \frac{1}{2\pi\lambda_{GROUT}\,dl}\left(\ln\left(\frac{r_1}{2r_D}\right) - \frac{\lambda_{GROUT}-\lambda_{GROUND}}{\lambda_{GROUT}+\lambda_{GROUND}}\cdot\ln\left(\frac{r_1^2-r_D^2}{r_1^2}\right)\right)$$

R_1 and the thermal capacity of the grout are the same as in the first model of Huber. The above networks are modelled by finite differences scheme and resolved in time using explicit Euler scheme. In order to keep the numerical scheme stable, the time step is kept below the stability criterion for explicit Euler scheme:

$$\Delta t \le \frac{1}{2\cdot\alpha\cdot\left(\frac{1}{\Delta r^2}\right)} \qquad (11)$$

The maximal value of the time step has been also kept below the time needed to rinse one-fourth of the shortest modelled pipe segment when the brine is being pumped. This assures that the assumptions behind the used heat balance equations remain valid.

Case definition

The simulations of thermal performance have been carried out for various combinations of the above models. Each simulated combination has been given a case number in order to simplify the presentation of results. The case numbers are shown in the table 1.

Table 1
Definition of the simulated cases

		1	2	3	4	5	6	7	8	9	10	11	12
ground	adiabat.	X			X			X			X		
	Zeng		X			X			X			X	
	new			X			X			X			X
brine	const.	X	X	X	X	X	X						
	linear							X	X	X	X	X	X
couplin	Huber1	X	X	X				X	X	X			
	Huber2				X	X	X				X	X	X

RESULTS

Integral coefficients of performance

A plethora of studies on efficiency of heat pumps exists. All of them use the term "coefficient of performance" as the ratio of the amount of heat gained from the heat pump system to the electrical energy used up for heat pump's operation. The last two concepts are almost never defined or defined in a number of different ways. For this reason the following definitions are proposed. The integral coefficients of performance (ICOP) are defined as internal (β_i), external (β_a) and total system's (β_{sys}) coefficients of performance.

The internal ICOP (β_i) equals the ratio of the total heat won from the heat pump during the heating period to the power consumption of the compressor.

$$\beta_i = \frac{\int_{t_{hp1}}^{t_{hp2}} \dot{Q}_{HP}\cdot dt}{\int_{t_{hp1}}^{t_{hp2}} P_C\cdot dt} \qquad (12)$$

In the external ICOP (β_a) the gained heat is related to the power consumption of the compressor and other parts of the heating system (ventilator, brine pump, storage charge pump).

$$\beta_a = \frac{\int_{t_{hp1}}^{t_{hp2}} \dot{Q}_{HP}\cdot dt}{\int_{t_{hp1}}^{t_{hp2}} \left(P_C + P_A + P_{Cont}\right)\cdot dt} \qquad (13)$$

The total ICOP (β_{sys}) of the whole system is defined as the ratio of the amount of heat gained from the heat pump unit diminished by the heat losses of the storage tank to the total power consumption of all components.

$$\beta_{sys} = \frac{\int_{t_{hp1}}^{t_{hp2}} \left(\dot{Q}_{HP} - \dot{Q}_S\right)\cdot dt}{\int_{t_{hp1}}^{t_{hp2}} \left(P_C + P_A + P_{Cont}\right)\cdot dt} \qquad (14)$$

The values of the ICOP coefficients for the analysed system are given in table 2 and in the following figures.

Table 2
ICOP coefficients for the analysed cases

case	model	β_i	β_a	β_{sys}
1	adiabatic/const./Huber1	3,97	3,46	3,38
2	Zeng/const./Huber1	4,17	3,63	3,54
3	new/const./Huber1	4,21	3,66	3,57
4	adiabatic/const./Huber2	3,62	3,17	3,09
5	Zeng/const./Huber2	3,82	3,33	3,25
6	new/const./Huber2	3,86	3,37	3,29
7	adiabatic/lin./Huber1	3,95	3,45	3,36
8	Zeng/lin./Huber1	4,16	3,62	3,53
9	new/lin./Huber1	4,20	3,65	3,57
10	adiabatic/lin./Huber2	2,71	2,39	2,33
11	Zeng/lin./Huber2	3,00	2,64	2,58
12	new/lin./Huber2	3,09	2,71	2,65

The results show that the influence of the ground temperature model is very small (see Figure 7).

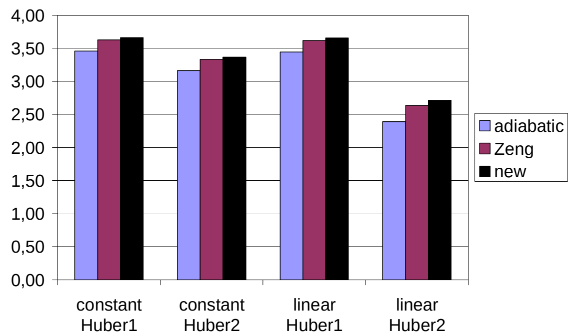

Figure 7 Influence of the earth model on ICOP β_a

The influence of the model of brine is much stronger but its influence depends strongly on the used coupling model (see Figure 8).

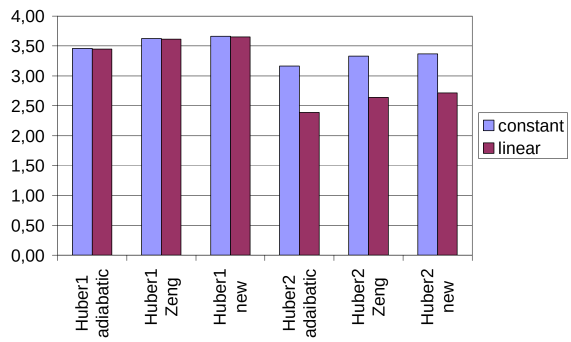

Figure 8 Influence of the brine model on ICOP β_a

The model with the strongest influence on the predicted ICOP values is clearly the model of coupling of the brine, grout and the earth surrounding the GHE (see Figure 9). The second model of Huber, which accounts for the possible short circuiting between the brine entering and leaving the GHE predicts the lowest temperatures of the brine which is reflected in the ICOP values. The more accurate simulation of the brine temperature makes this effect only more visible. The maximal difference between the integral COP values gained by using different GHE models circulates around 1.3 (1.50 / 1.27 / 1.24 for β_i / β_a / β_{sys} respectively). The most optimistic results are won by using the piecewise constant temperature of brine together with the first model of coupling and proposed ground model. The most pessimistic results are predicted by the combination of piecewise linear temperature distribution in the brine combined with the second model of coupling and adiabatic ground behaviour.

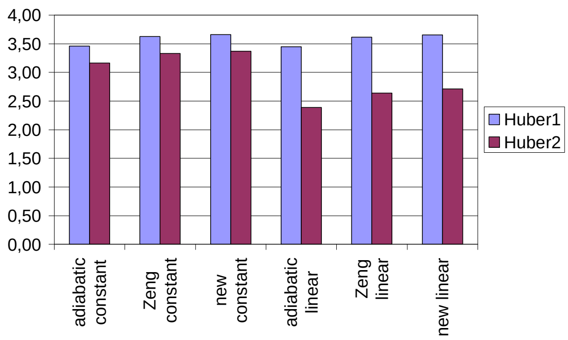

Figure 9 Influence of the coupling model on ICOP β_a

CONCLUSION

This paper has shown the influence of the models of GHE on the predicted integral coefficient of performance of the heat pump system with a parallel storage tank. The way of modelling the temperature of the brine and its heat exchange with the grout and the ground surrounding the GHE were shown to have the biggest impact on the results. The differences in annual COP can reach up to 1.5 points for different models' combinations. The question arises: which model does best reflect the reality? On one hand the COP values seem to fall with the growing sophistication of the applied models. That would mean, that lower COP values and stronger cooling down of the ground are more likely. On the other hand, the presented models do not account for the two dimensional heat transfer, moisture transport and the ground water flow. All those factors, when accounted for, would have positive influence on the attained COP value as stated for example in [Leong et al 1998] and [Diao et al. 2004].

The authors of the examined models all claim that they could get a good overlap of their simulated results with the experimental data, usually after minor adjustments of the model's coefficients. The experimental investigations [Auer and Schote 2008] suggest that the external values of integral COP for the examined hydraulic circuit lie in the range between 3.30 and 3.83. Those values are consistent with our results won with help of the coarser models. We believe the presented models to give the boundaries of the range in which the real values can be found. The expansion of the simulation program by accounting for the influence of advection, moisture transport and the two dimensional phenomena in the region close to the ground's surface could give more accurate and more optimistic results, reflecting the values won by the measurements. Such an extended model would obviously require more information on the boundary conditions such as geological structure of ground, thermal properties of its components as well as the magnitude of the local ground water flow and its temperature. Such data are unfortunately very scarce. The existing coarse models seem sufficient for the design purposes where information on physical properties of the ground is scarce or non-exsistent. When using them one must be aware that the values delivered by them contain overlapping errors and must be seen as an estimate rather than exact value. Such exact values could be won from more sophisticated models accounting for all relevant factors. That in turn would enable a more detailed analysis of the heat pump systems.

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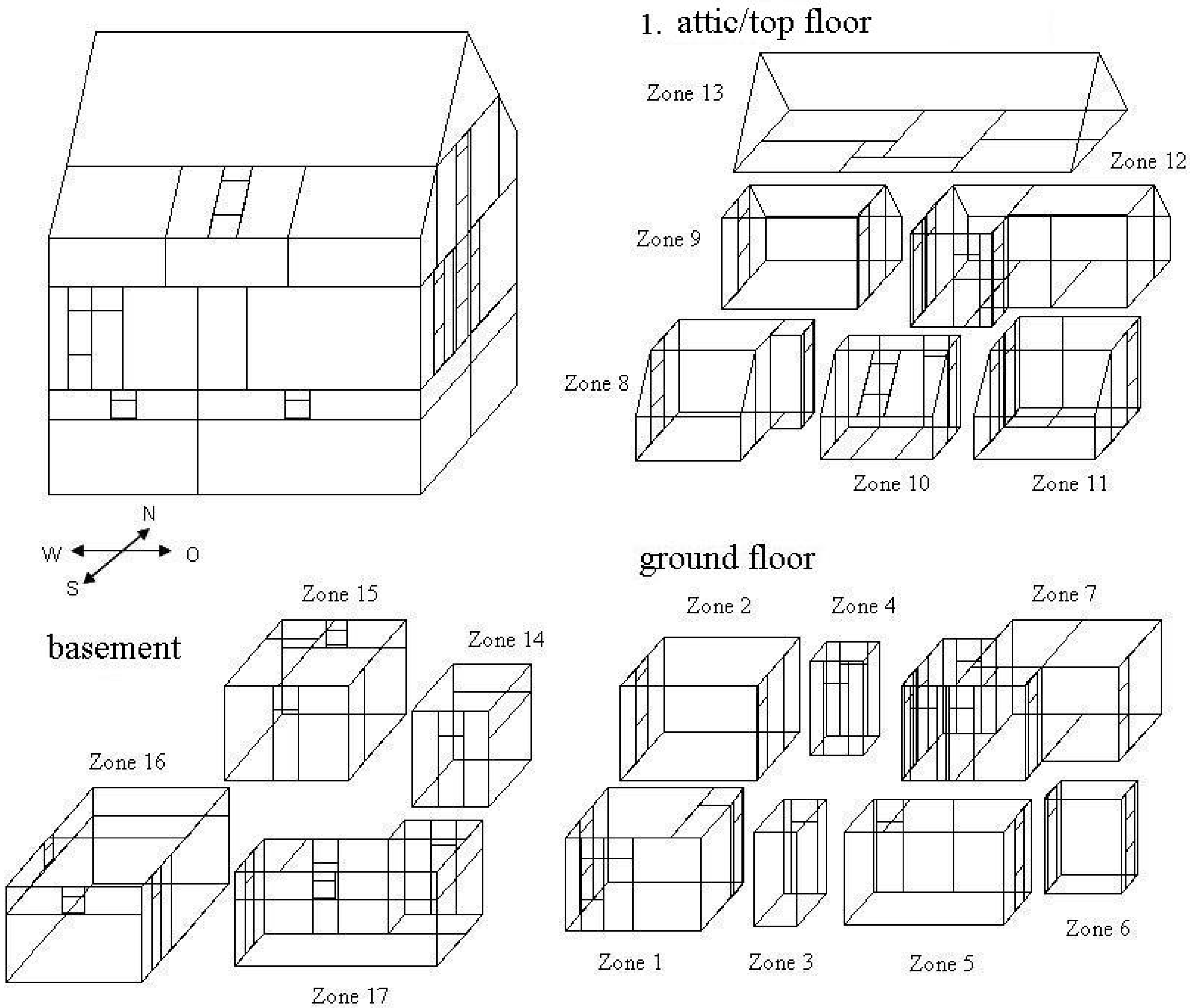

Figure 10 Sketch of the modelled building