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SIMULATION OF A DOMESTIC GROUND SOURCE HEAT PUMP SYSTEM USING A TRANSIENT NUMERICAL BOREHOLE HEAT EXCHANGER MODEL

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ABSTRACT

Common approaches to the simulation of Borehole Heat Exchangers (BHEs) assume heat transfer in circulating fluid and grout to be in a quasi-steady state and ignore fluctuations in fluid temperature due to transport of the fluid around the loop. However, in domestic ground source heat pump systems, the heat pump and circulating pumps switch on and off during a given hour; therefore the effect of the thermal mass of the circulating fluid and the dynamics of fluid transport through the loop has important implications for system design. This may also be important in commercial systems that are used intermittently. This paper presents transient simulation of a domestic Ground Source Heat Pump (GSHP) system with a single BHE using a dynamic three-dimensional numerical borehole heat exchanger model.

INTRODUCTION

The Climate Change Act 2008 has set the target for 2050 that the UK should reduce emissions of the carbon dioxide and the other greenhouse gases at least 80% by 2050 relative to the 1990 baseline. The UK residential sector accounts for around 30% of total final energy use and more than one-quarter of total CO_2 emissions; therefore, reducing energy consumption and CO_2 emission in the domestic sector can be significant (Kannan and Strachan, 2009). Ground Source Heat Pump (GSHP) systems, due to their higher coefficients of performance (COP) and lower CO_2 emissions, have been proposed as sustainable systems for domestic buildings to provide heating and hot water in the UK. A recent study shows that a suitably sized GSHP system could achieve almost 40% CO_2 savings when compared to a conventional gas boiler (Jenkins et al., 2009). Even though GSHP systems have well established in North America and many parts of Europe, there are still relatively a few systems installed in the UK. However, because of their potential to reduce energy consumption and CO_2 emissions, GSHP systems are receiving increasing interest.

Pipes formed in a 'U' loop and grouted into vertical boreholes are probably the commonest form of ground heat exchanger found in GSHP systems, known as Borehole Heat Exchangers (BHEs). Their careful design is critical to the long-term performance of the heat pump system. A horizontal cross-section of half of a typical BHE is shown in Figure 1. BHEs of this type are not only used in conventional building heating and cooling systems but also in large thermal storage schemes. BHEs can not be designed on the basis of steady-state calculations but require application of dynamic thermal models that are able to take account of the heat transfer inside the borehole as well as the surrounding soil/rock formation. The purpose of the model developments discussed here is to:

- Investigate the effects of the dynamics of the fluid transport along the pipe loop;
- Investigate the three-dimensional characteristics of heat transfer around the borehole;
- Develop insight into the limitations of two-dimensional models and suggest ways in which they can be improved.

In this paper, development of the numerical model is described in brief and results of application of the model in building heating system simulations are presented.

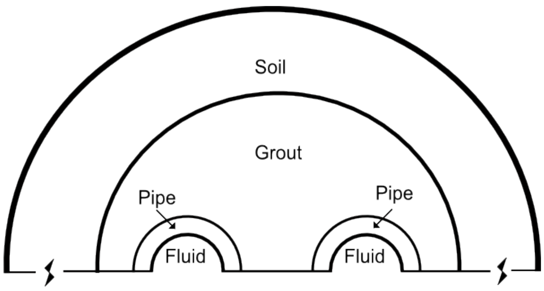

Figure 1 A half cross-section of a Borehole Heat Exchanger.

HEAT EXCHANGER MODELS

Models of BHEs have three principle applications:

1. Design of BHEs. This means sizing the borehole depth, number of boreholes etc.
2. Analysis of in-situ ground thermal conductivity test data.
3. Integration with building system simulation i.e with the model coupled to HVAC system

and building heat transfer models to study overall performance.

Analytical models have been developed by making a number of simplifying assumptions and applied to both the design of BHEs and analysis of in-situ test data. The analytical Cylinder Source solution presented by Carslaw and Jaeger (1947) has been applied by treating the two pipes as one pipe coaxial with the borehole. Further simplifying the pipe and the borehole as an infinitely long line source, the line source solution (Ingersoll et al., 1954) can also be used and is commonly done so in the analysis of in-situ thermal conductivity test data.

Although analytical solutions require less computing effort, they are less suited to design and simulation tasks where one would like to take account of time varying heat transfer rates and the influence of surrounding boreholes on long time scales. A number of approaches that have combined analytical and numerical methods have been developed with design tasks in mind. Eskilson (1987), and later Helstrom (1991) developed a response factor approach – using so called g-function - to design BHEs for thermal storage applications. Response to heat flux over timescales of approximately one month to more than ten years can be derived from application of these models and integration of the response according to the number of boreholes and the relationship to those neighbouring. The response can be normalised and so applied to ranges of BHE configurations.

Analytical models such as the line source approach and also the g-function models make simplifications about the grout and pipes within the borehole. The common assumption is that the relationship between the fluid and the borehole wall temperatures can be defined by a thermal resistance i.e. a coaxial pipe without thermal mass. The fluid temperature is one representative of the loop inlet and outlet temperatures (often their average). The borehole thermal resistance then becomes an important quantity for design purposes. There are a number of ways of calculating this resistance that take some account of pipe size and spacing. The most rigorous method is the multipole method (Bennet et al., 1987) which represents the pipes in the circular borehole using a series of line heat sources or sinks.

Application of models for system simulation tasks – unlike design tasks – requires the ability to operate at much shorter timescales than one month. The dynamic response of the grout material inside the borehole should also be considered. Yavuzturk and Spitler (1999) extended the g-function model to short time steps to be considered by applying the finite difference method on a two-dimensional radial-axial coordinate system to solve the partial differential heat conduction equation. This short time step g-function has been implemented in EnergyPlus and validated by Fisher et al. (2006). Also, Hellstrom developed the DST model (1991) to simulate BHEs using a one-dimensional radial mesh to calculate the thermal resistance of a borehole by approximating the steady-state heat transfer in a borehole. Likewise, the DST model has been implemented in TRNSYS (SEL, 1997).

Two-dimensional numerical models that discretise the material inside and outside the borehole (e.g. that of Yavuzturk) can be used to calculate the dynamic properties of all BHE components – pipes, grout and rock. Borehole resistance is calculated explicitly. Young (2004) has recently used such a model to include the fluid and the effect of its thermal mass. Such two-dimensional models avoid some of the simplifications of other models and can distinguish between different pipe and grout properties and geometry. However, as variation in fluid temperature with depth can not be considered explicitly, some assumption has to be made – as it does with simpler models – about the fluid temperatures in the two pipes and the associated boundary conditions. For example, both pipes could be assumed to be at a temperature equivalent to the average of the inlet and outlet temperatures. An alternative is to assume one pipe temperature is the same as that of the inlet and the other is at the outlet temperature. We discuss the significance of these assumptions later. These assumptions can be avoided in a three-dimensional numerical model.

In this study, we have applied a three-dimensional finite volume model. Several three-dimensional models have been developed to simulate BHEs (Bandyopadhyay et al., 2008; Lee and Lam, 2008; Zeng et al., 2003). The advantages of a three-dimensional model include:

- Fluid transport along the pipe loop and the dynamics of the fluid can be represented;
- Fluid, borehole and ground temperature variation along the borehole depth can be modelled;
- Different layers of rock and soil can be explicitly represented;
- Climate dependent boundary conditions at the surface can be applied;
- Heat transfer below the borehole can be explicitly considered;
- Initial vertical ground temperature gradients can be applied.

Two-dimensional models may now be computationally efficient enough for practical design and simulation purposes. Three-dimensional models offer most generality and most accurate representation of heat transfer and so are useful for detailed studies like that presented here but are not yet suited to practical simulation of annual or super annual performance.

MODEL DEVELOPMENT

A dynamic three-dimensional BHE numerical model has been developed that is built upon a finite volume solver known as GEMS3D (General Elliptical Multi-block Solver). This has been developed to simulate the dynamic response of the circulating fluid and transient heat transfer in and around BHEs. The GEMS3D model applies the finite volume method to solve the general advection-diffusion equation on three-dimensional boundary fitted grids. The approach is similar to that described by Ferziger and Peric (2002). The multi-block structured mesh allows the complex geometries around the pipes in BHEs to be explicitly represented (Figure 2).

A three-dimensional representation that includes cells representing the fluid means that transport of fluid along the pipe, down and up the borehole, allows the variation of fluid, grout and borehole temperatures with depth to be considered. This also and perhaps more importantly, allows the effects of the delayed response of the outlet to variations in inlet temperature to be studied.

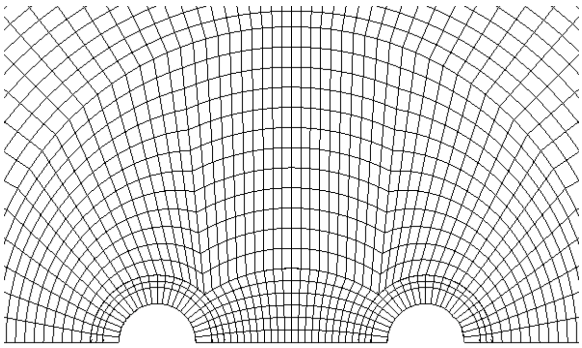

Figure 2 A cross-section of boundary fitted grid showing the pipe and grout region. Symmetry allows only half the borehole geometry to be included.

Precisely the same numerical method has been implemented in a two-dimensional version of the code (GEMS2D). The two-dimensional model can also be considered equivalent to a three-dimensional model of one cell depth (1m). This two-dimensional implementation has been used here to highlight the differences between model predictions that are due solely to three-dimensional effects and dynamic fluid transport. The two-dimensional model necessarily employs some of the simplifications of other existing models. One important issue in defining a two-dimensional model is relating the model boundary conditions to the inlet and outlet fluid temperatures. In this case, one pipe of the model is assumed to have a temperature the same as the inlet. The temperature boundary condition applied to the second pipe is calculated in an iterative manner so that the total ground heat transfer rate is consistent with the fluid heat balance.

There is no analytical solution for three-dimensional heat transfer in a borehole geometry that can be applied to try to validate the numerical model. It is useful however to show some validation using a two-dimensional calculation of borehole thermal resistance. Numerical values can be compared with the multi-pole analytical solution method (Bennet et al., 1987). This is done by making a two-dimensional steady-state calculation of the heat flux for a given fluid and far field temperature.

Assuming the heat transfer of BHEs is in steady-state, the total amount of heat flux between the fluid and the ground can be expressed as:

$$Q = \frac{T_f - T_{borehole}}{R} \tag{1}$$

where Q is the total heat flux, T_f is the fluid temperature, $T_{borehole}$ is the borehole wall temperature, and R is the borehole thermal resistance, which includes the convective resistance between the fluid and the inner side of the pipe, the conductive resistance of the pipe, and the conductive resistance of the grout.

Two different types of grout have been used in the validation study, one with the thermal conductivity of 0.75 W/mK, and the other one with the thermal conductivity of 1.5 W/mK. For the grout with the thermal conductivity equal to 0.75 W/mK, the borehole thermal resistance calculated by the numerical model was 0.1821K/W while by the multipole model is 0.1823K/W. In addition, for the grout thermal conductivity equal to 1.5 W/mK, the borehole thermal resistance by the numerical model was found to be 0.1157 K/W while by the multipole model is 0.1158 K/W. The model can be seen to be capable of matching analytical values extremely closely. Variation of mesh density by a factor of five (the mesh in Fig. 2 is in the middle of the range) showed variation of the calculated borehole thermal resistance of less than 0.4%. In practice calculation, using courser meshes to reduce computation times would be reasonable.

Fluctuations in fluid temperature due to transport of the fluid through the loop are usually ignored in common approaches to model BHEs. In situations where the heat pump and circulating pumps switch on and off during a given hour, and in situations where the building loads have noticeable peaks, the dynamic response of the circulating fluid is of great importance. The effect of the thermal mass of the circulating fluid and the dynamics of fluid transport through the loop is to damp out fluctuations in the outlet temperature of BHEs, which has important implications for system design.

Using a layer of cells inside the pipe allows the fluid to be discretised along the length of the borehole. Fluid velocity is imposed in these cells and the transport of heat from one cell to the next along the pipe is then represented by a convection term in the temperature differential equation being solved. Each finite volume cell can be considered as a well-mixed node that is defined by a single temperature T, and is transported at velocity V (Figure 3).

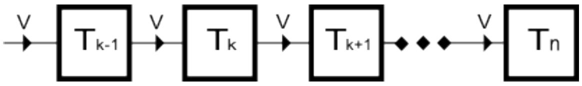

Figure 3 Diagram of fluid transport model.

The fluid cells in the model can be considered similar to a Compartments-In-Series model (Wen and Fan, 1975) . Fluid transport models of this type have been widely used in process engineering and their characteristics are well known. Thermal response of the pipe inside the borehole will be different from this simple model by virtue of heat transfer to the pipe wall. However, it is worth testing the model without this heat transfer for the purposes of validation. The transporting properties inside pipes (be it heat or a chemical species that travels along the pipe) can be thought of in terms of Residence Time Distribution (RTD). The RTD is considered as the fraction of fluid, which undergoes a step change at the inlet, appears in the outgoing fluid at time t, and it is represented by the function *F(t)*, illustrated in a *F*-Diagram. The analysis is simplified by using dimensionless time given by,

$$\tau = \frac{\dot{v}t}{V} \qquad (2)$$

where: $\dot{v}$: volume flow rate, m^3/s

V : system volume, m^3

The actual shape of the *F*-Diagram depends primarily on the velocity profile, in which case the faster-moving elements near the centreline will arrive at the end of the pipe more quickly than the average. Fluid undergoes a diffusion process so that step changes in inlet condition are smoothed. Hanby et al. (2002) examined the Compartments-in-Series model and found it performed well but the solution was not independent of the number of compartments. They made comparisons with an analytical solution for the RTD in turbulent flow. The results indicated that the optimum number of nodes is 46, but given computational constraints, 20 nodes give a reasonable approximation. Figure 4 shows the *F*-Diagram generated by GEMS3D using 40 cells compared with the analytical solution (Bosworth, 1949) and the results indicate the dynamics of fluid transport predicted by the GEMS3D model satisfactorily matches the analytical solution.

The delayed response to transient variations in inlet temperature is of significance in that GSHP system designs (i.e. choice of borehole depth) are sometimes constrained by peak load conditions. In these cases, selection of too small a BHE could result in fluid temperatures close to or outside the operating range of the heat pump for short periods. Two-dimensional models (numerical or analytical) are not able to consider the effects of fluid transport in the pipe.

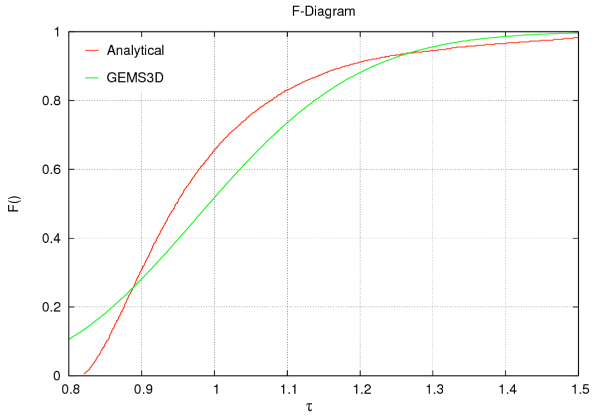

Figure 4. F-Diagrams by GEMS3D model compared with the analytical solution.

The significance of the transient fluid transport can be investigated by applying step changes in borehole inlet temperature. This has been done using step changes that might be typical of a domestic GSHP system and the on-and-off operating intervals of the heat pump operation. The heat pump cycles twice per hour (on for 15 min and off for 15 min, and then on for another 15 min and off for another 15 min), and when the heat pump is on, the inlet temperature of the BHEs maintains at 20 °C , and when it is off, the inlet temperature maintains at 10 °C. The initial ground temperature is 10 °C, and the fluid only circulates along the pipe loop when the heat pump is on.

A calculation using the two-dimensional model has been carried out for the purposes of comparison. In this model, the fluid outlet temperature necessarily shows an instant response to changes in inlet temperature. This is not only true of the GEMS2D two-dimensional model but is also true of all models that are formulated on a two or one-dimensional basis. The results of the simulations by the two models are shown in Figure 5.

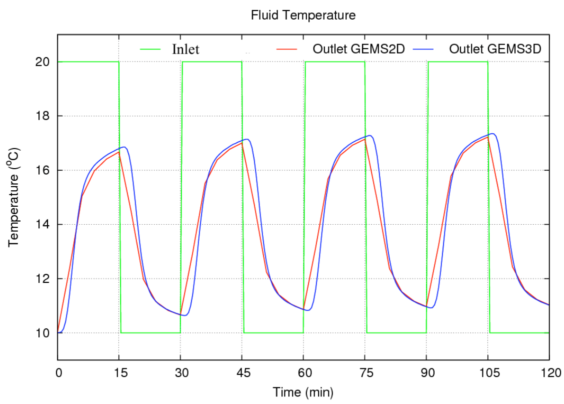

Figure 5 Fluid temperature variations due to step changes in inlet temperature predicted by two and three-dimensional numerical models.

At the start of each step increase in inlet temperature the 2D model shows an instant change in outlet temperature. Responses predicted by the 3D model show little change in the predicted outlet temperature until after three or four minutes (the nominal loop transit time is 200 s).

SYSTEM SIMULATION

The simulation of GSHP systems have been implemented in different building simulation tools, for example, HVACSim+ (Clark, 1985), TRNSYS (SEL, 1997), and EnergyPlus (Crawley et al., 2001). Both HVACSim+ and EnergyPlus use the short time step g-function model developed by Yavuzturk and Spitler (1999) to simulate BHEs, while TRNSYS uses the duct storage (DST) model by Hellstrom (1991). Both the g-function model and the DST model neglect the dynamics of fluid transport in the pipe loops. A new dynamic BHEs model has been implemented in TRNSYS by Wetter and Huber (1997), which takes into account those dynamics.

Kummert and Bernier carried out a study of residential GSHP systems and compared steady-state and dynamic model predictions of operating behaviour and performance. Their findings indicate that steady-state models can lead to overestimating the energy use by as much as 75% in extreme cases, because they predict quick temperature drops in the ground return temperature that prevents the heat pump from operating in heating mode (Kummert and Bernier, 2008).

In this study, a GSHP system with a BHE has been simulated using the short time step g-function model implemented in EnergyPlus., The results are to compared with those by the two and three-dimensional models (GEMS2D and GEMS3D).

Building Simulation

A typical UK two-storey domestic building with a GSHP system has been modelled using EnergyPlus. This has been done to derive fluid temperatures more typical of a building than step changes. The system simulation also allows transient heat transfer rates to be compared and differences in overall efficiency to be evaluated.

The building has been modelled in two zones, one is the living zone at the ground floor and the other is the bedroom zone at the first floor. The internal gains are modelled as a typical family of four. The heating floor area is 102 m^2 and the heating volume is 272 m^3. The heating period is from January to May, and then from September to December. The heating set point is 21 °C and the heating load is about 5.6 MWh/y. The annual building load profile is shown in Figure 6.

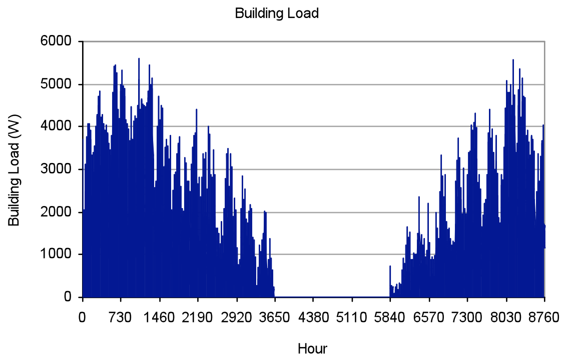

Figure 6 Building Load of a typical domestic building in the UK.

Heat Pump Model

A ground source water-to-water heat pump is used to provide the heating of the house. Hot water is delivered to the low temperature radiators installed in both zones. A simple water-water heat pump equation fit model (Tang, 2005) implemented in EnergyPlus is chosen to simulate the heat pump in this study. This model uses four non-dimensional equations or curves to predict the heat pump performance in cooling and heating mode. The methodology involved using the generalized least square method to generate a set of performance coefficients from the catalogue data at indicated reference conditions. Then the respective coefficients and indicated reference conditions are used in the model to simulate the heat pump performance. In this case, the output of the heat pump is proportional to the building load during the operation. Cyclic operation of the heat pump is not modelled.

The only variables that influence the water-to-water heat pump performance are load side inlet water temperature, source side inlet temperature, providing the source side water flow rate and load side water flow rate are constant. The EnergyPlus model allows the characteristics to vary according to both flow rates and temperatures but, as the manufacturer's data is only available for single design flow rate, the model can be defined solely in terms of load and source side inlet temperatures. The governing equations for the heating mode are consequently simplified and can be described as follows.

$$\frac{Q_h}{Q_{h,ref}} = C1 + C2\left[\frac{T_{L,in}}{T_{ref}}\right] + C3\left[\frac{T_{S,in}}{T_{ref}}\right] \quad (5)$$

$$\frac{Power_h}{Power_{h,ref}} = D1 + D2\left[\frac{T_{L,in}}{T_{ref}}\right] + D3\left[\frac{T_{S,in}}{T_{ref}}\right] \quad (6)$$

where:

C1-D3: Equation coefficients for the heating mode

T_{ref}: Reference temperature (283K)

$T_{L,in,}$: Entering load side water temperature, K

$T_{S,in}$: Entering source side water temperature, K

Q_h: Load side heat transfer rate (heating), W

$Power_h$: Power consumption (heating), W.

The model coefficients have been derived from data for the Viessmann Vitocal 200-G Type BWP 106 water-to-water heat pump, which has a 6kW rated capacity.

Borehole Heat Exchanger Model

The BHE has been designed using the GLHEPro tool (IGSHPA, 2007) based on the simulated heat pump monthly and peak loads. A single borehole with a diameter of 150 mm and a depth of 100 m is chosen and the configurations and thermal properties of the borehole are shown in Table 1. The spacing between pipes is the end-to-end distance. Three models have been applied to simulate the BHE, including the g-function model, the GEMS2D model, and the GEMS3D model.

Table 1 Configurations and thermal properties of the domestic building BHE.

Borehole Diameter		D	150	mm
Pipe Inner Diameter		D_{in}	26.2	mm
Pipe Outer Diameter		D_{out}	32	mm
Spacing between pipes		L_s	32.2	mm
Fluid	Conductivity	k_f	0.6	W/mK
	Thermal Capacity	ρc_p	3.59	MJ/m³K
Pipe	Conductivity	k_{pipe}	0.39	W/mK
	Thermal Capacity	ρc_p	1.77	MJ/m³K
Grout	Conductivity	k_{grout}	0.75	W/mK
	Thermal Capacity	ρc_p	3.9	MJ/m³K
Soil	Conductivity	k_{soil}	2.5	W/mK
	Thermal Capacity	ρc_p	2.5	MJ/m³K
Fluid Flow Rate		m	0.4	kg/s
Convective Coefficient		H	2280	W/m²K
Initial Ground Temp		T	10	°C

RESULTS AND DISCUSSION

The simulation of the GSHP system has been carried out in EnergyPlus with 10 min time steps for one year, using the existing g-function model implementation (Fisher et al., 2006) to simulate the BHE.

The simulation results have been used in two ways. Firstly, we take the borehole inlet temperatures calculated in the course of the annual simulation and use these as boundary conditions in the two and three-dimensional numerical models implemented in GEMS2D and GEMS3D respectively. The second way in which the annual simulation results have been used is to take the calculated building heating loads and use these as boundary conditions in simulations integrating the numerical borehole models with the heat pump model. This allows the overall effect of the different heat transfer rates and dynamic response to be evaluated.

Predicted fluid temperatures

The BHE inlet fluid temperatures (heat pump source-side outlet temperature) obtained from EnergyPlus have been used in the first comparison of alternative models. The resulting outlet temperatures predicted using the two and three-dimensional models and using twenty hours of inlet temperature data are shown in Figure 7. In addition, the results from the 28 hour to the 48 hour are shown in Figure 8. The simulations ran using 1-minute time steps.

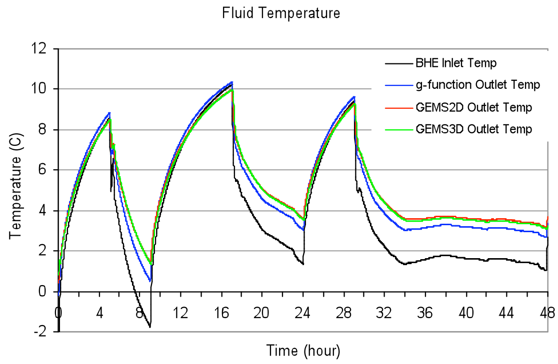

Figure 7 Comparison of outlet temperatures by g-function model, GEMS2D and GEMS3D model.

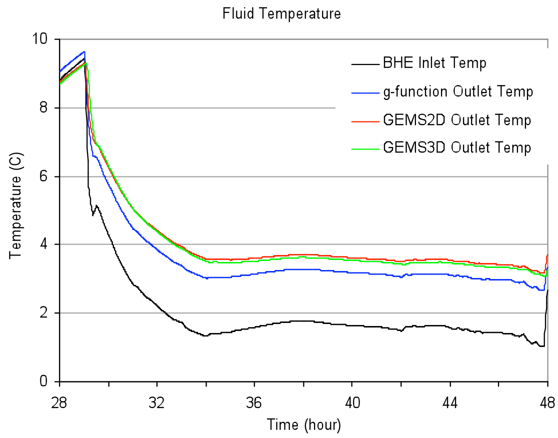

Figure 8 Comparison of outlet temperatures by g-function model, GEMS2D and GEMS3D model from 28 hour to 48 hour.

Over this long period of operation the outlet temperature predicted by the GEMS3D model is only slightly lower than that predicted by the two-dimensional GEMS2D model, but is slightly higher than the temperature predicted by the EnergyPlus g-function model. The effect of the dynamic response of the GEMS3D is demonstrated during the first 10 min running of the heat pump. Heat transfer rates calculated over the same period are shown in Figure 9. The patterns of the heat transfer rate for the g-function model and the GEMS2D model are similar. The main things to note are that heat transfer rates are higher in the GEMS3D model at the start of operation, and are otherwise slightly lower than the GEMS2D two-dimensional model.

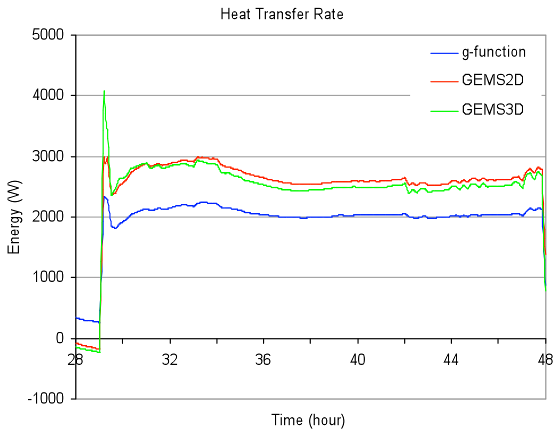

Figure 9 Comparison of heat transfer rates by g-function mode (EnergyPlus) , GEMS2D model and GEMS3D model.

Integrated system simulation results

In realistic simulation of GSHP system behaviour, the appropriate boundary conditions are the ones of building heating loads rather than inlet fluid temperatures. Ground loop conditions are dependent on heat pump characteristics as well as the BHE performance. To simulate loop and heat pump operation building heating loads and load-side inlet temperatures calculated from the annual simulation using EnergyPlus have been imposed on the load-side of the heat pump. Heat transferred to the ground loop then depends on the heat pump Coefficient of Performance (COP) that, in turn, is dependent on ground loop temperature.

The inlet and outlet temperatures of the BHE calculated by the GEMS2D and GEMS3D models during 24 hours simulation are shown in Figure 10. The three-dimensional model shows relatively higher heat transfer rates and delayed response at the short period when the heat pump starts. After slightly more than an hour, the fluid temperatures predicted by the three-dimensional model are lower than those predicted by the two-dimensional model are. This is consistent with previous results (Figure 9).

Differences in dynamic behaviour at sudden changes in inlet temperature do not seem significant over an operating period like that shown. However, Kummert and Bernier (2008) showed dynamic fluid transport could significantly change overall system behaviour when interaction with the heat pump control system (i.e. cycling) was considered.

Apparently high heat transfer rates at the start of heat pump operation are to be expected if the dynamics of the fluid in the borehole are considered. Heat transfer at a particular point down the borehole cannot be expected to be fundamentally different when three-dimensional effects are considered. However, the delay in transport of the initial cold fluid entering the loop means that, for a short period, the outlet temperature does not change and so a heat balance calculated using the inlet and outlet temperatures shows a high overall heat transfer rate.

The predicted ground loop temperatures are lower when the three-dimensional model is applied in this heating case. This indicates that the temperature difference between the borehole and the surrounding ground is larger. This corresponds to a lower predicted heat transfer rate over longer periods. Higher heat transfer can be expected in a two-dimensional model in that the temperature of the pipes is assumed to be the same along their whole length. The pipe temperatures in the two-dimensional model are the same as the inlet and outlet temperatures. These temperatures are higher and lower than the mean pipe temperatures predicted by the three-dimensional model. It may be more accurate to say then, that the two-dimensional model tends to over-predict the heat transfer rate.

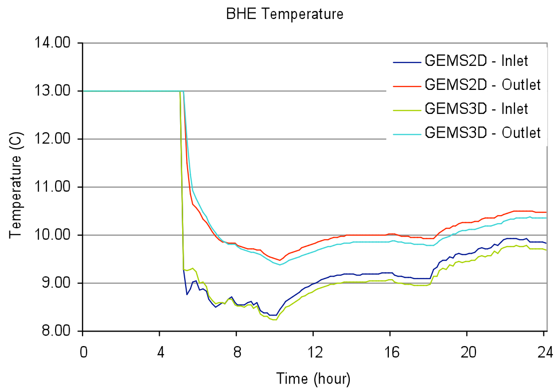

Figure 10 BHE temperature variance in 24 hours.

CONCLUSIONS AND FUTURE WORK

A three-dimensional numerical model, which can simulate the fluid transport along the pipe loop as well as heat transfer with the ground, has been used to study the dynamic response of a Borehole Heat Exchanger. The model has been validated by reference to analytical models of borehole thermal resistance and also fluid transport inside the pipe. It has been possible to compare predicted outlet temperature with those of a similar two-dimensional model and an implementation of a short time step g-function model.

The results show that delayed response associated with the transit of fluid around the pipe loop, is of some significance in moderating swings in temperature during the short period when the heat pump starts to operate. The GEMS3D three-dimensional model of the BHE shows a lower heat transfer rate will occur over longer periods of operation when compared to two-dimensional models. This is due to the mean temperature differences between the fluid and the ground being lower in the three-dimensional model – this seems more realistic.

A simple heat pump model has been used in this study and cannot simulate the on-and-off dynamic characteristics of a typical domestic heat pump. A more detailed dynamic heat pump model may be applied in further work to investigate system performance and control system operation.

Study of characteristics of BHEs using this detailed three-dimensional model should give insights into the limitations of two-dimensional models and highlight ways in which they may be improved. Implications for design methods are also to be investigated.

ACKNOWLEDGEMENTS

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