NUMERICAL MODELLING OF MULTIPLE STANDING COLUMN WELLS FOR HEATING AND COOLING BUILDINGS

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ABSTRACT

A model for simulating clusters of standing column wells (SCWs) for use in geothermal heating and cooling systems is described in this paper. The model is three-dimensional, dynamic and solves the governing equations using a finite volume discretisation scheme with a fully implicit algorithm. The slower-acting field equations are solved using a wider time interval than that used for the faster-acting well equations and the two sets of equations are coupled through the field equation source terms. A groundwater bleed feature is incorporated. The model is applied to two evaluative test cases the first of which involves heating only and the second, heating and cooling. Results of the applications suggest that SCWs can deliver substantially higher rates of heat transfer than conventional closed loop borehole heat exchanger arrays especially when groundwater bleed is operational. An important practical consequence of this is that far less geotechnical drilling is needed when using SCWs than is the case with closed loop arrays.

INTRODUCTION

Geothermal energy is a reliable and stable source for providing space heating and cooling with relatively low electricity consumption and high energy efficiency, when compared with conventional heating and cooling systems.

Geothermal heating and cooling systems (GHCS) can be categorised in two general ways according to the design of the ground heat exchangers: Closed loop systems and open loop systems. The distinction between these systems lies in the fluid circulation arrangements. The fluid (fresh water or antifreeze solution) is re-circulated around the embedded heat exchangers in the closed loop case but abstracted as groundwater in the open loop case. The open loop method has the advantage of reduced ground works and thermal resistance.

Standing column wells (SCWs) (Figure 1) are technically derived from a single-well open loop, which re-circulates the groundwater from the well to the building through two open end columns placed concentrically. They have merit in applications where open loop groundwater yields are limited.

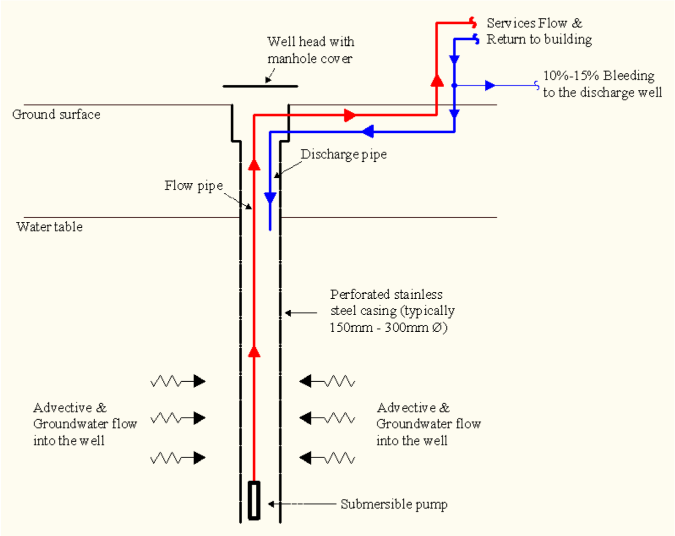

Figure 1 Typical standing column well (SCW) arrangement with bleed

Recent studies (Yavuzturk & Chiasson, 2002; Deng, Spitler & Rees, 2006) in the United States confirmed that SCWs allow a significant reduction in borehole depth requirement by comparing with the conventional closed loop system of single u-tube heat exchanger, due to the improved thermal heat transfer owing to the enhancement of the flow of groundwater into/out of the well by adopting open end columns.

In addition, the performance of SCWs can be improved by ‘bleeding’, i.e. part of the water from the system being bled (discharged) instead of fully recirculated to the annulus of the SCW to induce a flow of the groundwater and maintain the far field temperature in the well. A parametric study by Rees *et al*. (2004) showed that the bleed rate is one of the most significant parameters to affect SCW performance and offer reductions in borehole depth, capital cost and life cycle cost compared with the non-bleed case.

Orio, Johnson & Poor (2006) studied 10 years of performance of a SCW application in a New England school in the USA, which achieved a considerable saving in electricity use (about 1300MWh per year) after replacing the electricity heating system with a geothermal heating and cooling system (10 heat pumps coupled to 6 SCWs). The supply water temperature from the SCWs was measured after 10 years operation, and the data demonstrated that supply water temperature remained fairly constant and undisturbed with the outside air temperature directly. This is the key benefit of adopting the ground source rather than air source as a heat transfer medium to the heat pump and justifies the reliable and stable performance of geothermal systems.

Even though the merits of SCWs have been revealed, only a few studies (Oliver & Braud, 1981; Yuill & Mikler, 1995; Deng, 2004; Rees *et al.*, 2004; Deng, Rees & Spitler, 2005) concentrated on the SCW design. Most of these only considered either heating or cooling applications based on a single well applicable to North American applications, and little attention has been paid to UK applications.

Multiple boreholes arrangements are commonly used for large applications in conventional closed loop systems, but not often in SCW design. All existing SCW numerical models are merely capable of dealing with single well construction even though several multiple SCW arrangements have already appeared in North American non-residential building applications (Orio *et al.*, 2005).

The mild winters and cool summers experienced in the UK means that it should be possible to extract heat from the ground during winter and reject it back during summer to enhance the seasonal performance. In this work, a 3-dimensional numerical model is developed to explore the performance of small clusters of SCWs with/without bleed and to compare the results with what might be achieved using conventional closed loop methods based on typical UK common hydro-geological conditions.

PREVIOUS WORK

In earlier SCW designs, the well had an impermeable casing and hence the convection heat transfer surrounding the borehole wall due to natural groundwater movement was ignored in the energy transfer analysis.

Oliver & Braud (1981) analyzed the thermal performance of a completely cased borehole SCW design in the steady state. The temperature distribution in the pipes were solved analytically based on the temperature gradient across the earth, the annulus and the inner pipe (suction pipe) with pure conduction heat transfer through the pipe walls. It showed that the length of the ground heat exchangers can be reduced by increasing the thermal resistance (pipe insulation) of the inner pipe wall because of the reduction of short-circuit heat transfer between the inner pipe and the annulus.

Yuill and Mikler (1995) investigated the influence of natural ground water movement on the performance of standing column wells (referred as thermal well in this text), with an open well cased construction enhancing the flow of groundwater into/out of the well. The ratio of heat transfer to the SCW by conduction or convection (due to the groundwater movement) was obtained from a dimensionless term called the groundwater factor (*GF*). The outward and inward groundwater flow rates to the SCW was determined from the hydraulic gradient across the SCW and *GF*, according to the Darcy equation in cylindrical coordinates. The hydraulic head distributions along the SCW could only be measured experimentally, thus an 'equivalent thermal conductivity' was introduced to consider the impact of groundwater motion in an approximation of the water temperature inside the SCW. Therefore, the usability of this model is limited without drilling a test borehole to collect the hydraulic head conditions in advance.

Rees, *et al*. (2004) and Deng (2004) proposed a finite volume numerical model of SCW that is capable of dealing with the natural groundwater movement as well as the induced groundwater flow by bleed operation. A range from 5% to 15% was suggested to be most effective bleeding rate to enhance the SCW performance. Regarding to the groundwater flow analysis, the resistances of the groundwater flow along the borehole, dip tubes and the rocks were analysed by a nodal network. The borehole flux was calculated by the well borehole model according to thermal resistances and thermal mass analysis from the nodal network, and being passed onto a finite volume model (coupled by Darcy's flow equation and Bear’s (1972) porous medium energy equation) to deal with the excitation to the aquifer surrounding the SCW. A one-dimensional numerical SCW model was developed by Deng, Rees and Spitler (2005) in order to reduce the computation power consumption of their previous model (Deng, 2004; Rees *et al.*, 2004). A tri-diagonal matrix algorithm (TDMA) method was adopted in the finite difference model to speed up the simulation time. The water inside the SCW was assumed to be a perfectly mixed single zone to calculate the mean water temperature in the well. The leaving water temperature from the well can be estimated from this mean value and corrected by a short-circuit correction to account for the short-circuit phenomena inside the well. The groundwater movement caused by pumping and buoyancy was taken into account in this model through the improved value of thermal conductivity, referred as ‘enhanced thermal conductivity’, similar as the ‘equivalent thermal conductivity’ in Yuill and Mikler’s model (1995). The enhanced thermal conductivity can be worked out either from in-situ experiments (numerically or physically), or the correlations based on the actual hydraulic and thermal properties of the rock from the site.

The heat transfer mechanism in SCWs involves not only pure conduction through from/to rock to/from the fluid wall, but also the advection in the surrounding rock and convection along the dip tubes and borehole walls. Therefore, the impact of the groundwater movement on the thermal and hydraulic heat transfer must be considered in the SCW model in order to achieve a reasonable approximation representing the real SCW situation especially during bleed operation.

The ratio of convective to conductive heat transfer in the borehole is expressed by Nusselt's number, which is determined from the characteristic of flow (Reynolds number) and the properties of the water (Prandtl number). The convective coefficient can be derived from the Nusselt number and reflected in the borehole and suction-pipe surface resistances to account for the heat transfer by both convection. Gnielinski's simplified correlations were used in this work for convention across the inner annulus and suction pipe surfaces (Holman, 1997) with Norris's (1971) correction for roughness at the annulus outer surface. Lu and Wang's (2008) correlation was used for convection at the suction pipe outer surface.

STANDING COLUMN WELL MODEL

Previous SCW models tended to ignore the energy transfer in the aquifer in the vertical direction (Yuill & Mikler, 1995; Deng, 2004; Rees *et al.*, 2004; Deng, Rees & Spitler, 2005) in order to simplify the structure of the PDEs or reduce the model computational cost. This work is intended to focus on multiple SCWs applications and hence, the energy equations are solved in 3 spatial dimensions with a fully implicit finite volume scheme.

The regional groundwater flow (such as local pumping or recharge from local rivers) and the seasonal water table movement are not considered in the model; only the local flows caused by well pumping are considered.

Field model

The field model coupled with two sets of partial differential equations (PDEs), the Darcy flow equation in saturated flow conditions and continuity energy equation in porous medium (Bear, 1972) to handle the thermal and hydraulic energy transport in the aquifer. These two equations are coupled with the Darcy's velocity. Homogeneity and isotropy are assumed throughout the field domain.

Head equation:

$$S\frac{\partial h}{\partial t} - F = K\nabla^2 h \qquad [1]$$

Where:

K = hydraulic conductivity (m/s);

S = specific storage;

F = source term (m^3s^{-1});

h = hydraulic head (m);

t = time (s).

Darcian flow:

$$u_x = -\frac{K}{n}\frac{\partial h}{\partial x} \qquad [2]$$

Where:

u_x = the velocity in the x direction

n = rock porosity

(and, likewise, u_y & u_z).

Energy:

$$\left(n\rho_w c_{pw} + (1-n)\rho_s c_{ps}\right)\frac{\partial T}{\partial t} - n\rho_w c_{pw}\nabla uT - k_{eff}\nabla^2 T = Q \qquad [3]$$

Where:

ρ = density (subscripts: w – water, s – rock, kgm^{-3});

c_p = spec. heat cap. (subscripts as above, $Jkg^{-1}K^{-1}$)

T = temperature (°C);

k_{eff} = effective thermal conductivity ($Wm^{-1}K^{-1}$);

Q = source term (Wm^{-3}).

The SCW model consists of two sub-models, the well model and field model to deal with the energy transport in the borehole and the surrounding field respectively. These two sub-models are coupled by the well annulus heat transfer and groundwater transfer rates both of which are 'connected' via the relevant field equations' source terms. The source terms in the head equation (F) and energy equation (Q) refers to the amount of groundwater abstracted to SCW (bleed rate) and heat added/ removed from the ground respectively. Hence, the data from the field model are employed by well model to update the borehole flux according to the new aquifer conditions and the bleed flow rates forced by the well pump are likewise imposed on the head field equation. The method makes use of the stiffness of the problem in that the well equations act rapidly (timescale measured in minutes) whereas the field equations act slowly (timescale measured in days). Hence the well equations supply new values of F and Q to the field equations delayed by a short time interval (one hour) Figure 2 illustrates the algorithm.

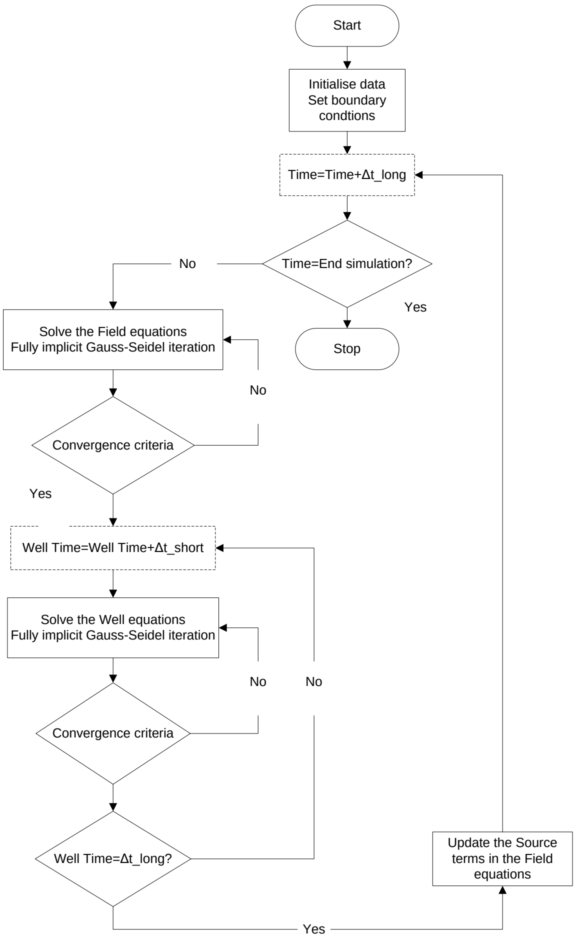

Figure 2 Flow chart of the computer algorithm of the SCW model

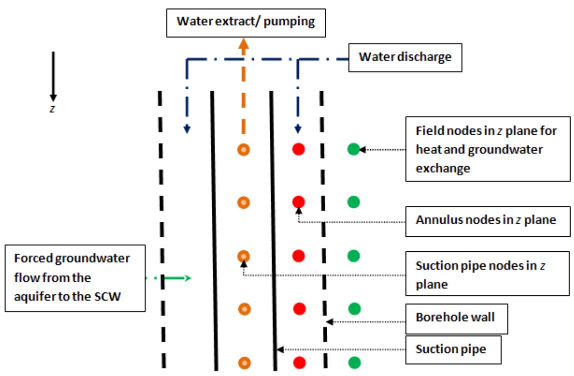

Figure 3 Cross section of the well model (the borehole and pipe wall resistances are omitted in this figure)

Well model

The well model is coupled to the field equations through the field equation source terms and is solved using a smaller time interval than that used to solve the field equations. In effect, each well is treated by the field equations as a line source/sink of finite depth. This decoupling means that the field equations can be solved independent of the standing column wells at the coarser time step appropriate to the field variables. The well equations are then solved iteratively at a shorter series of time steps within the coarser field time step and the source terms are then updated in the field equations. The advantage of this approach is that standing column wells of different types can be applied with other source types (e.g. closed loop heat exchangers) to form a fully flexible hybrid scheme is desired.

Water temperature in the annulus:

$$C_A \frac{\partial T_A}{\partial t} + c_{pw}\frac{\partial m_w T_A}{\partial z} - Q_A - Q_S = 0 \qquad \textbf{[4]}$$

Where:

C_A = annulus thermal capacity (JK^{-1});

m_w = water mass flow rate in the annulus (kgs^{-1});

T_A = annulus water temperature (℃);

Q_A = heat transfer (annulus to rock, W);

Q_S = heat transfer (annulus to suction pipe, W)

Water temperature in the suction pipe:

$$C\frac{\partial T_S}{\partial t} + \; m_w + m_b \; c_{pw}\frac{\partial T_S}{\partial z} + Q_S = 0 \qquad [5]$$

Where:

m_b = total bleed water flow rate (kg/s)

C_{SP} = heat capacity of the suction pipe water (J/K)

APPLICATION OF THE MODEL

The model was applied to two evaluative test cases:

- Heating only
- Heating and direct cooling

For evaluative purposes, a 4-well cluster was investigated consisting of 4 × 100m-deep standing column wells arranged on a 10m grid-spacing at the centre of a 50m × 50m × 120m (deep) domain.

For the numerical model settings, an initial meshing study considered uniform grid spacings of 0.25m – 3.0m and concluded that a 1m spacing would give the best balance between accuracy and computational cost. Checks were also conducted using the 1m x 1m x 1m grid size with classical line source theory (Ingersoll & Plass, 1948) for 3-day disturbance pulse inputs of first pumping rate and then heat. Model results at the first (1m) node from the disturbance were compared with line source theory results at a 1m radius with excellent agreement. Thus, a 1m grid spacing was adopted in the model. All PDEs being solved as an initial value problem and thus all temperature nodes were set at 10^{o}C whereas all initial heads were set at zero since the model was derived to predict the head distribution due to pumping only (i.e. local groundwater flow effects were not considered). Details of the earth properties and SCW parameters can be found in tables 1 and 2.

The first test case consisted of applying a heating load and well mass flow rate using values within the range of those observed for a survey of some 35 standing column well installations carried out by Orio *et al.* (2005) in North America. This would enable results to be compared with the range of observed capacities of the surveyed wells. The surveyed wells consisted of a mix of residential and commercial installations (heating mainly in residential with some commercial applications used for cooling) with a mean specific rate of heat transfer of 275W/m and a mean overall well mass flow rate of 1.4kg/s. Two simulations were carried out; one with bleed (set at 10% of nominal well flow rate) and one without bleed. In the former case, a simple bleed control strategy was adopted in which bleed was applied at all times when there is a demand for heat. It is stressed that this exercise was merely an attempt to *verify* the results of the model with the results summarised by Orio *et al.* (2005) rather than to attempt a full and precise comparison (which would not in any case be possible due to the incompleteness of the data presented in Orio *et al.*'s survey). Figure 4 shows the simulated heating delivered by the 4 well cluster (and, superimposed, are the bounds of heat transfer rates reported by Orio *et al*. (2005) for the 35 installations in North America), and Figure 5 shows the simulated mean monthly temperatures over one year of well cluster operation with, and without, bleed operation. In Figure 4, the mean rock temperatures 1m away from the 4 wells are also plotted.

Table 1 The earth properties

Thermal conductivity of rock *k* **(W/mK)**	**Hydraulic conductivity of rock** *K* **(m/s)**	**Specific heat capacity of rock** c_{ps} **(J/m^{3}K)**	**Porosity** *n*
3.9	0.00001	1.86x10^6	0.275

Table 2 The standing column well setting

SCW diameter (m)	**Total borehole length (m)**	**Pumping rate (L/s)**	**Bleed rate (%)**
0.2	400m	1	10%

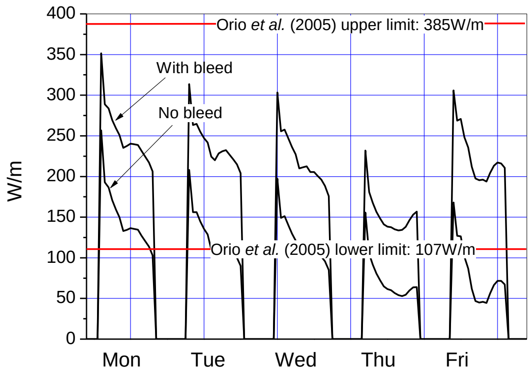

Figure 4 Simulated heating delivered by a cluster of 4 x 100m-deep SCWs operating at capacities within the range of that reported by Orio et al. (2005)

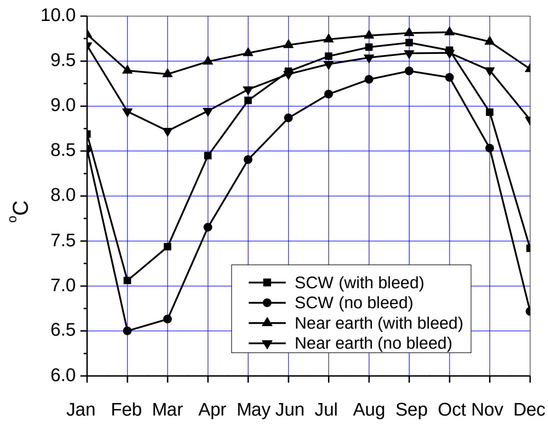

Figure 5 Mean well water temperatures and local rock temperatures for the 4 well cluster ('near earth' represents the earth temperature 1m from well centre)

The simulated isotherms and isobars abound the well cluster were found to be uniform as might be expected for the identical well specifications occupying a uniform grid pattern. For example, Figure 6 shows isobars on the *x-y* plane at half well depth.

The second test case consisted of a heating and direct cooling application using data for a heating and chilled ceiling application given by Underwood and Spitler (2007). In the latter work, a design analysis of vertical closed loop borehole heat exchangers was carried out for a range of air conditioning system alternatives. It is thus possible to compare the response of the closed loop array performance with that of a standing column well cluster in the present exercise.

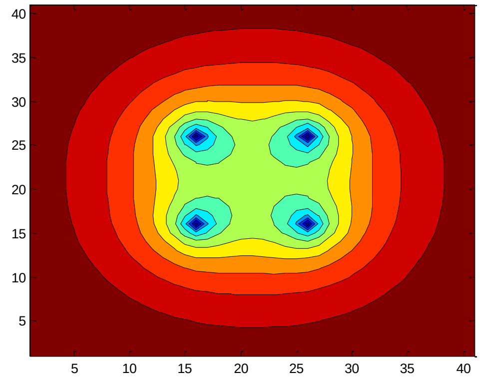

Figure 6 Simulated x-y isobars at half well depth for a cluster of 4 identical SCWs

Sample values…

Well centre	*-751Nm^{-2}*
Domain centre	*-362Nm^{-2}*
Between wells	*-353Nm^{-2}*
12,20	*-31Nm^{-2}*
6,20	*-13Nm^{-2}*
1,20	*-4Nm^{-2}*

The peak requirement of this application was 44kW (heat sourceed from the geothermal source) and 55kW (direct cooling heat rejected to the geothermal sink). The corresponding annual energy rates were 18,900kWh (heat sourced) and 41,400kWh (heat rejected to the geothermal loop). Thus the application is cooling-dominant. Again, the same 4-well cluster was applied as was used in the previous case and the simulated energy demands were applied to the well clusters first with conditional bleed rate of 10% of nominal well flow rate (bleed applied at all times a load exists) and then without any bleed. Results of the annual mean water loop temperatures and near rock temperatires are given in Figure 7.

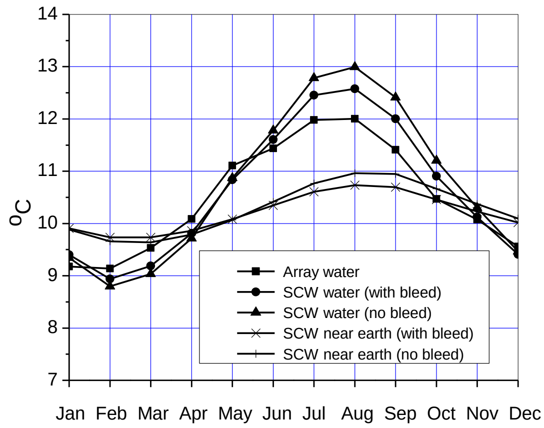

Figure 7 Comparsion of annual monthly mean water temperatures derived from a 2500m borefield and a 400m 4-well SCW cluster ('near earth' represents the earth condition at 1m from well centre)

DISCUSSION

For heating only, the 4 well cluster simulation resulted in per-metre well heat transfer rates that were between the limits observed in existing standing column well installations (Figure 4) and a significant increase in heat transfer is noted when groundwater bleed is used. The initial rock temperature at the start of simulation was 10^{o}C and, precisely one year later, had declined to 9.3^{o}C and 8.6^{o}C for the bleed and no bleed cases respectively. This implies a gradual but significant decline in rock temperature for the heating only case over several years of operation resulting in a corresponding decline in heat pump coefficient of performance and, of greater seriousness, incapacity through the danger of freezing. A larger cohort (or greater depth) of standing column wells would, of course, reduce this decline.

For the heating and cooling case, an exemplar 4 well cluster competes well with a traditional closed loop borehole heat exchanger array in that, for a similar performance in annual monthly mean water temperatures, just 400m of standing column well is needed as opposed to 2500m of closed loop array. Figure 7 shows that the mean water temperatures of the well cluster with and without bleed and the mean water temperature of the closed loop are consistently within 1K of one another over an annual simulation period. Furthermore, the mean temperatures imply satisfactory operation in winter with (essentially, in the case of the SCWs) fresh water and that the summer temperatures are sufficient to enable direct cooling using either chilled ceilings or chilled beams. Underwood and Spitler (2007) found that this combination can deliver carbon emission savings due to heating and cooling energy use of greater than

60%. The major issue here is that the SCW cluster involves significantly less ground works than would be needed with the 50 × 56m deep borehole heat exchangers depicted in the closed loop solution obtained by Underwood and Spitler (2007). In this cooling-dominant example, the mean earth temperature change after one year was found to be negligible. However, further work is needed to investigate well cluster performance over extended time horizons.

CONCLUSION

This paper has described the development of a model for simulating clusters of standing column wells for use in geothermal heating and cooling systems. The model has been applied to two test cases the first involving heating only (i.e. heat extracted from the well system in winter) and the second involving heating in winter and direct cooling in summer (i.e. heat both extracted and rejected to the well system over an annual operational cycle). The well cluster was found to offer a high rate of heat transfer of, typically, up to 250W/m especially when groundwater is bled into the well system. When heating only, besides enhancing heat transfer, the decline in surrounding rock temperature can be minimised through the use of bleed. For applications involving both heating and cooling, standing column well clusters offer the potential for very substantial reductions in geotechnical drilling compared with conventional closed loop vertical borehole heat exchanger arrays. This offers significant opportunities for geothermal heating and cooling systems in regions with high water tables such as is frequently found in the United Kingdom.

Further work is currently underway to improve the computational efficiency of the model so that it can be used for longer time-horizon simulations. The detailed calculation of well pressure gradients is also being incorporated. Finally, a test site is currently being investigated with a view to validating the model.

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