Multiphysics Modelling of Standing Column Well and Implementation of Heat Pumps Off-Loading Sequence

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Abstract: A simplified but fully coupled multiphysics model involving heat transfer and groundwater flow within a SCW and its surrounding ground was implemented in COMSOL Multiphysics 4.2a with MATLAB to simulate a 24-hour heating operation. The heat pumps were modeled using interpolation functions thereby allowing the effect of the pumped water temperature on the capacity and coefficient of performance of the heat pumps to be accounted for. In the model presented here, a three level bleed control is applied when the temperature of the pumped water drops to 7, 6 and 5°C. If the pumped water temperature drops below 4°C, an off-loading sequence implemented via a MATLAB function allows the heat pumps to automatically shut down one by one at 10 minute intervals. Results demonstrate that the numerical model developed in this paper can successfully evaluate the *EWT* over time and that both bleed and off-loading sequence played a key role in maintaining the *EWT* within the heat pump's operational range.

Keywords: Standing Column Well, Ground-Coupled Heat Pump System, Groundwater Flow.

1. Introduction

Ground-coupled heat pump systems such as Standing Column Wells (SCW) use groundwater as heat source/sink to heat or air conditioning buildings. In a SCW, groundwater is pumped at the base of a deep well, transferred to one or several heat pumps, and then re-injected at the top of the same well (see Figure 1). During peak periods, a portion of the pumped water is not re-injected into the well, thereby creating a drawdown that stimulates the groundwater flow to the SCW. This operation, known as bleed, helps maintain the pumped water temperature within the heat pump's operational range.

In cold climates however, the bleed is sometimes unable to maintain the pumped water within the heat pump's operational temperatures. In such situation, an off-loading sequence is initiated and the building's heat pumps are shut down sequentially until the pumped water comes back to a suitable temperature. To maintain a sufficient comfort level within the building, auxiliary systems are used during these periods, therefore lowering the energy efficiency of the whole system.

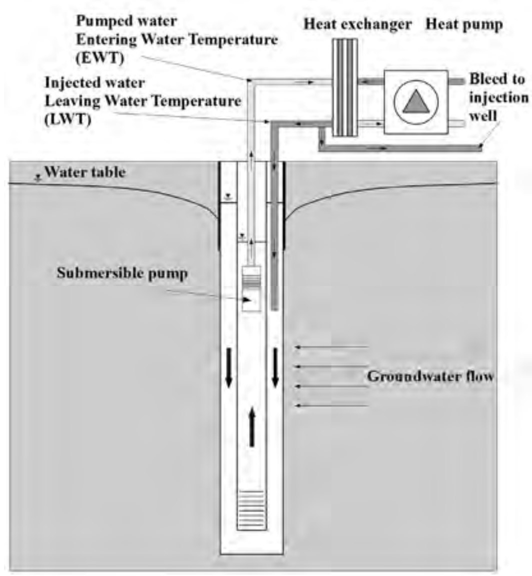

Figure 1. Illustration of a standing column well system

A growing number of SWCs have been installed in recent years (Orio et al., 2005; Deng et al., 2005) and are since receiving much more attention from the commercial and scientific community because of their high overall performance in regions where geological and hydrogeological conditions are suitable. Numerical analysis have shown that, by comparison to closed-loop systems of comparable power, the systems' size could be reduced by 49% to 78% with the use of SCW systems, thereby translating into significant cuts in construction costs (O'Neil et al., 2006). Also, financial simulations carried out over a 20-year life cycle showed that despite higher operating costs, the use of SCW systems translates into cost savings of around 27% compared to conventional closed-loop systems (O'Neil et al., 2006).

Various numerical models in the literature focused on the underground thermal and hydraulic processes of SCWs and their applications (Rees *et al.*, 2004; Deng *et al.*, 2005; Abu-Nada *et al.* 2008; Croteau, 2011; Ng et al., 2011). However, little work has been carried out about the coupling between a SCW and the heat pumps installed in a building.

The objective of this paper is to present 1) a coupled multiphysics model involving heat transfer and groundwater flow within and around a SCW and 2) the strategy used to implement a three-level bleed control and a heat-pump off-loading sequence.

2. Methodology

The various geometrical elements of a typical SCW range from a few millimeters for the pipe to more than 300 meters for the borehole and the aquifer, which leads to a dense mesh around the well and to significant computation times. In order to reduce computation time, a 2D axisymmetric model was chosen to represent the real geometry described in Figure 1. The simplified geometry and dimensions used for the model are summarized in Figure 2 and Table 1.

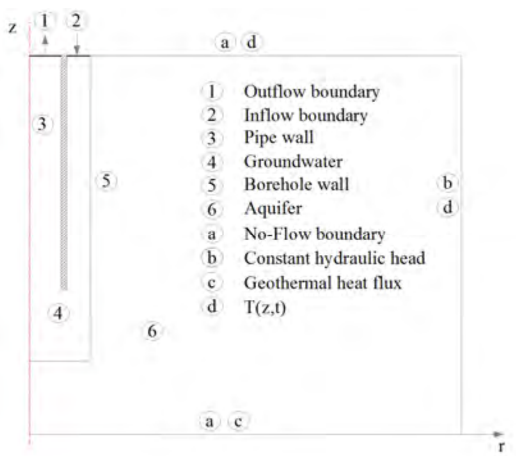

Figure 2. Simplified representation of a standing column well and boundary conditions of the model.

The state equation describing the groundwater flow is obtained by combining the continuity equation (1) with the Darcy's law (2) which describes the groundwater motion within a porous media. The governing equations solved for the groundwater flow are expressed by:

$$\rho S \frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad (1)$$

$$u = -\frac{K}{\rho g}(\nabla p + \rho g \nabla D) \qquad (2)$$

where u is Darcy velocity, K is the hydraulic conductivity, ρ is the fluid density, g is the gravitational acceleration , p is the pressure, D is the vertical coordinate and S is the storage coefficient. It should be noted that equations (1) and (2) consider a confined and fully saturated aquifer under the assumption of an equivalent porous media (or unfractured aquifer).

Table 1: Summary of the dimensions used for the SCW model.

Parameter	Value (m)
Domain radius	25
Domain depth	330
Inner pipe radius	0.051
Outer pipe radius	0.057
Pipe length	300
Borehole radius	0.076
Borehole length	305

At r=25 m, a constant hydraulic head of 350 m is set along the boundary. The normal velocity (v_o) at the outflow boundary is derived from the pumping rate Q and the cross sectional area of the inner pipe radius (A_o), which is obtained by:

$$v_o = \frac{Q}{A_o} \qquad (3)$$

Similarly, the normal velocity at the inflow boundary (v_i) is dependent of the injected water flow and the area of the annular space between the borehole wall and the outer pipe surface. The latter is provided by :

$$v_i = \frac{Q(1-B)}{A_i} \qquad (4)$$

where B is a parameter comprised between 0 and 1 which controls the bleed flow rate, and therefore the pumped water flow rate that is not re-injected into the well. Unless otherwise specified, all other boundaries are set as no-flow. The whole domain is initially set at a constant head of 350 m.

The model is composed of three different materials (aquifer, pipe and water present in the SCW). The thermal and hydrogeological properties of the aquifer are typical geological materials encountered in Eastern Canada. Water inside the SCW was modeled by assigning a very high to the hydraulic conductivity and by setting the porosity to one. A low permeability and porosity were assigned to the domain representing the impervious pipe. Table 2 summarised the material properties used.

Table 2: Summary of the properties used in the model

Property	Unit	Water	Pipe	Aquifer
ρ	kg/m^3	1000	1300	2700
θ	-	1	1e-10	5e-2
K	m/s	1000	1e-9	1e-6
k	W/m/K	0.6	0.138	2.2
C_p	J/kg/K	4200	1200	860

Heat transfer in a SCW involves both conduction and advection. The latter is induced by the water circulation in the well and the groundwater flow in the aquifer. The governing equation solved for the heat transfer is given by :

$$(\rho C_p)_{eq}\frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k_{eq} \nabla T) \quad (5)$$

where k_{eq} and $(\rho C_p)_{eq}$ are respectively the equivalent thermal conductivity and volumetric heat capacity. The equivalent thermal parameters consider both the properties of the fluid (represented by index l) and the solid matrix (represented by index p) and are given by:

$$k_{eq} = \theta_p k_p + (1-\theta_p) k_l \quad (6)$$

$$(\rho C_p)_{eq} = \theta_p \rho_p C_{p,p} + (1-\theta_p)\rho_l C_{p,l} \quad (7)$$

where k is the thermal conductivity, θ is the volumetric fraction of the component, ρ is fluid or solid matrix density and C_p is the specific heat capacity.

As done by Croteau (2011), the seasonal surface temperature variation and the natural geothermal heat flux q_g are integrated in the heat transfer model through the Lunardini (1981) model. The temperature profile over time $T(z,t)$ of this analytical expression is given by

$$T(z,t) = T_m + \frac{q_g z}{k_{eq}} - T_0 e^{-z\sqrt{\frac{2\pi}{2\alpha P}}} \cos\left(\omega(t-t_d) - z\sqrt{\frac{2\pi}{2\alpha P}}\right) \quad (8)$$

where T_m is the mean annual air temperature, z is the depth below the ground surface, T_0 is the amplitude of the seasonal variation relative to T_m, P is the period of the cycle, ω is the angular frequency, α is the thermal diffusivity and t_d is the time lag corresponding to the lowest annual temperature after January 1st.

The Lunardini model was used to specify the initial temperature distribution in the ground and along the boundaries at z=0 and r=25 m as a function of depth below the ground surface and time (for the boundary conditions only). Also, a normal heat flux q_g is applied at the very bottom boundary of the domain to represent the geothermal heat flux. Table 3 summarizes the parameter used in eq. (8).

Table 3: Summary of the parameters used in the Lunardini model

Parameters	Unit	Value
T_m	°C	6.9
q_q	W/m^2	0.03
T_0	°C	15.1
α	m^2/s	8.8e-7
P	s	3.2e7
ω	-	2.0e-7
t_d	s	1.8e6

The average temperature along the outflow boundary corresponds to the pumped water temperature, commonly known as the heat pump' entering water temperature (*EWT*). As illustrated in Figure 3, the *EWT* value influences the power delivered by the heat pump, or its capacity (CAP), and its coefficient of performance (COP).

Both CAP and COP affect the temperature variation within a heat pump. The latter can be modeled by

$$\Delta T(EWT) = \frac{n_{hp} CAP(EWT)}{Q\rho C_p}\left(1 - \frac{1}{COP(EWT)}\right) \quad (9)$$

where n_{hp} is the number of active heat pumps.

At the inflow boundary, the temperature of the fluid is set equal to the leaving water temperature (*LWT*) of the heat pumps, given by

$$LWT = EWT + \Delta T(EWT) \quad (10)$$

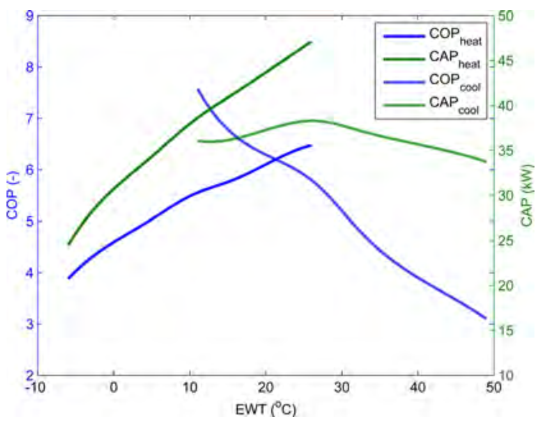

Figure 3. Interpolation functions used to describe the capacity (CAP) and the coefficient of performance (COP) of the heat pump used in the simulation.

Whenever the heat pump entering water temperature exceeds its operating temperatures, the bleed is activated and a drawdown is created in the well that modifies the groundwater velocity field u. The latter will affect the *EWT*, which controls the bleed flow rate and the boundary condition value along the outflow boundary (*LWT*).

3. Modelling Strategy

In the model presented in this work, the heat pumps were modeled using Comsol's interpolation functions. Those functions allow to evaluate the performance and the power delivered by a heat pump at any time step.

A three level bleed control is applied when the *EWT* drops to 7, 6 and 5°C. This feature was implemented via an analytical function (expressed as the sum of 3 step functions) wherein *EWT* was treated as an argument, as shown in Figure 4.

If the *EWT* drops below 4°C, an off-loading sequence implemented via a MATLAB function allows the heat pumps to automatically shut down one by one at 10 minute intervals until no heat pump is running.

The MATLAB function managing the off-loading sequence is being called at each time step taken by the COMSOL time dependent solver. The function compares the *EWT* with the heat pump temperature limit, which in this case is set at 4 °C. If the *EWT* drops below that limit, the current solver time step is assigned to the $t_{offload}$ variable in the MATLAB base workspace and the number of active heat pumps n_{hp} is reduced by 1. If the *EWT* is still below the temperature limit 10 minutes after the time corresponding to $t_{offload}$, the number of active heat pumps is reduced again by 1 and the current time t is assigned as the new $t_{offload.}$ The process is repeated until the number of active heat pumps reaches 0. If the *EWT* goes above 4°C, the number of active heat pumps is set at its initial value.

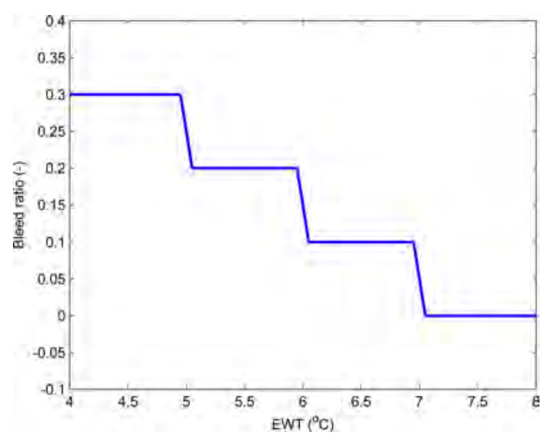

Figure 4. Function use to describe the bleed ratio as a function of *EWT*.

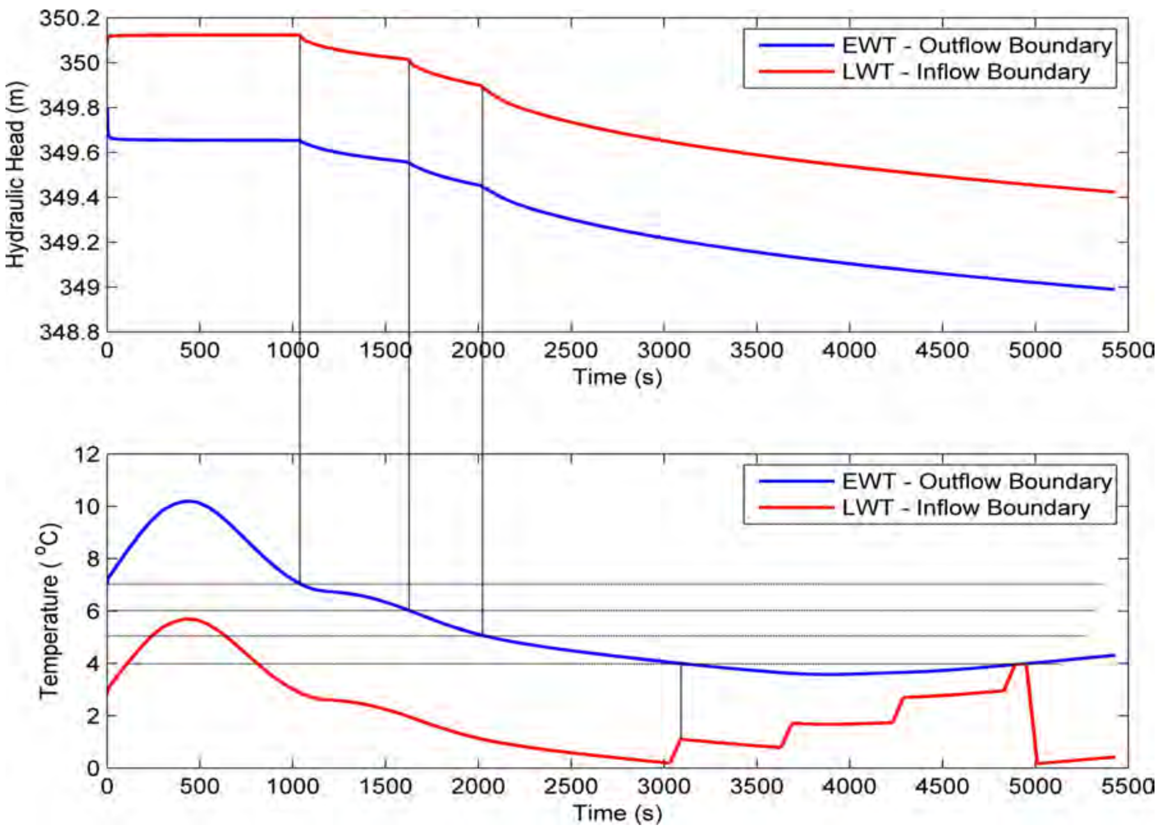

Figure 5. Illustration of a three level bleed control

4. Results

A simple example is used to demonstrate the various functionalities of the developed model. The example considers a constant heating load of 200 kW provided by a total of 4 heat pumps and a backup heating system, the latter having a *COP* of 1. The total pumping rate *Q* is set to 0.0063 m^3/s and the three bleed levels are set to 10, 20 or 30% of the total pumping rate.

Figure 5 shows the hydraulic head at the outflow and inflow boundaries and the corresponding temperature over time. At the beginning of the operation, the *EWT* increases toward a maximum value of 10 °C even when heat is extracted from the SCW. This is caused by the temperature profile *T(z,t)* which was initially warmer at the base of the well than at the surface. After about 500 seconds, the water is mixed and the *EWT* starts declining.

The three hydraulic head drops corresponding to *EWT* at 7, 6 and 5°C show that the implementation of the bleed operation was successfully achieved by the model. It also indicates that the off-loading sequence accurately started at 4°C and that a heat pump subsequently stopped every 10 minutes. One can also note that once the *EWT* went above the 4°C limit a few moments before *t*=5 000 seconds, all the heat pumps were allowed to reopen.

In this example, it is clear that bleed alone cannot stabilize and maintain the *EWT* within the heat pump's operational range. Thus, the implementation of an off-loading sequence was required and was fully achieved with the help of a MATLAB script.

Figure 6 shows the thermal loads provided by the heat pumps and the backup heating system as well as the COP of the heat pumps. The combined heating power of both subsystems correctly corresponds to the overall building heating requirements at each time step.

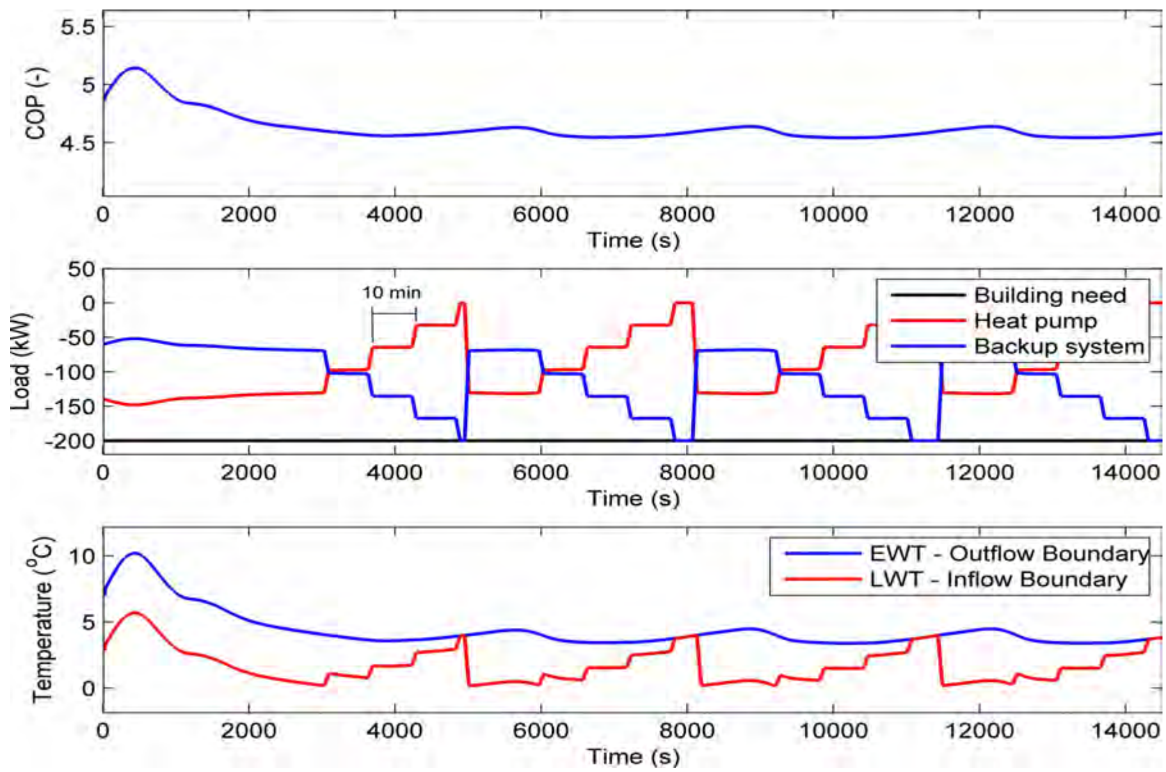

Figure 6. Illustration of an off-loading sequence.

5. Conclusions

In this paper, a coupled model of standing column well that integrates a three level bleed control and an off-loading sequence to evaluate the *EWT* was developed by the means of COMSOL 4.2a with MATLAB.

The results show that this numerical model can successfully evaluate the *EWT* over time and that both bleed and off-loading sequence played a key role in maintaining the *EWT* within the heat pump' operational range.

The current model can be used to forecast, for a homogeneous aquifer, the performance of the planned design and control system under different heat load scenarios. Ongoing research seeks to extend the model for fractured aquifer.

6. Acknowledgements

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7. References

1. Abu-Nada, E., Akash, B., Al-Hinti, I., Al-Sarkhi, A., Nijmeh, S., Ibrahim, A. and Shi-Shan, A., Modeling of a geothermal standing column well. International Journal of Energy Research, 32, 306-317 (2008)
2. Croteau, J-E., Évaluation des paramètres influençant les températures d'opération des puits à colonne permanente, Master Thesis, Polytechnique Montréal (2011)
3. Deng, Z., Rees, S., and Spitler, J., A Model for Annual Simulation of Standing Column Well Ground Heat Exchangers, HVAC&R Research, 11, 637-655 (2005)
4. Lunardini, V. J., Heat transfer in cold climates, 731 pp., Van Nostrand Reinhold Co, Toronto (1981)
5. Ng, B.M., Underwood, C.P., Walker, S.L., Standing column wells—Modeling the potential for Applications in Geothermal Heating and Cooling. HVAC&R Research, 17, 1089–1100 (2011)

6. O'Neill, Z.D., Spitler, J.D. and Rees., S.J., Performance Analysis of Standing Column Well Ground Heat Exchanger Systems. ASHRAE Transactions, 112, 633-643 (2006)
7. Orio, C., Johnson, C., Rees, S., Chiasson, A., Deng, Z. and Spitler, J., A Survey of Standing Column Well Installations in North America. ASHRAE Transactions, 111(2), 109-121 (2005)
8. Rees, S., Spitler, J., Deng, Z., Orio, C. and Johnson, C., A study of geothermal heat pump and standing column well performance. ASHRAE Transactions, 110, 3-13 (2004)