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A control strategy evaluation framework for Ground Source Heat Pumps using Standing Column Wells

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ABSTRACT

Standing column wells (SCWs) are efficient ground heat exchangers (GHEs) that have a significant cost saving potential. Recent developments have shown that they can also adapt successfully to cold climates despite previous concerns about operating near the freezing point. Therefore, new research frontiers are now being explored as the integration of this type of GHE to a real case study building model has hardly been analyzed until now. An institutional building has been selected for a SCW demonstration project in Mirabel, Canada. This paper includes in one single model the building, the Heating Ventilation and Air Conditioning (HVAC) system and the SCWs. The objective is to develop a software framework to analyze the impact of building operation strategies on the entire system during winter. Peak loads revealed to be the most critical points to control as the groundwater can freeze if the heat extraction is too high. Night indoor air temperature setbacks can bring significantly high peak loads whenever the building is heated to be occupied during the day. This paper shows that, using a bleed ratio above 20 %, a night setback can be successfully operated ramping up the temperature in around 3 hours.

INTRODUCTION

Worldwide efforts to fight global warming have resulted in stricter energy efficiency standards and regulations, particularly in the building sector (UNFCCC, 2015). Ground Source Heat Pumps (GSHP) have been identified as a technology with great energy savings potential and worldwide application potential (Sarbu and Sebarchievici, 2014). However, high drilling costs for conventional closed-loop Ground Heat Exchangers (GHE) are slowing down mass adoption of the GSHP technology (Alshehri et al., 2019). For this reason, different GHEs, have been studied over the years such as open-loop systems, that use groundwater as a heat carrier fluid for the heat pump, being therefore able to operate closer to the undisturbed ground temperature, with thermodynamic efficiency advantages (Snijders and Drijver, 2016). These systems need shallower or fewer boreholes than closed-loop GHE, thus significantly reducing the investment costs (Snijders and Drijver, 2016). However, the design of pumping and injection wells often requires heavy and expensive field investigations to ensure that the site has suitable hydrogeological conditions and that the aquifer is productive enough to sustain the operation of GSHPs (Pasquier et al., 2016).

Standing column wells (SCW) offer an interesting alternative to both systems: they draw water from the ground as open-loop systems, but the pumped groundwater is for the most part reintroduced in the same boreholes (Pasquier et al., 2016). For this reason, field investigations are not as extensive as for fully open wells. Moreover, a portion of the groundwater can also be reinjected in a separate well if required by the local jurisdiction. This process (called "bleed"

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or “bleeding”) makes water extracted by the well closer to the undisturbed ground temperature, leading to a better coefficient of performance (COP) of the heat pump. These characteristics make SCWs more economical and more suitable for high density urban areas. However, there are still some obstacles in their widespread application because of the lack of user-friendly and easily accessible tools for their design and operation.

This paper’s objective is to tackle the operation phase of SCWs during winter peak demands developing a simulation framework that can assess the impact of different control strategies on the entire system. An optimal control can reduce ground heat extraction peaks, reducing the risk of groundwater freezing and leading to capital cost savings as fewer or shorter boreholes would be required. To show the potential of this tool, some preliminary results will be presented analyzing the impact of variations in the indoor temperature setpoint, such as night setback strategies.

The case study building is a primary school, located in Mirabel (Québec, Canada), selected as a demonstration project for the application of SCWs in Québec. As heating is the main energy consumption driver in this location, this work is focused on the heating season.

Standing column wells in cold climates

The most recent convincing experimental demonstration of the benefits of SCWs in cold climates was published by Nguyen et al. (2020). The study was conducted in a geothermal laboratory located in Varennes, Québec, Canada. Results show that the heat extraction from the ground (between 120 W/m and 160 W/m) is around 2.5 times higher than for conventional closed-loop GHE system (in the range of 50-55 W/m (Michopoulos et al., 2013; Pahud and Matthey, 2001; Wang et al., 2013), while keeping the groundwater temperature above 0 °C during peak heating periods. Thus, it shows that previous concerns (Minea, 2013) about operating these GHEs in winter, can be addressed by proper design and control of SCWs and HVAC system. Noticeably, promising results were obtained despite the following issues:

- Bleed was operated in this experiment only for 30 % of the time to ensure that the outlet groundwater could stay over 7 °C. When bleeding was operated, for the 80 % of the time the bleed rate was limited to 10 %.
- The geological environment was not favorable: the hydraulic conductivity of the aquifer ($K = 5.7\ 10^{-7}$ m/s) in Varennes is low as well as the thermal conductivity ($k = 2.74$ W m^{-1} K^{-1}) (Beaudry et al., 2019). Furthermore, the groundwater composition promoted carbonate scaling (Cerclet et al., 2020).

In a recent study, Beaudry et al. (2022) used detailed heat transfer models to analyze the performance of cold-climate SCWs in more favorable geological conditions. The results show that the heat extraction can reach 197–246 W/m, meaning that SCWs require around 4-5 times fewer or shorter boreholes compared to closed-loop GSHPs systems.

In the literature both experimental (Beaudry et al., 2019; Cho et al., 2016; Lee et al., 2019; Lim and Lee, 2021; Minea, 2013; Nguyen et al., 2020; Orio et al., 2005; Pasquier et al., 2016) and simulation studies (Beaudry et al., 2022, 2021; Nguyen et al., 2013) addressed the performance of GSHP systems using SCWs, some of which also explored different groundwater bleeding strategies (Beaudry et al., 2022; Nguyen et al., 2020, 2013).

Few studies address the combined operation of the building HVAC system and the SCWs. Beurcq (2019) modeled a typical office building with a water loop exchanging heat with an SCW and distributed on-off water-to-air heat pumps. The simulation used a Thermal Resistance Capacitance Model (TRCM) to model the ground; this approach resulted in a long simulation time. The results show that both the bleeding control strategy and the building setpoints must be controlled in an integrated manner to optimize the system performance during cold periods.

In this paper, we use a detailed building model of a primary school with hot and cold water loops served by a central variable-speed water-to-water heat pump and an auxiliary electric heater. The water-to-water heat pump source side is connected to a heat exchanger with the SCW. The ground model relies on a fast convolution method (Dusseault et al., 2018) based on transfer functions generated in Beaudry et al. (2022) for this case study building..

A demonstration project for SCWs

The case study building is the "*Clé-des-champs*" primary school, a 2780 m² (net floor area) building with two floors located in Mirabel, about 40 km outside Montréal. The installation of the GSHP system has been deployed between 2021 and 2022. Robert et al. (2022) conducted experiments to assess the thermal response of the ground without bleeding and Beaudry et al. (2022), modeled the ground response of the 5 SCWs simulating different bleed strategies.

The ground-source heat pump system with 5 SCWs and one reinjection well replaces a system with fuel oil and electric boilers. The ventilation system was also retrofitted with a new Air handling Unit (AHU) and a heat recovery unit.

METHODOLOGY

To assess the impact of the building operation on the HVAC system and on the ground, all the components must be included in the same model. The methodology of this work is summarized in the following steps:

- Development and calibration of the building's thermal loads model in TRNSYS (Klein, 2017)
- Creation of a HVAC model in TRNSYS representing the mechanical plans of the renovation project
- Integration of boreholes' ground response through a co-simulation with MATLAB (Mathworks Inc., 2020) using fast convolution-based methods to calculate the groundwater temperatures (Dusseault et al., 2018)
- Adjustments on the controls to replicate the control sequence plans of the building
- Evaluation of different indoor air set temperature strategies

Building energy model

The Space Heating (SH) demand of the school has been estimated with a dynamic energy model developed in TRNSYS, a transient system simulation tool (Klein, 2017). Geometrical dimensions of walls, windows, roof and all the related layers' composition were retrieved from the building plans. The building has been modeled in 3D with SketchUp 2019 (Trimble Inc., 2019) using the TRNSYS SketchUp plugin (Figure 1).

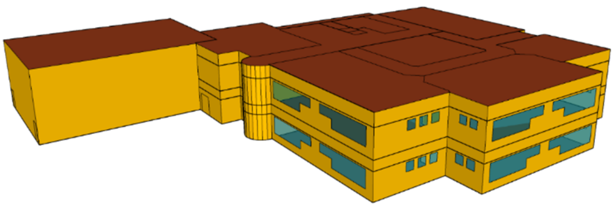

Figure 1 3D model of Cle-des-champs school built on SketchUp 2019

The thermal properties of the structures' layers were retrieved from Quebec's building certification standard (Novoclimat, 2020) and from ASHRAE Handbook 2017 (ASHRAE Inc, 2017). Transmittivity of structures (U values) and thermal capacities are listed in Table 1 for the main elements of the building envelope.

Table 1. Thermal properties of the building envelope

Structure	Thermal Capacity [kJ/(m² K)]	U value [W/(m² K)]
Roof	20.4	0.39
Suspended Ceiling	0.25	3.51
Floor (1st floor)	123.2	1.27
Internal Wall	172.5	1
External Wall	348.6	0.31
Ground Floor	1039.2	1.90

Schedules and densities for all internal gains are retrieved from school timetables. Their values have been estimated according to the Canadian National Energy Code for Buildings (NECB) (National Research Council of Canada, 2017), and to the ASHRAE 90.1 standard (ASHRAE Inc, 2019). They are reported in Table 2 together with ventilation rates and other HVAC parameters.

The weather data files used for the model validation (years 2015-2018) are retrieved from CWEEDS (Environment Canada, 2020) and from Whitebox Technologies Inc (WBT) (White Box Technologies, 2022) for the airport of Mirabel (Québec) which is located near the school.

Table 2. Internal Gains and HVAC parameters

Parameter	Value	Unit	Source / Notes
Occupancy heat gains	73.3	W / person	ASHRAE 90.1
Lights heat gains	8.7	W/m^2	CNEB 2017
Equipment heat gains	5	W/m^2	CNEB 2017
Ventilators heat gains	7	W/m^2	CNEB 2017
Ventilation air flow rate	≈ 6	ACH (h^{-1})	Mechanical plans, zone dependent
Sensible ventilation heat recovery	89	%	Mechanical plans (not considered for validation)
Temperature setpoint for validation	20-21	°C	Building Management System, zone dependent
Thermal power distribution limit	195.3	kW	Baseboard heaters + air handling unit

In TRNSYS, the ground's floor temperature is simulated with a 3D ground coupling model based on a finite difference approach available with Type 1244, which uses Kasuda's correlation (Kasuda and Archenbach, 1965). Also, as infiltration rates heavily influence energy calculations, a detailed infiltration model recently developed by NIST has been used (Ng et al., 2018). This model considers the impacts of wind velocity and of stack effect.

Previous electric and fuel oil bills were used for model validation. The model's energy demand predictions for 2016, 2017 and 2018 were respectively -4.32 %, -6.55 % and -0.7 % compared to the bills for those years. Since the bills also account for system losses like the fuel oil boiler's heat release (inside the building), the TRNSYS demand was considered consistent with the bills.

Ground response modelling

The objective of the ground response model is to predict the borehole outlet temperature as a function of inlet temperature, mass flow rate and ground temperature.

The fastest methods known in literature to simulate GHEs with varying heating power profile are based on the principle of superposition. For closed-loop systems, temporal and spatial superposition are used together to estimate the thermal interference between the boreholes (Spitler and Bernier, 2016) through transfer functions called "g-functions". A convolution combines these g-functions with an incremental load vector to give the thermal response. The transfer functions are usually generated beforehand using analytical solutions such as the Finite Line Source (FLS) (Cimmino and Bernier, 2014) and they depend exclusively on the geometry of the borehole's field and on time.

The same principle can be applied to SCWs with the exception of the transfer functions' generation (Beaudry et al., 2021). Analytical solutions such as the FLS are exclusively accounting for heat conduction, whereas for SCWs heat advection has a major role as most of the heat transfer is mostly made through the transfer of mass (Pasquier et al., 2016; Robert et al., 2022). Thus, the transfer functions for SCWs must be generated numerically. As some g-functions were already elaborated for the this case study by Beaudry et al. (2022) through a 3D finite difference model, they are also used in this work.

Regarding the type of existing efficient convolution methods, solutions in Laplace domain (Lamarche, 2009), spectral domain (Marcotte and Pasquier, 2008; Pasquier and Marcotte, 2013) or with matrix product (Dusseault et al., 2018) have shown to be much faster than time domain's non-recurrent summations. For this work, a matrix product has been used as it has been proved to be remarkably faster (stable at ≈ 4.7 ms) than time domain and spectral domain convolution's algorithms (linearly growing to 0.5 s after ≈ 5500 hours of simulation) when integrated to a timestep-by-timestep approach such as the one of TRNSYS. The matrix product uses different g-functions depending on the selected combination of pumping and bleeding flow rates.

It is worth mentioning that all convolution methods rely on linearity and stationarity of the model's response, which therefore requires a constant circulation and bleed flow rates. Only recently, Beaudry et al. (2021) developed a non-stationary convolution method to simulate GHEs using closed-loop or SCWs. However, this non-stationary convolution method has not yet been integrated into TRNSYS through matrix products, which would allow an acceptable simulation speed for this study. Therefore, at this stage only constant flow rates and bleeding rates are considered and non-stationary conditions will be implemented in future work.

The groundwater flow rate is a key parameter for the system's performance: the higher the flow rate, the smaller the temperature difference at the heat exchanger, thus reducing the risk of freezing. Precedent studies which analyzed bleeding strategies (Beaudry et al., 2022; Beurcq, 2019; Nguyen et al., 2020) used higher flow rates with higher energy demands. Since this work focuses on peak loads, the pumping rate is kept at its maximum (568 L/min).

To validate the ground response model integrated in TRNSYS, a simple setup has been created to replicate the results of Beaudry et al. (2022) when using constant flow rate conditions, in particular with the g-function produced with 408 L/min of pumping flow rate and 82 L/min of discharging flow rate. The model is validated over the EWT (outlet borehole temperature) and the LWT (inlet borehole temperature). For the LWT the RMSE results is 0.251 °C and the R2 score 97.6 %, for the EWT the RMSE is 0.122 °C and the R2 score is 97.7 %.

HVAC model

The HVAC system TRNSYS model is shown in Figure 2. The control of the 70 tons water to water heat pump consists in a 4 °C dead band control with a 48 °C setpoint on the return temperature.

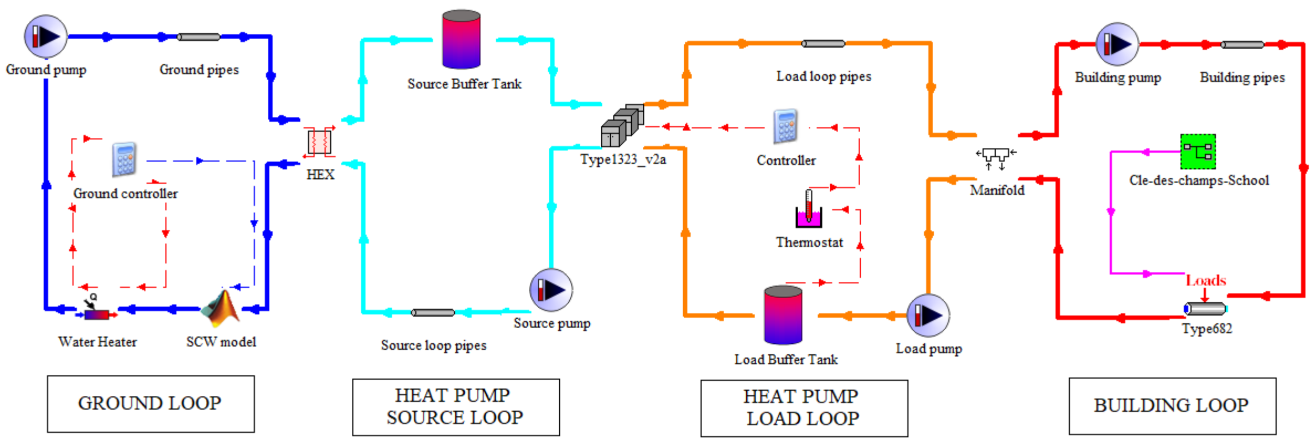

Figure 2 HVAC model in TRNSYS

The TRNSYS model is organized in 4 loops: (1) the ground loop, (2) the Heat Pump's (HP) source loop, (3) the HP's load loop and (4) the building loop.

1. **Ground loop.** To simulate the ground response, MATLAB is used through a co-simulation process. MATLAB stores the ground heat loads and the outlet flow rate temperatures in vectors, which are used to perform the convolutions with a matrix product. To prevent freezing in the heat exchanger, an electric heater is placed after the

boreholes as safety measure. This solution, inspired by previous studies (Beaudry et al., 2022; Nguyen et al., 2020), is a first attempt to deal with freezing issues without using solely the electric boiler to heat the building. This heater adds to, but does not replace, ground heat extraction, keeping the overall COP above 1. However, more efficient solutions will be evaluated in future work. As the heater is applied to the HP entering water temperature (EWT), it will be called “EWT heater” for the rest of the paper.

2. **HP source loop.** As the focus is on heating, the cold manifold is not modeled and the fluid (a solution of water and 30 %vol of propylene glycol) is directly pumped to the heat pump’s evaporator. A plate heat exchanger is put between the evaporator and the ground loop to prevent the heat pump’s evaporator to be in contact with the groundwater. The flow rate is kept constant at 9.46 L/s.
3. **HP load loop.** The flow rate is kept constant at 4.8 L/s to ensure stable operation of the heat pump. The connection to the load loop is operated with a manifold model which provides a thermal exchange depending on the flow rate ratio.
4. **Building loop.** As the HVAC system is complex some simplifying assumptions are taken into the TRNSYS model. For instance, the heating distribution system is all considered in one single load loop through a simple thermal load block which reads directly the total thermal load of the school. The flow rate in the load loop is controlled so that the temperature difference in the distribution system does not exceed 10 °C. Most of the time, however, the temperature difference is lower, as the flow rate in the load loop is set to a minimum of 2 L/s. The limitation of this approach is that the TRNSYS building model elaborates ideal loads based on an ideal internal temperature control that reaches exactly the setpoint required, and then imposes the calculated loads on the water loop. More realistic controllers can be implemented in TRNSYS but this has not been done at this stage.

RESULTS AND DISCUSSION

The objective of the paper was to develop a tool capable of assessing the impact of different control strategies on a HVAC system using SCWs. Some preliminary results will be presented here to show its potential.

Three indoor set temperature setback scenarios will be compared for the 2nd and 3rd days of February 2015, which contains the major load peaks of the year, an outside temperature varying between -14 °C and -26 °C and the wind speed that reaches peaks of around 4 m/s. The first one ramps up from a setback of 2 °C in about one hour and the other two recover the ramp more gradually in around 3 hours before the building is occupied (i.e. 8 AM).

Since the groundwater flow rate has to be kept constant due to the stationary convolution, a bleed of 20 % of the total groundwater flow rate is analyzed for the first two scenarios and a 30 % bleed ratio for the third one. The latter is analyzed to understand its potential advantages during demand peaks. Table 3 summarizes the three scenarios that have been tested.

Table 3. Simulated Scenarios

Characteristics	Scenario 1	Scenario 2	Scenario 3
Duration of setback	1 h	3 h	3 h
Bleed ratio	20 %	20 %	30 %
Power cap	No	Yes	Yes
HP’s compressor energy use (kWh)	1062.5	1066.3	1054.1
EWT heater energy use (kWh)	31.6	0	0
Maximum total power (kW)	68.7	37.9	37.5

The results of three scenarios are shown in Figure 3 for the total power consumed (on the middle) and boreholes' temperatures (on the bottom) in relation to the indoor air temperature (on the top).

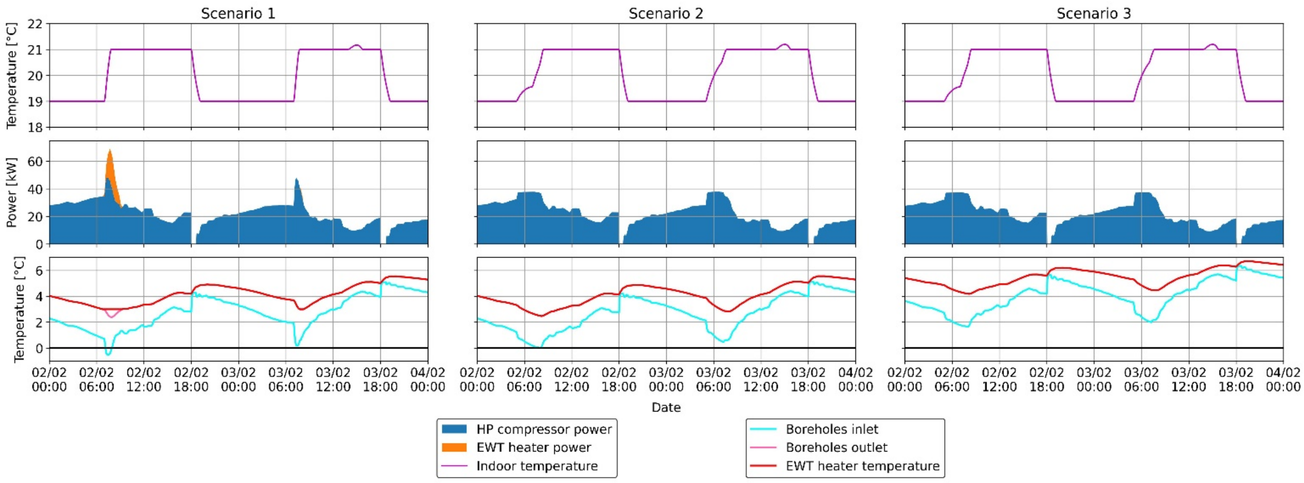

Figure 3 Results for the 3 Scenarios. On the top the indoor air temperature of the building. In the middle the power consumed by the HP compressor and the EWT heater. On the bottom the groundwater temperature at the inlet of the SCWs, on the outlet (visible in pink only in Scenario 1) and after the EWT heater.

Scenario 1. In the first day represented (2nd of February) the EWT heater is used to try to avoid groundwater freezing, but keeping the outlet temperature at 3 °C is not sufficient and the temperature after the heat exchanger drops below 0 °C. The power consumed by the water heater is above 20 kW bringing the total power spike to over 72 kW.

Scenario 2. The indoor temperature setback is ramped in about 3 hours through a power cap that limits the distribution of thermal power to the building. The power is capped using a linear interpolation method which takes the external temperature as independent variable. With this power cap, the total power peak spikes at around 38 kW. Thanks to this power limitation, the water heater is never required with 20 % bleed to avoid water freezing as the minimum borehole's inlet temperature is 0.01 °C. As this temperature is dangerously close to 0 °C, to avoid the freezing risk, either the bleed could be risen to 30 % during the temperature setpoint variations or the EWT heater could be switched on to keep at least 2.5 °C at the boreholes' outlet. As shown with Scenario 3, if the bleed ratio is kept at 30 %, the inlet temperature stays above 1.6 °C. A non-stationary convolution model would allow to simulate this bleed variation only near heat demand peaks, keeping a lower bleed rate for the rest of the time.

Scenario 3. Using a 30 % bleed ratio keeps the groundwater temperature after the heat exchanger safely above 1.6 °C. The total power peak is 37.5 kW. Just 0.5 kW less than with 20 % bleed (Scenario 2). In terms of performance, the difference with Scenario 2 stands in the groundwater temperature, showing that a 20 % bleed rate is already sufficient to have a high COP and a higher bleed is only required to avoid groundwater freezing during demand peak events.

Discussion. A fast conventional setback (Scenario 1), as expected, is not a viable option as the groundwater freezes even with a large use of the EWT heater. Using a more gradual setback to ramp up the temperature (Scenario 2) in 3 hours instead seems to be a more feasible solution even if the groundwater arrives near the freezing point. Operating 30 % bleed ratio (Scenario 3) near demand peaks could be useful to avoid groundwater freezing risks while it is reducing the power peaks only of a small amount. It should be noted that using a constant temperature setpoint could avoid these power peaks, but it would consume about 13 % more energy to keep a higher setpoint when the building is not occupied. These are preliminary results, which are shown to present the potential of this control strategy framework. Further work will be addressed to produce more complete results.

Limitations. The objective of this first stage of the project was to draft a first simplified control framework of a SCW system. The ideal indoor temperature control does not take into consideration fluctuations of a real thermostatic control which could alter the demand peaks. Constant groundwater flow rates limit the flexibility potential of the system but as shown in this article it is still possible to evaluate the behaviour of the system during demand peaks and how these can be addressed with preheating strategies. The highest possible groundwater flow rate was used specifically to analyse the peak demands and pumping energy was neglected at this stage. Finally, the heat pump on/off control is still a simple deadband, which limits the potential of the heat pump to operate more efficiently.

CONCLUSIONS

In this paper, a control strategy evaluation framework for buildings using GSHPs with SCWs has been developed. An HVAC system with SCWs is modeled together with a real case study building, located in Mirabel, Québec, Canada. In recent years most of previous concerns over the use of SCWs have been solved and a recent experimental application proved that SCWs can be used in cold climates despite not favorable ground conditions. The installation of SCWs in an institutional building in Québec allows to better explore their performance when interacting with a building. The impact of different indoor air set temperature strategies on the entire system is analyzed under maximum groundwater flow conditions, as most of control and water freezing problems are caused during peak loads. Simulations suggest that ramping the setback over 3 hours allow to operate the system without the use of the fluid heater with just a 20 % bleed, although a 30 % bleed would be recommended near peak loads as a safety factor. Future work with the model will focus on overcoming some current limitations and will explore more advanced control strategies, such as Model Predictive Control (MPC), with the objective of further reducing power peaks.

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