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Continuous Commissioning Techniques for Ground Source Heat Pumps: Review

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Abstract

This study offers a model-based continuous commissioning methodology to find control-related performance gaps in HVAC systems with ground-source heat pumps. Traditional continuous commissioning is still helpful in finding energy performance gaps, even if MBCCx employs a system model as a reference to find operational inefficiencies and control issues arising from subsystem integration. A calibrated physics-based model that depicts the system performance as intended during the design phase forms the basis of the suggested methodology. One major benefit is that, in contrast to data-driven approaches that depend on large historical datasets, it can be applied early in a building's operational phase when data is scarce. This enables the identification of energy-saving opportunities before the system reaches a stable operational state. This work pioneers the application of MBCCx to entire buildings equipped with GSHPs in order to overcome the limitations of previous research that frequently concentrate only on individual GSHP component performance. In order to forecast variables like room temperatures, heat pump power, and ground heat exchanger temperatures under typical circumstances, the suggested method makes use of a comprehensive 3D building model and component-level HVAC modeling. Under performing components or anomalies in the control sequence are indicated by significant differences between monitored values and model expectations. The HVAC system and GSHP performance indicators are then combined to increase the precision of anomaly identification. A case study of a recently renovated elementary school in Quebec, Canada, that has five standing column wells installed as ground heat exchangers is used to illustrate the methodology.

Keywords: White-box modeling, monitoring, building flexibility, HVAC systems, ground-source heat pumps

INTRODUCTION

The building industry, which accounts for 30% of the world's final energy use, may be crucial in reducing the effects of climate change. The International Energy Agency aims to meet 50% of the heating demand using heat pumps (HP) by 2045 and convert 50% of existing buildings to zero-carbon levels by 2040. But maintaining and optimizing performance over time is just as important as installing effective equipment. Innovative methods to heating systems, especially in buildings, are now necessary due to the shift towards sustainable energy solutions [1]. This study examined the economic feasibility of electricity price-based control strategies for the CO_2 heat pumps in Oslo, Norway, with a focus on improving the flexibility of a CO_2 heat pump system in school buildings and removing current obstacles.

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Commissioning and Model-based Commissioning

"Commissioning" (Cx) is the methodical process of confirming and recording that a building and its HVAC system satisfy specific performance requirements after construction or restoration. A targeted commissioning project run by a private company on an existing building has a median energy savings of 14%; in certain situations, it can reach over 50% of demand reduction, according to a recent survey that included 1500 structures in North America. Over time, Cx has been incorporated into building certifications and some of the most well-known standards in the world, as well as the international (ISO) and European (CEN) standards created by the ISO Technical Committees. The "design, installation, repair, and replacement" of any equipment or building element, "operations & controls" of the systems, and "maintenance" of the building comprised the three categories in the world's largest (at the time) survey on building commissioning [2]. According to its 2020 update, operations and controls account for 95% of the measures; these are also the ones with the greatest potential for energy savings. In a similar vein, energy audits of 33 Brazilian office buildings revealed that over 75% of the problems had to do with operation and maintenance rather than design and construction. The authors also demonstrated how Cx or operational modifications could address these problems. The schedule control capabilities created for the HVAC and refrigeration systems are essential to the building energy management system's (BEMS) potential to boost ROI.

As a result, the majority of research and industry initiatives have concentrated on "Continuous Commissioning" (CCx) (also known as ongoing commissioning), which Verhelst et al. defined as "a continuous performance evaluation in order to maintain, improve and optimise the performance of building systems during building operation and occupancy." In-situ monitoring techniques have been used in a number of projects to make the Cx and CCx processes more effective and manageable [3]. The technicians use sensory input and diagnostic instruments to find and measure energy-conserving opportunities (ECO) and other non-energy problems including indoor air quality. This Monitoring-Based Cx (MBCx) achieves statistically greater energy savings than the other Cx approaches, according to the aforementioned survey by Crowe et al. Later, the MBCx method developed into Model-Based Continuous Commissioning (MBCCx), which compares the measurement data using reference models as a benchmark. The reference models can be constructed from the measurements themselves (data-driven models) or from any other pertinent source, including design data (white-box models) or expert knowledge (heuristic). Three sub-domains were found by Verhelst et al. in their comprehensive evaluation of MBCCx: economically appealing energy conservation opportunities implementations (ECOI). Performance estimations (PE), benchmarking (BM), and energy-saving opportunities (ECOs) are all included in ECOI [4]. The three methods compare the existing building to: (i) the building's past performance (PE); (ii) an example building with a comparable layout (BM); and (iii) a different building configuration or modified HVAC installation (ECOs). FDD stands for fault detection and diagnosis. FDD focuses on component-level models that are capable of locating, identifying, detecting, and occasionally even forecasting operational or sensing issues throughout the HVAC system.

control based on models (MBC). From straightforward configurations (such as an open loop controller that resets a supply temperature based on a building steady-state model) to more intricate solutions like model predictive control (MPC), which forecasts the system's states to make control decisions, MBC encompasses all models designed to directly control the HVAC system. With the introduction of building automation systems (BAS), MBCCx can also be used to automatically identify abnormal or underperforming system activity. This kind of MBCCx uses the building's fault-free past energy performance as a baseline to run automatic FDD [5]. These automated MBCCx methods can be classified as a combination of FDD and ECOI. These techniques can be applied in a Building Information Modeling (BIM) framework or in a BAS, according to several research. Selecting the metrics and time intervals that are utilized to alert building energy managers is essential when using MBCCx for the automatic detection of anomalies. For their case study, a weekly interval with a 6% difference for electricity and a 15% variation for heating reduced alarm fatigue, according to Harmer and Henze's white-box MBCCx application. Additionally, they discovered that in order to avoid false alarms at lower loads, either a minimum absolute threshold of energy usage to be able to sound the alarm or a scaling ratio that weighs down small energy periods must be used. Piscitelli et al. identified aberrant electrical profiles of a university building using an Artificial Neural Network (ANN) model [6]. where they classified as "anomalous" the days where the electricity consumption exceeded three times the standard deviation computed between the ANN and the fault-free experimental data, at least for six hours, they achieved a 93.7% alarm precision.

Commissioning of Ground-source Heat Pump Systems

Another advancement in HVAC systems during the past few decades is the widespread use of ground-source heat pumps (GSHPs), which frequently consume three to five times less energy than electric or fossil fuel boilers. Additionally, GSHPs outperform air-source HPs in terms of performance and stability due to the thermal inertia of the ground. This enhanced performance and stability is typically more valued in cold climates (such as northern Europe, the northern USA, Canada, cold regions of China, etc.) where GSHPs have gained popularity [7]. This is because the higher installation costs can be justified by a significant performance advantage over air-source alternatives. GSHPs require the HVAC systems to have a completely new section with numerous pumps, pipelines, sensors, and other controls. As a result, managing the HVAC system becomes more challenging, and the integration of all the different parts makes the system more susceptible to control and performance issues. This topic is covered in detail in a recent report on the monitoring work of six GSHP installations in Germany (Bockelmann and Fisch), which claims that a regulation phase is required to achieve the best possible integration between the geothermal system, the building structure, additional thermal conditioning systems, and the end users [8]. According to the authors' experience, a successful integration requires the application of fully coordinated control approaches, which must be confirmed and monitored during operation until regular functioning is achieved. The high thermal inertia of GSHPs makes them more challenging to identify system and operating issues, which can mask operational defects that ultimately produce a ground energy imbalance and reduce the GSHPs' performance.

Numerous research in the literature address the performance monitoring of GSHPs. Spitler and Gehlin published the monitoring results of a GSHP system at a student facility in Stockholm, Sweden, with five 40 kW water-to-water HPs and twenty closed-loop boreholes dug in hard rock. It was discovered that simple operational issues, including the continuous operation of circulation pumps and high flow rates in the borehole circuit, or the 24-hour Legionella protection provided by an electric resistance heater, were the main causes of performance gaps [9]. The authors added that they discovered several issues with the current methods for figuring out the Seasonal Performance Factor in commercial buildings and that they should be expanded to include larger borders and account for the rest of the structure (e.g., ventilation fans, pumps). Cespedes et al. provided a novel method for determining the partial load factor (PLF) for double parallel stage GSHPs that accounts for efficiency degradation over time.They developed and tested their model using monitoring data from a GSHP system in a three-story office building in Catalonia, Spain. The case study's linear fit revealed a yearly reduction in COP and EER performance of 1.6% and 4.0%, respectively. These results led to a physical maintenance procedure, which discovered that one of the three-way valves had poor performance (incomplete shutting) and was causing an unwanted connection between the evaporator and the condenser water circuits.

Furthermore, a significant amount of material was found in the evaporator side water filter, which reduced the flow rate. In a number of studies, GSHPs monitoring data were used to build numerical models or train data-driven models. Barla provided a comprehensive monitoring and modeling analysis of the geothermal system used for air cooling by a groundwater heat pump in a large building in Turin, Italy [10]. After the wells' pumping testing and real-time monitoring were finished, a thorough Finite Element 3D model of the entire geothermal system was produced. This made it possible to successfully evaluate the results of the pumping tests and forecast the behavior of the aquifer in the long run. Park et al. built multiple linear regression (MLR) and artificial neural network (ANN) models using in-situ monitoring data of a large-scale GSHP system installed in a hospital in Southeast Korea. The hourly heating performance was satisfactorily predicted by the MLR (3.6%) and ANN (1.8%) models. Yan et al. also demonstrated how in-situ monitoring data may be used to accurately predict long-term GSHP behavior using data-driven models. They first used a Data Mining (DM) technique to determine the parameters to use as inputs and outputs for a Back-Propagation Neural Network (DPNN) model [11]. They also found that at least 71 winter days and 30 summer days of short-term monitoring data were required to train the model with a variance below 3%.

Paper Novelty and Objectives

Numerous instances of data-driven model training and performance monitoring for GSHP systems have been presented in the literature review. With the exception of the aforementioned study by Bockelmann and Fisc, which highlights the necessity of closer monitoring of the integration between the GSHP, the building, and the rest of the HVAC system, these studies typically concentrate on the GSHP alone without taking into account its integration into the building. MBCCx is promising for GSHP systems in light of these factors [12]. The growing complexity of the HVAC system and the overall integration of the subsystems could be better handled by a strong reference model. To the best of the authors' knowledge, no research has addressed MBCCx for buildings with a GSHP, despite this potential. In this study, a unique white-box MBCCx approach for GSHP-based HVAC systems is proposed. The suggested technique takes a "whole-building" approach, concentrating on how the building and its HVAC subsystems interact to find underlying subpar performance brought on by poor component integration. Even when individual parts operate as expected but the control sequences are unable to guarantee their effective coordination, such inefficiencies may still arise. By regularly comparing the system's performance with the model, these performance gaps can be automatically found. Finding a performance metric that takes into consideration several subsystems at once is crucial to ensuring an accurate anomaly detection. The goodness of-fit metric for the GSHP power consumption and a comparable metric for the ground heat exchanger (GHE) are combined in this work [13]. As opposed to a data-driven model, which would replicate the precise performance of the system, the white-box model, which is physics-based, can offer a benchmark of how the system should operate.

This advantage is particularly crucial in the initial months of a building's operation, when there is insufficient data to adequately train ANN models. However, it is already imperative to run CCx to make sure the system is operating as intended. Furthermore, white-box models enable the investigation of various control mechanisms that may enhance the total energy efficiency [14]. The MBCCx approach can be utilized for both FDD and the evaluation of ECOI measures because it allows for the exploration of hypothetical scenarios. The MATLAB ground model uses a nonstationary convolution method created by Beaudry et al. that combines the ground loads with multiple transfer functions that represent the ground's thermal response under various flow rate conditions, while the TRNSYS model takes into account both design data and field experimental data. This technique can be used to standing column wells (SCWs), which are covered in the following section, or to traditional closed-loop GHEs [15]. A ground coupling simulation for the ground temperatures and a comprehensive infiltration model created by NIST are included in the building model. The HVAC system consists of a water-to-water HP, an air handling unit (AHU) with ventilation control, a hydronic heating network that uses PID-controlled radiators to distribute thermal energy, and an air heat recovery device. The HVAC system setup is also easily adaptable to any real-world application because TRNSYS is modular.

The Role of MBCCx for Early Adopters of Technology: The case of Standing Column Wells (SCWs)

Building managers are interested in making sure the technology operates as intended when large investments are made to enhance performance and encourage energy savings. However, because of the lack of experience, implementing a technology that is not widely used involves a significant risk. This is the case with SCWs, a potential type of GHE, as practitioners are often more familiar with closed-loop GHEs. When other references are hard to come by, MBCCx is a useful tool that provides trustworthy performance insights. The high drilling costs of traditional closed-loop GHEs are a major barrier to the broad adoption of GSHPs, despite the technology achieving significant energy savings in the building industry [16]. Over the years, many GHE systems have been studied in an effort to lower expenses. The open-loop GHE is one such configuration that directly employs groundwater as a heat source and sink for the HP. Two advantages result from this: a source/sink temperature that is closer to the undisturbed ground temperature and an increase in heat exchange due to the transfer of mass. Consequently, fewer or shallower boreholes are needed, which lowers the overall cost of the project. However, for open-loop systems to function well, an extremely productive aquifer is needed. As a result, its application is restricted to appropriate locations with strong hydrogeological potential.

The standing column well (SCW), another kind of GHE, is described as an open borehole that is 75–450 m deep, primarily drilled in bedrock, and typically has a diameter of 150 mm [17]. SCWs use groundwater, just as open loop systems, but they reintroduce the majority of the water flow into the same wells. As a result, they don't need especially productive aquifers. By releasing a portion of the groundwater into a different well known as the "injection well," which is usually positioned at least 10 meters apart from the others, they can still profit from advection. This process, known as "bleed," produces a depression cone around the well that encourages advective heat transfer by causing water flow in the nearby fracture network. The SCW's groundwater becomes warmer in heating mode and colder in cooling mode as a result of the increased advection, bringing it closer to the undisturbed ground temperature [18]. The suggested methods and general recommendations for developing a model for CCx are presented in Section 2. The application of this technique to a case study demonstration with five 135-meter-deep SCWs and an injection well is shown in Section 3. The latter will contain some exemplary MBCCx process outcomes as well as simulation findings.

Proposed Novel Methodology

This MBCCx approach seeks to develop a thorough, "whole-building" representation that can faithfully replicate the performance and operation intended by design by concentrating on establishing a benchmark of perfect operation. Thus, it is important to avoid developing a model that unintentionally "picks up" operating problems in the mechanical system when data is available. While incorporating real-world factors like actual infiltration rates, occupancy profiles, and weather patterns, an MBCCx model should represent how the building systems are intended to function. A model that incorporates all of the building's subsystems is necessary for a "whole-building" MBCCx approach [19]. Therefore, it is advised to use a modular modeling software program that can depict how several blocks interact with one another.

The main proposed steps are the following:

1. Modeling the structure itself
    a. Building envelope, zoning, and internal gains
    b. Ground coupling and air infiltration rate models
2. HVAC modeling
    a. HP modeling and calibration
    b. HP and building model integration via a heating distribution system
    c. GHE thermal response model development and integration
3. Data tracking, validation, and model calibration
    a. Data processing and monitoring of the actual building
    b. Model validation and calibration using experimental data
4. MBCCx
    a. Identifying unusual days automatically
    b. Using a thorough parameter comparison to diagnose control sequence issues
    c. Finding improved control sequences that can result in energy savings

Modeling the Building Itself

When modeling a building, the first decision to be made is how to separate it into several thermal zones, or "thermal blocks." This zoning method makes it easier to match air zone measurements with the simulation [20]. The thermal mass capacity should receive particular consideration when defining the thermal properties of the building envelope because it significantly affects how the building responds to various control sequences. While the thermal characteristics of the external building envelope and the inner walls are normally well-defined, most modeling standards often disregard the remaining internal thermal mass (e.g. furniture, equipment). Internal heat gains have a major effect on the building's thermal balance. Compliance models frequently rely on standards and fixed schedules, but for CCx, actual building schedules should be preferred, and the occupancy of each zone should be estimated based on real-world data. A more accurate method relies on the definition of interior planar thermal mass objects that can be implemented in building energy simulation software [21]. A simpler way to account for the internal thermal mass is to multiply the air thermal capacity by a factor, typically between 5 and 10. By subtracting HVAC electric power from the total billed power, lights and equipment improvements should be inferred using prior data on total electricity usage to achieve the best level of accuracy. Lighting electric gains can still be calculated using per-area values from standards in the absence of observed data. However, in order to obtain the most accurate results, input data (especially operating hours) should be based on either a comprehensive examination of the precise requirements of future spaces or detailed monitoring data of existing spaces. When user behavior data from interviews, technical data from walk-in visits, and measurements of electric load consumption were used to estimate equipment electric load profiles, the results were in good agreement with experimental data.

Standard fixed air infiltration rates are usually recommended by compliance models. However, it is essential to design a more accurate infiltration rate for CCx since air infiltration has a major impact on heating loads and is very variable. Simpler regression models based on temperature variations and wind speed may also yield adequate accuracy, even though more complex bulk airflow models can be employed [22]. To find a model suitable for the particular building type and climate zone, it is advised to refer to the literature. The Energy Plus infiltration empirical formula for eight distinct U.S. climate zones and five distinct commercial building types. It is important to note that when mechanical ventilation is turned on or off, the fitted parameters are drastically changed. Building heat losses are also significantly influenced by the ground's boundary temperature. An annual or monthly average ground temperature is usually recommended by compliance models and standards. Nevertheless, the model's accuracy is somewhat diminished by this streamlined approach. It is advised to use physics-based techniques called "ground-coupling" to assess such temperatures. These models, which are usually based on a finite difference technique, distinguish the ground for various building zones. Near the external walls, where the temperature fluctuates rapidly, the meshes are denser to maintain excellent precision.

HVAC Modeling

Equipment

Technical diagrams for HVAC systems are often rather intricate and contain a number of elements that do not require representation in an energy model. As a result, the overall design of the HVAC system can be made simpler, but the core loops that carry the energy flows should remain exactly as they are in the real setup. For example, it's a good idea to maintain the same number of pumps and heat exchangers as the HVAC system itself. Additionally, it is advised that HVAC parts (such as pumps, buffer tanks, heat exchangers, and manifolds) be scaled in accordance with their precise design specifications. The design specifications for each zone should be used to determine the air flow rates in buildings with mechanical ventilation [23]. Because the Air Handling Unit (AHU) fan generates substantial heat gains that will be added to the building, the modeler should pay close attention to its size. It is advised to measure the fans' power needs in-situ. Heat gains for new buildings can be calculated using the electric motors' maximum rated power. Finding the heat pump's performance map is a first step in the GSHP modeling process. Manufacturers frequently only offer a few functioning points rather than the complete map. If this is the case, a model can still be fitted using the limited performance points that are available. In order to test and calibrate the HP model to provide the desired results when changing the source and load inlet temperatures, it is advised to first model the HP alone along with its load and source loop after obtaining the performance map. A simple GHE can be linked to the source loop as a first step, and its complete model can be added later [24]. The HP model can be linked to the building model once it is prepared. A heating distribution system and thermostats that control the building's heat flow must be installed in order to do this. The control sequences need special attention from the modeler.

The HVAC control in the model does not replicate the precise code used in the building management system (BMS) because one of the primary goals of CCx is to detect control sequence difficulties, especially supervisory control problems. Rather, it must replicate the expected functionality that the control contractor received from the HVAC designer via a generic control sequences document [25]. By using this method, the model will be able to identify abnormalities in the existing controls' configuration rather than just replicating these problems. However, it is allowed to directly incorporate recorded data when certain control sequences cannot be recreated within a model. One instance of this is when the system's pressure is not represented and fluid flow rates are dependent on the position of pressure-controlled valves. Achieving the desired performance requires proper calibration of some local controllers, such as the HP controller and room thermostats, which are the primary determinants of the thermal dynamics of the entire model [26]. This calibration is especially crucial since, no matter how accurate the model is, it will always deviate from reality, necessitating a new control calibration. It is important to note that, whereas compliance energy models usually employ a 1-hour time step, it is highly advised to use a 1 to 15-minute time step for CCx, which should correspond to the measurement sampling rate of the building's installed sensors. By using a high time resolution, the model can accurately replicate the HVAC system's quick dynamic responses, making it possible to compare them with the data and find systemic inefficiencies.

Ground Response Modeling

The ground response model's primary function is to determine the GHE's output temperature using the undisturbed ground temperature, mass flow rate, and inlet temperature. The notion of superposition is the basis for the quickest methods found in the literature to forecast the behavior of GHEs under different power loads. Over time, these techniques have mostly been developed for the more widely used closed-loop GHEs [27]. Through the convolution of transfer functions with an incremental power load vector, they employ simultaneous temporal and spatial superposition. Spitler and Bernier's book chapter provides a more thorough and in-depth analysis of this field. Nevertheless, each transfer function is produced for a particular fixed ground flow rate, and all of these superposition techniques depend on the linearity and stationarity of the model response. The influence of dynamic control schemes that modify the pumping power to optimize the operation of GSHP systems cannot be studied due to the assumption of fixed flow rates. For MBCCx applications, these superposition techniques are consequently inappropriate. In an effort to get around this restriction, a nonstationary convolution method for GHE simulation was recently devised. This is accomplished by permitting the inclusion of various transfer functions, each of which represents a different ground flow rate value, within the convolution matrices. Multi-flowrate thermal response tests (MF-TRT) were used to experimentally confirm the findings. The procedure for getting the transfer functions is different for SCWs, even though the same approach can be used. In contrast to closed-loop GHEs, SCWs mainly use advection to transport heat under ideal geological circumstances [28]. As a result, analytical solutions created for closed-loop systems (such as finite line sources) that only take conductive heat transfer into account are inapplicable to SCWs.Transfer functions for SCWs may currently only be produced using intricate 3D finite-element numerical models or by using a deconvolution algorithm to analyze thermal response test (TRT) data. Numerous studies have shown that by lowering the frequency during partial loads, the use of variable speed drives to pump the heat carrier fluid flowrate in GHEs results in significant annual energy savings. For the simulation of GHEs, it is therefore highly advised that MBCCx be followed using a non-stationary convolution approach.

Data monitoring, Model Validation and Calibration

Data collection, monitoring, and processing are the foundation of the first phase of the Cx process. Sensors that measure fluid temperatures, flow rates, current intensities, frequency modulation, power factors, and any other pertinent parameter should ideally be installed in every piece of HVAC equipment

[29]. Sensor data should be collected by the BMS and stored in a database at a high frequency (1–15 min). The data can be immediately compared with the model simulation results for validation after it has been appropriately cleaned and processed. It is recommended to either make sure the measurement time step is divisible by the simulation time step or to use a simulation time step equal to the measurement time step. This makes it possible to downsample the simulation findings without sacrificing their accuracy. Additionally, it is crucial to choose a time frame for the validation and calibration process when the building is functioning within the anticipated indoor temperature set points and there are no obvious flaws. The HP's thermal output and the GHE's inlet and outlet temperatures are the most crucial factors that must match experimental data [30]. The core of the energy flows from the source to the load is represented by these parameters, which specify that hourly simulated data should have a normalized mean bias error (NMBE) of less than 10% and a coefficient of variance of the root mean square error (CVRMSE) of less than 30%. By "smoothing out" the cyclic on/off patterns of dead band controllers, using hourly timestamps instead of sub-hourly timestamps for data validation streamlines the procedure. The validation procedure is made considerably more challenging by the difficulty of accurately capturing these cycles and the potential for serious errors. In conclusion, the model must be correctly calibrated in order to function well throughout validation [31]. This entails concentrating on elements such control set points and model estimates of internal gains, air infiltration rates, and building thermal mass that are not usually included in the normal FDD approach.

Model-based Continuous Commissioning

Fault Detection and Diagnosis (FDD)

After the model is calibrated and validated, it can be used to automatically determine which days are aberrant and to confirm the source of the divergency by comparing the model findings with the most important parameters. The primary heat pump's (HP) daily performance will be assessed using the "Goodness-of-fit" (GOF) measure. This is because building energy managers prefer models that replicate the mean energy use rather than the hourly volatility. However, in this work, a 1:2 weight better balances capturing the short-term variations of the HVAC system with reflecting overall energy use. The two GOFs are normalized (using min–max scaling) into GOF· HP and GOF· GHE, and CVRMSEGHE and NMBEGHE are computed using the same reasoning but with unitary weights [32]. When compared to the GOFHP or GOFGHE alone, combining these two performance metrics has been found to be more successful in reducing the false positives (normal days detected as anomalous) and false negatives (anomalous days detected as normal). The most ideal threshold for the new GOFGSHP metric was discovered to be 0.2, as the findings subsequently demonstrate. This means that days with a GOFGSHP above 0.2 can be identified as unusual. Model findings and anomalous experimental data can be examined side by side if anomalous days are identified. Where and how the actual system deviates from the anticipated behavior will be visible. To pinpoint the source of the variances, several system components might be compared. Additionally, the model will demonstrate how the system ought to have functioned as designed. This method enables the impact of identified errors or control issues to be quantified. Although the aforementioned method guarantees that the model accurately depicts the HVAC system's intended behavior, it does not ensure optimal performance [33]. Even if the system follows the planned design, it might be underperforming. A substantial quantity of energy can be wasted as a result of subpar control tactics or implementation. For example, in GSHP systems, the pumps' power consumption is frequently the cause of a notable drop in the system's seasonal COP (SCOP) as compared to the heat pump's independent seasonal performance. Nonetheless, several control mechanisms that can improve the overall efficiency of the system can be found and tested using the model. To guarantee their long-term efficacy, these tactics can also be assessed under various weather conditions.

CASE STUDY DEMONSTRATION

A elementary school in Mirabel, Quebec, Canada, serves as the case study building. In 2022, a 70-ton GSHP system with five 135-meter-deep SCWs and an injection well was added to the school's HVAC system. A new air heat recovery unit was added, and the majority of the convectors and ventilation ducts were replaced as part of the refurbishment. Peripheral convectors with a 126 kW capacity and a ventilation system with an AHU with a 41 kW capacity are used to disperse the heating throughout the building. In addition to ventilation and convectors, two building zones—the gym and the administration zone—have one 28.6 kW and two 8 kW water-to-air HPs, respectively. However, an undersized pump prevented the HPs supplying the administration zone from operating during 2023. A CCx application has been used to monitor the new system since it began operating in January 2023. Beaudry et al. have released the results for the full year. When compared to closed-loop GHEs, SCWs were shown to enable a 50% reduction in overall construction costs and a 73% reduction in total drilling length [34]. Instead, this study will concentrate on the first 40 days of operation (January 18–February 28) following the modification of the control sequences. Because the system is primarily sized for heating loads, which account for the majority of the building's overall energy demand, the focus is on the coldest time of year. Finding control problems with heat generation (heat pump and ground heat exchanger) and distribution (convectors, ventilation, etc.) has been the goal of the MBCCx method. Additional information about this case study can be found in other publications.

Building Modeling

Using the TRNSYS 3D plugin, the building was initially modeled in three dimensions in Sketch Up 2019. In accordance with ASHRAE norms, 23 thermal zones were included in this model (see section 2.1). As-built plans provided the construction details, and the ASHRAE Handbook 2017 and Quebec's building certification standard provided the thermal characteristics and layer densities [35]. The air thermal capacity was first multiplied by ten to add more thermal mass. Later, during calibration, wooden objects were added to the thermal zones to enhance thermal mass (see section 3.5 for additional details). In order to have more realistic thermal dynamics in the building, occupancy heat gain schedules are linearly interpolated hour by hour from the school building's schedules. The occupancy density in each room has been redistributed based on reasonable assumptions based on the usage type of each zone, and the total number of people in the building has been projected to be approximately 400 (360 students + 40 employees). The ASHRAE 90.1 standard is used to calculate the occupancy gain per person. Instead, calibrated profiles resulting from the entire measured electricity use are used to govern equipment and lighting increases. In cold weather, air penetration can have a significant impact on building demand [36]. This model takes into account the effects of both the stack effect and wind velocity. In order to give a realistic ground temperature as a boundary condition, the building model integrates a "ground coupling" model. A 3-D ground coupling model based on a finite difference method that makes use of Kasuda's correlation can be used in TRNSYS to simulate the ground temperature. To determine the near-ground temperature (two to three meters below the ground floor) for various areas of the building, the ground can be separated into multiple zones. However, precompiled boundary temperatures can be used in subsequent runs to cut down on computing time because this approach considerably slows down the TRNSYS simulation.

HVAC Modeling

The model's HVAC system diagram retained the same number of loops and heat exchangers as the actual system. Nonetheless, the following simplifications have been made:

- The SCWs' five submersible pumps are combined with the SCW circulating pump;
- The gym's water-to-air heat pump has been combined into the main water-to-water heat pump;
- The overall valve layout has been simplified, and their behavior has been modeled using manifolds and variable speed pumps.

Two heating distribution systems are included in this model: hydronic heating and ventilation. A manifold is used to control both of these systems. To enable temperatures below C, a 30% (v/v) propylene glycol solution is used on the source side. It is also used on the load side to keep the AHU coils from freezing in the case of a malfunction, which could cause the fluid to be considerably cooled by the fresh air [37]. Included as an auxiliary system, an electric boiler will only be used in situations where the water-to-water heat pump cannot provide the necessary amount of heating power. Based on nine operating points provided by the manufacturer, a polynomial regression was used to construct the heat pump performance map. The DOE-2 (Department of Energy, U.S.) empirical chiller model is modified for the heating mode and used in the regression. It takes into account changes in the temperature of the output condenser (the heat pump heating set point) and the inlet evaporator (the source temperature). However, it does not take into consideration variations in the flow rates of the condenser or evaporator. Since these flow rates are kept constant in the actual arrangement, this constraint is negligible. The ground loop, the Heat Pump (HP) source loop, the HP load loop, and the building loops comprise the four loops of the modeled HVAC system. The Air Handling Unit (AHU) is assigned to one of the building loops, while the hydronic convector heating system is assigned to the other. By exchanging inputs and outputs, the AHU and convectors communicate with the building model.

The plate heat exchanger, which shields the HP evaporator from groundwater contaminants, is linked to the SCW thermal response model. A multi-level pumping system that mimics the actual control sequences is used to regulate ground flow rates. Additionally, freeze prevention uses a dead band control to turn on the electric boiler and turn off the heat pump when the temperature of the groundwater input rises. A cubic regression based on total flow rate is used to estimate power consumption for the ground pump, which consists of five submersible and one circulating pump [38]. Although a VFD allows for several control schemes, the flow rate on the HP source side is fixed for durability. For system stability, a buffer tank is incorporated. In order to replicate a true heat pump dead band controller, the hot water collector on the HP load side is split into supply and return lines. The flow rate is fixed but can be changed with a VFD. When the flow reaches the supply collector, it divides into three streams: the return line, convectors, and the AHU. If the heat pump stops working because of freezing or malfunctions, an additional electric boiler connected in parallel to the heat pump can function on its own [39]. The building has two heating systems: a hydronic system that uses perimetric convectors (red loop) and a ventilation system that uses an AHU to heat air. A heat recovery device preheats the fresh air before it enters the AHU. 20 kW AHU fans run according to a set schedule and have a linear supply temperature adjustment from The convector water and propylene glycol solution are separated by a heat exchanger. Each building zone in the "Convectors" TRNSYS macro block includes a PID thermostat that regulates the flow of water through each convector; any excess flow is routed to the heat exchanger. Different building zones are served by the AHU and convectors, and each zone's controller receives feedback on the air temperature.

Ground Response Modeling

By connecting to the MATLAB engine, the TRNSYS HVAC system incorporates a ground response model. An interface layer that facilitates communication between the MATLAB engine and the TRNSYS Fortran procedure makes this feasible. As an alternative, a Python connection might produce comparable outcomes [40]. For this case study GHE, a 3D extension of the numerical model created by Jacques and Pasquier has produced a collection of 42 g-functions. The three geological units and five hydrostratigraphic units' combined distributions are used to get the median hydraulic and thermal parameters for the 3D extension. Six groundwater pumping flow rates (100, 200, 300, 400, 500, and 600 L/min) and seven bleed ratios (0%, 5%, 10%, 15%, 20%, 25%, and 30%) are combined to create the 42 g-functions. However, as in-situ experimental testing have demonstrated that exceeding this threshold can result in injection well overflow, only combinations with a bleed rate not exceeding 90 L/min will be taken into consideration.

Data Collection and Processing

In order to implement continuous commissioning on the case study building, a wide range of common HVAC sensors were used to gather data, which was then saved on a cloud platform. The building's air temperature and humidity, as well as the thermal and electrical characteristics of each piece of HVAC equipment, have been monitored by sensors every five minutes. Calculations of energy balance were performed to verify the accuracy of readings and, if required, to adjust the results of sensors that were not properly calibrated. See Baudry et al. for more information [41]. The HVAC system's electric power consumption by component for the week of January 23–29, 2023. The AHU has a significant energy demand because of its 20 kW fan.

Model Calibration

The building thermal mass and internal heat gains—more especially, the electric consumption of lights and equipment—were the main focus of the model calibration. The indoor temperatures behaved as expected during the error-free period of manual calibration. To make sure the building thermal loads were sufficiently precise, the building thermal mass was calibrated prior to the internal gains. In order to achieve this, layers of wood were added to the building's thermal zones until the mean indoor temperature (MAE) of four important zones fell below 0.25°C. The model and actual interior temperature ranges for four of the school's classrooms with perimetric convectors are compared [42]. The building's perceived capacity appears to be greater at night, but increasing the model's thermal capacity further reduces its accuracy during other times of the day. For the current application, the resulting MAE of 0.22 ◦C was considered acceptable.

Only standard specifications and practical scheduling were taken into account in the original internal gain estimate, which included 5 W/m2 (NECB) for the equipment and 8.7 W/m2 (NECB) for the lighting. The heat gains were estimated using measurements of electricity use to improve accuracy. In contrast, equipment gains were adjusted to guarantee that the total "Non-HVAC" metered electrical power is equal to the sum of the electrical loads of the equipment and lighting. Lighting heat gains were maintained in accordance with the regulations [43]. The building's monitored HVAC power consumption and the electricity bill from the electricity provider are contrasted. The equipment heat gains can be calculated by deducting the lighting power consumption from the "Non-HVAC" power. Not all electricity use, though, results in heat gains. For instance, the ventilation system may eject some gains or some loads may come from outside the structure. Herbinger et al. employed a metric known as "fElec2Heat" for calibration, which represents the ratio of electricity converted to sensible heat gain on a scale from 0 to 1. In this work, it was discovered that model validation performance parameters improved when Heat was fixed at about 0.5. Occupancy schedules were modified for both daytime and evening sessions, which had not been included in the publicly published timetables, after it was discovered during the calibration that occupancy gains had been underestimated.

Model Validation

A model is considered valid if the NMBE is less than 5% and the CVRMSE is less than 30% for important parameters that reflect the system's energy fluxes. Time steps of five minutes are used in the simulations to replicate the sampling rate of the experimental data. But the validation is done on an hourly basis. This allows for compliance with ASHRAE Guideline 14 while avoiding the cyclic patterns of on/off deadband controllers. Since they reflect the core of the energy flows from the source to the load, the HP's thermal output power and the groundwater temperatures at the intake and exit are the three main factors taken into account for validation. These three values are compared to experimental data for the faultless time [44]. The appropriate CVRMSE and NMBE values. The model can be deemed validated since the CVRMSE and the NMBE satisfy ASHRAE Guideline 14 requirements for all three essential system parameters. HVAC-related electric power consumption broken down per component in a stacked plot. Validation of the model for three key system parameters using experimental data for the calibration period (18–29 January 2023): (a) The GHSP's thermal output; (b) the temperature at the borehole's entrance; and (c) the temperature at the borehole's outflow and outside.

Identification of Energy Conserving Opportunities (ECO)

Initially, the SCW system was intended to run on variable-speed submersible pumps with variable flow rates. Each of the five pumps could only run close to the maximum capacity of 126 L/min since the VFD control of the pumps was not correctly configured to operate at the necessary range during the installation. As a result, the SCWs could only be run at 630 L/min or turned off. The model was adjusted to a constant 630 L/min SCW flow rate because the overall pumping flow rate fluctuated about 630 L/min during the entire period. However, because operating the circulating pump and the five submersible pumps needs approximately 5.7 kW of electric power, this high pumping rate is only intended to be used during times of high demand. To keep groundwater at a safe temperature above freezing, a high pumping rate must be used during times of high demand [45]. However, when the heating demand is reduced, pumping power can be preserved without any special worries. We can determine how much energy could be saved by changing the flow rate using various control strategies thanks to the MBCCx method. Ideal predictive tactics for a 5-level pumping and bleed control system were investigated in an earlier study on this case study with the goal of lowering energy consumption while preventing groundwater freezing. It was demonstrated through several model iterations that a "heuristic predictive strategy" could save up to 30% of total energy and 75% of pumping energy, even in the coldest winter of the previous ten years.

Although this ideal approach is predicated on accurate weather and occupancy forecasts, it can be used as a foundation for creating more straightforward rule-based control systems that are appropriate for practical applications. The derived ideal optimal pumping profiles were examined in connection to the external temperature and occupancy patterns in order to derive these principles [46]. Even during the coldest occurrence of the past ten years, our rule-based method reduced energy consumption while maintaining the SCW inlet temperature above 2°C.Simulations showed that this control method may have reduced the electrical consumption from 5.827 MWh (continuous maximum flow) to 1.278 MWh during the commissioning period, saving around 78% of the pumping energy. The precise whole-building model created for the MBCCx allows for the testing and optimization of control systems that would not otherwise be feasible, making these prospective energy savings estimates achievable.

DISCUSSION

An MBCCx approach for HVAC systems with GSHPs has been proposed in this research. This commissioning method uses a whole-building modeling approach to find and diagnose control sequence irregularities throughout the entire system because of the size and complexity of these systems. A "whole building" approach is appropriate for identifying suboptimal behaviors resulting from inadequate integration between disparate components and can take into account all the linkages between the subsystems. The suggested strategy is different from the approaches seen in the literature, which usually limited commissioning work to the GSHP alone without taking into consideration the possibility of underperformance resulting from control sequence problems that could occur in other system components. The suggested approach makes use of a precise physics-based model that includes all the subsystems (building, HVAC, and GHE), which should be represented and operated as intended by design in order to accomplish these goals [47]. This method avoids the replication of any errors in the control sequence implementation while giving priority to the system's expected performance as determined during the design process. In addition to highlighting the distinctions between this technique and the traditional procedures, this paper offers technical suggestions for pursuing such a modeling approach. Because a reliable result depends on precisely capturing the true dynamics of the building, this approach frequently necessitates stricter standards and comprehensive modeling. One important advantage to emphasize is that, in contrast to data-driven solutions, this approach does not require significant history datasets, making it suitable for usage during the initial months of operation, when commissioning work is most necessary. A goodness-of-fit score that takes into account both the fluid temperatures in the GHE and the output of the GSHP can be used to automatically identify abnormal days once the model has been calibrated and validated. These abnormalities can be identified by comparing the model's predictions with actual observations. Furthermore, investigating various control sequences and identifying possible energy-saving opportunities are made possible by such an exact model. However, this approach has limits in terms of the time and expertise needed to create and calibrate the model. The second section of the paper presents a case study example to illustrate the suggested approach. A ground source heat pump (GSHP) system with five 135-meter-deep SCWs completely replaced the HVAC system of a primary school in Québebec, Canada [48]. The first 42 days of operation after the control sequences were put into place could be examined once the system had been precisely modeled and calibrated. With no false positives, the suggested FDD approach was able to accurately identify every anomaly.

CONCLUSION

On the other hand, the GOF metric experienced multiple false positives and false negatives when analyzing the heat pump or GHE separately. By comparing important model parameters to the measurements, the abnormal days may then be diagnosed. Erroneous heat pump control and improper convector and ventilation unit heat delivery control were the three different types of control problems that were found and located inside the system. Lastly, it has been shown that the model's adaptability allows for the assessment of more effective control sequences; this is made possible by the model's capacity to execute many scenarios under various circumstances. For instance, the SCW groundwater was pumped at its maximum flow rate of 630 L/min. Several iterations of the model were used to evaluate a theoretically optimal pumping control, which allowed for the derivation of certain straightforward control rules that could be used in the BMS to get closer to the optimal performance. It has been demonstrated that during the examined commissioning time, this straightforward rule-based control technique might have led to a theoretical 78% decrease in pumping energy. These positive outcomes suggest that the MBCCx methodology could be useful in improving the commissioning phase's efficiency for complex systems, including GHSP systems. In order to establish the methodology's worth in a variety of situations, future initiatives should give priority to its wider use. This entails carrying out more case studies in various building kinds and geographical areas to confirm its resilience and pinpoint possible modifications. Lastly, including more FDD criteria for a greater range of HVAC subsystems would increase the methodology's analytical capabilities and offer a more comprehensive approach to MBCCx.

REFERENCES

1. E. Mills, Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States, Energy Effic. 4 (2011) 145–173, https://doi.org/10.1007/s12053-011-9116-8.
2. E. Crowe, E. Mills, T. Poeling, C. Curtin, D. Bjørnskov, L. Fischer, J. Granderson, Building commissioning costs and savings across three decades and 1500 North American buildings, Energy Build. 227 (2020) 110408, https://doi.org/10.1016/j.enbuild.2020.110408.
3. E.H. Borgstein, R. Lamberts, J.L.M. Hensen, Mapping failures in energy and environmental performance of buildings, Energy Build. 158 (2018) 476–485, https://doi.org/10.1016/j.enbuild.2017.10.038.
4. C.-C. Cheng, D. Lee, Return on investment of building energy management system: a review, Int. J. Energy Res. 42 (2018) 4034–4053, https://doi.org/10.1002/er.4159.
5. J. Verhelst, G. Van Ham, D. Saelens, L. Helsen, Model selection for continuous commissioning of HVAC-systems in office buildings: a review, Renew. Sustain. Energy Rev. 76 (2017) 673–686, https://doi.org/10.1016/j.rser.2017.01.119.
6. N. Zibin, R. Zmeureanu, J. Love, Automatic assisted calibration tool for coupling building automation system trend data with commissioning, Autom. Constr. 61 (2016) 124–133, https://doi.org/10.1016/j.autcon.2015.10.004.
7. E. Togashi, M. Miyata, Development of building thermal environment emulator to evaluate the performance of the HVAC system operation, J. Build. Perform. Simul. 12 (2019) 663–684, https://doi.org/10.1080/19401493.2019.1601259.
8. M. Jradi, N. Liu, K. Arendt, C.G. Mattera, An automated framework for buildings continuous commissioning and performance testing – a university building case study, J. Build. Eng. 31 (2020) 101464, https://doi.org/10.1016/j.jobe.2020.101464.
9. J.J. McArthur, A building information management (BIM) framework and supporting case study for existing building operations, Maintenance and Sustainability, Procedia Eng. 118 (2015) 1104–1111, https://doi.org/10.1016/j.proeng.2015.08.450.
10. D.K. Jung, D.H. Lee, J.H. Shin, B.H. Song, S.H. Park, Optimization of energy consumption using BIM-based building energy performance analysis, Appl. Mech. Mater. 281 (2013) 649–652, https://doi.org/10.4028/www.scientific.net/AMM.281.649.
11. L.C. Harmer, G.P. Henze, Using calibrated energy models for building commissioning and load prediction, Energy Build. 92 (2015) 204–215, https://doi.org/10.1016/j.enbuild.2014.10.078.
12. M.S. Piscitelli, S. Brandi, A. Capozzoli, F. Xiao, A data analytics-based tool for the detection and diagnosis of anomalous daily energy patterns in buildings, Build. Simul. 14 (2021) 131–147, https://doi.org/10.1007/s12273-020-0650-1.

13. J.W. Lund, A.N. Toth, Direct utilization of geothermal energy 2020 worldwide review, Geothermics 90 (2021) 101915, https://doi.org/10.1016/j.geothermics.2020.101915.
14. I. Sarbu, C. Sebarchievici, General review of ground-source heat pump systems for heating and cooling of buildings, Energy Build. 70 (2014) 441–454, https://doi.org/10.1016/j.enbuild.2013.11.068.
15. EurObserv'ER, Heat pumps barometer 2021, European Commission, 2021. https://www.eurobserv-er.org/heat-pumps-barometer-2021/ (accessed October 8, 2023).
16. F. Bockelmann, M.N. Fisch, It works—long-term performance measurement and optimization of six ground source heat pump systems in Germany, Energies 12 (2019) 4691, https://doi.org/10.3390/en12244691.
17. J.D. Spitler, S. Gehlin, Measured performance of a mixed-use commercial-building ground source heat pump system in Sweden, Energies 12 (2019) 2020, https://doi. org/10.3390/en12102020.
18. J. García-C´espedes, G. Arno, ´ I. Herms, J.J. de Felipe, Characterisation of efficiency losses in ground source heat pump systems equipped with a double parallel stage: a case study,Renew. Energy 147 (2020) 2761–2773, https://doi.org/10.1016/j. renene.2019.01.029.
19. G. Barla, Comprehensive study including testing, monitoring and thermo-hydro modelling for design and implementation of a geothermal system in Torino (Italy), Geomech. Geophys. Geo-Energy Geo-Resour. 3 (2017) 175–188, https://doi.org/10.1007/s40948-017-0050-x.
20. S.K. Park, H.J. Moon, K.C. Min, C. Hwang, S. Kim, Application of a multiple linear regression and an artificial neural network model for the heating performance analysis and hourly prediction of a large-scale ground source heat pump system, Energy Build. 165 (2018) 206–215, https://doi.org/10.1016/j.enbuild.2018.01.029.
21. L. Yan, P. Hu, C. Li, Y. Yao, L. Xing, F. Lei, N. Zhu, The performance prediction of ground source heat pump system based on monitoring data and data mining technology, Energy Build. 127 (2016) 1085–1095, https://doi.org/10.1016/j.enbuild.2016.06.055.
22. G. Beaudry, P. Pasquier, D. Marcotte, A fast convolution-based method to simulate time-varying flow rates in closed-loop and standing column well ground heat exchangers, Renew. Energy 174 (2021) 55–72, https://doi.org/10.1016/j. renene.2021.04.045.
23. G. Beaudry, P. Pasquier, A. Nguyen, New formulations and experimental validation of non-stationary convolutions for the fast simulation of time-variant flowrates in ground heat exchangers, Sci. Technol. Built Environ. (2023) 1–12, https://doi.org/ 10.1080/23744731.2023.2279468.
24. L.C. Ng, A. Musser, A.K. Persily, S.J. Emmerich, Multizone airflow models for calculating infiltration rates in commercial reference buildings, Energy Build. 58 (2013) 11–18, https://doi.org/10.1016/j.enbuild.2012.11.035.
25. F. Alshehri, S. Beck, D. Ingham, L. Ma, M. Pourkashanian, Techno-economic analysis of ground and air source heat pumps in hot dry climates, J. Build. Eng. 26 (2019) 100825, https://doi.org/10.1016/j.jobe.2019.100825.
26. A.L. Snijders, B.C. Drijver, Open-loop heat pump and thermal energy storage systems, in: S.J. Rees (Ed.), Adv. Ground-Source Heat Pump Syst., Woodhead Publishing, 2016: pp. 247-268. Doi: 10.1016/B978-0-08-100311-4.00009-1.
27. P. Pasquier, A. Nguyen, F. Eppner, D. Marcotte, P. Baudron, Standing column wells, in: S.J. Rees (Ed.), Adv. Ground-Source Heat Pump Syst., Woodhead Publishing, 2016: pp. 269–294. Doi: 10.1016/B978-0-08-100311-4.00010-8.
28. S.E. Mattsson, H. Elmqvist, Modelica - an international effort to design the next generation modeling language, IFAC Proc. 30 (1997) 151–155, https://doi.org/10.1016/S1474-6670(17)43628-7.
29. ASHRAE Inc, ASHRAE Standard 90.1-2022 - Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2022.
30. M. Shin, J.S. Haberl, Thermal zoning for building HVAC design and energy simulation: a literature review, Energy Build. 203 (2019) 109429, https://doi.org/10.1016/j.enbuild.2019.109429.

31. P. Ma, L.-S. Wang, Effective heat capacity of interior planar thermal mass (iPTM) subject to periodic heating and cooling, Energy Build. 47 (2012) 44–52, https://doi.org/10.1016/j.enbuild.2011.11.020.
32. W. Li, L. Yang, J. Zhu, R. Li, A pre-processing method of internal thermal mass for building energy simulation software, J. Build. Perform. Simul. 14 (2021) 328–342, https://doi.org/10.1080/19401493.2021.1917665.
33. C. Calistru, U. Pont, A. Mahdavi, Estimation of electrical lighting energy use in buildings: a method comparison, in: Fifth Ger.-Austrian IBPSA Conf. BauSIM 2014, Aachen, Germany, 2014.
34. J.A. Diaz-Acevedo, L.F. Grisales-Norena, ˜ A. Escobar, A method for estimating electricity consumption patterns of buildings to implement energy management systems, J. Build. Eng. 25 (2019) 100774, https://doi.org/10.1016/j.jobe.2019.100774.
35. S. Andolsun, C.H. Culp, J.S. Haberl, M.J. Witte, EnergyPlus vs DOE-2.1e: the effect of ground coupling on cooling/heating energy requirements of slab-on-grade code houses in four climates of the US, Energy Build. 52 (2012) 189–206, https://doi.org/10.1016/j.enbuild.2012.06.012.
36. J.D. Spitler, M. Bernier, Vertical borehole ground heat exchanger design methods, in: S.J. Rees (Ed.), Adv. Ground-Source Heat Pump Syst., Woodhead Publishing, 2016: pp. 29–61. Doi: 10.1016/B978-0-08-100311-4.00002-9.
37. P. Pasquier, A. Nguyen, F. Eppner, D. Marcotte, P. Baudron, Standing column wells, Adv. Ground-Source Heat Pump Syst. Chapter 10 (2016) 269–294, https://doi.org/10.1016/B978-0-08-100311-4.00010-8.
38. S. Robert, P. Pasquier, A. Nguyen, Impact of layered heterogeneity on thermal response test interpretation performed on a standing column well operated without bleed, Geothermics 101 (2022) 102353, https://doi.org/10.1016/j.geothermics.2022.102353.
39. G. Dion, P. Pasquier, D. Marcotte, Deconvolution of experimental thermal response test data to recover short-term g-function, Geothermics 100 (2022) 102302, https://doi.org/10.1016/j.geothermics.2021.102302.
40. D. Del Col, M. Azzolin, G. Benassi, M. Mantovan, Energy efficiency in a ground source heat pump with variable speed drives, Energy Build. 91 (2015) 105–114, https://doi.org/10.1016/j.enbuild.2014.12.048.
41. A. Zarrella, G. Emmi, M. De Carli, A simulation-based analysis of variable flow pumping in ground source heat pump systems with different types of borehole heat exchangers: a case study, Energy Convers. Manag. 131 (2017) 135–150, https:// doi.org/10.1016/j.enconman.2016.10.061.
42. C. Beurcq, Control strategies for standing column wells in a cold climate, Masc Thesis, Polytechnique Montr´eal (2019).
43. ASHRAE Inc, ASHRAE Guideline 14-2023 - Measurement of Energy, Demand, and Water Savings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023.
44. T.A. Reddy, I. Maor, C. Panjapornpon, Calibrating detailed building energy simulation programs with measured data—part I: general methodology (RP-1051), HVACR Res. 13 (2007) 221–241, https://doi.org/10.1080/10789669.2007.10390952.
45. G. Beaudry, J. Faucher, G. Tonellato, P. Pasquier, M. Kummert, Standing column wells in cold climates: lessons learned after one year of operating a demonstration system in Canada, in: 2024 Res. Conf. Proc. IGSHPA, International Ground Source Heat Pump Association, Montr´eal, QC, Canada, 2024. https://doi.org/10.22488/okstate.24.000028.
46. L. Jacques, P. Pasquier, Obtaining the hydraulic and thermal properties of the main hydrostratigraphic units surrounding a standing column well using a thermal response test, J. Hydrol. 623 (2023) 129823, https://doi.org/10.1016/j.jhydrol.2023.129823.
47. Novoclimat, Exigences techniques Novoclimat – Maison et Petit bˆ atiment multilogement, Qu´ebec ´energie et ressources naturelles, 2020. https://transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/novoclimat-maison PBM/Exigences-techniques-Novoclimat-M-PBM-01-2021.pdf.
48. ASHRAE Inc, ASHRAE Handbook 2017 - Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2017.