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(54) **SYSTEM AND METHOD FOR MONITORING AND OPERATING GROUND-SOURCE HEAT PUMPS**

(57) A method of operating a thermal system (100) implementing a ground-source heat pump (102) includes receiving design parameters associated with a design of the thermal system (100) and receiving one or more measurement inputs associated with a flow of a thermal fluid through a borefield (108) of a ground heat exchanger (110). The method further includes, based on the measurement inputs and the design parameters, predicting one or more predicted thermal values (162) of the thermal fluid using a forward model (146). The method further includes predicting one or more predicted borefield parameters (160) of the borefield (108) based on inverting the forward model (162). The method further includes monitoring the thermal system (100) based on the predicted borefield parameters (160).

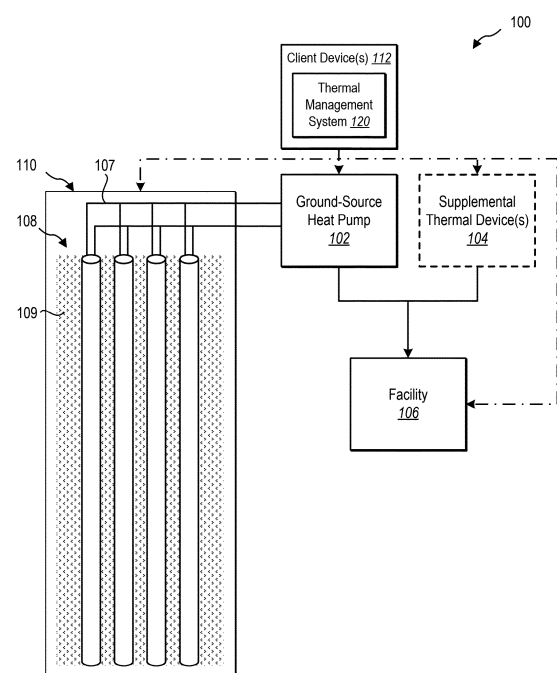


FIG. 1

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Description

BACKGROUND OF THE DISCLOSURE

[0001] Ground-source or geothermal heat pump systems offer energy-efficient heating and cooling solutions by leveraging the relatively stable temperature of the Earth's subsurface. Understanding and accurately modeling heat transfer between the ground and the heat pump can be important for optimal operation of such systems. In many cases, however, it may be difficult to accurately determine one or more properties of the heat pump system, such as the thermal conductivities and temperatures of various in-ground components. Conventional methods typically involve a combination of laboratory testing, in situ measurements, empirical correlations, and/or geophysical techniques for determining these properties which may impose practical limits on the ability to determine these properties frequently and/or during operation of the heat pump system. Thus, systems and methods for accurately determining system properties in real time and based on easily and commonly measured values during operation of the heat pump system may be desirable.

SUMMARY

[0002] In some embodiments, a method of operating a thermal system implementing a ground-source heat pump includes receiving design parameters associated with a design of the thermal system and receiving one or more measurement inputs associated with a flow of a thermal fluid through a borefield of a ground heat exchanger. The method further includes, based on the measurement inputs and the design parameters, predicting one or more predicted thermal values of the thermal fluid using a forward model. The method further includes predicting one or more predicted borefield parameters of the borefield based on inverting the forward model. The method further includes monitoring the thermal system based on the predicted borefield parameters. In some embodiments, the method is performed by a system. In some embodiments, the method is implemented as instructions stored on a computer-readable storage medium.

[0003] This summary is provided to introduce a selection of concepts that are further described in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter. Additional features and aspects of embodiments of the disclosure will be set forth herein, and in part will be obvious from the description, or may be learned by the practice of such embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] In order to describe the manner in which the

above-recited and other features of the disclosure can be obtained, a more particular description will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. For better understanding, the like elements have been designated by like reference numbers throughout the various accompanying figures. While some of the drawings may be schematic or exaggerated representations of concepts, at least some of the drawings may be drawn to scale. Understanding that the drawings depict some example embodiments, the embodiments will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

FIG. 1 is an example of a thermal system, according to at least one embodiment of the present disclosure; FIG. 2 illustrates an example environment in which a thermal management system is implemented in accordance with at least one embodiment of the present disclosure;

FIG. 3 illustrates an example implementation of the thermal management system, according to at least one embodiment of the present disclosure;

FIG. 4 illustrates an example implementation of the thermal management system, according to at least one embodiment of the present disclosure;

FIG. 5 illustrates an example implementation of the thermal management system, according to at least one embodiment of the present disclosure;

FIG. 6 illustrates an example implementation of a thermal model, according to at least one embodiment of the present disclosure;

FIG. 7 is an example of a borefield digital twin, according to at least one embodiment of the present disclosure;

FIG. 8 is an example validation of a thermal model, according to at least one embodiment of the present disclosure;

FIG. 9, is an example of an application of a digital twin to monitor a borefield temperature, according to at least one embodiment of the present disclosure;

FIG. 10 illustrates a flow diagram for a method of operating a thermal system as described herein, according to at least one embodiment of the present disclosure; and

FIG. 11 illustrates certain components that may be included within a computer system.

DETAILED DESCRIPTION

[0005] This disclosure generally relates to systems, methods, and computer readable storage media for analyzing, monitoring, and controlling thermal systems implementing ground-source heat pumps. For example, the ground source heat pump may be a heat pump in thermal communication with a ground heat exchanger having one or more ground loops running through a series of boreholes in a borefield. Based on the relatively constant

temperature of the ground, the ground-source heat pump may extract heat from, or reject heat to, the ground in order to provide heating and cooling to a facility. The thermal system may include one or more supplemental thermal devices to meet a (e.g., peak) thermal load of the facility above that which the ground source heat pump can provide.

[0006] In some embodiments, a thermal management system is implemented on or across one or more client devices. The thermal management system may be in data communication with one or more of the ground-source heat pump, the facility, the ground heat exchanger, the supplemental thermal devices, or any other component associated with the thermal system. The thermal management system may implement a thermal model to facilitate predicting and analyzing one or more values of the thermal system. For example, the thermal model may include a forward model. The forward model may be a physical model for simulating the thermodynamic response of the ground heat exchanger based on heat transfer to/from the ground-source heat pump. The forward model may be based on one or more physical design parameters (e.g., geometry, etc.) of the boreholes and of a completion of the boreholes. The forward model may also be based on one or more initial conditions, or initial borefield parameters, such as initial ground and grout thermal conductivities, and an initial ground average (or far-field) temperature. The forward model may receive one or more measurements as inputs, such as a thermal flux to/from the ground and/or the flow rate of a thermal fluid through the ground heat exchanger. Based on the inputs and parameters, the forward model may predict one or more thermal values of the thermal fluid, such as an inlet temperature, an outlet temperature, a pressure drop, etc. and/or one or more temperature associated with the borefield (e.g., temperature of the ground).

[0007] In some embodiments, the thermal model includes an inverted model, or in inversion of the thermal model. The inverted model may facilitate predicting the actual borefield parameters by adjusting the initial borefield parameters as part of the inversion of the forward model. For example, the inverted model may receive measured thermal values corresponding to the predicted thermal values output by the forward model. Based on comparing the measured and predicted thermal values, the inverted model may adjust one or more (or combinations) of the initial borefield parameters to find a best-fit set of borefield parameters that minimizes a target difference between the measured and predicted thermal values. In this way, the inverted model may predict the actual ground and grout thermal conductivities and the average ground temperature.

[0008] In some embodiments, the thermal model is calibrated or trained to ensure that the borefield parameter predictions are accurate. For example, once predicted, the thermal model may hold the set of borefield parameters constant for a validation period, while con-

tinuing to predict the thermal values with the forward model. During the validation period, the thermal management system may compare the predicted thermal values (e.g., based on the predicted borefield parameters) to the corresponding actual, measured thermal values to determine a degree of error between the predicted and actual values. In this way, and based on an error within a threshold range, the thermal model may be relied on with confidence to accurately predict the predicted borefield parameters.

[0009] The thermal management system may utilize the predicted borefield parameters in a variety of ways to monitor and/or control the thermal system. For example, the thermal management system may generate a digital twin of the borefield for inferring the temperature at one or more (or all) locations of the borefield. Based on the temperature field of the digital twin, the thermal management system may monitor a minimum temperature at any location of the borefield to prevent or mitigate freezing of the ground. The thermal management system may accordingly implement a control strategy for the thermal system to raise, or maintain, the ground temperature above freezing at one or more locations. The predicted borefield parameters may facilitate a variety of other monitoring and/or controlling functionalities of the thermal management system, such as detecting and predicting failures of the thermal system, determining a thermal state of charge of the ground battery, and forecasting future values for the thermal system, among other examples.

[0010] As will be discussed in further detail below, the present disclosure includes a number of practical applications having features described herein that provide benefits and/or solve problems associated with operating a thermal system. Some example benefits are discussed herein in connection with various features and functionalities provided by a thermal management system implemented on one or more computing devices. It will be appreciated that benefits explicitly discussed in connection with one or more embodiments described herein are provided by way of example and are not intended to be an exhaustive list of all possible benefits of the thermal management system.

[0011] For example, the thermal management system described herein may be implemented to determine one or more borefield parameters that conventional methods may not be equipped to determine. For example, as described herein, the thermal management system may determine thermal conductivities of the ground and grout, as well as an average ground temperature for the borefield. Conventional methods may implement sensors and other measurement devices to measure these values by using wire-line tools lowered into one or more of the boreholes (e.g., as part of in situ thermal response tests). Thus, by measuring these parameters, conventional methods have practical limits on what can be measured and how often measurements can be updated or validated. For example, after completion of the

boreholes, it may not be possible to measure these parameters through downhole tools, or at the very least it may require putting the thermal system offline. In contrast, the thermal management system described herein predicts or infers the borefield parameters based on actual, real-world values that are commonly and easily measured, such as heat flux and flow rate. These prediction techniques are validated based on real-world, measured values to ensure that the predictions are accurate. By inferring, as opposed to measuring, the thermal management system may iteratively determine and update the borefield parameters to provide a real-time overview of these important borefield properties. As described herein, the thermal management system may monitor and control the thermal system in a variety of ways based on the active tracking of the borehole parameters.

[0012] Further, the thermal management system may determine the borefield parameters in this way during operation of the ground-source heat pump. For example, the thermal management system may make its predictions based on values such as flow rates, including flow rate of the thermal fluid, which are commonly and easily measured as part of the operation of a ground-source heat pump. Thus, while the thermal management system may determine the borefield parameters in real-time, it also inherently may do so during operation of the ground-source heat pump. This may be advantageous over conventional methods, which, as described, either cannot determine (measure) the borefield properties after completion of the boreholes, or else cannot do so without taking the thermal system offline. Thus, the features and functionalities of the thermal management system may be implemented without the practical limits that conventional techniques face.

[0013] In addition to determining the ground and grout thermal conductivities and ground average temperature generally, the thermal management system may be implemented in some embodiments to generate a digital twin for providing ground temperatures of the borefield. The digital twin may infer the ground temperatures based on the predicted borefield parameters and may include a detailed temperature map giving a spatial overview of the ground temperature at any location in the ground. Additionally, the digital twin may offer these functionalities in real-time and during operation of the ground-source heat pump. This may be in contrast to conventional methods, which may rely on temperatures sensors and/or measurements in order to characterize temperatures of the borefield. For example, it may be prohibitively difficult to measure a temperature at one or more locations in the borefield, such as temperatures at great depths and/or temperatures within the ground that are not near to a borehole. Indeed, it may be realistically impossible to measure a temperature at every location in the borefield, especially all at once. Indeed, conventional techniques may be limited in their ability to take such measurements during operation of the thermal system as mentioned

above. In this way, the digital twin may provide valuable temperature data which may facilitate monitoring and operating the thermal system effectively and efficiently, as described herein.

[0014] Additional details will now be provided regarding systems described herein in relation to illustrative figures portraying example implementations. For example, FIG. 1 shows one example of a thermal system 100 for facilitating transferring heat between one or more components. The thermal system 100 may include a ground-source heat pump (GSHP) 102. The GSHP 102 may be in thermal communication with a ground (or borehole) heat exchanger 110. The ground heat exchanger 110 may include a borefield 108 having one or more boreholes within a volume of ground 109 defining the borefield 108. One or more ground loops 107 may be positioned within the one or more boreholes, and the boreholes may be at least partially filled with a grout, for example, to maintain the ground loops 107 in place and to facilitate heat transfer between the ground loops 107 and the ground 109. The ground loops have a fluid inlet and a fluid outlet but may have any configuration in the well-bore, for instance coaxial or U-shaped. The ground loops 107 may be operatively coupled to the GSHP 102, and a thermal fluid may flow through the ground loops 107 to facilitate transferring heat between the ground heat exchanger 110 and the GSHP 102. The GSHP 102 may be in thermal communication with a facility heat exchanger of the facility 106. The GSHP 102 may include a compressor and an evaporator (e.g., expansion valve) for implementing a refrigerant cycle between the facility heat exchanger 106 and a second heat exchanger in which both the refrigerant and the thermal fluid circulate. The heat from the facility 106 may then be transferred to the borefield 108, using the thermal fluid for cooling the facility, as well as to transfer heat from the borefield 108 to the facility 106, using the thermal fluid, to heat the facility 106. In this way, the GSHP 102 may be a geothermal heat pump for leveraging the thermal properties and conditions within the ground 109 for providing heating and cooling to the facility 106.

[0015] In some embodiments, the thermal system 100 includes one or more supplemental thermal devices 104. The supplemental thermal devices 104 may be configured to provide heating and cooling to the facility 106. For example, the supplemental thermal devices 104 may include one or more heating devices such as a boiler, furnace, or any other heating device. The supplemental thermal devices 104 may include one or more cooling devices such as a chiller, cooling tower, fin-fan cooler, or any other cooling device. The supplemental thermal devices 104 may be configured to provide heating and/or cooling to the facility 106 in addition to (e.g., in parallel with), or as an alternative to the GSHP 102. For example, in some embodiments, a capacity of the GSHP is not sufficient to meet a load or demand of the facility 106, and the supplemental thermal devices 104 supplement the GSHP 102 to meet the thermal load. In another example,

the supplemental thermal devices 104 may serve as a backup or failsafe for providing heating and/or cooling to the facility 106 if the GSHP 102 fails or is put offline (e.g., for maintenance). In this way, heating and cooling may be provided by both the GSHP 102 and the supplemental thermal devices 104. In some embodiments, the thermal system 100 does not include the supplemental thermal devices 104, and the thermal loads of the facility 106 are provided to the facility 106 by the GSHP 102 without the supplemental thermal devices 104.

[0016] In some embodiments, the thermal system 100 includes a thermal management system 120 implemented on one or more computing devices, such as one or more client devices 112. As shown, the thermal management system 120 may be in communication with one or more components of the thermal system 100 (e.g., via the network 116 as describe in connection with FIG. 2). In some embodiments, the thermal management system 120 is in communication with one or more of the ground heat exchanger 110, the GSHP 102, the supplemental thermal devices 104, and the facility 106. The thermal management system 120 may be in communication with any other component or system associated with the thermal system 100 consistent with that described herein. In some embodiments, the thermal management system 120 monitors one or more values, parameters, functions, and/or features of the thermal system 100. For example, the thermal management system 120 may be in communication with one or more sensors for receiving measurements of the thermal system 100. In another example, the thermal management system 120 may record and/or track one or more parameters over time. In some embodiments, the thermal management system 120 analyzes one or more values, parameters, functions, and/or features of the thermal system 100. For example, the thermal management system 120 may estimate or infer one or more values associated with the thermal system 100. In another example, the thermal management system 120 may characterize a behavior of the thermal system 100 and/or may predict future behaviors (e.g., faults) of the thermal system 100. In some embodiments, the thermal management system 120 controls one or more features and/or functions of the thermal system 100. For example, the thermal management system 120 may control one or more aspects of the GSHP 102, the ground heat exchanger 110, the facility 106, or any other component. In this way, the thermal management system 120 may perform one or more functions related to the thermal system 100 as described herein.

[0017] FIG. 2 illustrates an example environment 200 in which a thermal management system 120 is implemented in accordance with one or more embodiments described herein. As shown in FIG. 2, the environment 200 includes one or more server device(s) 114. The server device(s) 114 may include one or more computing devices (e.g., including processing units, data storage, etc.) organized in an architecture with various network

interfaces for connecting to and providing data management and distribution across one or more client systems. As shown in FIG. 2, the server devices 114 may be connected to and may communicate with (either directly or indirectly) one or more client devices 112 through a network 116. The network 116 may include one or multiple networks and may use one or more communication platforms or technologies suitable for transmitting data. The network 116 may refer to any data link that enables transport of electronic data between devices of the environment 200. The network 116 may refer to a hardwired network, a wireless network, or a combination of a hardwired network and a wireless network. In one or more embodiments, the network 116 includes the internet. The network 116 may be configured to facilitate communication between the various computing devices via any protocol or form of communication.

[0018] The client device 112 may refer to various types of computing devices. For example, one or more client devices 112 may include a mobile device such as a mobile telephone, a smartphone, a personal digital assistant (PDA), a tablet, a laptop, or any other portable device. Additionally, or alternatively, the client devices 112 may include one or more non-mobile devices such as a desktop computer, server device, surface or downhole processor or computer (e.g., associated with a sensor, system, function, etc., of the thermal system), or other non-portable device. In one or more implementations, the client devices 112 include graphical user interfaces (GUI) thereon (e.g., a screen of a mobile device). In addition, or as an alternative, one or more of the client devices 112 may be communicatively coupled (e.g., wired or wirelessly) to a display device having a graphical user interface thereon for providing a display of system content. The server devices(s) 114 may similarly refer to various types of computing devices. Each of the devices of the environment 200 may include features and functionalities described below in connection with FIG. 7.

[0019] As shown in FIG. 2, the environment 200 may include a thermal management system 120 implemented on one or more computing devices. The thermal management system 120 may be implemented on one or more client device 112, server devices 114, and combinations thereof. Additionally, or alternatively, the thermal management system 120 may be implemented across the client devices 112 and the server devices 114 such that different portions or components of the thermal management system 120 are implemented on different computing devices in the environment 200. In this way, the environment 200 may be a cloud computing environment, and the thermal management system 120 may be implemented across one or more devices of the cloud computing environment in order to leverage the processing capabilities, memory capabilities, connectivity, speed, etc., that such cloud computing environments offer in order to facilitate the features and functionalities described herein.

[0020] FIG. 3 illustrates an example implementation of

the thermal management system 120 as described herein, according to at least one embodiment of the present disclosure. The thermal management system 120 may include a data manager 122, a model engine 124, a validation manager 126, and a thermal system controller 128. The thermal management system 120 may also include a data storage 130 having thermal system attribute data 132 and predicted parameter data 134 stored thereon. While one or more embodiments described herein describe features and functionalities performed by specific components 122-128 of the thermal management system 120, it will be appreciated that specific features described in connection with one component of the thermal management system 120 may, in some examples, be performed by one or more of the other components of the thermal management system 120.

[0021] By way of example, one or more of the data receiving, gathering, and/or storing features of the data manager 122 may be delegated to other components of the thermal management system 120. As another example, while models may be generated and/or implemented by the model engine 124, in some instances, some or all of these features may be performed by the validation manager 126, data manager 122, or any other component of the thermal management system 120. Indeed, it will be appreciated that some or all of the specific components may be combined into other components and specific functions may be performed by one or across multiple of the components 122-128 of the thermal management system 120.

[0022] Additionally, while FIG. 1, for example, depicts the thermal management system 120 implemented on a client device 112 of the thermal system, it should be understood that some or all of the features and functionalities of the thermal management system 120 may be implemented on or across multiple client devices 112 and/or server devices 114. For example, data may be received by the data manager 122 on a (e.g., local) client device, and the data may be input to one or more models implemented by the model engine 124 on a remote, server, and/or cloud device. Indeed, it will be appreciated that some or all of the specific components 122-128 may be implemented on or across multiple client devices 112 and/or server devices 114, including individual functions of a specific component being performed across multiple devices.

[0023] As mentioned above, the thermal management system 120 includes a data manager 122. As shown in FIG. 4, the data manager 122 may receive and manage a variety of types of data of the thermal management system 120. For example, the data manager 122 may receive design data 136. The design data 136 may include information relating to a design, configuration, size, and/or capability of the thermal system 100. In some embodiments, the design data 136 includes information relating to a design of the borefield 108. For example, the design data 136 may identify a size, length, depth, trajectory, diameter, geometry, orientation, and/or location,

of one or more boreholes of the borefield 108. The design data 136 may identify a quantity, arrangement, and/or configuration of the boreholes in the borefield 108. The design data 136 may include and/or identify any other features of the boreholes. The design data 136 may identify one or more underground features of the ground 109, such as a material makeup, composition, lithology, facies, physical and/or chemical properties, formation, and/or underground resource of the ground 109. In some embodiments, the design data 136 includes information related to the design of the ground heat exchanger 110. For example, the design data 136 may identify a geometry of the ground heat exchanger 110 such as a size, length, diameter, trajectory, shank spacing etc., of one or more ground loops 107. The design data 136 may identify a configuration or completion of the ground loops 107, such as a single tube, double (U) tube, or coaxial configuration. The design data 136 may identify one or more thermal properties of the ground heat exchanger 110, such as a thermal conductivity, thermal resistivity, heat flux, temperature (e.g., average) of the ground loops 107, the grout, and/or the ground 109 (e.g., measured during a thermal response test). The design data 136 may identify a coolant, antifreeze, glycol, water, brine, or any other thermal fluid (e.g., heat transfer fluid) flowing through the ground heat exchanger 110 and/or implemented in the thermal system 100, including the properties of the thermal fluid.

[0024] In some embodiments, the design data 136 includes information relating to the GSHP 102. For example, the design data 136 may identify a size, capacity, efficiency, or any other configuration of the GSHP 102. For instance, the design data 136 may identify one or more values (e.g., maximum, minimum, average, and/or predicted values) for one or more of an electrical power rating and/or consumption, a thermal power rating and/or output, a heating and/or cooling capacity, an efficiency, a flow rate (e.g., of the GSHP, ground heat exchanger 110, or facility heat exchanger), a temperature (e.g., input, output, and/or operating temperature), or any other relevant information relating to the configuration of the GSHP 102 (and combinations thereof).

[0025] In some embodiments, the design data 136 includes information relating to the facility 106. For example, the design data 136 may identify a size of the facility 106 including a heating and/or cooling draw or load (e.g., average, expected, maximum, minimum, etc.). The design data 136 may identify a location of the facility 106 including seasonal and/or climate information about the location. The design data 136 may identify information about the heating, ventilation, and air-conditioning (HVAC) configuration of the facility 106. For example, in some embodiments, the facility 106 implements one or more devices such as the supplemental thermal devices 104 in addition to the GSHP 102 to provide heating and cooling. In another example, the design data 136 may include information about the facility heat exchanger of the facility 106. The design data 136 may include infor-

mation relating to the facility heat exchanger, such as similar features to that described above in connection with the ground heat exchanger 110. In this way, the data manager 122 may receive design data 136 related to a design of the thermal system 100.

[0026] In some embodiments, the data manager 122 receives sensor data 138. The sensor data 138 may include measurements from any number of sensors included or associated with the thermal system 100. For example, the sensor data 138 may include measurements associated with an operation of the thermal system 100. For instance, the sensor data 138 may include a flow rate (e.g., volumetric flow rate, mass flow rate) of one or more thermal fluids in the ground heat exchanger 110, GSHP 102, and/or the facility heat exchanger. The sensor data 138 may include one or more temperature measurements including one or more of a fluid temperature of thermal fluid(s) at one or more locations in the thermal system 100 (e.g., flowing into, through, and/or out of one or more components, such as the refrigerant, the thermal fluid flowing in the borefield, etc.), a borehole temperature of one or more boreholes in the borefield 108, a ground temperature at one or more locations in the ground of the borefield 108, and any other temperature of any other component. The sensor data 138 may include a fluid pressure and/or pressure differential of one or more thermal fluids at or across one or more locations in the thermal system 100 (e.g., flowing into, through, and/or out of one or more components). The sensor data 138 may include a measure of a thermal flux of one or more components of the thermal system 100, such as a thermal flux of the ground heat exchanger 110, the GSHP 102, the facility heat exchanger, or any other component. The thermal flux may be a heat flux, heat flux density, heat flow rate intensity, or any similar measure of thermal energy flow rate.

[0027] In some embodiments, the sensor data 138 includes a measure of an electrical power usage or consumption by one or more components of the thermal system 100, such as a power usage of the GSHP 102 and/or the supplemental thermal devices 104. The sensor data 138 may include one or more measurements associated with a thermal power output of the thermal system 100, such as a heating power and/or cooling power (e.g., kW) of one or more components of the thermal system 100.

[0028] In some embodiments, the sensor data 138 includes measurements associated with the borefield 108. For example, the sensor data 138 may include measurements from reservoir mapping tools, formation evaluation tools, logging while drilling (LWD) tools, and/or measurement while drilling (MWD) tools. The sensor data 138 may include measurements from downhole sensors and surfaces sensors. For example, the sensor data 138 may include measurements associated with a thermal response test of one or more boreholes in the borefield 108. The sensor data 138 may include measurements associated with an inclinometer survey, such

as measurements from accelerometers, magnetometers, gyroscopes, etc. The sensor data 138 may include measurements from gamma ray sensors, resistivity sensors, neutron density sensors, porosity sensors, acoustic sensors, temperature sensors, pressure sensors, depth sensors, wireline tools, any other sensor, and combinations thereof. The sensor data 138 may include data from one or more surveying tools. In some embodiments, some of the design data 136 is received and/or is based on one or more measurements from the sensor data 138. In this way, the data manager 122 may receive measurements from one or more sensors. The data manager 122 may receive the sensor data 138 from any sensor in communication with the thermal system.

[0029] In some embodiments, the data manager 122 receives model data 140 associated with one or more computer and/or software implemented models for performing one or more features of the thermal management system 120. For example, as described herein, the thermal management system 120 may implement one or more models to predict, estimate, and/or determine one or more thermal parameters of the thermal system 100. One or more models may estimate one or more measured values (e.g., sensor data 138) as described herein. A model may be implemented to infer the temperature at one or more (or all) locations in the borefield 108 (e.g., a borefield digital twin as described herein). The model data 140 may include one or more machine learning models, deep learning models, and/or artificial intelligence (AI) models. The model data 140 may include, forward models, inverse or reverse models, artificial neural networks, algorithms, regression models, or any other model or type of model, and combinations thereof. In some embodiments, the thermal management system 120 implements one or more models or algorithms of the model data 140 by inputting data or information into the models. In some embodiments, the thermal management system 120 calibrates, train, or tune one or more models or algorithms of the model data 140.

[0030] In some embodiments, the data manager 122 receives user input 142. The data manager 122 may receive the user input 142, for example, via any of the client devices 112 and/or server devices 114. Any of the data described herein may be input or augmented via the user input 142. For example, in some instances, some or all of the sensor data 138 may be received by the data manager 122 as user input. In some instances, some or all of the design data 136 may be received by the data manager 122 as user input 142. As will be described herein, one or more functions or features of the thermal management system 120 may be facilitated by receiving user input 142.

[0031] The data manager 122 may save and/or store any of the data it receives to the data storage 130. For example, the data manager 122 may store data associated with the design, operation, modelling, etc., of the thermal system 100 as thermal system attribute data 132. The data manager 122 may store data associated with

one or more predicted values, parameters, properties, models, etc., as predicted parameter data 134. Any of the data in the data storage 130 may include data received, manipulated, generated, and/or augmented by the data manager 122 as described herein.

[0032] As mentioned above, and as shown in FIG. 5, the thermal management system 120 includes a model engine 124. The model engine 124 may implement a thermal model 125 including a forward model 146 and an inverted model 148. In some embodiments, the model engine 124 receives the thermal model 125, such as by accessing the model data 140. In some embodiments, the model engine 124 generates, calibrates, and/or trains the thermal model 125.

[0033] FIG. 6 is an example implementation of the thermal model 125 as described herein, according to at least one embodiment of the present disclosure. As shown, the thermal model 125 may include a forward model 146. The forward model 146 may be a physical model of the ground heat exchanger 110. For example, the forward model 146 may be a computational tool that simulates and/or predicts the thermal behavior of the borefield 108, the ground 109, the boreholes, etc. The forward model 146 may receive (or may be based on) one or more parameters, and based on receiving one or more inputs, the forward model 146 may predict or estimate one or more output values. In this way, the forward model 146 may provide a detailed representation of the thermal response of the ground heat exchanger 110 due to heat transfer.

[0034] In some embodiments, the forward model 146 receives (or is based on) one or more borefield design parameters 152. The borefield design parameters 152 may include information related to the one or more boreholes of the borefield 108, such as a trajectory, length, diameter, location, position, layout, configuration, etc., of the boreholes. The borefield design parameters 152 may include any of the design data 136 related to the borefield as described herein.

[0035] In some embodiments, the forward model 146 receives (or is based on) one or more completion design parameters 154. The completion design parameters 154 may include information related to the completion of the boreholes of the borefield 108, such as a diameter, configuration, length, arrangement, shank spacing, etc., of the ground loops 107. The completion design parameters 154 may include thermal properties of the ground loops 107 and/or of the thermal fluid circulated in the ground loops 107.

[0036] In some embodiments, the forward model 146 receives (or is based on) one or more initial conditions, such as initial borefield parameters 164. The initial borefield parameters 164 may include information related to one or more properties of the borefield 108, such as an initial thermal conductivity of the ground 109, an initial thermal conductivity of the grout, and/or an initial average (or far-field) temperature of the ground 109. One or more of the initial borefield parameters 164 may be initial

conditions in that they may be initial starting points or estimates of the borefield parameters for use in simulating the thermal response with the forward model 146 (e.g., to output the predicted thermal values 162). As described below, one or more of the initial borefield parameters 164 may be variables that may be manipulated or changed through implementation of the inverted model 148 in order to determine one or more of the predicted borefield parameters 160.

[0037] The forward model 146 may receive (or may be based on) any other parameter. For example, the forward model 146 may receive one or more boundary conditions such as an ambient air temperature, heat pump condition (e.g., compressor and/or evaporator temperature), heat pump state (e.g., on/off), or any other factor that may influence the heat transfer process. The borefield design parameters 152 and/or the completion design parameters 154 may include information from the thermal system attribute data 132. In some embodiments, the borefield design parameters 152 and/or the completion design parameters 154 may be static inputs and, as just mentioned, one or more of the initial borefield parameters 164 may be variables.

[0038] In some embodiments, the forward model 146 receives one or more dynamic inputs, or measurement inputs. The measurement inputs may be associated with a flow of the thermal fluid through the ground heat exchanger 110. For example, the forward model 146 may receive a thermal flux input 156. The thermal flux input 156 may be a measure of a rate of energy transferred between the thermal fluid and the ground 109 as a result of the thermal fluid flowing through the ground loops 107 (e.g., energy per unit area per unit time, W/m²). The thermal flux input 156 may be measured at one or more locations of the ground heat exchanger 110, and may be part of the sensor data 138.

[0039] In some embodiments, the measurement inputs include a flowrate input 158. The flowrate input 158 may include a volumetric flow rate and/or a mass flow rate of the thermal fluid flowing through the ground heat exchanger 110. The flowrate input 158 may be measured at one or more locations of the ground heat exchanger 110, and may be part of the sensor data 138.

[0040] The forward model 146 being based on the borefield design parameters 152, the completion design parameters 154, and the initial borefield parameters 164 in this way may facilitate accurately simulating the heat transfer processes of the thermal system 100 (e.g., due to the inputs 156 and/or 158). For example, the forward model 146 may account for factors such as geophysical properties of the ground 109, the configuration of the borefield 108, and operational parameters of the GSHP 102. The forward model 146 may implement numerical techniques for capturing the interplay between one or more of the inputs and/or parameters in order to accurately characterize the thermal response of the ground heat exchanger 110. For example, the forward model 146 may incorporate mathematical heat transfer equations,

such as a g-function, that describe conductive, convective, radiative, and/or advective heat transfer within the thermal system 100, as well as the transient nature of heat transfer at changing temperatures. The forward model 146 may implement numerical calculations, finite element analyses, or any other techniques for modeling and solving the heat transfer of the thermal system 100.

[0041] In this way, the forward model 146 may model the temperature distribution and variation within the ground 109 over one or more discrete time intervals in response to a thermal rejection to (or thermal extraction from) the ground 109 by the thermal fluid and/or the ground loops 107. For example, the forward model 146 may include or may be based on robust heat transfer dynamics and/or equations that capture faster transients within the thermal system 100. In these situations, the forward model 146 may implement time intervals, such as every 1-5 minutes to simulate a more detailed or faster thermal response of the thermal system 100. In another example, the forward model 146 may include or may be based on more general or balanced thermodynamics and may accordingly implement longer time intervals, such as every 1-5 hours to simulate a more general thermal response or equilibrium of the thermal system 100 over a longer time period.

[0042] In some embodiments, the forward model 146 outputs or predicts one or more predicted thermal values 162. The predicted thermal values 162 may include predicted values associated with the thermal fluid, such as a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger 110, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger 110, a predicted pressure drop of the thermal fluid at or across one or more locations of the ground heat exchanger 110. The predicted thermal values 162 may include predicted values associated with the ground 109, such as a predicted temperature at one or more locations of the ground 109. In some embodiments, the predicted thermal values 162 are values or parameters of the thermal system 100 that will or can be measured or observed. For example, the predicted thermal values 162 output by the forward model 146 may correspond and may be compared to one or more actual, measured thermal values 166, such as a measured fluid inlet temperature, measured fluid outlet temperature, measured fluid pressure drop, etc. This may facilitate calibrating, tuning, or training the thermal model 125, as described herein. The predicted thermal values 162 may include any other value that may be predicted by the forward model 146 consistent with that described herein. In this way, the forward model 146 may characterize the thermal behavior of the ground heat exchanger 110 in order to predict one or more observable values of the thermal system 100. The model engine 124 may store any of the predicted thermal values 162 to the data storage 130 as predicted parameter data 134.

[0043] As mentioned, the thermal model 125 may include an inverted model 148. The inverted model 148

may facilitate estimating or predicting one or more of the parameters upon which the forward model 146 is based. In this way, the inverted model 148 may be an inversion or a reversal of the forward model 146. For example, the forward model 146 may predict, based on the model parameters, one or more values of the thermal system 100, and the inverted model 148 may facilitate finding the set of model parameters (e.g., in particular borefield parameters) that result in predicted values that best match actual measured values of the thermal system 100.

[0044] For example, as mentioned, the forward model 146 may determine one or more predicted thermal values 162 associated with the thermal system 100 based on a set of initial borefield parameters 164 (among other factors). As described, the data manager 122 may receive sensor data 138 including the measured thermal values 166. In some embodiments, the inverted model 148 compares the predicted thermal values 162 to the measured thermal values 166. For example, the inverted model 148 may include or may define an objective function or cost function that quantifies a target difference between one or more of the predicted thermal values 162 and the measured thermal values 166 for the set of parameters used by the forward model 146 (e.g., used for a given iteration performed by the forward model). In some embodiments, the inverted model 148 finds the set of parameters that minimizes this target difference. For example, the inverted model 148 may iteratively adjust or modify one or more (or all) of the initial borefield parameters 164 in order to iteratively change or modify the predicted thermal values 162 that the forward model 146 outputs.

[0045] In some embodiments, the inverted model 148 includes or defines an optimization algorithm or engine in order to find the best-fit values for the initial borefield parameters. For example, the inverted model 148 may try and/or modify different combinations of the initial borefield parameters 164 to yield a sufficient or desirable target difference. In some embodiments, the inverted model 148 functions iteratively in this way until a convergence occurs for the target difference. For example, the inverted model 148 may iterate until the target difference is within a predetermined threshold, such as substantially 0. In another example, the inverted model 148 may iterate until a change in the target difference is within a predetermined threshold (e.g., for a threshold quantity of consecutive iterations). In another example, the inverted model 148 may iterate until a minimum (or least) target difference is found, such as by iterating through a predetermined quantity of (or all) iterations.

[0046] In this way, the inverted model 148 may iteratively generate the predicted thermal values 162 and compare those values to the measured thermal values 166 in order to determine a set of best-fit borefield parameters. The inverted model 148 may output these best-fit parameters as predicted borefield parameters 160. For example, the predicted borefield parameters 160 may

include a ground thermal conductivity (k) and a grout thermal conductivity (kg). The predicted borefield parameters 160 may include an average temperature (T_0) of the ground 109 and/or a current temperature (T) of the ground in one or more locations of the ground in the neighborhood of the borefield. The average temperature T_0 may be an average far-field or undisturbed ground temperature. The borefield parameters 160 may be associated with one or more depths within the ground 109, or may be associated with the ground heat exchanger 110 generally (e.g., an average). In this way, the predicted borefield parameters 160 may represent an inference of one or more properties or parameters of the ground heat exchanger 110. In some embodiments, determining (e.g., measuring) an actual value of one or more of the predicted borefield parameters 160 may not be possible, may be prohibitively difficult or not feasible, or may be cumbersome in practice. By inferring the predicted borefield parameters 160 in this way, the thermal model 125 may facilitate understanding a state, change, condition, etc., of one or more of the thermal properties of the thermal system 100 which may otherwise not be known. As discussed herein, generating the predicted borefield parameters 160 may facilitate monitoring, analyzing, and/or controlling one or more aspects of the thermal system 100. The model engine 124 may store any of the predicted borefield parameters 160 to the data storage 130 as predicted parameter data 134.

[0047] The thermal model 125 may be implemented in order to determine the predicted borefield parameters 160. In some embodiments, the thermal model 125 iteratively and/or continuously determines the predicted borefield parameters 160. For example, the thermal model 125 may update the predicted borefield parameters 160 one or more times over a predetermined time interval. For instance, the thermal model 125 may receive the inputs (e.g., thermal flux input 156 and/or flowrate input 158) at discrete time intervals such as every 1 minute, 2 minutes, 3 minutes, 4 minutes, 5 minutes, or up to every 1 hour, 2 hours 3 hours, or more. The inputs may include an actual measured value and/or may include a statistical value such as an average, mean, median, mode, maximum, minimum, etc., calculated over several time intervals. In this way, the thermal model 125 may receive the inputs as live or real-time data inputs. The thermal model 125 may accordingly update the predicted borefield parameters 160 in real time based on the live data inputs. In this way, the thermal model 125 may facilitate a real-time estimation or inference of the predicted borefield parameters 160 to simulate changes in the thermal response over predetermined time intervals based on heat extracted or injected by the GSHP 102.

[0048] The thermal model 125 functioning based on the inputs and parameters discussed above, in this way, may facilitate determining the predicted borefield parameters 160 during operation of the thermal system 100 and/or the GSHP 102. For example, the borefield design parameters 152 and the completion design parameters

154 may include static values that may be known or calculated, for example, based on the design, construction, etc., of the thermal system 100. Additionally, the thermal flux input 156 and the flowrate input 158 may include values and/or may be calculated from values that are received and/or measured by the data manager 122 during operation of the thermal system 100, such as with temperature sensors, flow sensors, pressure sensors, etc. The predicted borefield parameters 160 may accordingly be determined during operation of the thermal system 100 based on this information that is known and/or collected during operations. In this way, the thermal management system 120 may provide the features and functionalities discussed herein without having to put the thermal system 100 offline.

[0049] In some embodiments, the model engine 124 utilizes the predicted borefield parameters 160 to generate and/or implement a digital twin 150, as shown in FIG. 5 and in FIG. 7. The digital twin 150 may be a digital representation of one or more aspects of the ground heat exchanger 110 and/or the borefield 108. For example, based on the predicted borefield parameters 160, the digital twin may infer one or more other parameters, properties, and/or states of the thermal system 100.

[0050] In some embodiments, the digital twin 150 indicates a temperature of the borefield 108 and/or the ground 109 at one or more locations. For example, given the known geometry and configuration of the ground heat exchanger 110, as well as the flow measurements of the thermal fluid, and by incorporating the thermal properties of the ground 109 (e.g., the predicted borefield parameters 160) the model engine 124 may generate a detailed temperature map of the borefield 108. The digital twin 150 may indicate one or more temperatures with respect to a (e.g., 2- or 3-dimensional) spatial coordinate. For example, the model engine 124 may generate a 2- or 3-dimensional grid consisting of individual cells associated with a specific location in the borefield 108. The size and/or quantity of cells may vary depending on a desired level of detail for the digital twin 150. For each cell in the grid, the model engine 124 may determine a temperature based on a physical modelling of the heat transfer to that location by implementing heat transfer equations and/or numerical methods (e.g., similar to that used in connection with the forward model 146). The model engine 124 may incorporate lithology data for the ground 109, data from thermal response tests, laboratory testing, or any other data such as data from the thermal system attribute data 132. In some embodiments the model engine 124 implements one or more methods of interpolation for estimating temperatures at the boundaries of cells of the grid and/or between cells. In this way, a continuous temperature field may be generated for an area of interest (or all of) the borefield 108 via the digital twin 150.

[0051] In some embodiments, the model engine 124 generates a plot, or a visual representation of the digital twin 150. For example, the model engine 124 may im-

plement color mapping or shading to represent different temperatures of the temperature field in order to generate a 2- or 3-dimensional temperature map of the borefield 108. In some embodiments, the model engine 124 displays the digital twin 150 via a graphical user interface. In this way, the digital twin 150 may be visually represented and presented in order that a user may analyze and/or interpret the inferred temperatures of the borefield 108.

[0052] In this way, the thermal management system 120 may facilitate inferring the temperature at any point in the ground 109 based on the digital twin 150. This detailed and real-time overview of the ground temperature may facilitate efficiently and/or effectively operating the thermal system 100. For example, as will be discussed herein in detail, the thermal management system 120 may monitor the digital twin 150 to maintain the ground temperature at or above a threshold level. The digital twin 150 may be especially advantageous in situations where the ground heat exchanger 110 has a complex configuration or geometry, such as having one or more inclined boreholes as shown in FIG. 7. Such geometries may result in temperature gradients and/or heat transfer that is not uniform over different depths within the ground 109, making it especially difficult to discern the temperature at one or more locations. The digital twin 150 may incorporate the design (e.g., geometry) of the ground heat exchanger 110 in order to accurately infer the temperature at every location in the ground 109 irrespective of the complexity of the design. In this way, the model engine 124 may facilitate inferring valuable temperature data for the ground heat exchanger via the digital twin 150. The model engine 124 may store and/or update the digital twin 150 to the data storage 130 as the predicted parameter data 134.

[0053] As mentioned above, the thermal management system 120 includes a validation manager 126. The validation manager 126 may facilitate validating the thermal model 125 (and the digital twin 150) by validating the predicted borefield parameters 160 generated by the thermal model 125. FIG. 8 illustrates an example validation 800.

[0054] As mentioned, the thermal model 125 may predict one or more thermal values 162 as an intermediate for predicting the borefield parameters 160. The validation manager 126 may validate the accuracy of the borefield parameters 160, and therefore the thermal model 125, by comparing the predicted thermal values 162 to equivalent real-world measurements for the thermal values. The example validation 800 illustrates an example comparison 802 of a predicted and measured outlet temperature.

[0055] In some embodiments, a set of predicted borefield parameters 160 are applied to the forward model 146 after being determined by the inverted model 148. For example, the model engine 124 may hold the predicted borefield parameters 160 constant over a validation period of operation of the thermal system 100, and the forward model 146 may determine the predicted

thermal values 162 based on those (constant) predicted borefield parameters for the duration of the validation period. In some embodiments, the validation manager 126 monitors the predicted thermal values 162 (e.g., outlet temperature) over the validation period and compares the predicted thermal values 162 (e.g., predicted outlet temperature) to the associated measured values over the validation period. For example, the comparison 802 illustrates the predicted vs measured outlet temperature over the course of several days and months. As shown in the example validation 800, the predicted outlet temperature tracks closely with the measured outlet temperature indicating the precision of the thermal model 125.

[0056] In some embodiments, the validation manager 126 determines an error 804 between the predicted value and the measured values for one or more time periods (e.g., hours) over the course of the validation period. Based on the error 804, the validation manager 126 may determine a statistical distribution (e.g., normal distribution) including one or more statistical values such as a mean, median, mode, average, maximum, minimum, standard deviation, variance, etc. The validation manager 126 may accordingly determine whether the predicted borefield parameters 160 are accurate and/or precise based on this comparison and analysis.

[0057] Based on the accuracy of the predicted borefield parameters 160 (e.g., held constant over the measurement period), the validation manager 126 may accordingly determine whether the thermal model 125 is accurate and/or precise. For example, as shown in FIG. 8, the error 804 for the outlet temperature has an average close to 0.0 °C with a standard deviation grouping the data tightly therewith. This may indicate that the thermal model 125 is accordingly calibrated or trained to a high degree of accuracy, and that the predicted borefield parameters 160 determined by the thermal model 125 may be relied on with a high confidence. In some embodiments, the validation manager 126 indicates this determination (and/or the error 804) to a user of the thermal management system 120, such as through a graphical user interface.

[0058] In some embodiments, the validation manager 126 determines that the thermal model 125 is not accurate to a sufficient degree, such as based on determined that the error 804 has an average and/or standard deviation that is not within a threshold range. The validation manager 126 may accordingly provide an indication of the error of the thermal model 125. For example, the validation manager 126 may provide an alarm or other indication to a user of the error 804. In another example, the validation manager 126 may provide an indication of which value(s) (e.g., outlet temperature, inlet temperature, etc.) are associated with the error 804, including one or more instances of departure between the measured and predicted values.

[0059] In this way, the validation manager 126 may facilitate validating that the thermal model 125 properly

functions to accurately determine the predicted borefield parameters 160 to a threshold degree. While the predicted borefield parameters 160 have been described as being applied and/or held constant, it should be understood that this may be as part of the validation process of the thermal model 125, and that, once validated, the thermal model 125 may again be implemented to adjust the predicted borefield parameters 160 in order to accurately determine (e.g., infer) the best-fit parameters in real-time, as described herein.

[0060] As mentioned above, the thermal management system 120 includes a thermal system controller 128. The thermal system controller 128 may facilitate implementing the thermal model 125 (more specifically the outputs of the thermal model 125) and/or the digital twin 150 in a variety of advantageous ways in connection with the thermal system 100. For example, the thermal system controller 128 may monitor and/or analyze one or more aspects of the thermal system 100 to provide valuable insights and/or overviews of the one or more aspects of the thermal system 100. In some embodiments, the thermal system controller 128 facilitates controlling or operating the thermal system 100, for example, based on one or more of these observations.

[0061] In some embodiments, the thermal system controller 128 monitors and tracks the thermal properties of the borefield 108 and/or the ground 109 by monitoring and tracking the predicted borefield parameters 160 over time. For example, the thermal system controller 128 may identify and/or track one or more changes in the predicted borefield parameters 160 over time corresponding to a change in the thermal properties of the ground 109. For instance, a decrease or degradation of the ground thermal conductivity (k) may correspond with a decreased water level of an underground aquifer (or vice versa for an increase or improvement in the ground thermal conductivity (k)). In other examples, a decrease in the grout thermal conductivity (kg) may correspond with a degradation (e.g., due to aging, borehole conditions, etc.) of the grout.

[0062] Similarly, the thermal system controller 128 may monitor and track any of the measured values (e.g., sensor data) and/or the predicted values over time. For example, the thermal system controller 128 may track and/or detect a decrease in the flow rate (and/or an increase in the pressure drop) of the thermal fluid over time, which may indicate that the ground loops have become damaged or blocked. In some embodiments, the thermal system controller 128 monitors and tracks one or more measured values against the predicted thermal values 162 over time. For example, as discussed above in connection with the validation manager 126, the thermal system controller 128 may determine and monitor the difference between one or more measured and predicted values of the thermal system 100. As discussed above, once calibrated, the thermal model 125 may be relied upon with confidence to accurately predict one or more values, and the thermal system controller

128 may monitor the difference for any significant deviation of the measured values. For example, a measured outlet temperature that deviates from that which is predicted or expected may indicate a fault (or future fault) with one or more components in the thermal system 100. The thermal system controller 128 may accordingly generate an alert or otherwise indicate that a fault has occurred or will occur in the future. In this way, the thermal system controller 128 may facilitate preventing or mitigating failures of the thermal system 100.

[0063] In some embodiments, the thermal system controller 128 determines and monitors a state of charge of the ground thermal battery over time. For example, based on the temperatures indicated by the digital twin 150, and based on the measured thermal flux of the ground heat exchanger, the thermal system controller 128 may determine an amount of heat energy that the thermal system 100 is injecting into, or extracting from, the borefield 108 and the ground 109. The thermal system controller 128 may accordingly determine a heat energy capacity for the borefield 108 to transfer heat to or from the GSHP 102 (e.g., via the thermal fluid). In this way, the thermal system controller 128 may monitor the state of thermal charge of the ground 109, for example, between seasons, in order to forecast a capacity for the thermal system 100 to provide heating and/or cooling during warmer or cooler (respectively) times of the year.

[0064] In some embodiments, the thermal system controller 128 monitors the digital twin 150. For example, the thermal system controller 128 may determine and track the lowest temperature at any point in the ground 109 based on the inferences of the digital twin 150. This may facilitate controlling and/or operating the thermal system 100. For example, in many cases it may be undesirable for the ground 109 to freeze. Freezing may reduce the thermal conductivity of the ground 109 and therefore reduce the efficiency of the GSHP 102. Similarly, freezing may increase energy consumption for the GSHP 102 to attempt to keep up with the decreased efficiency. Further, freezing and thawing cycles may risk damage or blockage to one or more components of the thermal system 100. Thus, it may be advantageous to prevent the ground 109 from freezing at one or more locations.

[0065] As shown in FIG. 9, the thermal system controller 128 may track the minimum ground temperature ($T_{g,min}$) over time. When it is determined that the minimum ground temperature $T_{g,min}$ is at or below 0 °C, the thermal system controller 128 may implement one or more measures to attempt to raise the minimum ground temperature $T_{g,min}$ up to above freezing. For example, the thermal system controller 128 may reduce a thermal power (e.g., reduce a flowrate or implement any other measure) of the GSHP 102 in order to slow the rate at which the GSHP 102 removes heat from the ground 109. In another example, the thermal system controller 128 may generate an alert, indication, or otherwise prompt a user to take one or more mitigating actions with respect to the minimum ground temperature $T_{g,min}$. The thermal

system controller 128 may act reactively in this way to the minimum ground temperature $T_{g,min}$ in order to prevent damage, inefficiencies, or other undesirable affects resulting from the ground 109 freezing.

[0066] In some embodiments, the thermal system controller 128 acts proactively to prevent freezing. For example, the thermal system controller 128 may identify one or more patterns, trajectories, or trends in the data that it monitors in order to forecast or project how the minimum ground temperature $T_{g,min}$ will change in the future. For example, the thermal system controller 128 may monitor and/or compare one or more (measured and/or predicted) values against the minimum ground temperature $T_{g,min}$ in order to identify how changes in these other values (or combinations of values) may affect the minimum ground temperature $T_{g,min}$. Based on a forecast that the minimum ground temperature $T_{g,min}$ will fall below 0°C , the thermal system controller 128 may implement one or more of the mitigating measures discussed above.

[0067] While freezing may generally be undesirable, in some embodiments, freezing at one or more locations in the ground 109 is acceptable within a threshold amount. For example, in some embodiments, the minimum ground temperature $T_{g,min}$ occurs at a borehole wall of one or more of the boreholes of the borefield 108. Accordingly, the minimum ground temperature $T_{g,min}$ at the borehole wall may fall below freezing, but the freezing may be relatively localized to an area immediately adjacent the borehole(s). In some embodiments, the thermal system controller 128 monitors one or more additional minimum temperatures, such as a minimum temperature at a threshold distance (e.g., radius) from or around the borehole(s). For example, as shown in FIG. 9, a minimum temperature within a 25 cm radius ($T_{g25,min}$ from the borehole(s)) may be monitored (e.g., in addition to the minimum ground temperature $T_{g,min}$). As shown, while the minimum ground temperature $T_{g,min}$ falls below 0°C , the 25 cm radius temperature $T_{g25,min}$ may remain well above 0°C , indicating that the freezing does not extend or permeate far from the borehole(s). The thermal system controller 128 may accordingly facilitate implementing a control strategy for the thermal system 100 that allows the minimum ground temperature $T_{g,min}$ to fall below freezing while maintaining the 25 cm radius temperature $T_{g25,min}$ (or any other threshold distance) above freezing.

[0068] The thermal system controller 128 may save data from any of its monitoring functions to the data storage 130 as predicted parameter data 134. In some embodiments, the thermal system controller 128 plots one or more of the values, parameters, and/or properties that it monitors and/or may present one or more plots via a graphical user interface.

[0069] FIG. 10 is a flow diagram illustrating a method 1000 or a series of acts for operating a thermal system implementing a ground-source heat pump as described herein, according to at least one embodiment of the

present disclosure. While FIG. 10 illustrates acts according to one embodiment, alternative embodiments may add to, omit, modify, and/or reorder any of the acts of FIG. 10.

5 **[0070]** In some embodiments, the method 1000 includes an act 1010 of receiving design parameters associated with a design of the thermal system. For example, the design parameters may include borehole geometry data for one or more boreholes of the borefield and completion geometry data for a completion of the one or more boreholes.

10 **[0071]** In some embodiments, the method 1000 includes an act 1020 of receiving one or more measurement inputs associated with a flow of thermal fluid through a borefield of a ground heat exchanger. For example, the measurement inputs may include a flowrate of the thermal fluid through the ground heat exchanger and/or a thermal flux between the thermal fluid and the borefield.

15 **[0072]** In some embodiments, the method 1000 includes and act 1030 of, based on the measurement inputs and the design parameters, predicting one or more predicted thermal values of the thermal fluid using a forward model. For example, the predicted thermal values may include one or more of a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger, a predicted flow rate of the thermal fluid flowing through the ground heat exchanger, and a predicted fluid pressure drop of the thermal fluid. The predicted borefield parameters may include one or more of a predicted ground thermal conductivity, a predicted grout thermal conductivity, and a predicted far-field ground temperature.

20 **[0073]** In some embodiments, the method 1000 includes an act 1040 of predicting one or more predicted borefield parameters of the borefield based on inverting the forward model. Inverting the forward model may include minimizing a target difference between the predicted thermal values and one or more measured thermal values (such as the temperature of the thermal fluid at the outlet of the borefield). In some embodiments, predicting the one or more predicted thermal values with the forward model and inverting the forward model to predict the one or more predicted borefield parameters are each performed in real-time during operation of the ground-source heat pump. In some embodiments, the forward model and the inversion of the forward model are validated based on predicting the one or more predicted thermal values while holding the predicted borefield parameters constant.

25 **[0074]** In some embodiments, the method 1000 includes an act 1050 of monitoring the thermal system based on the predicted borefield parameters. For example, a thermal management system may monitor the health of the thermal system based on tracking the predicted borefield parameters over time. In another example, the method 1000 may include generating a digital

twin of the borefield by inferring a temperature at one or more locations in the borefield based on the predicted borefield parameters. Inferring the temperature may further be based on lithology data of the borefield. The thermal management system may monitor a minimum inferred temperature for any location in the borefield based on the digital twin. In another example, the thermal management system may determine a fault of the thermal system based on a deviation of one or more measured thermal values from the one or more predicted thermal values. In another example, the thermal management system may determine a thermal state of charge of the borefield. In another example, the thermal management system may predict one or more future thermal values. In some embodiments, the method 1000 includes using the predicted borefield parameters for controlling an operation of a ground source heat pump, in particular controlling an operation of the ground source heat pump based on the predicted borefield parameters. Alternatively, a non-transitory computer-readable storage medium may include instructions that, when executed by one or more processors, cause a computing device to perform the acts of FIG. 10. In still further implementations, a system can perform the acts of FIG. 10.

[0075] Turning now to FIG. 11, this figure illustrates certain components that may be included within a computer system 1100. One or more computer systems 1100 may be used to implement the various devices, components, and systems described herein.

[0076] The computer system 1100 includes a processor 1101. The processor 1101 may be a general-purpose single- or multi-chip microprocessor (e.g., an Advanced RISC (Reduced Instruction Set Computer) Machine (ARM)), a special purpose microprocessor (e.g., a digital signal processor (DSP)), a microcontroller, a programmable gate array, etc. The processor 1101 may be referred to as a central processing unit (CPU). Although just a single processor 1101 is shown in the computer system 1100 of FIG. 11, in an alternative configuration, a combination of processors (e.g., an ARM and DSP) could be used.

[0077] The computer system 1100 also includes memory 1103 in electronic communication with the processor 1101. The memory 1103 may include computer-readable storage media and can be any available media that can be accessed by a general purpose or special purpose computer system. Computer-readable media that store computer-executable instructions are non-transitory computer-readable media (device). Computer-readable media that carry computer-executable instructions are transmission media. Thus, by way of example and not limitations, embodiment of the present disclosure can comprise at least two distinctly different kinds of computer-readable media: non-transitory computer-readable media (devices) and transmission media.

[0078] Both non-transitory computer-readable media (devices) and transmission media may be used temporarily

to store or carry software instructions in the form of computer readable program code that allows performance of embodiments of the present disclosure. Non-transitory computer-readable media may further be used to persistently or permanently store such software instructions. Examples of non-transitory computer-readable storage media include physical memory (e.g., RAM, ROM, EPROM, EEPROM, etc.), optical disk storage (e.g., CD, DVD, HDDVD, Blu-ray, etc.), storage devices (e.g., magnetic disk storage, tape storage, diskette, etc.), flash or other solid-state storage or memory, or any other non-transmission medium which can be used to store program code in the form of computer-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer, whether such program code is stored or in software, hardware, firmware, or combinations thereof.

[0079] Instructions 1105 and data 1107 may be stored in the memory 1103. The instructions 1105 may be executable by the processor 1101 to implement some or all of the functionality disclosed herein. Executing the instructions 1105 may involve the use of the data 1107 that is stored in the memory 1103. Any of the various examples of modules and components described herein may be implemented, partially or wholly, as instructions 1105 stored in memory 1103 and executed by the processor 1101. Any of the various examples of data described herein may be among the data 1107 that is stored in memory 1103 and used during execution of the instructions 1105 by the processor 1101.

[0080] A computer system 1100 may also include one or more communication interfaces 1109 for communicating with other electronic devices. The communication interface(s) 1109 may be based on wired communication technology, wireless communication technology, or both. Some examples of communication interfaces 1109 include a Universal Serial Bus (USB), an Ethernet adapter, a wireless adapter that operates in accordance with an Institute of Electrical and Electronics Engineers (IEEE) 802.11 wireless communication protocol, a Bluetooth® wireless communication adapter, and an infrared (IR) communication port.

[0081] The communication interfaces 1109 may connect the computer system 1100 to a network. A "network" or "communications network" may generally be defined as one or more data links that enable the transport of electronic data between computer systems and/or modules, engines, and/or other electronic devices. When information is transferred or provided over a communication network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a computing device, the computing device properly views the connection as a transmission medium. Transmission media can include a communication network and/or data links, carrier waves, wireless signals, and the like, which can be used to carry desired program or template code means or instructions in the form of computer-executable instruction or data struc-

tures and which can be accessed by a general purpose or special purpose computer.

[0082] A computer system 1100 may also include one or more input devices 1111 and one or more output devices 1113. Some examples of input devices 1111 include a keyboard, mouse, microphone, remote control device, button, joystick, trackball, touchpad, and light-pen. Some examples of output devices 1113 include a speaker and a printer. One specific type of output device that is typically included in a computer system 1100 is a display device 1115. Display devices 1115 used with embodiments disclosed herein may utilize any suitable image projection technology, such as liquid crystal display (LCD), light-emitting diode (LED), gas plasma, electroluminescence, or the like. A display controller 1117 may also be provided, for converting data 1107 stored in the memory 1103 into text, graphics, and/or moving images (as appropriate) shown on the display device 1115.

[0083] The various components of the computer system 1100 may be coupled together by one or more buses, which may include a power bus, a control signal bus, a status signal bus, a data bus, etc. For the sake of clarity, the various buses are illustrated in FIG. 11 as a bus system 1119.

[0084] The techniques described herein may be implemented in hardware, software, firmware, or any combination thereof, unless specifically described as being implemented in a specific manner. Any features described as modules, components, or the like may also be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a non-transitory processor-readable storage medium comprising instructions that, when executed by at least one processor, perform one or more of the methods described herein. The instructions may be organized into routines, programs, objects, components, data structures, etc., which may perform particular tasks and/or implement particular data types, and which may be combined or distributed as desired in various embodiments.

[0085] Further, upon reaching various computer system components, program code in the form of computer-executable instructions or data structures can be transferred automatically or manually from transmission media to non-transitory computer-readable storage media (or vice versa). For example, computer executable instructions or data structures received over a network or data link can be buffered in memory (e.g., RAM) within a network interface module (NIC), and then eventually transferred to computer system RAM and/or to less volatile non-transitory computer-readable storage media at a computer system. Thus, it should be understood that non-transitory computer-readable storage media can be included in computer system components that also (or even primarily) utilize transmission media.

INDUSTRIAL APPLICABILITY

[0086] In some embodiments, a thermal system may include a ground-source heat pump (GSHP). The GSHP may be in thermal communication with a ground heat exchanger. The ground heat exchanger may include a borefield having one or more boreholes within a volume of ground defining the borefield. One or more ground loops may be positioned within the one or more boreholes, and the boreholes may be at least partially filled with a grout, for example, to maintain the ground loops in place and to facilitate heat transfer between the ground loops and the ground. The ground loops may have a fluid inlet and a fluid outlet but may have any configuration in the wellbore, for instance coaxial or U-shaped. The ground loops may be operatively coupled to the GSHP, and a thermal fluid may flow through the ground loops to facilitate transferring heat between the ground (or borehole) heat exchanger and the GSHP. The GSHP may be in thermal communication with a facility heat exchanger of the facility. The GSHP may include a compressor and an evaporator (e.g., expansion valve) for implementing a refrigerant cycle between the facility heat exchanger and another heat exchanger in which flows a thermal fluid circulating into the ground heat exchanger to transfer heat from the facility to the borefield (e.g., cooling) via the thermal fluid, as well as to transfer heat from the borefield to the facility (e.g., heating), via the thermal fluid. In this way, the GSHP may be a geothermal heat pump for leveraging the thermal properties and conditions within the ground for providing heating and cooling to the facility.

[0087] In some embodiments, the thermal system includes one or more supplemental thermal devices. The supplemental thermal devices may be configured to provide heating and cooling to the facility. For example, the supplemental thermal devices may include one or more heating devices such as a boiler, furnace, or any other heating device. The supplemental thermal devices may include one or more cooling devices such as a chiller, cooling tower, fin-fan cooler, or any other cooling device. The supplemental thermal devices may be configured to provide heating and/or cooling to the facility in addition to (e.g., in parallel with), or as an alternative to the GSHP. For example, in some embodiments, a capacity of the GSHP is not sufficient to meet a load or demand of the facility, and the supplemental thermal devices supplement the GSHP to meet the thermal load. In another example, the supplemental thermal devices may serve as a backup or failsafe for providing heating and/or cooling to the facility if the GSHP fails or is put offline (e.g., for maintenance). In this way, heating and cooling may be provided by both the GSHP and the supplemental thermal devices. In some embodiments, the thermal system does not include the supplemental thermal devices, and the thermal loads of the facility are provided to the facility by the GSHP without the supplemental thermal devices.

[0088] In some embodiments, the thermal system includes a thermal management system implemented on

one or more computing devices, such as one or more client devices. The thermal management system may be in communication with one or more components of the thermal system (e.g., via the network as describe herein). In some embodiments, the thermal management system is in communication with one or more of the ground heat exchanger, the GSHP, the supplemental thermal devices, and the facility. The thermal management system may be in communication with any other component or system associated with the thermal system consistent with that described herein. In some embodiments, the thermal management system monitors one or more values, parameters, functions, and/or features of the thermal system. For example, the thermal management system may be in communication with one or more sensors for receiving measurements of the thermal system. In another example, the thermal management system may record and/or track one or more parameters over time. In some embodiments, the thermal management system analyzes one or more values, parameters, functions, and/or features of the thermal system. For example, the thermal management system may estimate or infer one or more values associated with the thermal system. In another example, the thermal management system may characterize a behavior of the thermal system and/or may predict future behaviors (e.g., faults) of the thermal system. In some embodiments, the thermal management system controls one or more features and/or functions of the thermal system. For example, the thermal management system may control one or more aspects of the GSHP, the ground heat exchanger, the facility, or any other component. In this way, the thermal management system may perform one or more functions related to the thermal system as described herein.

[0089] In some embodiments, a thermal management system is implemented in an environment in accordance with one or more embodiments described herein. In some embodiments, the environment includes one or more server device(s). The server device(s) may include one or more computing devices (e.g., including processing units, data storage, etc.) organized in an architecture with various network interfaces for connecting to and providing data management and distribution across one or more client systems. The server devices may be connected to and may communicate with (either directly or indirectly) one or more client devices through a network. The network may include one or multiple networks and may use one or more communication platforms or technologies suitable for transmitting data. The network may refer to any data link that enables transport of electronic data between devices of the environment. The network may refer to a hardwired network, a wireless network, or a combination of a hardwired network and a wireless network. In one or more embodiments, the network includes the internet. The network may be configured to facilitate communication between the various computing devices via any protocol or form of communication.

[0090] The client device may refer to various types of computing devices. For example, one or more client devices may include a mobile device such as a mobile telephone, a smartphone, a personal digital assistant (PDA), a tablet, a laptop, or any other portable device. Additionally, or alternatively, the client devices may include one or more non-mobile devices such as a desktop computer, server device, surface or downhole processor or computer (e.g., associated with a sensor, system, function, etc., of the thermal system), or other non-portable device. In one or more implementations, the client devices include graphical user interfaces (GUI) thereon (e.g., a screen of a mobile device). In addition, or as an alternative, one or more of the client devices may be communicatively coupled (e.g., wired or wirelessly) to a display device having a graphical user interface thereon for providing a display of system content. The server devices(s) may similarly refer to various types of computing devices. Each of the devices of the environment may include features and functionalities described below.

[0091] The environment may include a thermal management system implemented on one or more computing devices. The thermal management system may be implemented on one or more client device, server devices, and combinations thereof. Additionally, or alternatively, the thermal management system may be implemented across the client devices and the server devices such that different portions or components of the thermal management system are implemented on different computing devices in the environment. In this way, the environment may be a cloud computing environment, and the thermal management system may be implemented across one or more devices of the cloud computing environment in order to leverage the processing capabilities, memory capabilities, connectivity, speed, etc., that such cloud computing environments offer in order to facilitate the features and functionalities described herein.

[0092] The thermal management system may include a data manager, a model engine, a validation manager, and a thermal system controller. The thermal management system may also include a data storage having thermal system attribute data and predicted parameter data stored thereon. While one or more embodiments described herein describe features and functionalities performed by specific components of the thermal management system, it will be appreciated that specific features described in connection with one component of the thermal management system may, in some examples, be performed by one or more of the other components of the thermal management system.

[0093] By way of example, one or more of the data receiving, gathering, and/or storing features of the data manager may be delegated to other components of the thermal management system. As another example, while models may be generated and/or implemented by the model engine, in some instances, some or all of these features may be performed by the validation manager, data manager, or any other component of the thermal

management system. Indeed, it will be appreciated that some or all of the specific components may be combined into other components and specific functions may be performed by one or across multiple of the components of the thermal management system.

[0094] Additionally, while the thermal management system has been described as being implemented on a client device of the thermal system, it should be understood that some or all of the features and functionalities of the thermal management system may be implemented on or across multiple client devices and/or server devices. For example, data may be received by the data manager on a (e.g., local) client device, and the data may be input to one or more models implemented by the model engine on a remote, server, and/or cloud device. Indeed, it will be appreciated that some or all of the specific components may be implemented on or across multiple client devices and/or server devices, including individual functions of a specific component being performed across multiple devices.

[0095] As mentioned above, the thermal management system includes a data manager. The data manager may receive and manage a variety of types of data of the thermal management system. For example, the data manager may receive design data. The design data may include information relating to a design, configuration, size, and/or capability of the thermal system. In some embodiments, the design data includes information relating to a design of the borefield. For example, the design data may identify a size, length, depth, trajectory, diameter, geometry, orientation, and/or location, of one or more boreholes of the borefield. The design data may identify a quantity, arrangement, and/or configuration of the boreholes in the borefield. The design data may include and/or identify any other features of the boreholes. The design data may identify one or more underground features of the ground, such as a material make-up, composition, lithology, facies, physical and/or chemical properties, formation, and/or underground resource of the ground. In some embodiments, the design data includes information related to the design of the ground heat exchanger. For example, the design data may identify a geometry of the ground heat exchanger such as a size, length, diameter, trajectory, shank spacing etc., of one or more ground loops. The design data may identify a configuration or completion of the ground loops, such as a single tube, double (U) tube, or coaxial configuration. The design data may identify one or more thermal properties of the ground heat exchanger, such as a thermal conductivity, thermal resistivity, heat flux, temperature (e.g., average) of the ground loops, the grout, and/or the ground (e.g., measured during a thermal response test). The design data may identify a coolant, antifreeze, glycol, water, brine, or any other thermal fluid (e.g., heat transfer fluid) flowing through the ground heat exchanger and/or implemented in the thermal system, including the properties of the thermal fluid.

[0096] In some embodiments, the design data includes

information relating to the GSHP. For example, the design data may identify a size, capacity, efficiency, or any other configuration of the GSHP. For instance, the design data may identify one or more values (e.g., maximum, minimum, average, and/or predicted values) for one or more of an electrical power rating and/or consumption, a thermal power rating and/or output, a heating and/or cooling capacity, an efficiency, a flow rate (e.g., of the GSHP, ground heat exchanger, or facility heat exchanger), a temperature (e.g., input, output, and/or operating temperature), or any other relevant information relating to the configuration of the GSHP (and combinations thereof).

[0097] In some embodiments, the design data includes information relating to the facility. For example, the design data may identify a size of the facility including a heating and/or cooling draw or load (e.g., average, expected, maximum, minimum, etc.). The design data may identify a location of the facility including seasonal and/or climate information about the location. The design data may identify information about the heating, ventilation, and air-conditioning (HVAC) configuration of the facility. For example, in some embodiments, the facility implements one or more devices such as the supplemental thermal devices in addition to the GSHP to provide heating and cooling. In another example, the design data may include information about the facility heat exchanger of the facility. The design data may include information relating to the facility heat exchanger, such as similar features to that described above in connection with the ground heat exchanger. In this way, the data manager may receive design data related to a design of the thermal system.

[0098] In some embodiments, the data manager receives sensor data. The sensor data may include measurements from any number of sensors included or associated with the thermal system. For example, the sensor data may include measurements associated with an operation of the thermal system. For instance, the sensor data may include a flow rate (e.g., volumetric flow rate, mass flow rate) of one or more thermal fluids in the ground heat exchanger, GSHP, and/or the facility heat exchanger. The sensor data may include one or more temperature measurements including one or more of a fluid temperature of thermal fluid(s) at one or more locations in the thermal system (e.g., flowing into, through, and/or out of one or more components, such as the refrigerant, the thermal fluid flowing into the borefield, etc.), a borehole temperature of one or more boreholes in the borefield, a ground temperature at one or more locations in the ground of the borefield, and any other temperature of any other component. The sensor data may include a fluid pressure and/or pressure differential of one or more thermal fluids at or across one or more locations in the thermal system (e.g., flowing into, through, and/or out of one or more components). The sensor data may include a measure of a thermal flux of one or more components of the thermal system, such as a thermal flux of the ground

heat exchanger, the GSHP, the facility heat exchanger, or any other component. The thermal flux may be a heat flux, heat flux density, heat flow rate intensity, or any similar measure of thermal energy flow rate.

[0099] In some embodiments, the sensor data includes a measure of an electrical power usage or consumption by one or more components of the thermal system, such as a power usage of the GSHP and/or the supplemental thermal devices. The sensor data may include one or more measurements associated with a thermal power output of the thermal system, such as a heating power and/or cooling power (e.g., kW) of one or more components of the thermal system.

[0100] In some embodiments, the sensor data includes measurements associated with the borefield. For example, the sensor data may include measurements from reservoir mapping tools, formation evaluation tools, logging while drilling (LWD) tools, and/or measurement while drilling (MWD) tools. The sensor data may include measurements from downhole sensors and surfaces sensors. For example, the sensor data may include measurements associated with a thermal response test of one or more boreholes in the borefield. The sensor data may include measurements associated with an inclinometer survey, such as measurements from accelerometers, magnetometers, gyroscopes, etc. The sensor data may include measurements from gamma ray sensors, resistivity sensors, neutron density sensors, porosity sensors, acoustic sensors, temperature sensors, pressure sensors, depth sensors, wireline tools, any other sensor, and combinations thereof. The sensor data may include data from one or more surveying tools. In some embodiments, some of the design data is received and/or is based on one or more measurements from the sensor data. In this way, the data manager may receive measurements from one or more sensors. The data manager may receive the sensor data from any sensor in communication with the thermal system.

[0101] In some embodiments, the data manager receives model data associated with one or more computer and/or software implemented models for performing one or more features of the thermal management system. For example, as described herein, the thermal management system may implement one or more models to predict, estimate, and/or determine one or more thermal parameters of the thermal system. One or more models may estimate one or more measured values (e.g., sensor data) as described herein. A model may be implemented to infer the temperature at one or more (or all) locations in the borefield (e.g., a borefield digital twin as described herein). The model data may include one or more machine learning models, deep learning models, and/or artificial intelligence (AI) models. The model data may include, forward models, inverse or reverse models, artificial neural networks, algorithms, regression models, or any other model or type of model, and combinations thereof. In some embodiments, the thermal management system implements one or more models or algorithms of

the model data by inputting data or information into the models. In some embodiments, the thermal management system calibrates, train, or tune one or more models or algorithms of the model data.

[0102] In some embodiments, the data manager receives user input. The data manager may receive the user input, for example, via any of the client devices and/or server devices. Any of the data described herein may be input or augmented via the user input. For example, in some instances, some or all of the sensor data may be received by the data manager as user input. In some instances, some or all of the design data may be received by the data manager as user input. As will be described herein, one or more functions or features of the thermal management system may be facilitated by receiving user input.

[0103] The data manager may save and/or store any of the data it receives to the data storage 130. For example, the data manager may store data associated with the design, operation, modelling, etc., of the thermal system as thermal system attribute data. The data manager may store data associated with one or more predicted values, parameters, properties, models, etc., as predicted parameter data. Any of the data in the data storage may include data received, manipulated, generated, and/or augmented by the data manager as described herein.

[0104] As mentioned above, the thermal management system includes a model engine. The model engine may implement a thermal model including a forward model and an inverted model. In some embodiments, the model engine receives the thermal model, such as by accessing the model data. In some embodiments, the model engine generates, calibrates, and/or trains the thermal model.

[0105] The thermal model may include a forward model. The forward model may be a physical model of the ground heat exchanger. For example, the forward model may be a computational tool that simulates and/or predicts the thermal behavior of the borefield, the ground, the boreholes, etc. The forward model may receive (or may be based on) one or more parameters, and based on receiving one or more inputs, the forward model may predict or estimate one or more output values. In this way, the forward model may provide a detailed representation of the thermal response of the ground heat exchanger due to heat transfer.

[0106] In some embodiments, the forward model receives (or is based on) one or more borefield design parameters. The borefield design parameters may include information related to the one or more boreholes of the borefield, such as a trajectory, length, diameter, location, position, layout, configuration, etc., of the boreholes. The borefield design parameters may include any of the design data related to the borefield as described herein.

[0107] In some embodiments, the forward model receives (or is based on) one or more completion design parameters. The completion design parameters may include information related to the completion of the boreholes of the borefield, such as a diameter, configuration,

length, arrangement, shank spacing, etc., of the ground loops. The completion design parameters may include thermal properties of the ground loops and/or of the thermal fluid circulated in the ground loops.

[0108] In some embodiments, the forward model receives (or is based on) one or more initial conditions, such as initial borefield parameters. The initial borefield parameters may include information related to one or more properties of the borefield, such as an initial thermal conductivity of the ground, an initial thermal conductivity of the grout, and/or an initial average temperature of the ground. One or more of the initial borefield parameters may be initial conditions in that they may be initial starting points or estimates of the borefield parameters for use in simulating the thermal response with the forward model (e.g., to output the predicted thermal values). As described below, one or more of the initial borefield parameters may be variables that may be manipulated or changed through implementation of the inverted model in order to determine one or more of the predicted borefield parameters.

[0109] The forward model may receive (or may be based on) any other parameter. For example, the forward model may receive one or more boundary conditions such as an ambient air temperature, heat pump condition (e.g., compressor and/or evaporator temperature), heat pump state (e.g., on/off), or any other factor that may influence the heat transfer process. The borefield design parameters and/or the completion design parameters may include information from the thermal system attribute data. In some embodiments, the borefield design parameters and/or the completion design parameters may be static inputs and, as just mentioned, one or more of the initial borefield parameters may be variables.

[0110] In some embodiments, the forward model receives one or more dynamic inputs, or measurement inputs. The measurement inputs may be associated with a flow of the thermal fluid through the ground heat exchanger. For example, the forward model may receive a thermal flux input. The thermal flux input may be a measure of a rate of energy transferred between the thermal fluid and the ground as a result of the thermal fluid flowing through the ground loops (e.g., energy per unit area per unit time, W/m^2). The thermal flux input may be measured at one or more locations of the ground heat exchanger, and may be part of the sensor data.

[0111] In some embodiments, the measurement inputs include a flowrate input. The flowrate input may include a volumetric flow rate and/or a mass flow rate of the thermal fluid flowing through the ground heat exchanger. The flowrate input may be measured at one or more locations of the ground heat exchanger, and may be part of the sensor data.

[0112] The forward model being based on the borefield design parameters, the completion design parameters, and the initial borefield parameters in this way may facilitate accurately simulating the heat transfer processes of the thermal system (e.g., due to the inputs). For example,

the forward model may account for factors such as geophysical properties of the ground, the configuration of the borefield, and operational parameters of the GSHP. The forward model may implement numerical techniques for capturing the interplay between one or more of the inputs and/or parameters in order to accurately characterize the thermal response of the ground heat exchanger. For example, the forward model may incorporate mathematical heat transfer equations, such as a g-function, that describe conductive, convective, radiative, and/or advective heat transfer within the thermal system, as well as the transient nature of heat transfer at changing temperatures. The forward model may implement numerical calculations, finite element analyses, or any other techniques for modeling and solving the heat transfer of the thermal system.

[0113] In this way, the forward model may model the temperature distribution and variation within the ground over one or more discrete time intervals in response to a thermal rejection to (or thermal extraction from) the ground by the thermal fluid and/or the ground loops. For example, the forward model may include or may be based on robust heat transfer dynamics and/or equations that capture faster transients within the thermal system. In these situations, the forward model may implement time intervals, such as every 1-5 minutes to simulate a more detailed or faster thermal response of the thermal system. In another example, the forward model may include or may be based on more general or balanced thermodynamics and may accordingly implement longer time intervals, such as every 1-5 hours to simulate a more general thermal response or equilibrium of the thermal system over a longer time period.

[0114] In some embodiments, the forward model outputs or predicts one or more predicted thermal values. The predicted thermal values may include predicted values associated with the thermal fluid, such as a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger, a predicted pressure drop of the thermal fluid at or across one or more locations of the ground heat exchanger. The predicted thermal values may include predicted values associated with the ground, such as a predicted temperature at one or more locations of the ground. In some embodiments, the predicted thermal values are values or parameters of the thermal system that will or can be measured or observed. For example, the predicted thermal values output by the forward model may correspond and may be compared to one or more actual, measured thermal values, such as a measured fluid inlet temperature, measured fluid outlet temperature, measured fluid pressure drop, etc.. This may facilitate calibrating, tuning, or training the thermal model, as described herein. The predicted thermal values may include any other value that may be predicted by the forward model consistent with that described herein. In this way, the forward model may characterize the thermal

behavior of the ground heat exchanger in order to predict one or more observable values of the thermal system. The model engine may store any of the predicted thermal values to the data storage as predicted parameter data.

[0115] As mentioned, the thermal model may include an inverted model. The inverted model may facilitate estimating or predicting one or more of the parameters upon which the forward model is based. In this way, the inverted model may be an inversion or a reversal of the forward model. For example, the forward model may predict, based on the model parameters, one or more values of the thermal system, and the inverted model may facilitate finding the set of model parameters (e.g., in particular borefield parameters) that result in predicted values that best match actual measured values of the thermal system.

[0116] For example, as mentioned, the forward model may determine one or more predicted thermal values associated with the thermal system based on a set of initial borefield parameters (among other factors). As described, the data manager may receive sensor data including the measured thermal values. In some embodiments, the inverted model compares the predicted thermal values to the measured thermal values. For example, the inverted model may include or may define an objective function or cost function that quantifies a target difference between one or more of the predicted thermal values and the measured thermal values for the set of parameters used by the forward model (e.g., used for a given iteration performed by the forward model). In some embodiments, the inverted model finds the set of parameters that minimizes this target difference. For example, the inverted model may iteratively adjust or modify one or more (or all) of the initial borefield parameters in order to iteratively change or modify the predicted thermal values that the forward model outputs.

[0117] In some embodiments, the inverted model includes or defines an optimization algorithm or engine in order to find the best-fit values for the initial borefield parameters. For example, the inverted model may try and/or modify different combinations of the initial borefield parameters to yield a sufficient or desirable target difference. In some embodiments, the inverted model functions iteratively in this way until a convergence occurs for the target difference. For example, the inverted model may iterate until the target difference is within a predetermined threshold, such as substantially 0. In another example, the inverted model may iterate until a change in the target difference is within a predetermined threshold (e.g., for a threshold quantity of consecutive iterations). In another example, the inverted model may iterate until a minimum (or least) target difference is found, such as by iterating through a predetermined quantity of (or all) iterations.

[0118] In this way, the inverted model may iteratively generate the predicted thermal values and compare those values to the measured thermal values in order to determine a set of best-fit borefield parameters. The

inverted model may output these best-fit parameters as predicted borefield parameters. For example, the predicted borefield parameters may include a ground thermal conductivity (k) and a grout thermal conductivity (kg).

5 The predicted borefield parameters may include an average temperature (T_0) of the ground and/or a current temperature (T) of the ground in one or more locations of the ground in the neighborhood of the borefield. The average temperature T_0 may be an average far-field or undisturbed ground temperature. The borefield parameters may be associated with one or more depths within the ground, or may be associated with the ground heat exchanger generally (e.g., an average). In this way, the predicted borefield parameters may represent an inference of one or more properties or parameters of the ground heat exchanger. In some embodiments, determining (e.g., measuring) an actual value of one or more of the predicted borefield parameters may not be possible, may be prohibitively difficult or not feasible, or may be cumbersome in practice. By inferring the predicted borefield parameters in this way, the thermal model may facilitate understanding a state, change, condition, etc., of one or more of the thermal properties of the thermal system which may otherwise not be known. As discussed herein, generating the predicted borefield parameters may facilitate monitoring, analyzing, and/or controlling one or more aspects of the thermal system. The model engine may store any of the predicted borefield parameters to the data storage as predicted parameter data.

[0119] The thermal model may be implemented in order to determine the predicted borefield parameters. In some embodiments, the thermal model iteratively and/or continuously determines the predicted borefield parameters. For example, the thermal model may update the predicted borefield parameters one or more times over a predetermined time interval. For instance, the thermal model may receive the inputs (e.g., thermal flux input and/or flowrate input) at discrete time intervals such as every 1 minute, 2 minutes, 3 minutes, 4 minutes, 5 minutes, or up to every 1 hour, 2 hours, 3 hours, or more. The inputs may include an actual measured value and/or may include a statistical value such as an average, mean, median, mode, maximum, minimum, etc., calculated over several time intervals. In this way, the thermal model may receive the inputs as live or real-time data inputs. The thermal model may accordingly update the predicted borefield parameters in real time based on the live data inputs. In this way, the thermal model may facilitate a real-time estimation or inference of the predicted borefield parameters to simulate changes in the thermal response over predetermined time intervals based on heat extracted or injected by the GSHP.

[0120] The thermal model functioning based on the inputs and parameters discussed above, in this way, may facilitate determining the predicted borefield parameters during operation of the thermal system and/or the GSHP. For example, the borefield design parameters

and the completion design parameters may include static values that may be known or calculated, for example, based on the design, construction, etc., of the thermal system. Additionally, the thermal flux input and the flow-rate input may include values and/or may be calculated from values that are received and/or measured by the data manager during operation of the thermal system, such as with temperature sensors, flow sensors, pressure sensors, etc. The predicted borefield parameters may accordingly be determined during operation of the thermal system based on this information that is known and/or collected during operations. In this way, the thermal management system may provide the features and functionalities discussed herein without having to put the thermal system offline.

[0121] In some embodiments, the model engine utilizes the predicted borefield parameters to generate and/or implement a digital twin. The digital twin may be a digital representation of one or more aspects of the ground heat exchanger and/or the borefield. For example, based on the predicted borefield parameters, the digital twin may infer one or more other parameters, properties, and/or states of the thermal system.

[0122] In some embodiments, the digital twin indicates a temperature of the borefield and/or the ground at one or more locations. For example, given the known geometry and configuration of the ground heat exchanger, as well as the flow measurements of the thermal fluid, and by incorporating the thermal properties of the ground (e.g., the predicted borefield parameters) the model engine may generate a detailed temperature map of the borefield. The digital twin may indicate one or more temperatures with respect to a (e.g., 2- or 3-dimensional) spatial coordinate. For example, the model engine may generate a 2- or 3-dimensional grid consisting of individual cells associated with a specific location in the borefield. The size and/or quantity of cells may vary depending on a desired level of detail for the digital twin. For each cell in the grid, the model engine may determine a temperature based on a physical modelling of the heat transfer to that location by implementing heat transfer equations and/or numerical methods (e.g., similar to that used in connection with the forward model). The model engine may incorporate lithology data for the ground, data from thermal response tests, laboratory testing, or any other data such as data from the thermal system attribute data. In some embodiments the model engine implements one or more methods of interpolation for estimating temperatures at the boundaries of cells of the grid and/or between cells. In this way, a continuous temperature field may be generated for an area of interest (or all of) the borefield via the digital twin.

[0123] In some embodiments, the model engine generates a plot, or a visual representation of the digital twin. For example, the model engine may implement color mapping or shading to represent different temperatures of the temperature field in order to generate a 2- or 3-dimensional temperature map of the borefield. In some

embodiments, the model engine displays the digital twin via a graphical user interface. In this way, the digital twin may be visually represented and presented in order that a user may analyze and/or interpret the inferred temperatures of the borefield.

[0124] In this way, the thermal management system may facilitate inferring the temperature at any point in the ground based on the digital twin. This detailed and real-time overview of the ground temperature may facilitate efficiently and/or effectively operating the thermal system. For example, as will be discussed herein in detail, the thermal management system may monitor the digital twin to maintain the ground temperature at or above a threshold level. The digital twin may be especially advantageous in situations where the ground heat exchanger has a complex configuration or geometry, such as having one or more inclined boreholes. Such geometries may result in temperature gradients and/or heat transfer that is not uniform over different depths within the ground, making it especially difficult to discern the temperature at one or more locations. The digital twin may incorporate the design (e.g., geometry) of the ground heat exchanger in order to accurately infer the temperature at every location in the ground irrespective of the complexity of the design. In this way, the model engine may facilitate inferring valuable temperature data for the ground heat exchanger via the digital twin. The model engine may store and/or update the digital twin to the data storage as the predicted parameter data.

[0125] As mentioned above, the thermal management system includes a validation manager. The validation manager may facilitate validating the thermal model (and the digital twin) by validating the predicted borefield parameters generated by the thermal model.

[0126] As mentioned, the thermal model may predict one or more thermal values as an intermediate for predicting the borefield parameters. The validation manager may validate the accuracy of the borefield parameters, and therefore the thermal model, by comparing the predicted thermal values to equivalent real-world measurements for the thermal values. The example validation illustrates an example comparison of a predicted and measured outlet temperature.

[0127] In some embodiments, a set of predicted borefield parameters are applied to the forward model after being determined by the inverted model. For example, the model engine may hold the predicted borefield parameters constant over a validation period of operation of the thermal system, and the forward model may determine the predicted thermal values based on those (constant) predicted borefield parameters for the duration of the validation period. In some embodiments, the validation manager monitors the predicted thermal values (e.g., outlet temperature) over the validation period and compares the predicted thermal values (e.g., predicted outlet temperature) to the associated measured values over the validation period. For example, the comparison illustrates the predicted vs measured outlet temperature over

the course of several days and months.

[0128] In some embodiments, the validation manager determines an error between the predicted value and the measured values for one or more time periods (e.g., hours) over the course of the validation period. Based on the error, the validation manager may determine a statistical distribution (e.g., normal distribution) including one or more statistical values such as a mean, median, mode, average, maximum, minimum, standard deviation, variance, etc. The validation manager may accordingly determine whether the predicted borefield parameters are accurate and/or precise based on this comparison and analysis.

[0129] Based on the accuracy of the predicted borefield parameters (e.g., held constant over the measurement period), the validation manager may accordingly determine whether the thermal model is accurate and/or precise. For example, the error for the outlet temperature may have an average close to 0.0 °C with a standard deviation grouping the data tightly therewith. This may indicate that the thermal model is accordingly calibrated or trained to a high degree of accuracy, and that the predicted borefield parameters determined by the thermal model may be relied on with a high confidence. In some embodiments, the validation manager indicates this determination (and/or the error) to a user of the thermal management system, such as through a graphical user interface.

[0130] In some embodiments, the validation manager determines that the thermal model is not accurate to a sufficient degree, such as based on determined that the error has an average and/or standard deviation that is not within a threshold range. The validation manager may accordingly provide an indication of the error of the thermal model. For example, the validation manager may provide an alarm or other indication to a user of the error. In another example, the validation manager may provide an indication of which value(s) (e.g., outlet temperature, inlet temperature, etc.) are associated with the error, including one or more instances of departure between the measured and predicted values.

[0131] In this way, the validation manager may facilitate validating that the thermal model properly functions to accurately determine the predicted borefield parameters to a threshold degree. While the predicted borefield parameters have been described as being applied and/or held constant, it should be understood that this may be as part of the validation process of the thermal model, and that, once validated, the thermal model may again be implemented to adjust the predicted borefield parameters in order to accurately determine (e.g., infer) the best-fit parameters in real-time, as described herein.

[0132] As mentioned above, the thermal management system includes a thermal system controller. The thermal system controller may facilitate implementing the thermal model (more specifically the outputs of the thermal model) and/or the digital twin in a variety of advantageous ways in connection with the thermal system. For exam-

ple, the thermal system controller may monitor and/or analyze one or more aspects of the thermal system to provide valuable insights and/or overviews of the one or more aspects of the thermal system. In some embodiments, the thermal system controller facilitates controlling or operating the thermal system, for example, based on one or more of these observations.

[0133] In some embodiments, the thermal system controller monitors and tracks the thermal properties of the borefield and/or the ground by monitoring and tracking the predicted borefield parameters over time. For example, the thermal system controller may identify and/or track one or more changes in the predicted borefield parameters over time corresponding to a change in the thermal properties of the ground. For instance, a decrease or degradation of the ground thermal conductivity (k) may correspond with a decreased water level of an underground aquifer (or vice versa for an increase or improvement in the ground thermal conductivity (k)). In other examples, a decrease in the grout thermal conductivity (kg) may correspond with a degradation (e.g., due to aging, borehole conditions, etc.) of the grout.

[0134] Similarly, the thermal system controller may monitor and track any of the measured values (e.g., sensor data) and/or the predicted values over time. For example, the thermal system controller may track and/or detect a decrease in the flow rate (and/or an increase in the pressure drop) of the thermal fluid over time, which may indicate that the ground loops have become damaged or blocked. In some embodiments, the thermal system controller monitors and tracks one or more measured values against the predicted thermal values over time. For example, as discussed above in connection with the validation manager, the thermal system controller may determine and monitor the difference between one or more measured and predicted values of the thermal system. As discussed above, once calibrated, the thermal model may be relied upon with confidence to accurately predict one or more values, and the thermal system controller may monitor the difference for any significant deviation of the measured values. For example, a measured outlet temperature that deviates from that which is predicted or expected may indicate a fault (or future fault) with one or more components in the thermal system. The thermal system controller may accordingly generate an alert or otherwise indicate that a fault has occurred or will occur in the future. In this way, the thermal system controller may facilitate preventing or mitigating failures of the thermal system.

[0135] In some embodiments, the thermal system controller determines and monitors a state of charge of the ground thermal battery over time. For example, based on the temperatures indicated by the digital twin, and based on the measured thermal flux of the ground heat exchanger, the thermal system controller may determine an amount of heat energy that the thermal system is injecting into, or extracting from, the borefield and the ground. The thermal system controller may accordingly determine a

heat energy capacity for the borefield to transfer heat to or from the GSHP (e.g., via the thermal fluid). In this way, the thermal system controller may monitor the state of thermal charge of the ground, for example, between seasons, in order to forecast a capacity for the thermal system to provide heating and/or cooling during warmer or cooler (respectively) times of the year.

[0136] In some embodiments, the thermal system controller monitors the digital twin. For example, the thermal system controller may determine and track the lowest temperature at any point in the ground based on the inferences of the digital twin. This may facilitate controlling and/or operating the thermal system. For example, in many cases it may be undesirable for the ground to freeze. Freezing may reduce the thermal conductivity of the ground and therefore reduce the efficiency of the GSHP. Similarly, freezing may increase energy consumption for the GSHP to attempt to keep up with the decreased efficiency. Further, freezing and thawing cycles may risk damage or blockage to one or more components of the thermal system. Thus, it may be advantageous to prevent the ground from freezing at one or more locations.

[0137] The thermal system controller may track the minimum ground temperature (T_{gmin}) over time. When it is determined that the minimum ground temperature T_{gmin} is at or below 0°C , the thermal system controller may implement one or more measures to attempt to raise the minimum ground temperature T_{gmin} up to above freezing. For example, the thermal system controller may reduce a thermal power (e.g., reduce a flowrate or implement any other measure) of the GSHP 102 in order to slow the rate at which the GSHP removes heat from the ground. In another example, the thermal system controller may generate an alert, indication, or otherwise prompt a user to take one or more mitigating actions with respect to the minimum ground temperature T_{gmin} . The thermal system controller may act reactively in this way to the minimum ground temperature T_{gmin} in order to prevent damage, inefficiencies, or other undesirable affects resulting from the ground freezing.

[0138] In some embodiments, the thermal system controller acts proactively to prevent freezing. For example, the thermal system controller may identify one or more patterns, trajectories, or trends in the data that it monitors in order to forecast or project how the minimum ground temperature T_{gmin} will change in the future. For example, the thermal system controller may monitor and/or compare one or more (measured and/or predicted) values against the minimum ground temperature T_{gmin} in order to identify how changes in these other values (or combinations of values) may affect the minimum ground temperature T_{gmin} . Based on a forecast that the minimum ground temperature T_{gmin} will fall below 0°C , the thermal system controller may implement one or more of the mitigating measures discussed above.

[0139] While freezing may generally be undesirable, in some embodiments, freezing at one or more locations in

the ground is acceptable within a threshold amount. For example, in some embodiments, the minimum ground temperature T_{gmin} occurs at a borehole wall of one or more of the boreholes of the borefield. Accordingly, the minimum ground temperature T_{gmin} at the borehole wall may fall below freezing, but the freezing may be relatively localized to an area immediately adjacent the borehole(s). In some embodiments, the thermal system controller monitors one or more additional minimum temperatures, such as a minimum temperature at a threshold distance (e.g., radius) from or around the borehole(s). For example, a minimum temperature within a 25 cm radius (T_{g25min} from the borehole(s)) may be monitored (e.g., in addition to the minimum ground temperature T_{gmin}). While the minimum ground temperature T_{gmin} falls below 0°C , the 25 cm radius temperature T_{g25min} may remain well above 0°C , indicating that the freezing does not extend or permeate far from the borehole(s). The thermal system controller may accordingly facilitate implementing a control strategy for the thermal system that allows the minimum ground temperature T_{gmin} to fall below freezing while maintaining the 25 cm radius temperature T_{g25min} (or any other threshold distance) above freezing.

[0140] The thermal system controller may save data from any of its monitoring functions to the data storage as predicted parameter data. In some embodiments, the thermal system controller plots one or more of the values, parameters, and/or properties that it monitors and/or may present one or more plots via a graphical user interface.

[0141] In some embodiments, a method or a series of acts is disclosed for operating a thermal system implementing a ground-source heat pump as described herein, according to at least one embodiment of the present disclosure.

[0142] In some embodiments, the method includes an act of receiving design parameters associated with a design of the thermal system. For example, the design parameters may include borehole geometry data for one or more boreholes of the borefield and completion geometry data for a completion of the one or more boreholes.

[0143] In some embodiments, the method includes an act of receiving one or more measurement inputs associated with a flow of thermal fluid through a borefield of a ground heat exchanger. For example, the measurement inputs may include a flowrate of the thermal fluid through the ground heat exchanger and/or a thermal flux between the thermal fluid and the borefield.

[0144] In some embodiments, the method includes an act of, based on the measurement inputs and the design parameters, predicting one or more predicted thermal values of the thermal fluid using a forward model. For example, the predicted thermal values may include one or more of a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger, a predicted flow rate of the thermal fluid flowing through the ground heat exchanger,

and a predicted fluid pressure drop of the thermal fluid.

[0145] In some embodiments, the method includes an act of predicting one or more predicted borefield parameters of the borefield based on inverting the forward model. Inverting the forward model may include minimizing a target difference between the predicted thermal values and one or more measured thermal values (such as the temperature of the thermal fluid at the outlet of the borefield). In some embodiments, predicting the one or more predicted thermal values with the forward model and inverting the forward model to predict the one or more predicted borefield parameters are each performed in real-time during operation of the ground-source heat pump. In some embodiments, the forward model and the inversion of the forward model are validated based on predicting the one or more predicted thermal values while holding the predicted borefield parameters constant. The predicted borefield parameters may include one or more of a predicted ground thermal conductivity, a predicted grout thermal conductivity, and a predicted far-field ground temperature.

[0146] In some embodiments, the method includes an act of monitoring the thermal system based on the predicted borefield parameters. For example, a thermal management system may monitor the health of the thermal system based on tracking the predicted borefield parameters over time. In another example, the method may include generating a digital twin of the borefield by inferring a temperature at one or more locations in the borefield based on the predicted borefield parameters. Inferring the temperature may further be based on lithology data of the borefield. The thermal management system may monitor a minimum inferred temperature for any location in the borefield based on the digital twin. In another example, the thermal management system may determine a fault of the thermal system based on a deviation of one or more measured thermal values from the one or more predicted thermal values. In another example, the thermal management system may determine a thermal state of charge of the borefield. In another example, the thermal management system may predict one or more future thermal values. In some embodiment, the method includes controlling an operation of the ground source heat pump based on the predicted borefield parameters. Alternatively, a non-transitory computer-readable storage medium may include instructions that, when executed by one or more processors, cause a computing device to perform the acts of the method. In still further implementations, a system can perform the acts of the method.

[0147] The following are non-limiting examples of embodiments of the present disclosure:

1. A method of operating a thermal system implementing a ground-source heat pump, comprising:

receiving design parameters associated with a design of the thermal system;

receiving one or more measurement inputs associated with a flow of a thermal fluid through a borefield of a ground heat exchanger;
based on the measurement inputs and the design parameters, predicting one or more predicted thermal values of the thermal fluid using a forward model;
predicting one or more predicted borefield parameters of the borefield based on inverting the forward model; and
monitoring the thermal system based on the predicted borefield parameters.

2. The method of 1, wherein the design parameters include borehole geometry data for one or more boreholes of the borefield, and/or completion geometry data for a completion of the one or more boreholes.

3. The method of 1 or 2, wherein the measurement inputs include a flowrate of the thermal fluid through the ground heat exchanger and/or a thermal flux between the thermal fluid and the borefield.

4. The method of any of 1-3, wherein inverting the forward model includes minimizing a target difference between the predicted thermal values and one or more measured thermal values.

5. The method of any of 1-4, wherein the predicted thermal values include one or more of a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger, a predicted flow rate of the thermal fluid through the ground heat exchanger, and a predicted fluid pressure drop of the thermal fluid.

6. The method of any of 1-5, wherein predicting the one or more predicted thermal values with the forward model and inverting the forward model to predict the one or more predicted borefield parameters are each performed during operation of the ground-source heat pump, for instance in real-time.

7. The method of any of 1-6, further comprising validating the forward model and the inversion of the forward model based on predicting the one or more predicted thermal values while holding the predicted borefield parameters constant.

8. The method of any of 1-7, wherein monitoring the thermal system includes monitoring a health of the thermal system based on tracking the predicted borefield parameters over time.

9. The method of any of 1-8, further comprising generating a digital twin of the borefield by inferring a temperature at one or more locations in the borefield based on the predicted borefield parameters.

10. The method of 9, wherein monitoring the thermal system includes monitoring a minimum inferred temperature for any location in the borefield based on the digital twin.

11. The method of 9 or 10, wherein inferring the

temperature is further based on lithology data of the borefield.

12. The method of any of 9-11, wherein the digital twin illustrates a temperature map of the borefield.

13. The method of 12, wherein it comprises providing a visualization of the temperature map of the borefield to a user.

14. The method of any of 1-13, wherein monitoring the thermal system includes determining a fault of the thermal system based on a deviation of one or more measured thermal values from the one or more predicted thermal values.

15. The method of any of 1-14, wherein monitoring the thermal system includes determining a thermal state of charge of the borefield.

16. The method of any of 1-15, wherein monitoring the thermal system includes predicting one or more future thermal values.

17. The method of any of 1-16, further comprising controlling an operation of the ground-source heat pump based on the predicted borefield parameters.

18. The method of any of 1-17, wherein the one or more predicted borefield parameters include one or more of a predicted ground thermal conductivity, a predicted grout thermal conductivity, and a predicted far-field ground temperature.

19. A system, comprising:

at least one processor;

memory in electronic communication with the at least one processor; and

instructions stored in the memory, the instructions being executable by the at least one processor to:

receive design parameters associated with a design of the thermal system;

receive one or more measurement inputs associated with a flow of a thermal fluid through a borefield of a ground heat exchanger;

based on the measurement inputs and the design parameters, predict one or more predicted thermal values of the thermal fluid using a forward model;

predict one or more predicted borefield parameters of the borefield based on inverting the forward model; and

monitor the thermal system based on the predicted borefield parameters.

20. A computer-readable storage medium including

instructions that, when executed by at least one processor, cause the processor to:

receive design parameters associated with a design of the thermal system;

receive one or more measurement inputs associated with a flow of a thermal fluid through a borefield of a ground heat exchanger;

based on the measurement inputs and the design parameters, predict one or more predicted thermal values of the thermal fluid using a forward model;

predict one or more predicted borefield parameters of the borefield based on inverting the forward model; and

monitor the thermal system based on the predicted borefield parameters.

[0148] The embodiments of the thermal management system have been primarily described with reference to wellbore and/or borefield applications. The thermal management system described herein may be used in applications other than in association with one or more wellbores. In other embodiments, the thermal management system according to the present disclosure may be used outside of a wellbore and/or downhole environment. For instance, the thermal management system of the present disclosure may be used in connection with air-source heat pumps, water-source heat pumps, or any other thermal system, heat transfer engine, or thermal cycle. Accordingly, the terms "wellbore," "borehole" and the like should not be interpreted to limit tools, systems, assemblies, or methods of the present disclosure to any particular industry, field, or environment.

[0149] One or more specific embodiments of the present disclosure are described herein. These described embodiments are examples of the presently disclosed techniques. Additionally, in an effort to provide a concise description of these embodiments, not all features of an actual embodiment may be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous embodiment-specific decisions will be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one embodiment to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0150] Additionally, it should be understood that references to "one embodiment" or "an embodiment" of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. For example, any element described in relation to an embodiment herein may be combinable with any element of any other em-

bodiment described herein. Numbers, percentages, ratios, or other values stated herein are intended to include that value, and also other values that are "about" or "approximately" the stated value, as would be appreciated by one of ordinary skill in the art encompassed by embodiments of the present disclosure. A stated value should therefore be interpreted broadly enough to encompass values that are at least close enough to the stated value to perform a desired function or achieve a desired result. The stated values include at least the variation to be expected in a suitable manufacturing or production process, and may include values that are within 5%, within 1%, within 0.1%, or within 0.01% of a stated value.

[0151] A person having ordinary skill in the art should realize in view of the present disclosure that equivalent constructions do not depart from the spirit and scope of the present disclosure, and that various changes, substitutions, and alterations may be made to embodiments disclosed herein without departing from the spirit and scope of the present disclosure. Equivalent constructions, including functional "means-plus-function" clauses are intended to cover the structures described herein as performing the recited function, including both structural equivalents that operate in the same manner, and equivalent structures that provide the same function. It is the express intention of the applicant not to invoke means-plus-function or other functional claiming for any claim except for those in which the words 'means for' appear together with an associated function. Each addition, deletion, and modification to the embodiments that falls within the meaning and scope of the claims is to be embraced by the claims.

[0152] The terms "approximately," "about," and "substantially" as used herein represent an amount close to the stated amount that is within standard manufacturing or process tolerances, or which still performs a desired function or achieves a desired result. For example, the terms "approximately," "about," and "substantially" may refer to an amount that is within less than 5% of, within less than 1% of, within less than 0.1% of, and within less than 0.01% of a stated amount. Further, it should be understood that any directions or reference frames in the preceding description are merely relative directions or movements. For example, any references to "up" and "down" or "above" or "below" are merely descriptive of the relative position or movement of the related elements.

[0153] The present disclosure may be embodied in other specific forms without departing from its spirit or characteristics. The described embodiments are to be considered as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. Changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

Claims

1. A method of operating a thermal system (100) implementing a ground-source heat pump (102), comprising:
 - receiving design parameters associated with a design of the thermal system (100);
 - receiving one or more measurement inputs associated with a flow of a thermal fluid through a borefield (108) of a ground heat exchanger (110);
 - based on the measurement inputs and the design parameters, predicting one or more predicted thermal values (162) of the thermal fluid using a forward model (146);
 - predicting one or more predicted borefield parameters (160) of the borefield (108) based on inverting the forward model (162); and
 - monitoring the thermal system (100) based on the predicted borefield parameters (160).
2. The method of claim 1, wherein the design parameters include borehole geometry data for one or more boreholes of the borefield, and/or completion geometry data for a completion of the one or more boreholes.
3. The method of claim 1 or 2, wherein the measurement inputs include a flowrate of the thermal fluid through the ground heat exchanger and/or a thermal flux between the thermal fluid and the borefield.
4. The method of any of claims 1-3, wherein inverting the forward model includes minimizing a target difference between the predicted thermal values and one or more measured thermal values.
5. The method of any of claim 1-4, wherein the predicted thermal values include one or more of a predicted inlet temperature of the thermal fluid flowing into the ground heat exchanger, a predicted outlet temperature of the thermal fluid flowing out of the ground heat exchanger, a predicted flow rate of the thermal fluid through the ground heat exchanger, and a predicted fluid pressure drop of the thermal fluid.
6. The method of any of claims 1-5, wherein predicting the one or more predicted thermal values with the forward model and inverting the forward model to predict the one or more predicted borefield parameters are each performed during operation of the ground-source heat pump.
7. The method of any of claims 1-6, wherein the one or more predicted borefield parameters includes one or more of a predicted ground thermal conductivity, a

predicted grout thermal conductivity, and a predicted far-field ground temperature.

8. The method of any of claims 1-7, wherein monitoring the thermal system includes monitoring a health of the thermal system based on tracking the predicted borefield parameters over time. 5
9. The method of any of claims 1-8, further comprising generating a digital twin of the borefield by inferring a temperature at one or more locations in the borefield based on the predicted borefield parameters. 10
10. The method of claim 9, wherein monitoring the thermal system includes monitoring a minimum inferred temperature for any location in the borefield based on the digital twin. 15
11. The method of claim 9 or 10, wherein inferring the temperature is further based on lithology data of the borefield. 20
12. The method of any of claims 1-11, wherein monitoring the thermal system includes determining a fault of the thermal system based on a deviation of one or more measured thermal values from the one or more predicted thermal values. 25
13. The method of any of claims 1-12, wherein monitoring the thermal system includes predicting one or more future thermal values. 30
14. The method of any of claims 1-13, further comprising controlling an operation of the ground-source heat pump based on the predicted borefield parameters. 35
15. A system, comprising:
 - at least one processor;
 - memory in electronic communication with the at least one processor; and 40
 - instructions stored in the memory, the instructions being executable by the at least one processor to:
 - receive design parameters associated with a design of the thermal system;
 - receive one or more measurement inputs associated with a flow of a thermal fluid through a borefield of a ground heat exchanger; 50
 - based on the measurement inputs and the design parameters, predict one or more predicted thermal values of the thermal fluid using a forward model; 55
 - predict one or more predicted borefield parameters of the borefield based on inverting the forward model; and

monitor the thermal system based on the predicted borefield parameters.

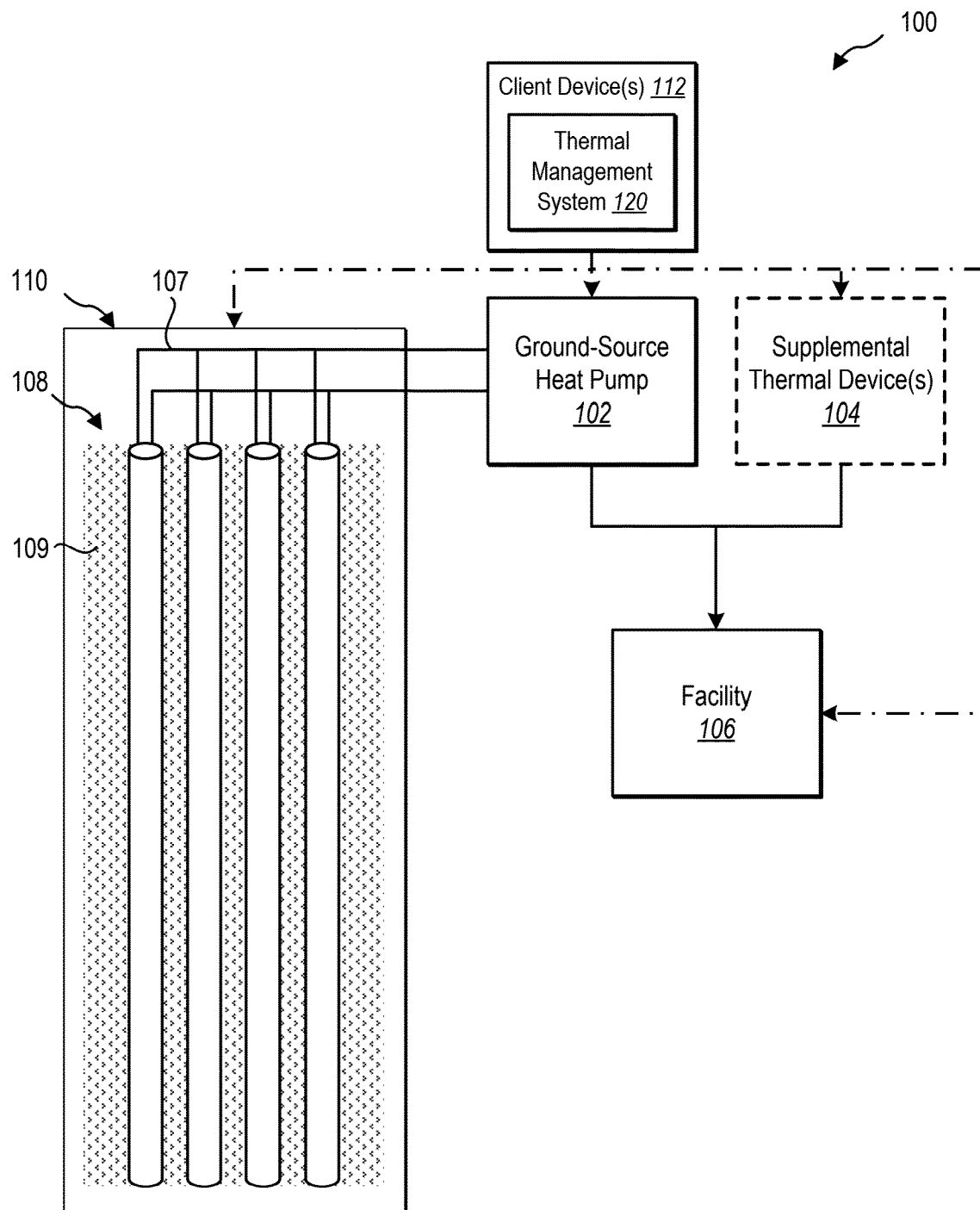


FIG. 1

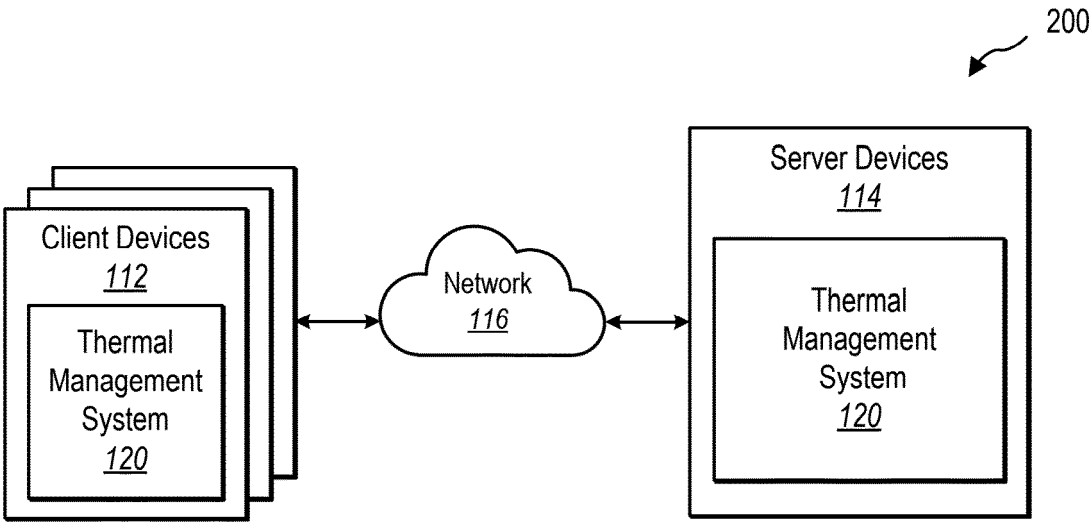


FIG. 2

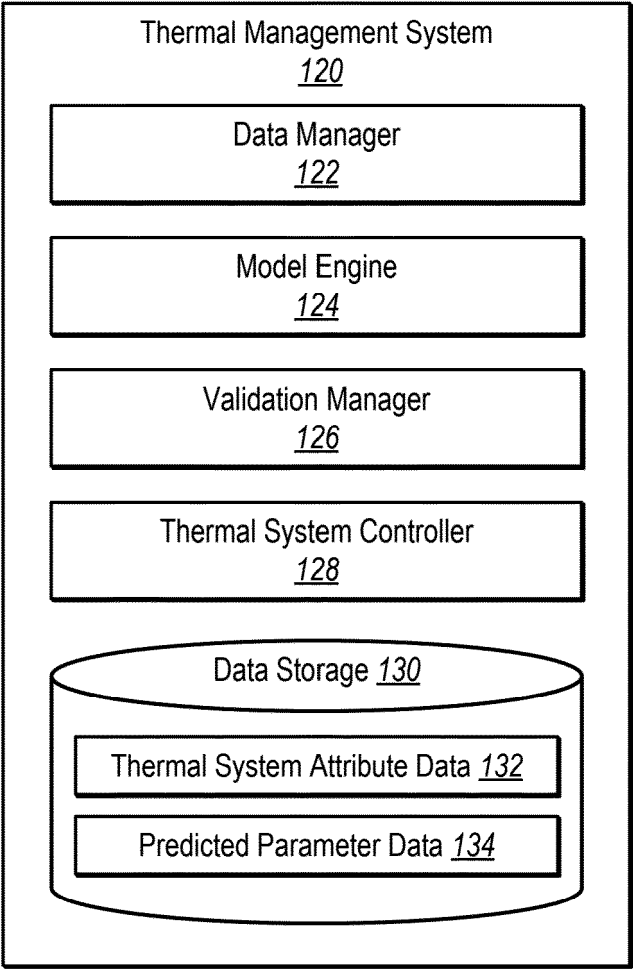


FIG. 3

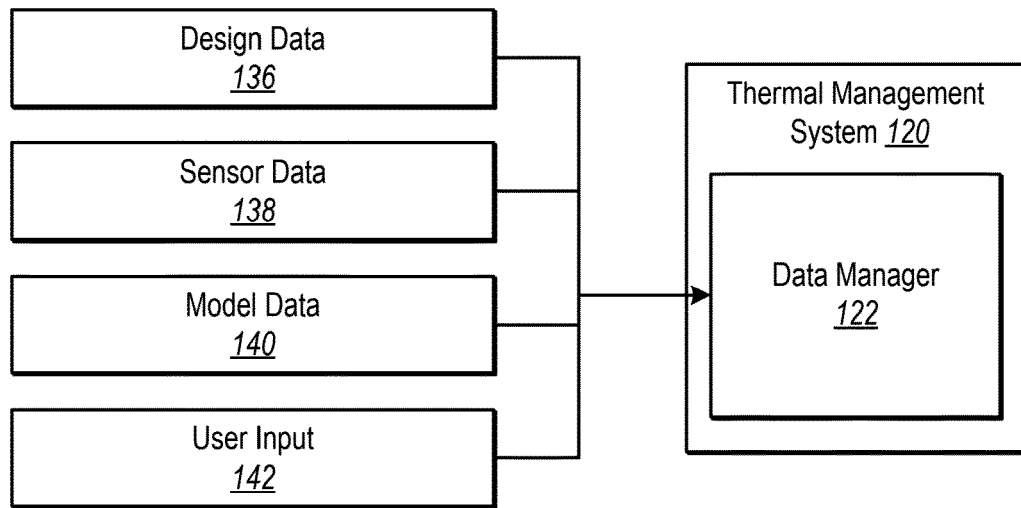


FIG. 4

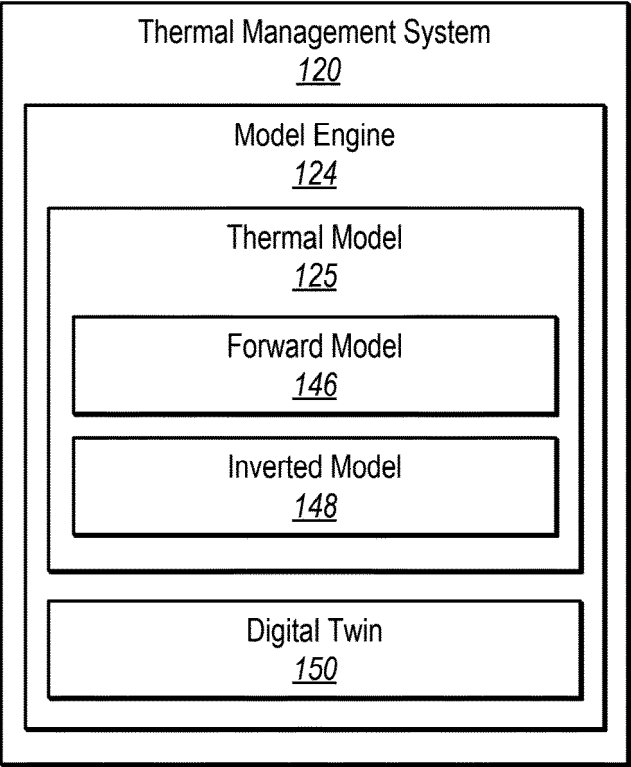
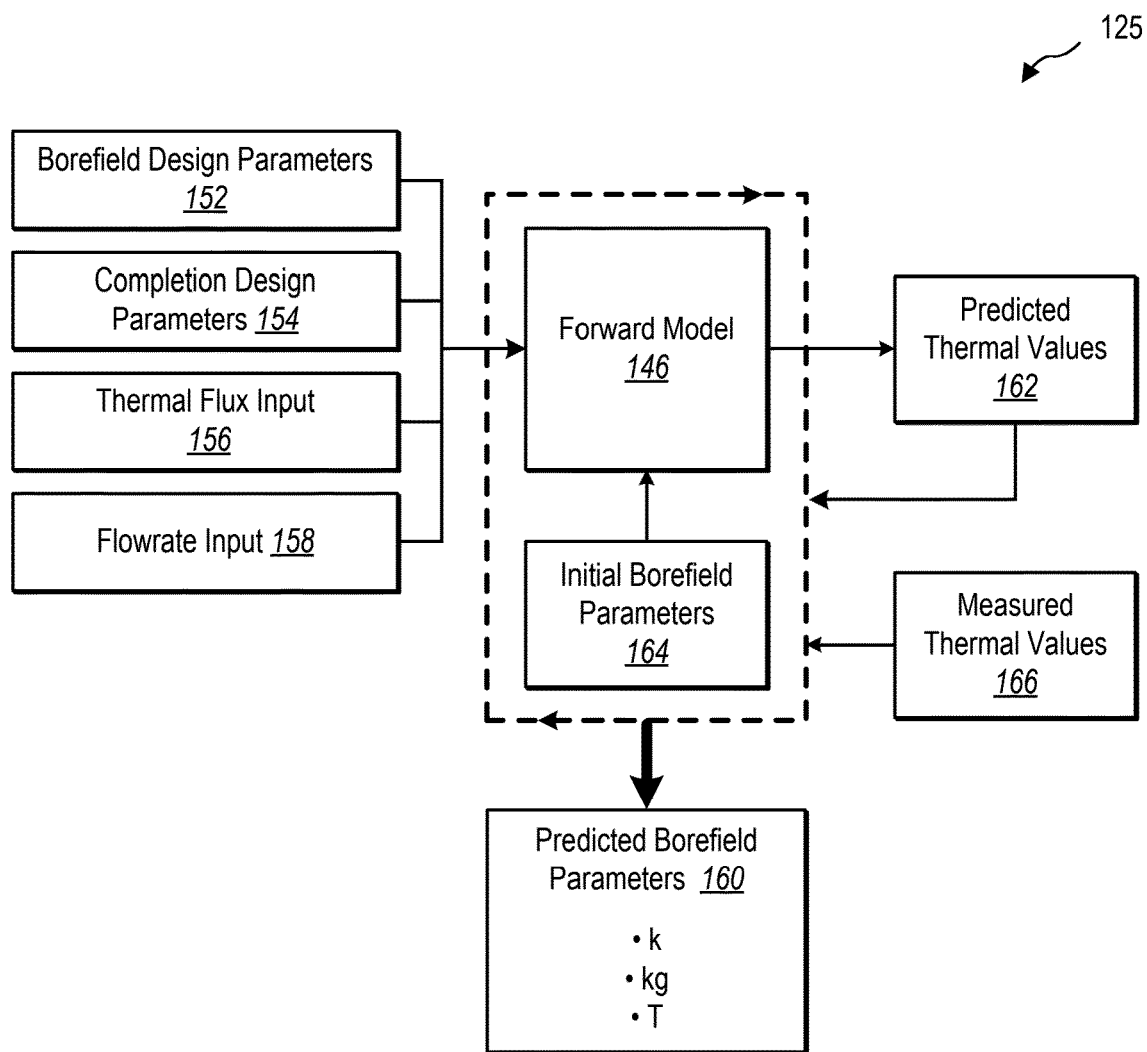


FIG. 5

**FIG. 6**

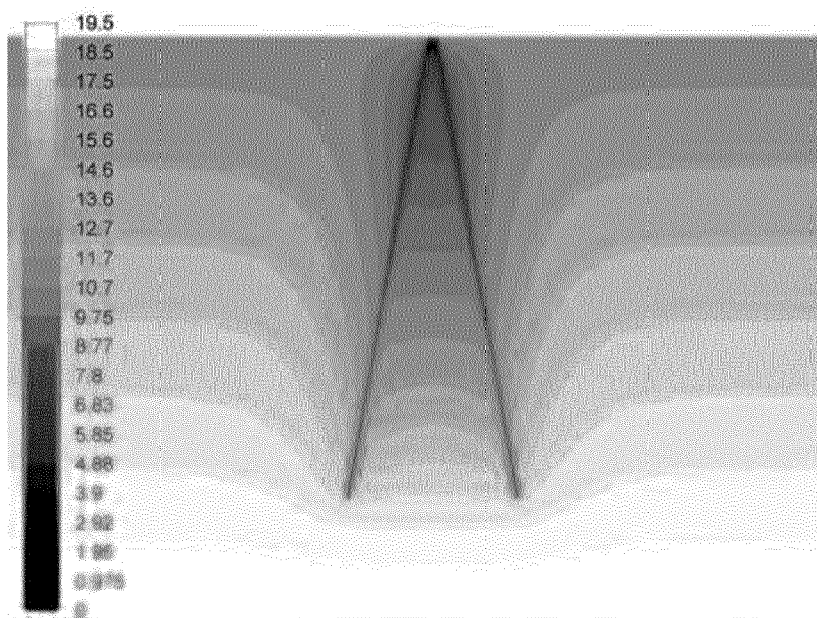
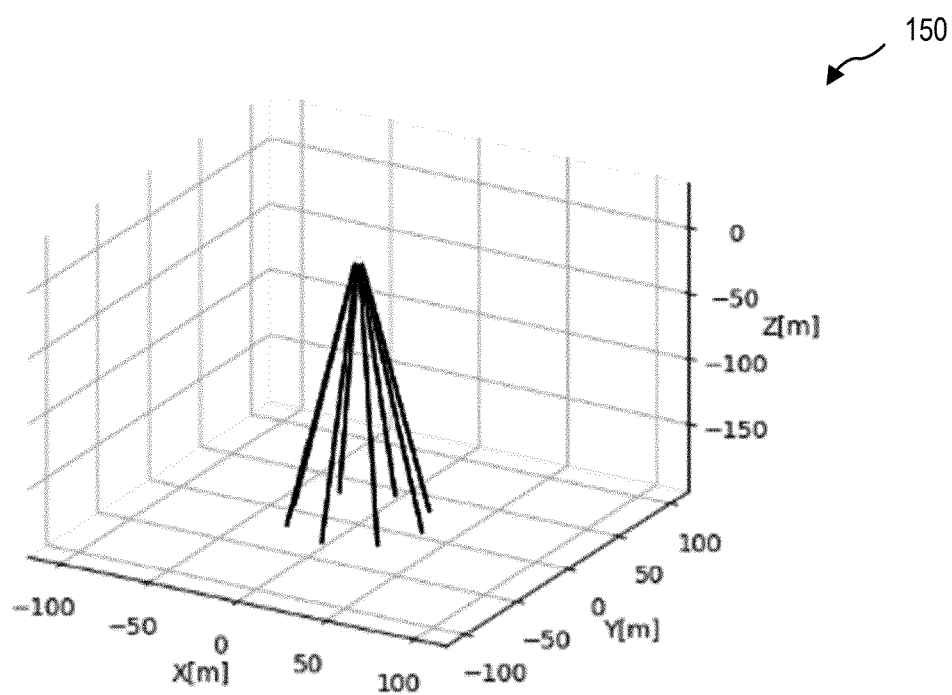


FIG. 7

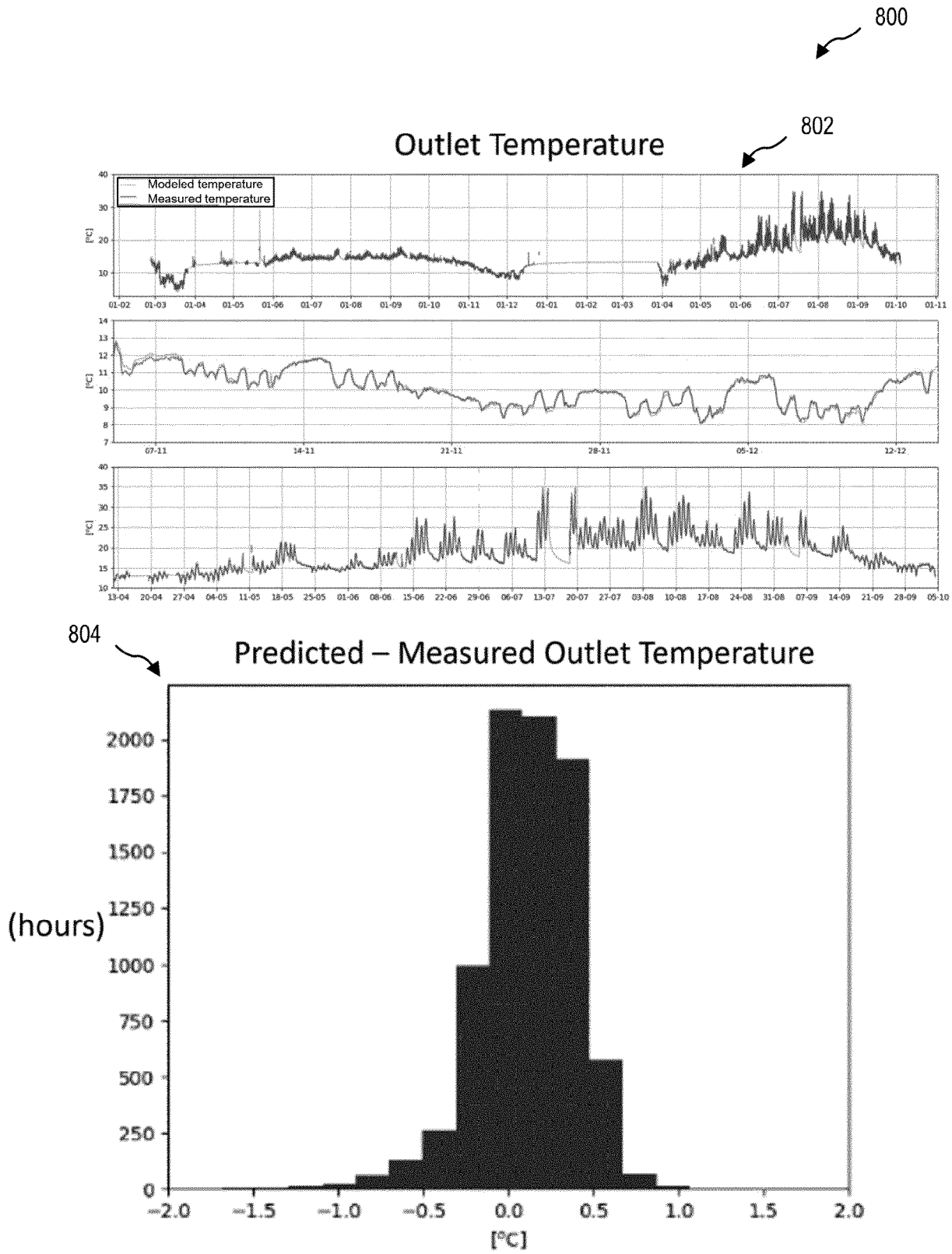
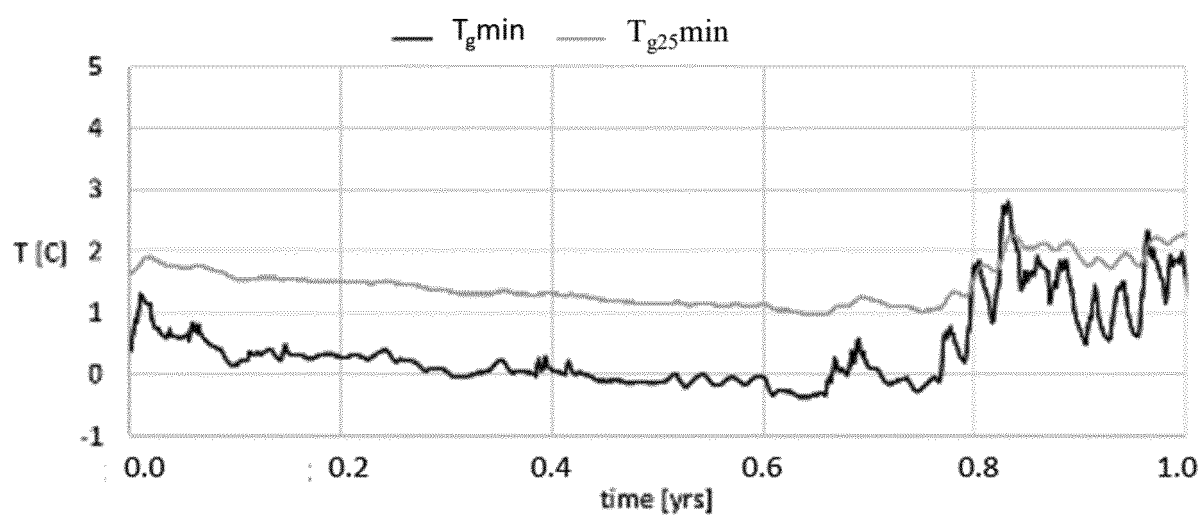
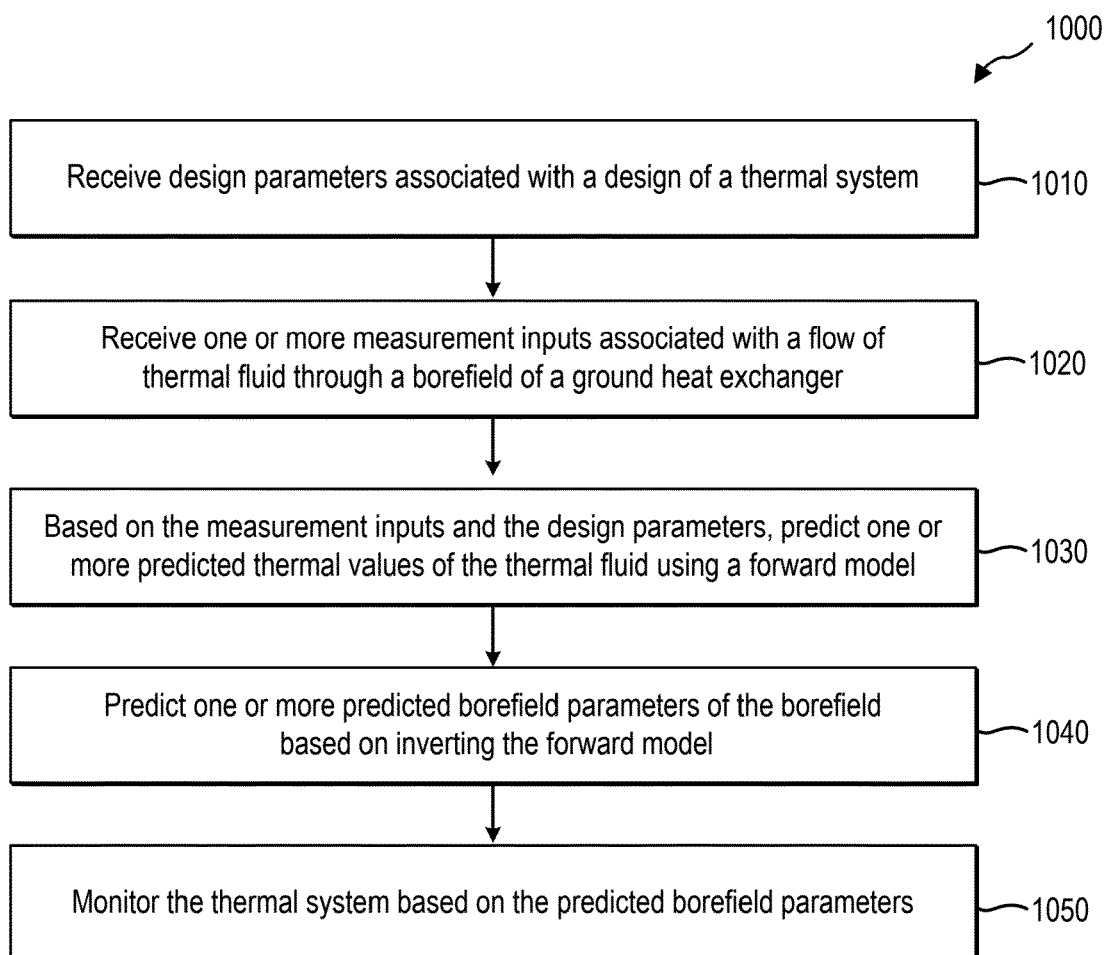


FIG. 8

**FIG. 9**

**FIG. 10**

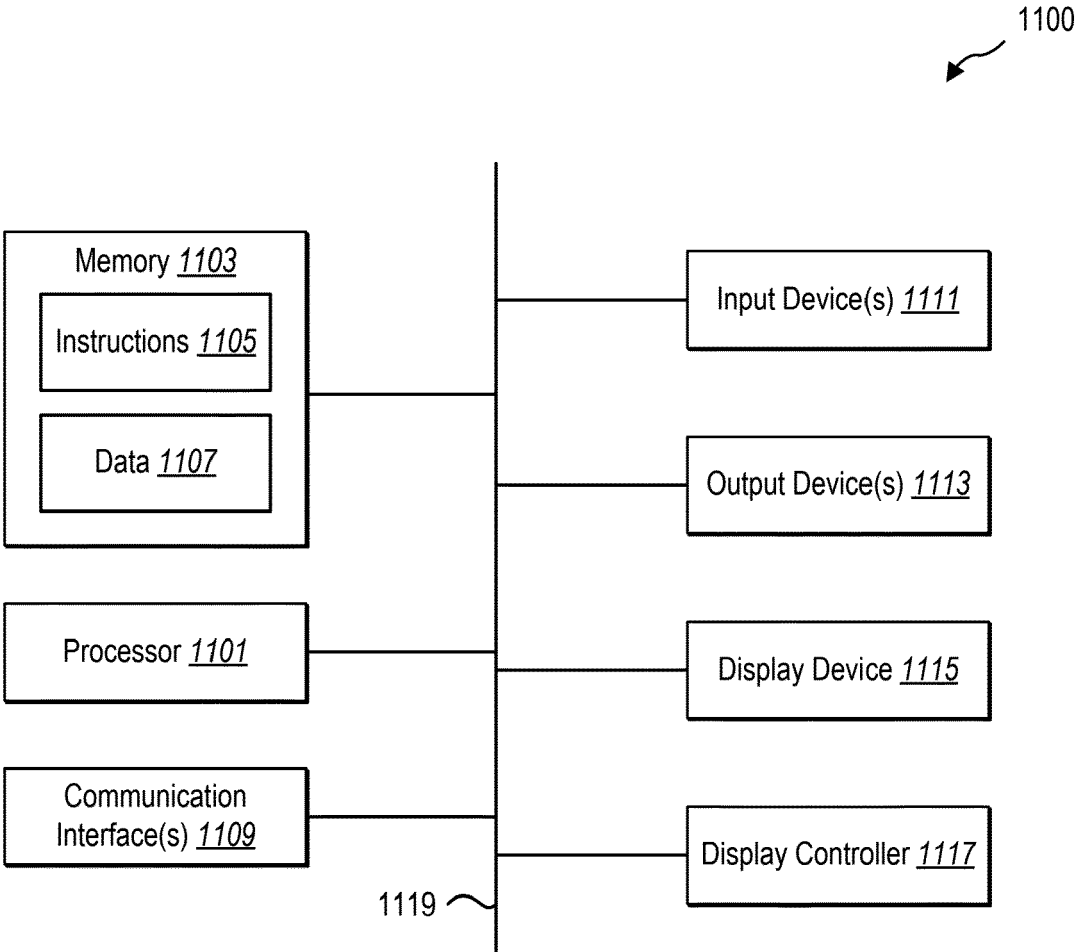


FIG. 11



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