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(54) MODULAR WATER HEATING AND TANK SYSTEM MANAGEMENT

(57) A water heating system includes a storage tank, at least one heating unit, and a control system. The storage tank includes a recirculation supply port, a return port arranged above the recirculation supply port, and a tank temperature sensor arranged between the recirculation supply port and the return port in a vertical direction. The at least one heating unit includes a water inlet port fluidly coupled to the recirculation supply port and a water outlet port fluidly coupled to the return port. The control system is configured to receive a signal from the tank temperature sensor indicative of a temperature of water in the storage tank, determine a need for heating based on the signal, activate the at least one heating unit to draw water from the storage tank, heat the water, return the heated water to the storage tank, and reduce a rate at which the water is heated.

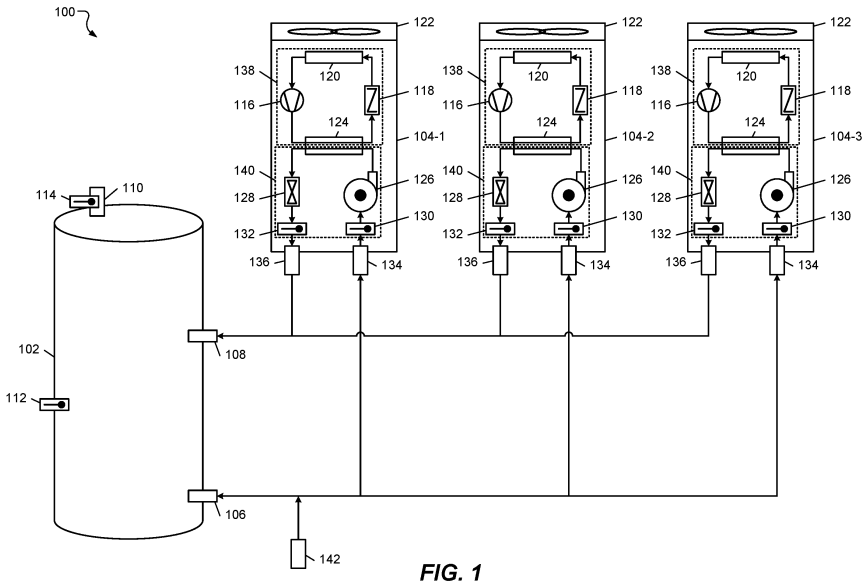


FIG. 1

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Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/587,495 filed October 3, 2023. The entire disclosure of the above application is incorporated by reference.

FIELD

[0002] The present disclosure relates to water heating systems and, more particularly, to control systems for modular water heater systems.

SUMMARY

[0003] Heat pump water heater systems operate on the principle of moving heat from an external environment to water within the system, rather than generating heat directly through combustion or electrical resistance and transferring the generated heat to the water. Heat pump heater units - which form a part of heat pump water heater systems - use a refrigeration cycle to extract heat from an external source (such as the ambient atmosphere, the ground, or an external water source) and transfer the extracted heat into water in the system. Because heat pump heater units move heat rather than generating heat directly, they may use less electricity than traditional electric resistance water heater units for the same volume of hot water produced. For example, while traditional electric resistance water heater units may convert nearly 100% of the electrical energy they consume into heat, they must create substantially all of this heat, which can require a significant amount of energy. By contrast, in a heat pump water heater system, heat pump heater units use a relatively small amount of electrical energy to move heat from the external environment into the water in the system. Because it generally requires less energy to move heat than to create it, heat pump water heater systems can be significantly more energy efficient than conventional systems.

[0004] While heat pump water heater systems are energy efficient, there can be a variety of technical challenges associated with designing such systems - particularly in larger-scale commercial applications. For example, commercial applications often have highly variable hot water demands. Thus, commercial heat pump water heater systems may have a modular design, and may also include a variable number of water storage tanks paired with a variable number of heat pump heater units, depending on the particular requirements of the individual application. Given the potential complexity and variability of commercial heat pump water heater systems, managing and coordinating multiple heat pump heater units so that they work together seamlessly and efficiently can be a complex and technically challenging task. For example, the control systems should effectively regulate when each heat pump heater unit operates while avoiding short cycling individual units and maintaining consistent water temperatures in the system. Furthermore, for commercial applications with high levels of hot water demand, control systems should effectively regulate the operation of the heater units to allow the system to keep up with both high- and low-demand scenarios while maximizing the overall efficiency of the system.

[0005] In some modular applications, the water storage tank can be paired with one or more heat pump heater units. Cold water may be drawn from the bottom of the tank, routed through the heat pump heater units (which move heat from the external environment into the water), and returned to top of the tank at a higher temperature. When there is demand for hot water, the heated water may be drawn from the top of the tank. This water may then be replaced with new cold water (typically at the bottom of the tank) from a water supply. The new cold water may then be routed through the heat pump heater units, which move additional heat from the external environment into the new cold water. In such systems, at least a portion of the water within the water storage tank may be below the desired temperature. If not properly managed, this can have negative effects on the overall thermal efficiency of the system.

[0006] Heat pump water heater systems described in this specification address these technical challenges by being modular and scalable across a wide range of applications. Furthermore, heat pump water heater systems described in this specification include control systems that automatically adapt to and account for the variety of operating conditions such scalable heat pump water systems may encounter, all the while optimizing the efficiency of the systems under many operating conditions.

[0007] A water heating system includes a storage tank, at least one heating unit, and a control system. The storage tank includes a recirculation supply port, a return port arranged above the recirculation supply port in a vertical direction, and a tank temperature sensor arranged between the recirculation supply port and the return port in the vertical direction. The at least one heating unit includes a water inlet port and a water outlet port. The water inlet port is fluidly coupled to the recirculation supply port. The water outlet port is fluidly coupled to the return port. The control system is communicatively coupled to the tank temperature sensor and the at least one heating unit. The control system is configured to receive a signal from the tank temperature sensor indicative of a temperature of water in the storage tank at a location of the tank temperature sensor, determine a need for heating based on the signal received from the tank temperature sensor, activate the at least one heating unit to draw water from the storage tank by way of the recirculation supply port in response to determining the need for heating, heat the water, return the heated water to the storage tank by way of the return port, and reduce a rate at which the water is heated in response to determin-

ing that a first criterion and a second criterion have been met.

[0008] In other features, reducing the rate at which the water is heated comprises stopping operation of the at least one heating unit. In other features, the at least one heating unit is a heat pump heating unit. In other features, the control system is configured to determine that the need for heating is caused by one of a draw demand and a standby loss. In other features, the at least one heating unit includes an inlet water temperature sensor arranged to measure a temperature of water entering the water inlet port and an outlet water temperature sensor arranged to measure a temperature of water exiting the water outlet port. The inlet water temperature sensor and the outlet water temperature sensor are communicatively coupled to the control system. The control system is configured to determine that the first criterion and the second criterion have been met based on signals received from the inlet water temperature sensor and the outlet water temperature sensor.

[0009] In other features, the control system is configured to determine that one of the first and second criterion have been met by comparing the temperature of water exiting the water outlet port to a predetermined temperature limit. In other features, the control system is configured to determine that the other of the first and second criterion has been met by comparing the temperature of water entering the water inlet port to a predetermined temperature limit. In other features, the at least one heating unit is one of a plurality of such heating units connected fluidly in parallel with one another to the recirculation supply port and the water outlet port. The control system is configured to determine which one of the plurality of heating units to activate in response to determining the need for heating.

[0010] In other features, after activating one of the plurality of heating units in response to determining the need for heating, the control system is further configured to receive temperature signals from the tank temperature sensor over a period of time, determine that an increased rate of heating is desired based on the temperature signals, and increase the rate of heating by the plurality of heating units in response to determining that the increased rate of heating is desired. In other features, the control system is configured to increase the rate of heating by activating another one of the plurality of heating units to draw water from the storage tank by way of the recirculation supply port, heat the water, and return the heated water to the storage tank by way of the return port. In other features, the control system is configured to determine that an increased rate of heating is desired at least in part by determining that a temperature change of water at the location of the tank temperature sensor over the period of time is below a threshold.

[0011] A method for controlling a water heating system includes receiving a signal from a tank temperature sensor indicative of a temperature of a fluid in a storage tank at a location of the tank temperature sensor, determining a need for heating based on the signal received from the tank temperature sensor, activating at least one heating unit to draw fluid from the storage tank in response to determining the need for heating, and reducing a rate at which the water is heated in response to determining that a first criterion and a second criterion have been met.

[0012] In other features, reducing the rate at which the water is heated includes stopping operation of the at least one heating unit. In other features, the method includes determining that the need for heating is caused by one of a draw demand and a standby loss. In other features, the method includes determining that the first criterion and the second criterion have been met based on signals received from an inlet water temperature sensor of the at least one heating unit and an outlet water temperature sensor of the at least one heating unit. In other features, determining that one of the first and second criterion has been met includes comparing a temperature of water exiting a water outlet port of the at least one heating unit to a predetermined temperature limit. In other features, determining that the other of the first and second criterion has been met includes comparing a temperature of water entering a water inlet port of the at least one heating unit to a predetermined temperature limit.

[0013] In other features, the at least one heating unit includes a plurality of heating units fluidly connected in parallel and activating the at least one heating unit to draw water from the storage tank includes determining which one of the plurality of heating units to activate. In other features, the method includes, after activating one of the plurality of heating units, receiving temperature signals from the tank temperature sensor over a period of time, determining that an increased rate of heating is desired based on the received temperature signals, and increasing the rate of heating by the plurality of heating units in response to determining that the increased rate of heating is desired. In other features, the method includes increasing the rate of heating by activating another one of the plurality of heating units to draw water from the storage tank and return heated water to the storage tank, and determining that an increased rate of heating is desired at least in part by determining that a temperature change of fluid at the location of the tank temperature over the period of time is below a threshold.

[0014] An apparatus for controlling a water heating system includes an electronic controller operatively coupled to a tank temperature sensor positioned at a vertical location in a tank. The electronic controller is configured to receive a signal from the tank temperature sensor, determine whether a fluid temperature at the vertical location transitions from a first temperature region to a second temperature region based on the signal, and command one or more heater units to begin a draw demand response in response to determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region. A temperature of the first region is greater than a temperature of the second temperature region. The first

temperature region is separated from the second temperature region by a thermocline. The electronic controller is configured to determine that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region by detecting the thermocline passing over the tank temperature sensor.

[0015] In other features, the vertical location is located between a recirculation supply port of the tank and a return port of the tank. In other features, the electronic controller is configured to command the one or more heater units to begin the draw demand response by activating a first heater unit, determining whether a heating rate of the first heater unit is sufficient to meet a draw demand, and activating a second heater unit in response to determining that the heating rate of the first heater unit is not sufficient to meet the draw demand. In other features, the electronic controller is configured to receive a second signal from an inlet temperature sensor arranged to measure a temperature of fluid entering an inlet of one of the one or more heater units, receive a third signal from an outlet temperature sensor arranged to measure a temperature of fluid exiting an outlet of the one or more heater units, and deactivate the one or more heater units based on the first signal and the second signal meeting one or more conditions.

[0016] In other features, the electronic controller is configured to deactivate the one or more heater units based on the first signal and the second signal meeting one or more conditions by comparing the temperature of fluid entering the inlet of the one or more heater units to a first temperature threshold. In other features, the electronic controller is configured to deactivate the one or more heater units based on the first signal and the second signal meeting one or more conditions by comparing the temperature of fluid exiting the outlet of the one or more heater units to a second temperature threshold. In other features, the one or more heater units includes a plurality of heater units. The electronic controller is configured to monitor each heater unit of the plurality of heater units for a fault condition and deactivate the first heater unit and activate a second heater unit of the plurality of heater units in response to detecting a fault condition at a first heater unit of the plurality of heater units.

[0017] In other features, the electronic controller is configured to receive a fourth signal from a supply temperature sensor arranged to measure a temperature of fluid exiting the tank through a hot water supply port and compare the temperature of fluid exiting the tank to a temperature limit. In other features, the electronic controller is configured to increase a heating rate of the one or more heater units in response to determining that the temperature of fluid exiting the tank is below the temperature limit. In other features, the electronic controller is configured to increase the heating rate of the one or more heater units by activating an additional heater unit.

[0018] A method for controlling a water heating system includes receiving a signal from a tank temperature sensor positioned at a vertical location in a tank, determining whether a fluid temperature at the vertical location transitions from a first temperature region to a second temperature region based on the signal, and commanding one or more heater units to begin a draw demand response in response to determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region. A temperature of the first region is greater than a temperature of the second temperature region. The first temperature region is separated from the second temperature region by a thermocline. Determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region includes detecting the thermocline passing over the tank temperature sensor.

[0019] In other features, the vertical location is located between a recirculation supply port of the tank and a return port of the tank. In other features, commanding the one or more heater units to begin the draw demand response includes activating a first heater unit, determining whether a heating rate of the first heater unit is sufficient to meet a draw demand, and activating a second heater unit in response to determining that the heating rate of the first heater unit is not sufficient to meet the draw demand. In other features, the method includes receiving a second signal from an inlet temperature senor arranged to measure a temperature of water entering an inlet of one of the one or more heater units, receiving a third signal from an outlet temperature sensor arranged to measure a temperature of water exiting an outlet of the one or more heater units, and deactivating the one or more heater units based on the first signal and the second signal meeting one or more conditions.

[0020] In other features, deactivating the one or more heater units based on the first signal and the second signal meeting one or more conditions includes comparing the temperature of water entering the inlet of the one or more heater units to a first temperature threshold. In other features, deactivating the one or more heater units based on the first signal and the second signal meeting one or more conditions includes comparing the temperature of water exiting the outlet of the one or more heater units to a second temperature threshold. In other features, the one or more heater units includes a plurality of heater units. The method includes monitoring each heater unit of the plurality of heater units for a fault condition and deactivating the first heater unit and activating a second heater unit of the plurality of heater units in response to detecting the fault condition at a first heater unit of the plurality of heater units.

[0021] In other features, the method includes receiving a fourth signal from a supply temperature sensor arranged to measure a temperature of water exiting the tank through a hot water supply port and comparing the temperature of water exiting the tank to a temperature limit. In other features, the method includes increasing a heating rate of the one or more heater units in response to

determining that the temperature of water exiting the tank is below the temperature limit. In other features, increasing the heating rate of the one or more heaters includes activating an additional heater unit.

[0022] Other examples, embodiments, features, and aspects will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023]

FIG. 1 is a schematic illustration of an example modular water heater system.

FIG. 2 is a block diagram showing an interconnected hardware control system of an example modular water heater system.

FIGS. 3A-3B are schematic illustrations showing thermodynamic behavior of water within a tank of an example modular water heater system during a hot water draw sequence.

FIGS. 4A-4B are flowcharts of an example process for detecting draw demand and standby loss within a hot water storage tank in a modular water heater system.

FIG. 5 is a flowchart of an example process for controlling heater units of a modular water heater system.

FIGS. 6A-6C are flowcharts of an example process for determining whether a heating rate of a modular water heater system is sufficient.

FIGS. 7A-7B are flowcharts of an example process for determining whether a heating rate of a modular water heater system is sufficient.

FIG. 8 is a flowchart of an example process for determining when a heating demand of a modular water heater system is satisfied.

FIGS. 9A-9B are flowcharts of an example process for boosting a rate at which heat is added to a tank of a modular water heater system.

[0024] In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

[0025] FIG. 1 is a schematic illustration of an example modular water heater system 100. As illustrated in the example of FIG. 1, some embodiments of system 100 include one or more hot water storage tanks, such as tank 102 and one or more water heaters, such as heater units 104-1-104-3. Although a single tank 102 and three heater units 104 are shown in the example of FIG. 1, the modular nature of system 100 means that it can be scaled to have any number of tanks 102 and any number of heater units 104. While the heater units 104 illustrated in FIG. 1 are airsource heat pump units, heater units 104 may be any combination of suitable heater unit (such as water-source heat pump units, combustion heater units, electrical-resistance heater units, and/or hybrid units including any combination of heat pump units, combustion heater units, and/or electrical-resistance heater units). In various implementations, tank 102 includes an outer shell, an inner lining, and an insulation layer between the outer shell and the inner lining. The outer shell may include a pressure-resistant material such as steel. The inner lining may include a corrosion-resistant material such as glass or a polymer coating. The insulation material may include any suitable material - such as fiberglass or a polyurethane foam - to minimize heat transfer from an interior of tank 102 to an external ambient environment. A fluid (e.g., water) may be contained within the inner layer of tank 102.

[0026] In various implementations, tank 102 includes one or more water ports, such as recirculation supply port 106, return port 108, and hot water supply port 110. In some examples, recirculation supply port 106 is positioned near the bottom of tank 102 (for example, within the bottom half, third, quarter, fifth, or tenth of tank 102) so that the coldest, least buoyant water can be supplied to heater units 104. In some embodiments, return port 108 is located towards the top of the tank 102 (for example, within the top half, third, quarter, fifth, or tent of tank 102) so that water heated by heater units 104 can be returned near the top of tank 102. By positioning return port 108 nearer to the top of tank 102, heated water provided by heater units 104 will be returned nearer to the top of tank 102 - and therefore closer to hot water supply port 110 so that the heated water may be readily supplied through hot water supply port 110 in response to a hot water draw demand. In some examples, return port 108 is positioned at the very top of tank 102 (for example, in some single-pass arrangements). In some embodiments, hot water supply port 110 is positioned at the top of tank 102. In various implementations, return port 108 is connected to hot water supply port 110 via a T-connection at the top of tank 102.

[0027] Tank 102 may also include one or more temperature sensors, such as tank temperature sensor 112 and supply temperature sensor 114. In some examples, the various temperature sensors of system 100 include one or more thermocouples, resistance temperature detectors, thermistors, infrared sensors, semiconductor temperature sensors, bimetallic temperature sensors, fiber optic temperature sensors, and/or digital temperature sensors. Tank temperature sensor 112 may be positioned at a location vertically between recirculation supply port 106 and return port 108 to measure a tempera-

ture of water within tank 102 at that location. Supply temperature sensor 114 may be positioned at or near hot water supply port 110 to measure a temperature of water being drawn from tank 102 through hot water supply port 110. In various implementations, tank 102 includes only tank temperature sensor 112 and not supply temperature sensor 114. In other examples, tank 102 includes both tank temperature sensor 112 and supply temperature sensor 114.

[0028] As shown in FIG. 1, some examples of heater unit 104 include a refrigerant circuit 138 and a water circuit 140. The refrigerant circuit 138 may include a compressor 116, an expansion device 118, an evaporator coil 120, and a fan 122. In various implementations, compressor 116, expansion device 118, evaporator coil 120, and heat exchanger 124 may be fluidly coupled by one or more refrigerant lines as illustrated in FIG. 1. In operation, the refrigerant circuit 138 transfers heat from the external ambient environment to water within system 100. For example, compressor 116 compresses and circulates refrigerant through the refrigerant circuit 138. Various types of refrigerant may be used in the refrigerant circuit 138. For example, heater unit 104 may use hydrofluorocarbon (HFC) refrigerants (such as R-134a, R404A, R-407C, R-410A, R-32, and others). Heater unit 104 may also use hydrofluoroolefin (HFO) refrigerants (such as R-1234yf, R-1234ze, R-1233zd, and others). In various implementations, heater unit 104 uses natural refrigerants (such as carbon dioxide, propane, and others).

[0029] Compressor 116 compresses the refrigerant (for example, from a low-pressure, low-temperature gaseous state to high-pressure gaseous state), which increases the temperature and pressure of the refrigerant. The compressed refrigerant is moved from compressor 116 to expansion device 118, where the expansion device reduces the pressure of the compressed refrigerant. For example, the refrigerant expands from a high-pressure, high-temperature liquid state to a low-pressure, low-temperature vapor-liquid mixture at or after passing through expansion device 118. This reduction in pressure causes the refrigerant to also significantly reduce in temperature without the need for an external cooling source. The low-temperature refrigerant is then moved from expansion device 118 to evaporator coil 120. Evaporator coil 120 serves as a heat exchanger between the external ambient environment and low-temperature refrigerant passing through evaporator coil 120. For example, fan 122 moves ambient air across evaporator coil 120. Heat from ambient air naturally transfers from the external ambient environment into the refrigerant, increasing the overall heat energy of the refrigerant. The heated refrigerant is again moved to compressor 116, which compresses the refrigerant (thereby substantially increasing the temperature of the refrigerant).

[0030] In various implementations, hot refrigerant in the refrigerant circuit 138 passes through heat exchanger 124 as it travels between compressor 116 and expansion device 118. Heat from the refrigerant is then transferred from the refrigerant circuit 138 to the water circuit 140 via heat exchanger 124, thereby cooling and condensing the refrigerant from a gaseous state to a liquid state. For example, the water circuit 140 may include pump 126 and flow control valve 128. Heater unit 104 may include an inlet port 134 for receiving water from system 100 and an outlet port 136 for outputting water to system 100. In various implementations, inlet port 134 and outlet port 136 may be fluidly coupled to heat exchanger 124, pump 126, and/or flow control valve 128 as illustrated in FIG. 1. In some embodiments, inlet port 134 is fluidly coupled to recirculation supply port 106 via one or more manifolds, lines, and/or pipes. In some examples, outlet port 136 is fluidly coupled to return port 108 via one or more manifolds, lines, and/or pipes. In operation, pump 126 may draw cold water from tank 102 through recirculation supply port 106, receive the cold water through inlet port 134, pump the cold water through pump 126 and heat exchanger 124 (where heat from the heated and compressed refrigerant - which includes the additional heat energy transferred from the external ambient environment into the refrigerant circuit 138 - is transferred from the hot refrigerant to the cold water to heat the cold water). The heated water may be output via flow control valve 128 and outlet port 136 back to tank 102 (via return port 108).

[0031] In various implementations, heater unit 104 includes an inlet temperature sensor 130 for measuring a temperature of water entering the heater unit 104 (e.g., cold water) and an outlet temperature sensor 132 for measuring a temperature of water exiting the heater unit 104 (e.g., heated water). In some embodiments, inlet temperature sensor 130 is located between inlet port 134 and pump 126. In other examples, inlet temperature sensor 130 is located between pump 126 and heat exchanger 124. In various implementations, outlet temperature sensor 132 is located between flow control valve 128 and outlet port 136. In other embodiments, outlet temperature sensor 132 is located between heat exchanger 124 and flow control valve 128.

[0032] As shown in the example of FIG. 1, some embodiments of system 100 include a cold-water inlet, such as inlet port 142. In various implementations, inlet port 142 may be fluidly coupled to recirculation supply port 106 - for example, via one or more manifolds, lines, and/or pipes. In other examples, inlet port 142 may be directly coupled to tank 102. The cold water inlet port 142 can be connected to the cold water manifold at a location between the recirculation supply port 106, as shown in FIG. 1, or alternatively between a first branch connection to one of the heater units 104 and a second branch connection to another one of the heater units 104, or alternatively after all of the branch connections to heater units 104. In some embodiments, inlet port 142 is not connected directly to the cold water manifold at all and is instead provided near the bottom of tank 102 (for example, at the level of or below recirculation supply port 106).

Inlet port 142 may provide water to tank 102 to replace heated water drawn from tank 102. As illustrated in FIG. 1, in some examples of system 100, heater units 104 are arranged to be fluidly in parallel with one another.

[0033] In various implementations, system 100 may be operated in a single-pass arrangement or a multi-pass arrangement. In a single-pass arrangement, the water that is to be heated is heated to a desired set-point temperature in a single pass through heater units 104. The set-point temperature may refer to a temperature set by a user - for example, through a user interface 206 (FIG. 2) - at which hot water is stored in tank 102 and/or drawn from tank 102 through hot water supply port 110. In a single-pass arrangement, the flow rate of water should be controlled to the rate such that the heated water exits the heater unit 104 at the set-point temperature. In a multi-pass arrangement, heater units 104 heat the water incrementally in multiple passes through heater units 104 until water in tank 102 and/or drawn from hot water supply port 110 reaches the set-point temperature. For example, in a multi-pass arrangement, system 100 circulates water through heater units 104 as many times as necessary for water in tank 102 and/or drawn from hot water supply port 110 to reach the set-point temperature.

[0034] FIG. 2 is a block diagram showing an interconnected hardware control system of modular water heater system 100. As illustrated in FIG. 2, each heater unit 104 may include a heater unit controller 202, which may be in communication with compressor 116, fan 122, pump 126, flow control valve 128, inlet temperature sensor 130, and/or outlet temperature sensor 132. Each heater unit controller 202 may be in communication with a master controller 204. In various implementations, master controller 204 may be provided as part of tank 102, as part of a separate control unit, as part of a building management system, or integrated into one of the heater units 104. Master controller 204 may also be in communication with tank temperature sensor 112 and/or supply temperature sensor 114. System 100 may also include the user interface 206 in communication with master controller 204. In various implementations, user interface 206 includes one or more displays (which may include a touchscreen), one or more buttons, and/or one or more switches with which a user can input commands and/or receive information about operations of system 100. The user interface 206 may be provided as part of tank 102, as part of a separate control unit, as part of a building management system, or integrated into one of the heater units 104.

[0035] FIGS. 3A-3B are exemplary schematic illustrations showing thermodynamic behavior of water within tank 102 during a hot water draw sequence. In fluids, stratification may refer to a condition where the fluid organizes into distinct layers that vary in temperature and/or density. In a hot water tank such as tank 102, stratification may result in different layers of water forming at different heights in tank 102 with each layer having a distinctly different temperature. This occurs as a result of hot water being less dense than cold water. As water in the tank is heated, it becomes lighter and rises to the top of the tank while the colder, denser water sinks to the bottom. This creates distinct layers of water at different temperatures, with a transition layer - such as thermocline 302 - between the hot water layer and the cold-water layer. These stratified layers of water tend to be relatively stable. While water is a relatively good conductor of heat, the heat transfer between layers of water in a large tank tends to be relatively slow, especially when there is little movement to mix the layers. This stable stratification may be beneficial to the overall energy efficiency of system 100. By keeping hot water near the top of tank 102 - where it can be drawn off as needed without disturbing the cooler water below - tank 102 can deliver the hot water more efficiently. This design can reduce the frequency and duration that the heating units 104 must operate to maintain the desired water temperature of water drawn from tank 102.

[0036] Chart 304 illustrates the relationship between temperature of water in tank 102 (shown along the x-axis) and its height or vertical location within tank 102 (shown along the y-axis). As shown in chart 304, the temperature of the water at the bottom of tank 102 (below thermocline 302) may be colder than the temperature of the water at the top of tank 102 (above thermocline 302). For example, temperature of water below thermocline 302 may have a temperature substantially equal to the temperature of cold-water entering tank 102 through recirculation supply port 106 ($T_{cold\ in}$), while temperature of water above thermocline 302 may have a temperature substantially equal to the temperature of hot water supplied from heater units 104 through return port 108, which may be at the set-point temperature (T_{set}). In various implementations, the incoming water temperature $T_{cold\ in}$ may be about 40° F, while the set-point temperature T_{set} may be about 140° F.

[0037] The thickness of the thermocline 302 depends on how much mixing occurs when heated water returns to tank 102 through return port 108. For example, the more frequently heater units 104 are cycled, the thicker thermocline 302 may be. When tank 102 is fully charged (or filled with heated water), thermocline 302 may be near the very bottom of tank 102. As hot water is drawn from the top of tank 102 through hot water supply port 110, the hot water will be replaced with incoming cold water that enters at the bottom of tank 102 through recirculation supply port 106. This causes thermocline 302 to move upwards in the tank, as shown in FIG. 3B. Eventually, when enough hot water is drawn from tank 102, thermocline 302 may reach and/or move past tank temperature sensor 112. In various implementations, master controller 204 may detect the hot water draw by detecting thermocline 302 as it moves past tank temperature sensor 112.

[0038] Additionally, when there is no hot water draw and/or no heating of the water in tank 102 for a sustained period of time, the heated water in tank 102 will eventually drop in temperature due to the gradual heat transfer from

the interior of tank 102 to the external ambient environment. This temperature drop may be more gradual but can also be detected by master controller 204 by monitoring tank temperature sensor 112. In some embodiments, master controller 204 may use a single sensor - such as tank temperature sensor 112 - to detect both hot water draw demand (for example, by detecting thermocline 302) and the standby loss (for example, by detecting the gradual heat loss from water in tank 102).

[0039] FIGS. 4A-4B are flowcharts of an example process 400 for detecting draw demand and standby loss within a hot water storage tank 102 in a modular water heater system 100. At 402, master controller 204 receives a signal from tank temperature sensor 112 indicative of a temperature in tank 102 (T_{tank}). At 404, master controller 204 compares the temperature in tank 102 (T_{tank}) to a first threshold temperature (T_{lim1}). In various implementations, the value of the first threshold temperature (T_{lim1}) is set by the user via user interface 206. In other examples, the value of the first threshold temperature (T_{lim1}) is a preset value. In some embodiments, the value of the first threshold temperature (T_{lim1}) is a value offset by a fixed amount from the set-point temperature of tank 102. In various implementations, the first threshold temperature (T_{lim1}) may be about 100° F. Master controller 204 detecting a temperature reading at tank temperature sensor 112 below the first threshold temperature (T_{lim1}) may indicate that thermocline 302 has reached or passed tank temperature sensor 112, which indicates that a draw of hot water from tank 102 is occurring.

[0040] In response to master controller 204 determining that the temperature in tank 102 (T_{tank}) is below the first threshold temperature (T_{lim1}) ("YES" at decision block 406), master controller 204 begins a draw demand response at 408. In various implementations, the draw demand response includes activating one or more of heater units 104. Additional details associated with the draw demand response will be described further on in this specification with reference to FIG. 5. In response to master controller 204 determining that the temperature in tank 102 (T_{tank}) is not below the first threshold temperature (T_{lim1}) ("NO" at decision block 406), master controller 204 compares the temperature in tank 102 (T_{tank}) to a second threshold temperature (T_{lim2}) at 410. In various implementations, the second threshold temperature (T_{lim2}) is greater than the first threshold temperature (T_{lim1}). In some embodiments, the second threshold temperature (T_{lim2}) may be a number of degrees less than the set-point temperature of tank 102. For example, the second threshold temperature (T_{lim2}) may be about 5° F lower than the set-point temperature of tank 102. Master controller 204 detecting a temperature reading at tank temperature sensor 112 below the second threshold (T_{lim2}) may indicate that a standby loss of heat has occurred and that water in tank 102 should be reheated. However, in some scenarios, it may take a substantial amount of time before water in tank 102 loses that much heat. Thus, in order to prevent frequent short cycles of the heater units 104 - and increase the overall efficiency of system 100 while reducing wear and tear on heater units 104 - a minimum of time off after conclusion of a previous heating cycle can be met before master controller 204 initiates a new heating cycle to address standby losses.

[0041] In response to master controller 204 determining that the temperature in tank 102 (T_{tank}) is not below the second threshold temperature (T_{lim2}) ("NO" at decision block 412), master controller 204 receives an updated signal from tank temperature sensor 112 indicative of temperature in tank 102 (T_{tank}) at 414 and process 400 proceeds back to block 404. In response to master controller 204 determining that the temperature in tank 102 (T_{tank}) is below the second threshold temperature (T_{lim2}) ("YES" at decision block 412), master controller 204 determines an amount of time that has elapsed since the previous heating event (e.g., how long heater units 104 have remained off) at 416. At decision block 418, master controller 204 determines whether the amount of time elapsed since the previous heating event exceeds a threshold. In response to master controller 204 determining that the amount of time elapsed since the previous heating event does not exceed the threshold ("NO" at decision block 418), master controller 204 receives an updated signal from tank temperature sensor 112 indicative of temperature in tank 102 (T_{tank}) at 414.

[0042] In response to master controller 204 determining that the amount of time elapsed since the previous heating event exceeds the threshold ("YES" at decision block 418), master controller 204 begins a timer at 420. At 422, master controller 204 monitors the timer. At decision block 424, master controller 204 determines whether the timer has run for a period of time exceeding a predetermined delay period (t_{delay}). In some embodiments the predetermined delay period (t_{delay}) may be preprogrammed into master controller 204. In various implementations, the predetermined delay period (t_{delay}) may be set and/or adjusted by the user via user interface 206. In some examples, the predetermined delay period (t_{delay}) may be about five minutes. In response to master controller 204 determining that the timer has not run for the period of time exceeding the predetermined delay period (t_{delay}) ("NO" at decision block 424), master controller 204 continues monitoring the timer at 426 and process 400 returns to decision block 424. In response to master controller 204 determining that the timer has run for the period of time exceeding the predetermine delay period (t_{delay}) ("YES" at decision block 424), master controller 204 receives an updated signal from tank temperature sensor 112 indicative of the temperature in tank 102 (T_{tank}) at 428. At decision block 430, master controller 204 determines whether the updated temperature in tank 102 (T_{tank}) is less than the second threshold temperature (T_{lim2}) at decision block 430.

[0043] In response to master controller 204 determining that the updated temperature in tank 102 (T_{tank}) is still

less than the second threshold temperature (T_{lim2}) ("YES" at decision block 430), master controller 204 begins a standby loss response at 432. In some embodiments, the standby loss response includes activating one or more of heater units 104. Additional details associated with the standby loss response will be described further on in this specification with reference to FIG. 5. In response to master controller 204 determining that the updated temperature in tank 102 (T_{tank}) is not less than the second threshold temperature (T_{lim2}) ("NO" at decision block 430), process 400 proceeds back to block 414. In various implementations, both the draw demand response and the standby loss response may begin by heating water using a single heater unit 104. Generally, system 100 may be most efficient when operating with a lowest number of heating units 104 possible. Thus, in some scenarios, the standby loss response may recover the standby loss using only a single heater unit 104 (so long as there is sufficient time to do so before a hot-water draw occurs). In response to a draw demand, the number of heating units 104 that need to operate in order to match the demand and prevent depletion of the hot-water storage may depend on the magnitude and duration of the hot-water draw. For example, master controller 204 may initially activate a single heater unit 104, then add or remove additional heater units 104 to meet demand - for example, based on the magnitude and/or duration of the hot-water draw.

[0044] FIG. 5 is a flowchart of an example process 500 for controlling heater units 104. In various implementations, process 500 may be suitable as a draw demand response and/or a standby loss response. At 502, master controller 204 selects an order in which heater units 104 will be operated. In various implementations, master controller 204 may use a rotating order. For example, if system 100 includes three heater units 104-1, 104-2, and 104-3, master controller 204 may (i) set the operating order for the first heating cycle as heater unit 104-1, heater unit 104-2, then heater unit 104-3, (ii) set the operating order for the next heating cycle as heater unit 104-2, heater unit 104-3, then heater unit 104-1, and (iii) set the operating order for the subsequent heating cycle as heater unit 104-3, heater unit 104-1, then heater unit 104-2. Master controller 204 may continue rotating through the heater units by moving the first heater unit 104 of a previous cycle to the end of the next cycle. In other embodiments, master controller 204 tracks a total accumulated run time of each heater unit 104 and sets the order to give preference to units in order from those with the least run time to those with the most.

[0045] At 504, master controller 204 selects the initial heater unit 104 based on the heater unit order selected at block 502. At 506, master controller 204 starts the selected heater unit 104. For example, master controller 204 sends a command to heater unit controller 202 to run the associated heater unit 104 to heat water in the system 100. In some embodiments, compressor 116 of the selected heater unit 104 is a constant speed compressor. In various implementations, compressor 116 of the selected heater unit 104 is a variable speed compressor. In examples where the compressor 116 is a variable speed compressor, master controller 204 and/or heater unit controller 202 may adjust the speed of compressor 116 to adjust the heat output of heater unit 104. In some examples, master controller 204 and/or heater unit controller 202 adjusts the flow rate of water through the water circuit 140 of the selected heater unit 104 by adjusting the pump speed of pump 126 and/or a flow rate through flow control valve 128. In examples where system 100 is configured as a single-pass system, master controller 204 and/or heater unit controller 202 may adjust the flow rate of water through the water circuit 140 by adjusting the pump speed of pump 126 and/or the flow rate through flow control valve 128 to until the temperature of water exiting the selected heater unit 104 sensed by outlet temperature sensor 132 substantially matches the setpoint temperature or a different temperature.

[0046] At 508, master controller 204 determines whether the heating rate is sufficient. In various implementations, master controller 204 determines whether the heating rate is sufficient by monitoring tank temperature sensor 112. For example, master controller 204 may initiate the draw demand response after it detects thermocline 302 passing tank temperature sensor 112 as heated water is drawn from the top of tank 102. Because heated water is added to tank 102 above tank temperature sensor 112, a sufficient heating rate may result in enough heated water being added to tank 102 to push thermocline 302 back below tank temperature sensor 112. Master controller 204 may monitor tank temperature sensor 112 and determine that the heating rate is sufficient in response to master controller 204 detecting thermocline 302 passing tank temperature sensor 112 after the draw demand response is initiated. In various implementations, master controller 204 monitors tank temperature sensor 112 to determine whether a rate of change of temperature in tank 102 meets or exceeds a threshold. If the heating rate is not sufficient, thermocline 302 may continue to rise and not pass back below tank temperature sensor 112. Accordingly, in some embodiments, master controller 204 determines that the heating rate is not sufficient in response to not detecting thermocline 302 pass below tank temperature sensor 112 for a period of time after initiating the heating cycle. Additional details associated with determining whether the heating rate is sufficient will be described further on in this specification with reference to FIGS. 6A-7B.

[0047] In response to master controller 204 determining that the heating rate is not sufficient, ("NO" at decision block 510), master controller 204 increases heating at block 512. For example, master controller 204 may increase heating by starting an additional heater unit 104. In various implementations, master controller 204 increases the compressor speed of compressor 116. In examples where heater unit 104 includes combustion heater units, master controller 204 may increase fuel flow

to heater unit 104. In embodiments where heater unit 104 includes electrical-resistance heater units, master controller 204 may increase power supplied to electrical heating elements of heater unit 104. After master controller 204 increases heating at block 512, process 500 returns to block 508. In response to master controller 204 determining that the heating rate is sufficient ("YES" at decision block 510), process 500 returns to block 508. In various implementations, master controller 204 waits a predetermined delay period before again determining whether the heating rate is sufficient at block 508. In some examples, the predetermined delay period may be the same as the predetermined delay period (t_{delay}) previously described with reference to process 400. In some embodiments, the predetermined time period may be different from the predetermined time period (t_{delay}) previously described with reference to process 400.

[0048] FIGS. 6A-6C are flowcharts of an example process 600 for determining whether a heating rate is sufficient. In various implementations, master controller 204 begins process 600 after one or more heater units 104 are started - for example, during a demand response. For example, process 600 may begin after a single heater unit 104 is started and determine whether the heating rate of the single heater unit 104 is sufficient. In some embodiments, process 600 begins after multiple heater units 104 have been started and determines whether the heating rate of the multiple heater units 104 are sufficient. In some examples, process 600 begins after one or more heater units 104 have been added in response to master controller 204 determining the heating rate of the previously running heater units 104 was not sufficient, and process 600 determines whether the increased heating rate is sufficient. In various implementations, process 600 may begin at any point during the demand response cycle, and/or master controller 204 may execute process 600 multiple times - for example, after the initial heater units 104 are started and/or after additional heater units 104 are added and/or removed.

[0049] At 602, master controller 204 determines a time elapsed since one or more heater units 104 have been started. For example, master controller 204 may determine how long the one or more heater units 104 have been operating in response to the current demand draw response or standby loss response cycle, or how long the one or more heater units 104 have been operating since master controller 204 increased the heating rate. In various implementations, the one or more heater units 104 have been operating since the beginning of the current demand draw response or standby loss response cycle, and the time elapsed represents a time since the beginning of the current demand draw response or standby loss response cycle. In some embodiments, the one or more heaters 104 were started in response to master controller 204 determining that the heating rate was not sufficient, and the time elapsed represents a time since master controller 204 last increased heating (for example, by starting one or more additional heater units 104). At 604, master controller 204 determines whether the time elapsed meets or exceeds a minimum delay threshold. In some embodiments, the minimum delay threshold may be about 15 seconds. In some examples, implementing the minimum delay threshold allows operation of the heater unit 104 to stabilize before master controller 204 determines whether additional heating is necessary. This reduces inefficiencies and/or additional wear and tear associated with frequently cycling heater units 104 on and off In response to determining that the time elapsed does not meet or exceed the minimum threshold ("NO" at decision block 604), master controller 204 continues to determine the time elapsed since the selected heater unit 104 started (at 606) and process 600 returns to decision block 604. In response to determining that the time elapsed meets or exceeds the minimum threshold ("YES" at decision block 604), master controller 204 receives an initial signal from tank temperature sensor 112 indicative of the temperature in tank 102 (T_{tank}) at 608.

[0050] At 610, master controller 204 sets the current temperature in tank 102 (T_{tank}) as a reference temperature (T_{ref}). At 612, master controller 204 initializes a timer to monitor temperatures in tank 102 over a duration divided into M intervals. In various implementations, master controller 204 monitors tank temperatures at each time increment m over the duration (the total number of increments may equal M). At 614, master controller 204 initializes an increment counter and sets the initial increment counter to 0 ($m = 0$). At 616, master controller 204 receives an updated signal from tank temperature sensor 112 indicative of the updated temperature in tank 102 at the current timer increment m ($T_{tank,m}$). At 618, master controller 204 determines whether the current timer increment is the initial time increment ($m = 0$). In response to determining that the current timer increment is the initial timer increment ($m = 0$ - "YES" at decision block 618), master controller 204 sets the current temperature in tank 102 ($T_{tank,m}$) as an initial temperature (T_0) at 620 and process 600 proceeds to block 622.

[0051] In response to determining that the current timer increment is not the initial timer increment ($m \neq 0$ - "NO" at decision block 618), master controller 204 compares the temperature in tank 102 at the current timer increment m ($T_{tank,m}$) with the reference temperature (T_{ref}) at 622. The reference temperature (T_{ref}) may be the maximum temperature previously measured in tank 102 during the current timer duration M. By comparing the temperature in tank 102 at the current temperature increment m ($T_{tank,m}$), master controller 204 determines whether water in tank 102 is increasing in temperature. In response to determining that the temperature in tank 102 at the current timer increment m ($T_{tank,m}$) is not greater than the reference temperature (T_{ref}) ("NO" at decision block 624), then the temperature in tank 102 is not increasing and master controller 204 determines whether the current timer increment m has reached its maximum value M ($m = M$), which indicates that the timer has

reached the end of the duration. In response to master controller 204 determining that the current timer increment m has reached its maximum value M ($m = M$- "YES" at decision block 626), master controller 204 determines that the heating rate is not sufficient at 628. In response to master controller 204 determining that the current timer increment m has not reached its maximum value M ($m \neq M$ - "NO" at decision block 626), master controller 204 increases increment counter m by 1 (sets $m = m + 1$) at 630 and process 600 proceeds back to block 616.

[0052] In response to determining that the temperature in tank 102 at the current timer increment m ($T_{tank,m}$) is greater than the reference temperature (T_{ref}) ("YES" at decision block 624), then the temperature in tank 102 is increasing and master controller 204 sets the temperature in tank 102 at the current timer increment m ($T_{tank,m}$) as the reference temperature (T_{ref}) at 632. At 634, master controller 204 compares the reference temperature (T_{ref}) with a threshold temperature (T_{lim}). In various implementations, the threshold temperature (T_{lim}) is set below the second threshold temperature (T_{lim2}) used to initiate the standby loss response in process 400. Accordingly, master controller 204 avoids increasing the heating rate during a standby loss response cycle.

[0053] In response to determining that the reference temperature (T_{ref}) meets or exceeds the threshold temperature (T_{lim}) ("YES" at decision block 636), master controller 204 determines that the heating rate is sufficient and process 600 proceeds back to block 612. In response to determining that the reference temperature (T_{ref}) does not meet or exceed the threshold temperature (T_{lim}) ("NO" at decision block 636), master controller 204 computes the difference between the reference temperature (T_{ref}) and the initial temperature (T_0) and compares the computed difference to a threshold difference (dT_{min}) at 638. In various implementations, the threshold difference (dT_{min}) is about 0.6° F. In response to master controller 204 determining that the computed difference meets or exceeds the threshold difference (dT_{min}) ($T_{ref} - T_0 \geq dT_{min}$ - "YES" at decision block 640), master controller 204 determines that the heating rate is sufficient and process 600 proceeds back to block 612. In response to master controller 204 determining that the computed difference does not meet or exceed the threshold difference (dT_{min}) ("NO" at decision block 640), process 600 proceeds to decision block 626.

[0054] FIGS. 7A-7B are flowcharts of an example process 700 for determining whether a heating rate is sufficient. At 702, master controller 204 initializes a buffer of size n. At 704, master controller 204 receives a signal from tank temperature sensor 112 indicative of a temperature in tank 102 at an initial time ($t = i$). Master controller 204 may receive updated signals from tank temperature sensor 112 at regular intervals. At 706, master controller 204 determines whether the buffer is full. In response to determining that the buffer is not full ("NO" at decision block 706), master controller 204 adds the temperature reading of tank 102 (T_{tank}) to the buffer at 708. At 710, master controller 204 receives an updated signal from tank temperature sensor 112 indicative of the temperature in tank 102 (T_{tank}) at the next time interval (for example, after the initial time $t = i$ has advanced by an interval j) and process 700 proceeds back to decision block 706.

[0055] In response to determining that the buffer is full ("YES" at decision block 706), master controller 204 removes the oldest temperature reading from the buffer at 712. At 714, master controller 204 adds the updated temperature reading (T_{tank}) to the buffer. At 716, master controller 204 determines a minimum temperature reading (T_{min}) of temperature readings present in the buffer. At 718, master controller 204 determines a maximum temperature reading (T_{max}) of temperature readings present in the buffer. At 720, master controller 204 computes a difference ($T_{max} - T_{min}$) between the maximum temperature reading (T_{max}) in the buffer and the minimum temperature reading (T_{min}) in the buffer and compares the computed difference to a threshold (ΔT_{thresh}). In response to determining that the computed difference does not exceed the threshold (ΔT_{thresh}) ("NO" at decision block 722), master controller 204 determines that the heating rate is not sufficient at 724. In response to determining that the computed difference exceeds the threshold (ΔT_{thresh}) ("YES" at decision block 722), master controller 204 determines that the heating rate is sufficient and process 700 proceeds back to block 710.

[0056] As shown in FIGS. 5-7B, in some embodiments, the demand draw response and the standby loss response may follow the same control logic. This has the technical benefit of simplifying the control logic of master controller 204, which reduces complexity from system 100. However, specific parameters may be different for each response. For example, if the heater units 104 are heat pumps with variable speed compressors 116, then in a standby loss response, the initial heater unit 104 may start operating at a minimum compressor speed (while in a demand draw response, the initial heater unit 104 may start operating at a higher compressor speed in an attempt to catch the demand). In some embodiments, master controller 204 may increase the set-point temperature communicated to heater unit controller 202 in a demand draw response (for example, as compared to the set-point temperature communicated to heater unit controller in a standby loss response). In various implementations, the threshold temperature (T_{lim}) of process 600 is set below the second threshold temperature (T_{lim2}) used to initiate the standby loss response in process 400. This logic allows master controller 204 to avoid increasing the heating rate during a standby loss response cycle. Since it is typically most efficient to overcome a standby loss using only a minimum rate of heating, this logic optimizes the overall efficiency of system 100.

[0057] FIG. 8 is a flowchart of an example process 800 for determining when a heating demand is satisfied. In various implementations, master controller 204 and/or heater unit controller 202 monitor inlet temperature sen-

sors 130 and outlet temperature sensors 132 at each individual heater unit 104. Master controller 204 and/or heater unit controller 202 then may shut down or reduce heating at individual heater units 104. Inlet temperature sensor 130 senses a heater inlet temperature (T_{in}) indicative of a temperature of water entering heater unit 104. Outlet temperature sensor 132 senses a heater outlet temperature (T_{out}) indicative of a temperature of water exiting heater unit 104. In various implementations, master controller 204 and/or heater unit controller 202 uses the heater inlet temperature (T_{in}) and/or the heater outlet temperature (T_{out}) to determine whether one or more terminating criterion are met. If the terminating criterion is met, master controller 204 and/or heater unit controller reduces heat load of system 100 - for example, by reducing heat output from or shutting down one or more heater units 104.

[0058] At 802, master controller 204 and/or heater unit controller 202 determines a time elapsed since the selected heater unit 104 started the current heating cycle. In response to determining that the time elapsed does not meet or exceed a minimum delay ("NO" at decision block 804), master controller 204 and/or heater unit controller 202 continues to determine the time elapsed since the selected heating unit started the current heating cycle at 806 and process 800 returns to decision block 804. In various implementations, it may not be preferable to overly cycle the compressor 116 of a heat pump heater unit 104, so operating the heat pump heater unit 104 for a minimum period of time may be preferable to reduce unnecessary wear and tear on system 100. In some examples, the minimum delay may be about three minutes. In some cases, the plumbing after heat exchanger 124 may have hot water remaining in it from a previous heating cycle, and incorporating the minimum delay allows heater unit 104 to operate through this transient event without shutting down prematurely. In response to determining that the time elapsed meets or exceeds the minimum delay ("YES" at decision block 804), master controller 204 and/or heater unit controller 202 receives a signal from inlet temperature sensor 130 indicative of the heater inlet temperature (T_{in}) at 808.

[0059] At 810, master controller 204 and/or heater unit controller 202 receives a signal from outlet temperature sensor 132 indicative of the heater outlet temperature (T_{out}) at 810. At decision block 812, master controller 204 and/or heater unit controller 202 determine whether a first terminating criterion is met. In various implementations, the first terminating criterion may be based exclusively on the heater outlet temperature (T_{out}). For example, the first terminating criterion may be met when the heater outlet temperature (T_{out}) exceeds a temperature limit. In various implementations, the temperature limit may be related to the set-point temperature. In some embodiments, the temperature limit may be a maximum allowable outlet temperature for the heater unit 104. In response to master controller 204 and/or heater unit controller 202 determining that the first terminating criterion is not met ("NO" at decision block 812), process 800 proceeds back to block 808. In response to master controller 204 and/or heater unit controller 202 determining that the first terminating criterion is met ("YES" at decision block 812), master controller 204 and/or heater unit controller 202 determine whether a second terminating criterion is met at decision block 814.

[0060] In various implementations, the second terminating criterion may be based exclusively on the heater inlet temperature (T_{in}). For example, the second terminating criterion may be met when the heater inlet temperature (T_{in}) is less than a minimum temperature differential (ΔT) below the maximum allowable outlet temperature. In some embodiments, the minimum temperature differential (ΔT) may be set as a temperature rise the water flow can be expected to have when heater unit 104 is operating at its maximum water flow rate. In response to master controller 204 and/or heater unit controller 202 determining that the second terminating criterion is not met ("NO" at decision block 814), process 800 returns to block 808. In response to master controller 204 and/or heater unit controller 202 determining that the second terminating criterion is met ("YES" at decision block 814), master controller 204 and/or heater unit controller 202 reduces the heating load. In various implementations, master controller 204 and/or heater unit controller 202 reduces the heating rate of the heater unit 104 by reducing the speed of compressor 116. In some examples, master controller 204 and/or heater unit controller 202 shuts down the heater unit 104. In other embodiments, master controller 204 and/or heater unit controller 202 shuts down another heater unit 104 in system 100 - for example, one that has been operating longer, or has had more operating cycles, or has a greater accumulated total operating time.

[0061] In various implementations, master controller 204 and/or heater unit controller 202 reduces heating load at 816 by shutting down one or more heater units 104 in series. Master controller 204 and/or heater unit controller 202 may impose a minimum delay between shutting down each heater unit 104. This minimum delay can allow cold incoming water to reach another heater unit 104, which may prevent the terminating criterion from being met for that unit. This results in an improved overall stability for system 100. The control logic of process 800 offers additional technical benefits to system 100. For example, by requiring that both the first terminating criterion and the second terminating criterion to be met before reducing the heating load, a more stable operation of system 100 may be achieved. Even when the control logic of system 100 implements various time delays as previously described, temperature oscillations can still occur within the water circuit 140. These temperature oscillations may be transitory in nature - and do not indicate a true need to reduce heating load. Requiring both criteria to be met allows the system 100 to avoid reacting prematurely to such oscillations in water temperature.

[0062] In some embodiments, requiring both the first terminating criterion and the second terminating criterion to be met before reducing the heating load also allows any active heater units 104 to operate up to the point where the incoming water temperature is such that the heat pump unit is not able to effectively transfer heat to the water within its operating envelope. In various implementations, process 800 may operate on each heater unit 104 in operation. Depending on the specific plumbing arrangement of the heater units 104 and tanks 102, terminating criterion may be met on one heater unit 104 but not other heater units 104. Removing the heater unit 104 for which the terminating criterion is met can also allow for a better and more efficient response to a draw demand (for example, by ensuring that each operating heater unit 104 is operating within an efficient envelope).

[0063] In addition to reducing heating load based on terminating criterion (as described in process 800), master controller 204 and/or heater unit controller 202 can also shut down the operation of a heater unit 104 in response to detecting a fault condition. In various implementations, the fault condition can include anything that indicates an undesirable or abnormal condition. For example, if the heater outlet temperature (T_{out}) greatly exceeds the maximum allowable outlet temperature, then this may indicate a fault condition in the heater unit 104. Similarly, an excessively high-pressure condition at the outlet of compressor 116 or an excessively low temperature condition at the evaporator fan may also indicate a fault condition. In various implementations, master controller 204 may turn on another heater unit 104 in response to shutting down another heater unit 104 for a fault condition to make up for the lost capacity.

[0064] When tank temperature sensor 112 does not indicate a need to increase heating and all of the heater units 104 have stopped operating due to the terminating criterion having been met, then the demand can be said to have been satisfied. These conditions typically arise when thermocline 302 has been pushed down in tank 102 to a position at or below the recirculation supply port 106 near the bottom of tank 102 and tank 102 has been substantially filled with hot water.

[0065] FIGS. 9A-9B are flowcharts of an example process 900 for boosting a rate at which heat is added to tank 102. In some embodiments, control logic for system 100 may include a boost feature. In normal operation, the water flow rate to an individual operating heater unit 104 may be regulated to achieve a heater outlet temperature (T_{out}) substantially equal to the set-point temperature of the tank 102. In some embodiments, hot water return port 108 may not be located at the very top of tank 102. In such examples, water held in tank 102 above the return port 108 could be at a lower temperature than the set-point temperature. Since water may be drawn from the top of tank 102 through hot water supply port 110 to satisfy the draw demand, master controller 204 may monitor supply temperature sensor 114 to determine whether water being drawn through hot water supply port 110 is at the set-point temperature. In various implementations, master controller 204 may initiate process 900 to boost the rate at which heat is added to tank 102 in response to supply temperature sensor 114 detecting that water being drawn through hot water supply port 110 is below the set-point temperature. In some scenarios, the temperature of water being drawn through hot water supply port 110 may drop below the set-point temperature in response to a long-sustained draw of hot water.

[0066] At 902, master controller 204 begins a timer. At 904, master controller 204 receives a signal from supply temperature sensor 114 indicative of a supply temperature (T_{supply}) at an initial time increment. At 906, master controller 204 compares the supply temperature (T_{supply}) to a temperature limit (T_{lim}). In various implementations, the temperature limit (T_{lim}) may be a small temperature differential below the set-point temperature (for example, about 1° F, 2.5° F, 5° F, or 10° F below the set-point temperature). In response to master controller 204 determining that the supply temperature (T_{supply}) is less than the temperature limit (T_{lim}) ("YES" at decision block 908), master controller 204 receives a signal from tank temperature sensor 112 indicative of the temperature in tank 102 (T_{tank}) at 910. At 912, master controller 204 compares the temperature in tank 102 (T_{tank}) to the temperature limit (T_{lim}). In response to master controller 204 determining that the temperature in tank 102 (T_{tank}) is below the temperature limit (T_{lim}) ("YES" at decision block 914), master controller 204 increments the timer at 916. At decision block 918, master controller determines whether the timer has expired. In various implementations, the timer may be set for a duration of time, and the timer expires after the during of time passes. In some embodiments, the duration of time may be about 30 seconds.

[0067] In response to master controller 204 determining that the timer has not expired ("NO" at decision block 918), master controller receives an updated signal from supply temperature sensor 114 indicative of the supply temperature (T_{supply}) at the next time increment at 920 and process 900 proceeds back to block 906. In response to master controller 204 determining that the timer has expired ("YES" at decision block 918), master controller 204 determines whether the boost is at a maximum level at decision block 922. In response to master controller 204 determining that the boost is not at the maximum level ("NO" at decision block 922), master controller increases the boost at 924. In various implementations, master controller 204 increases the boost by increasing the set-point temperature communicated to heater units 104. In response to master controller 204 determining that the boost is already at the maximum level ("YES" at decision block 922), process 900 returns to block 902. At 926, master controller 204 ends the boost in response to determining that the supply temperature (T_{supply}) does not exceed the temperature limit (T_{lim}) ("NO" at decision block 908) or determining that the temperature in tank 102 (T_{tank}) is not less than the temperature limit (T_{lim})

("NO" at decision block 914). In some embodiments, master controller 204 ends the boost by reverting the set-point temperature communicated to heater units 104 back to the set-point temperature input by the user at user interface 206.

[0068] Process 900 includes technical features that offer benefits for improving the efficiency of system 100. For example, after master controller 204 checks whether the supply temperature (T_{supply}) is less than the temperature limit (T_{lim}), master controller 204 next checks whether the temperature in tank 102 (T_{tank}) is also less than the temperature limit (T_{lim}). By implementing a check of temperature in tank 102 (T_{tank}) against the temperature limit (T_{lim}), process 900 ensures that the boost is stopped when the temperature at tank temperature sensor 112 reaches the temperature limit (T_{lim}) - which may indicate that the tank 102 is sufficiently charged as the thermocline 302 is driven below tank temperature sensor 112. This prevents the unnecessary continued boost of the system 100. For example, if the draw of hot water from tank 102 ceases in the middle of boosted operation, the draw of hot water through hot water supply port 110 ceases, and supply temperature sensor 114 may no longer detect the temperature of water at the top of tank 102. Thus, in such a scenario, master controller 204 will not be able to determine whether the heating demand is satisfied based on signals from the supply temperature sensor 114 alone.

[0069] Although only a single tank temperature sensor 112 is needed to control the operation of system 100, tank 102 may be equipped with multiple temperature sensors at varying heights. In some embodiments, master controller 204 may switch between different ones of the multiple temperature sensors to control system 100. For example, master controller 204 may be in communication with an electric grid demand response system to receive "shed load" commands when the electric grid is overloaded. In response to receiving such a "shed load" command, master controller 204 can switch to receiving signals from a tank temperature sensor that is located higher up in tank 102 such that thermocline 302 must travel further up in tank 102 before the temperature sensor signal triggers a heating demand. This reduces the relative amount of hot water stored in tank 102, which reduces the idle power draw of system 100. In some examples, master controller 204 may adjust (such as by decreasing) the set-point temperature in response to "shed load" commands. In various implementations, master controller 204 may increase the time delays that must be met before bringing on additional heating loads in response to "shed load" commands.

[0070] The foregoing description is merely illustrative in nature and does not limit the scope of the disclosure or its applications. The broad teachings of the disclosure may be implemented in many different ways. While the disclosure includes some particular examples, other modifications will become apparent upon a study of the drawings, the text of this specification, and the following claims. In the written description and the claims, one or more steps within any given method may be executed in a different order - or steps may be executed concurrently - without altering the principles of this disclosure. Similarly, instructions stored in a non-transitory computer-readable medium may be executed in a different order - or concurrently - without altering the principles of this disclosure. Unless otherwise indicated, the numbering or other labeling of instructions or method steps is done for convenient reference and does not necessarily indicate a fixed sequencing or ordering.

[0071] Unless the context of their usage unambiguously indicates otherwise, the articles "a," "an," and "the" should not be interpreted to mean "only one." Rather, these articles should be interpreted to mean "at least one" or "one or more." Likewise, when the terms "the" or "said" are used to refer to a noun previously introduced by the indefinite article "a" or "an," the terms "the" or "said" should similarly be interpreted to mean "at least one" or "one or more" unless the context of their usage unambiguously indicates otherwise.

[0072] Spatial and functional relationships between elements - such as modules - are described using terms such as (but not limited to) "connected," "engaged," "interfaced," and/or "coupled." Unless explicitly described as being "direct," relationships between elements may be direct or include intervening elements. The phrase "at least one of A, B, and C" should be construed to indicate a logical relationship (A OR B OR C), where OR is a non-exclusive logical OR, and should not be construed to mean "at least one of A, at least one of B, and at least one of C." The term "set" does not necessarily exclude the empty set. For example, the term "set" may have zero elements. The term "subset" does not necessarily require a proper subset. For example, a "subset" of set A may be coextensive with set A, or include elements of set A. Furthermore, the term "subset" does not necessarily exclude the empty set.

[0073] In the figures, the directions of arrows generally demonstrate the flow of information - such as data or instructions. However, the direction of an arrow does not imply that information is not being transmitted in the reverse direction. For example, when information is sent from a first element to a second element, the arrow may point from the first element to the second element. However, the second element may send requests for data to the first element, and/or acknowledgements of receipt of information to the first element. Furthermore, while the figures illustrate a number of components and/or steps, any one or more of the components and/or steps may be omitted or duplicated, as suitable for the application and setting.

[0074] Throughout this application, the term "module" or the term "controller" may be replaced with the term "circuit." A "module" may refer to, be part of, or include processor hardware that executes code and memory hardware that stores code executed by the processor hardware. The term "module" may include one or more

interference circuits. In various implementations, the interference circuits may implement wired or wireless interfaces that connect to or are part of communications systems. Modules may communicate with other modules using the interference circuits. In various implementations, the functionality of modules may be distributed among multiple modules that are connected via communications systems. For example, functionality may be distributed across multiple modules by a load balancing system. In various implementations, the functionality of modules may be split between multiple computing platforms connected by communications systems.

[0075] The term "code" may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, data structures, and/or data objects. The term "memory hardware" may be a subset of the term "computer-readable medium." The term computer-readable medium does not encompass transitory electrical or electromagnetic signals or electromagnetic signals propagating through a medium - such as on an electromagnetic carrier wave. The term "computer-readable medium" is considered tangible and non-transitory. Modules, methods, and apparatuses described in this application may be partially or fully implemented by a special-purpose computer that is created by configuring a general-purpose computer to execute one or more particular functions described in computer programs. The functional blocks, flowchart elements, and message sequence charts described above serve as software specifications that can be translated into computer programs by the routine work of a skilled technician or programmer.

[0076] It should also be understood that although certain drawings illustrate hardware and software as being located within particular devices, these depictions are for illustrative purposes only. In some embodiments, the illustrated components may be combined or divided into separate software, firmware, and/or hardware. For example, instead of being located within and performed by a single electronic processor, logic and processing may be distributed among multiple electronic processors. Regardless of how they are combined or divided, hardware and software components may be located on the same computing device, or they may be distributed among different computing devices - such as computing devices interconnected by one or more networks or other communications systems.

[0077] In the claims, if an apparatus or system is claimed as including an electronic processor or other element configured in a certain manner, the claim or claimed element should be interpreted as meaning one or more electronic processors (or other element as appropriate). If the electronic processor (or other element) is described as being configured to make one or more determinations or one or execute one or more steps, the claim should be interpreted to mean that any combination of the one or more electronic processors (or any combination of the one or more other elements) may be configured to execute any combination of the one or more determinations (or one or more steps).

Claims

1. A water heating system comprising:

a storage tank having a recirculation supply port, a return port arranged above the recirculation supply port in a vertical direction, and a tank temperature sensor arranged between the recirculation supply port and the return port in the vertical direction;

at least one heating unit having a water inlet port and a water outlet port, the water inlet port being fluidly coupled to the recirculation supply port and the water outlet port being fluidly coupled to the return port; and

a control system communicatively coupled to the tank temperature sensor and the at least one heating unit, the control system configured to:

receive a signal from the tank temperature sensor indicative of a temperature of water in the storage tank at a location of the tank temperature sensor,

determine, based on the signal received from the tank temperature sensor, a need for heating,

activate, in response to determining the need for heating, the at least one heating unit to draw water from the storage tank by way of the recirculation supply port, heat said water, and return said heated water to the storage tank by way of the return port, and

reduce a rate at which said water is heated in response to determining that a first criterion and a second criterion have been met.

2. The water heating system of claim 1, wherein reducing the rate at which said water is heated comprises stopping operation of the at least one heating unit.

3. The water heating system of claim 1, wherein:

(i) the at least one heating unit is a heat pump heating unit; and/or

(ii) the control system is configured to determine that the need for heating is caused by one of a draw demand and a standby loss.

4. The water heating system of claim 1, wherein the at least one heating unit includes an inlet water temperature sensor arranged to measure a temperature of water entering the water inlet port and an outlet

water temperature sensor arranged to measure a temperature of water exiting the water outlet port, the inlet water temperature sensor and the outlet water temperature sensor being communicatively coupled to the control system, and wherein the control system is configured to determine that the first criterion and the second criterion have been met based on signals received from the inlet water temperature sensor and the outlet water temperature sensor;
optionally wherein:

the control system is configured to determine that one of the first and second criterion have been met by comparing the temperature of water exiting the water outlet port to a predetermined temperature limit;
further optionally wherein:
the control system is configured to determine that the other of the first and second criterion has been met by comparing the temperature of water entering the water inlet port to a predetermined temperature limit.

5. The water heating system of claim 1, wherein the at least one heating unit is one of a plurality of such heating units connected fluidly in parallel with one another to the recirculation supply port and the water outlet port, and wherein the control system is configured to determine which one of the plurality of heating units to activate in response to determining the need for heating.

6. The water heating system of claim 5, wherein, after activating one of the plurality of heating units in response to determining the need for heating, the control system is further configured to:

receive temperature signals from the tank temperature sensor over a period of time;
determine, based on said temperature signals, that an increased rate of heating is desired; and
increase the rate of heating by the plurality of heating units in response to determining that the increased rate of heating is desired;
optionally wherein:

the control system is configured to increase the rate of heating by activating another one of the plurality of heating units to draw water from the storage tank by way of the recirculation supply port, heat said water, and return said heated water to the storage tank by way of the return port; and/or
the control system is configured to determine that an increased rate of heating is desired at least in part by determining that a temperature change of water at the location of the tank temperature sensor over the period of time is below a threshold.

7. A method for controlling a water heating system comprising:

receiving a signal from a tank temperature sensor indicative of a temperature of a fluid in a storage tank at a location of the tank temperature sensor;
determining, based on the signal received from the tank temperature sensor, a need for heating;
activating, in response to determining the need for heating, at least one heating unit to draw fluid from the storage tank; and
reducing a rate at which the water is heated in response to determining that a first criterion and a second criterion have been met.

8. The method of claim 7, wherein:

(i) reducing the rate at which the water is heated includes stopping operation of the at least one heating unit; and/or
(ii) the method further comprises determining that the need for heating is caused by one of a draw demand and a standby loss.

9. The method of claim 7, further comprising:

determining that the first criterion and the second criterion have been met based on signals received from an inlet water temperature sensor of the at least one heating unit and an outlet water temperature sensor of the at least one heating unit;
optionally wherein:

determining that one of the first and second criterion has been met includes comparing a temperature of water exiting a water outlet port of the at least one heating unit to a predetermined temperature limit;
further optionally wherein:
determining that the other of the first and second criterion has been met includes comparing a temperature of water entering a water inlet port of the at least one heating unit to a predetermined temperature limit.

10. The method of claim 7, wherein:

the at least one heating unit includes a plurality of heating units fluidly connected in parallel; and
activating the at least one heating unit to draw water from the storage tank includes determining which one of the plurality of heating units to activate;
optionally wherein the method further com-

prises:
after activating one of the plurality of heating units:

receiving temperature signals from the tank temperature sensor over a period of time,
determining, based on the received temperature signals, that an increased rate of heating is desired, and
increasing the rate of heating by the plurality of heating units in response to determining that the increased rate of heating is desired;
further optionally wherein the method further comprises:

increasing the rate of heating by activating another one of the plurality of heating units to draw water from the storage tank and return heated water to the storage tank; and
determining that an increased rate of heating is desired at least in part by determining that a temperature change of fluid at the location of the tank temperature over the period of time is below a threshold.

11. An apparatus for controlling a water heating system comprising:
an electronic controller operatively coupled to a tank temperature sensor, the electronic controller configured to:

receive a signal from the tank temperature sensor, the tank temperature sensor positioned at a vertical location in a tank,
determine, based on the signal, whether a fluid temperature at the vertical location transitions from a first temperature region to a second temperature region, wherein a temperature of the first region is greater than a temperature of the second temperature region, the first temperature region is separated from the second temperature region by a thermocline, and the electronic controller is configured to determine that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region by detecting the thermocline passing over the tank temperature sensor; and
in response to determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region, command one or more heater units to begin a draw demand response.

12. The apparatus of claim 11, wherein:
(i) the vertical location is located between a recirculation supply port of the tank and a return port of the tank; and/or
(ii) the electronic controller is configured to command the one or more heater units to begin the draw demand response by:

activating a first heater unit;
determining whether a heating rate of the first heater unit is sufficient to meet a draw demand; and
in response to determining that the heating rate of the first heater unit is not sufficient to meet the draw demand, activating a second heater unit.

13. The apparatus of claim 11, wherein the electronic controller is configured to:

receive a second signal from an inlet temperature sensor arranged to measure a temperature of fluid entering an inlet of one of the one or more heater units;
receive a third signal from an outlet temperature sensor arranged to measure a temperature of fluid exiting an outlet of the one or more heater units; and
deactivate the one or more heater units based on the first signal and the second signal meeting one or more conditions;
optionally wherein the electronic controller is configured to deactivate the one or more heater units based on the first signal and the second signal meeting one or more conditions by comparing:

the temperature of fluid entering the inlet of the one or more heater units to a first temperature threshold; and/or
the temperature of fluid exiting the outlet of the one or more heater units to a second temperature threshold.

14. The apparatus of claim 11, wherein:

the one or more heater units includes a plurality of heater units; and
the electronic controller is configured to:

monitor each heater unit of the plurality of heater units for a fault condition,
in response to detecting a fault condition at a first heater unit of the plurality of heater units, deactivate the first heater unit and activate a second heater unit of the plurality of heater units.

15. The apparatus of claim 11, wherein the electronic

controller is configured to:

receive a fourth signal from a supply temperature sensor arranged to measure a temperature of fluid exiting the tank through a hot water supply port; and
compare the temperature of fluid exiting the tank to a temperature limit; optionally wherein the electronic controller is configured to:
in response to determining that the temperature of fluid exiting the tank is below the temperature limit, increase a heating rate of the one or more heater units; optionally wherein the electronic controller is configured to increase the heating rate of the one or more heater units by activating an additional heater unit.

16. A method for controlling a water heating system comprising:

receiving a signal from a tank temperature sensor, the tank temperature sensor positioned at a vertical location in a tank;
determining, based on the signal, whether a fluid temperature at the vertical location transitions from a first temperature region to a second temperature region, wherein a temperature of the first region is greater than a temperature of the second temperature region, the first temperature region is separated from the second temperature region by a thermocline, and determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region includes detecting the thermocline passing over the tank temperature sensor; and
in response to determining that the fluid temperature at the vertical location transitioned from the first temperature region to the second temperature region, commanding one or more heater units to begin a draw demand response.

17. The method of claim 16, wherein:

(i) the vertical location is located between a recirculation supply port of the tank and a return port of the tank; and/or
(ii) commanding the one or more heater units to begin the draw demand response includes:

activating a first heater unit;
determining whether a heating rate of the first heater unit is sufficient to meet a draw demand; and

in response to determining that the heating rate of the first heater unit is not sufficient to meet the draw demand, activating a second heater unit.

18. The method of claim 16, further comprising:

receiving a second signal from an inlet temperature senor arranged to measure a temperature of water entering an inlet of one of the one or more heater units;
receiving a third signal from an outlet temperature sensor arranged to measure a temperature of water exiting an outlet of the one or more heater units; and
deactivating the one or more heater units based on the first signal and the second signal meeting one or more conditions;
optionally wherein deactivating the one or more heater units based on the first signal and the second signal meeting one or more conditions includes:

comparing the temperature of water entering the inlet of the one or more heater units to a first temperature threshold; and/or
comparing the temperature of water exiting the outlet of the one or more heater units to a second temperature threshold.

19. The method of claim 16, wherein:

the one or more heater units includes a plurality of heater units; and
the method includes:

monitoring each heater unit of the plurality of heater units for a fault condition; and
in response to detecting the fault condition at a first heater unit of the plurality of heater units, deactivating the first heater unit and activating a second heater unit of the plurality of heater units.

20. The method of claim 16, further comprising:

receiving a fourth signal from a supply temperature sensor arranged to measure a temperature of water exiting the tank through a hot water supply port; and
comparing the temperature of water exiting the tank to a temperature limit;
optionally the method further comprising:
in response to determining that the temperature of water exiting the tank is below the temperature limit, increasing a heating rate of the one or more heater units; optionally wherein increasing the heating rate of the one or more heaters includes activating an additional heater unit.

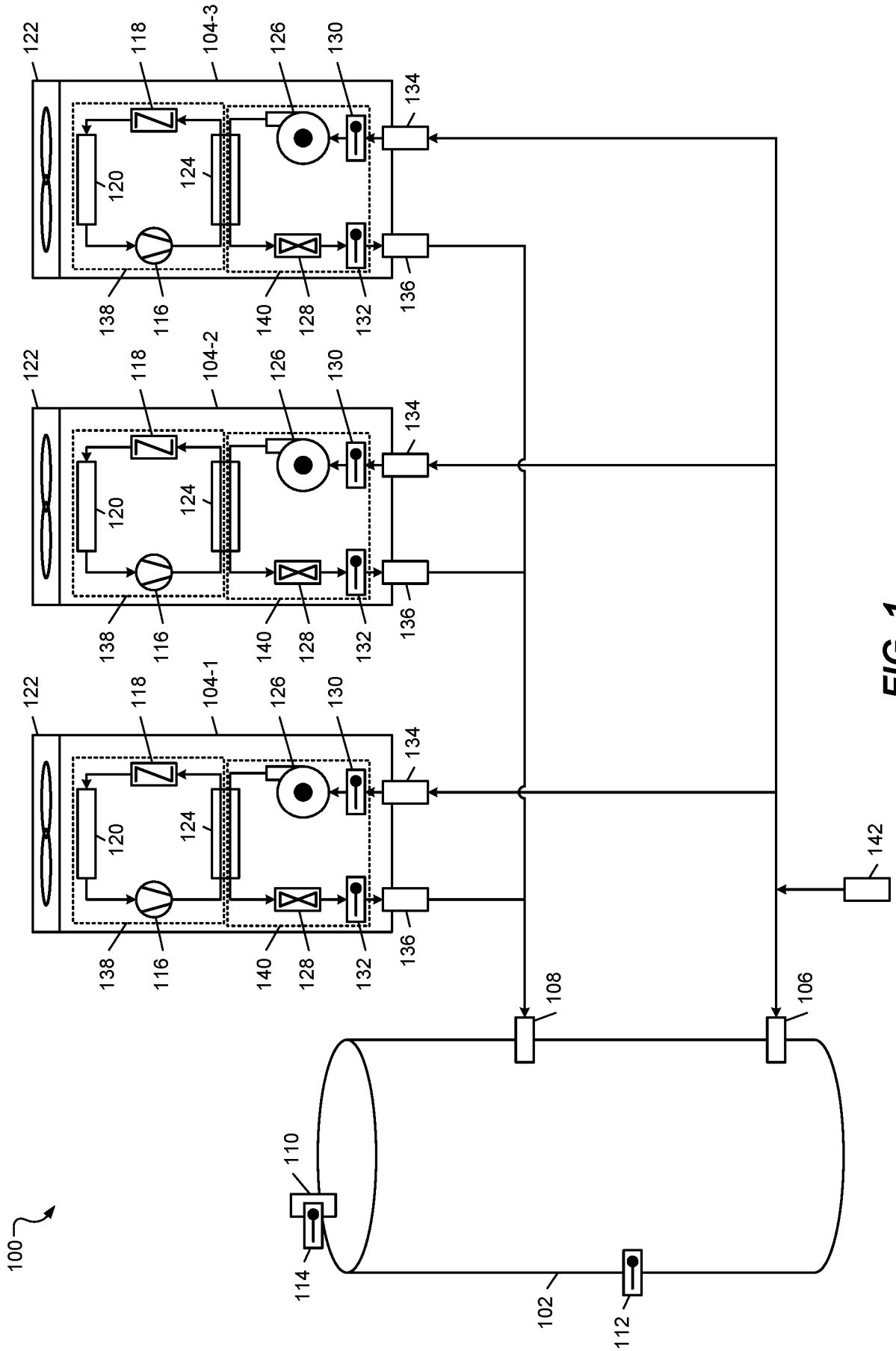

100
102
104-1
104-2
104-3
106
108
110
112
114
116
118
120
122
124
126
128
130
132
134
136
138
140
142

FIG. 1

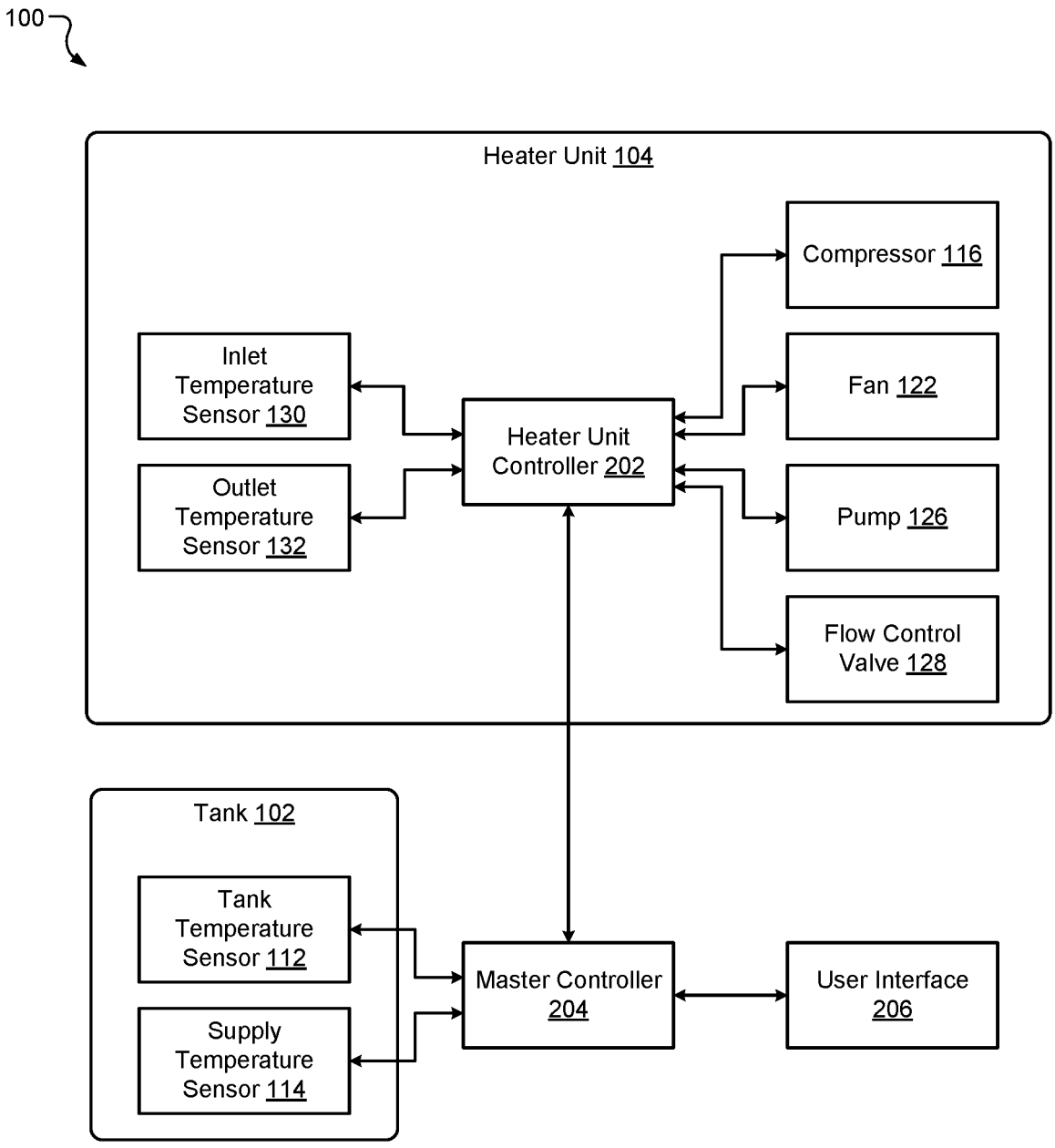

100
Heater Unit 104
Compressor 116
Inlet Temperature Sensor 130
Fan 122
Heater Unit Controller 202
Outlet Temperature Sensor 132
Pump 126
Flow Control Valve 128
Tank 102
Tank Temperature Sensor 112
Master Controller 204
User Interface 206
Supply Temperature Sensor 114

FIG. 2

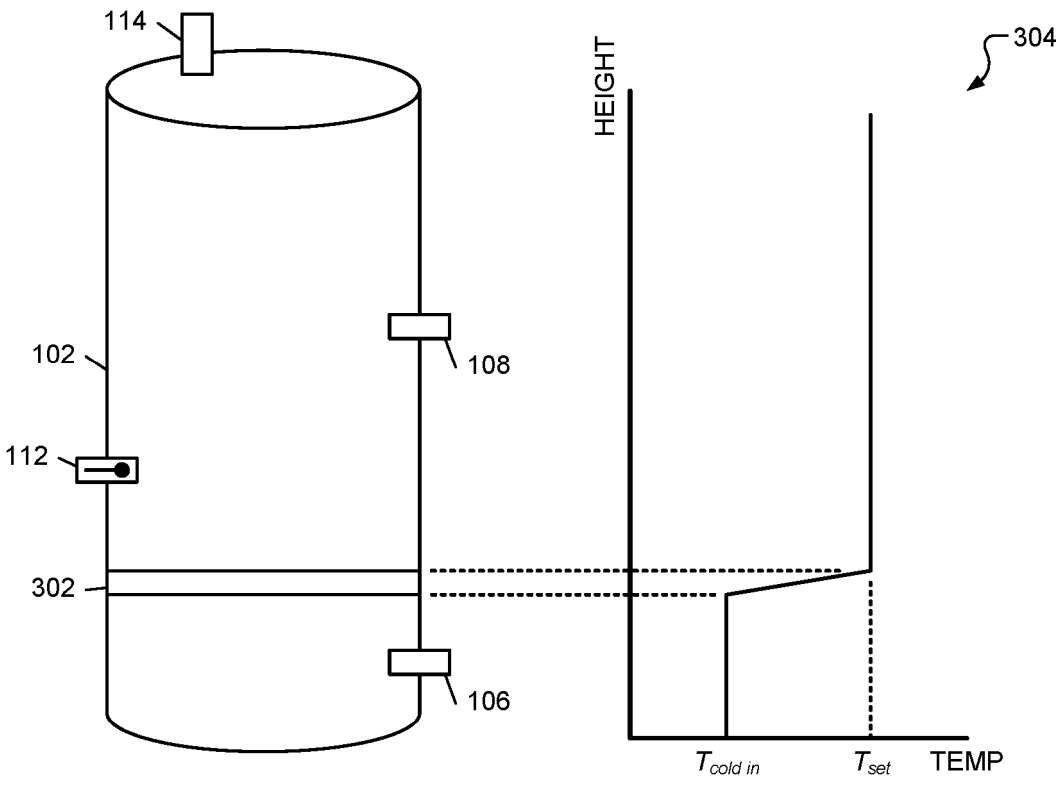

114
304
HEIGHT
102
108
112
302
106
$T_{cold\ in}$
T_{set}
TEMP

FIG. 3A

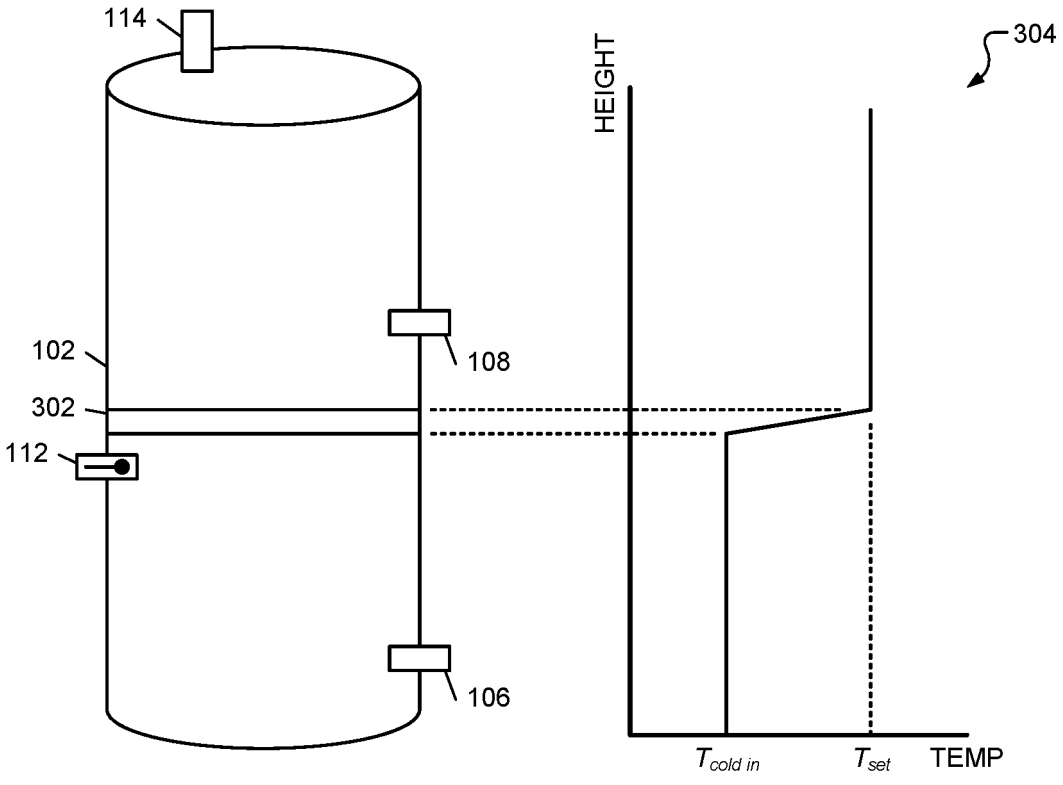

114
304
HEIGHT
102
108
302
112
106
$T_{cold\ in}$
T_{set}
TEMP

FIG. 3B

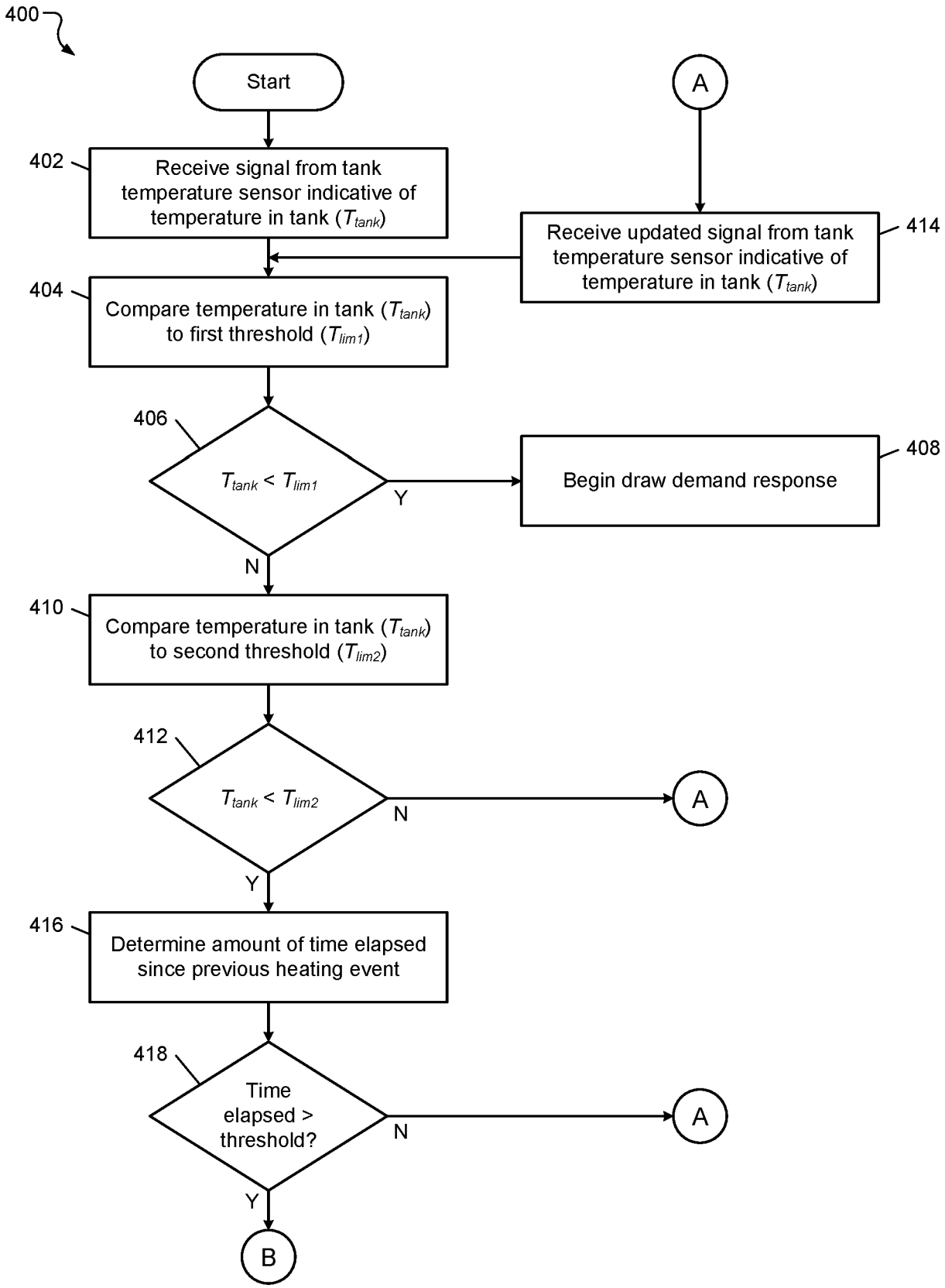

400
Start
A
402
Receive signal from tank temperature sensor indicative of temperature in tank (T_{tank})
Receive updated signal from tank temperature sensor indicative of temperature in tank (T_{tank})
414
404
Compare temperature in tank (T_{tank}) to first threshold (T_{lim1})
406
$T_{tank} < T_{lim1}$
Y
Begin draw demand response
408
N
410
Compare temperature in tank (T_{tank}) to second threshold (T_{lim2})
412
$T_{tank} < T_{lim2}$
N
A
Y
416
Determine amount of time elapsed since previous heating event
418
Time elapsed > threshold?
N
A
Y
B

FIG. 4A

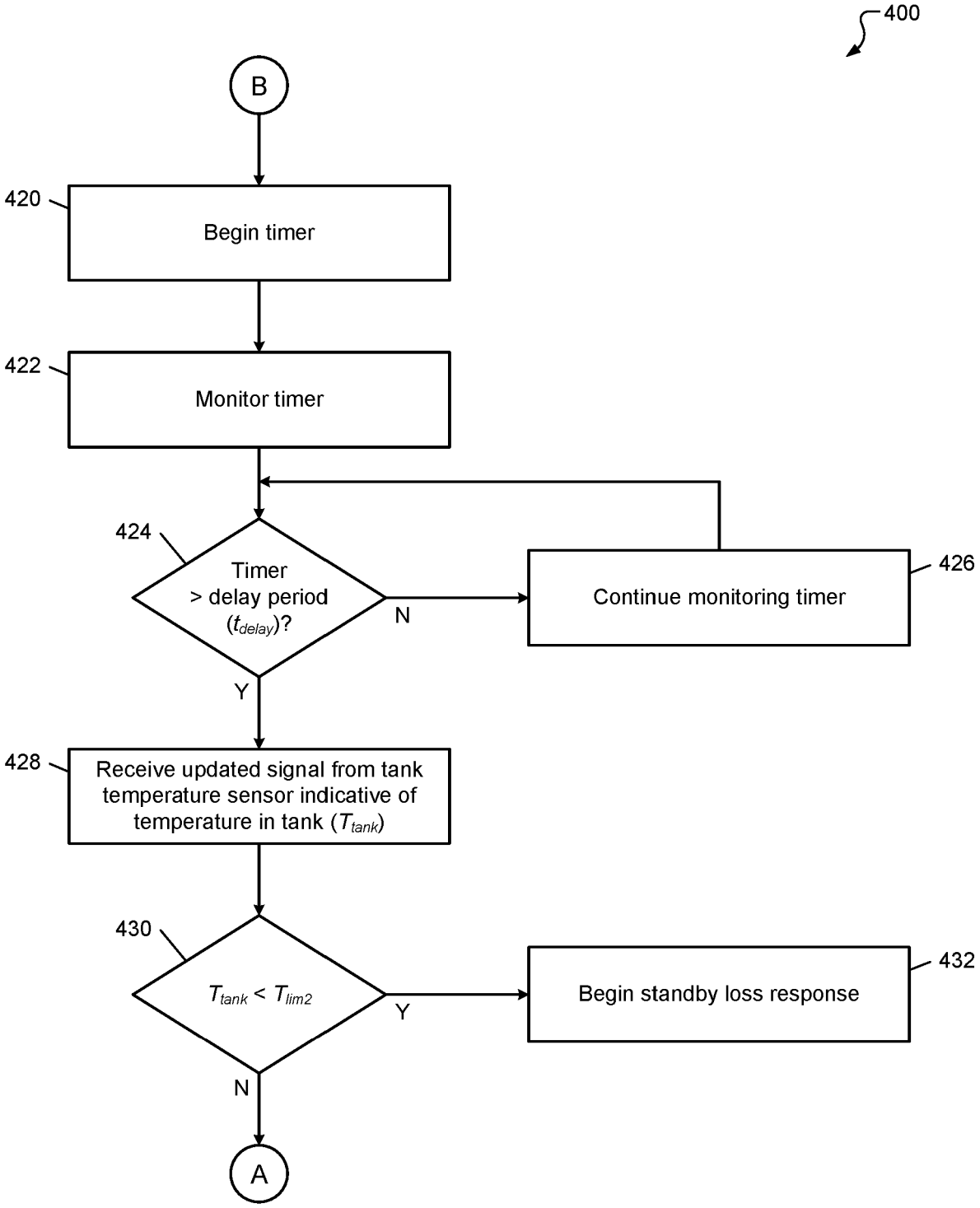

400
B
420
Begin timer
422
Monitor timer
424
Timer
> delay period
(t_{delay})?
N
426
Continue monitoring timer
Y
428
Receive updated signal from tank temperature sensor indicative of temperature in tank (T_{tank})
430
$T_{tank} < T_{lim2}$
Y
432
Begin standby loss response
N
A

FIG. 4B

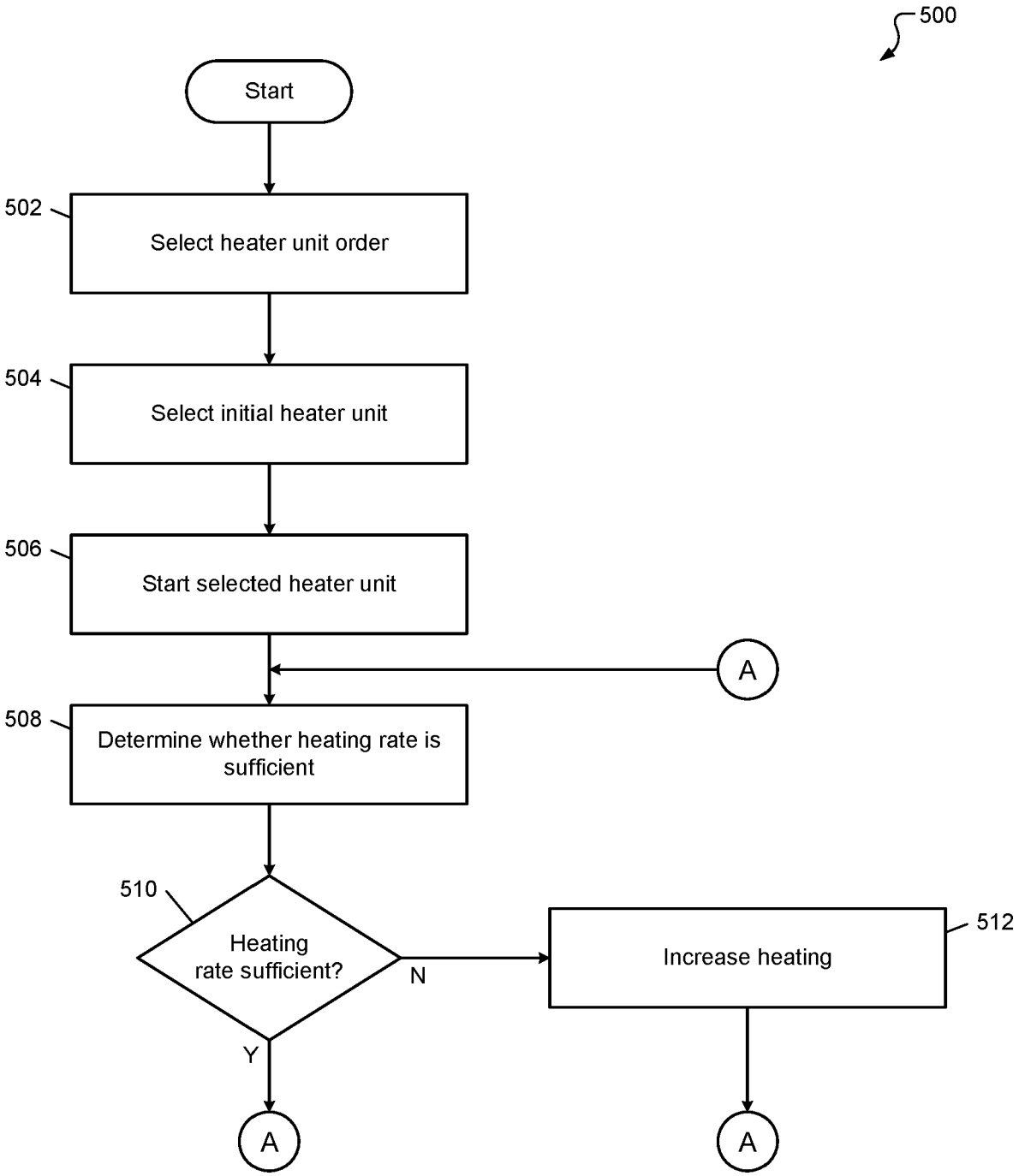

500
Start
502
Select heater unit order
504
Select initial heater unit
506
Start selected heater unit
A
508
Determine whether heating rate is sufficient
510
Heating rate sufficient?
N
Y
512
Increase heating
A
A

FIG. 5

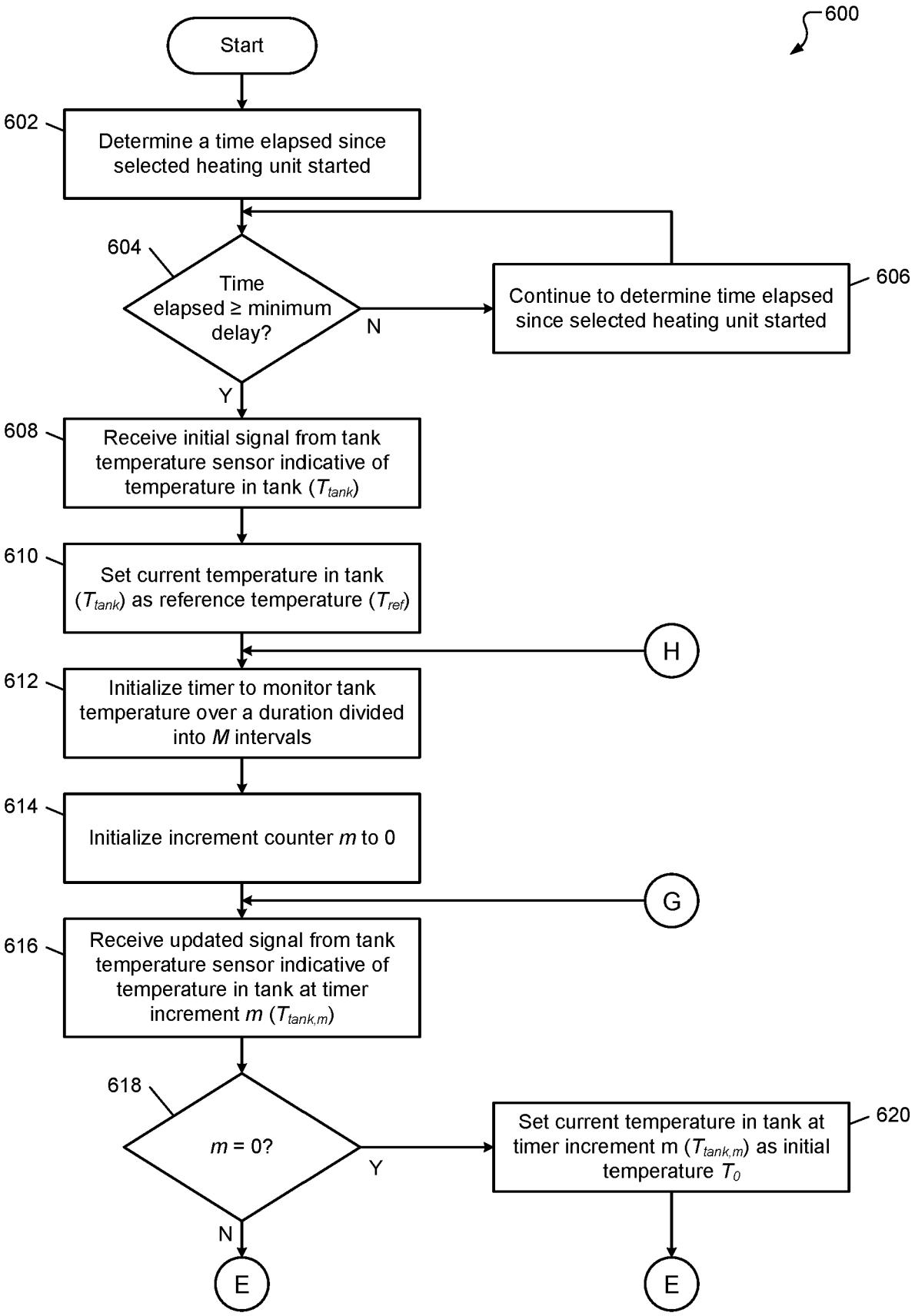

600
Start
602
Determine a time elapsed since selected heating unit started
604
Time elapsed ≥ minimum delay?
N
606
Continue to determine time elapsed since selected heating unit started
Y
608
Receive initial signal from tank temperature sensor indicative of temperature in tank (T_{tank})
610
Set current temperature in tank (T_{tank}) as reference temperature (T_{ref})
H
612
Initialize timer to monitor tank temperature over a duration divided into M intervals
614
Initialize increment counter m to 0
G
616
Receive updated signal from tank temperature sensor indicative of temperature in tank at timer increment m ($T_{tank,m}$)
618
m = 0?
Y
620
Set current temperature in tank at timer increment m ($T_{tank,m}$) as initial temperature T_0
N
E
E

FIG. 6A

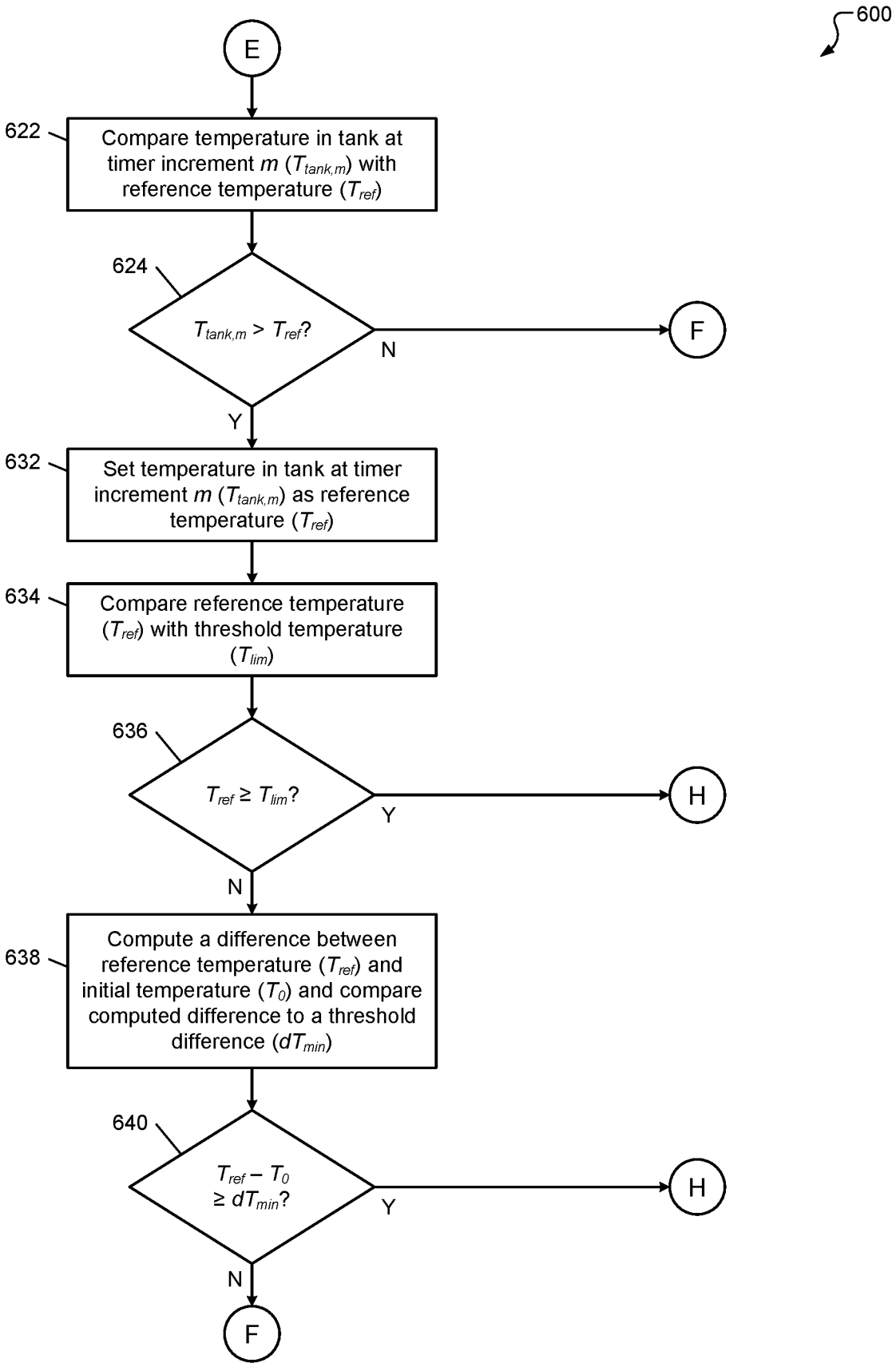

600
E
622
Compare temperature in tank at timer increment m ($T_{tank,m}$) with reference temperature (T_{ref})
624
$T_{tank,m} > T_{ref}$?
N
F
Y
632
Set temperature in tank at timer increment m ($T_{tank,m}$) as reference temperature (T_{ref})
634
Compare reference temperature (T_{ref}) with threshold temperature (T_{lim})
636
$T_{ref} \geq T_{lim}$?
Y
H
N
638
Compute a difference between reference temperature (T_{ref}) and initial temperature (T_0) and compare computed difference to a threshold difference (dT_{min})
640
$T_{ref} - T_0 \geq dT_{min}$?
Y
H
N
F

FIG. 6B

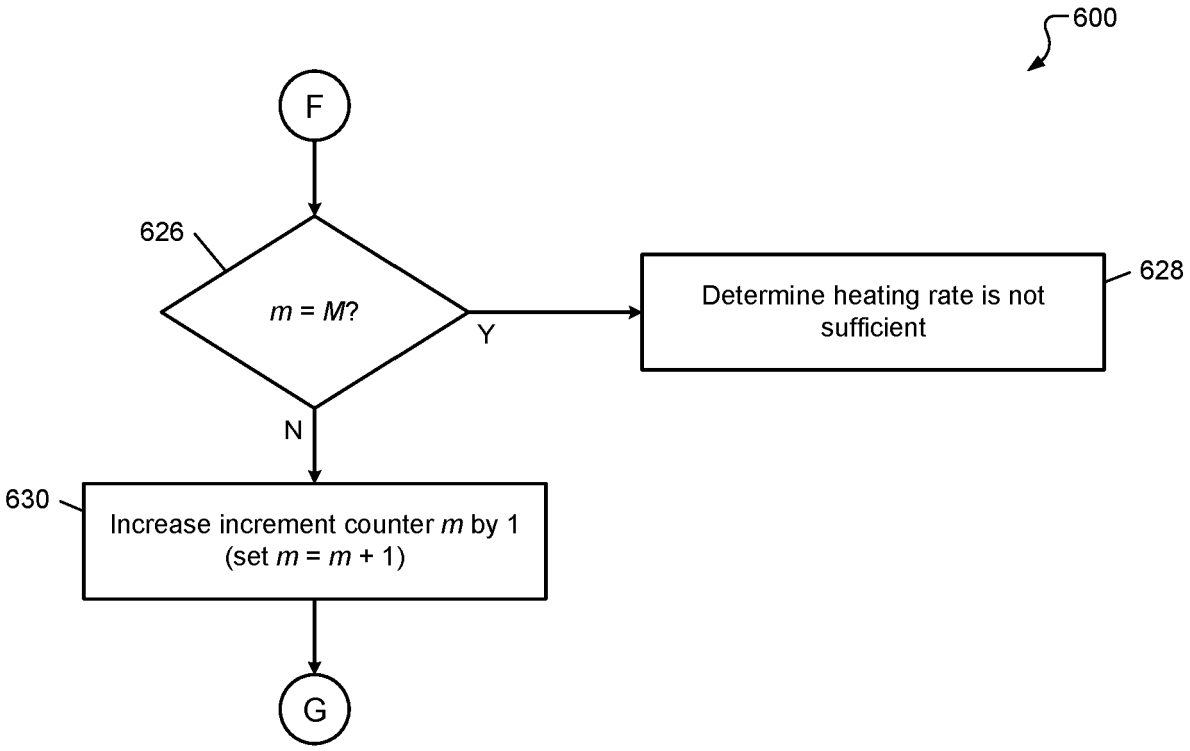

600
F
626
m = M?
Y
628
Determine heating rate is not sufficient
N
630
Increase increment counter m by 1 (set m = m + 1)
G

FIG. 6C

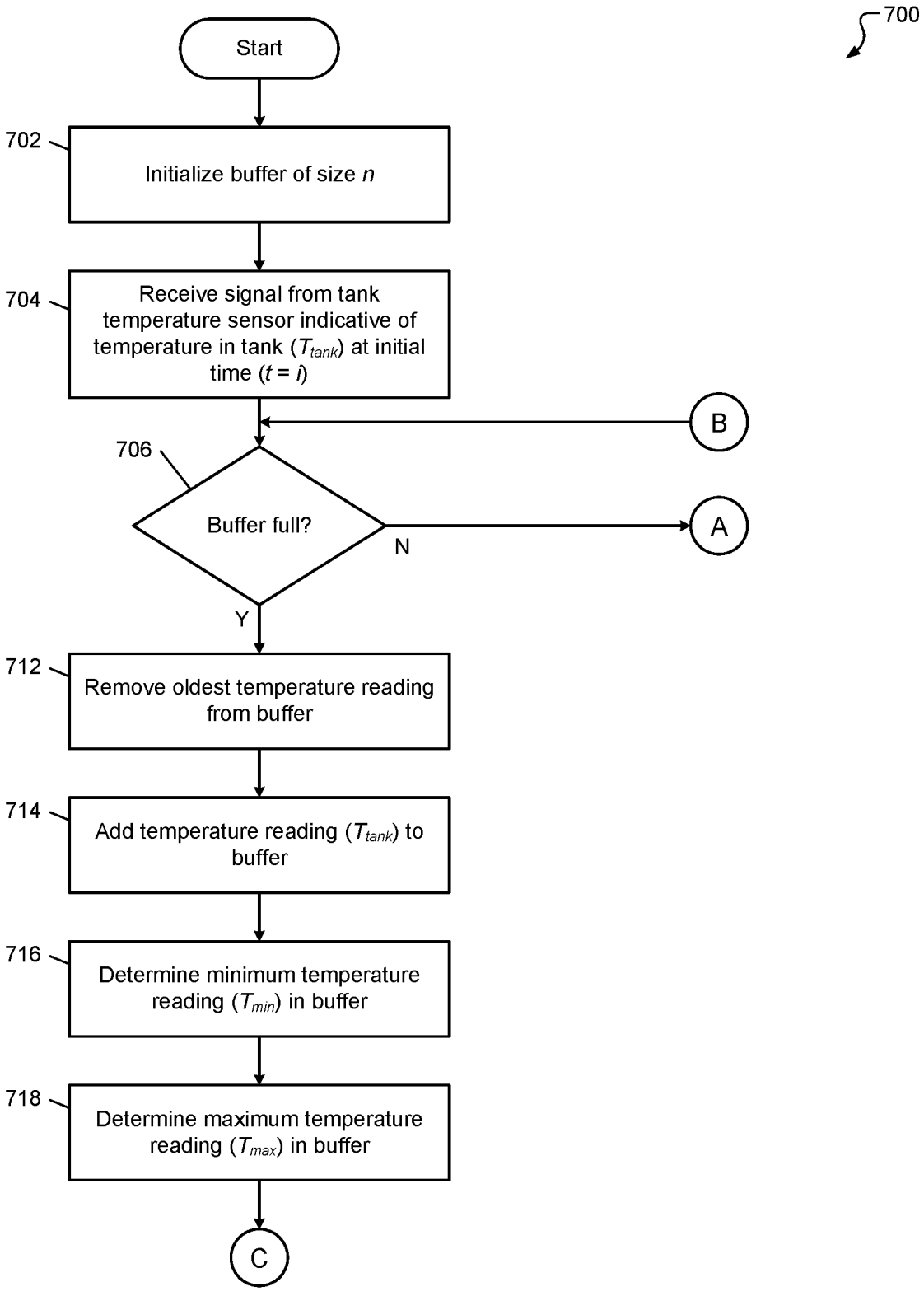

700
Start
702
Initialize buffer of size n
704
Receive signal from tank temperature sensor indicative of temperature in tank (T_{tank}) at initial time ($t = i$)
B
706
Buffer full?
N
A
Y
712
Remove oldest temperature reading from buffer
714
Add temperature reading (T_{tank}) to buffer
716
Determine minimum temperature reading (T_{min}) in buffer
718
Determine maximum temperature reading (T_{max}) in buffer
C

FIG. 7A

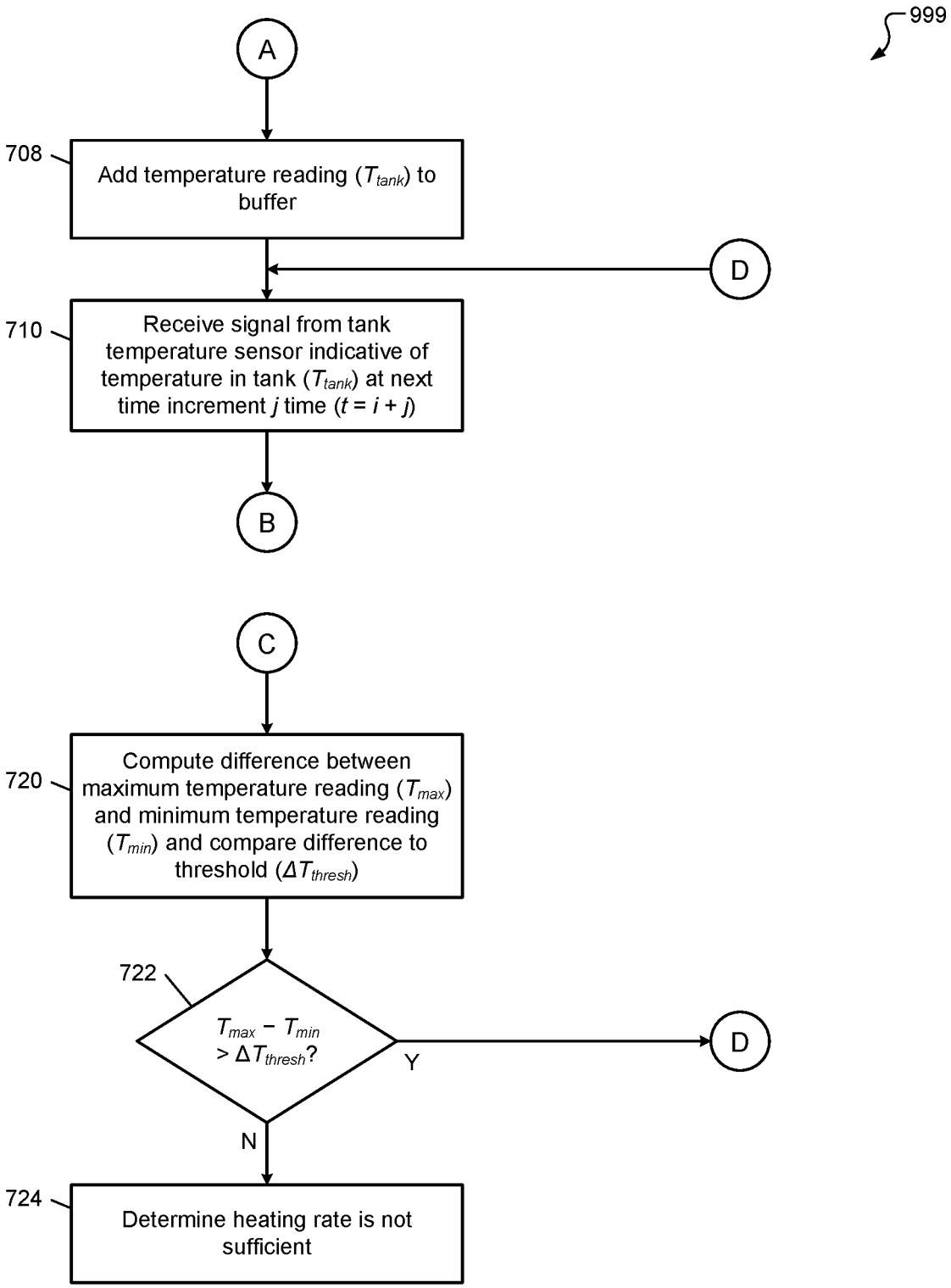

999
A
708
Add temperature reading (T_{tank}) to buffer
D
710
Receive signal from tank temperature sensor indicative of temperature in tank (T_{tank}) at next time increment j time ($t = i + j$)
B
C
720
Compute difference between maximum temperature reading (T_{max}) and minimum temperature reading (T_{min}) and compare difference to threshold (ΔT_{thresh})
722
$T_{max} - T_{min} > \Delta T_{thresh}$?
Y
D
N
724
Determine heating rate is not sufficient

FIG. 7B

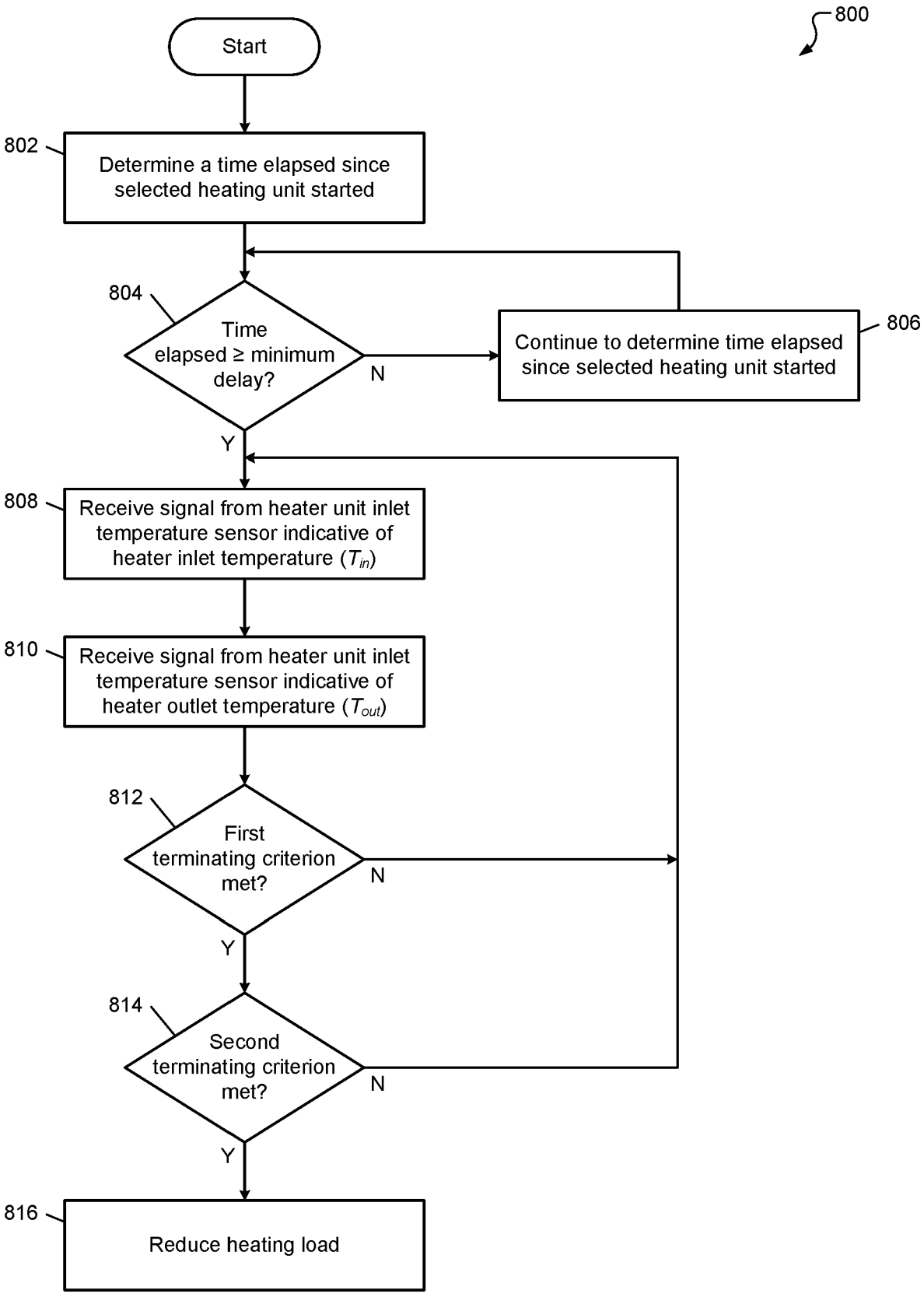

800
Start
802
Determine a time elapsed since selected heating unit started
804
Time elapsed ≥ minimum delay?
N
806
Continue to determine time elapsed since selected heating unit started
Y
808
Receive signal from heater unit inlet temperature sensor indicative of heater inlet temperature (T_{in})
810
Receive signal from heater unit inlet temperature sensor indicative of heater outlet temperature (T_{out})
812
First terminating criterion met?
N
Y
814
Second terminating criterion met?
N
Y
816
Reduce heating load

FIG. 8

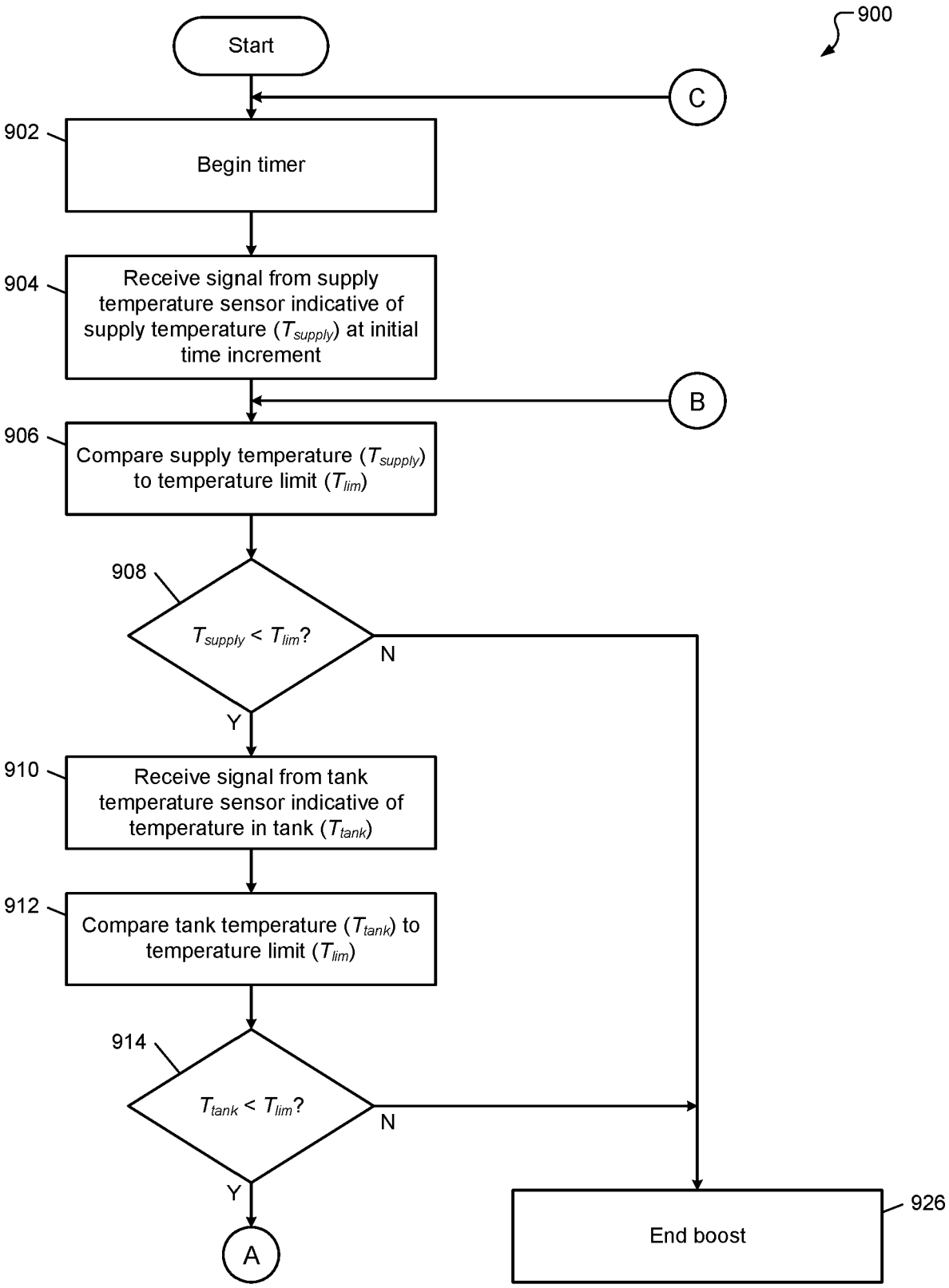

900
Start
C
902
Begin timer
904
Receive signal from supply temperature sensor indicative of supply temperature (T_{supply}) at initial time increment
B
906
Compare supply temperature (T_{supply}) to temperature limit (T_{lim})
908
$T_{supply} < T_{lim}$?
N
Y
910
Receive signal from tank temperature sensor indicative of temperature in tank (T_{tank})
912
Compare tank temperature (T_{tank}) to temperature limit (T_{lim})
914
$T_{tank} < T_{lim}$?
N
Y
A
926
End boost

FIG. 9A

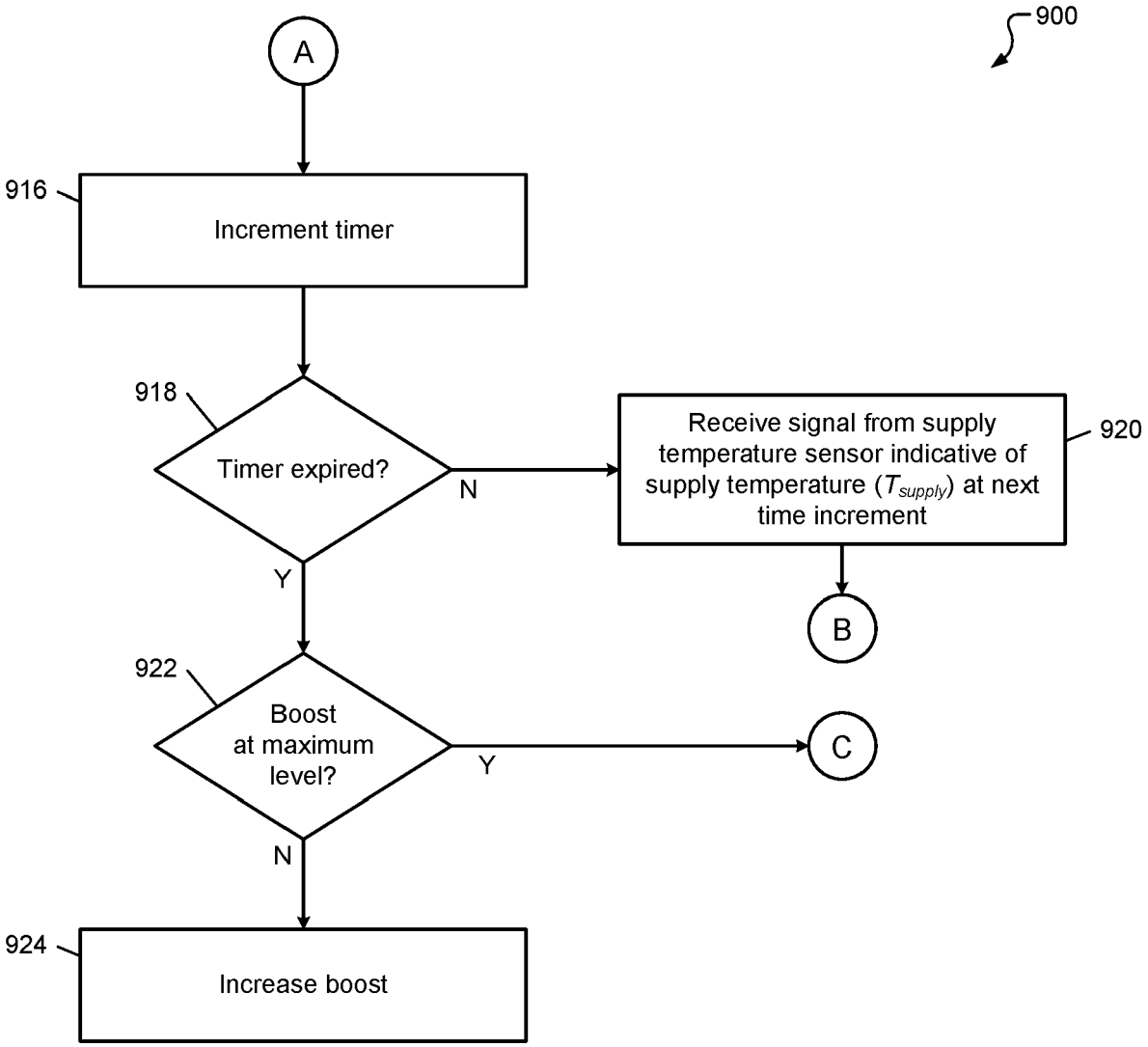

900
A
916
Increment timer
918
Timer expired?
N
Receive signal from supply temperature sensor indicative of supply temperature (T_{supply}) at next time increment
920
Y
B
922
Boost at maximum level?
Y
C
N
924
Increase boost

FIG. 9B

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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